VOLUME 24 · NO 1 · AUGUST 2016

PAST GLOBAL CHANGES

MAGAZINE

TIPPING POINTS

EDITORS

Chris S.M. Turney, Chris J. Fogwill, Tim M. Lenton, Richard T. Jones and Lucien von Gunten

News

PAGES 5th OSM and 3rd YSM

Preparations are well underway for PAGES' flagship event, the Open Science Meeting and associated Young Scientists Meeting, to be held in Zaragoza, Spain, in May 2017. The YSM runs from 7-9 May and the selection process is competitive. The OSM runs from 9-13 May. Following an open call, 33 sessions have been chosen.
Read more and register: http://pages-osm.org
The social media hashtag for both events will be #PAGES17.

New PAGES domain

Following the end of the International Geosphere-Biosphere Programme (IGBP) in December 2015, PAGES' new domain name is www.pastglobalchanges.org. We encourage everyone to resave old bookmarks.

New PAGES' working groups

Five new working groups have recently been launched:

- **Forest Dynamics** http://pastglobalchanges.org/ini/wg/forest-dynamics/intro
- **Climate Variability Across Scales (CVAS)** http://pastglobalchanges.org/ini/wg/cvas/intro
- **Global Paleofire 2 (GPWG2)** http://pastglobalchanges.org/ini/wg/gpwg2/intro
- **Paleoclimate Reanalyses, Data Assimilation and Proxy System modeling (DAPS)** http://pastglobalchanges.org/ini/wg/daps/intro
- **Resistance, Recovery and Resilience in Long-term Ecological Systems (EcoRe3)** http://pastglobalchanges.org/ini/wg/ecore3/intro

Read more about Forest Dynamics, CVAS and Global Paleofire 2 in their Program News articles in this issue, and read about all groups on our website. All PAGES' working groups are open for participation to interested scientists.

PAGES' SSC meeting 2016 and new SSC members

PAGES' Scientific Steering Committee (SSC) met in Cluj-Napoca, Romania, in May 2016. PAGES' two-day Central and Eastern Europe Paleoscience Symposium followed the SSC meeting.
At the end of 2016, co-chair Hubertus Fischer and Claudio Latorre finish their tenures, and we take this opportunity to thank them for their commitment throughout their two terms.
We welcome the two new incoming members starting January 2017:

- **Willy Tinner** - head of paleoecology at the University of Bern's Institute of Plant Sciences, Switzerland. His department addresses ecological and climatic questions on annual to millennial time scales and uses quaternary sedimentary sequences (e.g. pollen, macrofossils, charcoal, diatoms, chironomids) and modeling approaches to study the long-term interactions among climate, the biosphere and society. Tinner will also be PAGES' co-chair.
- **Ed Brook** - geology program director at the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University, USA. He specializes in paleoclimatology and geochemistry plus ice-core trace gas records, cosmogenic isotopes and extraterrestrial dust.

PAGES at AGU 2016

PAGES' working groups have organized sessions at the AGU Fall meeting in San Francisco this December. For a full list, go to the calendar entry: http://pastglobalchanges.org/calendar/upcoming/127-pages/1458-agu-fall-meeting-2016

Apply for meeting support or suggest a new working group

Each year, PAGES supports many workshops around the world. We also have an open call for new working groups. The next deadline is 10 October 2016. Read more about workshop support and working group proposals here: www.pastglobalchanges.org/my-pages/introduction

Help us keep PAGES' People Database up to date

Have you changed institutions or are you about to move? Please check if your details are current. http://pastglobalchanges.org/people/people-database/edit-your-profile

Upcoming issues of PAGES Magazine

The next issue of PAGES Magazine will be on climate change and cultural evolution. Contact Claudio Latorre (clatorr@bio.puc.cl) now if you wish to contribute to this issue.

The following issue will be on biodiversity and guest edited by our SSC members Lindsey Gillson (lindsey.gillson@uct.ac.za) and Peter Gell (p.gell@federation.edu.au). Contact them or the PAGES office if you are interested in contributing.

In general, if you wish to lead a special section of the magazine on a particular topic, contact the PAGES office or speak with one of our SSC members. http://pastglobalchanges.org/about/structure/scientific-steering-committee

Calendar

2nd QUIGS workshop
18-20 October 2016 - Montreal, Canada

Past land-cover change in Latin America
29-30 October 2016 - Salvador de Bahia, Brazil

1st CVAS workshop
28-20 November 2016 - Hamburg, Germany

Fire and land-cover changes in Europe
5-8 December 2016 - Frankfurt, Germany

PAGES 5th OSM and 3rd YSM
7-13 May 2017 - Zaragoza, Spain

2nd VICS workshop
8 May 2017 - Zaragoza, Spain

www.pastglobalchanges.org/calendar

Featured products

PIGS

The final product from the former working group PIGS (now morphed into QUIGS), "Interglacials of the last 800,000 years" is a mammoth undertaking (2016, *Rev Geophys* 54).

2k Network

- Charpentier Ljungqvist et al. discuss how rainfall patterns have changed during the 20th century compared with the last twelve centuries (2016, *Nature* 532).
- McKay and Emile-Geay set out their plans for a Linked Paleo Data (LiPD) framework (2016, *Clim Past* 12).
- Huge media interest surrounded the Euro-Med2k consortium paper on European summer temperatures (2016, *Env Res Lett* 11).
- Recent temperatures experienced in Australia and New Zealand are warmer than any other 30-year period over the past 1,000 years (Gergis et al. 2016, *J Climate* 29).

PALSEA2

- Editorial by Stockholm Resilience Centre Director Johan Rockström highlights the quality of work done by the PALSEA working group, and PAGES in general. He also discusses the importance of our parent organization Future Earth and summarizes the legacy of the IGBP (2016, *Science* 351).
- Assessing the impact of fossil corals on studying past sea-level change (Hibbert et al. 2016, *Quat Sci Rev* 145).

Special Issues from PAGES-supported meetings

- "Mediterranean Holocene Climate, Environment and Human Societies" from a meeting in Greece in 2014 (2016, *Quat Sci Rev* 136).
- "Understanding Change in the Ecological Character of Internationally Important Wetlands" is the outcome of a 2013 meeting in Australia (2016, *Mar Freshwater Res* 67).

Cover

Where the Greenland Ice Sheet meets the North Atlantic

Icebergs in high summer in Sermilik Fjord, one of the largest fjords in southeast Greenland. Helheim Glacier, which drains into the fjord, has seen some of the highest acceleration of ice velocity recorded across the Greenland Ice Sheet over the past decade (credit C.J. Fogwill).

Tipping Points: Lessons from the Past for the Future

Chris S.M. Turney[1], C.J. Fogwill[1], T.M. Lenton[2] and R.T. Jones[2]

Many natural and human systems are vulnerable to long-term forcing that can push them into a different mode of operation. The “tipping points” where such abrupt changes occur are notoriously hard to predict. Looking ahead, a key problem for reducing the uncertainty in future projections is that historical records of change are too short to test the skill of the current generation of climate and environmental models, raising concerns over our ability to successfully predict abrupt change and plan for it. Published records only allow a robust reconstruction of global temperature back to 1880 and show a long-term increase of 0.85°C. At regional scales, there have been some abrupt changes within the instrumental record. Looking further back in time, a wealth of geological, chemical and biological records capture large-scale, abrupt and often irreversible (centennial to millennial in duration) shifts in environmental and climate systems, providing an opportunity to better understand and therefore predict potential future changes.

The forcing associated with these changes in the past appears to have been relatively small, implying the existence of underlying tipping points where self-propelling change – i.e. strong, positive feedback – is triggered within the systems in question. Many regions of the world are now recognized as potentially highly-sensitive to abrupt changes caused by the passing of tipping points within different components of the climate system (Fig. 1). Some are of global significance, such as the collapse of the West Antarctic and Greenland ice sheets (leading to a sea level rise of several meters) or reorganization of the Atlantic Meridional Overturning Circulation (AMOC), and corresponding southward shift in the inter-tropical convergence zone of rainfall. Others are of more regional importance, such as the greening of the Sahara.

