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# PAST GLOBAL CHANGES

MAGAZINE



## ANNUAL RECORDERS OF THE PAST

### EDITORS

Bernd Zolitschka, Jennifer Pike, Lucien von Gunten and Thorsten Kiefer

### MINI SECTION

Human impact on soils and sediments in Asia

# News

## A new look and a new name

Following our review of 20 years of *PAGES news* in the last issue, we realized, based on our track record, that a facelift was overdue. But this time we've gone even further and we've also changed the name to *Past Global Changes Magazine*, or *PAGES Magazine* for short. We believe that this more accurately reflects *PAGES news'* evolution in recent years from a simple newsletter into more of a magazine-style publication. We also hope that our new look magazine, with its more descriptive title, will attract a broader audience.

## SSC Meeting in Paris

PAGES' Scientific Steering Committee (SSC) met in Paris in January 2014. In addition to approving four new Working Groups, the SSC also reviewed Working Group annual reports, met with Future Earth representatives and discussed PAGES' strategic direction in the coming year. The article on the opposite page gives an overview of the ongoing developments. The meeting was preceded by a day-long symposium featuring research talks by PAGES SSC members and a range of Parisian paleo-scientists.

## New SSC members

We are pleased to welcome three new members to the SSC in 2014:

- Peter Gell is a paleolimnologist at the University of Ballarat in Australia, and is leader of the Focus 4 Water Theme.
- Kathy Willis is a paleoecologist at the University of Oxford, UK, and has also recently been appointed Director of Science at Kew Royal Botanical Gardens in London. She is the leader of the Focus 4 Biodiversity Theme.
- Michal Kucera is a paleoceanographer and micropaleontologist at the University of Bremen, Germany, and was co-leader of the MARGO glacial sea surface reconstruction initiative.

Current SSC member, Sheri Fritz, was elected to serve on the Executive Committee (EXCOM) to replace outgoing SSC member, John Dearing. We'd like to take this opportunity to thank John in addition to the other members who recently rotated off the SSC, Eric Wolff, Michael Schulz and Fátima Abrantes, for their invaluable support and contributions throughout their terms.

## Support for meetings

At its two most recent meetings in October 2013 and January 2014, the EXCOM granted support for a total of 19 scientific and educational meetings, which are either organized by PAGES working groups or relevant to PAGES' scientific priorities. The PAGES-supported meetings are highlighted in our online calendar at: [www.pages-igbp.org/calendar/pages-sponsored-events](http://www.pages-igbp.org/calendar/pages-sponsored-events).

The next deadline for PAGES meeting support applications is 2 June. Details and application forms can be found on the PAGES website > My PAGES > Meeting Support.

## Staff update

Welcome to Brigitte Schneider, who has recently joined our team in the Finance and Office Manager role.

## Upcoming PAGES Magazine issues

The next issue of *PAGES Magazine* will focus on atmospheric dust and will be edited by members of the ADOM Working Group. Contributions to this issue are now closed. The following issue will be coordinated by the Past4Future project, of which PAGES is a project partner, and will focus on interglacials. Contributions will be sought in the coming months.

## PAGES 2<sup>nd</sup> YSM special issue

Published articles have begun appearing in the *Climate of the Past* special issue emerging from the PAGES 2<sup>nd</sup> Young Scientists Meeting in Goa, India in February 2013. All of the first authors and most of the guest editors are early-career researchers who attended the YSM. You can view the papers, some published, some still in discussion at: [www.clim-past-discuss.net/special\\_issue74.html](http://www.clim-past-discuss.net/special_issue74.html)

## PAGES' product database update

Over the last few months we have been working hard to improve the PAGES online product database. This database provides a record of all the products from the Past Global Changes project. We can now allocate products to Working Groups or events to produce an online archive of a group's activities.

You can view the database at: [www.pages-igbp.org/products/latest](http://www.pages-igbp.org/products/latest) or go to the relevant Working Group page and view their products. Please let us know if you see any gaps or errors, and send us any meeting documents e.g. presentations and posters, which we can post to create a complete online archive of an event or activity.

# Calendar

## 2<sup>nd</sup> PAGES Solar Forcing Workshop

20-23 May 2014 - Davos, Switzerland

## 3<sup>rd</sup> Asia 2k Workshop

26-27 May 2014 - Beijing, China

## 3<sup>rd</sup> Sea Ice Proxy Working Group meeting

23-25 June 2014 - Bremerhaven, Germany

## North America 2k - Phase 2

23-27 June 2014 - Fort Collins, USA

## Australasia 2k Working Group workshop

26-27 June 2014 - Melbourne, Australia

## LOTRED-SA 3<sup>rd</sup> symposium and training course

07-12 July 2014 - Medellín, Colombia

## IMBER ClimEco4 Summer School

04-08 August 2014 - Shanghai, China

## PALSEA 2014

16-23 September 2014 - Lochinver, Scotland

## Reconstruction of the Pliocene climate

17-19 September 2014 - Barcelona, Spain

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

# Featured products

## Sea Ice in the Paleoclimate System

The Sea Ice Proxies Working Group's special issue (de Vernal et al. 2013; *Quat Sci Rev* 79) aims to address some of the uncertainties in sea ice modeling; lays the methodological groundwork for sea ice reconstructions for both polar regions; and makes some of the first inferences on past sea ice cover in the Arctic.

## Paleoecology community identifies 50 priority research questions

In a recent paper from the Focus 4 Biodiversity Theme, Seddon et al. (2014; *J Ecol* 102) describe the process and outcomes of a workshop in December 2012, which used a unique community-consultation approach to produce a list of priority research questions in paleoecology.

## Using paleo-climate comparisons to constrain future projections in CMIP5

Schmidt et al. (2014; *Clim Past* 10) of the CLIVAR/PAGES Intersection demonstrate that paleo-climate simulations can help constrain, and thus improve future projections, and propose guidelines towards future research.

# Cover

## Varved sediment section from Lake Belauer

In 1912, when Gerard de Geer established one of the first chronological methods in geosciences by examining the annual laminations i.e. varves in a sediment core, the potential of natural archives for environmental reconstruction was unrecognized. However, just over a century later modern analytical techniques allow for the measuring of environmental changes at annual to sub-annual time scales, thereby bridging the gap between proxy records and instrumental data. This image shows a beautiful example of a varved sediment section from Lake Belauer in northern Germany.



# PAGES restructured

The Earth System Science landscape is being shaken thoroughly these days; the associated changes bear risks as well as opportunities. Accordingly, the coming one to two years will be a time of transition in PAGES' internal organization and external relationships. The overview below outlines the developments in the global change program framework, the plans for PAGES, and a call for new working groups.

## Evolving program setting

At the macro level, Future Earth, the new platform for global sustainability research, is getting ready to assimilate PAGES' parent organization, the International Geosphere-Biosphere Program (IGBP), by the end of 2015, in addition to two other Global Environmental Change programs, DIVERSITAS, and the International Human Dimensions Programme. The World Climate Research Program (WCRP) will also become an affiliate.

These structural changes serve expanding scientific ambitions: to provide "the knowledge and support to accelerate our transformations to a sustainable world" by integrating research better across disciplines, involving natural and social scientists, and engaging users of scientific information (a.k.a. stakeholders) in developing scientific questions and output strategies.

Over the last half year, Future Earth has become functional by establishing management structures and its first scientific activities. The recently launched website, [futureearth.info](http://futureearth.info), and the blog are worth a visit.

Twenty-seven Global Environmental Change projects, PAGES being one of them, have been invited to join the Future Earth network, and PAGES' Scientific Steering Committee (SSC) has indeed decided to request official membership over the coming months. At the same

time, it was decided to strengthen collaborative ties with WCRP to ensure that the traditionally strong paleoclimate research in PAGES has a productive platform.

In the recently submitted funding proposals to the US and Swiss National Science Foundations, PAGES proposed a revised, streamlined science structure. It responds to the changing landscape of science programs and encourages integrative activities related to the sustainability issues prioritized by Future Earth and WCRP.

## Science structure changes

The new PAGES science structure was inspired by community feedback solicited at the PAGES Open Science Meeting in 2013 in Goa and by discussions within the frameworks of IGBP, Future Earth and WCRP. The revised scheme reflects the key components of the Earth system: climate, environment, and humans (Fig 1). These three themes define the range of PAGES' scientific scope. Dissolving the boundaries between them may better reflect the increasingly integrative nature of PAGES' science than the current siloed foci structure. The Climate theme represents quantitative climate system dynamics from a paleo-perspective. The Environment theme deals with biogeosphere and ecosystem dynamics that interact with climate and introduce long-term feedbacks into the Earth system. The Humans theme covers long-term environmental changes where humans are a major agent and where environmental changes have a demonstrable effect on the functioning of both ecosystem services and societies.

A new format, cross-topical integrated activities, has been introduced to facilitate scientific exchange, synthesis, and outreach across the existing working groups and the Future Earth and WCRP networks. Targets for

such cross-topical integrated activities so far include Thresholds, tipping points and multiple equilibria in the Earth system; Extreme events and risk assessment; The Earth system in a warmer world; and Data management in support of data service efforts such as US NSF's EarthCube.

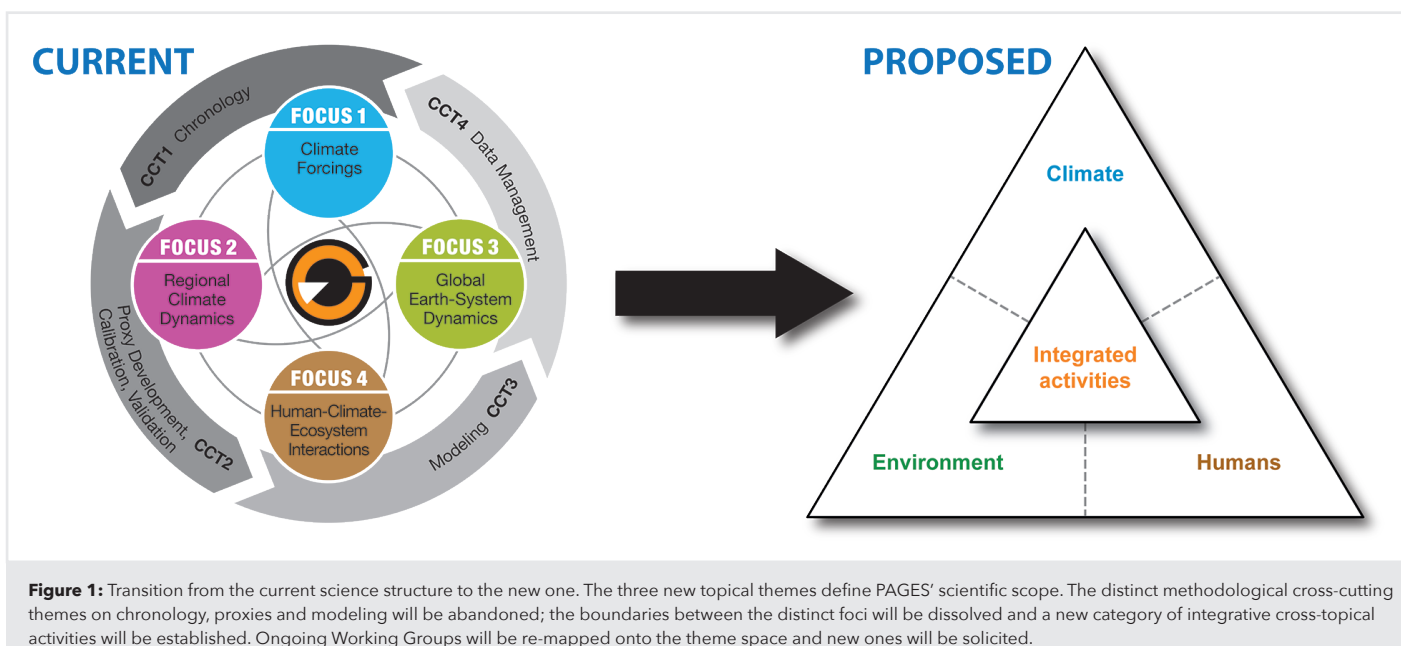
Over the next year, the current structure will be replaced by the new one (Fig. 1) and the ongoing current PAGES Working Groups will be mapped onto the new framework.

## Call for new working groups

With the structural changes afoot, and the fact that a significant number of the current working groups are now entering their final phases, it's an opportune time to announce an open call for new working groups to populate the new science structure, particularly the Humans and Environment Themes.

Based on a review of PAGES working groups, the PAGES SSC recently tightened the definition and organizational requirements of PAGES working groups: Working groups should run in ca. 3-year phases with each phase culminating in an intermediary or final major product (e.g. synthesis article, special issue, database, methodology, web-tool). After completing the phase, the working group either sunsets, or proposes a follow-up phase with a new work plan and another major product at the end.

The next deadline for new Working Group proposals is June 2 for consideration at an Executive meeting in June. The guidelines and application form are available at: [www.pages-igbp.org/workinggroups/intro](http://www.pages-igbp.org/workinggroups/intro). You can also contact Thorsten Kiefer ([kiefer@pages.unibe.ch](mailto:kiefer@pages.unibe.ch)) to discuss your proposal ideas.



# Maximizing the information yield from annually resolving natural archives

Bernd Zolitschka<sup>1</sup> and Jennifer Pike<sup>2</sup>

Natural archives containing yearly information are impressive, not only esthetically (see cover picture) but also in terms of their scientific potential. They hold the key to bridging the divide between long but low-resolution paleoscience and short but detailed climatic and environmental monitoring. Annually layered archives theoretically can combine the best from both worlds by delivering long records at sub-annual resolution. In practice, however, reality often stands in the way by presenting considerable challenges that need to be overcome before producing paleorecords at monitoring quality. Therefore, researchers are working hard to improve methodologies and understanding in order to maximize the yield from annual-resolution archives, and we report in this magazine issue on some of the latest advances and their limitations.

## The Varves Working Group

The potential of annually laminated (varved) sediments for developing detailed chronologies of past environmental change was recognized by geologists more than a century ago. However, methodological limitations in the handling of varved sediments and in developing quantitative paleoenvironmental interpretations established a perception of subjective and unreliable results. Since the end of the 20th century, with the advent of new coring techniques and innovative analytical methods, varved records have now been established as an important resource for environmental and climatic research, and scientists are working towards seasonal resolution.

The PAGES Varves Working Group (VWG) is the nucleus for this magazine issue. The group was initiated in 2010 to maximize the gain from varved lacustrine and marine records in association with other annually resolving archives (tree rings, corals, bivalve shells, ice cores, speleothems). Since its inception, the VWG has addressed a number of topics including: methodological achievements; setting up the best possible varve chronologies including age uncertainties; calibration of inherent climatic and environmental signals; data management and processing. Additionally, learning from, and integrating, other annually resolved archives is crucial for developing an understanding of the past.

The VWG organized three dedicated, cross-disciplinary workshops to discuss cutting

edge topics in high-resolution natural archives. These workshops were held in Lääne-Virumaa, Estonia (2010; Francus et al. 2010), Corpus Christi, USA (2011; Besonen et al. 2011) and Manderscheid, Germany (2012; Zolitschka et al. 2012). During this most recent workshop the idea of dedicating a PAGES magazine on year-to-year analysis of annually resolved natural archives was born. The following twelve articles document the state-of-the-art of the challenge of working at the highest temporal resolution and of harnessing a maximum of environmental and climatic information. An underlying research question for this PAGES magazine is: How can we use natural archives to approach the temporal resolution of instrumental records? Some of the articles address this by reporting on previous research (*Lamoureux and Francus; St. George; Turney et al.; Liangcheng et al.*), or new or advanced techniques (*Nakagawa; Grosjean et al.; Rasmussen et al.*), or new results (*Ojala et al.; Kemp; Schöne and Surge; Fairchild et al.; Schwikowski et al.*). Overall, the articles demonstrate that the process-level understanding of records has improved tremendously in recent years. Natural annual recorders can provide accurate reconstructions of past behavior of climate-system components on the robust and absolute timescales that are needed to better understand the mechanisms involved, and to test models of future change.

## Sediments (lacustrine, marine)

The study of varved sediments is progressing quickly towards analyses at annual and seasonal resolution. High-precision depth control is a necessity for high-resolution studies. When using "destructive methods" that require sampling the sediment core, new cutting and subsampling techniques have been developed that enable core sectioning and parallel core correlation at annual resolutions. These new methods also correct for depth changes due to expansion and contraction during storage (*Nakagawa et al.*).

To reach sub-annual resolution, non-destructive scanning techniques such as element count-rates analyzed by micro-XRF scanning (Fig. 1) are often more effective. Another such method is hyperspectral imaging, which is used to identify organic components and minerals on the basis of their diagnostic light absorption. Not only is this method promising for lake and marine sediments but it is also

applicable to tree rings and speleothems (*Grosjean et al.*).

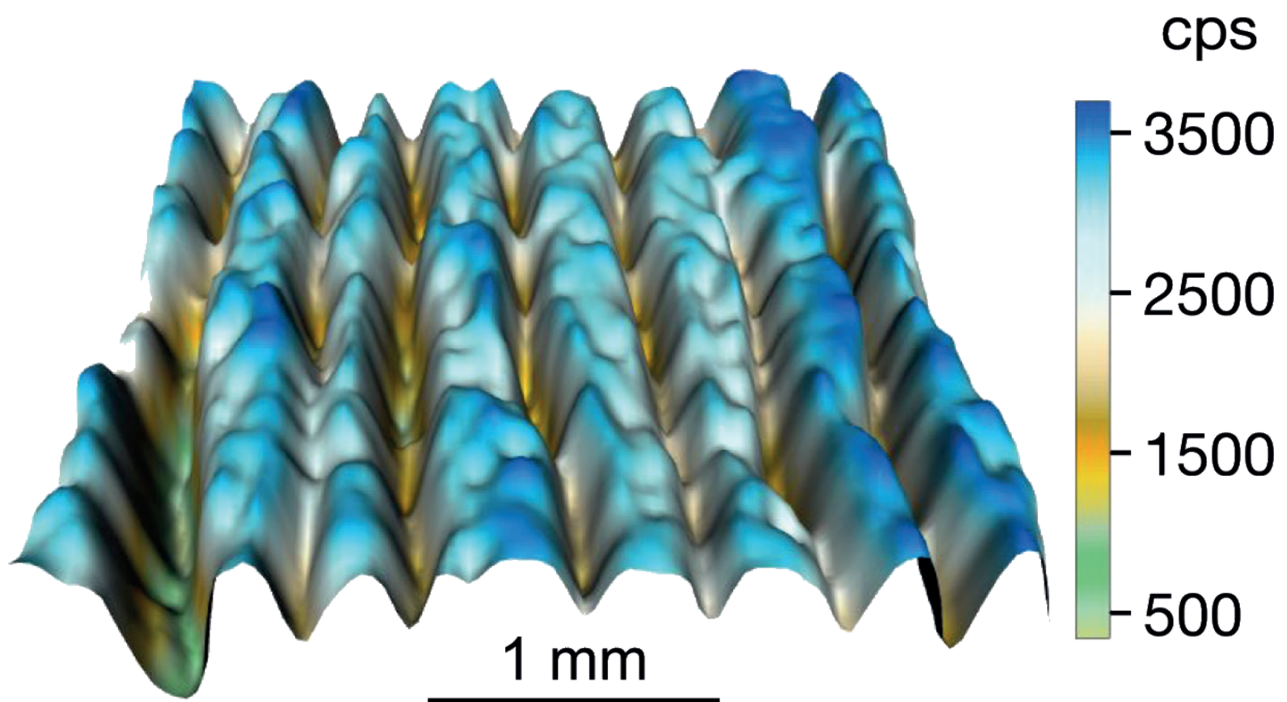
Just as important as high-resolution chronology and analysis is the understanding of sediment-formation processes. Deposition of abiotic and biotic components can be monitored with sediment traps and time-series data used to calibrate varves and their paleolimnological proxies against instrumental data (*Ojala et al.*). Long-term monitoring with sediment traps in the Arctic has permitted the identification of quantitative processes that form varves and the documentation of the climate signals conveyed through runoff generation and downstream sediment transport. Thus, previously unrecognized hydroclimatic control mechanisms on sediment delivery are detectable (*Lamoureux and Francus*).

Marine varved sediments are not restricted to oxygen-depleted or silled basins, or to productive shelves and slopes. They are also found at deep-sea sites with massive particle fluxes that suppress benthic faunal activity and therefore preserve laminations. Thus, the traditionally centennial-resolution quantitative paleoceanographic reconstructions can be increased to annual or seasonal resolution using scanning electron microscope techniques. Moreover, stable isotopes derived from diatoms preserved within varves offer insights into dynamic processes of ocean-atmosphere variability on seasonal timescales (*Kemp*).

## Organisms (trees, bivalves)

Tree-ring width records have been developed at thousands of locations, particularly in the Northern Hemisphere. Their broad regional coverage and extended replication forms the basis of a global network representing a valuable resource for high-resolution climate reconstruction (*St. George*). In the Southern Hemisphere relatively few tree-ring records are available but new methods are being developed in Australasia to exploit their potential in this region. Analytical advances can characterize wood at the level of single cells, enabling a detailed study of the role of environmental conditions in tree-ring formation. These wood-property chronologies are developed for samples without any seasonal signal in tree-ring width and thus demonstrate the paleoscientific potential of trees in regions where standard analyses have failed. Another exciting possibility in Australasia is radiocarbon





**Figure 1:** Micro-XRF elemental grid scan of a varved sediment section from the Piánico paleolake (Italy) documenting a subannual geochemical profile for the element Ca (image courtesy of Peter Dulski).

calibration using subfossil kauri trees from northern New Zealand that potentially cover the complete range of  $^{14}\text{C}$  dating (Turney *et al.*).

Bivalves, present in many aquatic environments, can record environmental changes at unprecedented temporal resolution - from years to days. Their individually short growth-increment chronologies can be combined by cross-dating segments with overlapping life spans of other individuals to develop composite chronologies covering millennia, while stable isotope data and elemental ratios provide process-driven environmental information (Schöne and Surge).

#### Physical records from travertine and ice

Calcareous cave deposits (speleothems) are common features in karst environments. Statistical analyses of their growth-rates reflect the mixing of rainfall with groundwater and are used to reconstruct hydroclimate and, more recently, annual temperature changes (Tan *et al.*). Seasonal climatic signals are transmitted to speleothems via the quantity, chemistry and isotopic composition of percolating water in caves. Advances in high-resolution measurements of stable isotopes, trace elements and organic fluorescence reveal sub-annual variations in speleothem chemistry that result not only in improved chronologies, but also in seasonal climatic and environmental changes (Fairchild *et al.*).

Polar ice caps provide a wealth of information on past climates and environments as well as a very accurate chronology through counting the annual layers. Historically, ice-core chronologies have relied on manually detecting

and counting annual layers; however, the development of novel algorithms for automated and objective annual layer counting has allowed researchers to refine and extend these chronologies. Parallel analysis of different impurity records is also recommended to establish a robust chronology (Rasmussen *et al.*). High-mountain ice cores have the potential to provide subannual ice-core records; however, annual layer thinning with increasing depth increases dating uncertainties. While new continuous flow analysis-techniques are increasing the spatial resolution, calibration with instrumental data is often still restricted to multi-year resolution, which limits the potential of annual resolution from mountain glacier ice cores (Schwikowski *et al.*).

A major aim of the VWG is to connect research groups working on different annual archives, eventually leading towards integrated model-data comparisons at an annual to subannual scale. Products of the VWG include overview articles (Ojala *et al.* 2012; Francus *et al.* 2013) and the "Varves Image Library" (work in progress), providing easy access especially for young scientists to digital images of a wide range of varved sediments, the "Varve Data Base" (Ojala *et al.* 2012) with a large variety of data for well-published varved sequences, and the "Varves Literature Archive", a constantly updated and searchable text file with varve-related publications.

#### LINKS

**Varves Image Library:**  
[www.pages-igbp.org/workinggroups/varves-wg/varve-image-library](http://www.pages-igbp.org/workinggroups/varves-wg/varve-image-library)

#### Varves literature archive:

[www.pages-igbp.org/download/docs/working\\_groups/vwg/Varve%20publications.pdf](http://www.pages-igbp.org/download/docs/working_groups/vwg/Varve%20publications.pdf)

#### Varves database:

[www.pages-igbp.org/workinggroups/varves-wg#data](http://www.pages-igbp.org/workinggroups/varves-wg#data)

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# Layers within layers: quantifying seasonal versus event processes in Arctic clastic varved sediments

Scott F. Lamoureux<sup>1</sup> and Pierre Francus<sup>2</sup>

**Advances in the interpretation of Arctic clastic varved sediments have emerged from long-term process monitoring, and micro-sedimentological and micro-geochemical analyses. These developments permit the identification and interpretation of the quantitative processes that form varves and allow novel paleoclimate records to be generated.**

Clastic annually laminated (varved) lake sediments are important paleo-records from Arctic regions. They offer high temporal resolution where other natural archives are localized (ice cores) or unavailable (tree rings), and substantially contribute to regional paleoclimate syntheses (Kaufman et al. 2009). Clastic varves are composed of mineral material introduced to the lake by streams and rivers. The climate signal is conveyed through the generation of runoff and downstream sediment transport into the lake. Since the pioneering work of Hardy et al. (1996), who conducted field process studies in Arctic Canada to determine a quantitative relationship between climate, hydrology, sediment transport and varve deposition, a number of sedimentary studies have refined our understanding of the control mechanisms over sediment delivery to lakes and the type of paleoenvironmental information contained within clastic varves.

## Hydroclimate controls over sediment transport

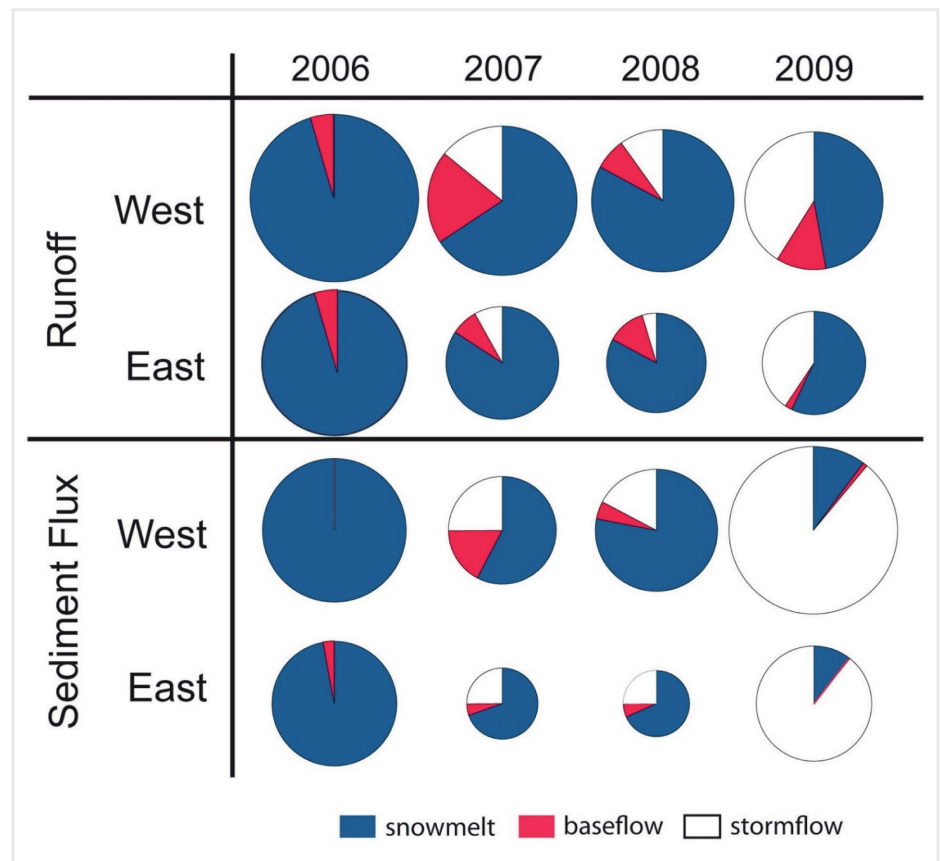
A key limitation to most field process studies has been their short-term nature of often only 2-3 years. Sustained monitoring efforts have emerged during the past decade, particularly the Cape Bounty Arctic Watershed Observatory (CBAWO; <http://geog.queensu.ca/cbawo>) in the Canadian High Arctic. This project, initiated in 2003, develops long-term climate, hydrological and sediment datasets to investigate the processes that contribute to the formation of clastic varves and their paleoclimate record.

The work of Hardy et al. (1996) established a quantitative process relationship between upper air temperatures, discharge, and suspended sediment transport at Lake C2 on northern Ellesmere Island. Based on this relationship, meteorological data from the nearest long-term weather station were used to estimate total suspended sediment transport for the years 1950-1992. These estimates were

then compared to the varve thickness record. Results showed strong similarity between the varve record and the modeled results, suggesting that the varve thickness was primarily controlled by summer air temperatures.

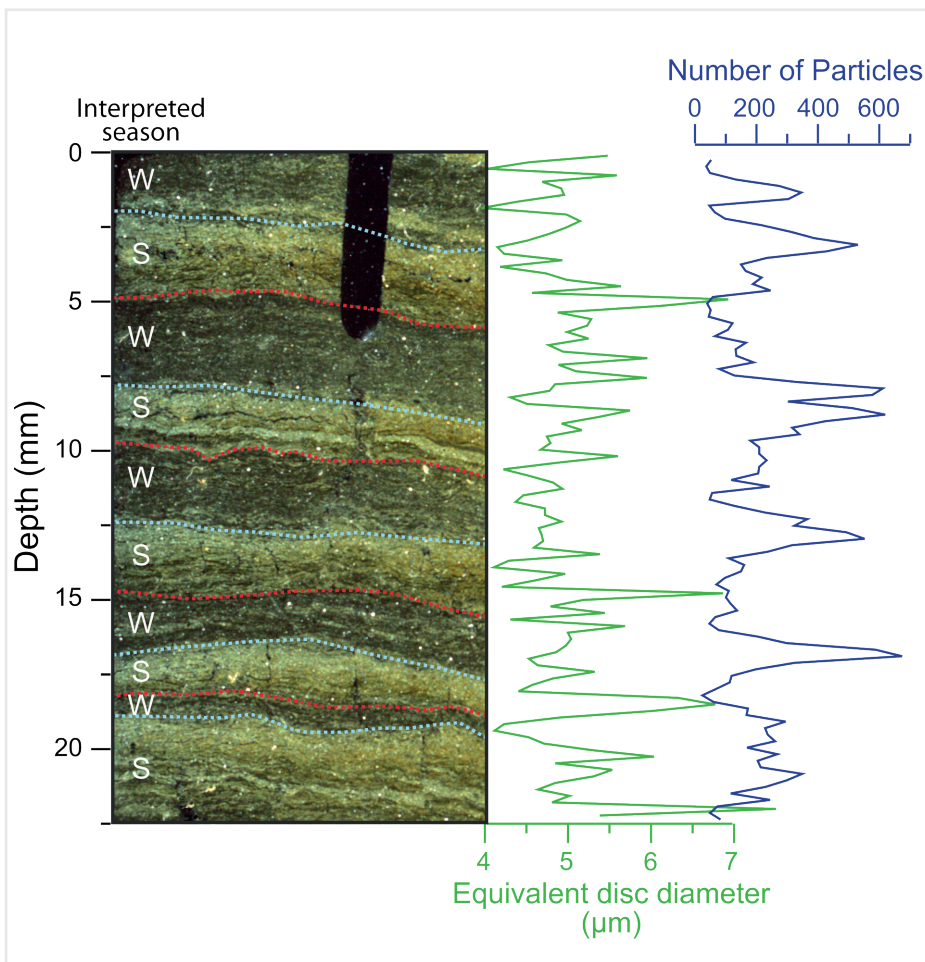
However, longer studies at CBAWO and elsewhere have shown limitations to the

temperature-runoff relationship. For example in spring, the snowpack becomes exhausted as the season progresses with the result being that sediment transport is controlled at the seasonal scale by the quantity of available snow (Cockburn and Lamoureux 2008). While the melting snow in the catchment controls the total runoff and sediment transport during the



**Figure 1:** Four years of river discharge and suspended sediment flux at Cape Bounty Arctic Watershed Observatory (CBAWO). Pie size is scaled to the magnitude of flux. Note the contrast between 2006 when snowmelt dominated runoff and sediment transport, compared to 2009 when two major rainfall events were responsible for 89% of sediment transport (after Lewis et al. 2012).





**Figure 2:** Results of an image analysis of particles in five varves from marine sediments in Saanich Inlet, British Columbia. This image was obtained using a flatbed scanner under cross-polarized light while particle size analysis was carried out at 220  $\mu\text{m}$  intervals (102 measurements in total). Interpreted seasons are indicated as winter (W) and summer (S) (Lewis et al. 2010). Blue dashed lines indicate the transition from underlying terrigenous sediment to overlying biogenic sediment and red lines indicate the opposite transition.

spring freshet, few studies have been able to assess the role of major rainfall on sediment transport and varve formation. Some studies in northwestern North America (Cockburn and Lamoureux 2007) and the Arctic (Francus et al. 2002; Chutko and Lamoureux 2008) have suggested rainfall only plays an intermittent role in the formation of clastic varves, but these studies depend on statistical assessment of the varve and related meteorological records, while direct rainfall and sediment transport data from the region were largely non-existent.

Therefore the long record from CBAWO provides valuable first systematic indications of the role of major rainfall events (although the likelihood of observing a rainfall event is low and unpredictable in the relatively dry High Arctic). Monitored rainfall events demonstrated that the sediment transport by a single rainfall event can equal, or exceed, that of the snow melt freshet (Lewis et al. 2012; Fig. 1). For example, a 35.7 mm rainfall event lasting several days in July 2009 transported 89% of the seasonal sediment flux, and would have presumably dominated the annual sedimentary structure. Analyses of smaller rainfall events from other years further suggest that the associated increase in runoff and sediment transport is non-linear (Lewis et al. 2012). For example, prior dry soil conditions can result in minimal discharge response and sediment transport. Hence, the sediment response to rainfall

depends on both the amount and intensity of the rainfall, and the levels of soil moisture.

The results that have emerged from a decade of observation at CBAWO demonstrate the challenge of quantifying the role of rainfall in the process of varve formation; however, they also suggest that statistical associations of rainfall influence inferred from detailed sedimentology (Francus et al. 2002; Cockburn and Lamoureux 2007; Cuven et al. 2010; Lapointe et al. 2012) are highly plausible. Further refinement of these approaches is warranted, given the challenge of recognizing rainfall character from proxy evidence.

#### Emergent analysis methods and new proxies

There is a substantial need to systematically identify and determine operational proxies for interpreting long-term variations in fine-scale facies. The sedimentological analysis of varves has traditionally been done using thin sections, and the detailed study of intra-varve (or subannual) structures has been fruitful to identify single snowmelt and rainfall events (Cockburn and Lamoureux 2007; Chutko and Lamoureux 2008). Now, new techniques including micro X-ray fluorescence ( $\mu\text{-XRF}$ ) core scanning permit even more detailed characterization of subannual sedimentary structures, recognition of additional facies, and analysis of grain sizes (Cuven et al. 2010). Furthermore,

semi-automated scanning electron microscopy acquisition and image analysis have made scanning of particle size structures possible even at (sub)annual resolution (Fig. 2). In a recent study, Lapointe et al. (2012) developed a 1750-year particle size distribution record from a High Arctic varve record, and through statistical analysis revealed significant relationships with summer rainfall. Hence, these new sedimentological approaches are providing the means to further discern the influence of rainfall and other climatic events on the sedimentary varve record in the Arctic and elsewhere.

#### Future developments

Recent work with Arctic varves has uncovered previously unrecognized hydroclimatic controls over sediment delivery to lakes, particularly the important, occasionally dominant, role of summer rainfall on sediment yield. Recognition of these hydroclimatic influences has been advanced through sustained field monitoring efforts, while new methodologies and an emphasis on fine-scale sediment facies analysis in clastic varves has yielded new proxy indicators and novel paleoclimate records. These substantial advances will help to improve the fidelity of paleoclimatic interpretations of Arctic varves and clastic varves in general. The next frontier will be the explicit combination of detailed facies analysis with proxy indicators (e.g.  $\mu\text{-XRF}$  geochemical data) and other novel sedimentological methods such as image analysis.

#### ACKNOWLEDGEMENTS

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Lewis T et al. (2012) *Hydrol Processes* 26: 2003-2018

# Understanding varve formation processes from sediment trapping and limnological monitoring

Antti E.K. Ojala<sup>1</sup>, C. Bigler<sup>2</sup> and J. Weckström<sup>3</sup>

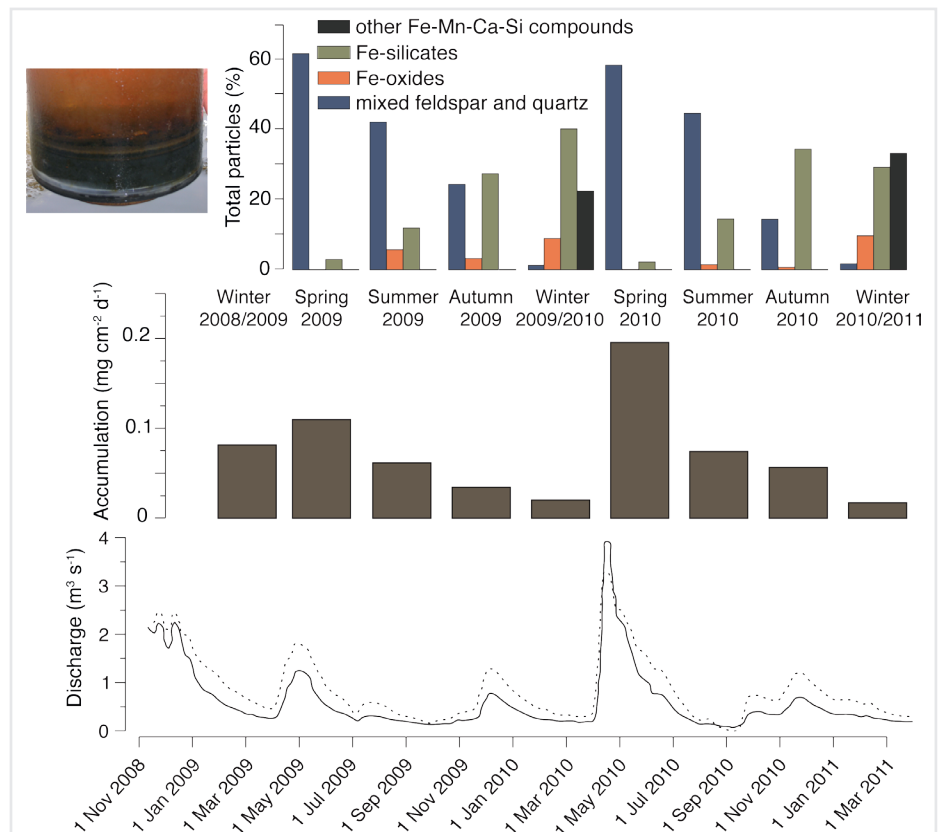
**Sediment trapping and monitoring is essential for paleolimnological research. It has allowed us to understand the seasonal deposition of the abiotic and biotic components within varved lakes in Sweden and Finland, thus providing a basis for paleoenvironmental interpretations.**

Varved sediments are rich and detailed archives of paleoenvironmental information. Interpreting these archives correctly requires that the sedimentological processes leading to the varve deposition and their controlling factors are known, understood and quantified. Modern lake research, particularly when dealing with seasonally to annually resolved varved sediments, combines limnological monitoring, sediment trapping and sediment analysis (Leemann and Niessen 1994; Bigler et al. 2012; Ojala et al. 2013). The reason for such an integrative approach is to understand to what extent the sediments and its components reflect the ongoing sedimentary and biogeochemical processes within a lake basin (Ryves et al. 2013). Monitoring and trap studies also enable us to better understand the seasonal information within a varve (i.e. definition of a local varve model) and effectively calibrate varves and paleolimnological proxies against instrumental hydrological and meteorological data.

## Varve formation

For proglacial lakes with clastic varves (Leemann and Niessen 1994; Lamoureux 1999) and Boreal lakes with clastic-biogenic varves (Renberg 1982; Zillén et al. 2003; Ojala et al. 2000), the deposition of varves is a function of hydrometeorological parameters, in particular seasonal runoff and the associated discharge of suspended sediment from the catchment into the depositional basin. However, as discussed by Lamoureux (2012), the deposition of allochthonous clastic material is also affected by limnological and geomorphological features, which determine sediment pathways to deposition and the yield from the catchment area. Understanding these processes through monitoring and sediment trapping is a prerequisite for the correct interpretation of physical varve data and their calibration against instrumental observations. Awareness that many varved records in Europe and North America contain both a climate-environmental as well as a superimposed local anthropogenic signal has focused scientists on gaining more comprehensive information on the ongoing sedimentary processes in these lakes (Snyder 2012; Stockhecke et al. 2012; Tylmann et al. 2012; Ojala et al. 2013).

Based on three years of monitoring data on seasonal particle pulses in Lake Van in Turkey,



**Figure 1:** Hydrological data, seasonal sediment accumulation, and seasonal sedimentation of different components in Lake Nautajärvi (Finland) during the monitoring period between spring 2009 and winter 2010/2011 (Ojala et al. 2013). The photograph of the sediment collected in a plastic tube shows deposits of two minerogenic spring laminae and uncompacted laminae of biogenic material deposited during summer, autumn and winter.

Stockhecke et al. (2012) were able to show for the first time that the seasonal particle flux is linked to hydrological and meteorological forcing, which is ultimately controlled by atmospheric circulation patterns. They demonstrated pronounced temporal and lateral variations in suspended-matter concentration within the lake, providing a basis for the reconstruction of past seasonal climate patterns based on the varved lithology.