Innovative analyses of high-resolution records of past change suggest the climate system characteristically slowed down when a tipping point was approached. This raises the prospect that science may be able to provide society with early warning of future approaching tipping points. However, to do this successfully for inherently “slow” components of the Earth system, such as the AMOC and ice sheets, will require high-resolution paleo reconstructions of the variability of these systems in the run-up to the industrial era – providing a new motivation for PAGES' research. In addition, accurate reconstructions of the past behavior of climatic, environmental and archeological systems on quantified, absolute-dated and robust timescales provide the opportunity to better understand the underlying mechanisms and test models of future change.

This *Past Global Changes Magazine* describes developments in modeling past tipping points and human systems to better understand future change. Reflecting the nature of tipping points within the Earth system, the articles presented reflect a range of truly multidisciplinary research, which crosses traditional time periods or horizons. We hope the selected articles provide valuable insights into the role that tipping points play in understanding past change, and, importantly, highlight the potential of tipping points to provide lessons from the past that will help define the future.

AFFILIATIONS
[1]Climate Change Research Centre, University of New South Wales, Australia
[2]Department of Geography, University of Exeter, UK

CONTACT
Chris Turney: c.turney@unsw.edu.au

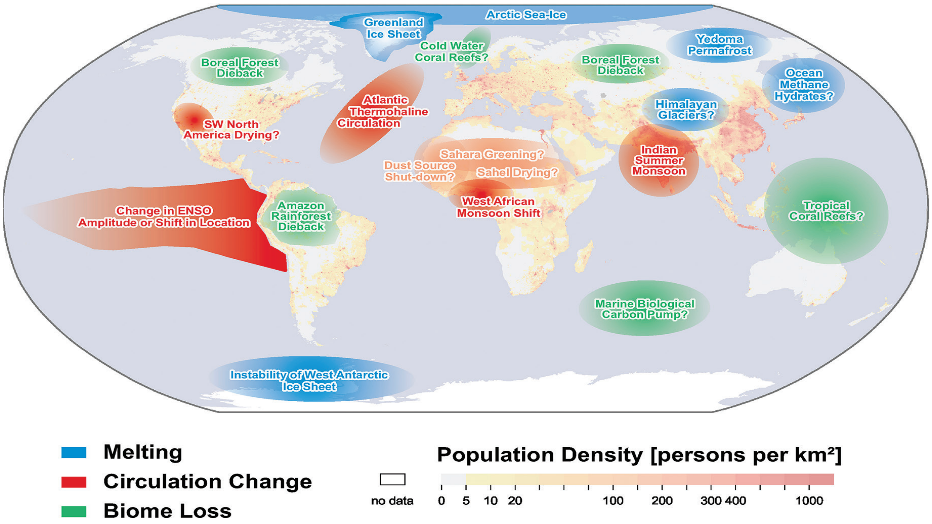

Figure 1: Map of potential policy-relevant tipping elements in the climate system overlain on global population density. Question marks indicate systems whose status as policy-relevant tipping elements is particularly uncertain. Figure by Veronika Huber, Martin Wodinski, Timothy M. Lenton and Hans Joachim Schellnhuber.

Tipping points in the past: the role of stochastic noise

Zoë A. Thomas[1] and Richard T. Jones[2]

The analysis of paleo-environmental archives provides a mechanism for identifying systems vulnerable to abrupt change or "tipping points". Perturbations to natural systems, so-called "stochastic noise", can play a significant role in understanding past and future variability.

Abrupt changes or "tipping points" in environmental systems are often characterized by a nonlinear response to gradual forcing, and may have severe and wide-ranging impacts, including an irreversible shift to a new state (on human timescales). Arguably one of the best ways to identify and potentially predict threshold behavior in environmental systems is through the analysis of natural archives (paleo records). Generic rules can be used to identify early warning signals that may be identified on the approach to a tipping point, generated from characteristic fluctuations in a time series as a system loses stability.

Recently developed methods to detect these early warning signals exploit a phenomenon called "critical slowing down". This phenomenon predicts that as a system nears a tipping point, the recovery time to its initial equilibrium after a perturbation should increase. This increase in recovery time can be measured as increasing autocorrelation and variance over a sliding window (Kleinen et al. 2003; Lenton et al. 2012). With the popularity of the free statistical software "R", this analysis is becoming increasingly applied by the paleo community to understand mechanisms of change (for instance, Early-Warning-Signals Toolbox at http://cran.r-project.org/web/packages/earlywarnings/earlywarnings.pdf). Time-series precursors from natural archives thus have a great potential to enhance our understanding of past abrupt change and provide a means of forewarning potential tipping points. Critical in this regard is recognizing that different rates of forcing significantly influence the temporal resolution required to identify such forewarnings in paleo-environmental time series.

Linking theory to the past

While previous studies have demonstrated the value of natural archives for identifying tipping points (e.g. Dakos et al. 2008), considerable scope exists to expand this work. A major challenge is that paleoenvironmental data typically have high noise levels and a low sampling resolution, whereas theoretical early warning indicators assume only weak stochastic disturbances. When systems are characterized by high levels of stochastic noise, early warning signals may not always detect the approach to a bifurcation (defined as the point at which a system exits its stable equilibrium), since high levels of noise can mask the signal of critical slowing down.

Although the efficacy of the leading indicators (autocorrelation and variance) has been interrogated using a long time series with low noise levels (Dakos et al. 2012), the predictive ability of these indicators with strong noise and a low sampling resolution has been less well studied. Ecological literature, however, has led the way in this regard. The importance of environmental variability in the modeling of ecological systems was first emphasized by Holling (1973), who noted that stochastic noise reduced the resilience of a system. Similarly, analysis of the leading early warning indicators using a multi-species model (Carpenter and Brock 2004) found that both increased noise intensity and decreased sampling rate were found to have a strong negative effect on the ability to detect early warning signals of an impending shift (Perretti and Munch 2012).

Simple bifurcation models can be used to illustrate the role of stochastic noise. It is important to note that the bifurcation point (where intrinsic stability properties of a system changes) and the point at which the system actually tips are not always the same; high noise levels often tip the system before the bifurcation point is reached (Kleinen et al. 2003). Figure 1 depicts the effect of noise on the timing of the abrupt change, showing that (1) the point of tipping varies much more with a higher noise level, and (2) the point of tipping generally occurs much earlier. Early warning signals tend to be much stronger with reduced noise intensity, when the system tends to tip closer to the bifurcation point. When the noise level is too high, the system may not have time to recover from the perturbations and thus the signals of critical slowing down may not be detected.

Critical slowing down or flickering?

When multiple stable states exist and if stochastic forcing is strong enough,

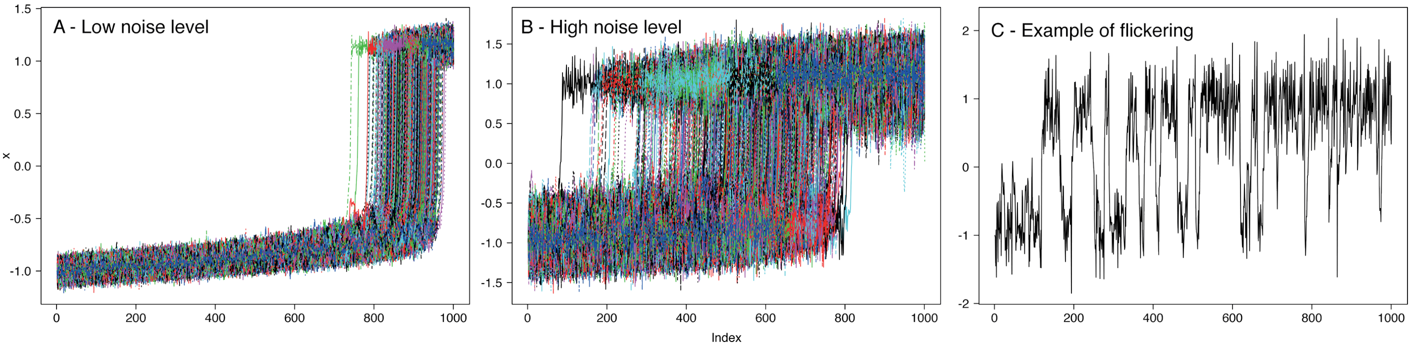

Figure 1: Typical behavior of systems with **(A)** low and **(B)** high noise levels, and **(C)** an example of flickering.