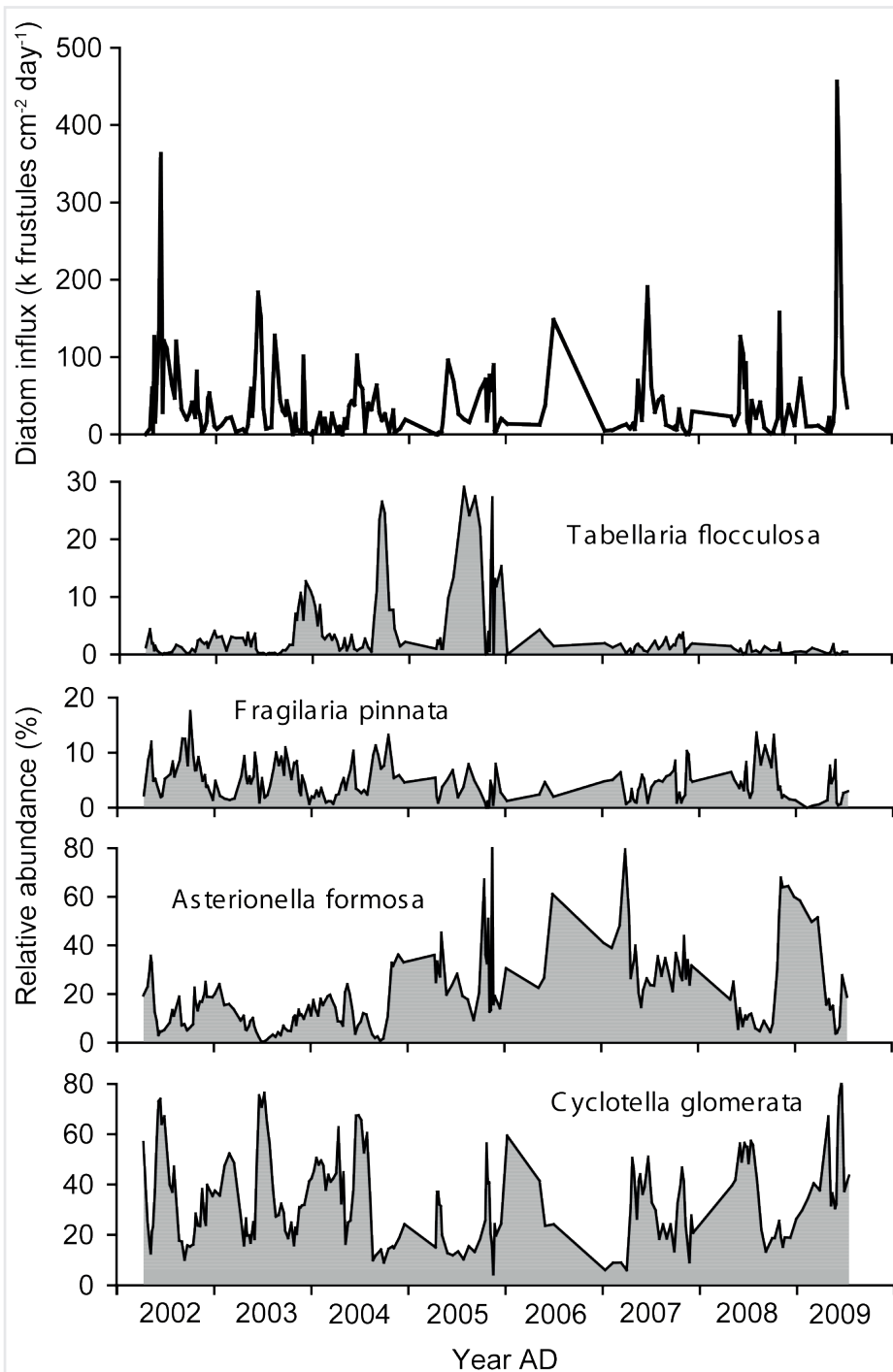
In the Finnish boreal forest zone, Ojala et al. (2013) have monitored the seasonal accumulation patterns of allochthonous clastic material and organic remains in Lake Nautajärvi, which contains a nearly 10,000-year-long continuous record of clastic-biogenic varves (Ojala and

Alenius 2005). Comparison of the seasonal sediment fluxes between the climatologically and hydrologically different years of 2009 and 2010 showed that the seasonal fluxes recorded in sediment traps correspond with environmental changes. Deviation in seasonal accumulation was most apparent in the rate of spring deposition of allochthonous mineral matter and less pronounced for summer, autumn and winter sediment fluxes (Fig. 1).

## Sediment flux and deposition

Sediment fluxes undergo burial, compaction and various bio-geochemical changes before being preserved as a sedimentary deposit. Understanding the spatial and temporal variability of these processes is essential for a reliable





**Figure 2:** Total diatom influx and relative abundance of major diatom taxa in Nylandssjön since 2001 based on sediment trap data (Bigler et al. 2012).

interpretation of any sediment record. Since 1979, Renberg (1986), Petterson et al (1993) and Gälman et al. (2006) have collected >15 freeze-cores from Lake Nylandssjön (northern Sweden) and analyzed the clastic-biogenic varves in order to quantify the sedimentation processes. Their study showed that sediment compaction is most rapid in the first years after deposition, i.e. varve thickness decreases by about 60% within five years (Maier et al. 2013). At Nylandssjön the rate of compaction is linked to a loss of pore water, but despite compaction, the initial signal of varve thickness variations was preserved following burial and compaction. Similarly, the concentration of carbon and nitrogen in the sediment decreased by 20% and 30%, respectively, within the first five years after deposition, but only 23% and 35%

after 27 years (Gälman et al. 2008). The study also demonstrated that this process affected the stable isotope ratios of  $\delta^{13}\text{C}$  (increase over time) and  $\delta^{15}\text{N}$  (decrease over time) (Gälman et al. 2009).

#### Deposition of biotic indicators

The biotic component of varved sediments provides additional paleoenvironmental paleoecological information if its accumulation and deposition dynamics is understood. From a sedimentological perspective, Simola (1977) was a pioneer in verifying the annual character of seasonal laminae based on diatom succession in the biogenic varves of Lake Lovojärvi, Finland. Recently, Ojala et al. (2013) found that in Lake Nautajärvi, Finland, the sedimentation processes differ substantially between

abiotic and biotic components: the abiotic fraction is predominantly of allochthonous origin, whereas the biotic fraction is mainly of autochthonous origin. This has a great impact on the relative proportions of abiotic and biotic components as aquatic biota are more dependent on seasonal processes (e.g. spring and autumnal overturns) than on rapid, short-lived environmental episodes, such as the spring snowmelt discharge-peak. So the accumulation rates of, for instance, diatoms and chrysophyte cysts in Lake Nautajärvi revealed firstly, very similar inter-annual trends despite different climatic conditions between the two studied years, but secondly, distinctive differences between the seasons of a same year (Ojala et al. 2013).

Similarly, the diatom record from Lake Nylandssjön, northern Sweden, is dominated by the same recurring set of diatom taxa every year, as observed in plankton survey-data, sediment traps and varved sediments. However, the dominant taxa show different abundance patterns from year to year. The abundance pattern of a certain diatom taxa is seemingly independent of other diatom taxa, and not obviously explained by a single environmental factor (Fig. 2; Bigler et al. 2012). This indicates complex interaction of physical (e.g. temperature, stratification, ice-cover), chemical (nutrient concentrations, water quality) and biological (life cycles, grazing pressure) processes controlling biological signal formation on an annual basis. The above examples demonstrate that sediment trap studies can provide essential information to understand the sedimentation processes that control the generation of varved lake sediments. This, in turn, enables us to extract the paleoenvironmental signal from these high-resolution sediment archives with greater confidence.

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# Hyperspectral imaging: a novel, non-destructive method for investigating sub-annual sediment structures and composition

Martin Grosjean<sup>1</sup>, B. Amann<sup>1</sup>, C. Butz<sup>1</sup>, B. Rein<sup>2</sup> and W. Tylmann<sup>3</sup>

**Hyperspectral imaging offers a rapid and cost-effective way of generating records of sediment properties and composition at the micrometer-scale. Photopigments and clay minerals detected using this method can reflect temperature, precipitation or runoff and primary production in lake sediments.**

The quest for maximizing the resolution of long paleoenvironmental data sets from sedimentary archives has prompted rapid developments in analytical methods and techniques. Non-destructive scanning techniques such as X-ray radiography and computer tomography of sediment structures and density, and scanning micro-X-ray fluorescence ( $\mu$ XRF) to map elemental composition are now widely used. Other powerful, although still less well-known methods are digital image analysis and color codes (e.g. CIELAB color space; Debret et al. 2011), and scanning multi-channel reflectance spectroscopy in the visible and near infrared range (typically 380-1000 nm). These techniques are used to identify organic substances and minerals in sediments on the basis of their diagnostic color absorption properties.

Scanning techniques have a number of advantages: they do not require sub-sampling of sediments; are non-destructive; operate at (sub-)millimeter spatial resolution; are very cost effective; allow us to quickly produce long data series; and offer the opportunity to replicate data sets, which is often impossible or inefficient with analytical techniques. Disadvantages are that measured values are often not substance-specific and can be influenced by matrix effects (water content, porosity), thereby limiting the interpretation of results.

## Reflectance spectroscopy VIS-RS

While  $\mu$ XRF techniques are routinely used in many laboratories, the potential of reflectance spectroscopy in the visible range (VIS-RS, 380-730 nm) has only been demonstrated relatively recently. VIS-RS has been successfully applied to fresh sediment cores to measure carbonate content in marine sediments (Balsam and Deaton 1996), and on marine and freshwater sediments to measure clay minerals (mainly illite and chlorite; Rein and Sirocko 2002), Fe-species (Debret et al. 2011), organic carbon, sedimentary photopigments (mainly chlorophyll-a and diagenetic products) and sedimentary carotenoids (Rein and Sirocko 2002; Das et al. 2005; Rein et al. 2005; Wolfe et al. 2006; Michelutti et al. 2010; Trachsel et al. 2013).

Interpretation of the reflectance spectra remains challenging. However, spectral indices characteristic of lithogenic material and sedimentary pigments (e.g. the relative absorption band depth between 660-670 nm,  $RABD_{660:670}$  indicative of chlorophyll-a and diagenetic

products) compare very well with analytical measurements (typical  $R^2$  between 0.70 and 0.98).

Built on the rationale that the substances measured by VIS-RS (clay minerals, carbonate, pigments, etc.) contain a climate signal in certain lakes, recent studies have demonstrated that VIS-RS data measured on fresh sediment cores can be directly calibrated to meteorological data, which makes them powerful sources for high-resolution quantitative climate reconstruction. For example, VIS-RS indices diagnostic for photopigments ( $\approx$ algal productivity) and clay minerals (lithogenic influx) were calibrated to temperature or precipitation in organic sediments from eutrophic lakes in Central Chile, Patagonia and Tasmania (von Gunten et al. 2009, 2012; Saunders et al. 2012, 2013; Elbert et al. 2013; de Jong et al. 2013) and to inorganic sediments from the Swiss Alps (Trachsel et al. 2010).

## Hyperspectral imaging

Here, we present the first results from the next generation measurement device, a hyperspectral core scanner that combines micro remote-sensing techniques with lake sediment analysis. The Specim Ltd. scanner (Fig. 1) consists of a hyperspectral camera and a sample tray that moves underneath an illumination

chamber and the camera slit. The camera takes reflectance spectra from the sediment surface in the range 400-1000 nm with a spectral resolution of 0.8 nm and a spatial resolution (pixel size) as small as  $38 \times 38 \mu\text{m}$ . One meter of sediment core is measured in ca. 15 min and produces ca. 45 GB of data. Data normalization and analysis is made using remote sensing software.

Figure 2 presents the first example of hyperspectral imaging using biochemical varves from Lake Żabińskie, a dimictic lake in the Masurian Lakeland, Poland. The varves are 3-4 mm thick and consist of a white calcite layer formed in early summer and a dark layer composed mostly of aquatic organic matter deposited from late summer until winter.

Figure 2c shows a high resolution  $RABD_{660:670}$  profile covering a two year period. Each varve is represented by 40-60 data points depending on varve thickness. These data can be obtained from fresh sediment cores or from resin embedded polished sediment slabs. The measurements show low chlorin concentrations in calcite layers and high concentrations in dark organic layers. It remains to be tested whether the precise position of the  $RABD_{660:670}$  peak actually represents the timing of the algal bloom in the summer season.

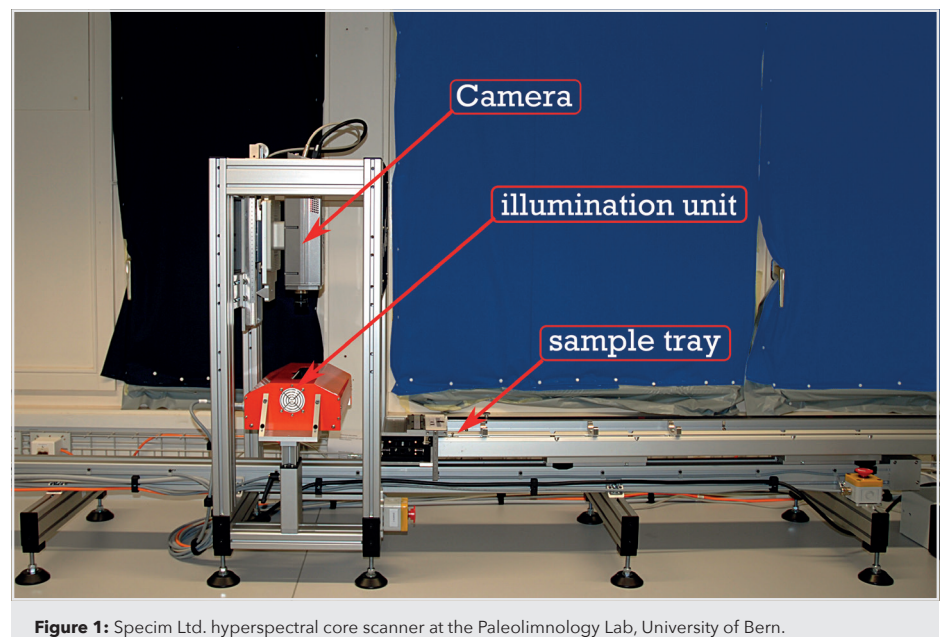


Figure 1: Specim Ltd. hyperspectral core scanner at the Paleolimnology Lab, University of Bern.



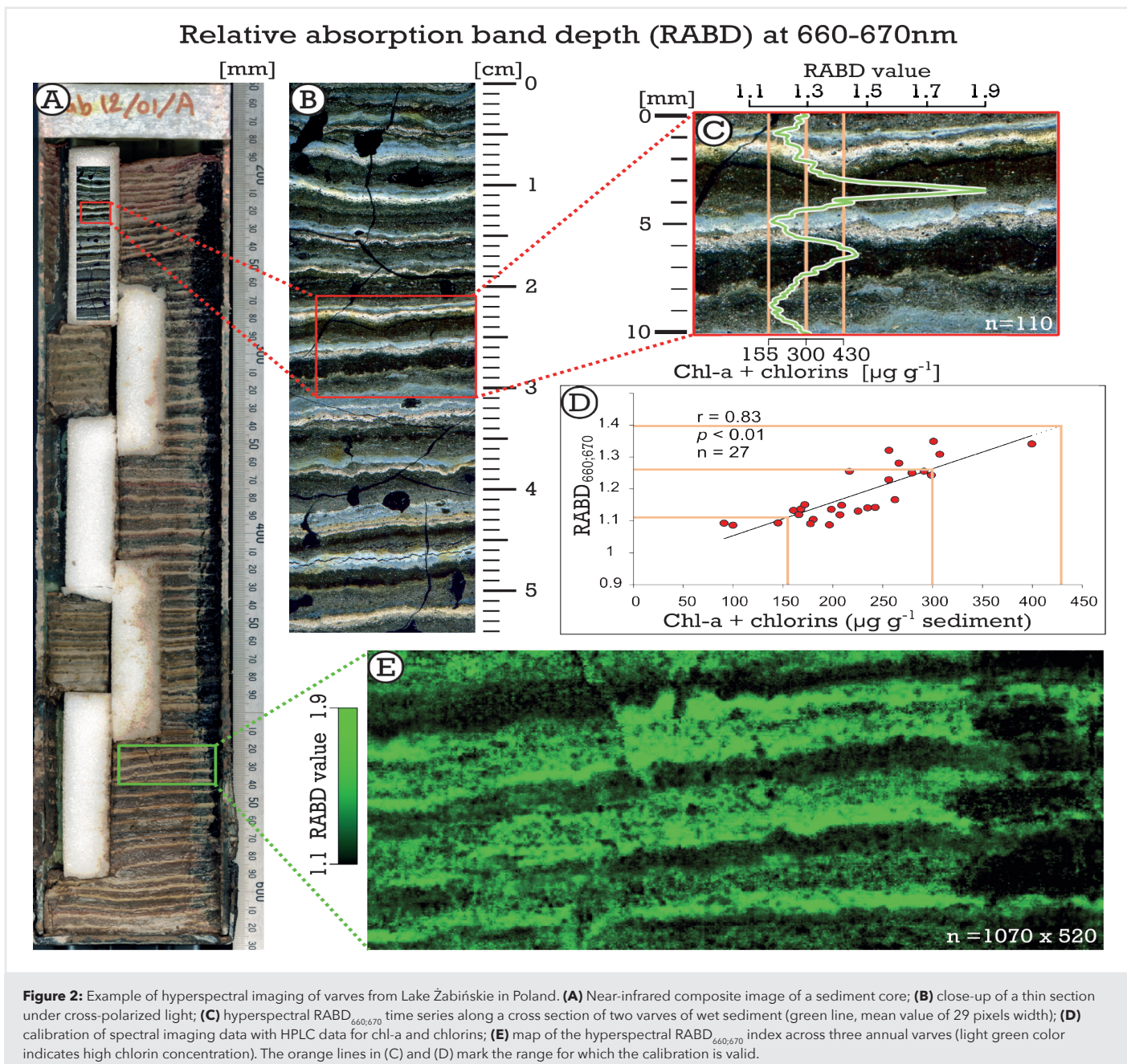


Figure 2d shows the regression between high-performance liquid chromatography (HPLC) measurements of photopigments in dry sediment (after pigment extraction) and  $RABD_{660,670}$  measured on the wet sediment. This suggests that the spectral index used here represents chl-a and chlorins, and that it can be converted into concentration values ( $\mu\text{g g}^{-1}$ ).

Figure 2e shows the same spectral index but now as a map of  $RABD_{660,670}$  values with 1070 x 520 pixels (individual data points). The optically lighter calcite layers have low chlorin values and appear as darker areas while the green areas reflect the high chlorin concentrations found in the organic-rich layers.

### Outlook

The example presented here demonstrates the rich potential of hyperspectral imaging as a relatively novel non-destructive sediment analysis. Further opportunities and challenges are found in the following areas:

- Higher spectral resolution (0.8 nm) potentially allows the detection and diagnosis of further substances and a more detailed speciation (e.g. separation of chl-a from chlorins);
- Very high spatial resolution (pixel size 38  $\mu\text{m}$ ) allows sub-varve scale investigation (e.g. seasonality of chl-a production) and the detection of sand-size grains (e.g. macro charcoal and fire history).
- The similar resolution as attained with  $\mu\text{XRF}$  scanning allows one to compare these two data types at very high resolution.
- Attributing the spectral properties of sediments to specific substances and minerals (proxy-proxy calibration) remains a great challenge since most of the pixels contain information from a mix of substances. Statistical techniques applied in remote sensing, such as pixel classification, end-member spectra, spectral unmixing, might help to improve the calibration between hyperspectral index data and the concentration

of specific substances in sediments. Making this step is fundamental for improving the interpretation of hyperspectral data.

In summary, hyperspectral imaging offers great opportunities for the analysis of lake sediments at the sub-varve scale. The method can also be applied to marine sediments, tree rings or speleothems.

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# High-precision sampling of laminated sediments: Strategies from Lake Suigetsu

Takeshi Nakagawa<sup>1</sup> and Suigetsu 2006 Project Members<sup>2</sup>

**High-precision depth control is an absolute necessity for varve studies. The Lake Suigetsu 2006 project developed simple yet effective solutions to the most common problems related to core preparation and archival.**

Depth control is crucial for all sediment studies and very small differences, even at the mm-scale, can be critical when studying past environmental changes at high resolution. However, achieving and maintaining such precision along a long core is challenging.

Splitting a cylindrical core into sampling and archival halves is common practice, and at some point, when the sediment of the sampling half is already exploited, researchers may wish to take complementary samples from the archive half. But even the seemingly simple task of taking a sample from exactly the same position as in the sampling half is not always easy because cores can expand or contract during storage. Also, tops and bottoms of core sections do not always retain clean and flat surfaces from which precise distances can be measured.

The earlier phase of the Lake Suigetsu project (SG93) revealed such problems; however, most were resolved through innovative techniques developed during the follow-up project that started in 2006 (SG06). This article outlines how we achieved depth control with millimeter or even sub-millimeter precision on a >40 m long quasi-continuously laminated sediment core.

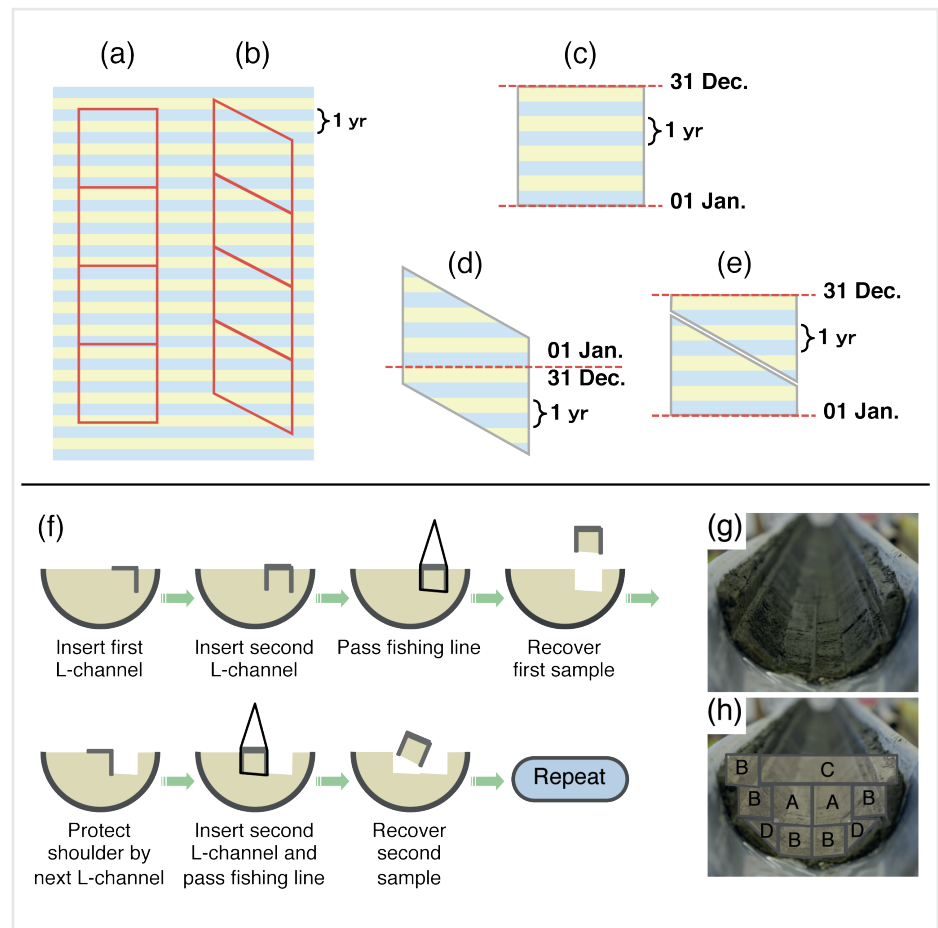
## Sampling techniques

It is common practice to slice varved sediments into regular thin (typically 0.5 or 1.0 cm) disks to avoid depth uncertainties between sub-samples from the same slice. However, this is not ideal because the varved sediment samples are then likely to either under- or over-represent a specific season (Fig. 1a). This is particularly a problem when producing measurements of signals with strong seasonality, i.e. most paleoclimatological proxies. If a sample represents around ten years, such as those typically used for pollen or diatom analysis, inclusion or exclusion of one seasonal layer can result in up to 10% difference in the proxy signal. Indeed, it is mainly for this reason that the pollen data from the precursor SG93 project (e.g. Nakagawa et al. 2003) had a low signal to noise ratio. A simple solution to overcome this problem of introducing a seasonal bias from arbitrarily sampling the 'last seasonal layer' is diagonal cutting. If one can avoid cutting cores into disks, but instead cut them into longitudinal bars and slice these bars diagonally into individual samples, then the "last seasonal layer" of each sample becomes blended (Fig. 1b). Or, in other words, the number of years represented in each sample becomes almost uniform for all seasons. This can be geometrically understood

by flipping upper and lower parts of the same sample (Fig. 1c-e).

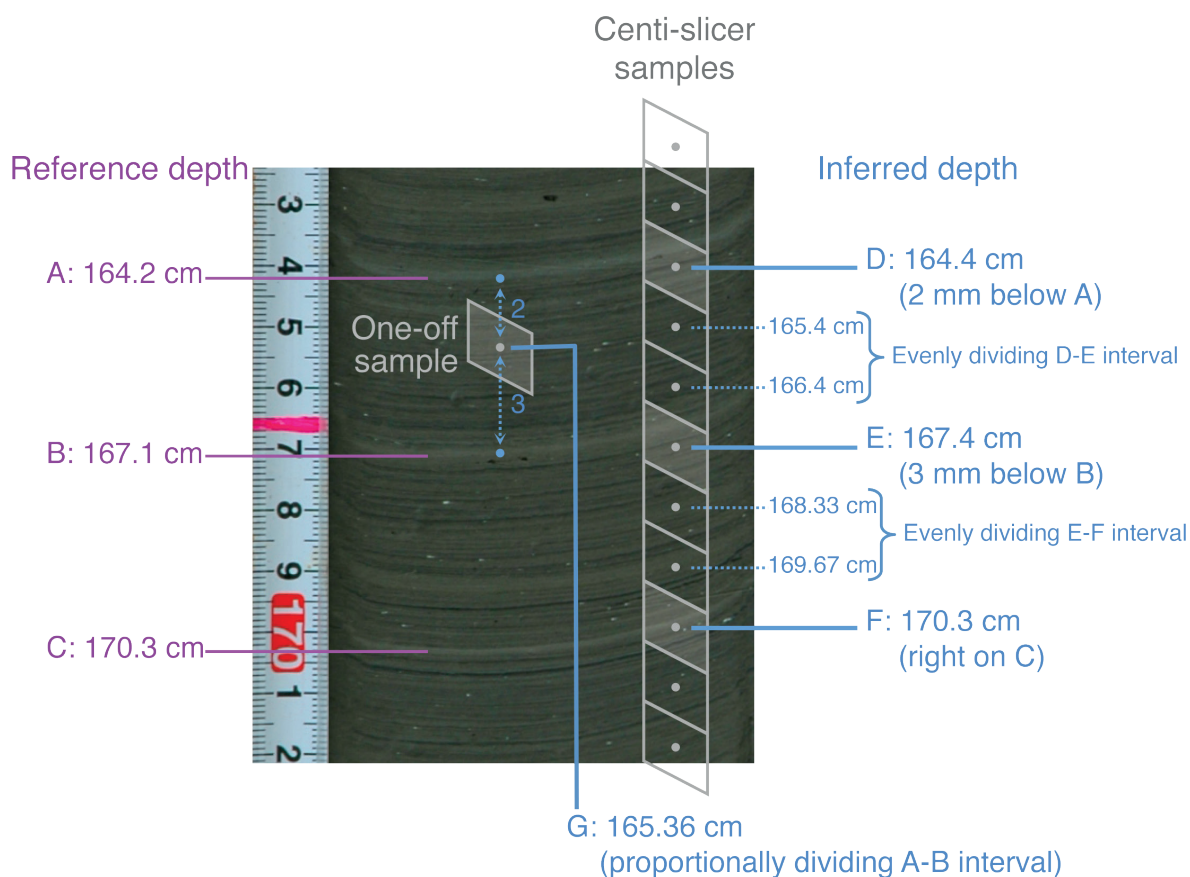
U-channel sampling is common, especially for paleo-magnetism studies, as a method to obtain longitudinal sediment bars from cylindrical cores. However, it is not easy to take multiple U-channel samples from the same core because the first U-channel makes an exposed fragile "shoulder", which is very

likely to be destroyed by subsequent insertion of a new U-channel. Therefore, for the SG06 project, we invented a double-L (LL) channel (Nakagawa et al. 2012). The LL-channel is almost identical to the U-channel, but consists of two L-shaped angles, which together form the "U" shape. The first L-channel protects the fragile shoulder regions. The second L-channel can then be inserted to produce the combined U-channel. Finally, the sediment underneath is



**Figure 1: Top.** Parallel samples (a) may contain four blue and three yellow "seasonal" layers, or vice versa, depending on sampling position, making the resulting samples incoherent. This effect is considerably reduced in diagonal samples (b). If one could cut samples precisely between 1 January and 31 December, then we would not have the "last seasonal layer" problem (c). Such ideal cutting is not possible in the real world. However, diagonal cutting is almost equivalent to such ideal cutting. Theoretically (i.e. not in practice), it is possible to cut a diagonal sample into two blocks precisely at the transition from one year to the next (d). By flipping the upper and lower blocks of (d), we can obtain a sub-sample (e), which is very close to the ideal cutting (c) in terms of the number of included seasonal layers. **Bottom:** (f) Procedure to recover multiple LL-channel samples (modified after Nakagawa et al. 2012) and (g-h) an example of intense sub-sampling by double-L (LL) channels. A and B: 15x15 and 12x12 mm LL-channel samples. C: Slab samples for soft X-radiography. D: 12 mm single L-channel samples. 84% of the entire core and 94% of the undisturbed part (i.e. excluding the outer 2 mm) of the core were recovered.





**Figure 2:** (A-C) Marker layers with reference depth. (D-G) Depths measured relative to the marker layer. The sediment picture is artificially distorted for demonstration purposes in order to enhance the impact of non-horizontal layers.

cut with a fishing line to recover the sediment bar from the rest of the core. The LL-channel method allows multiple sampling of the same core section (Fig. 1f), typically allowing >90% of the undisturbed part (i.e. excluding the outer 2 mm) of the core to be recovered (Fig. 1g-h).

Another advantage of the LL-channel technique is that we can remove one of the L-channels after recovering the sample and leave the sediment sitting on only one L-channel. This exposes two sides of the longitudinal sediment bar, instead of just one, as with the U-channel. The exposure of two sides allows an easy diagonal slicing of the bar-shaped samples. This approach is much tidier than digging holes from U-channel samples and provides an almost ideal solution to the problem of the "last seasonal layer". Finally, L-shaped angles are less expensive than specifically manufactured U-channels and are easy to obtain in a range of sizes from hardware stores.

We have also developed relatively simple tools (SG06 Centi-slicer and Milli-slicer) to facilitate the diagonal slicing of LL-channel-derived samples at a regular interval of either 1 cm or 1 mm, respectively. The relevant explanatory video-clips and comprehensive description of sampling techniques can be viewed online.

#### Precise depth control

Because laminae are not always perfectly parallel and the samples often expand or contract depending on storage conditions, the multiple LL-channel samples do not provide perfectly identical replicates. The distance between

a given pair of layers varies across multiple LL-samples from the same section. Slicing those bars at an even interval would not yield sub-samples that are stratigraphically identical. We therefore used an interpolation technique to control depth determinations at sub-millimeter precision.

The varved sediment cores from Lake Suigetsu occasionally have macroscopic layers with distinct characteristics. First, we gave numbers to these marker layers and precisely defined their depths (Fig. 2A-C) using high-resolution digital photographs taken immediately following core extraction, i.e. before any color changes through oxidation or subsequent expansion or contraction of the sediment could occur. The depth of samples bound between these marker layers is defined in one of the following ways:

- In the case of continuous sampling using the Centi-slicer, one can precisely define the depth of samples containing one of the marker layers based on the offset from that layer at the center of the sample (Fig. 2D-F). The depth of the remaining samples is then inferred by linear interpolation.
- In the case of one-off sampling (Fig. 2G), one can calculate the position of each sample by proportionally dividing the interval between two marker layers with known depths using the distances measured from the center of the sample to the nearest marker layers above and below it.

Importantly, both procedures use a defined reference depth, rather than the actual position one would measure in the laboratory. Thus, the problem of secondary expansion or contraction of cores is bypassed. The software LevelFinder has been specifically developed for the SG06 project to facilitate all the calculations during the routine sampling described above. LevelFinder is freely available online.

SG06 Centi-slicer:  
[http://youtu.be/q\\_-D24zzzTA](http://youtu.be/q_-D24zzzTA)  
<http://youtu.be/LsZNVvJyaqg>

SG06 Milli-slicer:  
<http://youtu.be/FUxLAoRGsUI>  
<http://youtu.be/PacliEeKfSE>

LL-channel sampling:  
<http://youtu.be/SsgYG6VNW5Q>

LevelFinder:  
<http://dendro.naruto-u.ac.jp/~nakagawa/>

[www.suigetsu.org/methods.html](http://www.suigetsu.org/methods.html)

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# Seasonal laminae in marine sediments: applications and potential

Alan E.S. Kemp

Laminated marine sediments have the potential for seasonal resolution that can be exploited using scanning electron microscope techniques. This article provides examples of the power of such an approach.

Marine varved and laminated sediments are widely distributed (Kemp 2003). They are not restricted to oxygen-depleted marginal basins with shallow sill depths or to productive shelves and slopes, but are increasingly being found in the deep sea where massive particle flux has suppressed benthic activity, preserving seasonal flux events as sedimentary laminae (Kemp et al. 2006). Scanning Electron Microscope (SEM) methods using back-scattered electron imagery (BSEI) have enabled the identification and sub-sampling of near-monospecific diatom laminae from seasonal blooms and flux events. BSEI, when combined with ecological insights, allows the development of a species-based seasonal approach for climate reconstruction in the marine realm. Highlighted here are new methodologies that have increased the resolution of stable isotope proxy applications to a seasonal scale, and also other integrative studies that have provided insights into interannual climate variability and to the biogeochemical carbon cycle.

## Diatom stable isotope records

Quantitative paleoceanographic reconstructions of temperature, salinity and ice volume from marine sediments have traditionally used

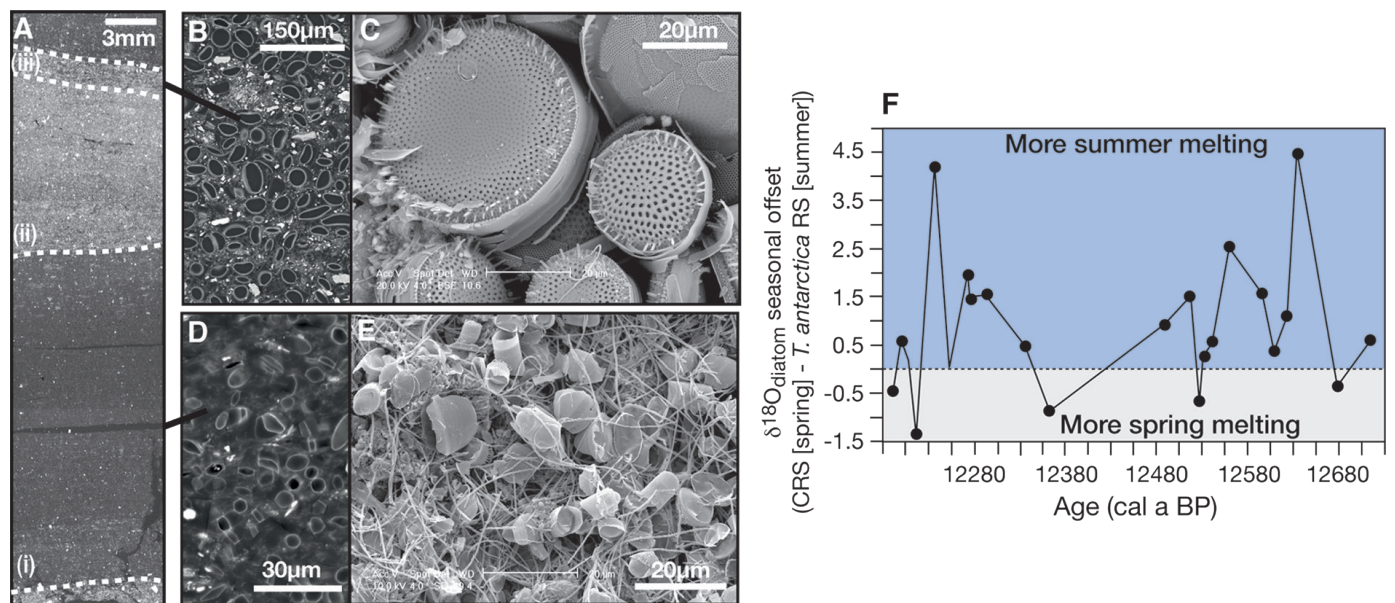
oxygen and carbon isotope analysis of calcite foraminifera shells. However, the resolution of such records is typically centennial at best due to low sedimentation rates or low foraminifera abundance in rapidly accumulating sediments. To overcome this limitation and increase the resolution of paleoceanographic research, isotope records are derived from the frustules of diatoms (De La Rocha 2006; Swann and Leng 2009). Near-monospecific diatom blooms can form laminae from millimeters to centimeters in thickness (Fig. 1). The challenge has been to avoid seasonality, habitat, and inter-species effects by isolating diatom samples from a single taxon that grows in a known season and, typically, at known depths in the water column.

The potential for such seasonal-scale isotope proxy resolution is shown by new analyses of sediments from the West Antarctic Peninsula (Swann et al. 2013). In this pioneering study, a micro-manipulator technique has been developed that permits the separation of diatom species for oxygen isotope analysis (Snelling et al. 2013). Two separate species groups were identified as dominant in the laminae: (i) the near-monospecific *Hyalochaete Chaetoceros* spp. resting spores (CRS) represent spring

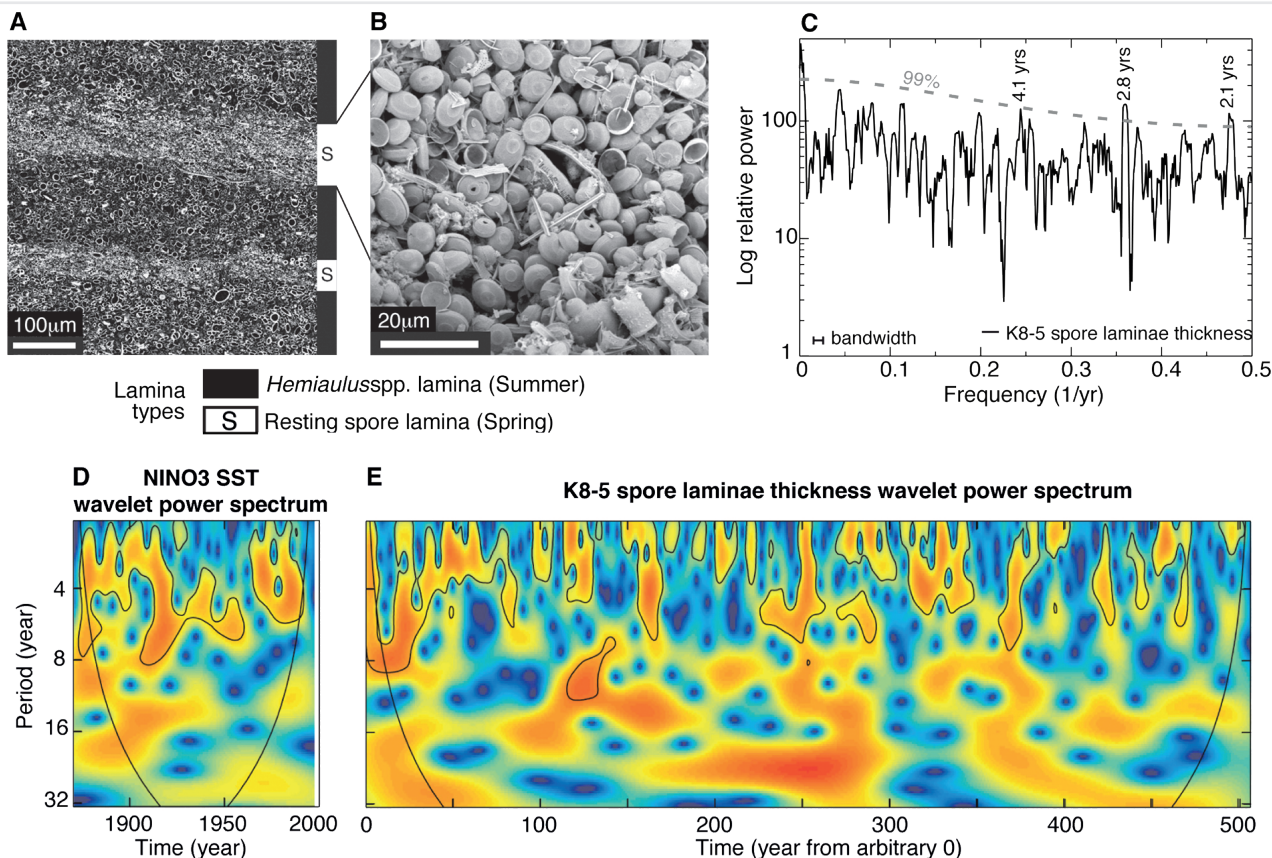
deposition linked to sea-ice melt; and (ii) the *Thalassiosira antarctica* resting spores relate to summer deposition. Oxygen isotope analysis of these two species groups, together with coarse and fine diatom fractions from the same samples, have been used to develop records of changes in magnitude of spring melting and changes in the relative importance of spring sea-ice versus summer glacial-ice melting (Fig. 1). These results offer insights into glacial dynamics and ocean-atmosphere variability on seasonally resolved timescales and, more broadly, point to a future treasure trove of archives for quantitative seasonal palaeoclimatic information.