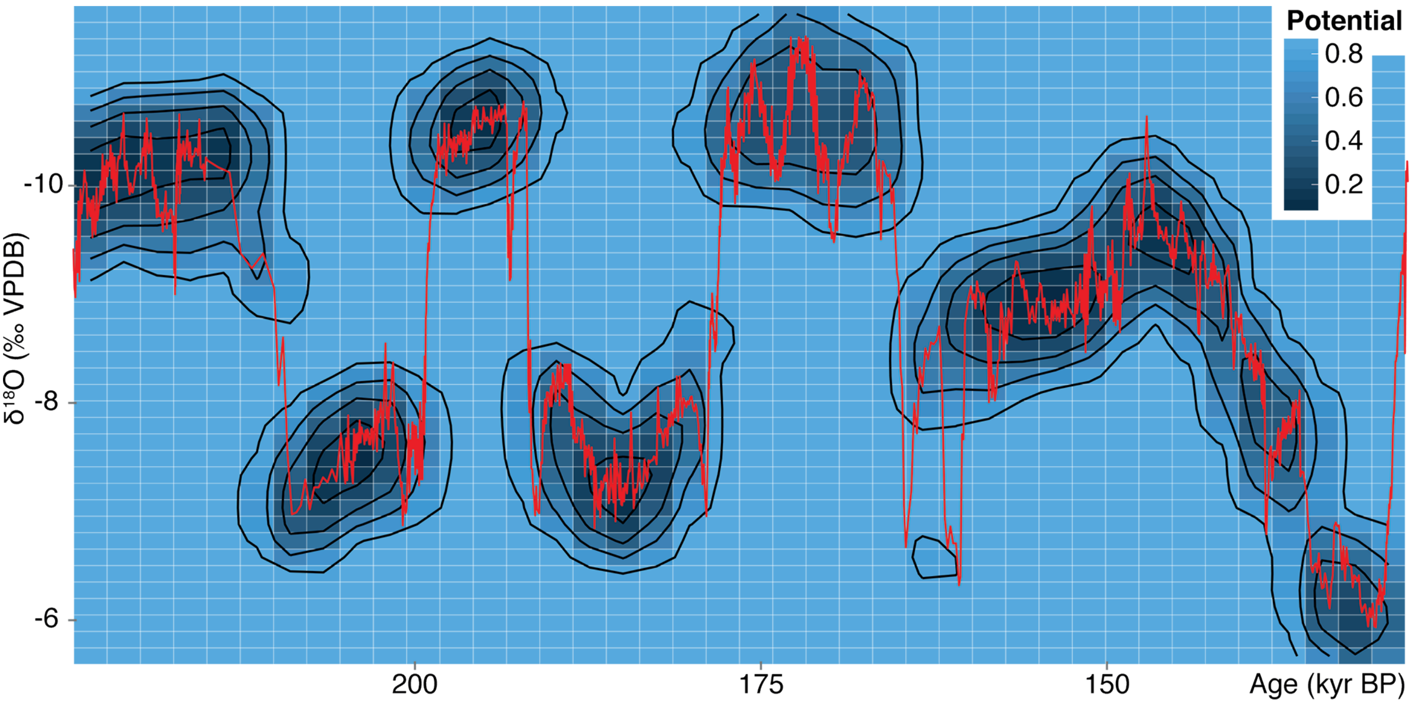

Figure 2: Visualization of the potential function derived from the speleothem δ^{18}O data (overplotted in red; x-axis inverted), showing the presence of multiple stable states (Wang et al. 2008; Thomas et al. 2015). The potential function gives an intuitive picture of the stability of the system, where darker blue indicates a deeper, more stable potential, and the lighter blue areas an unstable region of the potential basin.

the system can "flicker" back and forth between two basins of attraction as the system reaches this bistable region before the bifurcation (Scheffer et al. 2009; e.g. Fig. 1c). This can be seen in the behavior of lakes prior to a switch from oligotrophic to eutrophic conditions, observed as short-term eutrophication events and algal blooms before a more long-term switch (e.g. Wang et al. 2012). Importantly, many studies which give empirical evidence of critical slowing down do so under a small amplitude of noise, which allows the system to display critical slowing down rather than flickering (Dakos et al. 2013), but is generally unrealistic in paleoenvironmental systems. Since "flickering" seems to occur when there is a high noise level, this behavior is probably more prevalent in climate systems than first thought.

An appreciation of the number of states within the system can be beneficial to understand the underlying dynamics of a system. For some time series, this can be visually obvious or is pre-determined by a theoretical model, such as Stommel's two box model of the thermohaline circulation (Stommel 1961). The exact number of states in a system is sometimes difficult to determine by eye, however, particularly when there are more than two states present. Potential analysis is a technique that can be used to determine the number of states in a system over time, by reconstructing the changing state-space of a system through the modality of the data distribution (Livina et al. 2010). In systems with a relatively high level of noise, if there are multiple stable states present, the system is likely to sample these states over time and this represents a kind of flickering in the system (Dakos et al. 2012).

Multiple stable states: A case study

The techniques described above have been used in the analysis of speleothem sequences from China to gain an understanding of the mechanisms of abrupt changes in the Asian monsoon system (Thomas et al. 2015). Figure 2 shows the δ^{18}O values from a speleothem from Sanbao Cave in China (Wang et al. 2008), spanning the penultimate glacial cycle. More negative δ^{18}O values indicate higher rainfall amount (strong monsoon), while less negative δ^{18}O values indicate lower rainfall amount (weak monsoon), over millennial timescales. Potential analysis undertaken on this data shows that the system jumps between different stable states (indicated by the darker blue areas in Fig. 2), from a strong monsoon state to a weak monsoon state and vice versa. This is particularly prominent during the older half of the record.

Conclusion

The recognition of multiple stable states in natural archives provides a powerful means of understanding Earth system dynamics. The ability to identify periods in the past where thresholds have been crossed is critical if we are to predict and avoid dangerous abrupt climate change in the future.

ACKNOWLEDGEMENTS
This work is supported by the Australian Research Council Laureate Fellowship (FL100100195). Thanks to Chris Turney and Tim Lenton for help editing this paper.

AFFILIATIONS
[1]Climate Change Research Centre, University of New South Wales, Sydney, Australia
[2]Department of Geography, University of Exeter, UK

CONTACT
Name: z.thomas@unsw.edu.au

REFERENCES

Carpenter SR, Brock WA (2004) Ecol Soc 9: 8-38
Dakos V et al. (2008) PNAS 105: 14308-14312
Dakos V et al. (2012) PLoS One 7, doi:10.1371/journal.pone.0041010
Dakos V et al. (2013) Theor Ecol 6: 309-317
Holling CS (1973) Annu Rev Ecol Syst 4: 1-23
Kleinen T et al. (2003) Ocean Dyn 53: 53-63
Lenton TM et al. (2012) Phil Trans Roy Soc Math Phys Eng Sci 370: 1185-1204
Livina VN et al. (2010) Clim Past 6: 77-82
Perretti CT, Munch SB (2012) Ecol Appl 22: 1772-1779
Scheffer M et al. (2009) Nature 461: 53-59
Stommel H (1961) Tellus 13: 224-230
Thomas ZA et al. (2015) Clim Past 11: 1621-1633
Wang R et al. (2012) Nature 492: 419-422
Wang Y. et al. (2008) Nature 451: 18-21

Tipping ice ages

Michel Crucifix

Simple models formulated in the 1960s started a research tradition focused on stability and transitions in the climate system. Later, climate scientists realized the importance of stochasticity. What do these concepts imply for ice ages today?

In 1969, M.I. Budyko in Russia and W.D. Sellers in the US published two very similar studies. From reasoning about the energy balance of the Earth's system, they found that comparatively small variations of atmosphere transparency (Budyko) or in solar constant (Sellers) would be enough to drive the Earth into an ice age. Their key discovery was that Earth's climate could exhibit two steady states. Earlier that decade, Stommel (1961) deduced the existence of irreversible transitions between two thermohaline circulation structures in a simple model of abyssal water flow. Now we also think that vegetation-atmosphere coupling can lead to multiple states (Brovkin 1998).

The existence of multiple steady states leads naturally to the concept of “tipping”. Within a state, a system is largely self-stabilizing, but too large a perturbation may shift it into another self-stabilizing state, with little probability of escaping back to the original state. The ideas behind the models of Budyko, Sellers and Stommel provided a basis to interpret a range of paleoclimate events, including glacial inception, Heinrich events, and the end of African Humid Period.