## Permanent El Niño hypothesis

It has been suggested that the present climate may be approaching a threshold or tipping point that may move the Pacific equatorial ocean-atmosphere system into a permanent El Niño state, with far-reaching implications for global climate (Fedorov and Philander 2000; Fedorov et al. 2006). Supporting evidence has come from foraminiferal paleotemperature studies at multi-millennial resolution suggesting that such a permanent El Niño state existed during the Pliocene warm period



**Figure 1:** (A) Back-scattered electron imagery (BSEI) photomosaic of a polished thin section (PTS) of resin-embedded seasonally laminated sediments of deglacial age from Palmer Deep, West Antarctic Peninsula. The core interval shows three seasonal flux laminae: (i) spring diatom lamina dominated by *Hyalochaete Chaetoceros* spp. resting spores (CRS); (ii) summer terrigenous lamina; and (iii) late summer lamina characterized by high abundances of *Thalassiosira antarctica* resting spores. (B) BSEI of PTS and (C) topographic SEM images of *T. antarctica* resting spore lamina (iii). (D) BSEI and (E) topographic SEM images of CRS lamina (i). (F) Seasonal offset between  $\delta^{18}\text{O}_{\text{diatom}}$  for CRS (spring) and *T. antarctica* RS (summer) sampled from the same year (modified from Maddison 2006 and Swann et al. 2013).



**Figure 2:** (A) Back-scattered electron imagery (BSEI) of seasonally laminated sediments of Cretaceous age from the Alpha Ridge of the Arctic Ocean. (B) Topographic SEM image of spring *Chaetoceros*-type resting spore lamina. (C) Multi-taper method (MTM) power spectra of time series of resting spore lamina thickness from a 507-year interval showing peaks significant at 99% confidence level in the quasi-biennial and typical ENSO low frequency band (4.1 years). (D) and (E) Wavelet power spectra (D) of the Niño3 SST index from 1871 to 1998 (Torrence and Compo 1998) resampled to annual resolution to mimic laminated data, and (E) a 507-year Alpha Ridge record from the late Cretaceous. Late Cretaceous periodicities in the ENSO-band (broadly, 2-8 years) are non-stationary, that is to say, the dominant frequencies vary with time, and show a striking resemblance to similar behavior in the modern ENSO time series. (Adapted from Figs 2-4 of Davies et al. 2011).

(Wara et al. 2005). However, new records from laminated sediments and other seasonally resolved archives from ancient greenhouse periods contradict this hypothesis. Corals from the Pliocene (Watanabe et al. 2011), bivalves from the Eocene (Ivany et al. 2011), annual lamina thicknesses from late Miocene evaporites (Galeotti et al. 2010) and Eocene oil shales (Huber and Caballero 2003; Lenz et al. 2010) have all produced robust El Niño signals during warm periods. The application of BSEI to identify sub-annual lamina components has also contributed to this debate. Further evidence comes from the Cretaceous greenhouse period from California, where time series of alternating seasonal diatom and terrigenous sediment laminae record a strong influence of the El Niño–Southern Oscillation (ENSO) on marine productivity, terrestrial rainfall and run-off (Davies et al. 2012). Exceptionally-preserved Cretaceous-age laminated diatomites from the Arctic Ocean that reveal alternating laminae of spring diatom resting spores and late summer and fall vegetative cells (Davies et al. 2009) have been analyzed to produce a thousand-year time series (Davies et al. 2011). Strong cycles in both the quasi-biennial and the 4-5 year ENSO low frequency band indicate robust El Niño teleconnections to high latitude climate, as occurs today (Fig. 2). This extensive, and increasing, evidence from laminated sediments and other seasonally-resolved archives for a continuously dynamic ENSO even during warm periods does not support the permanent El Niño hypothesis.

### Marine biological carbon pump

One of the long-standing priorities in oceanographic research is to better understand the workings of the biological carbon pump that draws down CO<sub>2</sub> from the atmosphere and exports it to the ocean depths. A widespread view has been that increased warming-induced stratification of the oceans will lead to a shift from diatom production to smaller phytoplankton, reducing the effectiveness of the biological pump and acting as a positive feedback that promotes the build up of atmospheric CO<sub>2</sub> concentrations and warming of the atmosphere (Steinacher et al. 2010). However, our current understanding of the biological carbon pump is poor. Many of the algal production events that dominate carbon export are spatially and temporally highly restricted, and subsurface processes are not well captured by the conventional oceanographic observations that are biased towards the surface, typically the topmost ~20 m (McGillcuddy et al. 2007; Lomas et al. 2009). Sediment traps have been used to record flux from the surface ocean but their positions are localized and they only represent, on aggregate, a record of a few centuries. In contrast, over the past ~20 years studies of laminated marine sediments have generated many thousands of years of seasonally resolved time series of sediment deposition in widely distributed locations, covering periods from the Cretaceous to the Holocene.

There has recently been a convergence between new oceanographic observations of

diatoms in stratified seas and studies of the same taxa in laminated deep-sea sediments. These show that key large-diatom species may bloom and concentrate in stratified surface waters and generate massive carbon flux exceeding that of the spring bloom. Thus, in opposition to the previously favored ideas, stratified oceans may actually enhance carbon export, drawing down CO<sub>2</sub> and providing negative feedback to global warming (Kemp and Villareal 2013).

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# The global network of tree-ring widths and its applications to paleoclimatology

Scott St. George

**The width of an annual tree ring is without question a very simple indicator of the character of that year's weather, but collectively, the global network of tree-ring width measurements represents an invaluable resource for high-resolution paleoclimatology.**

For over five centuries, it's been known that the annual growth rings of trees in temperate and boreal forests are shaped by variations in weather and climate (Stallings 1937). It was not until the 1960s, however, that research showed how the environmental information recorded in tree-ring widths can be obscured or sharpened by interactions between climate and ecology (Fritts et al. 1965).

Based on these insights, which established the theoretical foundation for the nascent field of dendroclimatology (Fritts 1976; Cook and Kairiukstis 1990), scientists have spent the last five decades developing tree-ring width records at thousands of locations around the world. In part because these data are so widespread and so massively replicated, the combined network of tree-ring widths is now one of the most important sources of proxy climate information on the planet (Solomon et al. 2007; Mann et al. 2008; Villalba et al. 2012; PAGES 2K Consortium, 2013).

The largest archive of tree-ring width data is held within the International Tree-Ring Data-bank (ITRDB; Grissino-Mayer and Fritts 1997),

an open-access database currently maintained by the National Oceanic and Atmospheric Administration (NOAA) in Colorado, USA. Established in 1974 as a permanent repository for digital tree-ring measurements, the ITRDB includes more than 3,200 ring-width records from all continents except Antarctica (Fig. 1). Most records housed by the ITRDB are from North America and Europe, but the archive also includes major regional collections from Siberia (Schweingruber and Briffa 1996), Mongolia (Pederson et al. 2001; Davi et al. 2013), the Tibetan Plateau (Cook et al. 2003; Borgeonkar 2011), the southern Andes (Villalba et al. 2010, 2012), North Africa (Touchan et al. 2011), and New Zealand (Dunwiddie 1979; Ogden and Ahmed 1989). Many more ring-width records are held outside the ITRDB in separate databases operated by research groups and individual scientists.

Recent collection efforts have filled major gaps in the global network in Southeast Asia and India (Cook et al. 2010; Linderholm et al. 2013; Pumijumnong 2013), but despite these successes ring-width records are largely absent from the tropics and much of the Southern

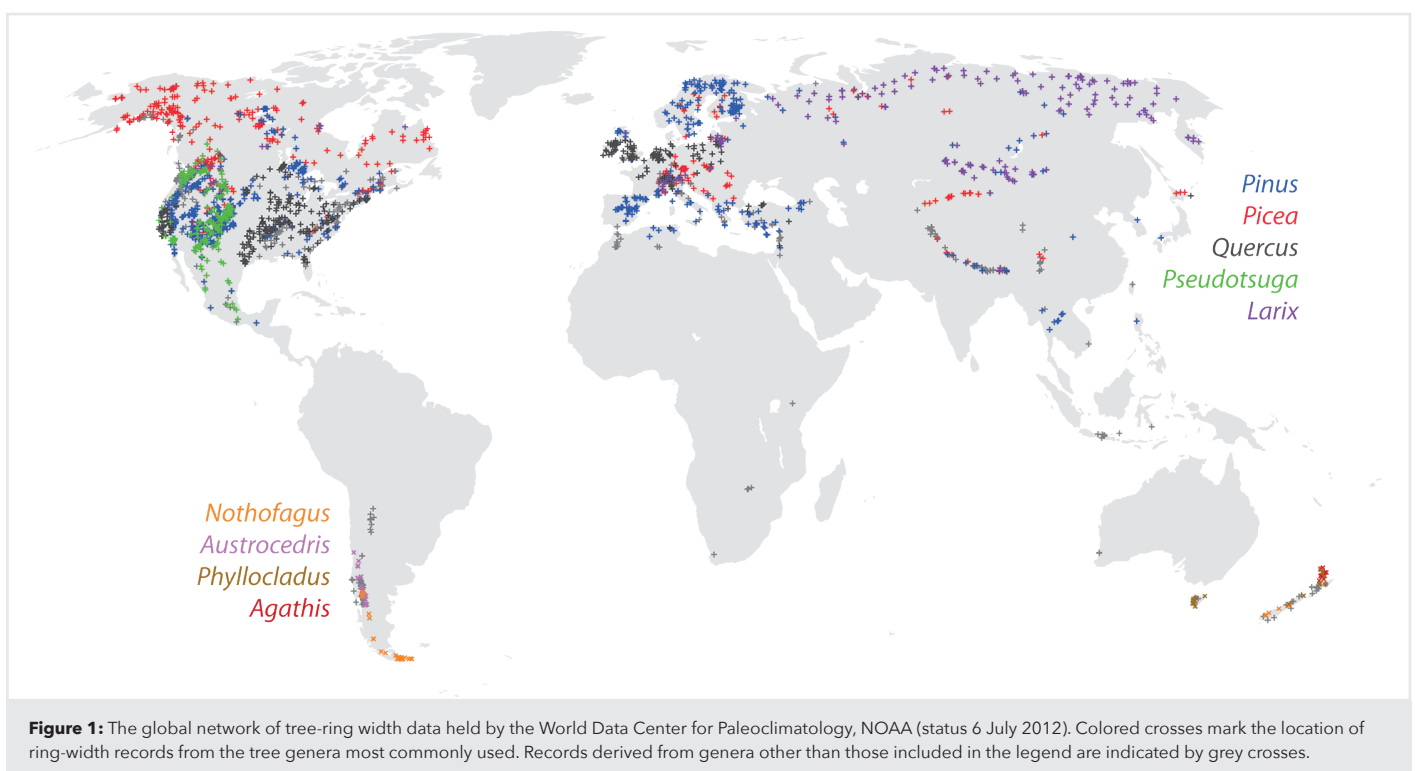
Hemisphere. This is either because the climate of these areas is not seasonal enough to induce dormancy in trees (e.g. in areas such as Amazonia, tropical Africa and Indonesia) or is too arid to support forests (e.g. Saharan Africa, the Middle East and central Australia).

## Strengths of network-based analyses

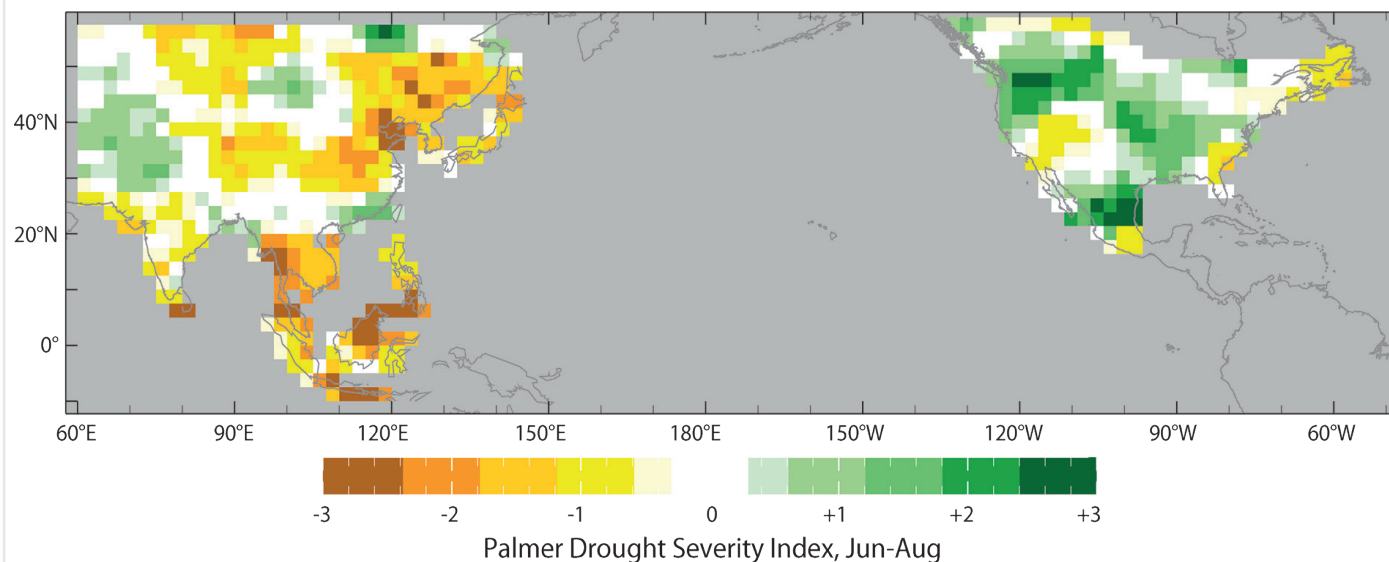
Because it is made up of thousands of records, which themselves are built from hundreds of thousands of tree-ring series, the data in the global tree-ring width network are replicated to an extent unequalled by any other high-resolution climate proxy.

For each individual record, ring-width measurements from two to several hundred tree-ring specimens are combined to produce a mean-value function, often called a "chronology". This averaging procedure amplifies the environmental signals shared by most trees and reduces noise related to non-climatic factors such as tree age or ecological disturbance (Cook 1987; Cook and Pederson 2011).

In the same way, but on a grander scale, large networks of tree-ring records allow the







**Figure 2:** Drought severity in North America (Cook et al. 2004) and monsoon Asia (Cook et al. 2010) during the late Victorian Great Drought of 1876 to 1878 AD. Cook et al. have used ring-widths and other tree-ring parameters to produce year-by-year maps of summer drought severity (as represented by the Palmer Drought Severity Index) extending back to 1 BC in North America and 1300 AD in Asia.

opportunity to assign more weight to behavior shared among many records and tree species, reduce emphasis given to unusual records that may be dominated by non-climatic factors, and (potentially) improve the accuracy of large-scale climate reconstructions (Meko et al. 1993). Networks also allow for the use of reconstruction methods, such as canonical-correlation analysis (Fritts et al. 1971) and principal-component regression (Cook et al. 2004; 2010), that cannot be applied to small sets of ring-width records.

Large networks can also be used to verify relationships between tree growth and climate that have been identified previously within single records or small collections. Some reconstruction approaches, either explicitly or implicitly, conduct an initial screening to select tree-ring records as potential predictors; however, under some circumstances this process can cause records to be incorrectly identified as sensitive to the target climate parameter (Bürger 2007). Statistical experiments conducted on networks of ring-width records can help distinguish between climate-tree relations that are reliable and those that might be artifacts caused by chance (St. George and Ault 2011).

#### Paleoclimate products based on tree-ring width networks

For several decades tree-ring widths have been one of the main proxies used in high-resolution paleoclimatology (Bradley 2011; Hughes 2011) and these data continue to be used regularly as the sole or leading source for paleoclimate reconstructions spanning the late Holocene.

Many products have exploited the extensive replication and broad distribution of tree-ring networks to develop spatially-explicit estimates of past climate at regional, hemispheric or global scales. The leading example of this approach is provided by the North American Drought Atlas (Cook and Krusic 2004; Cook et al. 1999, 2004, 2007), which used a very large set of moisture-sensitive tree-ring width records to generate yearly maps of drought

severity across the continent. A parallel product for monsoon Asia was released in 2010 (Cook et al. 2010) and although these reconstructions also incorporated other tree-ring measurements including sub-annual increments and maximum wood density, tree-ring widths were still the main predictors of past drought (Fig. 2).

Large sets of ring-width data have also provided the foundation for proxy estimates of hemispheric and global surface temperatures (Mann et al. 2008), the first near-continental scale reconstructions of precipitation and temperature in the Southern Hemisphere (Neukom et al. 2010, 2011), and most of the regional reconstructions in the recent PAGES 2k synthesis (PAGES 2k Consortium 2013).

Finally, ring-width networks have been used recently to gauge the relative influence of environmental stressors on forest health (Williams et al. 2012), set real-world targets for process models that simulate tree-ring formation (Tolwinski-Ward et al. 2011; Breitenmoser et al. 2013), and to argue against the hypothesis that major volcanic eruptions caused widespread shutdowns in wood formation in forests across the Northern Hemisphere (St. George et al. 2013; D'Arrigo et al. 2013).

#### Conclusions

The width of an annual growth ring is without question a very simple indication of a tree's biological activity and the character of that year's weather. In spite of that simplicity, the millions of observations that make up the global tree-ring network collectively provide us with a powerful and flexible tool to study forest vigor and climate over a broad range of spatial and temporal scales (Cook and Pederson 2011).

As we develop more and more records that describe tree-ring parameters such as maximum latewood density (Briffa et al. 2004), isotopic composition (Csank 2009) or sub-annual increments (Griffin et al. 2011), it should be possible to use analytical methods first applied

to tree-ring widths to improve our understanding of tree-climate relations and identify robust climate signals within these other metrics.

Tree rings offer several advantages as a proxy, including their annual or sub-annual resolution and unmatched dating accuracy. However, beyond the archive's own intrinsic qualities, the central role played by ring-width records in modern paleoclimatology is also due to the global network's massive replication and widespread geographic coverage. Those qualities are testament to the dendrochronological community's long-standing commitment to field collection, record development, and data sharing.

#### ACKNOWLEDGEMENTS

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# The potential of tree rings in *Terra Australis*

Chris Turney<sup>1</sup>, J. Palmer<sup>1</sup>, K. Allen<sup>2</sup>, P. Baker<sup>2</sup> and P. Grierson<sup>3</sup>

To overcome the relative dearth of paleoclimate records in Southern Hemisphere mid-latitudes, new methods are being developed in Australasia to exploit the potential of tree rings across the region.

The Australasian region is potentially highly sensitive to climate change, including abrupt transitions caused by the crossing of thresholds within different components of the climate system (Fig. 1). Accurate reconstructions of the past behavior of the climate system are needed to better understand the mechanisms, and to validate projections of future change at the junction between tropical and polar regions (PAGES 2k Consortium 2013). Tree-rings are critical in this regard.

Over the 20<sup>th</sup> century, dendroclimatic research in the Northern Hemisphere has advanced in leaps and bounds. In the Southern Hemisphere the much smaller land mass and less amenable tree species have limited the development of long proxy climate records from trees. However, during the past five years, significant technical advances and discoveries have created an exciting set of opportunities for increasing the quality and understanding of tree-ring-based climate reconstructions in the Australasian region and, potentially, other tree-bearing regions of the world.

## Tree ring growth analysis

Like most proxy-climate reconstructions, those from tree rings are developed from statistical models relating observed climate data to measured tree-specific features such as ring widths. While these models are typically based on the correlation between two variables, causation is inferred from detailed understanding of the physiological mechanisms that drive tree growth and tree-ring formation. Recent technological and analytical advances have created the potential to monitor radial growth and wood cell formation at sub-hourly resolution over multiple years (Drew and Downes 2009). For the first time, this enables an assessment of the role of weather and climate in tree-ring formation for long-lived trees of global paleoclimatic importance from Australia and New Zealand (Drew et al. 2013; Wunder et al. 2013).

## Wood properties beyond ring-width

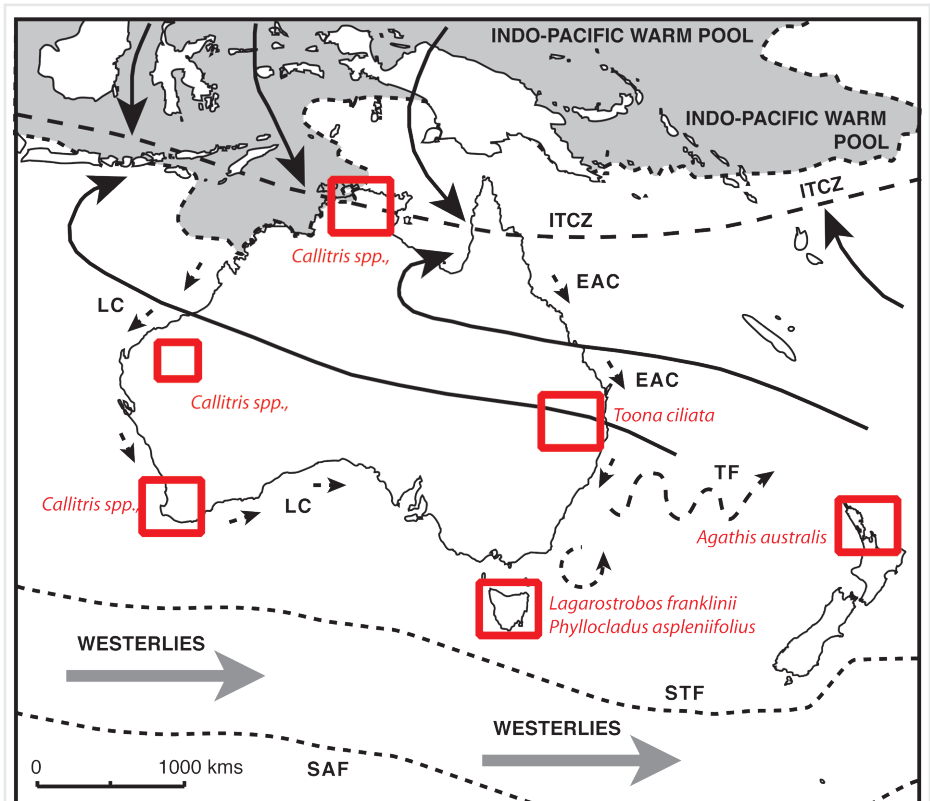
Particular interest has been focused on the recent development of tree-ring chronologies based on wood microfibril angle (MFA; angle of cellulose microfibrils in the cell wall relative to the long axis of the cell) and tracheal radial

diameter (TRD). Both exhibit a strong temperature sensitivity during the austral summer, i.e. November to April (Drew et al. 2013), extending across much of temperate south-eastern Australia (Allen et al. 2013). This development is particularly important as the wood-property chronologies were developed from samples that exhibited no sign of a climate signal in ring width, although the wood-properties based results appear stronger and more temporally stable than the widely cited Mt Read summer temperature reconstruction from Tasmanian Huon pine (Cook et al. 2000). As these authors point out, the results demonstrate the potential of wood property chronologies to open up vast areas for dendroclimatic research in data-sparse regions of Australasia, and beyond,

where standard ring-width chronologies have provided little dendroclimatic value.

## Investigating divergence

The relative paucity of climate-sensitive, multi-millennial tree-ring chronologies in the Southern Hemisphere makes it particularly important to examine whether the existing chronologies exhibit signs of anomalous growth reduction (the so-called "divergence problem"), as identified in the Northern Hemisphere (D'Arrigo et al. 2008). A program is currently underway to update long, climate-sensitive chronologies in the Southern Hemisphere as many lack ring-width data from the last 20 years or more. The investigation includes an assessment of several factors: the impact of various methods of standardization; the impact of



**Figure 1:** Location of Australasian tree-ring sites discussed in the text with major climatic and oceanographic boundaries shown. ITCZ denotes Intertropical Convergence Zone, LC the Leeuwin Current, EAC the East Australian Current, TF the Tasman Front, STF the Sub Tropical Front, and SAF the Subantarctic Front.



**Figure 2:** Ancient kauri tree (*Agathis australis*) prior to commercial processing in Northland, New Zealand (Jonathan Palmer pictured for scale).

signal-free processing (Melvin and Briffa 2008); and whether or not relationships between climate and wood-properties (e.g. density, TRD, MFA) may be more temporally stable than for ring-width. In addition, high-resolution data will provide a better empirical understanding of the climate response of trees at key sites (Fig. 1) and of the mechanisms underpinning any observed patterns of divergence between tree-ring properties and climate.

#### Filling in knowledge gaps

The eucalypts and acacias that dominate the Australian landscape generally lack discernible annual growth rings and, until recently, have not been considered suitable for climatic reconstructions (Brookhouse 2006). However, annually-resolved tree-ring chronologies have been recently developed from selected high-elevation species of these genera. The early despondent reports of the poor potential for tree-ring chronologies across much of Australia is being overcome by the development of a range of new chronologies that are based on measurements of ring width coupled with  $\delta^{13}\text{C}$

and  $\delta^{18}\text{O}$  isotope data. To date, these studies have mostly focused on long-lived *Callitris* trees that occur across much of inland Australia (Baker et al. 2008; Cullen and Grierson 2009). Other notable advances include using the methodological approach of “reverse-late-wood”, which is characterized by a sharp transition from earlywood- to latewood-type fiber tracheids followed by a gradual transition from latewood into earlywood (Brookhouse et al. 2008); chronology development from the only Australian alpine conifer (McDougall et al. 2012); and preliminary climate reconstructions based on the sub-tropical *Toona ciliata* (Heinrich et al. 2008). Finally, new techniques using  $^{14}\text{C}$ -wobble-matching have further enhanced the capacity to accurately date tree-ring chronologies in Australasia (e.g. Wood et al. 2010).

When these techniques are coupled with isotope analysis, wood density and elemental chemistry it should be possible to identify common sequences or patterns in reconstructions that reflect regional hydroclimatic histories (Evans et al. 2013), including the frequency

of cyclones that drive rainfall patterns across much of northern Australia (Cullen and Grierson 2007). Such an approach is needed to provide the spatial infilling crucial for exploring teleconnections and their temporal stability, particularly regarding the influence of climate modes, such as the El Niño-Southern Oscillation, the Southern Annular Mode and the Indian Ocean Dipole, on the Australasian region (e.g. Neukom and Gergis 2010).

#### Reconstructing changes in the carbon cycle

Despite considerable effort, the reliable tree-ring dated section of the most recent internationally-accepted calibration curve (IntCal13; Reimer et al. 2013) based on North American and European trees extends back only to 12.59 cal ka BP (Schaub et al. 2008). An exciting Southern Hemisphere possibility for radiocarbon calibration exists in the form of subfossil kauri trees buried in bogs scattered over a 300 km stretch of northern New Zealand (Palmer et al. 2006). We know of nowhere else in the world with such a rich resource of subfossil wood that is capable of capturing the complete temporal range of radiocarbon. The time span preserved within these bogs covers more than 130 ka. These trees are of vast proportions and almost perfectly preserved (Fig. 2); individual trees can measure up to 4 m across and live for up to 2000 years. Within this precious archive is an annual record of past climate but, equally importantly, of changing atmospheric radiocarbon levels. The kauri trees have considerable potential to assist in the development of a Southern Hemisphere component of a unified global calibration curve. In addition, the tree-ring sequences can be superposed on other radiocarbon records to constrain carbon cycling in marine and atmospheric reservoirs at times of abrupt change (Turney et al. 2010). Most recently, the detailed analysis of kauri trees has been used to identify errors in Northern Hemisphere radiocarbon datasets (Hogg et al. 2013), providing a more accurate calibration for the transition to the Holocene, and potentially for the last glacial period.

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# Bivalve shells: ultra high-resolution paleoclimate archives

Bernd R. Schöne<sup>1</sup> and Donna Surge<sup>2</sup>

**Shells of bivalve mollusks provide time-constrained, multi-proxy records of climate change in any aquatic setting with unprecedented temporal resolution ranging from years to individual days. We explain why this archive is unique and list current research foci.**

Climate proxy-data are crucial to better understand natural environmental variability prior to the instrumental era (Jones et al. 2001). In particular, there is a need for more sub-seasonal to annual resolutions of well-constrained and quantifiable proxy data from environmental settings for which only limited data are available, e.g. in coastal marine regions and mid- to high-latitude oceans (Solomon et al. 2007). Sclerochronology describes the investigation of the growth patterns and geochemical properties of the skeletal hard parts of bivalve shells. During the last decade, many sclerochronological studies (e.g. Schöne and Gillikin 2013) have confirmed that bivalve shells can record climate at sub-seasonal time scales (Butler et al. 2013; Schöne et al. 2003; Wanamaker et al. 2012).

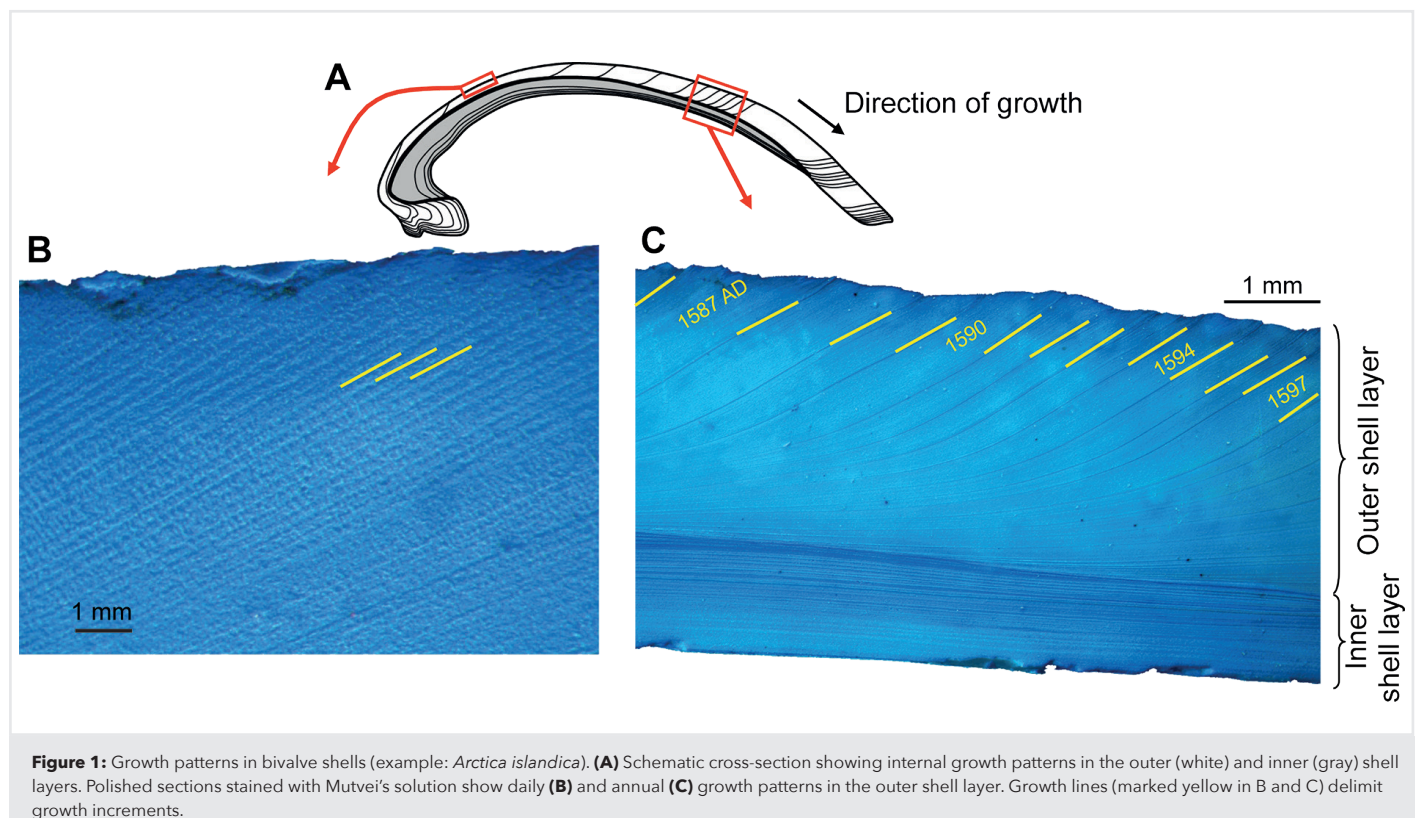
## Bivalve shells as paleoclimate archives

Bivalve shells can provide a precise chronology because calcium carbonate is periodically accreted to all growing shell margins (Barker 1964; Clark 1974; Jones 1980; Schöne and Surge 2012; Fig. 1). Regularly changing rates of

skeletal formation are controlled and maintained by so-called biological clocks, which are constantly reset by environmental pacemakers (light, tides, food availability, etc.; Kim et al. 2003; Williams and Pilditch 1997). These internal time-keeping mechanisms ensure that the shell growth pattern is divided into time slices of approximately equal duration (Dunca and Mutvei 2001; Witbaard et al. 1997), which produce growth increments and growth lines. Growth increments represent periods of fast growth and growth lines periods of slow growth. Together, they are prerequisite for sclerochronological analyses because they can be used to measure time, and place each shell portion into a precise temporal context. Periodic growth patterns in bivalves include annual cycles (Jones and Quitmyer 1996; Pulteney 1781; Weymouth 1922), fortnightly cycles (15 and 13.5 lunar days; Evans 1972; House and Farrow 1968; Ohno 1989), as well as circadian (ca. 24 hours; Schwartzmann et al. 2011), circalunidian (lunar-daily, ca. 24.8 hours; Richardson 1987), circatidal (semidiurnal, ca. 12.4 hours, ebb/neap tide cycle; Beentjes and Williams

1986) and ultradian cycles (periods of minutes to hours; Rodland et al. 2006). This makes shells unrivaled archives for measuring time in the geological past at high resolution.

Bivalve shells also function as faithful and sensitive recorders of environmental change (Fig. 2). Like other cold-blooded animals, bivalve growth is largely controlled by external energy input in the form of temperature, and food quantity and quality. As a result, relative changes in shell growth, expressed through varying increment widths, can provide information on changes in these environmental variables (Kennish and Olsson 1975). Furthermore, the ambient physicochemical conditions (salinity, water quality and temperature, food availability, etc.) that prevailed during its growth are also preserved in the shell as geochemical and crystallographic properties. For example, shell oxygen isotope ratios ( $\delta^{18}\text{O}_{\text{shell}}$ ) provide an ideal means to estimate past water temperature and salinity because almost all bivalve species form their shells very close to



**Figure 1:** Growth patterns in bivalve shells (example: *Arctica islandica*). (A) Schematic cross-section showing internal growth patterns in the outer (white) and inner (gray) shell layers. Polished sections stained with Mutvei's solution show daily (B) and annual (C) growth patterns in the outer shell layer. Growth lines (marked yellow in B and C) delimit growth increments.

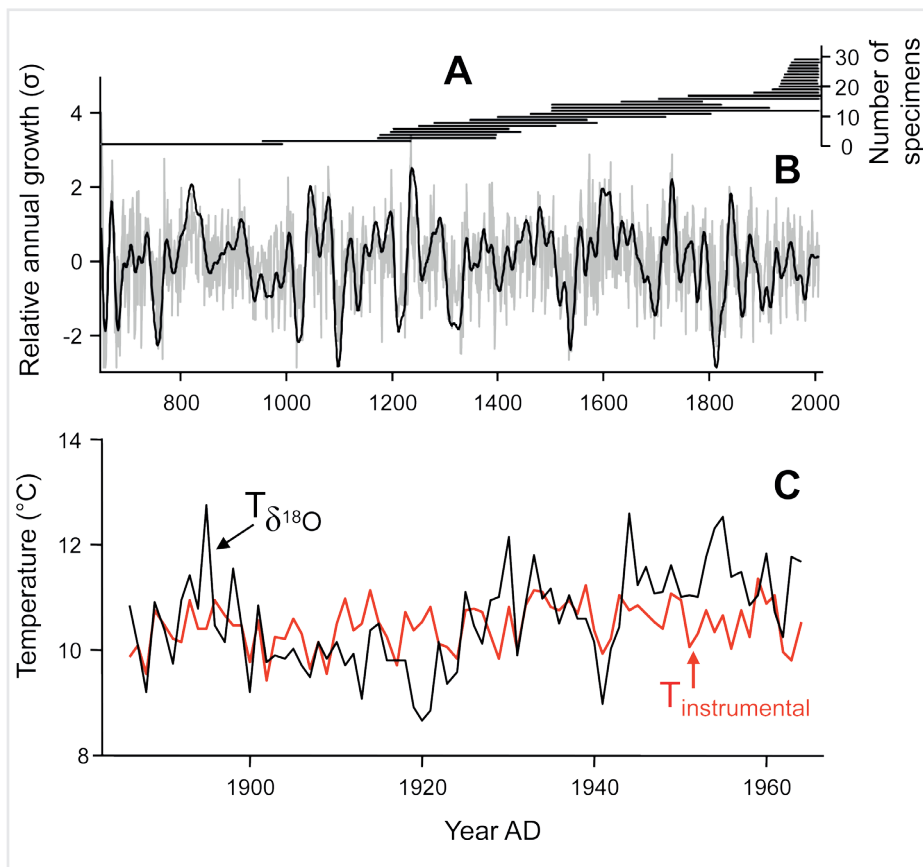
oxygen isotopic equilibrium with the ambient environment (Epstein et al. 1953; Wefer and Berger 1991).

Whereas the life of some bivalves such as *Donax variabilis* ends only after a few months (Jones et al. 2005), some species of the class Bivalvia are extremely long-lived (Schöne et al. 2005; Thomson et al. 1980; Zolotarev 1980), and lead the list of the longest-lived solitary (non-colonial) animals. For example, the Pacific geoduck (*Panopea generosa*) reaches a lifespan of 160 years (Strom et al. 2005), the European freshwater pearl mussel (*Margaritifera margaritifera*) can live for well over 200 years (Mutvei and Westermarck 2001), and lifespans exceeding 500 years have been reported from the deep-sea oyster *Neopycnodonte zibrowii* (Wisshak et al. 2009) and the ocean quahog, *Arctica islandica* (Butler et al. 2013). Thus, individual fossil shells open multi-century windows into past climate and provide details on paleoseasonality as well as quasi- and multi-decadal climate variability. However, such analyses are not limited to climatic snapshots. Since contemporaneous specimens from the same habitat exhibit a common response to changing environmental conditions, growth increment width-chronologies of specimens with overlapping lifespans can be combined by wiggle-matching (cross-dating) to form composite chronologies covering centuries to millennia (Butler et al. 2013; Jones et al. 1989; Lohmann and Schöne 2013; Marchitto et al. 2000; Witbaard et al. 1997; Fig. 2). With just one calendar date (e.g. the date of death of live-collected specimens), each sample can be aligned to reveal a complete chronology.

Bivalves exhibit an impressively broad and unrivaled biogeographic distribution. They have adapted to a wide range of different aquatic habitats. Today, bivalves occur in the tropics and near the poles, in shallow waters and in the deep sea, and inhabit the whole range from hypersaline to freshwater settings. Furthermore, bivalves occur abundantly in the fossil record. In fact, their evolutionary history started early in the Cambrian, i.e. 500 Ma ago. Since humans settled along the coasts tens of thousands years ago and exploited shallow marine resources, a vast number of bivalve shells are also preserved in archeological shell middens, i.e. ancient domestic waste deposits. To date, this material has largely been used to infer human subsistence practices by reconstructing the season of collection of the bivalves (Andrus 2011; Burchell et al. 2013).

### Current research foci

Growing interest in bivalve sclerochronology over the last decade has fuelled a soaring number of publications and research projects and four main research directions: (1) construction of millennial-scale master chronologies; (2) paleoclimate snapshot analysis (climate reconstruction from single specimens); (3) identification of chemical disequilibrium effects and quantification of vital and possible kinetic effects in order to optimize existing and develop new climate proxies; and (4) season-of-collection studies in archeology and anthropology. Recently, a large collaborative research initiative was funded by the EU (ARAMACC.com), whose goals include: (1) construction



**Figure 2:** A 1357-year master chronology of *Arctica islandica* from the North Icelandic shelf (data from Butler et al. 2013). **(A)** Sample depth. Each horizontal line indicates the lifespan of one specimen. **(B)** Stacked record of growth increment width-chronologies of the 30 specimens shown in (A). The black line represents the 30-year low-pass filtered annual growth data (gray). **(C)** Growth increment data can be combined with high-resolution geochemical analysis. The example from Schöne and Fiebig (2009) illustrates the annual temperature evolution in the southern North Sea during the late 19<sup>th</sup> and the 20<sup>th</sup> century reconstructed from δ<sup>18</sup>O<sub>shell</sub> values. Instrumental sea surface temperatures are given for comparison.

of millennial-scale *Arctica islandica* master chronologies from different settings in the boreal North Atlantic to produce paleoclimate reconstructions using stable isotopes (δ<sup>18</sup>O<sub>shell</sub>, δ<sup>13</sup>C<sub>shell</sub>), Sr/Ca ratios and growth-increment widths; and (2) development of novel bivalve shell-based paleoclimate proxies on the basis of microstructures (overall fabrics, shell architectures), or trace and minor elements. This will require stronger cross-disciplinary collaboration with biochemists to better understand the mechanisms of biomineralization in bivalves, in particular the complex pathways and fractionation processes involved in the transport of elements from the ambient environment to the site of calcified tissue formation (Marin et al. 2012).

### The future of bivalve sclerochronology

The potential of bivalve sclerochronology in the fields of archeology and anthropology, evolution, retrospective environmental monitoring, and ecology is still waiting to be fully exploited; however, it will likely have a significant impact on paleoclimate and paleoenvironmental studies. Linking different high-resolution paleoclimate archives advances our knowledge of coupled climate systems, which will further improve predictive numerical climate models. The ubiquitous occurrence of bivalves in shallow-marine settings, especially longer-lived species, makes them suitable candidates for the construction of long master chronologies in both hemispheres. This would, for example,

permit deeper analyses of cross-hemispheric climate dynamics in the future.

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# Annually laminated speleothems in paleoclimate studies

Liangcheng Tan<sup>1</sup>, I.J. Orland<sup>2</sup> and H. Cheng<sup>2,3</sup>

**New analytical techniques enable the extraction of annual climate information from speleothems for times long before historical climate records began.**

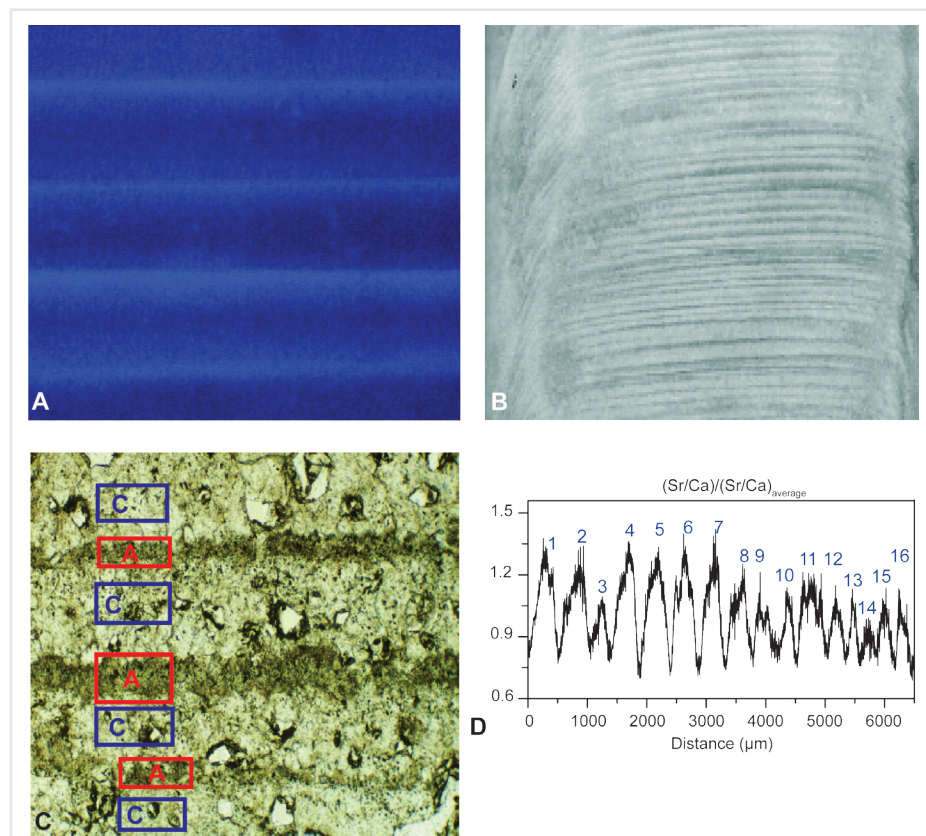
Speleothems (stalagmites, stalactites and flowstones) are natural paleoclimatic and paleoenvironmental archives. They are widespread in karstic environments and grow from drip water that degases CO<sub>2</sub> upon entering caves (Fairchild and Treble 2009). If seasonal climate variations outside the cave (e.g. precipitation, temperature, snow melting) or inside the cave (e.g. humidity, air CO<sub>2</sub> partial pressure, air ventilation) are large enough, this seasonality may be preserved as annual laminas in the speleothems (Tan et al. 2006; Baker et al. 2008). Therefore, speleothems have the potential to record past climate with annual resolution.

## Annual laminas in speleothems

Four main types of speleothem laminas have been reported (Fig. 1): (1) fluorescent laminas, which can be observed by using conventional mercury light-source UV reflected-light microscopy (Shopov et al. 1994) and confocal laser fluorescent microscopy (Orland et al. 2012); (2) visible laminas, which can be observed using conventional transmitted and reflected-light microscopy (Genty and Quinif 1996); (3) calcite-aragonite couplets, which show seasonal alternations of calcite and aragonite growth layers (Railsback et al. 1994); and (4) geochemical laminas (Johnson et al. 2006) defined by the annual variability of their chemical constituents such as stable isotopes ( $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ ) and trace elements (e.g. Mg, Sr, Ba). To confirm the annual character of banding, the number of layers counted in a speleothem is compared with the duration of growth measured independently by radiometric dating techniques. For samples of late Pleistocene age, <sup>230</sup>Th dating is used most commonly (Baker et al. 1993; Tan et al. 2000), while samples younger than 150 years can be dated with <sup>210</sup>Pb and <sup>226</sup>Ra methods (Baskaran and Iliffe 1993; Condomines and Rihs 2006) or with the atomic bomb testing <sup>14</sup>C signature that characterizes the last 50 years (Genty et al. 1998; Matthey et al. 2008).

## Application in paleoclimate studies

The annual laminations in speleothems provide accurate age indications for paleoclimate proxies measured within the speleothem, and allow reconstructing the accurate timing and structure of abrupt climate changes. The temporal relationships between the regional expressions of an abrupt event are crucial for understanding its origination and its transferring mechanisms. For example, Liu et al. (2013)

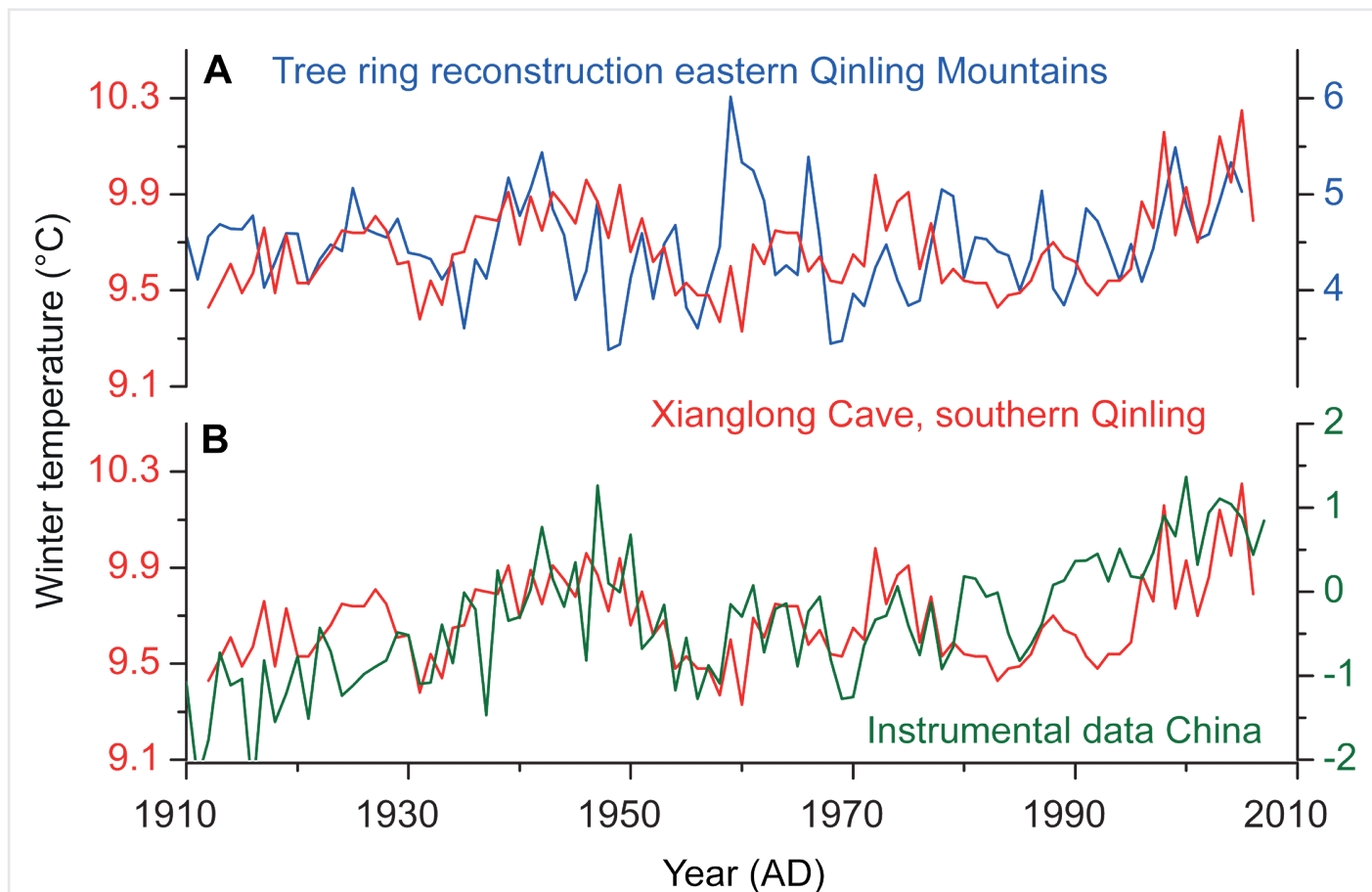


**Figure 1:** Four types of speleothem laminas. **(A)** Fluorescent laminas excited by UV light. **(B)** Visible laminas observed under reflected-light microscopy. **(C)** Calcite (C) and aragonite (A) couplets, observed under transmitted-light microscopy, and **(D)** geochemical laminas where the normalized Sr/Ca peaks were used to define 16 years. Modified from Tan et al. (2006) and Johnson et al. (2006).

reconstructed the timing and structure of the 8.2 ka event in the East Asian monsoon region based on  $\delta^{18}\text{O}$  and Mg/Ca ratios of a stalagmite from central China. Their results show that the duration and evolution of precipitation during this event is indistinguishable from temperature recorded in Greenland ice cores, suggesting a rapid atmospheric teleconnection between the North Atlantic and the East Asian monsoon region. Likewise,  $\delta^{18}\text{O}$  records from other Chinese stalagmites indicate that the Asian monsoon transition into the Younger Dryas (YD) extended over ca. 340 years (Liu et al. 2008; Ma et al., 2012), while the shift out of the YD took less than 38 years (Ma et al. 2012).

Precise chronologies are also crucial for comparing proxies from speleothems with instrumental meteorological data to identify their climatic and environmental significances. For example, Baker et al. (1998) found a correlation between the content of high-molecular-weight organic acids and annual rainfall in an annually laminated stalagmite from England, and used this correlation to reconstruct precipitation during the last interglacial. In a stalagmite from central Belize, variations of  $\delta^{13}\text{C}$  co-vary with the observed Southern Oscillation Index (Frappier et al. 2002) and were shown to be influenced by changes to the carbon budget of the overlying rainforest. The forest is sensitive to the local weather and, in turn, controlled by the Southern Oscillation.





**Figure 2:** Comparison of temperature from September to May reconstructed by speleothem layer thickness from Xianglong Cave in southern Qinling Mountains, central China (red lines) with **(A)** tree ring-based winter temperature reconstruction from nearby, and **(B)** surface winter temperature across China during the last hundred years. Modified from Tan et al. 2013.

The layer thickness of annual laminae can be used to infer the speleothem growth-rate per year. Growth rates have been used to quantitatively reconstruct past temperature (Tan et al. 2003), as well as precipitation and associated changes in atmospheric circulation (Proctor et al. 2000).

Tan et al. (2006) reviewed the applications of stalagmite laminae to paleoclimate reconstructions and compared them to the dendroclimatological approaches. Baker et al. (2007) suggested that a transfer function reflecting the mixing of water from rainfall events and groundwater storage could be used to reconstruct high-resolution hydroclimatic records from stalagmites. More recently, Tan et al. (2013) developed a two-variable linear regression between stalagmite growth rate and temperature that accounts for smoothing and lag effects of stalagmite growth in response to climatic changes. With this regression, they quantitatively reconstructed temperature changes from September to May between AD 1912 and 2006. This stalagmite-based reconstruction is coherent with a nearby tree-ring temperature reconstruction (Fig. 2), which documents the sensitivity of this archive to air temperatures (Tan et al. 2013).

### Perspectives

Annually laminated speleothems are often found in caves with a shallow depth and an outside climate that exhibits strong seasonality (Tan et al. 2006). Recent methodological

advances have the potential to expand the applications of speleothems as paleoclimate recorders and to reduce their uncertainties in climate reconstruction. For example, digital image analysis, e.g. with a hyperspectral scanner, allows for faster and more accurate counting of laminae compared to traditional optical analyses (Jex et al. 2008). High-precision and high-resolution in situ measurements of stable isotopes and trace elements using ion microprobe (Orland et al. 2009), laser-ablation inductively coupled plasma mass spectrometry (Johnson et al. 2006), and synchrotron radiation micro X-Ray fluorescence (Borsato et al. 2007) have all revealed annual and sub-annual variations in speleothem chemistry. As a result, improved speleothem chronologies can be built by measuring geochemical variability along the growth axis. Furthermore, by pairing images of annual laminae with seasonal-resolution measurements of geochemical variability in speleothems, seasonal climate patterns can be reconstructed. For example, the combination of fluorescent imaging and ion microprobe analysis of  $\delta^{18}\text{O}$  in speleothems from Israel has been used to identify regional changes in seasonality across abrupt climate events and over millennial time scales (Orland et al. 2009, 2012).

Future research should focus on quantitative and qualitative reconstructions of paleoclimate and paleoenvironment by using multiple proxies from annually laminated speleothems, including stable isotopes, trace elements, as well as layer thickness. Finally, efforts are being

made to apply statistical approaches better suited to reconstruct past climate quantitatively using speleothem records (Tan et al. 2006, 2013).

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# Seasonality in speleothems

Ian J. Fairchild<sup>1</sup>, M. Bar-Matthews<sup>2</sup>, P. M. Wynn<sup>3</sup> and I. J. Orland<sup>4</sup>

**Seasonal signals are transmitted to speleothems via the quantity, chemistry and isotopic composition of dripping water in caves. Modern techniques allow seasonality to be interpreted through variations in trace elements, stable isotopes, and organic fluorescence within annual layers.**

Records from calcareous cave deposits (speleothems) can reveal large-scale variations in the climate system over long time periods (Bar-Matthews et al. 2003; Fairchild and Baker 2012). These records require the direct transmission of an atmospheric signal to the speleothem, and uranium-series dating to construct a precise and accurate age model (Cheng et al. 2009). As with other natural archives, ambiguities remain with the climatic interpretation of speleothem records. For example, the mean oxygen isotope composition of speleothems in monsoon-influenced areas has been interpreted as indicating the relative strength of summer versus winter monsoons (Wang et al. 2001). Hence, it is desirable to resolve and understand seasonal processes, particularly those related to rainfall (Johnson et al. 2006; Hu et al. 2008; Orland et al. 2009, 2012). However, how are seasonal signals captured in a cave?

## Cave climate and seasonality

Seasonal changes are muted in cave interiors, which are archetypically isothermal, fetid and humid. Therefore, temperatures are usually close to the external annual mean. The difference in external and internal temperatures can lead to density-driven air circulation, which is typically enhanced in the winter, which is also the season of lower levels of CO<sub>2</sub> in the cave atmosphere. This leads to more degassing of CO<sub>2</sub> from dripwaters and causes speleothems to grow faster in winter than in summer (Wong et al. 2011). A common consequence of this seasonal bias in calcite precipitation is seasonal oscillation of <sup>13</sup>C, Mg and Sr concentrations in speleothems (Fairchild et al. 2000; Frisia et al. 2011; Tremaine and Froelich 2013).

The flow-path of dripwater into the cave can also affect the preservation of seasonal signals in speleothems. Overlying karstic carbonate bedrock contains fractures that provide a rapid routing of water away from the surface, while networks of finer pores in the matrix only enable seepage flow. Fracture and pore flow are mixed in varying proportions in dripwaters. Therefore, the quantity and chemical composition of dripwater reflect the magnitude and pattern of rainfall or snowmelt and the pathways of its delivery to the karst system via the overlying soil.

A range of potential consequences arises from the drip-specific hydrological regime – thin laminae in speleothems contain chemical impurities from rainfall infiltration events whereas the dry season usually results in enrichments in trace elements (Baker et al. 2000; Fairchild et al. 2000; Fairchild and Treble 2009). When travel times of water are short, seasonal variations in the oxygen isotope composition of rainfall are

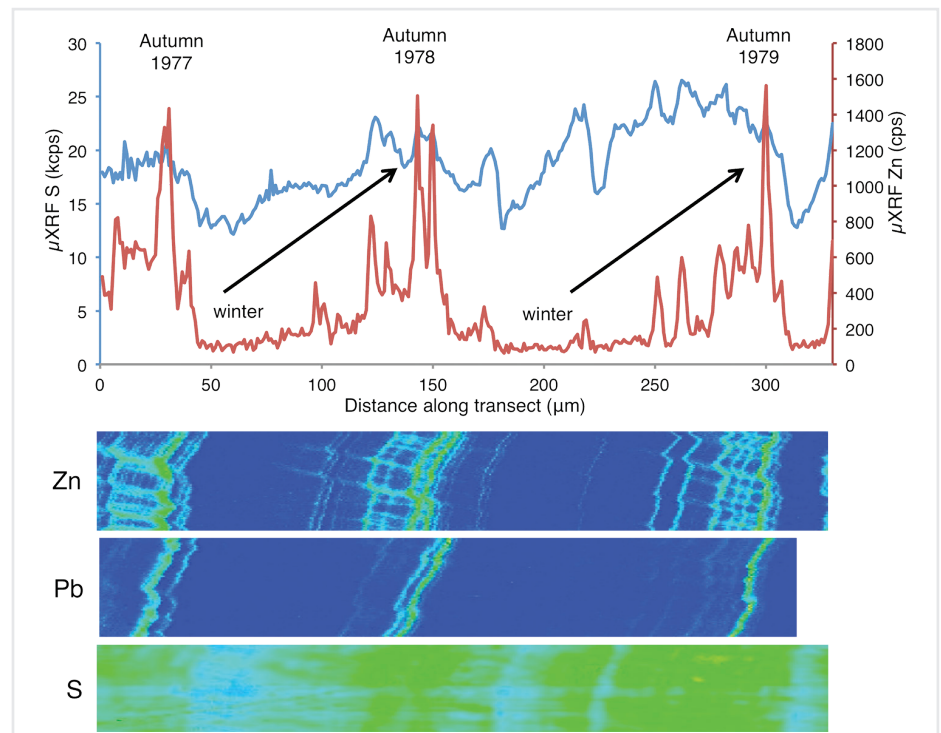
transmitted to caves and speleothems, but sites fed purely by seepage flow may have seasonally invariant δ<sup>18</sup>O compositions. Crucially, these properties can vary between adjacent speleothems in the same cave because of local variations in hydrological properties of the host rock. Hence, for scientists wanting to study climate at high resolution, a cave with speleothems is like the “à la carte” menu to a food-allergy sufferer: careful selection of what item to choose is vital.

## Annual and sub-annual properties of speleothems

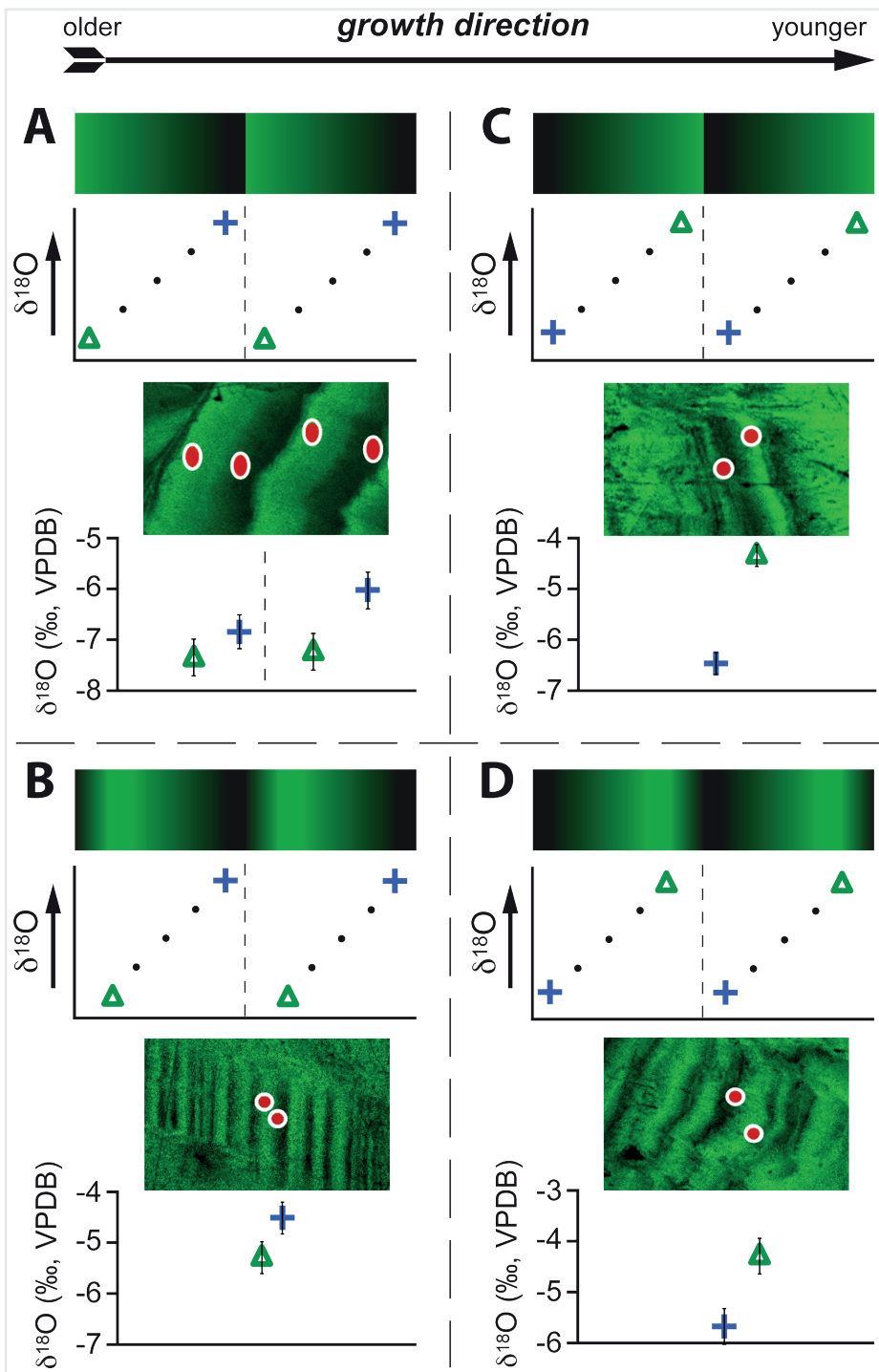
Annual lamination has been established as a common feature of stalagmites under a variety of climatic conditions (Baker et al. 1993; Orland et al. 2009). One type of lamination consists of narrow bands enriched in soil-derived organic matter. These bands are made visible by fluorescence microscopy. The laminae are enriched in trace elements (Borsato et al. 2007), which travel in water and are bound to organic ligands in colloids (Fairchild and Baker 2012). Background transmission of seepage waters containing fine humic molecules with a

particular trace element signature should be distinguished from pulses of coarse colloids, which require hydrologically active conditions for their trace element patterns to be recorded (Hartland et al. 2012). Figure 1 illustrates what is perhaps the highest number of precipitation events in a single year ever documented in speleothems (Wynn et al. 2014). In Obir Cave in the Austrian Alps, high levels of lead and zinc, derived from local bedrock, record infiltration from individual synoptic rainfall events. Sensitivity is higher in autumn when vegetation dieback facilitates leaching loss of humic substances and of associated metals from the soil (Borsato et al. 2007).

The time of year is independently documented by the sulfate content of the calcite (analyzed as sulfur; Fig. 1). More sulfate ions are incorporated at high PCO<sub>2</sub> (cave air CO<sub>2</sub> partial pressure; Frisia et al. 2005). In the Obir cave PCO<sub>2</sub> is higher during summer when the external air is warmer (and hence air density is lower) than in the cave. Thus, each summer and winter can be identified as high- (green-colored)



**Figure 1:** Three annual growth cycles in a speleothem from the Obir cave, Austrian Alps (Obi84) depicting relative concentrations of lead (Pb), zinc (Zn) and sulfur (S; known to be in the form of sulfate by absorption studies) mapped by micro-XRF synchrotron radiation. High-intensity banding (“greener”) represents transport of organic-ligand-bound Pb and Zn during synoptic rainfall events. Highest intensity bands represent intense autumnal rainfall and loss of organic molecules and associated metals from the soil zone during times of vegetation dieback. Relative concentrations of S demonstrate independent verification of seasonality and timing of the autumnal flush of Zn and Pb. Low winter S concentrations are a product of low cave chamber PCO<sub>2</sub> and high carbonate to sulfate ratios during speleothem growth. From Wynn et al. (2014) with permission.



**Figure 2:** Examples of four patterns (A-D) of fluorescent banding and  $\delta^{18}\text{O}$  variability observed on annual growth bands in a stalactite from Soreq Cave (Israel) that grew from 34 to 4 ka. A schematic of each pattern is shown above an example from the speleothem. The spots analyzed for  $\delta^{18}\text{O}$  by ion microprobe are marked by red dots,  $\sim 10\ \mu\text{m}$  in diameter, on the image of fluorescent banding acquired by confocal laser fluorescent microscopy. Green triangles and blue crosses mark  $\delta^{18}\text{O}$  values measured in areas of bright and dark fluorescence, respectively; each with  $2\sigma$  error bars. Note the range of  $\delta^{18}\text{O}$  analyses within single bands varies from 0 to  $>2\%$  (Figure adapted from Orland et al. 2012, which includes a climatic interpretation of these patterns).

and low-sulfate (blue-colored) zones in the speleothem, respectively (Fig. 1). Year-to-year variations in the seasonal sulfate oscillations can reveal the relative length of the warm and cold seasons.

A second type of annual lamination consists of couplets, alternately richer and poorer in fluid inclusions, varying in Mg-Sr chemistry and sometimes differing in mineralogy (Baker et al. 2008). Fundamentally, these laminae reflect

an annual bimodality of water chemistry which usually can be correlated with either alternating warm and cold seasons that lead to varying  $\text{PCO}_2$  levels, or with summer drought, which leads to increases in Mg, Sr and  $\delta^{13}\text{C}$  (Mattey et al. 2008; Boch et al. 2011; Orland et al. 2014).

The changing isotopic composition of water molecules is preserved in the  $\delta^{18}\text{O}$  signal of speleothem  $\text{CaCO}_3$ . The  $\delta^{18}\text{O}$  variation within annual laminae can reflect the seasonal variability

in composition of infiltrating water as well as the rainfall amount. However, evaporation in the soil zone and dampening of the seasonal signal by mixing processes during the infiltration can also influence the  $\delta^{18}\text{O}$  values (Ayalon et al. 1998).

A modern well-dated speleothem from Soreq Cave in Israel has revealed characteristic properties that can be used to trace the nature of seasonality and rainfall variability over time. Annual laminae are marked by fluorescent zones that are brighter in wetter years and are associated with  $\delta^{18}\text{O}$  variation. The range of  $\delta^{18}\text{O}$  correlates with the amount of rainfall in the corresponding year (Orland 2012). In older speleothems from Soreq Cave (Fig. 2), changes in the patterns of fluorescent banding and annual  $\delta^{18}\text{O}$  variability are also interpreted to reflect different seasonal climate regimes (Orland et al. 2012).

### Analytical frontiers

The identification of sub-annual properties in speleothems depends on the presence of fast-growing, compact crystals (columnar fabrics are best, Frisia et al. 2000) with a growth surface that is either flat, or, if irregular, can be clearly imaged (Fig. 2). For trace elements, the  $\mu\text{m}$ -scale resolution of X-ray fluorescence analysis by synchrotron radiation provides the highest resolution that can be obtained to date. SIMS (secondary ionization mass spectrometry) has a resolution of several microns and provides unique data on elements that are difficult to analyze by other means (Fairchild et al. 2001). Accurate and precise laser-ablation inductively coupled plasma mass spectrometry (LA-ICPMS) has  $\sim 10\ \mu\text{m}$  resolution, which is sufficient to resolve seasonal properties for faster growing samples. For stable isotopes, faster-growing samples can be sub-sampled by micromilling with a resolution of  $\sim 100\ \mu\text{m}$  and analyzed by mass spectrometry (Drysdale et al. 2012). Laser ablation offers a more rapid alternative for stable isotope analysis if care is taken to screen out artifacts (Spötl and Mattey 2006). The oxygen isotope SIMS analysis of Figure 2 was achieved with a spot size of  $10\ \mu\text{m}$ , resolving seasonal variations in bands as narrow as  $20\text{--}30\ \mu\text{m}$  (Orland et al. 2009, 2012).

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# State of the art of ice core annual layer dating

Sune O. Rasmussen, A. Svensson and M. Winstrup

**Polar ice cores reveal past climate change in ever-growing temporal resolution. Novel automated methods and improved manual annual layer identification allow for bipolar year-to-year investigations of climate events tens of thousands of years back in time.**

Ice cores from Antarctica, from the Greenland ice sheet, and from a number of smaller glaciers around the world yield a wealth of information on past climates and environments including unique records of past temperatures, atmospheric composition (for example greenhouse gasses), volcanism, solar activity, dustiness, and biomass burning. Some ice-core records from Antarctica extend back in time more than 800,000 years (Jouzel et al. 2007), while ice cores from sites with higher accumulation offer continuous records of very high temporal resolution. For example, Greenland ice-core records reach back into the penultimate interglacial 130,000 years ago with annual or close to annual resolution (NEEM community members 2013).

To maximize the knowledge gain from ice cores it is essential to establish accurate and precise chronologies that assign an age to each depth segment. A key property of high-resolution ice-core records is annual layering, which allows for the construction of a very accurate chronology by counting layers back as far as tens of thousands of years. New high-resolution measurements and improved algorithms for automated and objective annual layer counting are currently being developed to allow refinement and extension of these chronologies.

## Annual layering in ice cores

Seasonal variations in isotopic composition and impurity content of the snowfall provide the basis for a distinct annual signal in the snowpack, which may be preserved in the ice under favorable conditions. The ability of an ice core to provide (sub-)annual information depends on the accumulation rate. It typically ranges from a few centimeters of ice per year in high-elevation areas of Antarctica to several meters at coastal sites of Greenland and on low latitude glaciers. In the upper part of an ice sheet, snow slowly compacts into incompressible ice. Due to the continuous accumulation of snow, annual layers become buried in the ice sheet over time. Gravity causes the ice to flow toward the ice sheet margins, which results in thinning of the annual layers with depth (Fig. 1). Close to the base of an ice sheet, ice flow over bedrock undulations causes folding and shearing leading to stratigraphic disturbances that can complicate precise dating of the lowermost section of an ice core.

## Detecting the annual signal

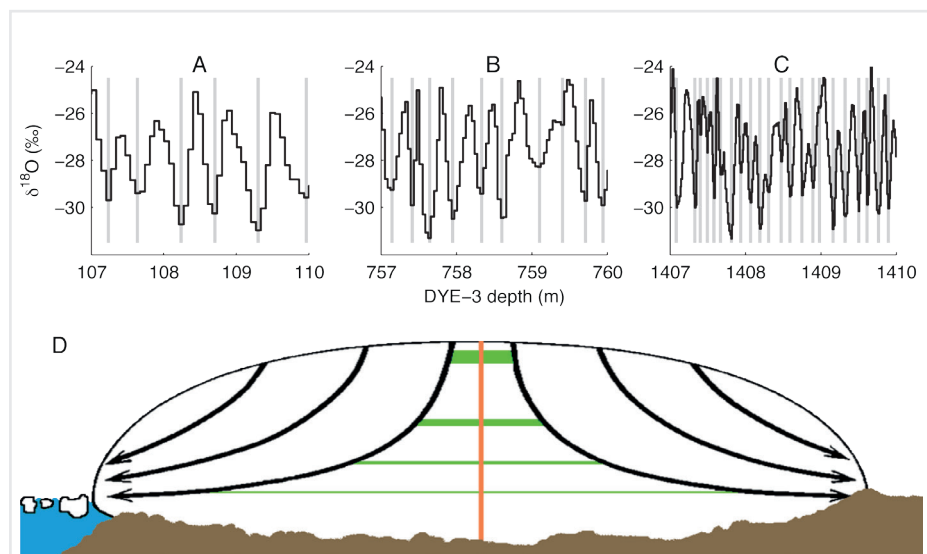
The ratios of stable oxygen and hydrogen isotopes in glacier ice (expressed as  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values) reflect seasonal variations in local temperature at the time of precipitation (Dansgaard 1964). In ice cores from

high accumulation sites, such as the South Greenland DYE-3 core (Fig. 1), the seasonal signal may be traced 8,000 years back in time (Vinther et al. 2006). However, at lower accumulation sites, diffusion of water molecules during the transition from snow to ice reduces, or completely erases, the amplitude of the seasonal cycle. Moreover, ice flow-induced layer thinning and diffusion of water molecules within the deep ice ultimately obliterates the seasonal  $\delta^{18}\text{O}$  and  $\delta\text{D}$  cycles even in high-accumulation areas (Johnsen et al. 2000). Therefore, in deeper ice, other proxies less prone to diffusion must be employed for annual layer detection.

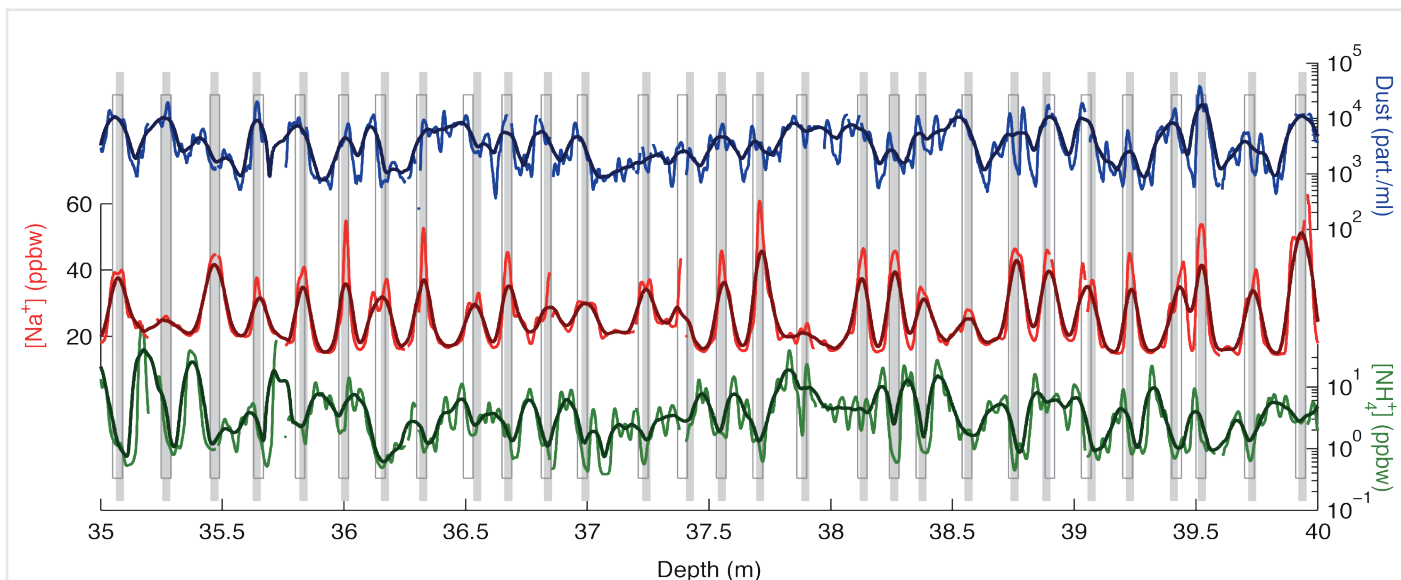
An annual signal may also be preserved in the impurity content of an ice core, as many impurities display a seasonal variation (Fig. 2). In Greenland, for example, dust concentrations generally reach a maximum during spring, whereas the amount of sea-salt aerosols peaks during winter (Rasmussen et al. 2006). The annual dust cycle can sometimes be identified from the visible layering of an ice core (Svensson et al. 2005), but most impurity records are obtained by measurements on melted samples, often using a melting device and a high-resolution continuous flow analysis (CFA) system (Röthlisberger et al. 2000).

## Counting of annual layers

In general, impurity records are more complex to interpret than isotope records as they also contain non-annual signatures, e.g. input from volcanic eruptions, biomass burning, and other episodic sources. For this reason, the parallel analysis of several impurity records of different origin is recommended when establishing a chronology. Extensive high-resolution CFA datasets have allowed for manual multi-proxy layer identification in ice cores from both hemispheres. In Greenland, data from several cores form the basis of the Greenland Ice Core Chronology 2005 (GICC05), which extends 60,000 years back in time (Svensson et al. 2008). Annual layers have also been identified back to ~30,000 years BP in the ice core drilled on the West Antarctic Ice Sheet Divide (WAIS Divide Project Members 2013), in the Antarctic EPICA Dronning Maud Land ice core (EDML), and in numerous younger ice cores from both hemispheres. These ice-core chronologies rely on manually identifying annual layers, which is laborious and inherently entails subjectivity. However, it is also a very flexible approach that



**Figure 1:** Three 3-meter long sections (A-C) of annually resolved  $\delta^{18}\text{O}$  data from different depths of the 2,037 m long South Greenland DYE-3 ice core. The ages are (A) 175-180, (B) 1845-1854, and (C) 4657-4678 years before A.D. 2000, respectively. Gray bars show manually identified winter minima. (D) The ice flow leads to annual layer thinning that together with diffusion ultimately leads to a loss of the annual signal with depth.



**Figure 2:** Example of continuous flow analysis data (smoothed curves in bold) from a shallow ice core from the North East Greenland Ice Stream (NEGIS) site. Several different impurities are measured, but here we show only the concentration of insoluble dust, Sodium ions, and Ammonium ions, chosen because the annual signal is expressed in different ways in these three data series. Manually identified winter layers (grey solid bars) and automated dating results (open gray bars; for method see Winstrup et al. 2012) agree in sections where the annual signal is clearly expressed in all three data series with a resolution sufficient to resolve even relatively thin layers.

can accommodate changes in the expression of annual layers, data quality, and resolution.

#### Development of new methods

New analytical techniques are widening the array of impurities that can be analyzed at annual resolution (McConnell et al. 2002). Moreover, refinement of CFA setups and data processing is increasing data resolution, now allowing detection of strata at the millimeter scale (Bigler et al. 2011). The resulting improvements in data quality and quantity allow for the extension and improvement of current ice-core chronologies as annual layers can now be detected in sections of the cores where annual layer identification has not previously been possible. Furthermore, development of new methods for statistical annual layer detection may soon supplement manual layer identification. Several automated approaches are being developed and have been applied to both single-record and multi-parameter data sets (Winstrup et al. 2012; Wheatley et al. 2012; McGwire et al. 2011). Among the more sophisticated approaches, the Bayesian algorithm by Winstrup et al. (2012) considers all possible divisions of a data series into an arbitrary number of layers, and selects the optimal division based on the appearance of layers and their individual thicknesses (Fig. 2). The method relies on assumptions of the statistical nature of the annual signal, the validity of which should be tested where independent dating methods allow for this. Providing that these assumptions are correct, the automated method produces objective annual layer-based ice-core chronologies with well-quantified uncertainties. Integrated uncertainty estimation is a key quality of this automated Bayesian method that represents a significant advance compared with manual subjective error estimates.

#### The accuracy-precision issue and new common chronological frameworks

As with any annually laminated record dated by layer counting, the uncertainty accumulates with increasing age. Consequently,

the determination of absolute ages is very accurate for recent periods, while the accumulated uncertainty often becomes large (i.e. low accuracy) compared to e.g. radiometric dating uncertainties in the last glacial period. However, even when the absolute accuracy is relatively low, layer counting still provides the possibility to determine event durations as recorded in the ice cores very precisely. For example, the accuracy of the GICC05 time scale at the onset of the Holocene is about a century, while the outstanding precision allows for the analysis of how the transition into the Holocene is expressed in different proxy records with a maximum relative dating error of only a few years (Steffensen et al. 2008). In a similar way, the GICC05 counting uncertainty of a few percent in the glacial period makes it possible to constrain the duration of interstadial 11 in the Greenland record to 1100 years with a maximum counting error of just 54 years (high precision). In contrast, the absolute age of the event (43 ka before present) has a rather low accuracy due to an accumulated maximum counting error of 1700 years.

Ice cores from different sites can be synchronized using common time marker horizons of, for example, volcanic origin (Rasmussen et al. 2008; Severi et al. 2007; Parrenin et al. 2012) or common variations in methane levels (Blunier and Brook 2001; Pedro et al. 2011). Hence records from different sites can be aligned for parallel analysis with a precision that is often several orders of magnitude better than the absolute dating accuracy. Following this approach, the GICC05 chronology is currently being applied to all main Greenland ice cores to allow analysis of the climatic information from all cores in a consistent chronological framework. Recent studies also have employed a set of global event markers to synchronize ice cores from both hemispheres (Raisbeck et al. 2007; Svensson et al. 2013; Sigl et al. 2013) and are incorporating other sources of dating and ice flow information in a modeling framework in order to construct a consistent multi-ice-core

chronology (Lemieux-Dudon et al. 2010). The fidelity of chronologies modeled that way increases with the addition of more data and better quantification of the entailing uncertainties (Veres et al. 2013; Bazin et al. 2013). However, annual layer counted sections have yet to be included in a way that respects the nature of the annual layer counting process and the involved uncertainty. Therefore, modeled chronologies following this approach must still be considered complementary to annual layer counted chronologies.

Experimental and analytic innovations keep pushing the construction of annual-scale ice-core chronologies forward. Upcoming developments may allow stratigraphic ice-core chronologies to reach further back in time, to reduce and better quantify uncertainties, and to become better integrated both regionally and on a global scale.