What about the deglaciation? In a quite mathematical but pioneering article, Saltzman and Verbitzky (1993) pointed out that two possible destabilization mechanisms could be at play: the mechanical collapse of Northern Hemisphere ice sheets and the abrupt release of CO_2 accumulated in the deep ocean to the atmosphere. These two processes are still considered relevant today (Abe-Ouchi et al. 2013; Paillard and Parrenin 2004)

Tipping to ping pong

Is the deglaciation, however, really the consequence of passing a “tipping point”? Or, to paraphrase Crowley (2002), are we looking obsessively for "tipping, tipping everywhere"?

Models such as Stommel’s feature a specific mathematical property, known in the specialized literature as a "fold bifurcation". It is a common feature of non-linear systems that fits well with the idea that a slow change in environmental conditions can induce a rapid and irreversible transition towards a new state once a "threshold" is crossed (Fig. 1A). However, this is only one of a very rich set of possibilities. For example, in the Paillard-Parrenin model (2004), a glacial maximum is inherently unstable, and CO_2 outgassing ejects the system toward an interglacial. A background glaciation process then brings the system back to a glacial state, from where it is ejected again. In this model, the glacial-interglacial process no longer requires an externally forced tipping: it is the manifestation of a self-sustained oscillation, also known as a limit cycle. Instead of tipping, this (Fig. 1B) is ping pong!

Accounting for Randomness

Fold bifurcations and limit cycles are examples of concepts defined by a branch of mathematics called "dynamical systems theory". Since the 1960s, this discipline has provided climate scientists with an inexhaustible framework for depicting, characterizing and hypothesizing about possible system transitions and cycles. Ghil (1976) wrote one of the pioneering papers on the subject. More recently, Crucifix (2013), and Aswhin and Ditlevsen (2015) have analyzed models akin to those shown in Figure 1 in the context of ice ages.

Such models represent a very small class of possibilities. In particular, they are "deterministic": the trajectory is entirely determined by original conditions and forcing. Since the seventies, however, climate scientists have realized that this framework needs to be extended. The problem is that spectral analysis shows that the climate system varies on all timescales (Fig. 2), yet deterministic models always neglect a part of this spectrum. So we need, somehow, to account for the unresolved fluctuations to realistically represent dynamical effects.

This is where stochastic theory can help. A stochastic quantity is a mathematical concept used to represent a variable which is not known precisely, but which can be described in terms of probability distributions. The idea is to account for atmospheric variability with a stochastic process taking different random values with time (Hasselman 1976; Saltzman 1981).

This leads to an interesting mathematical problem: what happens to tipping points

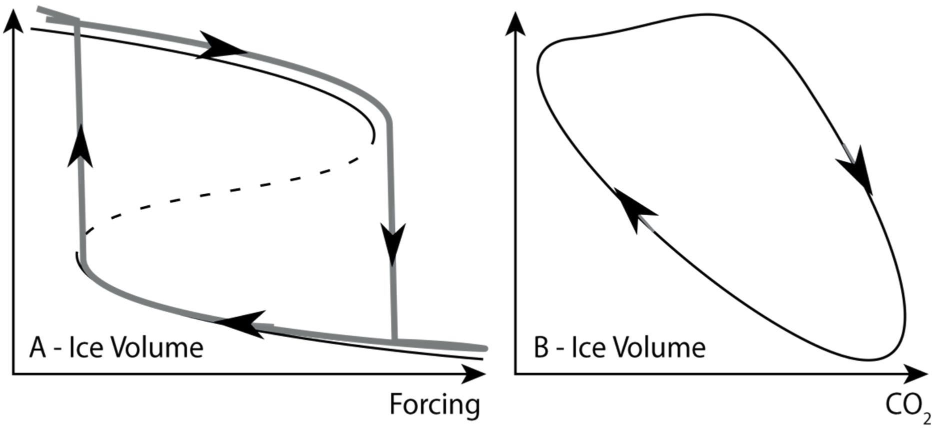

Figure 1: Two examples of conceptual models for paleoclimate dynamics. **(A)** The Budyko-Sellers model envisions two stable states for a range of forcing. Large forcing deviations from the resting state may precipitate a transition; **(B)** In a limit cycle, glacial interglacial stages succeed each other as a result of internal dynamics, without the need for forcing. In this case, insolation forcing is but a pacemaker that controls the timing of transitions.

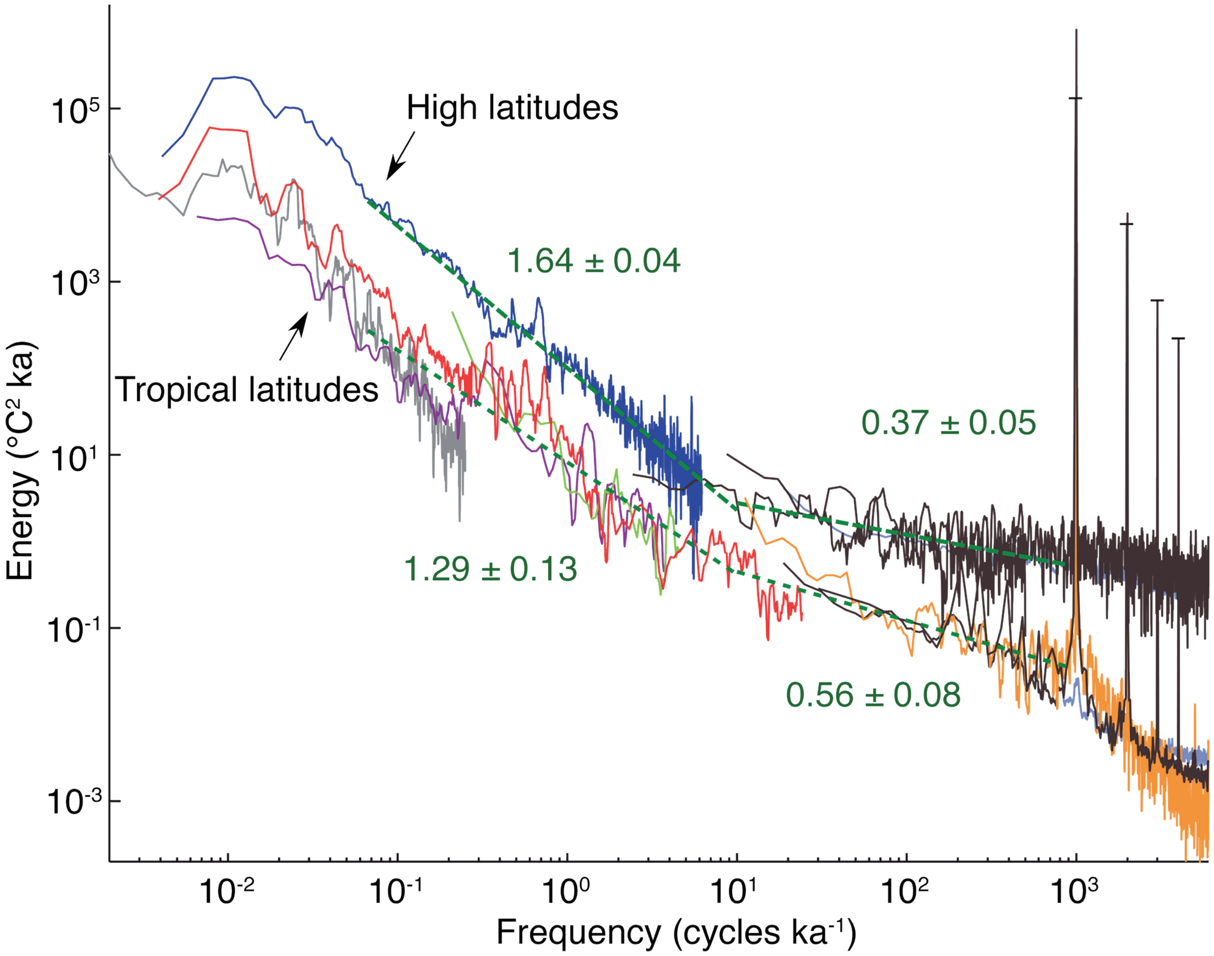

Figure 2: Estimate of the energy spectrum from annual to astronomical scales, adapted from (Huybers and Curry 2006). Numbers in green are spectral slopes on the logarithmic plot. All time scales may potentially interact: there is no gap between astronomical and centennial time scales.

when stochastic terms are included? With small amounts of stochasticity, the system may exhibit "early warning signals" before a transition: a valuable property, indeed, if we want to predict the occurrence of a large transition. In some cases, however, the presence of stochastic components modifies the structure of the deterministic model so drastically that the tipping point completely vanishes. In this case, systems like the one depicted in Figure 1 lose their relevance. We do not know whether this scenario applies to ice ages, but in some models even small amounts of stochasticity can substantially modify the timing of ice ages (Ditlevsen 2009; Crucifix 2012).