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# Annually resolved climate signals in high-alpine ice cores

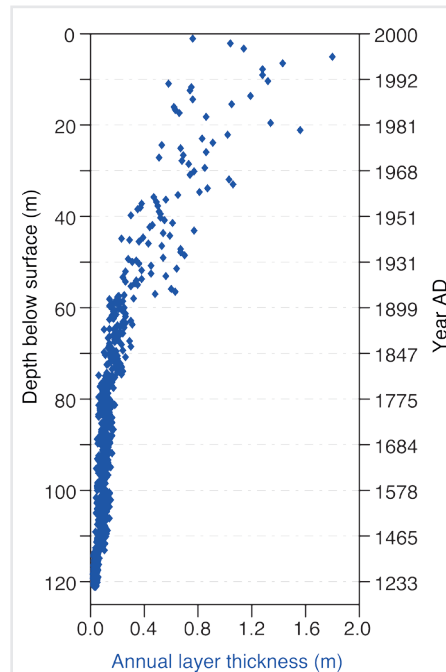
Margit Schwikowski, A. Eichler, T.M. Jenk and I. Mariani

**High-alpine ice cores offer great potential to obtain paleorecords with subannual resolution. However, calibration using instrumental data is often only possible at annual to multi-year resolution due to the strongly varying distribution of seasonal snowfall, post-depositional processes, and dating uncertainty.**

High-alpine glaciers are generally characterized by high annual snow accumulation rates in the range of half a meter to several meters water equivalent, allowing paleorecords with subannual resolution to be obtained. A number of ice core parameters such as the stable isotope ratio of hydrogen or oxygen in the water ( $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ ), the concentration of trace components (e.g. ammonium, mineral dust related compounds, black carbon), and the presence of melt layers vary with the seasons and have been used to identify annual layers. These variations are caused by the seasonality of temperature ( $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ , melt layers), precipitation ( $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ , mineral dust), or atmospheric transport and the emission source strengths of air pollutants (e.g. ammonium; Preunkert et al. 2000). However, even when subannually-resolved ice core records can be obtained, their calibration with climate indices remains difficult.

## Layer thinning with depth

The depth-age relationship of high-alpine glaciers is strongly non-linear as annual layers become thinner with depth. This is due to plastic deformation of the ice under the weight of the overlying mass, resulting in horizontal ice flow that stretches the layers with increasing depth. Thinning rates are particularly high in cold glaciers where the ice is frozen to bedrock, whereas in polythermal glaciers the ice slides down to the ablation area before it thins strongly. Depending on precipitation rates, annual layers in the upper part of the glacier may consist of several meters of firn, whereas in the deeper part flow-induced thinning reduces the layers to a thickness of a few centimeters or even less (Fig. 1). Using analytical methods with high spatial resolution, such as measuring the electrical conductivity of the ice or counting the micro-particles present in dust bands formed during the dry season, over 800 years annual cycles were detected in the Illimani ice core from Bolivia (Knüsel et al. 2003) and up to 1300 years in the Quelccaya ice core from Peru (Thompson et al. 2013). In the future this may be extended even further back in time as recent developments with continuous flow analysis techniques now allow increasing the spatial resolution to the mm scale (Bigler et al. 2011). For this approach, a section of the ice core is melted continuously on a melt head, and the meltwater from the inner part, not contaminated by handling and prevented from contact with the modern environment, is directly fed into the respective analytical instrument to determine the concentration of trace components.



**Figure 1:** Annual layer thickness for the Illimani ice core from Bolivia as function of the depth below the ice surface and the associated age of the ice.

## Issues with seasonality and dating

Due to the strong thinning of annual layers at depth, subannual information is only detectable in the upper part of the record, where ice-core dating can be performed by counting the successive annual layers. However, the seasonality of a recorded climatic variable may vary from year to year, according to meteorological conditions. For example, the minimum temperature as preserved in the Fiescherhorn  $\delta^{18}\text{O}$  record from the Swiss Alps (Fig. 2a) may have occurred in January, February or in some years even in December or March. Also, the stratification of the atmosphere controlling the concentration of ammonium by preventing vertical transport from the emission sources to glacier, which is used to distinguish winter from summer precipitation, may become unstable already in early spring in some years, but not until late spring in others.

Preservation of most parameters occurs only during precipitation. Accordingly the ice core record is strongly discontinuous at sites with high interannual variability of precipitation. In such cases only a precipitation weighted parameter, for example "precipitation weighted

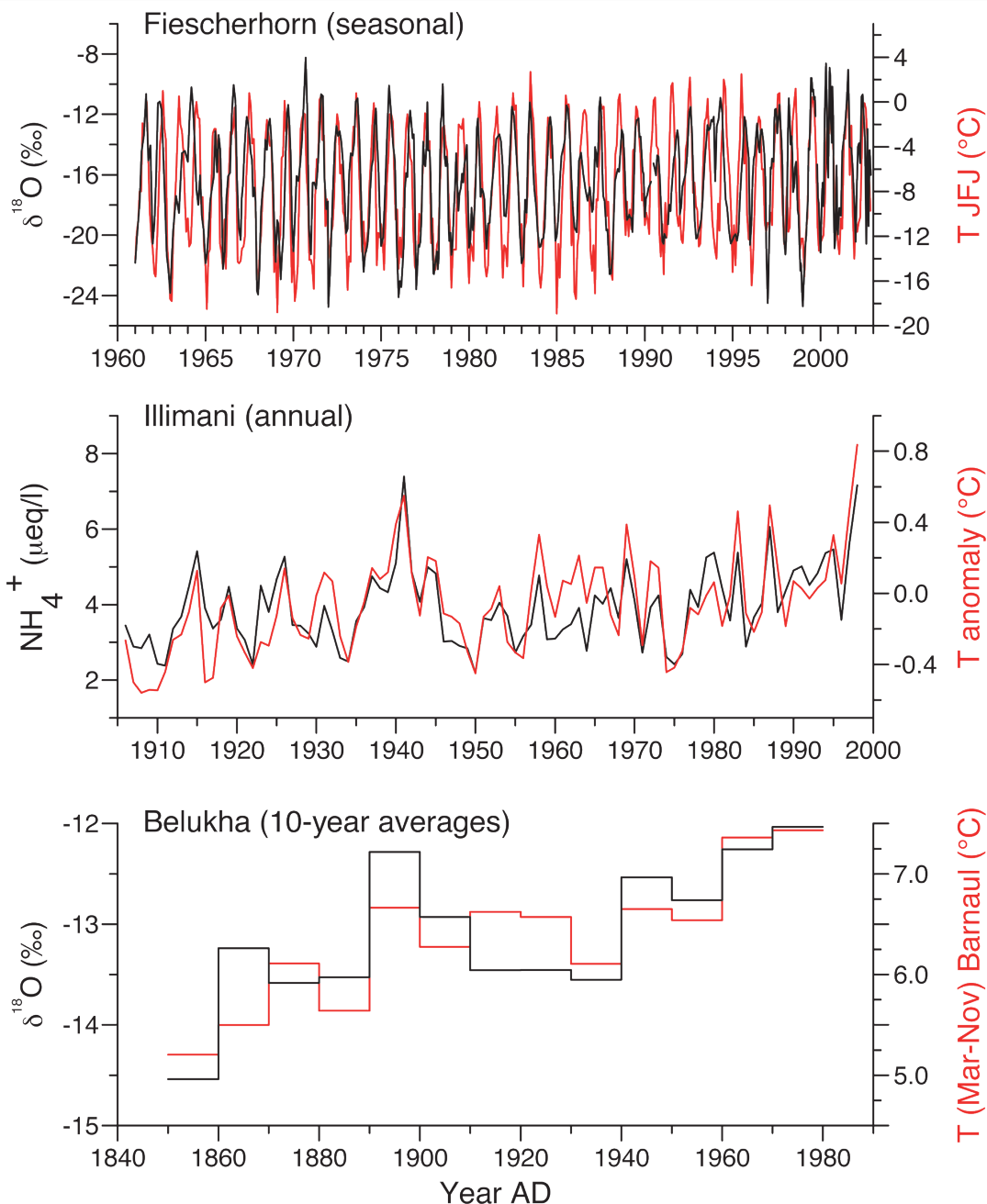
temperature", can be reconstructed (Brönnimann et al. 2013). But in most cases the seasonal distribution of precipitation is unknown for high-alpine sites, hence assumptions have to be made in order to dissect the record into seasonal or monthly data. Either constant seasonal distribution of precipitation is assumed or data from a nearby instrumental station at a lower elevation are used. However, both approaches introduce additional uncertainties to the interpretation of the paleoclimatic record (Mariani et al. 2012; Knüsel et al. 2005; Eichler et al. 2009).

The identification of annual layers can be ambiguous and result in dating uncertainties. Indeed, the formation of clear annual signals is often hampered by post-depositional wind erosion or surface melting and by the strongly varying distribution of snowfall in high-alpine environments. A further complication, which is confined to  $\delta^2\text{H}$  or  $\delta^{18}\text{O}$ , is that the record is smoothed by diffusion during the snow-to-ice metamorphosis. In addition to annual layer counting, reference horizons such as the radioactivity peak resulting from nuclear weapon tests in the 1960s or tephra and aerosol layers caused by volcanic eruptions place additional dating constraints. While the measurement of peaks in radioactivity is relatively unambiguous, the identification of volcanic layers is not always straightforward given the high background level of the indicative chemical compounds such as sulfate in mid-latitude and low-latitude glaciers. To our knowledge, volcanic eruptions have not yet been identified in non-polar ice cores prior to AD 1258, probably because no major eruptions occurred for several centuries prior to this date and the volcanic signals cannot be resolved anymore further back in time due to ice layer thinning. Other chronologic methods, such as radiocarbon dating or ice flow modeling, are crucial for dating the lower parts of the records, but have uncertainties far above annual (Jenk et al. 2009; Lüthi and Funk 2000). Accordingly, dating uncertainty beyond the range of reference horizons quickly accumulates to several years and further increases with depth. With that dating uncertainty working at annual resolution becomes meaningless.

## Calibrating ice-core records

Calibrating ice-core proxy records directly with instrumental data on an annual timescale is difficult. For example the high accumulation Fiescherhorn site provides paleodata with subannual resolution during the recent time





**Figure 2:** Calibration of ice core data (black) with instrumental temperatures (red) at different resolution: **(A)** Fiescherhorn ice core  $\delta^{18}\text{O}$  and Jungfrauoch (JFJ) temperature (seasonal values; Mariani et al. 2012), Switzerland **(B)** Illimani ice core  $\text{NH}_4^+$  and HadCRUT3 (Amazon subset: 82–34°W, 12–20°S) temperature (annual values; Kellerhals et al. 2010), Bolivia, and **(C)** Belukha ice core  $\delta^{18}\text{O}$  and Barnaul (March–November) temperature (10-year averages; Eichler et al. 2009), Russia.

period (1961–2001). Temperature records from the nearby Jungfrauoch station are highly correlated with the Fiescherhorn seasonal  $\delta^{18}\text{O}$  record (Fig. 2a,  $n=164$ ,  $r=0.70$ ,  $p<0.001$ ). However, this correlation is lost after subtracting the seasonal cycle ( $r=0.09$ ), due to the dating uncertainty of  $\pm 1$  year and changes in seasonal precipitation.

In fact, only a few studies have successfully calibrated ice-core proxy records directly with instrumental data on an annual timescale (e.g. Kaspari et al. 2007; Kellerhals et al. 2010). An example comes from Illimani ice core, where annual  $\text{NH}_4^+$  concentrations were used as a temperature proxy for the first time (Fig. 2b). Ice core records are often smoothed (e.g. multi-year average) before calibration. This is done to minimize the effect of potential dating offsets of the ice core data from meteorological

records. For example, the correlation of the Belukha ice core  $\delta^{18}\text{O}$  record with instrumental temperature data from the Barnaul station (both Russia) was significant only for the 10-year averages but not at higher time resolutions (Fig. 2c; Eichler et al. 2009).

Another attempt to get a more robust dataset with smaller dating uncertainty is to stack several independently dated ice cores (Bohleber et al. 2013). However, even then, the relationship with direct observations from instrumental data is best captured on multi-annual time scales. Accordingly, results and data sets are commonly not presented in subannual and annual resolution.

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# MINI SECTION: HUMAN IMPACT ON SOILS AND SEDIMENTS IN ASIA

## EDITORS

Thomas Hoffmann and Robert J. Wasson

## PAGES' Focus 4 Theme on Soils and Sediments: an Asian perspective

Thomas Hoffmann<sup>1</sup>, R. Wasson<sup>2</sup> and A. Ziegler<sup>3</sup>

**Studying soil erosion and sediment transport is essential to understand human-induced environmental change. In Asia, this research is underrepresented despite pronounced and long-term anthropogenic impact - a new Asian working group on soils and sediments is filling this research gap.**

PAGES' Focus 4 Theme on Soils and Sediments aims at providing understanding of the interactions between climate, human activity, soil erosion and sediment transport in fluvial systems through time. Although focused on the past, this research informs our understanding of the present and the future by documenting trajectories of change, investigating human interactions with fluvial systems, and delivers knowledge to enable societies to meet their goals on sustainable land use and river management.

The Soils and Sediments Theme derived from the former project "Land Use and Climate Impacts on Fluvial Systems during the period of agriculture" (LUCIFS), which was launched in 1994 (Wasson 1996). Recently, Hoffmann et al. (2010) re-defined its aims as: (1) quantifying land-use and climate change impacts on river-borne fluxes of water, sediment, C, N, and P; (2) identifying their key controls at the catchment scale; and (3) understanding the feedbacks on human society and biogeochemical cycles of long-term changes in the fluxes of these materials. In the same review article, the following research agenda was set out: (1) synthesizing the data available from existing case studies; (2) targeting research in data-poor regions; (3) integrating sediment, C, N and P fluxes; (4) quantifying the relative roles of allogenic and autogenic forcing on fluvial regimes, extreme events and sediment fluxes; (5) improving long-term river basin modeling; and (6) integrating the Theme with other working groups within PAGES.

Research under the banner of the Theme has progressed well in Europe (e.g. Hoffmann et al. 2007; Erkens et al. 2011; Verstreoten et al. 2009), North America (e.g. Trimble 1999; Stinchcomb et al. 2011) and Australia (Fryirs et al. 2007; Fryirs 2013). However, research on the long-term interaction of climate and land use and its impact on soils, sediments and river systems in Asia has lagged, except in China (see the contribution by Ran and Lu, this issue). Much of Asia is therefore a data-poor region in terms of fluvial research. This is critically important since Asia's physiography and climate supports a disproportionate number of the world's

largest rivers by discharge, and is therefore the source of much of the sediment reaching the global oceans (Syvitski et al. 2005), and a major source of nutrients to the seas (e.g. Green et al. 2004). Moreover, Asia is home to a large fraction of Earth's people, and is the most rapidly urbanizing region on Earth with growing conurbations on the region's mega-deltas.

As in Europe, land use by clearing, settled cultivation, and urbanization has a long history in Asia. Also, and unlike in Europe and the Americas, deforestation and settled agriculture are now spreading rapidly in Asian areas previously only slightly impacted by humans. Therefore some catchments have been subjected to multiple episodes of land use impacts over the last millennia, while others are just being impacted for the first time. In principle it should be possible to use records from the long-impacted catchments to anticipate the future trajectories of the still pristine catchments.

With this background in mind a workshop was convened in November 2012, hosted by the National University of Singapore (NUS). Twenty-five participants, including experts from Germany, Singapore, Japan, Malaysia, Indonesia, Australia and Thailand represented the disciplines of archeology, environmental history, geomorphology, hydrology, remote sensing, engineering, soil science, and biogeochemistry. The goal of this meeting was to set up a regional working group on soils and sediments (WGSS) for Asia and to coordinate its activities.

After two days of discussion, the participants reached the following resolutions:

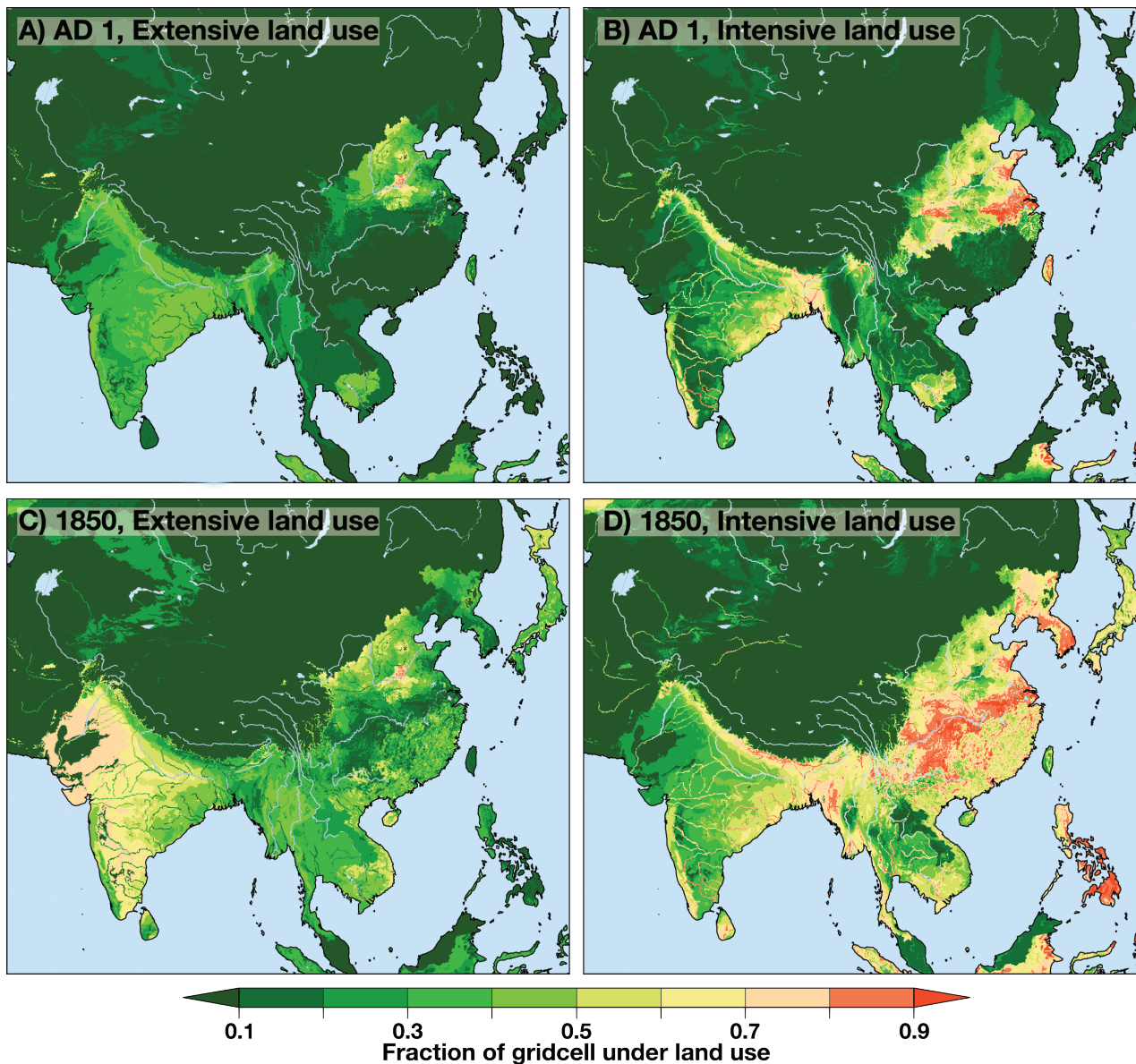
- The Asian-WGSS will be convened and led by Dan Penny (University of Sydney, Australia) and Lu XiXi (NUS).
- Initial efforts will build on existing work in a few case studies: (A) Angkor and the Tonle Sap Lake in Cambodia; (B) the Huang He in China; (C) the Palembang River catchment in Indonesia; (D) the Saru River catchment in Japan and; (E) the Ping River catchment in Thailand.

- A panel discussion on the Asian perspectives on soils and sediments was held at the Asia Oceania Geosciences Society conference in Brisbane in June 2013.

- Further meetings of the Asian WGSS will be held to coordinate activities.

In addition, there was considerable discussion regarding a common strategy for an Asia-wide analysis of human-environmental interaction with a focus on soils, sediments and river systems. Before the recent rise in greenhouse gases, the most profound cause of global human impact during the Holocene was the onset of settled agriculture several thousand years ago, and there is now a call for the beginning of the Anthropocene to be defined by this major change (Balter 2013). The period of settled agriculture would also clearly be a meaningful time scale for Asian WGSS research; however, unlike the boundaries between geological epochs, the onset of settled agriculture is diachronous - which is a problem for stratigraphers, but provides an interesting research question for the WGSS.

Settled agriculture was established in NE China by 8000 BP and in NW South Asia by 7500 BP. It subsequently spread across China and South Asia, arriving in Taiwan about 400 BP, and then extending across the mountains of mainland Southeast Asia, joining with a second wave of agricultural development coming up from South Asia, what is now Myanmar and Thailand, within the last 500 years (Elvin 2004; Elvin and Liu 1998; Wyatt 1984; Stark 2006; Boyle et al. 2011; Kaplan et al. 2011). While there are ancient origins for agriculture in insular SE Asia, the conversion of large areas from native vegetation only occurred within the last few centuries. These usage patterns are wonderfully captured in animated form for the period 8000 BP to 100 BP at [http://grkapweb1.epfl.ch/pub/KK12\\_totallanduse.mov](http://grkapweb1.epfl.ch/pub/KK12_totallanduse.mov) (Kaplan et al. 2011). Figure 1 also shows the amount of land employed for both extensive and intensive uses as at AD 1, when agriculture extended over most of China, South Asia and much of peninsula SE Asia, and then again in AD 1850, when there were few places left not affected by agriculture.



**Figure 1:** Amount of land employed for both extensive (A and C) and intensive (B and D) uses as at AD 1 (A and B), and then again in AD 1850 (C and D). The land use patterns were extracted from the animation shown at [http://grkapweb1.epfl.ch/pub/KK12\\_totallanduse.mov](http://grkapweb1.epfl.ch/pub/KK12_totallanduse.mov) (Kaplan et al. 2011).

This large-scale conversion into agricultural land continues nowadays in Malaysia and Indonesia with the replacement of lowland rainforest by rubber and oil palm plantations and large-scale deforestation, which began after the Second World War (e.g. De Koninck et al. 2011). Recent research by the NUS has shown that in Johor, southern peninsula Malaysia, conversion of lowland rainforest to rubber and then oil palm plantations in the last ca. 60 years has produced sedimentologic evidence in valley floors, similar to those seen in catchments in Australia and the USA when impacted by the European settlers.

The wave-like development of settled agriculture in much of Asia provides an opportunity for the PAGES Focus 4 Theme on soils and sediments to develop chronologies of disturbance in fluvial networks that have been subject to diachronous agricultural development. These fluvial networks may also have been affected differently by climate variability during the Holocene. For example, the Huang He in northern China was most affected by agriculture and Holocene climate changes, while the rivers of

Johor are likely to have been affected mainly by very recent land cover conversion. Similarly, much of the large-scale land-cover change in the montane mainland of SE Asia occurred within the last century.

By studying catchments of similar size and topography, as well as the onset times of settled agriculture in the last 2000 years, it should be possible to determine the impact of agriculture, as climate variability was relatively small during this period. However, for catchments where settled agriculture began in the early Holocene, a climate change signal is to be expected given the mid Holocene experienced the largest shift in climate since the deglaciation. Applying this framework to the Asian working group on soils and sediment will inventory current knowledge of both climate change and agricultural beginnings. The empirical results from such research could be used to test soil erosion and sediment flux models being developed by the "geomorphic prediction" working group (<http://geomorphicprediction.geo.arizona.edu>). Ultimately, we hope to facilitate a better understanding of

fluvial response to land use and climate change in the most populous, biodiverse and dynamic region on Earth.

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# Social upheaval in ancient Angkor resulting from fluvial response to land use and climate variability

Dan Penny

**Recent archeological and paleoclimatic work indicate that the demise of Angkor – the world’s largest pre-industrial city – was related to tight feedbacks between climatic variability, massive infrastructure, extensive land use, and water and sediment flux.**

Angkor, in present-day Cambodia, was primate city to the sprawling Khmer empire from the 9<sup>th</sup>-15<sup>th</sup> century AD. Recent and on-going mapping exercises (Evans et al. 2007; Pottier 1999) have demonstrated that Angkor covered an area in excess of 1000 km<sup>2</sup> (Evans et al. 2007). At its peak in the 11-12<sup>th</sup> centuries AD, the city supported a population of several hundred thousand people. The scale of the settlement implies an enormous environmental footprint, with the widespread conversion of primary forest to intensive banded rice agriculture, and the systematic modification of natural rivers to stifle the seasonal flood pulse and feed massive reservoirs.

## Disrupting infrastructures

Angkor developed a large infrastructural system to manipulate surface water and sediment flux (Fig. 1). By the 13<sup>th</sup> century, the elaborate system of canals, embankments, ponds and reservoirs had become massive, deeply interdependent, brittle and sclerotic (Groslier 1979). In fact, the system had become so large and so complex that it began to exert an inertial force (Fletcher 2011) over the people that built it by effectively reducing the range of strategies they might use in changing circumstances (Groslier 1979) – an historical example of Graham’s “disrupting infrastructures” (Graham 2009). Archeological research within the remains of the system has identified numerous attempts to modify or even destroy existing infrastructure, presumably to maintain some aspect of its function as the system began to break down (Buckley et al. 2010; Fletcher et al. 2008; Lustig et al. 2008; Penny et al. 2005).

Angkor was established on an extremely low relief catchment. Sediment and nutrient flux were therefore controlled by population size and the nature of land-use rather than by slope movement or mass wasting (Wasson 1996). However, the effect of extensive forest conversion to intensive rice agriculture is not clearly reflected in accelerated rates of soil loss and/or sediment accumulation.

Equally, there is no empirical evidence to suggest a mechanistic link between accelerating soil erosion in the catchment and the demise of the settlement. In fact, rates of sediment accumulation in depositional basins throughout Angkor are low, an average of < 1 mm a<sup>-1</sup>, during the Angkorian period. In some cases these were very large basins, the largest being 16 km<sup>2</sup> in area, with contribution areas in excess of 200 km<sup>2</sup> (Penny et al. 2005). Banded rice agriculture mimics natural wetlands, and on a low-relief alluvial plain such as in Angkor, extensive agriculture of this kind represents both a sink for sediment and particulate-bound nutrients and an effective buffer between the catchment and its fluvial network. It may be, then, that despite its size the type of land-use at Angkor and the nature of its catchment mitigated the loss of soil from catchment slopes to river channels and canals.

## Drought and floods

More dramatic evidence for changing sediment flux is apparent within the network of channels and canals itself. Ad hoc, probably quite localized, modifications had been made to the infrastructural network to maintain water flow and function during prolonged drought. However, these changes made the structures more vulnerable to erosion when a particularly intense summer monsoon occurred. The demise of Angkor as a viable city coincides with prolonged ENSO-related summer monsoon failure in the mid 14<sup>th</sup> and early 15<sup>th</sup> centuries (Buckley et al. 2010; Cook et al. 2010). While evidence of drought is reported at Angkor (Day et al. 2012), the most dramatic physical evidence from this period relates, counter-intuitively, to extreme flood events. Indeed, Buckley et al. (2010) indicate that long periods of weak summer monsoon rainfall were punctuated by extremely wet years – six of the twenty wettest years of the past millennium occurred during these multi-decadal drought episodes. The abrupt reversions to intense summer monsoon rainfall triggered a destructive succession, including

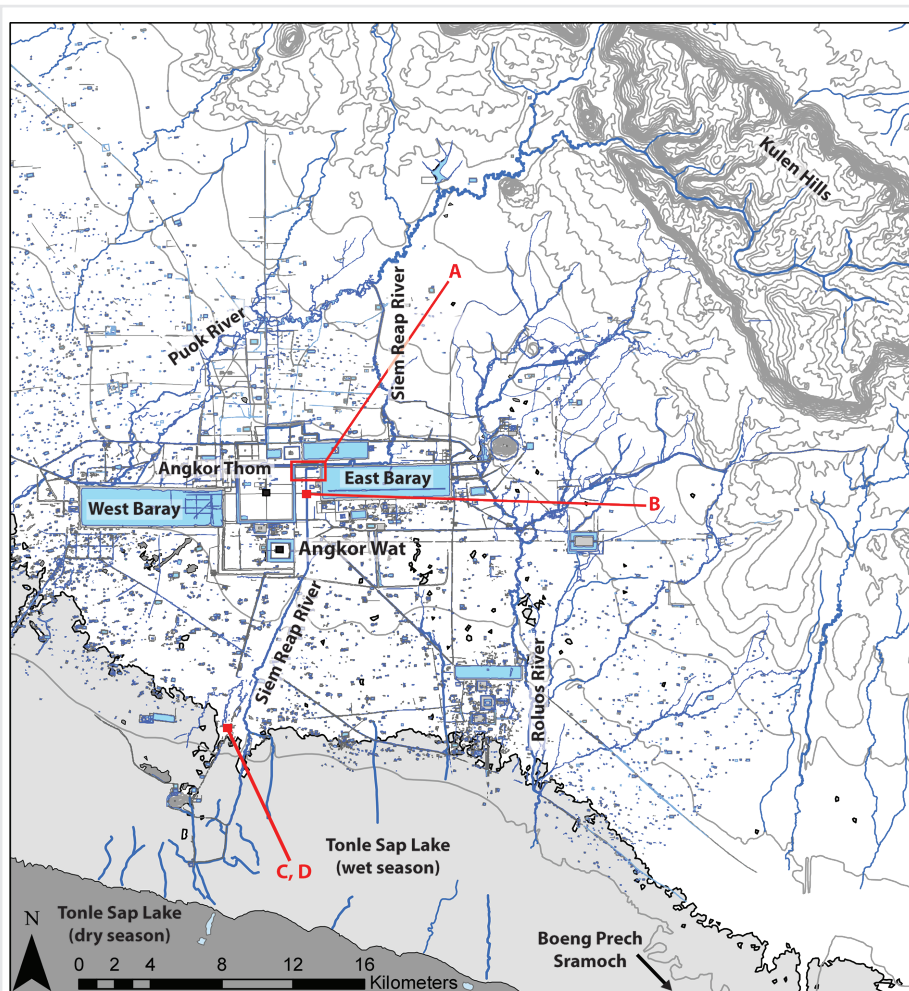
deep incisions in the middle reaches of the Siem Reap canal in the order of 5-6 meters, in-filling of canals and channels in the lower reaches with relatively coarse, cross-bedded sands, and the avulsion of the Siem Reap canal (Buckley et al. 2010; Lustig et al. 2008).

## Tonle Sap Lake

Angkor’s failing water management network resulted in an increased flux of particulate-bound phosphate and sediment to Tonle Sap Lake, with implications for lacustrine ecology and sedimentation rates in the lake.

Sedimentation in Tonle Sap Lake itself effectively ceased in the middle of the Holocene when the lake became so shallow that wind-driven mixing prevented net sediment accumulation (Penny 2006). Since that time, the sequestration of suspended sediment from the Mekong River, in the order of 5.67 10<sup>9</sup> kg per annum into Tonle Sap, has occurred preferentially on the northern side of the lake (Kummu et al. 2008) due to winnowing of suspended sediment by the extensive swamp forest communities that occur there. This has created a “ridge-and-swale” morphology observed also in other large lake basins (Albert et al. 2005).

Any significant increase in the flux of sediment from Angkor to Tonle Sap Lake due to the destabilization of the water management network is likely to have contributed to the lateral accretion of the basin in the area upstream of the depositional loci. Within the sediment of the backswamps along this shoreline the transition from well-sorted siliciclastic mud to primarily organic sediment can be taken to represent the isolation of the backswamp from the main lake during the dry season following the development of the lakeward ridge. Radiocarbon ages at the transitional boundary from site Boeng Prech Sramoch post-date the 17<sup>th</sup> century (110±40 and 180±40 <sup>14</sup>C BP, respectively), suggesting nearly 4 km of horizontal progradation since that time. It is unclear if this accretion



represents the storage of material eroded from Angkor's infrastructure, a change in volume of suspended sediment yielded to the lake from the Mekong River, or a conflation of the two phenomena.

### Collapse and transformation

In the case of Angkor, the interaction between extensive land-use and climatic variability triggered dramatic changes in both the canal system and, through nickpoint migration, the fluvial network to its north. Given that Angkor's agriculture, and perhaps even the legitimacy of the administration, was closely tethered to the management and distribution of surface waters, the social outcomes of these fluvial responses were profound and resulted in unprecedented social upheaval.

By the end of the 15<sup>th</sup> century, Angkor and its city-region had collapsed, abandoned by the administration and the elite in favor of a succession of cities in the vicinity of the modern Cambodian capital of Phnom Penh. The elite were followed, it is presumed, by an urban diaspora from the Angkorian cities to the new "Middle Period" centers.

Ultimately, Angkor's massive, brittle and inter-dependent water management infrastructure failed to suppress climate impacts on biogeochemical flux from catchments. Instead, it both sensitized the attendant fluvial networks to ENSO-related climatic variability and reduced the range of adaptive strategies available to the administration.

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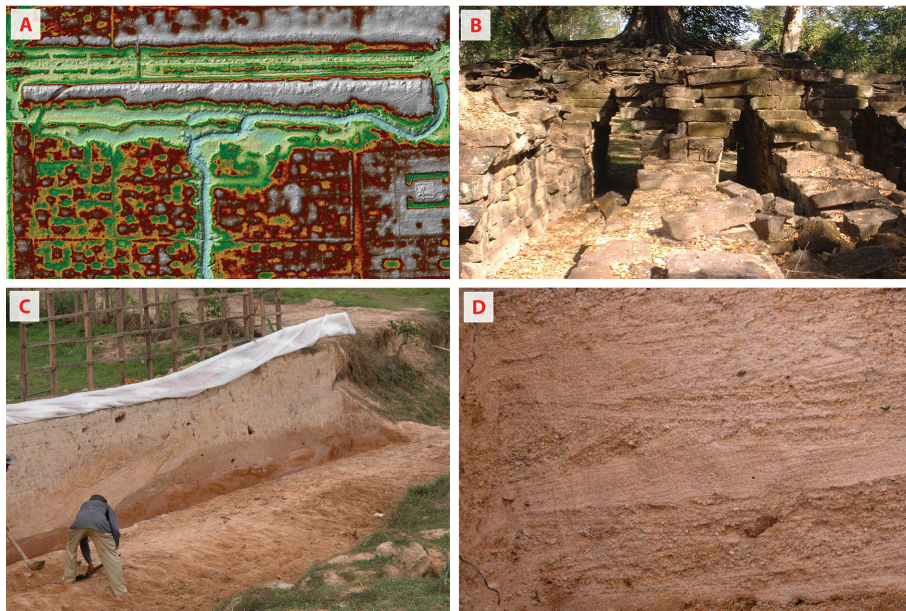
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**Figure 1:** Archeological map of Greater Angkor, emphasizing the complexity of the water management network, and the articulation of canals and rectilinear reservoirs with the natural fluvial network. Data from Evans et al. (2007), Pottier (1999), Mekong River Commission, Japanese International Cooperation Agency. **(A)** False color digital terrain model derived from a LiDAR point cloud. Erosion caused by uncontrolled water flow through the canal network is clearly apparent as pale blue and green colors. Such water flow events triggered significant vertical incision of the canal bed. Image courtesy of Khmer Archaeology LiDAR Consortium/Damian Evans. **(B)** *Spean Thma* (lit. stone bridge), immediately east of the famous walled enclosure of Angkor Thom, once spanned the Siem Reap canal. Destabilization of the canal during the 14<sup>th</sup> century caused the canal to incise several meters below the bridge, destroying its eastern half and leaving its western half, seen here, abandoned on the dry canal bed. **(C)** Many of the ancient canals south of the city, presumably critical in linking the ports at the edge of the lake to the markets in the central urban area, are now filled with several meters of sediment, including coarse (28% by weight) to very-coarse (17%) cross-bedded sand and gravel **(D)**, with the largest clasts > 5 φ, > 32 mm in diameter. These deposits indicate an increase in the flux of sediment and other materials from the canal network, and flows of sufficient energy to entrain them. Post-dating the 14<sup>th</sup> century, these events broadly coincide with multi-decadal scale drought.



# Sediment load and carbon burial in the Yellow River during the Holocene

Lishan Ran and Xixi Lu

**Sediment load in the Yellow River has increased dramatically during the Holocene in response to human land use. However, dams and reservoirs have reverted that trend, and sediment load has now reached levels even below those of the early Holocene.**

Fluvial sediment transport by the world's rivers has generally been affected by humans throughout the Holocene (Sluyter 1997; Hoffmann et al. 2010). However, the exact effect of human activities was specific for each river due to the differences in landform, climate, and the cultural history. Different types of human activities can result in distinctively different sediment load processes.

Extensive agricultural practices and deforestation accelerate soil erosion and thus considerably increase riverine sediment load, while large-scale soil conservation measures and dam construction can reduce it. Being the cradle of the Chinese civilization, the Yellow River basin has been strongly influenced by intensive human activity during the Holocene. Thanks to the long and continuous historical records available, the Yellow River is well suited for studying the long-term human impact on rivers and sedimentary basins.

Located in northern China (Fig. 1), the Yellow River basin is nowadays characterized by semiarid to arid climate and poor vegetation cover. The Yellow River basin is in large part surrounded by the highly erodible loess deposits of the Loess Plateau. Accordingly, it is well known for its strong soil erosion, which ranks amongst the highest in the world. During the early and middle Holocene, the sediment

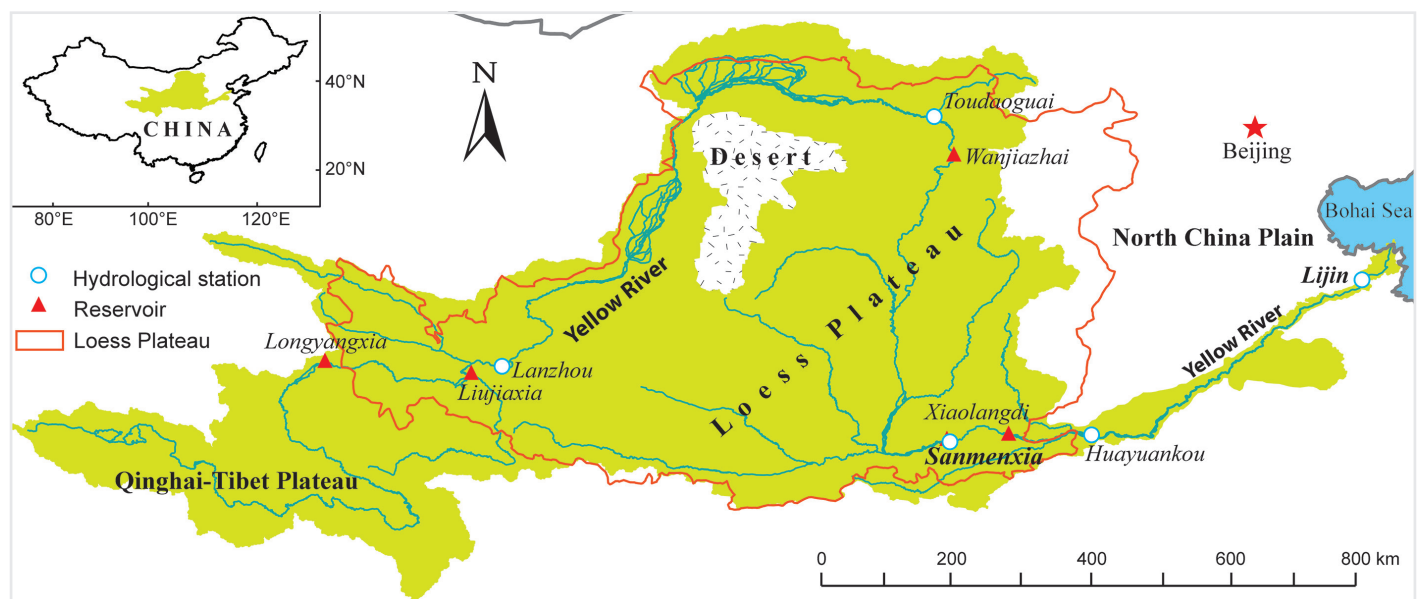
load of the Yellow River was estimated to be approximately 0.7-0.8 Gt/yr at the location of the Sanmenxia hydrological station (Shi et al. 2002; Fig. 2). This number includes accumulation on the lower alluvial plains and the delta. High sediment load during this period may have resulted from poor vegetation cover and/or an increasingly arid climate on the Loess Plateau following glacial retreat (Milliman et al. 1987). Due to intensive human activities, in particular agricultural cultivation and deforestation on the Loess Plateau (Ren and Zhu 1994; Liu et al. 2002; Saito et al. 2001; Wang et al. 2007), the sediment load increased strongly to 1.6-1.8 Gt/yr ca. 1000 years ago. Over the past 1000 years the Yellow River sediment load passing Sanmenxia remained overall stable at a high level of 1.7-1.8 Gt/yr, resulting in increasingly serious channel sedimentation in the lower Yellow River and progressive delta growth. The total sediment deposition downstream of Sanmenxia during the Holocene has been estimated, through radiocarbon dating, to be 8000 Gt, of which 5280 Gt was deposited on the North China Plain and 2720 Gt settled on the seafloor (Shi et al. 2002). As a result, the delta area was growing at a mean rate of 20-25 km<sup>2</sup>/yr (Wang et al. 2007).

However, during the past few decades the sediment load recorded at Sanmenxia has decreased markedly, particularly since the

1950s with the onset of extensive human activities (Fig. 2). Compared with the period of 1950-1959, the decadal mean sediment load in 2000-2010 has decreased by 80%, reaching a load even lower than the pristine level of the early Holocene. It is evident that massive dam construction and vegetation restoration within the basin are the primary reasons for this reduction. For example, artificial dams and reservoirs have trapped 40.3 Gt of sediment during the period 1950-2010 (Ran et al. 2013), corresponding to an annual mean of 0.67 Gt/yr. In comparison, the mean sediment load at Sanmenxia station over that same period was about 1.1 Gt/yr. Human activities have been estimated to contribute 70-80% to the sediment reduction, while the remaining 20-30% are related to a trend of decreasing precipitation (Lu et al. 2003; Wang et al. 2007). As a result, the present sediment budgets appear to be reverting to levels comparable to those before human impact due to the combined effects of damming and climate change.