Some will say that Nature isn't "chaotic", "deterministic", or "stochastic". These properties only apply to models. What mathematics has to offer us is the ability to characterize the model which, among alternatives, best explains the data at hand about the real world. If this best model presents tipping points, then we can take decisions accordingly.

Identifying a “best” model among alternatives is a problem that can be framed statistically. In general, statistics work best with models that do not include too many parameters. A simple model is also easier to analyze and characterize. This is why there is still a research tradition focused on conceptual models similar to those of Figure 1.

However, our knowledge of environmental systems relies also on complex numerical models, which allow us to infer emergent constraints on the basis of physical laws of ice, atmospheric and oceanic motion, and such models tend to include hundreds of parameters. A key challenge for climate scientists is thus to articulate models of different levels of complexity within a consistent framework, from the conceptual models to the complex numerical codes.

A challenge for the decade

Stochastic theory may again provide a way forward. Stochastic parameterizations of interannual and interdecadal variability could be developed on the basis of experiments with general circulation models. Such parameterizations could then be included in models of intermediate complexity (EMICs) to estimate the effects of interdecadal variability on the slower modes of motion. This would provide a means to model the cascade of variability effects, from interannual to ice-age time scales: a revolution with respect to modern practices. Whether such stochastic EMICs will still present tipping points similar to those depicted on Figure 1 is an important question waiting to be answered.

AFFILIATION
Earth and Life Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium

CONTACT
Michel Crucifix: michel.crucifix@uclouvain.be

REFERENCES

Abe-Ouchi A et al. (2013) Nature 500: 190-193
Ashwin P, Ditlevsen P (2015) Clim Dyn 45: 2683-2695
Budyko MI (1969) Tellus 21: 611-619
Brovkin V et al. (1998) J Geophys Res 103: 31613-31624
Crowley TJ (2002) Science 295: 1473-1474
Crucifix M (2012) Phil Trans R Soc A 370: 1140-1165
Crucifix M (2013) Clim Past 9: 2253-2267
Ditlevsen PD (2009) Paleoceanography 24, doi:10.1029/2008PA001673
Ghil M (1976) J Atmos Sci 33: 3-20
Hasselmann K (1976) Tellus 28: 473-485
Huybers P, Curry W (2006) Nature 441: 329-332
Paillard D, Parrenin F (2004) Earth Planet Sci Lett 227: 263-271
Saltzman B et al. (1981) J Atmos Sci 38: 494-503
Sellers WD (1969) J Appl Meteo 8: 392-400
Saltzman B, Verbitsky MY (1993) Clim Dyn 9: 1-15

The East Antarctic Ice Sheet as a source of sea-level rise: A major tipping element in the climate system?

Christopher J. Fogwill[1], N.R. Golledge[2,3], H. Millman[1] and C.S.M. Turney[1]

Sea-level reconstructions suggest significant contributions from the East Antarctic Ice Sheet may be required to reconcile high interglacial sea levels. Understanding the mechanism(s) that drove this loss is critical to projecting our future commitment to sea-level rise.

The stability of the Antarctic ice sheets and their potential contribution to sea level under projected future warming remain highly uncertain. In part, this uncertainty arises from comparison with past interglacial periods when, despite only small apparent increases in mean atmospheric and ocean temperatures, eustatic sea levels are interpreted to have been 5-20 meters higher than present (e.g. Dutton et al. 2015). To achieve these highstands, undefined mechanisms or feedbacks that substantially increased the net contribution of the Earth's ice sheets to global sea level must have been at work. Understanding the feedbacks and tipping points that drove sea-level rise during past interglacial periods are therefore not only key to improving sea-level projections over the next century, but critically, given that ice-sheet response times are far longer than those of the atmosphere or ocean, they are important for quantifying our commitment to ice loss and sea-level rise over millennia.

Last Interglacial sea levels

The Last Interglacial (LIG; 135,000-116,000 years ago) is a key period in this regard; described as a "super-interglacial", empirical evidence suggests that the LIG was only around 2°C warmer than pre-industrial times, whilst sea levels were far higher (Turney and Jones 2010). Critically, the LIG was associated with an early rate of global sea-level rise that exceeded 5.6 meters per kyr, culminating in global sea levels 6.6-9.4 meters above present (Kopp et al. 2009). At present, the LIG eustatic sea-level-rise budget remains unresolved. Recent reassessments of potential contributions, including ocean thermal expansion (McKay et al. 2011) and wasting of the Greenland and West Antarctic ice sheets, leaves some 0.8 to 3.5 meters of global mean sea level (GMSL) unaccounted for during the LIG. To date, research and media attention has largely focused on the West Antarctic Ice Sheet (WAIS), however the question over the possible contribution made by the far larger East Antarctic Ice Sheet (EAIS) has been raised by both recent contemporary observations (e.g. Greenbaum et al. 2015) and ice-sheet model simulations (e.g. Golledge et al. 2015; Deconto and Pollard. 2016). This raises an important question: might hitherto unidentified mechanisms or feedbacks have induced accelerated mass loss from marine-based sectors of the EAIS?

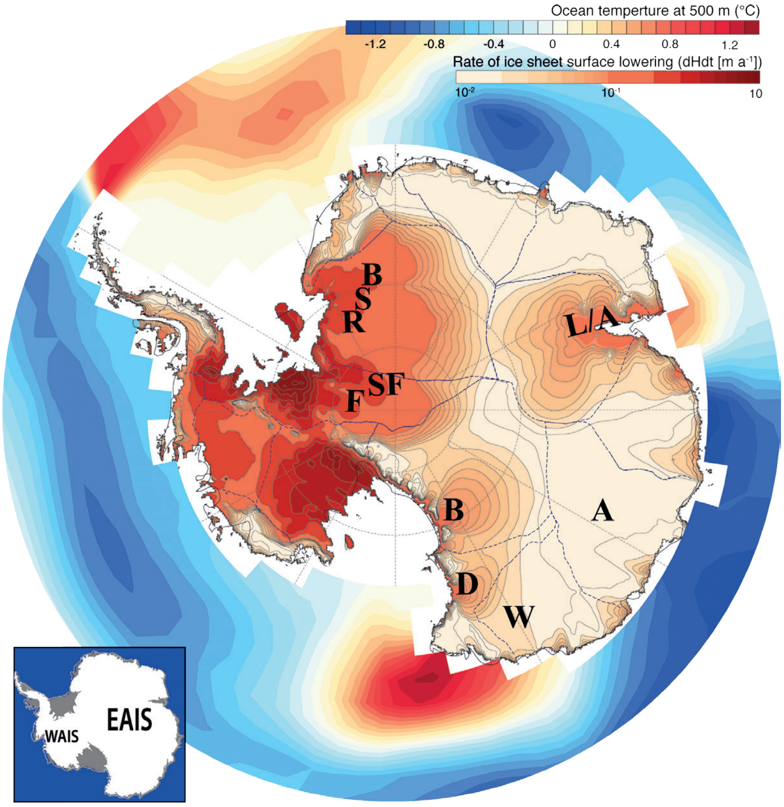

Figure 1: Southern Ocean temperature anomalies at 500 m depth under 135 ka BP boundary conditions with the Southern Hemisphere Westerlies shifted south (for a Southwards shift Southern Hemisphere westerly winds minus control simulation), together with the pattern of ice-sheet thinning from an independent glacial-interglacial ocean-forcing model experiment using the Parallel Ice Sheet Model (PISM) at 5 km resolution. The major EAIS drainage basins are marked F: the Foundation, SF: Support Force, R: Recovery, S: Slessor, B: Bailey basins, L/A: the Ambert/Amery basin, B: the Byrd, D: David, W: Wilkes, and A: Aurora. Inset Map of the Antarctic Continent showing WAIS and EAIS. Adapted from Fogwill et al. (2014).