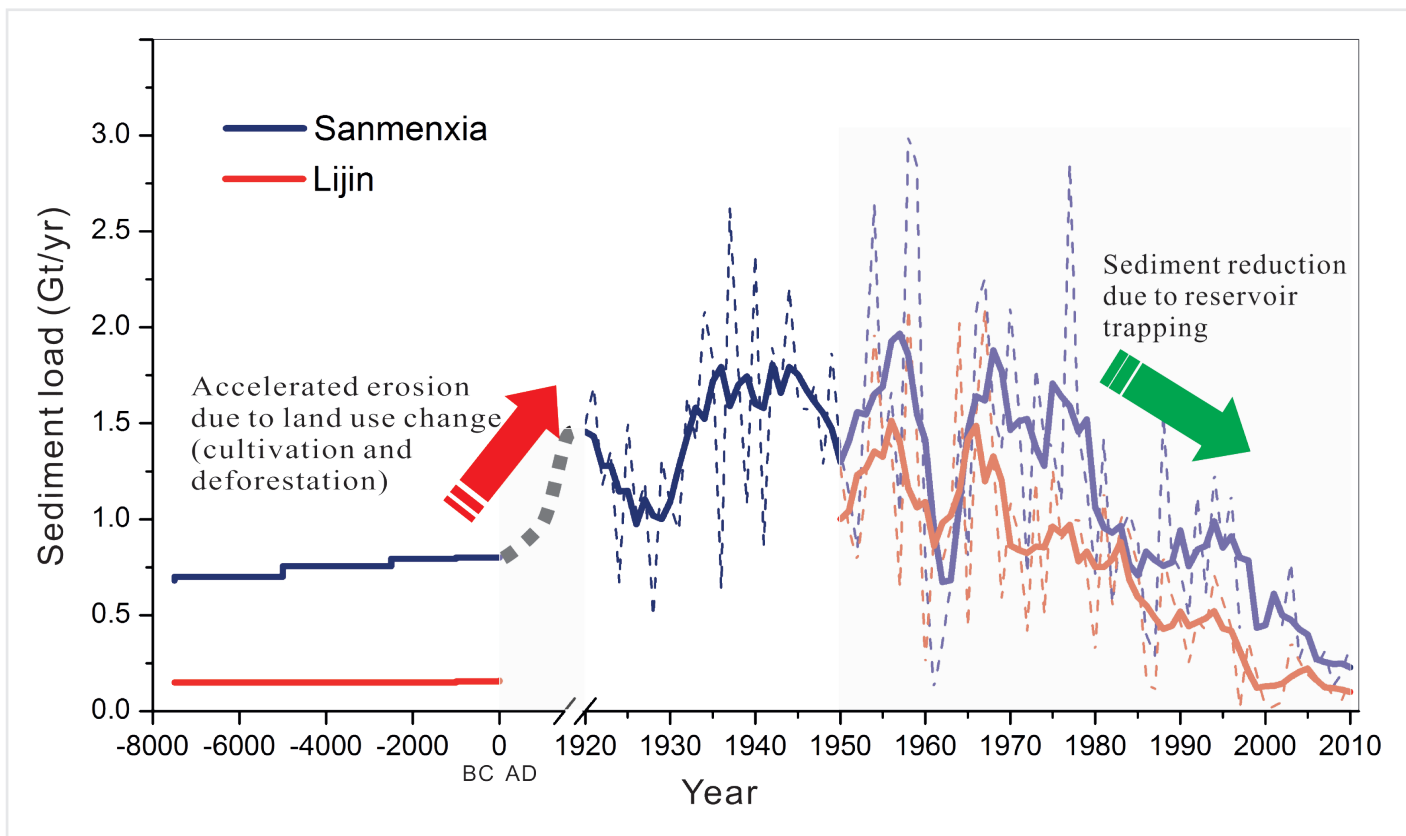
## Carbon budget implications

Variations in sediment dynamics over time are critical for budgeting the biogeochemical cycling of carbon and nutrients (e.g. Battin et al. 2009; Hoffmann et al. 2010). Despite the lack of direct evidence due to the absence of historical records, it is likely that the amount of particulate organic carbon (POC) transported in the



**Figure 1:** Location of the Yellow River basin with its middle reaches covered by the Loess Plateau that serves as the major sediment source.





**Figure 2:** Changes in sediment load from the Yellow River basin during the Holocene as measured at Sanmenxia and Lijin stations (Fig. 1). Measurements at Sanmenxia are referred to as the total sediment load from the Yellow River basin, those at Lijin monitor the discharge to the delta and the ocean. The “pristine” sediment load during the early and middle Holocene was estimated from the sediment volume of deltaic and marine depositions and the sediments accumulated on the fluvial plains in the lower Yellow River basin (Milliman et al. 1987; Shi et al. 2002; Wang et al. 2007).

Yellow River has varied significantly during the Holocene. Most of the Yellow River sediment (~90%) originates from the Loess Plateau where eroded top soils have a uniformly low organic carbon content. It can therefore be expected that riverine POC fluxes was dominantly controlled by temporal variations in the fluxes of total sediment. If the soil POC content was 0.5-1% as suggested by new unpublished data, then approximately 40-80 Gt of POC have been buried due to sedimentation during the Holocene.

Human activities over the past six decades have also resulted in considerable carbon burial, for example through sediment trapping. Assuming the same POC content as above suggests that 0.2-0.4 Gt of POC have been trapped by dams during 1950-2010. The sediments accumulated in reservoirs should sequester POC relatively effectively because the anaerobic waters in the reservoirs prevent the buried carbon from oxidation, limiting decomposition to anaerobic processes such as methanogenesis. More research is needed to quantify mineralization rates and residence times of POC in reservoirs. As POC accounts for more than 90% of total organic carbon in the Yellow River (Cauwet and Mackenzie 1993), the reduced POC fluxes, together with decreased sediment loads, have resulted in far-reaching physical and biogeochemical responses in the estuary and in marine ecosystems within the discharge plume. Continuous retreat of the Yellow River delta in recent decades has been observed due to the reduced sediment supply, and the decreased riverine supply of carbon and nutrients has significantly

influenced its ecological integrity (Xu et al. 2004; Li et al. 2009; Syvitski et al. 2005). For example, reduced sediment and nutrient discharge and intrusion of salt water into the delta wetlands have led to substantial salinization, resulting in rapid degradation of bird habitats (Cui et al. 2009).

#### Future perspectives

Human activities are now reducing the sediment load in the Yellow River basin at an unprecedented pace. In addition to the numerous dams under construction and in the planning, large-scale soil conservation programs, such as the Grain-for-Green Project, are being carried out in the drainage basin, in particular the Loess Plateau, to control soil erosion and mitigate land degradation. These activities, combined with decreasing amounts of rainfall, suggest that the sediment load and associated carbon transported by the Yellow River will further decrease in future. Furthermore, the accelerating human activity in the region is likely to increase the role of anthropogenic over natural factors on sediment and carbon dynamics even more over the next decades.

With respect to greatly reduced sediment loads, attempts have been made to explore the geomorphological, ecological, and other environmental impacts (Wang et al. 2007); however, in comparison, less attention has been devoted to studying the implications of carbon burial of sediments within the basin and of the decreased carbon fluxes reaching the ocean. As one of the rivers in the world with the highest sediment flux (Milliman et al. 1987), the associated carbon amount in the Yellow

River is considerable. The carbon and nutrient dynamics of the basin are likely to undergo further substantial changes in the near future. The details of the sediment dynamics and the biogeochemical consequences are not well understood. Consequently, effective mitigation strategies are difficult to develop. Analyzing the river's storage and transport history over the Holocene and the associated environmental impacts provides an opportunity to improve our quantitative understanding of fluvial systems and associated ecosystems.

The Yellow River's well-defined thousand-year sediment yield increase, resulting from land use change, and the subsequent sudden decrease after 1950 AD, largely due to reservoir construction, is exceptional, and thus provides an almost ideal “experimental” case study for research under the Soil & Sediment and Carbon Themes of PAGES.

#### ACKNOWLEDGEMENTS

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# Tectonic and volcanic forcing on fluvial systems: two case studies from Hokkaido, Japan

Thomas Parkner<sup>1</sup> and Mio Kasai<sup>2</sup>

**Two case studies from Japan demonstrate that tectonic and volcanic forcing notably increased the sediment flux in fluvial systems. Therefore fluvial system studies in geomorphically active regions should also consider such forcings alongside land use and climate considerations.**

Land use and climate impacts are frequently studied as the main modulators of fluvial systems since the onset of agriculture (Wasson 1996). However, in geomorphically active regions such as along the Pacific Rim human impacts are modulated by tectonics and volcanic eruptions. In two case studies from Hokkaido, the northern Japanese island (Fig. 1), we investigate the impacts of geomorphic factors on human-impacted river systems. In the Saru River system, fragile lithology and steep slopes have resulted in a dynamic sedimentary system with high natural sediment flux, which is sensitive to tectonic impact. In contrast, the sediment dynamics in the Bibi River system, our second case study, is strongly influenced by volcanic impact due to its vicinity (15 km) to the caldera of an active volcano.

## The island of Hokkaido

The landscape of Hokkaido is shaped by active plate tectonics. The central part of the island consists of erodible metamorphic rock and hills with steep slopes. In addition, active volcanism causes pyroclastic flows and debris avalanches, regularly covering large parts of the island with tephra (Furukawa et al. 1997; Machida and Arai 2003).

Immigration to Hokkaido started with the end of Japan's isolation policy in AD 1868. Before then, land use was limited to small areas along the coast, and to lowland rivers and lakes (Imai 1975). The rest of the island was inhabited by the indigenous Ainu people, who relied dominantly on salmon fishing and deer hunting. After AD 1900 the area of cultivated land increased rapidly (Imai 1975). European style farming and industrialization were introduced and large areas of wetlands and forests were converted into paddy fields, crop fields, dairy farms and urban areas.

Outback mountain areas, despite their almost intact forest cover, are frequently subject to landslides. They are triggered by episodic storms in summer and autumn or by spring melt events. The resulting high sediment supply rates from hillslopes lead to increased sediment storage in rivers.

## Case study Saru River

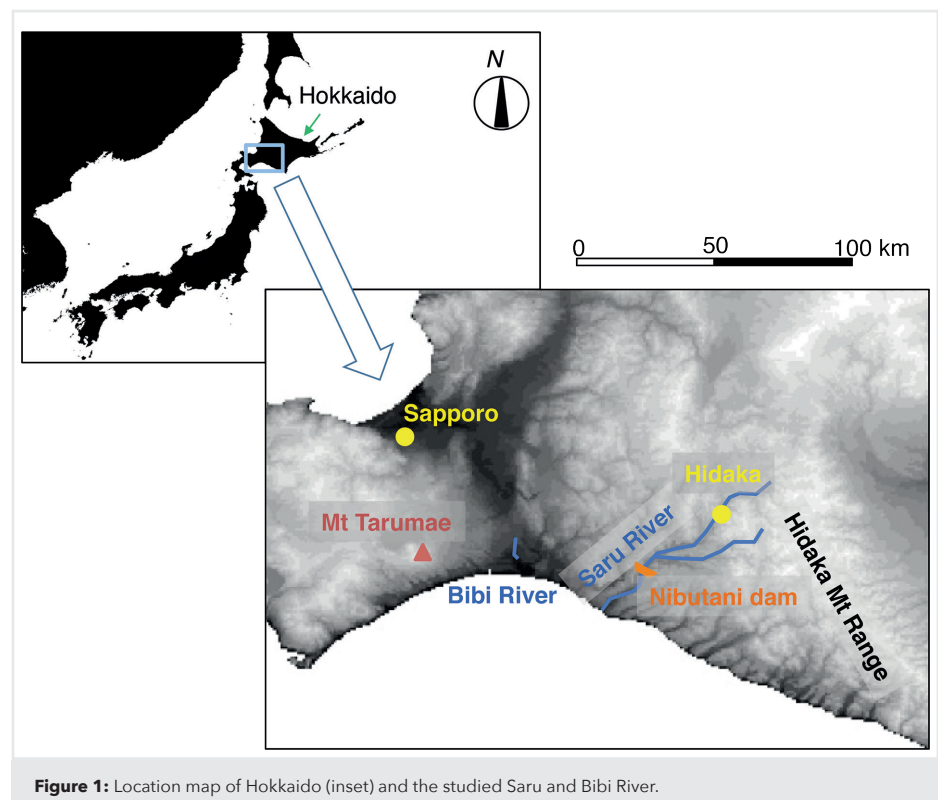
The high sediment flux of 470,000 m<sup>3</sup> a<sup>-1</sup> on average in the upper Saru River catchment (1350

km<sup>2</sup>) in the Hidaka Mountain Range is strongly controlled by catchment lithology, steep slopes (highest peak reaches 2052 m) and high average annual precipitation (1350 mm in Hidaka; Fig. 1). Most of the mountainous area is covered by forest (87% in 2006). Agriculture is mainly limited to the alluvial floodplain, where intense storms occasionally cause landslides and flood disasters. For the purposes of flood protection, water utilization and power generation, the Nibutani dam reservoir (Fig. 1) was completed in 1997. But rapid sediment delivery from the headwaters had already filled 85% of the reservoir's initial storage capacity by 2011.

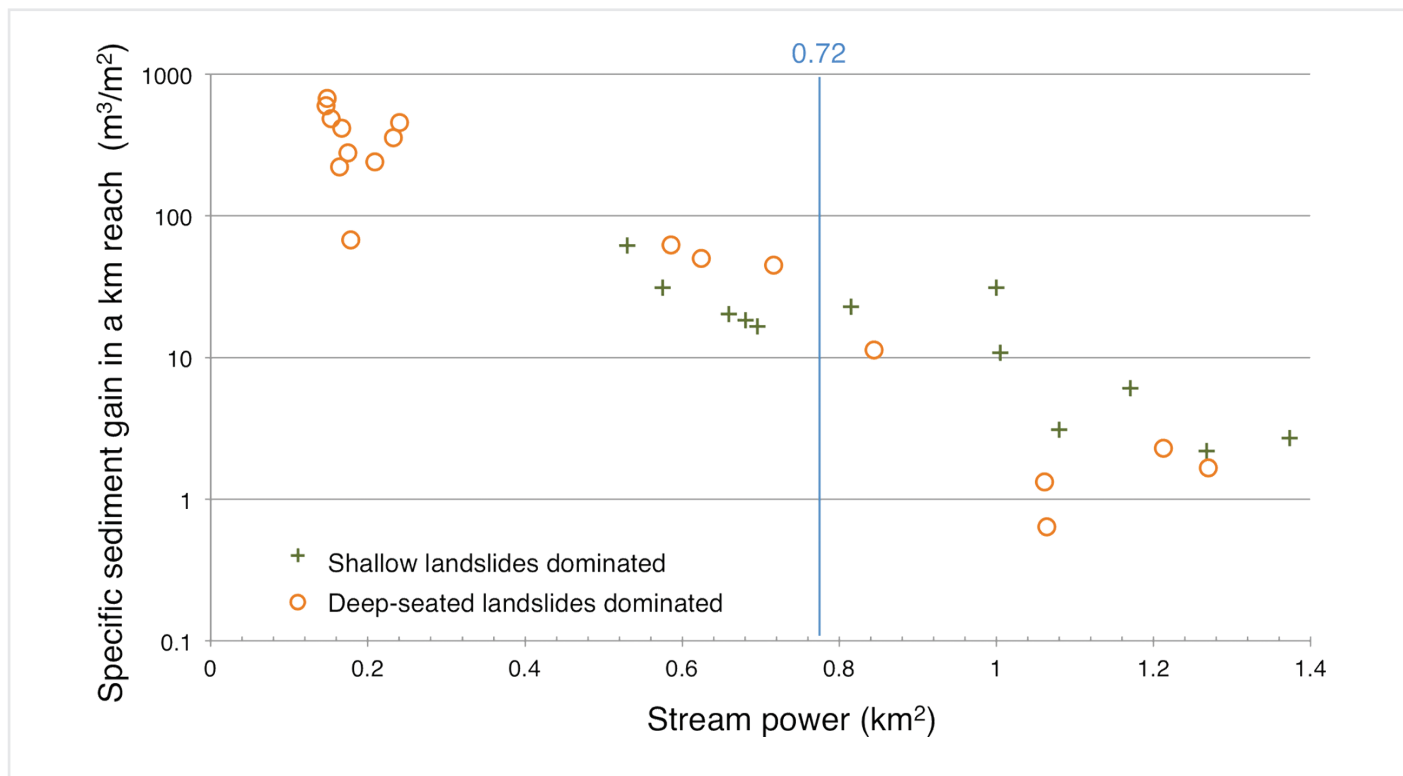
Deep-seated and shallow landslides dominate in the mountain areas. Deep-seated landslides, common on sedimentary and serpentine rocks, are characterized by slow but steady movement in the order of several meters per year, depending on ground water conditions. The sliding planes are often located more than ten meters below the ground and associated with deeply weathered rock layers. In contrast,

shallow landslides are only a few meters deep and frequently occur on crushed basalt rocks. Their temporal activity is more episodic and caused by rainfall events. Different from deep-seated landslides, they often stop producing sediment after a few years.

The last major storm in 2003 caused numerous landslides and aggradation throughout most of the course of Saru River. Elevation models for 2006 and 2010 derived from LiDAR remote sensing data show that the channel bed degraded rapidly over this period. The specific sediment loss (i.e. sediment loss per catchment area) along the river reaches was strongly related to their average channel bed slope, which is largely determined by the hardness of the underlying rocks. On the other hand, stream power  $\Omega$  (the product of catchment area and bed slope), largely determined the specific sediment gain (i.e. sediment aggradation per catchment area). When  $\Omega$  was <0.72 km<sup>2</sup>, more sediment was deposited in reaches where deep-seated landslides dominated in tributary



**Figure 1:** Location map of Hokkaido (inset) and the studied Saru and Bibi River.



**Figure 2:** Relationship between stream power and specific sediment gain in a channel reach. Reaches were grouped according to the dominant landslide type (i.e. deep-seated vs. shallow landslides) in their tributary catchments.

catchments compared to the reaches where shallow landslides dominated (Fig. 2). This relationship was inverted for  $\Omega > 0.72$  km<sup>2</sup>. These results imply a balance between continuous sediment supply from deep-seated landslides and the rivers' capacity to flush out sediment. We conclude from this study that lithology-driven differences in landsliding processes and sediment production effectively control the volume of fluvial sediment transport.

In line with our results, Simizu (1998) indicated that sediment production in the headwater basin has been high at the almost same rates over the past 8,000 years. Local place names in the Ainu language (such as Shishirimuka, the Ainu name of the Saru River meaning choked with too much sediment) also suggest that the Saru River system was always characterized by abundant sediment transported. These evidences highlight the significance of tectonic activity alongside human and climatic impacts in similarly dynamic fluvial systems.

#### Case study Bibi River

The 17 km long Bibi river system (Fig. 1) has been impacted by human activity and volcanic eruptions over the last 3,000 years. The catchment consists mainly of volcanic sequences from the active Shikotsu-Tarumae complex, with a floodplain forming on a flat mid-Holocene coastal plain. The eastern part of the catchment was continually used for agriculture since the beginning of the last century.

The impact of human activities and volcanic eruptions on the area was studied by means of six sediment cores from the floodplain. To distinguish between air-fallen tephra and fluvial sediment, the dry density, loss-on-ignition and grain-size data of each core was compared with standard tephra stratigraphies (Furukawa et al. 2003).

Three air-fall tephra layers from nearby Tarumae volcano from 1736 AD, 1667 AD and ca. 1000 BC, correspond to a total of 2.7 Mt tephra deposition on the floodplain. The tephra deposits devastated the floodplain, covering it as thick as 60 cm. The thickness of the purely air-deposited (non-reworked) tephra layer on the floodplain depended on the wind direction during the eruption. The air-fallen tephra was reworked by fluvial processes and deposited on the floodplain with decreasing sediment thickness downstream. After a phase of rapid adjustment of the fluvial system expressed by accumulation of mineral floodplain deposits, sediments with high (30-86%) levels of organic matter mark a return to low sediment delivery to the floodplain. All in all, about 0.8 Mt of post-eruption sediment was re-deposited by the river on the floodplain during the last 3,000 years.

Human impact on the fluvial system is only reflected in the middle reach where roads crossed the floodplain. The sediment production related to the road construction is in the order of 160 kg m<sup>-2</sup> and thus comparable to the fluvial sediment deposition derived from volcanic eruptions. At other locations, however, no human-induced increase in sediment input was evident. We conclude from this that volcanic tephra deposition is the dominant forcing on sediment deposition in the Bibi River, despite society having achieved an advanced industrial level in the catchment.

#### The Hokkaido perspective

Many studies use paleoenvironmental records to assess the difference between present and past environmental conditions (Dearing et al. 2006). The quantification of background conditions, base lines or pre-impact references is difficult in very active geomorphic regions such as the Hidaka Mountains. The example

from the Bibi River shows that volcanic forcing needs to be integrated with the effects of land use and climate change to understand the trajectory of fluvial systems.

Other impacts, not described in the two shown examples, include tsunamis, sea level change, and earthquakes. The recurrence interval of unusually large earthquakes and tsunamis along the Kuril subduction zone is about 365-553 years (Nanayama et al. 2007). In the past, such events impacted landscapes up to three kilometers inland, disturbing river regimes in the flat, lowest reaches. In addition, large earthquakes during the last 300 years raised the coastlines and the lowest reaches of rivers in eastern Hokkaido by about one meter. All these impacts and controls need to be taken into consideration when studying fluvial systems, not only in Hokkaido but also in other tectonically active regions.

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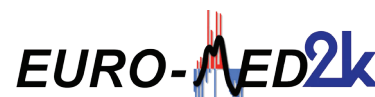
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# Hydroclimatic reconstructions over Europe and the Mediterranean



Jürg Luterbacher<sup>1</sup>, J. Werner<sup>1</sup>, D. Fleitmann<sup>2</sup>, J.F. Gonzalez-Rouco<sup>3</sup>, D. McCarroll<sup>4</sup>, S. Wagner<sup>5</sup>, E. Zorita<sup>5</sup>, J. Gómez-Navarro<sup>6</sup>, U. Büntgen<sup>7,8</sup> and J. Esper<sup>9</sup>

Meeting of the Euro-Med2k Working Group - Reading, UK, 25-26 March 2013

Water availability has been a crucial constraint on both past societies and ecosystems; therefore identification of historical extreme hydrological events (severity and duration of droughts, magnitude of floods) is important. These characteristics were addressed at a meeting of the PAGES Euro-Med2k Working Group in Reading where a number of presentations highlighted the variability of those extremes, and identified the space- and time-scales that are resolved at various European proxy sites.

During the first day, participants presented overviews of high- and low-resolution hydroclimatic proxy records from different archives. Discussion revealed that it is often unclear whether individual proxies reflect moisture availability, soil moisture, precipitation, flood events, drought intervals or some combination. The large variety and different sensitivity of hydrological proxy records thus complicates their integration and the reconstruction of one specific target variable. For instance, a measure of hydroclimate, such as the Palmer Drought Severity Index, is not even well defined for the observational period and different algorithms (e.g. Thornwaite versus Penman-Monteith

scheme) may produce markedly different results (van der Schrier et al. 2011).

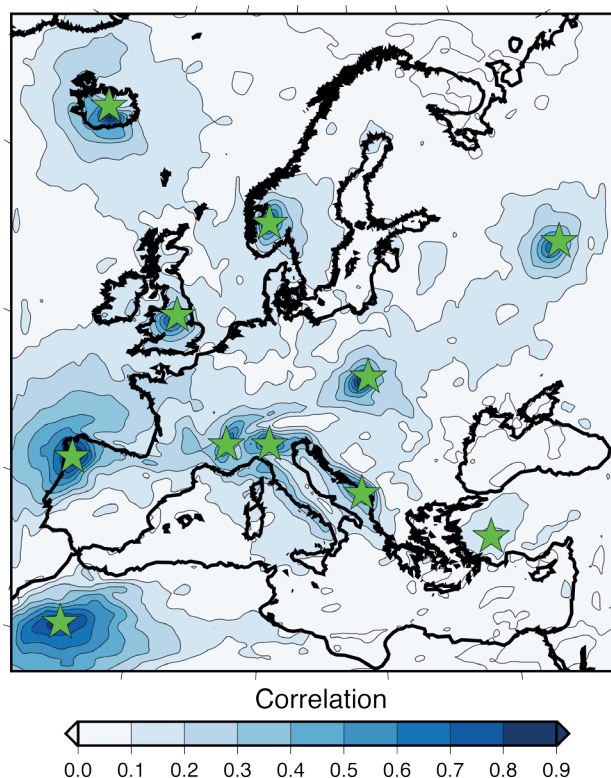
Further emphasis was also placed on dating issues; distinguishing climatic and non-climatic influences; seasonal biases in proxy records and archive-specific aspects of these proxies that can contribute to reconstruction uncertainties. The potential and limitations of documentary and natural proxies to reconstruct the full range of variations in the regional hydrological cycle were discussed. Discussion centered upon the problems of obtaining a comprehensive overview of the proxy information that is currently available for different aspects of hydroclimate, which is a necessary step before making decisions about how to combine them or translate them into a common target.

It became clear that in contrast to temperature, hydrological parameters have a much shorter de-correlation distance. Thus, without a dense network of precipitation proxies spatially highly resolved reconstructions are limited (Büntgen et al. 2010).

The second day focused on the comparisons between proxy-reconstructed precipitation

records and climate model simulations, to assess model veracity and explore mechanisms of internal or externally forced variability contributing to hydroclimate changes. For instance, results from regional climate model simulations for the last two millennia can be used to carry out pseudo-proxy experiments (PPE), i.e. reconstructing the modeled precipitation fields using only the pseudo proxy locations (Fig. 1). A PPE was carried out for precipitation using the "analog method" (Zorita and von Storch 1999) but the short de-correlation distance of precipitation demonstrates that the reconstructions only have skill at the local scale, especially during summer. This is due to the local-scale processes involved in generating summer precipitation. The coupling schemes between soil moisture and atmospheric variables may influence regional hydroclimate independently of the large-scale driving conditions (Gómez-Navarro et al. 2013), so an ensemble of regional models is advisable. Simulations with global models participating in the CMIP5 project indicate that internal unforced modes of climate variability tangle temperature and hydroclimate. A possible, though challenging, strategy could be to reconstruct both temperature and hydroclimate simultaneously.

The next workshop will aim at expanding and improving the 2k proxy database in order to develop more reliable trans-regional synthesis products. Application of modern, more elaborated reconstruction methods that can model the complex spatio-temporal processes in hydroclimatology will be needed to produce gridded products.



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**Figure 1:** Correlation map between summer precipitation reconstructed using the "analog method" based on the pseudo-proxy locations (green stars) and the original regional climate model output. The reconstructed period is 1-1999 AD (Gomez et al., unpublished data).

# 12<sup>th</sup> International Workshop on Subfossil Chironomids

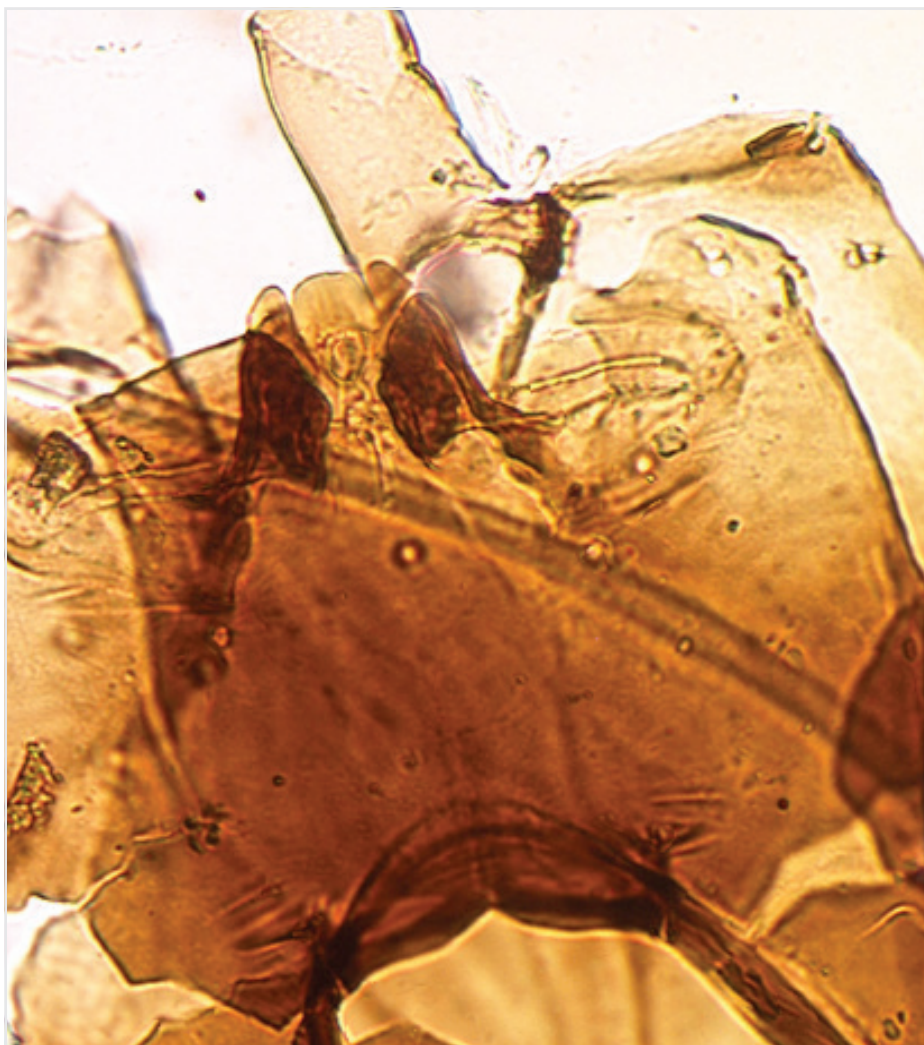
Peter Langdon<sup>1</sup> and Steve Brooks<sup>2</sup>

New Forest, UK, 10-13 June 2013

Forty scientists met in the New Forest to attend the 12<sup>th</sup> International Workshop on Subfossil Chironomids. This three-day meeting, hosted by the University of Southampton, brought together researchers from Europe, North America, South America and Asia.

Since 1997 the series of international subfossil ("deadheads") chironomid workshops have been fundamental for furthering developments in research on chironomid paleoecology. In particular, the workshops have been important in fostering coherence and cooperation within the community and introducing and integrating new researchers into the field. They have also been instrumental in developing a standard approach to subfossil chironomid larval taxonomy and analytical methods, which has been vital in maintaining rigor in the subject. Furthermore, they have enabled the community to keep abreast of new developments and methods to tackle emerging problems, and have provided a forum for developing new joint research initiatives. This meeting continued in the same vein - delegates discussed a range of key topics that have dominated paleoecological techniques in recent years in addition to many new developments.

The use of transfer functions in chironomid paleoecology was central to many discussions. This has been an important topic of recent debate within the whole paleolimnology and paleo-science communities, following the recent work of Juggins (2013). Steve Juggins attended the meeting and presented a précis of his research. The discussion that followed was very positive, focusing on the best way to move the science forward. Clearly there is still a lot of potential in using chironomid-based transfer functions to reconstruct summer temperatures (and other parameters where appropriate), but as a community we need to consider the ecological relationships in our calibration sets carefully, and how well these relationships are replicated in space, before applying them in time. Indeed one study showed how training set selection, taxonomic resolution and taxon deletion can be critical in influencing model performance and resulting reconstructions. Much of the discussion around this subject focused on two key issues: (i) how to develop more stringent ways to test calibration data (training sets) and evaluate the performance of inference models; and (ii) improving the reliability of the reconstructions by identifying the effects of confounding secondary variables. It was agreed that cross-validation of results from other sites or against other independent proxies is an appropriate way to validate chironomid-inferred reconstructions.



**Figure 1:** Subfossil head capsule of *Corynocera ambigua* (image from Brooks et al. 2007). This taxon is relatively easy to identify but its (paleo)ecology is not straightforward. It is seemingly a good cold indicator in the Lateglacial and in northern regions but also appears to tolerate warm, eutrophic conditions in southern parts of its range during the late Holocene. This illustrates the potential problems of using transfer functions, as raised by Juggins (2013).

Another key topic discussed at length was the effectiveness of using chironomids for temperature inferences from sequences spanning the last interglacial to the Holocene from sites across the world. Other discussions focused on the responses of chironomids as environmental gradients are crossed, and how best to interpret the effects of secondary gradients; trophic changes and human impacts; the use of stable isotopes within chironomid paleoecology; and biodiversity and lake restoration.

The location and date of the next International Workshop on Subfossil Chironomids is still to be confirmed, but may coincide with the next International Paleolimnology Symposium to be held in China in 2015.

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# Multi-Scale Analyses of Fire-Climate-Vegetation Interactions on Millennial Scales

Boris Vanni re<sup>1</sup>, O. Blarquez<sup>2,3</sup>, J. Marlon<sup>4</sup>, A.-L. Daniou<sup>5</sup> and M. Power<sup>6,7</sup>

Workshop of the PAGES Global Paleofire Working Group - Frasn , France, 2-6 October 2013

The aim of the Global Paleofire Working Group (GPWG) is to facilitate scientific research on fire activity in the Earth system through the development of a global charcoal dataset (GCD). Analysis and synthesis of sedimentary charcoal records from around the globe has enabled the identification and explanation of spatio-temporal patterns in paleofire activity, created a framework for exploring fire-climate-vegetation linkages at decadal-to-millennial time scales, and allowed evaluation of fire model simulations at regional to global scales. Science emerging from the GPWG community includes a public-access database and multi-authored publications describing observed spatiotemporal changes in fire at global and regional scales as well as their causes and consequences (e.g. time series and maps; Power et al. 2008).

Paleofire science has developed rapidly during the past decade; new charcoal records are being produced, new statistical tools and analytical approaches are being developed, and

novel strategies for combining multiple records for regional-to-global scale syntheses are being employed (e.g. Daniou et al. 2012). These recent developments present paleofire scientists with the challenge of dealing with highly quantitative, complex, and multivariate data documenting the timing, magnitude, and drivers of past fire activity (e.g. Vanni re et al. 2011). Previous data exploration and synthesis of the GCD were done using analytical procedures developed by P.J. Bartlein (unpublished) using Fortran. The GPWG is currently developing toolkits using the R statistical language to broaden the access to students and researchers. The paleofire R package is allowing for rapid growth of GCD analyses and innovative paleofire studies.

The main objectives of this workshop were to 1) develop a new version of the GCD; 2) explore trends in fire history at the geographic scale of biomes using the new version of the dataset; 3) test and understand the operation of the newly developed paleofire R package, designed

specifically to synthesize multiple records from the GCD (Fig. 1); and 4) discuss a new architecture for housing and disseminating the GCD into the future. The workshop was sponsored by the Region of Franche-Comt  through the French-Swiss Environmental studies network, by UMR Chrono-Environnement (CNRS - University of Franche-Comt ) and by PAGES. Fourteen participants from six countries (USA, Canada, France, Spain, Germany, China) and from various career stages presented their research, and were trained in the paleofire R-package functions. Moreover, version 3 of the GCD was prepared for public release. Participants were encouraged to develop new project ideas for global and regional charcoal syntheses. A set of comparative regional analyses that examine biome-scale fire signals and their forcings were initiated and are now in preparation for publication. Several other planned analyses, including regional studies and methodological research such as comparing micro- versus macro-charcoal records are also now underway. The paleofire R package can be installed directly from: <http://cran.r-project.org/web/packages/paleofire/index.html>

Finally, a new database architecture and web portal for the GCD was discussed and designed. The database is currently being transferred from ACCESS to MySQL in preparation for a large input of new data in the next version of the GCD and the new associated management needs. The new GCD will have a web-based user-interface to improve community access and use, as well as simplified data input and export. All of these enhancements are expected to greatly expand the user base of the GCD and thus promote paleofire research both within and beyond the paleo community.

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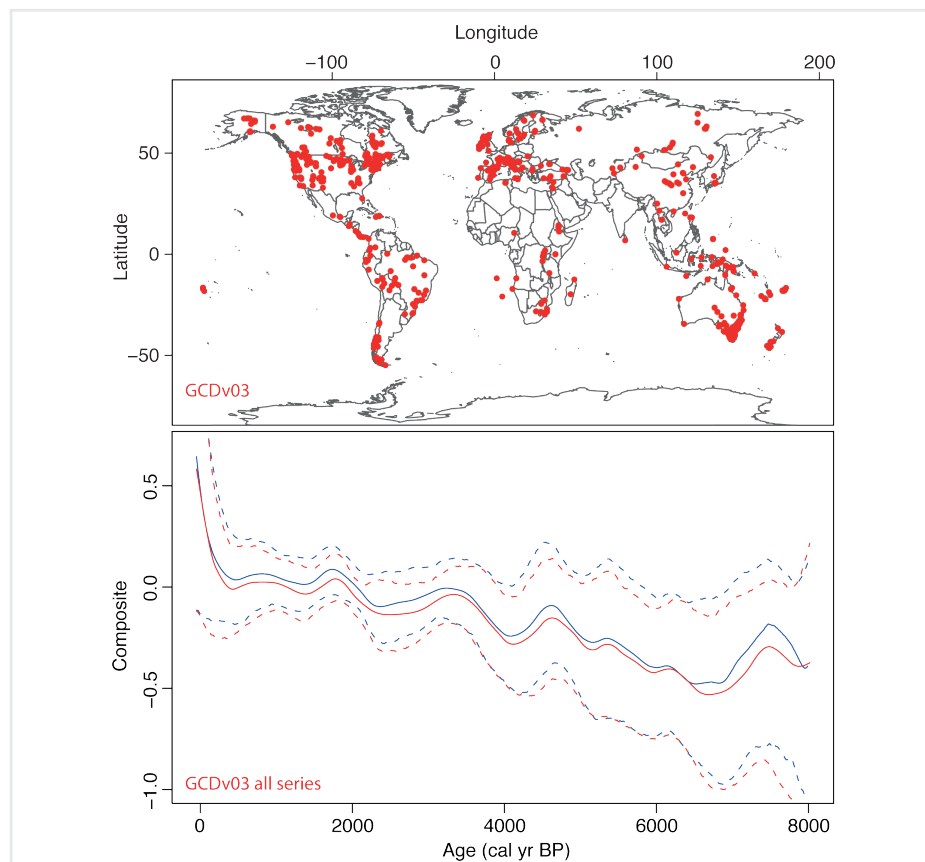
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**Figure 1:** Map of sites available in GCDv3 (top panel) and comparison of the Fortran (e.g. Marlon et al. 2013) and paleofire R package compositing outputs for all GCDv3 charcoal sites (bottom panel). Composite curves (plain line) and associated 95% confidence intervals are displayed in blue for the Fortran procedure and in red for the paleofire R package. The results were obtained using the same arguments for both procedures. The results from both approaches are highly correlated ( $r > 0.99$ ) and significant ( $p < 0.001$ ). The paleofire R-package offers comparable results for charcoal series synthesis to former analyses based on the Fortran's method. The 500 year smoothing window-width used in this analysis does not capture the most recent downturn known to have occurred in global fire activity since the turn of the 20<sup>th</sup> century.



# Holocene circum-Arctic peatland carbon dynamics

Zicheng Yu and Julie Loisel

Bethlehem, United States, 13-15 October 2013

Northern peatlands represent the largest biosphere carbon (C) pool in the Earth system, containing about 500 GtC (Gorham 1991; Yu 2012); however, how this large C pool responds to climate change is still poorly understood. The overarching goal of this workshop was to understand climate and other controls on Holocene C accumulation through a community-wide collaborative and coordinated effort. This Holocene-scale synthesis aims at extending the effort on the peat C synthesis of northern peatlands for the last millennium as reported in Charman et al. (2013).

At the workshop, we reviewed and finalized the newly expanded Holocene peat C accumulation database that now contains peat property (bulk density, C content) data for 232 peat cores from 181 sites, and peat C accumulation records for 151 cores from 127 sites (Fig. 1; Loisel et al. in press). This is a major expansion from a previous synthesis of C accumulation, which combined records from 33 sites in northern peatlands (Yu et al. 2010). Workshop participants also discussed strategies for further analyzing and synthesizing peat C data along with other relevant datasets, including bioclimate records of seasonal temperature, moisture and photosynthetically

active radiation (PAR). In order to address the overarching question "what controls Holocene peat C sequestration?", participants identified eight topical areas that need to be addressed in a coordinated way. Topics for these working groups include peatland carbon database management (leader: J. Loisel); age and peat C uncertainty analysis and modeling (M. Blaauw); Bayesian Monte Carlo Empirical Orthogonal Function (MCEOF) analysis (C. Massa); hierarchical cluster analysis (J. Nichols); lateral expansion data and modeling analysis (L. Belyea); net carbon balance and "true" C rate reconstructions (Z. Yu); Holocene bioclimate reconstructions (S. Brewer); and peatland carbon - climate analysis (S. Harrison, R. Spahni, and Z. Yu). An improved technique (using Bayesian MCEOF) that accounts for uncertainties in both ages and peat properties is being developed for a spatiotemporal analysis of the C records. In addition, some groups plan to focus on improving our understanding of important peatland processes, including large-scale lateral expansion (e.g. Ruppel et al. 2013), peat C flux reconstructions at individual sites (e.g. Yu 2011), and PAR controls on peat C sequestration (e.g. Charman et al. 2013).

The database used for the synthesis will be archived at <https://peatlands.lehigh.edu>, and will be linked or ported to other public databases such as Neotoma (neotomaDB.org). New peat C records are to be published in a special issue on "Holocene Peatland Carbon Dynamics in the Circum-Arctic Region" in *The Holocene* (guest-edited by Z. Yu et al.). In addition to improving understanding of the controlling factors on Holocene C accumulation, the new database will be useful for calibrating and evaluating Earth system and climate-carbon cycle models (e.g. Spahni et al. 2013) that need to adequately account for the role played by peatlands in the global C cycle.

The three-day workshop at Lehigh University was followed by a one-day meeting in San Francisco, USA, before the AGU 2013 Fall Meeting. At this meeting, the participants discussed their progress within the working groups and other future research directions. Those included synthesizing and modeling global peat C over the last millennium; synthesizing tropical peat C; studying pre-Holocene peat C accumulation and the structural and functional differences between permafrost and non-permafrost peatlands; and preparing the proposal for the new PAGES "Peat On Earth through Time (POET)" working group.

A total of 25 peatland researchers, including postdoc fellows and PhD students, from seven countries attended the October workshop, and about 40 participants attended the December workshop.

## ACKNOWLEDGEMENTS

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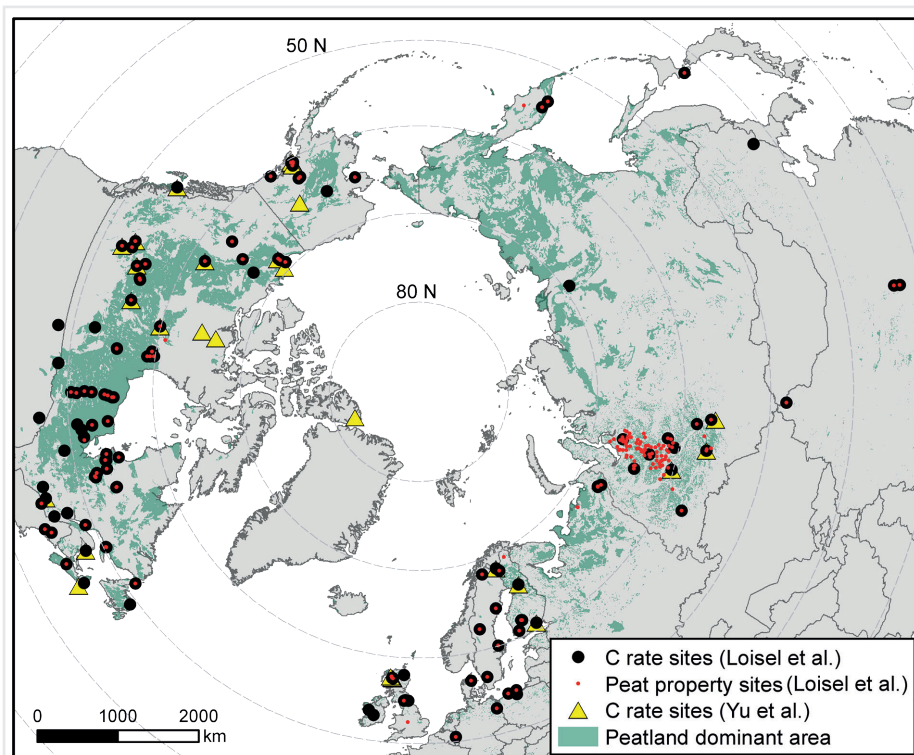
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**Figure 1:** Map showing the locations of peatland sites for C accumulation and peat properties in the database (Loisel et al. in press). Also shown are C accumulation sites used in a previous synthesis (Yu et al. 2010) and the distribution of northern peatlands (green area from Yu et al. 2010). Figure modified from Loisel et al. (in press).

# Estimating rates and sources of sea level change during past warm periods



P A L S E A

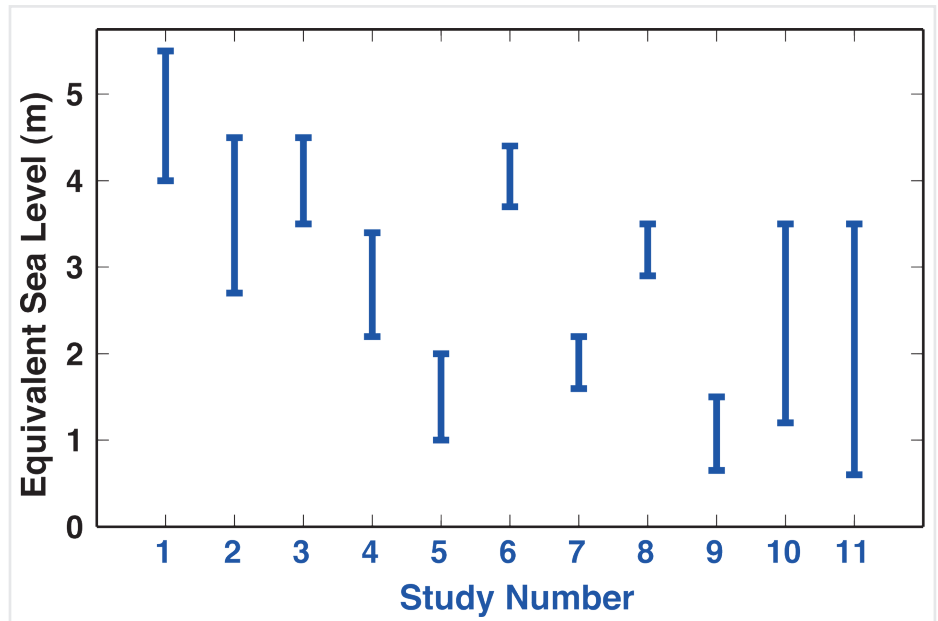
Glenn Milne<sup>1</sup>, A. Carlson<sup>2</sup>, A. Dutton<sup>3</sup>, A. Long<sup>4</sup> and O. Rybak<sup>5,6</sup>

PALSEA2 Workshop, Rome, Italy, 21-25 October 2013

The greatest uncertainty in projecting future sea level rise is that associated with the response of Earth's ice sheets to climate change. The primary aim of the PALeo constraints on SEA level rise (PALSEA) Working Group is to reduce this uncertainty using geological information of past ice sheet and sea level variability with a focus on past warm periods when the configuration of ice on Earth was similar to today. Due to the success of this working group during its first phase, it has been approved for a second phase (PALSEA2) and the meeting reported on here is the first in this second phase.

Estimating rates and sources of sea level change during the last interglaciation (LIG; ca. 130-115 ka ago) was the dominant part of the meeting. Recently, significant progress has been made in improving estimates of the minimum volume of land ice during this period with a range of 5.5-9m currently documented as the most likely (Kopp et al. 2009; Dutton and Lambeck 2012). A number of observations suggest more than one sea level high stand during this period. Reconstructions based on a range of sea level indicators from different regions were presented at the workshop and all support temporal variability within the LIG with millennial average rates ranging from the order of decimeters per century to meters per century. The discrepancy in these values relates primarily to limitations in height and time precision of the reconstruction methods used. Therefore, an important target for the community is the production of more precise sea level records for this period.

Interpreting both the volume and variability of reconstructed LIG sea levels requires consideration of near-field constraints on ice extent for both the Greenland and Antarctic ice sheets as well as models of their evolution across the LIG. While there remains considerable variation in estimates of the minimum volume extent of the Greenland ice sheet during the LIG, most recent studies indicate relatively stable rates of mass loss with a maximum sea level contribution in the range 0.5-3.5 m for this period (Fig. 1), consistent with observations (e.g. Colville et al. 2011; NEEM 2013). There is much less data control on Antarctic ice sheet changes, making this an important research goal in the coming years. Modeling results presented at the meeting suggest that a relatively large and rapid retreat of the Antarctic ice sheets first requires significant warming of the Southern Ocean in order to melt ice shelves.



**Figure 1:** Estimates of the contribution of the Greenland ice sheet to global mean sea level during the Last Interglacial. The studies numbered in publication order along the x-axis are: (1) Cuffey and Marshall (2000); (2) Tarasov and Peltier (2003; most likely range shown); (3) L'homme et al. (2005; most likely range shown); (4) Otto-Bliesner et al. (2006); (5) Oerlemans et al. (2006); (6) Robinson et al. (2011; most likely range shown); (7) Colville et al. (2011); (8) Born and Nisancioglu (2012); (9) Quiquet et al. (2012); (10) Helsen et al. (2013); (11) Stone et al. (2013). Only studies that provided a range of values are shown here.

An issue common to all time periods discussed at the workshop was the challenge of estimating global mean sea level (to determine past ice volume) from a limited set of site specific relative sea level data. Reconstructions of the latter for the middle Pliocene (ca. 3.3-2.9 Ma) can be significantly affected by both glacial isostatic adjustment and dynamic topography driven by internal mantle buoyancy (e.g. Rowley et al. 2013). Uncertainty in model estimates of the contribution of these processes to Pliocene sea levels is a primary limitation in estimating ice volume within a reasonable precision (~10 m). A similar problem relates to the interpretation of high-resolution sea-level records for the past few centuries to millennia. As more records become available, it is becoming clear that there is a large overprint associated with ocean dynamical changes. This has important implications for using these records to calibrate semi-empirical models of global mean sea level (e.g. Kemp et al. 2011).

Through future workshops and conference sessions, the PALSEA2 Working Group will stimulate and encourage researchers to address the data and knowledge gaps highlighted above.

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# COMPARE 2013: Constraining tropical ocean cooling during the Last Glacial Maximum

David W. Lea<sup>1</sup>, M. Kienast<sup>2</sup>, T. de Garidel-Thoron<sup>3</sup>, M. Kageyama<sup>4</sup>, A. Paul<sup>5</sup> and E. Bard<sup>3</sup>

Corvallis, USA, 3 December 2013

Establishing a sea surface temperature (SST) distribution for the Last Glacial Maximum (LGM) has long been a primary goal in paleoclimate research, with the CLIMAP (Climate Long range Investigation, Mapping and Prediction) reconstruction standing out as a landmark accomplishment. The development of new SST proxies such as UK37' and Mg/Ca paleothermometry in the 1980s and 90s spurred the international community to re-evaluate LGM SSTs. The publication of the SST reconstruction of MARGO (Multiproxy Approach for the Reconstruction of the Glacial Ocean surface) was the culmination of an international collaboration to update and improve LGM SST reconstructions (MARGO Project Members 2009). The MARGO reconstruction is an important validation target for the modeling community because the climate forcing and response during the LGM are relatively well known and allow for an assessment of climate sensitivity determinations.

The purpose of the COMPARE 2013 workshop was to follow up on an initial meeting of COMPARE 2012 (Comparing Ocean Models with Paleo-Archives) in Bremen, Germany (18-21 March 2012) which had discussed ways to further improve the MARGO data set and how to apply it to data-model intercomparisons (Kucera et al. 2012). The MARGO SST reconstruction synthesizes both more traditional approaches (i.e. faunal transfer functions) and newer geochemical approaches (i.e. Mg/Ca and UK37'). But because the original MARGO data set for the tropics is still dominated by estimates based on transfer functions, the reconstructed SST changes do not optimally represent the different proxy results. The COMPARE 2013 workshop brought together observationalists and modelers to exchange their latest insights on tropical SST proxies and the efficacy of the MARGO low latitude reconstructions.

There are many reasons for re-evaluating LGM tropical SST, including the MARGO compilation itself, which displays a much stronger level of spatial heterogeneity in the tropics than has been simulated by coupled model runs (Kageyama et al. 2013); the validity of the SST proxies and their overall compatibility; advances in linking climate sensitivity to LGM tropical cooling in models (Hargreaves et al. 2012); downward revisions of LGM cooling based on MARGO; and advances in analyzing and attributing deglacial SST records, which are increasingly based on geochemical proxy records (Shakun et al. 2012).

We identified two overarching research questions to frame the problem:

- Can we reconcile UK37' and Mg/Ca data within acceptable brackets by using harmonized calibration schemes and by considering differences in habitat depth and season? If so, what was the magnitude of mean annual LGM tropical surface cooling?
- How much heterogeneity was there in tropical surface cooling during the LGM?

To address these questions, we propose to develop a new LGM tropical SST geochemical database. This database will focus on measured parameters: i.e. raw Mg/Ca and UK37' measurements (Fig. 1). It will include the full data sequence from 0-30 ka BP with chronological constraints and uncertainties, associated parameters such as oxygen isotopes, alkenone abundance, dissolution parameters, Mg/Ca on other species, and relevant metadata (e.g. how the samples were processed or cleaned, foraminiferal size fraction and morphotypes).

The proposed approach will provide an SST field using harmonized calibrations, which will allow direct comparison of Mg/Ca and alkenone temperatures. It will also provide a

basis of comparison with the MARGO (2009) database as well as a target for modeling. Statistical analysis of the dataset, considering the interproxy difference, the spatial reproducibility, as well as the calibration uncertainty, will provide uncertainty estimates for the SST field. The raw measurements can also be adapted to improved or alternative calibrations, data assimilation or forward modeling. Furthermore, assembling a database with records covering the full sequence since the last glacial opens the possibility of developing time slices for target periods other than the LGM (e.g. Heinrich Stadial 1 or the Younger Dryas).

We will try to implement a dynamic database approach that allows for the addition of new data as they become available, and, possibly, implementation of different calibration schemes. We invite members of the paleoceanographic community to submit UK37' and Mg/Ca data sets that will enhance the COMPARE effort.

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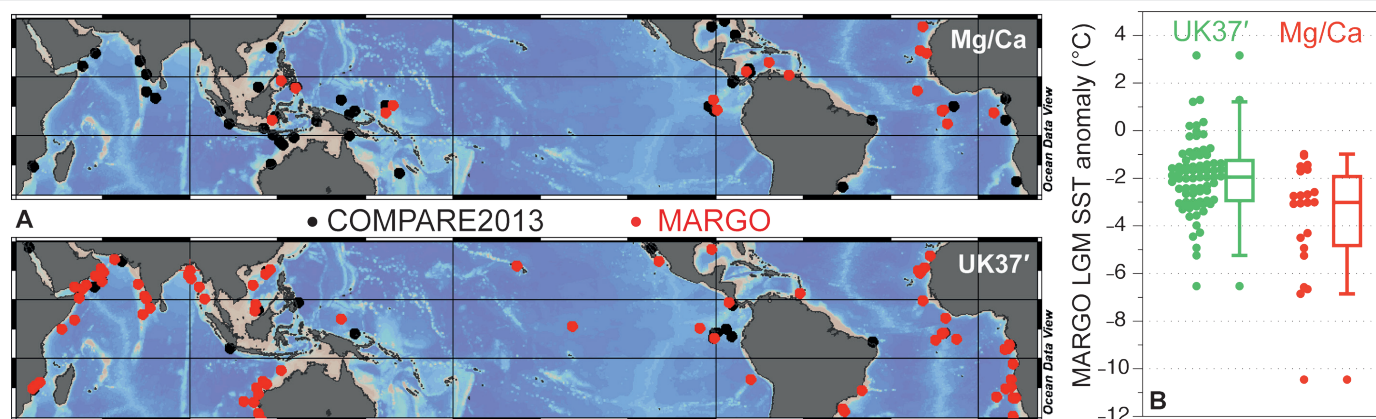
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**Figure 1:** (A) Distribution of newly available low latitude records (black dots) compared to the MARGO (2009) dataset (red dots) that have Mg/Ca (top panel) and UK37' (lower panel) paleothermometry data. Note that sites are concentrated along oceanic margins. (B) Whisker plot comparison of low latitude UK37' and Mg/Ca data compiled in MARGO (2009). On average, Mg/Ca data indicates 3°C of tropical cooling vs. 2°C for UK37'.



# Integrated analyses of reconstructions and multi-model simulations for the past two millennia



Johann H. Jungclaus<sup>1</sup>, H. Goosse<sup>2</sup>, E. García-Bustamante<sup>3,4</sup>, L. Fernández-Donado<sup>4</sup> and J.F. González-Rouco<sup>4</sup>

Madrid, Spain, 4-6 November 2013

Comparing model simulations with proxy-based climate reconstructions offers the possibility of improving our understanding of the mechanisms contributing to climate variability and their links to external forcing or internal processes. It helps to identify deficiencies in the way climate variability is represented by proxy records or by model simulations, with implications for future climate change projections. The Past2K group of the Paleoclimate Modelling Intercomparison Project (PMIP3) is promoting model-data comparison activities focusing on the climate of the last millennium. The PAGES 2k Network is fostering similar activities covering the last 2000 years and has promoted the development of regional-scale data syntheses resulting in an ensemble of reconstructions for nearly all the continents (PAGES2k Consortium 2013). The meeting held in Madrid gathered members of both communities with a main focus on comparing the PMIP3 "past1000" simulations with the PAGES2k reconstructions.

Activities started a few months before the actual workshop as most of the 32 workshop participants volunteered to contribute to the analyses of some diagnostics within one of the three working groups (WGs) focused on: 1) PAGES2K regions and PMIP3 simulations; 2) PMIP3 simulations and reconstructed circulation

modes; 3) best practices and new approaches in model-data comparison. In addition, participants were identified to prepare reviews. The three-day meeting was structured into review talks (days 1 and 2) and WG presentations (days 2 and 3), allowing time for ample discussion slots. The last day of the workshop focused on discussion and planning future joint activities, including 1) the preparation of manuscripts focused on the comparison of PMIP3 simulations and PAGES2k regional reconstructions, 2) comparison between reconstructed and simulated modes of variability, and 3) on best practices in data-model comparison. Additionally, an outreach event was organized on communicating climate and climate change science.

Several issues from the discussions can be highlighted. For instance, significant correlations between regional temperature reconstructions and climate model simulations (Fig. 1) suggest that, at multidecadal scales and above, regional temperatures respond to external forcing (PAGES2k Consortium 2013; Sundberg et al. 2012; Schurer et al. 2014). The specific fingerprints of volcanic, solar and anthropogenic contributions were analyzed from the perspective of various methodologies, with the role of solar forcing being acknowledged as comparatively smaller. The inter-regional correlations were shown to be lower in the

reconstructions than within the models' world, the latter evidencing a more homogeneous spatial temperature response. The implications of these differences for climate reconstructions and also for the assessment of confidence in climate models were discussed.

The reconstructions of modes of atmosphere and ocean variability such as PDO, ENSO, IPO, PNA, NAO, SAM or the gyre system in the North Atlantic were presented. In most cases, they show very limited resemblance to their simulated counterparts. This suggests an overall lack of evidence for a direct external forcing imprint on the variability of many climate modes. Since internal variability seems to be the dominant factor, model simulations are useful for identifying the dynamics explaining some of the reconstructed changes. However, a more fundamental issue with methodological implications is the limited agreement found in various reconstructions of particular modes. Such inconsistencies may reflect large spatial changes in the positions of the centers of action that are not captured with index definitions based on fixed locations or eigenvector approaches. Here, model-guided mode definition and proxy-site selection (e.g. Lehner et al. 2012) appears to emerge as a promising field of research.

## ACKNOWLEDGEMENTS

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Meeting website: [www.palma-ucm.es/members/workshop/Home.html](http://www.palma-ucm.es/members/workshop/Home.html)

Outreach event: [www.palma-ucm.es/activities/](http://www.palma-ucm.es/activities/)

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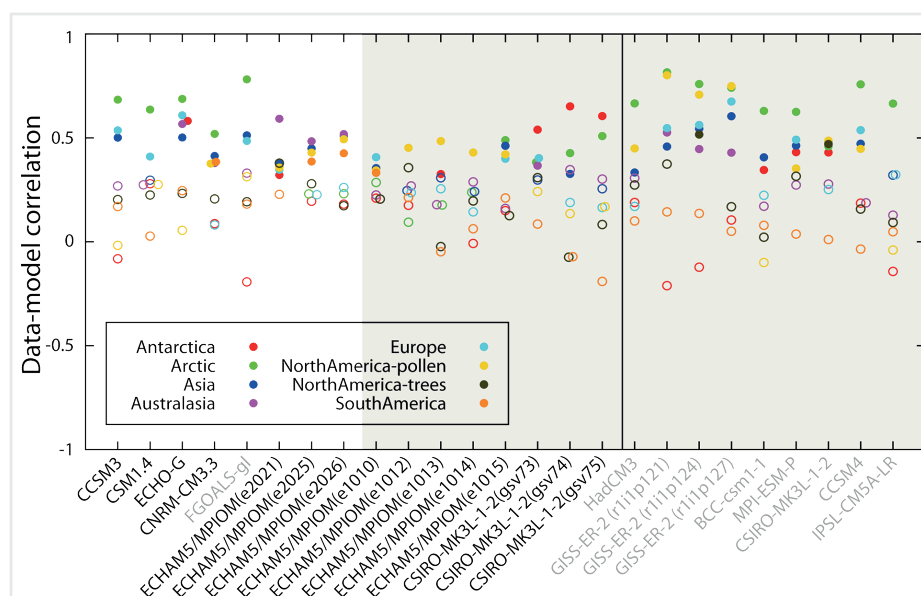
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**Figure 1:** Correlation values between PAGES2k reconstructions and PMIP3 (grey) and pre-PMIP3 (black) simulations. Regions are depicted with colors. The full (empty) circles indicate a correlation value (not) significantly different from zero ( $p < 0.05$ ). The gray shaded area highlights the simulations that included a comparatively lower solar forcing variability scenario. Time series were 31-year low pass filtered and the full period of overlap between simulations and reconstructions used. See Table 5.A.1 in Masson-Delmotte et al. (2014) for details on model names and forcing.

# PMIP Ocean - Understanding changes since the Last Glacial Maximum



Andreas Schmittner<sup>1</sup>, S.P. Harrison<sup>2</sup>, A.E. Carlson<sup>1</sup>, A.C. Mix<sup>1</sup>, M. Kageyama<sup>3</sup> and Michal Kucera<sup>4</sup>

Corvallis, USA, 4-6 December 2013

More than 40 scientists met in Corvallis, Oregon, to discuss how ocean data can be better used to evaluate results from the Paleoclimate Model Intercomparison Project (PMIP). Focus was on the Last Glacial Maximum (LGM; 19-23 ka ago) and the Mid-Holocene (MH; 6 ka ago). However, many talks went beyond these time periods and showed new and exciting paleo-data from the deglacial transition from the LGM to the Holocene, and model simulations. The idea of a new community experiment for transient modeling of the deglaciation in the next PMIP was discussed with enthusiasm.

Talks and discussions during the first day focused on methods of model-data comparison (Fig. 1), quantifying uncertainty and ocean temperature reconstructions, particularly from the tropics (including a report from a one-day prelude workshop on tropical sea-surface temperatures). Systematic differences between various proxies (e.g. alkenones, Mg/Ca, TEX86, foraminifera faunal assemblages) were diagnosed and new methods of quantifying uncertainties and forward modeling of individual foraminifera species were presented. It appears likely that the seasonal and vertical attribution of sea surface temperature reconstructions is a major reason for discrepancy among different proxies. Contrary to previous interpretation, it seems that in some cases

foraminifera assemblages do record shallow subsurface temperatures rather than surface temperatures. Temperatures at the subsurface may also show larger climate signals than at the surface in some areas, as suggested by model simulations.

The second day focused on the deep ocean. Stable carbon isotopes ( $\delta^{13}\text{C}$ ) and radiocarbon ( $\Delta^{14}\text{C}$ ) provide important constraints on deep-ocean circulation and carbon cycling. Inverse model solutions using  $\delta^{13}\text{C}$  data indicate that the Atlantic Meridional Overturning Circulation (AMOC) during the LGM may not have been significantly different from today. Another presentation highlighted that in model simulations of the LGM, ocean circulation requires thousands of years to equilibrate. This raised the issue of whether the LGM (or in fact any time interval) can be considered to ever be in an equilibrium state, either for models or data reconstructions. Although radiocarbon is perhaps the most direct proxy for deep ocean circulation, independent dating is needed to allow its interpretation as a circulation tracer. The assumption of constant surface reservoir ages made in many previous studies may in some cases not be true, at least during the deglaciation. Nevertheless, new radiocarbon data from the North Pacific and Southern Ocean advance our understanding of deep

ocean circulation changes during the LGM and deglacial intervals.

Modeling studies highlighted the role of Laurentide ice-sheet topography in affecting global-mean LGM climate, model biases in the Southern Ocean for AMOC LGM simulations, and uncertainties in physical and biological processes in reproducing carbon cycling in the ocean.

During the last day, the potential for focused studies of past warm periods and new approaches to community databases were discussed. One presentation argued that an unfavorable signal-to-uncertainty ratio in the currently available sea surface temperature reconstructions prevents the use of MH data in constraining model simulations. Model simulations of the Miocene considering changes in the Antarctic ice sheet were also presented.

Databases are essential for the efficient creation of syntheses and for making paleoceanographic data more accessible. Two new approaches were introduced: one web based system and one offline tool, both of which can be expected to become available to the community in 2014.

The workshop proceeded with discussions in breakout groups on data reporting standards, model-data comparison, and an outline for new PMIP simulations of the deglacial. A document recommending paleoceanographic data reporting standards has been started and will be further developed through PAGES. Another document outlining the discussions of the proposed new deglacial PMIP simulation was started and will be presented to the wider PMIP community at the upcoming PMIP3 conference in May 2014. This workshop was co-sponsored by the US NSF, PAGES, and INQUA. The meeting program and all of the abstracts can be found at:

[http://people.oregonstate.edu/~schmitta2/Projects/PMIP\\_LGM\\_C13/PMIP\\_ocean\\_WS.html](http://people.oregonstate.edu/~schmitta2/Projects/PMIP_LGM_C13/PMIP_ocean_WS.html)

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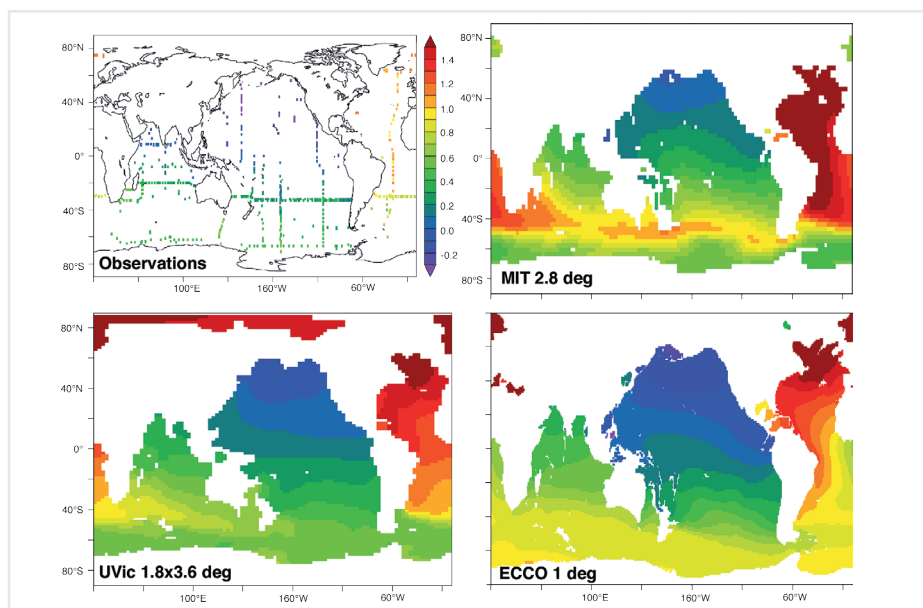
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**Figure 1:** Comparison of deep (2 km) ocean  $\delta^{13}\text{C}_{\text{DIC}}$  distributions in modern observations (top left) and three different circulation models calculated using the same underlying biogeochemistry model (MOBI; Schmittner et al. 2013) and transport tracer matrix method (Khatiwala et al. 2005). The model simulations do not account for the anthropogenic rise in atmospheric  $\delta^{13}\text{C}$ . Note the effect of higher resolution ( $1^\circ \times 1^\circ$  MIT-ECCO lower right) on the simulation of the western boundary current in the Atlantic compared with the coarser resolution models ( $2.8^\circ \times 2.8^\circ$  MIT upper right and  $1.8^\circ \times 3.6^\circ$  UVic lower left). PMIP3 LGM simulations using this offline method of calculating tracer distributions will be used in the future to predict isotope distributions for comparison with paleo data from ocean sediments.

# Quaternary paleoecology: Reconstructing past environments

Sonia L. Fontana<sup>1</sup> and Keith D. Bennett<sup>2</sup>

Jujuy, Argentina, 19-30 August 2013

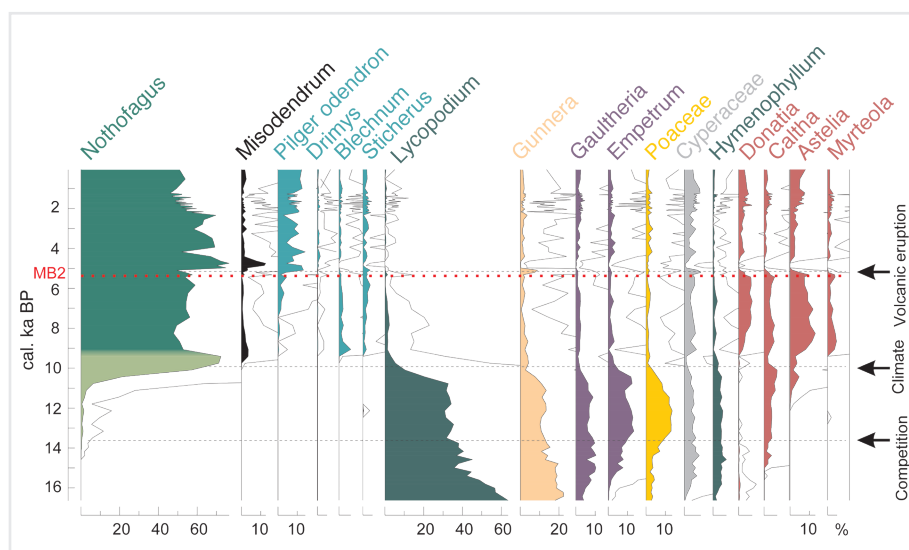


Paleoecological studies provide data on changes in vegetation and other aspects of the environment through time. Numerous paleoecological records from around the world have demonstrated that vegetation has changed, often dramatically, since the last glacial maximum (LGM). Changes are usually attributed to various external forcing factors, including climatic change, volcanic eruptions, fire, or human activity. Additionally, vegetation has changed as result of its own internal dynamics (Bennett and Willis 1995), which include migration, competition and succession across different timescales. An example of postglacial changes in vegetation from southern-most South America is illustrated in Figure 1; it specifies the different processes that have caused vegetation changes since the LGM (Fontana and Bennett 2012). Disentangling these forcing factors of environmental change is challenging, especially when they operate and interact at different spatial and temporal scales (Fontana et al. 2012).

The purpose of this workshop was to bring together Latin American researchers working on Quaternary environmental change to discuss and build up a network, exchange perspectives and promote international interactions. Forty-two senior and early career scientists, and postgraduate students from Mexico, Venezuela, Colombia, Brazil, Bolivia, Chile and Argentina attended the meeting. A broad range of expertise was represented covering palynology, diatoms, ostracods, foraminifera, nanoplankton, charophytes, phytoliths, dendrochronology, and archeology.

The workshop provided (1) an overview of the spatial and evolutionary responses of organisms to different Quaternary driving forces with the aim of providing insight into general questions of species survival, spread and biodiversity; (2) an outline of the principles, methods and applications of selected paleoecological techniques; and (3) an overview of methods and software used for data analyses.

The event comprised lectures, practical classes, poster presentations, a field trip and the development of a joint research project. The lectures addressed the paleoecology of the oceans, long Quaternary terrestrial records with multiple glacial-interglacial oscillations, an overview of key sites for the last glacial-interglacial transition, paleogenetics (including molecular clocks and ancient DNA), refugia, individualistic communities, plant migration, late Quaternary extinctions, and consideration of the role of Quaternary events on the



**Figure 1:** Pollen percentage diagram of selected taxa from Lake Ballena, indicating different processes that have caused main vegetation changes since the LGM. MB2 indicates the position of the tephra layer from the Mt Burney 2 eruption. Figure modified from Fontana and Bennett (2012).

evolution of organisms. Important discussions centered around data collection issues: site selection and coring, sub-sampling techniques, routine sediment analyses, overview of pollen and microfossil analyses and the value of multi-disciplinary research in paleoenvironmental reconstructions. The practical classes focused on data handling: chronology, the radiocarbon method and calibration, zonation, rate of change, ordination techniques and diversity estimates.

A field trip to Laguna Rontuyoc took place, following which participants engaged in the Latin American co-operative project for young scientists, Synergy Latina, and designed a multi-disciplinary research project with the main goal being to disentangle possible interactions between the environment and humans of the Altiplano of northern Argentina. Attention was paid to the influence that climatic changes had on the development of Andean civilizations and the consequent impact of human activities on the landscape. The initial phase of this project was conducted during the course (describing and sub-sampling the sediment core), while the different analyses will be carried out at a later stage at the participants' home institutions.

This first workshop was hosted by the University of Jujuy and coordinated by Julio Kulemeyer and Liliana Lupo. It was a successful start to the task of enhancing paleoecological investigations in Latin America and we look

forward to larger scale joint investigations, the ongoing exchange of knowledge leading to the development of new ideas and research questions, and continued cooperation. Further annual workshops are planned.

In addition to PAGES, participants received support from their home institutions, universities and research councils. The <sup>14</sup>CHRONO Centre at Queen's University Belfast, financially supported and ran the radiocarbon dating of the sediment records for the Synergy Latina project.

The full program of activities, including poster abstracts can be viewed at: [www.uni-goettingen.de/en/413062.html](http://www.uni-goettingen.de/en/413062.html).

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# Long-term perspectives on ocean and climate dynamics – Three decades of ICP



Eva Calvo<sup>1</sup>, I. Cacho<sup>2</sup>, C. Pelejero<sup>1,3</sup>, J.O. Grimalt<sup>4</sup>, P.G. Mortyn<sup>5</sup>, R. Zahn<sup>3,5</sup> and P. Ziveri<sup>5</sup>

11<sup>th</sup> International Conference on Paleoceanography – Sitges, Spain, 1-6 September 2013

Over the past 30 years, the International Conference on Paleoceanography (ICP) events have established a strong tradition in pushing paleoceanographic research forward, as well as witnessing and stimulating the great progress and achievements that this multi-disciplinary field has made. The ICP11 took place in Sitges, a small Mediterranean coastal hamlet south of Barcelona, and was attended by 576 participants (including 196 students) from 41 different nationalities.

The conference was organized along five themes, addressed through five plenary sessions. The mornings were dedicated to oral presentations (30 in all) and three poster sessions were held in the afternoons, featuring a total of 527 posters. The Scientific Committee designed the session themes to guarantee a multidisciplinary approach to past climates at various timescales, from the most recent past back to the Paleozoic using both empirical and modeling approaches (the full program is available at: [www.icp2013.cat](http://www.icp2013.cat)). ICP11 also committed to providing early-career scientists the opportunity to present their research to an international audience, and therefore they accounted for more than half of the selected speakers. For the first time in ICP events, three “perspective lectures” were included: two highlighting work in disciplines closely related to paleoceanography - modern ocean geochemistry from the GEOTRACES program’s perspective, and ice core paleoclimate studies and the third presenting the ideas for a follow-up project to the International Marine Global Change Study. As in previous ICPs, the Scientific Committee awarded 12 students poster prizes ([www.icp2013.cat/index.php/best-student-awards.html](http://www.icp2013.cat/index.php/best-student-awards.html)).

A number of challenging and important findings were presented during the ICP. For example, we learned of advances and refinements in geochemical proxies and their application on issues such as sea ice cover (IP25), ice sheet stability (Nd isotopes, Sr-Nd-Pb isotopes) or glacial CO<sub>2</sub> sequestration (radiocarbon, B isotopes, foraminifera-bound N isotopes, C isotopes).

Participants also learnt of remarkable efforts to combine major “data mining” and modeling to examine global and regional oceanographic patterns and causes of past climate changes.

These efforts focused on several climatic and oceanic variables including global and regional temperature changes since the Last Glacial Maximum, the Meridional Overturning Circulation over the last 40 ka, ocean oxygenation across the last deglaciation and a sea surface temperature compilation for the past two millennia, conducted by the PAGES Ocean2k project.

New geochemical records and modeling experiments provided insight on the coupling between past climates and ocean biogeochemistry, in general, and the carbon cycle in particular. Evidence of the breakdown of North Pacific stratification during the last deglaciation prompted a lively discussion on the possibility of North Pacific deep-water formation at that time. At millennial time scales, modeling simulations also showed the relevance of circulation

changes, both in the Atlantic and in the Pacific, in controlling atmospheric CO<sub>2</sub>. At longer time-scales, an unusual attempt to shed light on the C isotopic vital effects in coccoliths provided a new avenue to detect a global atmospheric CO<sub>2</sub> decrease about 7-5 Ma ago that was coupled to ocean temperature decrease. For these ancient times, a wealth of new results from deep-time paleoceanography and paleo-modeling demonstrated the substantial recent progress in quantitatively tackling several key parameters, such as deep-ocean oxygenation during extreme climates and exotic events of the Cenozoic and beyond.

Efforts to improve the resolution and accuracy of marine proxy records were also presented, and the associated value for gaining further knowledge about ocean-land-atmosphere interactions was demonstrated. Excellent examples came from coral records, which allow us to more accurately decipher past inter-annual climate variability such as the El Niño-Southern Oscillation, but also from sediment and pollen records from the Mediterranean, the Atlantic and Antarctica’s margins.

Another memorable event of the conference was the traditional ICP paleomusicology concert where conference attendees put on a diverse range of outstanding musical performances for their colleagues. The next tri-annual meeting, ICP12, will be held in Utrecht in The Netherlands in summer 2016.

## ACKNOWLEDGEMENTS

The organizers thank PAGES and SCOR for their financial support allowing 19 students and early career scientists from developing countries to attend ICP11. We also thank EGU for supporting three key contributors as EGU Ambassadors. Nature Publishing Group provided five subscriptions for student poster presentation awards.

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**Figure 1:** “Castells”, Human Towers, a Catalan tradition that accelerates your heartbeat. This picture shows a performance of the “Castells of Poble Sec” during the ICP11 ice breaker with the participants’ help to support the tower. This is an excellent example of team effort and the importance of every single member to the success of the project, in this case, the human tower. “Team spirit, strength, balance, courage and common sense”, the “castells” motto also defines the essence of the ICP conferences and the paleoceanographic community.

# 4<sup>th</sup> Polar Marine Diatom Taxonomy and Ecology Workshop

Zuzia Stroynowski<sup>1</sup>, R. Minzoni<sup>2</sup> and S.K. Shukla<sup>3</sup>

Cardiff, UK, 4-9 August 2013

The Polar Marine Diatom Workshops (PMDW) arose to meet the need for a forum that would encourage the exchange of taxonomic skills and associated new techniques, while providing an excellent platform for students to receive training and guidance from experienced diatomists. Since 2005, the workshop has become a successful biennial event, bringing polar diatomists together to exchange new ideas, share recent results and data, and build future collaborations with other researchers around the world. The 4<sup>th</sup> PMDW was hosted by Jennifer Pike at Cardiff University and was attended by 36 participants from 14 countries. It consisted of research presentations and practical microscope-based sessions on polar diatom taxonomy and ecology.

Diatoms are a major phytoplankton group accounting for 40% of global marine primary productivity; in high latitudes this figure is over 60%. They play an integral role in the export of carbon and are extremely sensitive to changing environments. As research continues in the polar regions, novel applications emerge as a result of our increased understanding of species-specific ecology. Diatom studies in such extreme environments are essential for

improving our understanding of glacio-marine settings - an understanding that may be applied to reconstruct paleoenvironments including temperature, sea ice extent, the growth and decay of ice sheets, and to assess future climate scenarios. The PMDW provided an indispensable forum for polar diatomists to discuss all these issues.

Fifteen 1.5-hour microscope sessions dominated the week's activities, and were complemented by nine 30-minute lectures and 12 poster presentations. Microscope tutorials spanned both the Arctic and Antarctic, and covered topics on diatom morphology, modern day communities, fossil records and biostratigraphy.

Some of the highlights of the meeting were the following: M. A. Bárcena presented new data on *Eucampia antarctica* as a proxy for paleoceanography and sea-ice concentration in the Drygalski Basin (Fig. 1). Under higher light intensity and thinner/less sea-ice cover, *E. antarctica* undergoes more cell divisions and average chain length increases (Fryxell and Prasad 1990). However plankton net samples (L. Armand) suggest this paleoproxy

may underestimate sea ice extent because the ratio used to estimate chain lengths from fossil frustules might be biased.

R. Crawford presented a new morphological investigation on the understudied genus *Corethron*. This was further complemented by modern-day plankton net studies at Anvers Island and Biscoe Bay, Antarctica, where *Corethron* sp. dominated the assemblage (D. Karentz). Future work will compare species with environmental variables as well as RNA sequencing to determine their proteomic response to temperature changes (D. Karentz). A. Leventer presented a laminated *Corethron* ooze record from Iceberg Alley, East Antarctica.

C. Allen ran a practical session on the largely overlooked giant diatom species *Arachnoidiscus* sp. from the Firth of Tay, Antarctic Peninsula. The importance of this species to the silica and carbon export budget was discussed. Another large species, *Coscinodiscus* sp. and its morphology and identification were presented in practical sessions with sedimentary samples from Southern Iceland (K. Hendry) and plankton net samples from Admiralty Bay, Antarctica (B. Jerzak).

R. Jordan and K. Abe presented Eocene diatoms from IODP 302 (Arctic) and other siliceous fossils. The earliest diatom Cretaceous deposits were also reviewed and their origins discussed (D. Harwood).

One of the goals of the workshop was to provide a launch pad for future collaboration between early career and established researchers, and we hope to see the fruits of these collaborations at the 5<sup>th</sup> PMDW, which will be take place at Salamanca University, Spain in 2015. Further information about the workshops, previous workshop publications and future events can be found at: <https://sites.google.com/site/polarmarinediatom-workshop/>. This workshop was supported by PAGES, the Micropalaeontological Society, Linnean Society of London, BetaAnalytic, GX Optical, and the Annals of Botany Company.