Ice-sheet model simulations

Global and regional model-based ocean-atmosphere simulations for both future and paleoclimate scenarios are the most powerful tools currently available for establishing both the spatial pattern and variability of environmental perturbations through time, as well as the likely magnitudes of change. This is especially true when such models are empirically constrained, for example, by the verification of model outputs against geological proxy data.

However, to establish likely sea-level changes that may take place under warmer-than-present conditions (either during past interglacials or in the future), it is necessary to employ numerical models capable of accurately simulating the major ice sheets. Together, the Greenland and Antarctic ice sheets act as reservoirs, whose combined freshwater storage capacity must account for the majority of interglacial sea-level variability. The two main ice sheets of Antarctica, the West and the East Antarctic ice sheets contain ~3.9 and ~51.6 m sea-level-equivalent ice volume respectively, thus even relatively small changes in their extents and thicknesses may lead to global sea-level changes of several meters. In Antarctic terms, changes in ice-sheet extent over paleoclimate timescales are primarily controlled by oceanic conditions (Joughin et al. 2012), but in both paleo and future ice-sheet model

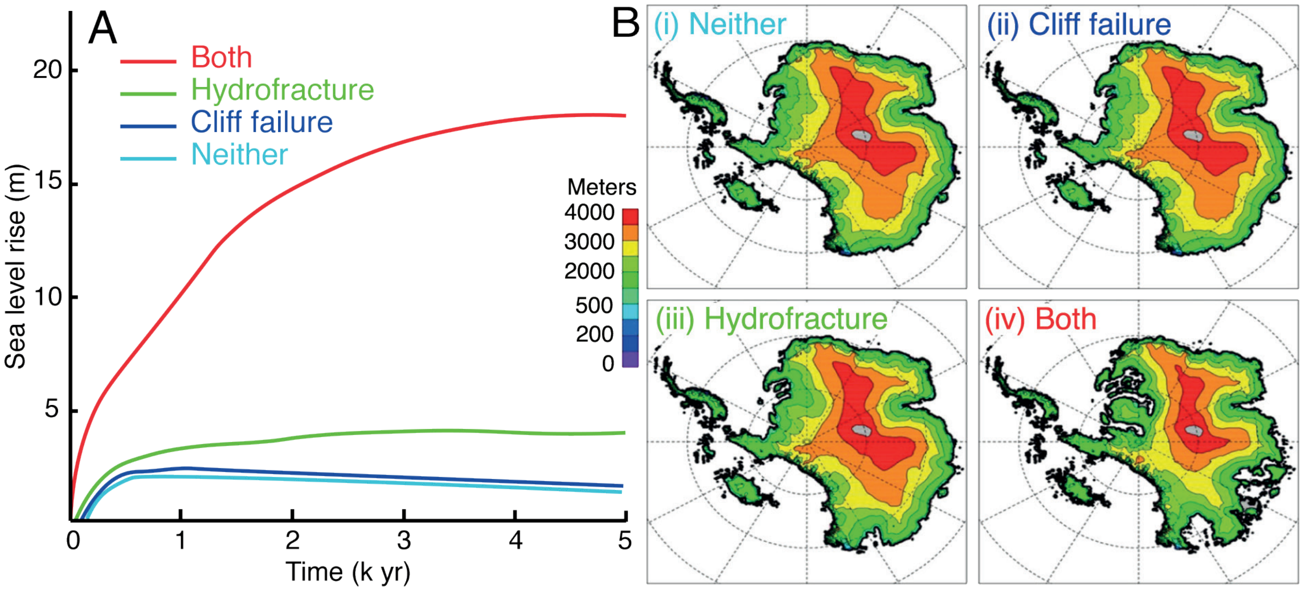

Figure 2: (A) Global mean equivalent sea-level rise in Pliocene warm-climate simulations. Time series of global mean sea-level rise above modern are shown, implied by reduced Antarctic ice volumes. The calculation takes into account the lesser effect of melting ice that is originally grounded below sea level. Cyan: with neither cliff failure nor melt-driven hydrofracturing active. Blue: with cliff failure active. Green: with melt-driven hydrofracturing active. Red: with both these mechanisms active. **(B)** Ice distribution across the Antarctic continent with (a) neither cliff-failure or melt-driven hydrofraturing, (b) cliff failure active, (c) Melt-driven hydrofrature, and (d) both cliff failure and hydrofracturing incorporated to model simulations equilibrated after 5,000 years of warm-climate forcing. Demonstrating the marked loss of EAIS outlets under scenario d incorporating both cliff failure and hydrofracture. Adapted from Pollard et al. (2015), reprinted with permission of Elsevier.

simulations, inter-model discrepancies may arise because of the manner in which key processes are implemented and parameterized, or the spatial resolution at which experiments are run (Favier et al. 2014).

New directions

Uncertainties over the sources of sea-level rise during the LIG have driven an increased interest in paleo-ice-sheet model simulations, because empirical data exist with which the models can be "ground-truthed", in contrast to forward projections that are unconstrained. Recent studies have highlighted that the Antarctic ice sheets may be highly sensitive to circulation changes in the Southern Ocean triggered by changes in circulation patterns driven by anthropogenic warming over the next century (Hellmer et al. 2012). To explore the effect that atmospheric circulation changes may have on marine-based sectors of the Antarctic ice sheets during the LIG, Fogwill et al. (2014) examined the role that physical changes in the location of the Southern Hemisphere westerly winds could play in driving WAIS and EAIS change through changing Southern Ocean circulation using Earth System Climate Models (ESCMs). Simulations demonstrated that sectors of the EAIS found to be most sensitive include the Eastern Weddell Sea, the Amery/Lambert region and the western Ross Sea, which when combined could add 3-5 m to GMSL (Fig. 1). Whilst ESCMs provide useful insights into broad scale ocean changes, Regional Ocean Models (ROMs) may prove critical to connect the ice sheet to broad scale ocean circulation changes (e.g. Hellmer et al. 2012).

Paleo-ice-sheet experiments have also been used to explore the possible drivers and mechanisms of EAIS change during past interglacials to provide insights into the future. In one such study, Mengel and Levemann (2014) demonstrated that it is possible to drive self-sustained discharge of the entire Wilkes Basin simply by removing a specific coastal ice volume (termed an ice plug). The GMSL equivalence of such a collapse is on the order of 3-4 m, but the question of how this ice plug could be removed remains unresolved.

One potential scenario involves catastrophic glaciological changes such as ice-shelf hydrofracture and ice-cliff failure. Pollard et al (2015) implemented these two mechanisms on a whole-Antarctic ice-sheet scale for climatic conditions representative of the warm Pliocene. The results of these simulations are dramatic, driving rapid ice-sheet collapse across huge areas of the WAIS and EAIS on centennial timeframes, and producing GMSL equivalence in excess of ~17 m within millennia (Fig. 2). Whilst the mechanisms are highly parameterized, together ice-shelf hydrofracture and ice-cliff failure provide potential "missing links" in the current generation of ice-sheet models (DeConto and Pollard 2016). They are therefore important candidates for future process studies, given that when combined, their effect is far greater than the sum of their individual effects – it is such strong nonlinearities that are the hallmark of a tipping element. Similarly, there is a need to include more accurate simulation of basal hydrological processes at the ice-sheet scale (Bueler and van Pelt 2015), or the ability for changes in basal friction to effect changes in ice-sheet behavior (Golledge et al 2015).

Conclusions

To understand and quantify the potential of the EAIS as a major tipping element in the Earth's climate system, future developments are needed so that ice-sheet models incorporate the complex interactions between ice sheets and their beds, their connection to ice shelves, and also the continental- and local-scale atmospheric and oceanic forcings that the ice sheets are exposed to (e.g. Bracegirdle et al. 2015). Simulating more realistic ice-flow behavior to external drivers is key if we are to robustly model the response of the Antarctic ice sheets to future changes both at the periphery and the bed. With emerging evidence that the EAIS may be highly susceptible to ocean forcing (Greenbaum et al. 2015), and the concept of marine-ice-sheet instability becoming increasingly accepted and well understood, parameterizing the non-linear mechanisms occurring at the ice-ocean interface is essential if we are to reduce uncertainty in future sea-level rise projections.

AFFILIATIONS

[1]Climate Change Research Centre, University of New South Wales, Sydney, Australia

[2]Antarctic Research Centre, Victoria University of Wellington, New Zealand

[3]GNS Science, Lower Hutt, New Zealand

CONTACT

Christopher J. Fogwill: c.fogwill@unsw.edu.au

REFERENCES

Bracegirdle TJ et al. (2015) BAMS 97: ES23-ES26

Bueler E, van Pelt W (2015) Geosci Model Dev 8: 1613-1635

Dutton A et al. (2015) Science 349, doi: 10.1126/science.aaa4019

DeConto RM, Pollard D (2016) Nature 531: 591-597

Favier L et al. (2014) Nature Clim Change 4: 117-121

Fogwill CJ et al. (2014) J Quat Sci 29: 91-98

Golledge NR et al. (2015) Nature 526: 421-425

Greenbaum JS et al. (2015) Nature Geosci 8: 294-298

Hellmer HH et al. (2012) Nature 485: 225-228

Joughin I et al. (2012) Science 338: 1172-1176

Kopp RE et al. (2009) Nature 462: 863-867

McKay NP et al. (2011) Geo Res Lett 38, doi:10.1029/2011GL048280

Mengel M, Leverman A (2014) Nature Clim Change 4: 451-455

Pollard D et al. (2015) Earth Plan Sci Lett 412: 112-121

Turney CSM, Jones RT (2010) J Quat Sci 25: 839-843

Did synchronized ocean warming in the North Pacific and North Atlantic trigger a deglacial tipping point in the Northern Hemisphere?

Summer K. Praetorius[1] and Alan C. Mix[2]

Rapid Northern Hemisphere warming during the last deglaciation involved synchronization of the North Pacific and North Atlantic. Threshold-like transitions to hypoxia occurred in conjunction with abrupt ocean warming, implying synergistic ocean heat transport triggered both physical and ecological tipping points.

The rapid warming transitions into the Bølling-Allerød interstadial and Holocene interglacial are striking examples of nonlinearities in the climate system. A leading hypothesis for the trigger of these events has been changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC) (McManus et al. 2004). However, records from the North Pacific and other distant locations document equally abrupt climate changes as those observed in the North Atlantic (Hendy and Kennett 1999; Wang et al. 2001; Praetorius and Mix 2014). This calls into question whether these are teleconnected responses to changes in the AMOC, or whether they involve orchestration of northern hemisphere climate dynamics and reflect critical transitions in the climate system, possibly involving multiple "tipping elements" (Lenton et al. 2008).

Proposed early warning signals (EWS) of tipping points include enhanced spatial correlation, increased autocorrelation, and high variance (Dakos et al. 2010; Scheffer et al. 2012). Evidence for enhanced variance and autocorrelation prior to the Bølling-Allerød and Holocene transitions is mixed, leading to debate as to whether these abrupt climate shifts are stochastic perturbations or climate bifurcations (Lenton et al. 2012). High spatial correlation may be a more reliable EWS (Dakos et al. 2010), but so far has not been widely applied to paleoclimate data. Detection of EWS in paleoclimate data remains challenging due to requirements for records with high signal-to-noise ratios and precise chronologies.

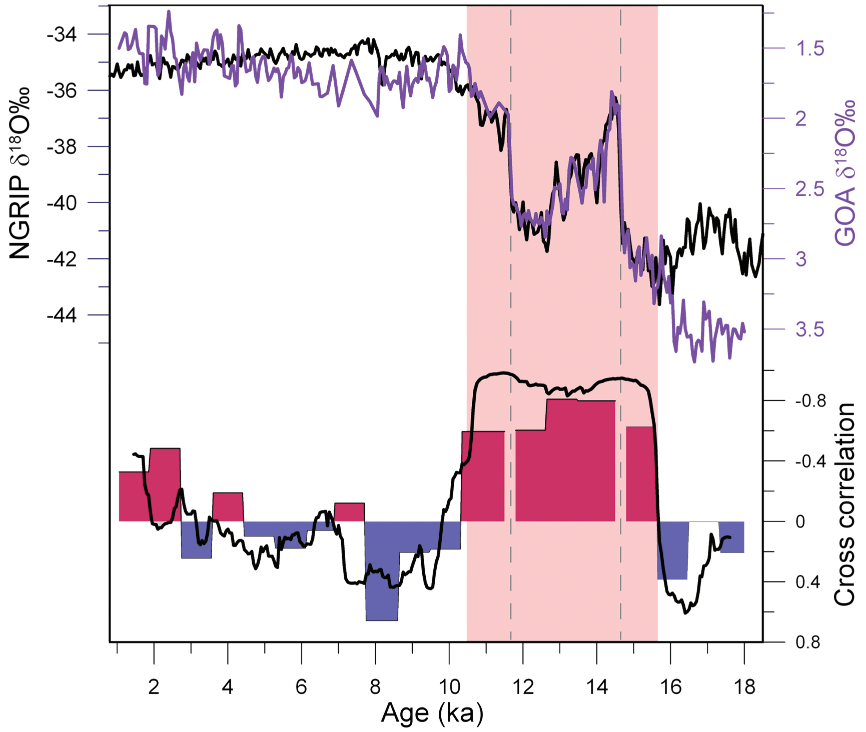

Figure 1: Changes in the correlation between the Greenland NGRIP (Rasmussen et al. 2006) and the Gulf of Alaska (GOA) $\delta^{18}O$ records (inverted Y-axis; Praetorius and Mix 2014). Each record is interpolated on a 25 yr time step with a 125 yr Gaussian filter, and the cross correlation is evaluated with both a 2,000 yr centered moving average (black), and in 800 yr stationary windows (red: negative correlation, blue: positive correlation), excluding the 200 years surrounding the abrupt Bølling and Holocene transitions (dashed lines). Both the cross correlation in stationary windows and the moving average indicate a switch from positive to negative correlation (synchronized) prior to the Bølling transition. The interval of high negative correlation is highlighted with pink shading. Negative correlation implies a positive temperature relationship. A center-weighted moving average monitors broad trends in the record by approximating the timing of changes in cross correlation. It is not suited for detecting EWS in isolation of other evaluation as it smooths variance in abrupt transitions. Both the cross correlation in stationary windows and the moving average indicate a switch from positive to negative correlation (synchronized) prior to the Bølling transition.

North Pacific – North Atlantic climate flip-flop?

We recently developed a decadal-resolution planktonic oxygen isotope record from the Gulf of Alaska with a centennial-scale radiocarbon chronology (Praetorius and Mix 2014) and compared changes to the Greenland NGRIP oxygen isotope record (Rasmussen et al. 2006). The two regions appear to flip-flop between correlation and anticorrelation (Fig. 1). A few hundred years prior to the abrupt warming transition into the Bølling-Allerød warm period at 14.7 ka, these records became synchronized, and maintained high correlation throughout the remainder of the deglaciation, encompassing abrupt climate fluctuations such as the Younger Dryas cooling episode and the rapid warming into the Holocene. Coupling of North Pacific and North Atlantic heat transport could act as an amplifying mechanism in abrupt northern hemisphere climate change, whereas opposing oceanic regimes could act to balance northern hemisphere heat transport, and thus promote climate stability.

Although this analysis was based on oxygen isotope data due to its high signal-to-noise ratio, $\delta^{18}O$ may be sensitive to temperature, global ice volume changes, and local salinity effects. We have now expanded this work into specific sea-surface temperature proxies (Praetorius et al. 2015), and show that the rapid North Atlantic warming events (as recorded in Greenland) are indeed accompanied by abrupt, high-amplitude warming in the Northeast Pacific, and that abrupt changes in paleo-salinity play only a minor role in the oxygen isotope record. Because these massive warming events are found in the northward advective pathway of waters from lower latitudes, a substantial increase in net northward heat transport is likely. This is somewhat surprising, as the initial warming into the Bølling-Allerød occurred prior to the opening of Bering Strait, during a time when low salinity surface waters would have been trapped in the high North Pacific; radiocarbon evidence suggests that the warming events are not associated with enhanced local overturn (Davies et al. 2014).

Coupled global climate models show an amplified surface warming in the North Pacific on centennial time scales in response to increasing radiative forcing due to a shallow mixed layer depth (Long et al. 2014). Such a mechanism may help to explain rapid North Pacific warming in concert with the deglacial rise in atmospheric CO_2 concentrations.