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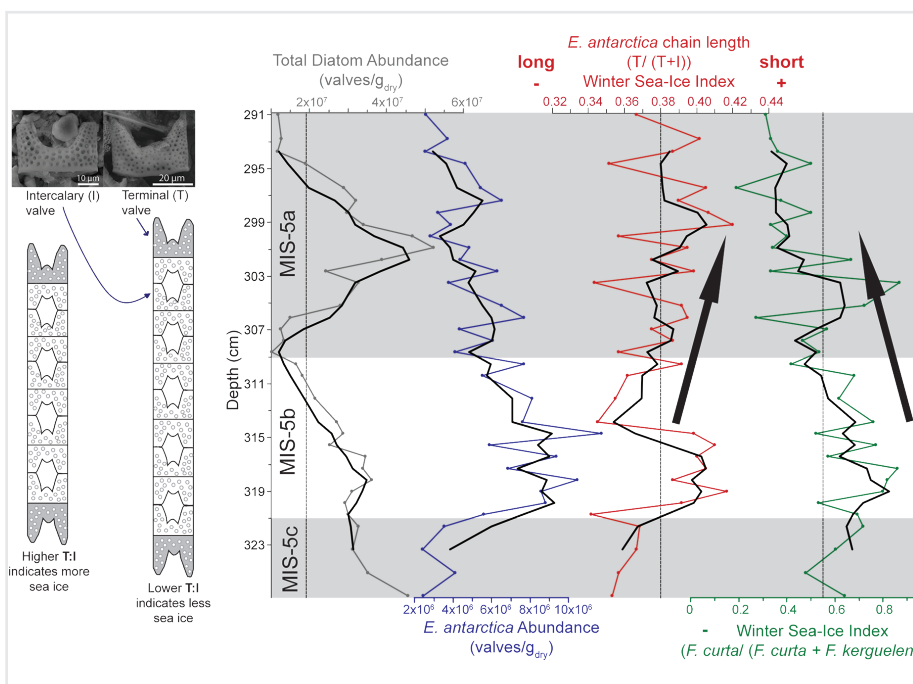
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**Figure 1:** Morphometrics of horned diatom *Eucampia antarctica* as a proxy for sea-ice occurrence during Marine Isotope Stage 5 at Drygalski Basin, Antarctica (M.A. Bárcena, personal communication). The ratio of Terminal (T) and Intercalary (I) valves is calculated as a measure of chain length. Longer chains (i.e. lower T:I) indicate higher light conditions and thinner/less sea-ice cover (Fryxell and Prasad 1990). The interpretation of these results differs from a *Fragilariopsis* Index that compares sea-ice related species *F. curta* with open marine species *F. kerguelensis* (after Denis et al. 2010), and suggests our understanding of these proxy indices needs to be updated.

# Isotopes of carbon, water and geotracers in paleoclimate research

Fortunat Joos<sup>1</sup>, B. Otto-Bliesner<sup>2</sup> and E. Brady<sup>2</sup>

Bern, Switzerland, 26-28 August 2013

Isotopes of water, carbon, oxygen, and of rare earth elements offer the opportunity to quantitatively understand physical and biogeochemical processes in the Earth System and to unravel past and modern climate change. Past climate and greenhouse gas variations provide insight into how climate might evolve under ongoing anthropogenic forcing. Yet, our understanding of past climate and biogeochemical variations over glacial-interglacial time scales, of past abrupt climate swings, or of climate variability during the last few millennia is still limited. The mechanisms of past climate change are intensively debated. What drives glacial inception and terminations? How and why did precipitation vary in the monsoon system and at high latitudes? How did ocean circulation evolve? What regulated the reconstructed variations in atmospheric CO<sub>2</sub> and other greenhouse gases?

The obstacles to exploiting the full potential of isotopes in order to answer these questions include the scarcity of measurements and of easily accessible and quality-flagged isotope data compilations from paleoclimate archives, incomplete understanding and corresponding uncertainties in isotope process parameterizations in Earth System models, and a lack of systematic multi-model model-data intercomparisons for isotopes.

More than 80 participants attended this conference organized by the Oeschger Centre for Climate Change Research and the Climate and Environmental Physics group at the University of Bern in collaboration with the CESM

Paleoclimate Working Group at the National Center for Atmospheric Research. The meeting is intended to be the first in a series of conferences. The objective is to provide a networking platform for specialists from the data and modeling communities to integrate information from isotopes across the Earth System components and scientific disciplines, to assess the state-of-the-art, and to identify and address knowledge gaps.

The presentations as well as the many outstanding posters addressed a broad set of topics including using water isotopes in speleothems to reconstruct temperature and precipitation changes; using carbon and water isotopes in ice cores and marine sediments to understand past climatic and biogeochemical changes (e.g. Fig. 1); the constraints on past ocean circulation from rare earth and carbon isotopes; N<sub>2</sub>O and nitrogen isotopes in ice cores; how carbon and water isotopes in tree rings can be used to identify physiological mechanisms and document environmental change; the representation of isotopes in models; the interpretation of reconstructed changes with the help of models; the exploitation of synergies between process models, contemporary observations, Earth System Models and paleodata; and the use of present-day monitoring and dedicated process studies for the interpretation of proxy data.

As highlighted in the presentations, much progress has been made in recent years to reconstruct isotopic composition in various archives. Improved proxy records are emerging that extend the previous scope in spatial

and temporal resolution and will permit us to draw a more and more detailed picture on their spatio-temporal evolution. At the same time, isotopes of carbon and water and of rare earth elements are increasingly implemented as a standard module in comprehensive Earth System Models and in Earth System Models of Intermediate Complexity.

Concluding discussions revolved around the best way to organize and quality flag existing isotope data to make them more easily accessible to the modeling and experimental communities. It is expected that the meeting stimulated bottom-up research initiatives among the participants that will foster progress on the use of various geotracers in paleoclimate research, in particular in the form of new collaborative efforts that combine information from models and proxies. A follow-up conference is planned to be held in Paris, following the template of this first event in Bern.

## ACKNOWLEDGEMENTS

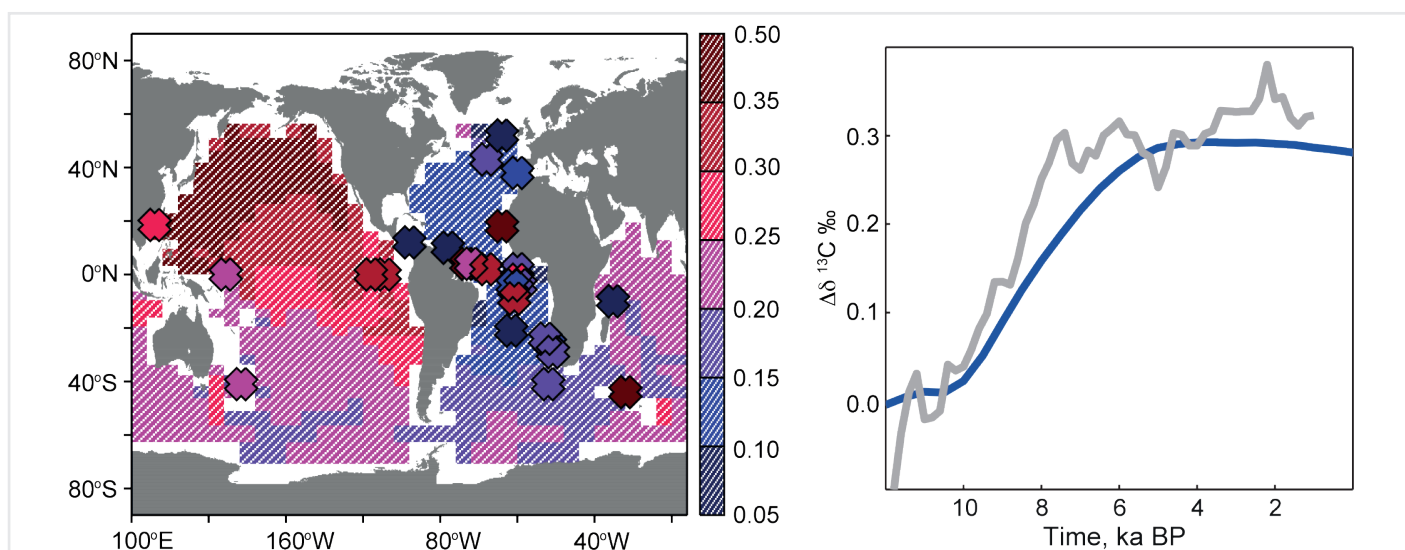
The organizers thank the Oeschger Centre for Climate Change Research, PAGES, and the Johanna Dürrmüller-Bol Foundation for the generous financial support that made this workshop possible. More information, including the abstracts and program, is available at [www.oeschger.unibe.ch/events/conferences/isotopes/](http://www.oeschger.unibe.ch/events/conferences/isotopes/)

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**Figure 1:** Spatio-temporal evolution of  $\delta^{13}\text{C}$  in the deep ocean (> 3000 m) as reconstructed from ocean sediment data (symbols) and simulated with an Earth System Model of Intermediate Complexity. The map shows the total change over the Holocene; the right panel shows the evolution from the stacked proxy data (grey) and the globally-averaged model results (blue).



# Reconstructing past sea ice

Eric W. Wolff<sup>1</sup>, R. Gersonde<sup>2</sup> and A. de Vernal<sup>3</sup>

2<sup>nd</sup> Sea Ice Proxies (SIP) Working Group workshop - Cambridge, UK, 22-24 July 2013

The recent rapid reduction in the extent and volume of Arctic sea ice makes it especially urgent to obtain long time series that can allow us to put recent events in context. The satellite dataset reaches only 40 years into the past, while syntheses using ship and aircraft observations have been taken back to the late 19<sup>th</sup> century. Before that, we are reliant almost entirely on proxy data – from marine sediments, ice cores, and coastal material, each providing evidence of past sea ice presence or absence.

However, there is generally a complex chain of processes connecting ice extent or presence to the measured proxy. An assessment of the basis for each individual proxy was the main business of the first SIP workshop in Montréal in 2012 (de Vernal et al. 2013a). This resulted in a special issue, entitled “Sea Ice in the Paleoclimate System: the Challenge of Reconstructing Sea Ice from Proxies” in the journal, *Quaternary Science Reviews*. Among the 18 papers published, there are three authoritative review papers, one on the use of dinocysts to estimate northern hemisphere sea ice (de Vernal et al. 2013b), another on the biomarker IP25 (Belt and Müller 2013), and the last on ice core proxies of sea ice extent (Abram et al. 2013). An introductory paper (de Vernal et al. 2013c) provides a table highlighting the advantages and disadvantages of each method.

The second workshop took this as its starting point and proceeded to explore the new ideas that had emerged in the last year. Although most of the work discussed was based on proxies discussed at the first workshop, a new candidate proxy in ice cores (halogens) was presented, and the use of material such as driftwood and sedimentological material was also considered.

The main issue for the workshop was to consider ways in which multiple proxies from many sites can be used together to create credible reconstructions of sea ice proxies. Issues arise at each stage (Fig. 1). For some proxies, such as the biomarker IP25, even ensuring comparable analytical results is challenging. A recent intercomparison exercise was presented, and based on this, new recommendations for standardizing analytical methods will be prepared. Once the measurement is complete, it is often reported in terms of a sea ice property, such as seasonal extent, presence/absence, or months of ice cover. The basis for calibrating each proxy against a particular property needs careful examination. Study of the modern processes that link ice to, for example, a biological vector that may be present only seasonally, and to its deposition in sediment, is essential. The workshop participants were urged to take

advantage of existing field campaigns in each polar region, led by people studying current sea ice conditions, to gather further data.

Perhaps the biggest challenge is to synthesize data from different proxy types, often reporting different ice properties, into a single reconstruction. Few multi-proxy comparisons exist, and the meeting participants agreed to set up such a study on some exemplar marine core sections. Despite these problems, reconstructions have been attempted, and the workshop was presented with first efforts at Holocene time slices for both the Arctic and Southern Ocean, and for the last interglacial in Antarctica. Discussion centered on how to improve and enhance these efforts, and how to best report the ice conditions in a way that is compatible both with modern datasets and with the requirements of sea ice modelers. Completion of such work will be the main task

for the third workshop, to be held in Bremerhaven, Germany, on 23-25 June 2014.

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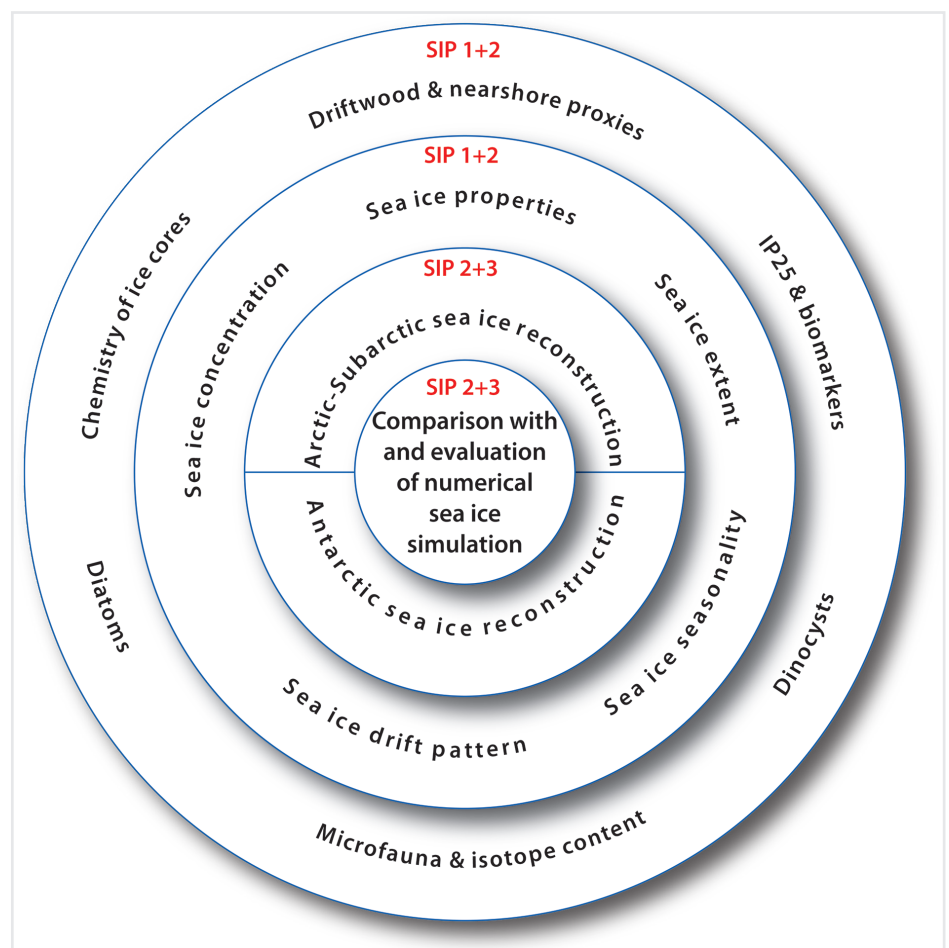
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**Figure 1:** Through its three workshops, SIP has considered all the issues (of sampling, measurement, process understanding, reporting and statistics) which intervene between measurements of different proxies and the production of sea ice reconstructions that are suitable for comparison with modern data and models.

# 1<sup>st</sup> Summer School on Speleothem Science

Michael Deininger<sup>1,2</sup>, S. Winterhalder<sup>2,3</sup>, M. Boyd<sup>4,5</sup>, K. Braun<sup>6,7</sup>, Y. Burstyn<sup>6,7</sup>, L. Comas-Bru<sup>8</sup> and A.D. Häuselmann<sup>9</sup>

Heidelberg, Germany, 28 July - 2 August 2013

Speleothems provide highly resolved and precisely datable paleoenvironmental proxy records with a wide geographic distribution that can capture a range of climatic regimes and their variability over various timescales. Established methods for the analysis of speleothems are constantly being improved, while new methods and proxies are being developed to take full advantage of this unique archive. Henderson (2006) stated: "for paleoclimate, the past two decades have been the age of the ice core. The next two may be the age of the speleothem." And indeed recent years have

of its kind, S<sup>4</sup> was organized by a team of PhD students and gathered 46 students from 22 countries.

Over 20 experts gave lectures covering every stage of investigation and analysis of cave environments and speleothems. S<sup>4</sup> students were led through the entire process from the first stages of site identification, monitoring, sample characterization and selection, through to complex analytical and statistical data handling. A field trip to Herbstlabyrinth cave system provided an example of ongoing

most appropriate. Presentations of commonly used methods provided a platform for discussions regarding known difficulties and how to handle unexpected results. Many experts were on-site for the entire week and actively participated in these discussions providing a wealth of information and troubleshooting strategies.

As with most summer schools and conferences, S<sup>4</sup> provided attendees with the valuable opportunity to build networks and make new academic contacts. Lively discussions during the shared lunches and coffee breaks showed that expert participation extended far beyond the classroom lectures. The organizing committee was overwhelmed by the positive feedback which has been received from the participants and experts, and as a result the next S<sup>4</sup> is planned for 2016. It will be organized by a "fresh" team of PhD students. We are hopeful that this will establish a tradition of international collaboration and knowledge sharing between young scientists in the speleothem field.

For more detailed information please visit: [www.speleothem2013.uni-hd.de](http://www.speleothem2013.uni-hd.de)

## ACKNOWLEDGEMENTS

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**Figure 1:** Finding a suitable stalagmite for paleoclimate studies is still one of the most challenging parts of speleothem science. The picture is showing a cave chamber of the Herbstlabyrinth, Germany, which was visited during the S<sup>4</sup> field trip. Photo by Simon Mischel.

witnessed an exponential increase in speleothem based climate studies. While speleothem science has developed into an advanced branch of paleoclimate research, no organized training program for young scientists in the field had been developed. Filling this gap was the inspiration behind organizing this workshop, the "1<sup>st</sup> Summer School on Speleothem Science (S<sup>4</sup>)".

The aim of S<sup>4</sup> was to bring students and young scientists together from across the globe and provide them with the opportunity to explore in-depth traditional speleothem science methods and receive an introduction to some of the newer developments in the field from established experts. The first summer school

monitoring methods, while hands-on activities including workshops on petrographic analysis, specialized age-modeling software, and statistical analysis gave students the chance to work with real data from their own sites. The evening program of poster sessions and discussion allowed for 36 student projects to receive feedback and advice from peers and experts.

As in many other branches of science, not all researchers and students have analysis facilities at their home institution. Lectures detailing the basics of sensitive analytical procedures and how they apply specifically to speleothems gave many students an excellent overview of the available methods, limitations, costs, locations of labs, and when specific methods are

# 1<sup>st</sup> Workshop on Paleoecological Databases in South America

Claudio Latorre<sup>1,2</sup>, P.I. Moreno<sup>2,3</sup> and E.C. Grimm<sup>4</sup>

Olmué, Chile, 12-16 June 2013

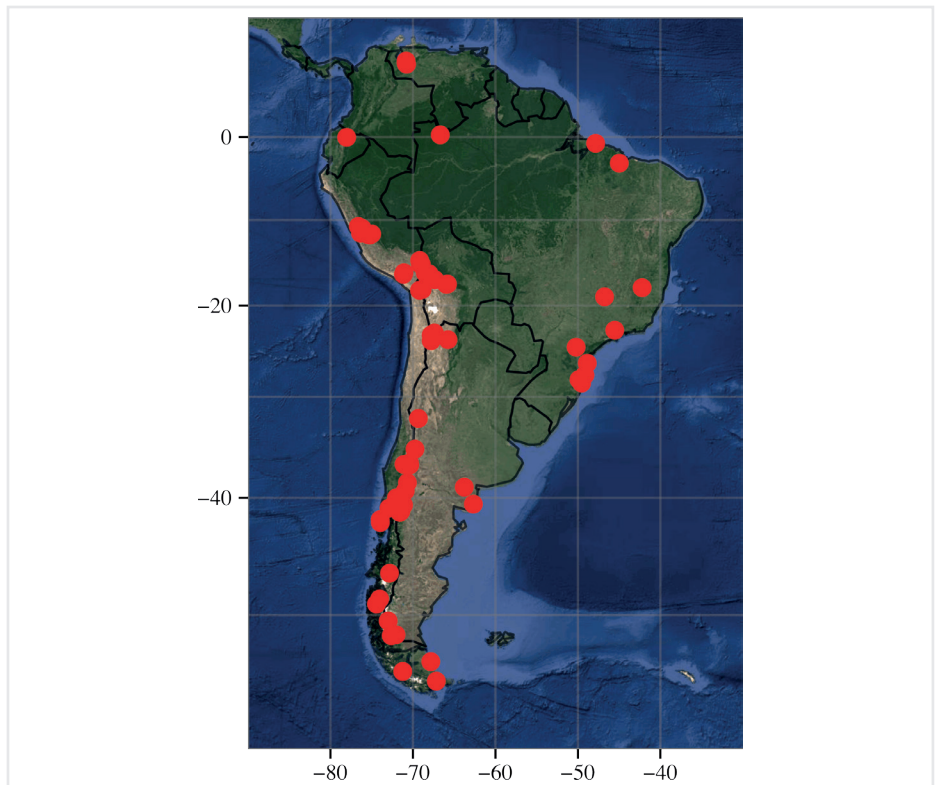
Creating a state-of-the-art database for paleoecological data is an expensive and time-consuming endeavor that requires long-term funding. Currently, no institution in South America is likely to have access to the necessary funding for such an effort. An existing open-access platform, however, now available through the Neotoma Paleoecological Database ([www.neotomadb.org](http://www.neotomadb.org)) offers an extremely valuable infrastructure that scientists can use throughout the developing world. The use of this common platform would maximize compatibility among the regions and the versatility of this global open access archive of paleoenvironmental data.

Forty-one scientists from seven South American countries gathered in Olmué (located north of Santiago in the foothills of La Campana National Park) for an intense two-day meeting on the policy and practices involved in creating a public-access database for South American paleoecologists. The workshop was followed by a three-day course for young scientists taught by Eric Grimm on how to access and use the Neotoma database, and on how to use the newest versions of the Tilia (pollen analysis; Grimm 1991) and Bacon (age modeling; Blaauw and Christen 2011) applications.

## Why Neotoma?

Neotoma is a large, multi-proxy database that includes datasets spanning back to the Pliocene. It is a client-server database housed at the Center for Environmental Informatics at Pennsylvania State University, USA, and is comprised of many virtual databases representing different data types and geographic regions. It arose from a partnership between IT domain scientists and developers in an attempt to answer large-scale questions about paleoenvironmental evolution including climate, fauna and flora.

Workshop participants included archeologists, paleoecologists, zooarcheologists, paleontologists, diatomists, and experts in other paleo fields, who addressed the following questions: (1) How to involve South American scientists in a ground-up effort to build and to contribute to a database? (2) Where can funding be sought to assemble legacy data? (3) Who owns the intellectual rights to the contributions made? (4) What data should be publicly available or restricted (e.g. locations of geographically sensitive sites such as unprotected archeological sites)? (5) Who could act as data stewards for the different South American data types (vertebrates, pollen, rodent middens, zooarcheofaunas, etc.)? (6) Should it be possible to upload unpublished datasets? (7) Should it be possible to upload data to Neotoma for ongoing research projects to take advantage of database analysis and visualization tools but



**Figure 1:** Current South American paleoecological sites in Neotoma. The vast majority of these are part of the constituent Latin American Pollen database. Future collaborations could add much needed faunal data as well as other databases (for figure source code see <http://pastebin.com/fgQSVTKb>; image credit: Simon Goring)

have it embargoed for public release until after publication?

Workshop attendees were divided into breakout groups for further discussion. While recognizing the importance of these large public-access databases, several key concerns need to be addressed, such as data propriety rights. In particular, when dataset authors should be invited to be co-authors on data-synthesis papers and how should the use of data be adequately cited, especially for previously unpublished data. A proposed solution would be to make datasets themselves citable, with for example, a DOI number. This solution could stimulate the publication of legacy data, probably one of the more cost-intensive efforts of creating such a database for South America.

Also, there is the attractive possibility of creating “embargoed” contributions, i.e. datasets uploaded to Neotoma but not publicly available for a determined amount of time. This would allow time to take advantage of the database’s infrastructure and ample time to publish an article before releasing data. Other important aspects discussed included how to create “fuzzy” coordinates for geographically sensitive sites, in which only the data contributors and relevant land management agencies

know the actual locations (e.g. to protect sites from looting).

Clearly much work lies ahead, but researchers were enthusiastic about the possibility of generating a public database which could address and generate new and exciting research questions, particularly those associated with broad-scale climate and land-use change that could contribute to published data and incorporate the vast quantity of legacy data generated in South America for over a century.

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# Eastern African Quaternary Climate change and variability

Christine A. Ogola

Nanyuki, Kenya, 23-27 July 2013

The fourth Eastern Africa Quaternary Research Association (EAQUA) Conference was held in Nanyuki near Mt. Kenya and was hosted by National Museums of Kenya. It was attended by 55 delegates from 14 countries and co-sponsored by the National Museums of Kenya (NMK), the International Union for Quaternary Research (INQUA), the Embassy of France (Nairobi), the French Institute for Research and Development (IRD) and PAGES.

Then Director General NMK, Idle Omar Farah and INQUA President Margaret Avery graciously attended the opening ceremony. Dr Farah, delighted to host the conference, stressed the commitment of NMK to capacity building of scientists and communities from areas with good natural archives of past environmental change. He also noted that EAQUA members' research dealt with relevant global issues such as climate change and adaptation, and encouraged the participants to make use of the immense paleoecological, geological and cultural records at NMK for their research. Finally, he briefly outlined how NMK was streamlining the processes for Quaternary research in Kenya. Dr Avery encouraged members to publish their conference research and papers to make EAQUA more visible.

The papers presented in sessions 1 and 2 themed "Habitat and paleoenvironmental reconstruction of pre-historic sites (paleobotany, isotopes, fauna and sedimentology)"

and "Highland biodiversity and ecosystems", explored the proxies used in paleoclimate and paleoenvironmental reconstructions of prehistoric sites and different depositional environments and how they help with understanding the environmental context of evolution and adaptation and the dispersal of humans (Fig. 1). Sessions 3 and 4 on "Late Pleistocene-Holocene climate and rainfall variability, and human environment interactions" and "Global change impacts, adaptations and vulnerability assessment" focused on patterns and evidence of global change, and its effects on ecosystems, human populations and adaptation. Session 5 on "The quaternary fossil and archeological record" explored various fossil and archeological records from early Pleistocene and Holocene contexts to historic ones. Session 6 on "Heritage resource governance and sustainable development" showcased selected heritage resources, their vulnerabilities, enhanced management and conservation statuses, and their use as instruments for improving local community livelihoods and sustainable development.

During general discussion, plans for two possible collaborative research areas in carnivore ecology and heritage resource development were shared and interested researchers invited to take part.

At the EAQUA business meeting held at the end of the conference new executive members

were elected and the following resolutions made:

- The EAQUA secretariat will work on various publicity and outreach programs to increase the membership base, including affiliation with similar research associations and reaching out to other eastern African countries not yet participating in EAQUA activities e.g. South Sudan, Rwanda, Burundi, Eritrea, Djibouti and Somalia with the aim of mobilizing more researchers and students from eastern Africa to join the association.
- Set up a mentoring and capacity building program designed to be a pre-conference activity involving training on research, technical and logistical planning, grant applications as well as preparation of conference presentations and publications.
- Funds will be sourced for an EAQUA research program to include field training of students and young researchers.
- The local organizing committee and EAQUA secretariat will coordinate the publication of the current conference proceedings in Quaternary International.
- Members were urged to participate in the upcoming INQUA early career researchers and Pan African Quaternary research association workshops.

The participants elected Asfawossen Asrat as president, Christine Ogola as vice president, Morgan Andama as secretary general, Jackline Nyiracyiza as treasurer, Elgidius Ichumbaki as newsletter editor, Stephen Rucina and Pastory Bushozi as national representatives for Kenya and Tanzania, respectively, Alfred Muzuka as ex-officio member, and Margaret Avery as INQUA representative, for the next two years.

## AFFILIATIONS

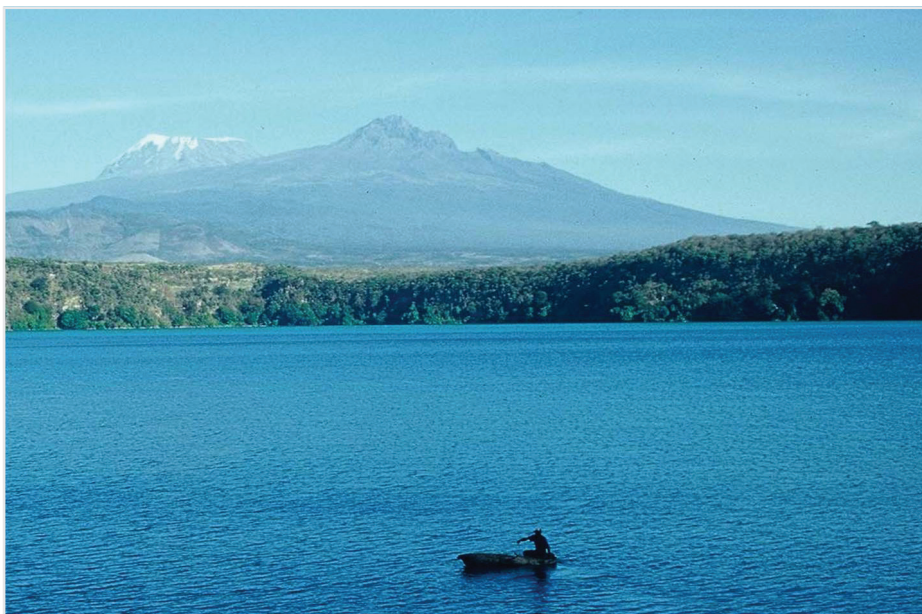
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**Figure 1:** Lake Chala southeast of Mt Kilimanjaro. Sediments from this lake are one of the longest archives of climate change in the region, reaching back at least 25,000 years (Moernaut et al. 2010).

# African climate-vegetation interaction since the last glacial period

Ilham Bouimetarhan<sup>1</sup>, L. Dupont<sup>1</sup>, C. Itambi<sup>2</sup> and J.-B.W. Stuut<sup>1,3</sup>

Bremen, Germany, 4-8 November 2012

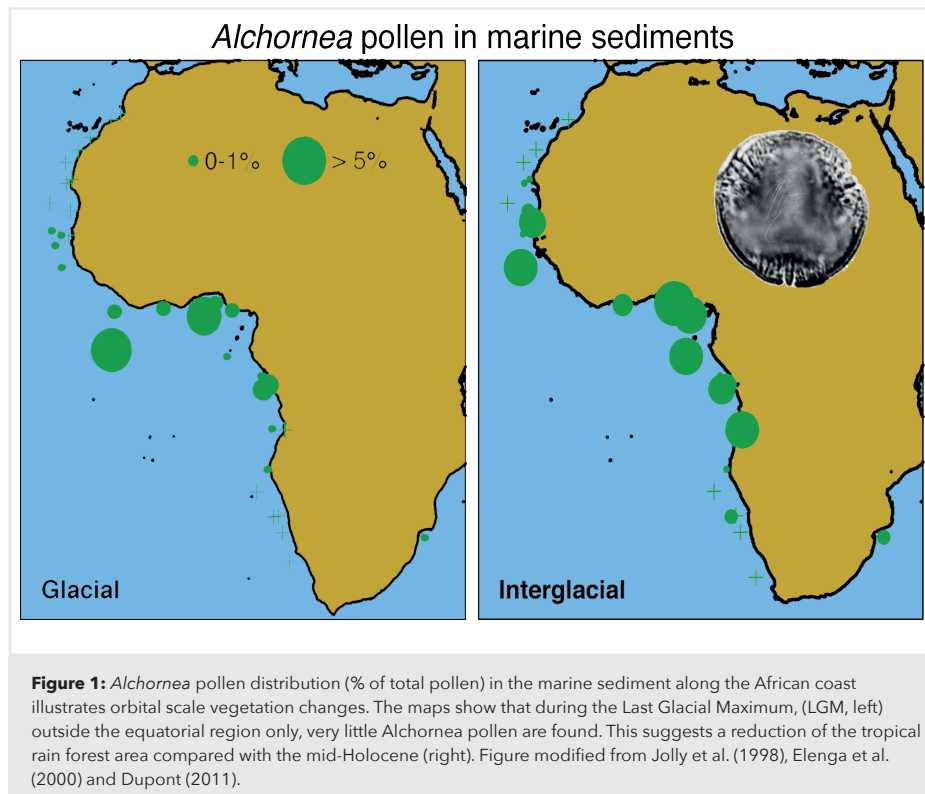
The global distribution and composition of vegetation is largely controlled by climate. Vegetation can however, exert an important influence on surface energy fluxes and the hydrological cycle through alteration of the surface albedo and biogeochemical processes, thus impacting climate locally. In Africa, where climate and vegetation data are sparse, our understanding of the interaction between vegetation and climate and its consequences for the formation and maintenance of terrestrial ecosystems is still poor. But this understanding is crucial to identify feedback effects on different spatial and temporal scales.

This four-day workshop focused on the study of dynamic interaction of climate and vegetation by combining a large set of African vegetation and hydrology records. These sedimentary records were recovered from marine and terrestrial sites in West, East and Southern Africa. Forty scientists from 13 countries participated in the workshop, 11 of them are based in Africa.

The workshop began with a two-day educational program for early-career scientists. Keynote lectures provided networking opportunities with international experts on African vegetation, meteorology, climate observations, and model simulations. The presentations addressed the topics climate-vegetation interactions, model simulations of past vegetation changes, and the understanding of modern climate processes. The early career scientists had the opportunity to visit the labs at MARUM, the IODP core repository center, and the Department of Geosciences, and were also familiarized with the various funding opportunities for collaborative research projects at German institutions.

The second part of the workshop consisted of five oral presentation sessions dealing with: 1) present-day vegetation, environmental degradation, meteorology and remote sensing; 2) past vegetation and its response to abrupt climate change in West Africa; 3) South African paleoenvironments; 4) hydroclimate and vegetation in East Africa; and 5) an open discussion on scientific challenges in Africa and futures activities.

A number of scientific questions emerging from the workshop reflected that African scientists are more involved in research on the actual consequences of ongoing climate change and their impact on local communities, rather than on more fundamental questions regarding climate mechanisms. For example, the consequences of present-day rising sea levels are of greater concern to communities than understanding sea-level changes in the past. There



are also concerns about the intensification of rainfall already leading to increased erosion of tropical soils, and potentially damaging infrastructure and drinking water facilities.

Several key research foci were agreed on in the plenary discussion on the last day of the workshop: a) comparison of terrestrial and marine records; b) addressing age model uncertainties; c) the driving forces of climate and vegetation change, including the Atlantic meridional overturning circulation, Indian Ocean sea surface temperatures, insolation, ITCZ/tropical rainbelt migration; d) East-West versus North-South gradients; e) timing and mechanism leading to the African Humid Period. Possibilities are presently being explored to collaborate on these research foci.

Proxy studies were also discussed, including how to improve vegetation reconstructions using pollen analysis with emphasis on provenance, transport pathways and modern analogs (e.g. Fig. 1). New proxy types should be thoroughly reviewed before application, especially stable hydrogen isotopes. But, stable carbon isotopes, a common proxy for the contribution of  $C_3$ - and  $C_4$ -plants, should also be reviewed because interpretations can vary locally depending on the impact of temperature or aridity on the vegetation.

The importance of involving people from the modeling community was also discussed, since patterns of past vegetation changes can be used to improve climate models and the accuracy of future predictions. Finally, the need for better communication between marine and terrestrial research communities, and between data and modeling communities was identified and discussed. It is acknowledged that the availability of climate information in Central Africa is sparse. This gap needs to be filled in order to obtain a more complete overview of African climate-vegetation interaction.

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# SynTraCE-21 Workshop

James M. Russell<sup>1</sup>, B. Otto-Bliesner<sup>2</sup> and Z. Liu<sup>3</sup>

Providence, USA, 4-7 November 2012

Recent years have seen rapid advances in the study of climate changes during the last 21-ka driven both by new proxy evidence and new modeling activities. On the proxy reconstruction side, new high resolution records based upon speleothems, marine, and lacustrine sediments have documented a highly variable evolution of regional climate, with considerable spatiotemporal variability that includes responses to freshwater forcing (e.g. the Younger Dryas and Heinrich 1 events), greenhouse gas and orbital forcing, and coupled vegetation-climate changes. On the modeling side, climate models and computer power have been enhanced significantly in recent years such that the transient climate evolution can now be simulated with state-of-the-art fully coupled general circulation models (e.g. Fig. 1). The flood of new proxies and model data requires community-wide activities to critically assess and synthesize proxy reconstructions, and evaluate these in light of the comprehensive, global framework afforded by climate model simulations.

PAGES and the US NSF sponsored a SynTraCE-21 (Synthesis and Transient Climate

Evolution of the last 21 ka) workshop to discuss and plan a synthesis of proxy climate records and model simulations of the major features of global climate of the last 21 ka. The workshop, attended by 43 participants from five countries used plenary sessions and breakout discussions to define critical hypotheses and questions in the three following areas.

## Tropical hydrology of the past 21 ka

Proxy data indicate that tropical precipitation exhibits complex spatio-temporal patterns during deglacial and Holocene times. These include north-south migration of the Intertropical Convergence Zone, as well as more poorly understood zonal reorganizations of the ocean-atmospheric circulation. Proxy records are now sufficiently dense to compare reconstructed patterns of deglacial precipitation changes in the tropics to transient model simulations. This allows the assessment of the response and sensitivity of zonal and meridional circulation in the tropics to deglacial climate forcings, including orbital forcing, radiative forcing from greenhouse gases, and glacial processes. Data-model comparison could also be used

to investigate the evolution of millennial-scale precipitation changes in the tropics.

## Deglacial ocean circulation change

Changes in ocean circulation are known to have played a critical role in the Earth's climatic and biogeochemical evolution during the last glacial termination. Marine sediment records also indicate important changes in deglacial ocean circulation in response to meltwater forcing. Despite these advances, many of the key mechanisms and circulation changes of the deglaciation are still poorly understood. Deglacial meltwater pulses, for instance, are known to have strong impacts on climate, but where do deglacial meltwater pulses go in the ocean, and how do they impact convection and circulation? Similarly, although changes in ocean circulation are known to have strong effects on global biogeochemical cycles, we know little about changes in the ocean's most biogeochemically active waters: the intermediate ocean. How did intermediate ocean circulation vary across the last glacial termination?

## Abrupt changes in the Holocene

Many regions experienced abrupt climate changes during the Holocene due to feedbacks between climate, land surfaces, and sea surface temperature variations. The collapse of the North African "Green Sahara" ecosystem due to interactions between the African monsoon, subtropical Atlantic sea surface temperatures, and North African vegetation is a prime example. Key questions to be addressed through data-model comparison activities include the dynamics of abrupt climate changes during the Holocene (rates of change, spatial synchronicity), the role of vegetation feedbacks in amplifying or even triggering abrupt climate change, and the ability of climate models to simulate abrupt climate change in the Holocene in the absence of abrupt forcing.

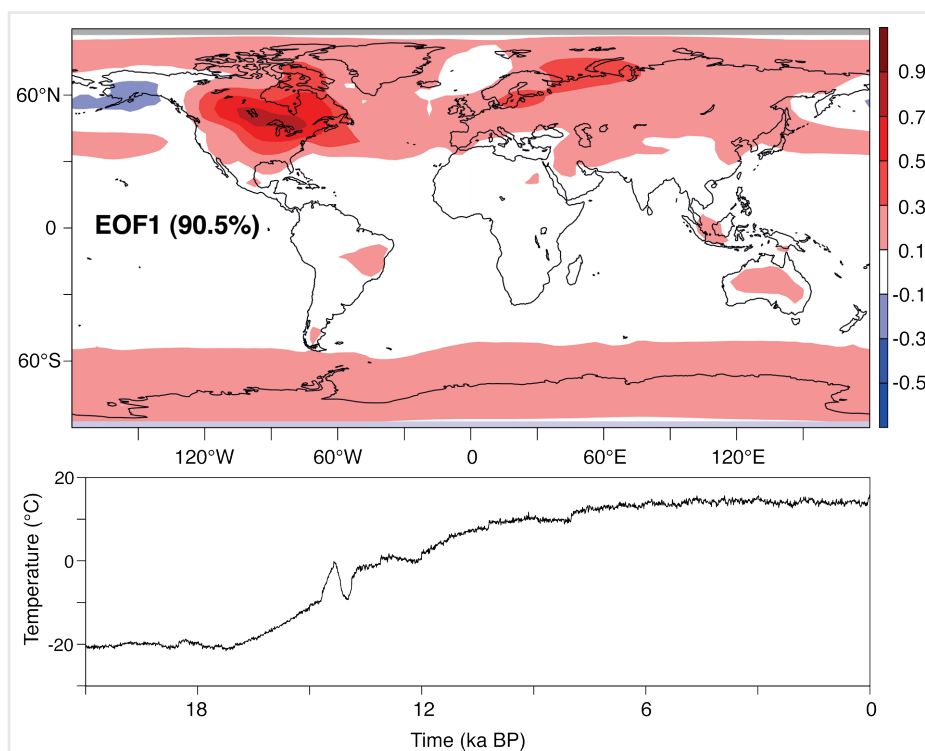
These questions will be addressed by the SynTraCE-21 working group through focused data-model activities in the coming year.

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**Figure 1:** The first empirical orthogonal function of global temperature change from 21 ka BP to the present, simulated by CCSM 3. Nearly the entire planet warmed, with warming focused over the high latitudes, and North America and Northern Europe in particular, with both gradual and abrupt temperature changes occurring during the past 21 ka BP.



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