Ecological and biogeochemical responses to physical tipping points

Biological and chemical systems may have been entrained in their own dynamics as the deglacial world tipped into warming. For example, it has been known for some time that the oxygen minimum zone expanded abruptly in the North Pacific during both the Bølling-Allerød and early Holocene (Jaccard and Galbraith 2012). These hypoxic events coincided with surface warming (Praetorius et al. 2015), implying strong feedbacks between ocean warming, deoxygenation, and marine productivity, with evidence for tipping-point impacts on the benthic fauna. Abrupt transitions to sedimentary laminations, in close association with enhanced burial of diatom algae, points to a strong role for enhanced sea-surface productivity and subsequent sinking of organic matter in pushing this system across a threshold of hypoxia that was sustained for millennia during each event. Sea-surface warming preceded the increase in productivity and initiation of hypoxia during the Bølling-Allerød transition, suggesting that warming triggered an array of biogeochemical feedbacks in the past, and may imply that future warming could trigger similar feedbacks, leading to more rapid or severe deoxygenation of the North Pacific than what is predicted based on thermal solubility alone.

An abrupt intensification of hypoxia is also observed in the Cariaco Basin in the tropical North Atlantic at similar times to those we observed in the North Pacific (Fig. 2; Gibson and Pederson 2014). The remarkably similar timing and magnitude of sea-surface temperature increase and the near synchronous onset of hypoxia in different oceanic regions in the North Pacific and North Atlantic during the Bølling-Allerød and Holocene transitions, in spite of rather different baseline conditions in the two oceans, imply a prominent role for ocean warming in pushing low-oxygen regions across thresholds of hypoxia. Exactly how the feedback mechanisms work remains poorly known and a subject for future observations and modeling.

Outlook

New high-resolution paleoceanographic records from the subpolar North Pacific document rapid changes during the last deglacial transition similar in timing to those observed in the Greenland ice cores. Rather than deglacial changes in the North Pacific merely reflecting a downstream response to changes in the North Atlantic region, interactions between basins may be a key element in the emergence of abrupt climate transitions in the Northern Hemisphere.

Although changes in inter-ocean coupling may have important consequences for climate, it remains unclear what regulates connectivity between the North Pacific and North Atlantic. This will be a worthy target for future studies. Development of high-fidelity paleoclimate records with precise and accurate chronology is challenging. Nevertheless, assessing the potential for tipping points in the future demands that we understand the dynamics of rapid climate changes and the biogeochemical responses and feedbacks they triggered in the past.

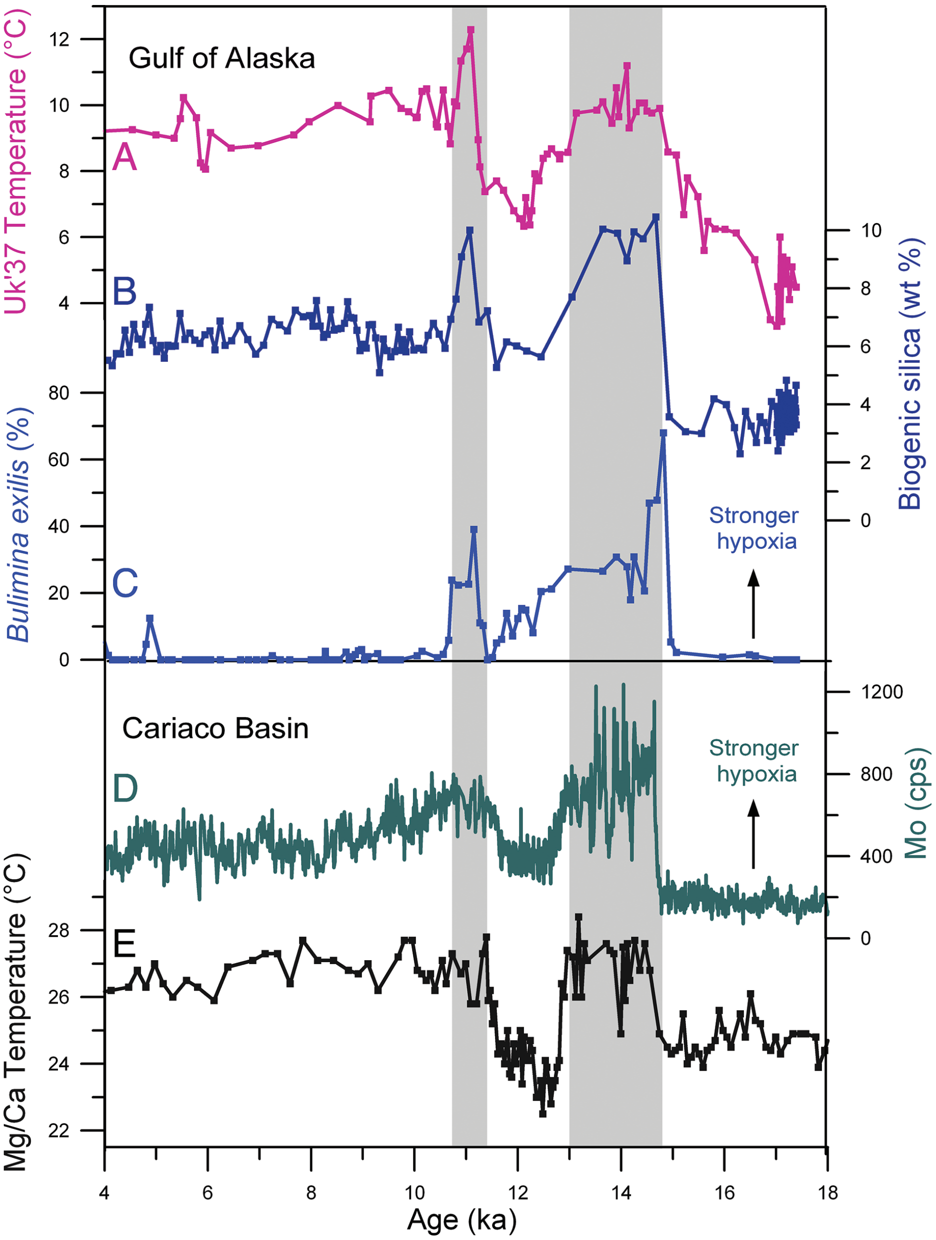

Figure 2: (A) Alkenone (Uk'37)-based sea surface temperature reconstructions from the Gulf of Alaska, North Pacific (Praetorius et al. 2015), with records of (B, C) productivity from the same location and (D) sedimentary redox and (E) temperature from the Cariaco Basin, North Atlantic. **(B)** Weight percent of biogenic silica (Davies et al. 2011) and **(C)** abundance of low-oxygen-tolerant benthic species Bulimina exilis (Praetorius et al. 2015). **(D)** Scanning-XRF record of Mo from the Cariaco Basin (Gibson and Pederson 2014), and **(E)** Mg/Ca paleotemperature reconstruction (Lea et al. 2003). Gray shaded bars reflect the laminated intervals in the Gulf of Alaska, which also correspond to intervals of strong hypoxia in the Cariaco Basin sediments.

AFFILIATIONS

[1]Department of Global Ecology, Carnegie Institution for Science, Stanford, USA

[2]College of Earth, Ocean, & Atmospheric Sciences, Oregon State University, Corvallis, USA

CONTACT

Summer Praetorius: spraetorius@carnegiescience.edu

REFERENCES

Dakos V et al. (2010) Theor Ecol 3: 163-174

Davies M et al. (2011) Paleoceanography 26, doi:10.1029/2010PA002051

Gibson K, Peterson L (2014) Geophys Res Lett 41: 969-975

Hendy I, Kennett J (1999) Geology 27: 291-294

Jaccard S, Galbraith E (2012) Nat Geosci 5: 151-156

Lea D et al. (2003) Science 301: 1361-1364

Lenton TM et al. (2008) PNAS 105: 1786-1793

Lenton TM et al. (2012) Clim Past 8: 1127-1139

Long S-M et al. (2014) J. Clim 27: 285-299

McManus J et al. (2004) Nature 428: 834-837

Praetorius S, Mix A (2014) Science 345: 444-448

Praetorius S et al. (2015) Nature 527: 362-366

Rasmussen S et al. (2006) J Geophys Res 111, doi:10.1029/2005JD006079

Scheffer M et al. (2012) Science 338: 344-348

Wang Y et al. (2001) Science 294: 2345-2348

Ice cores: High-resolution archive of rapid climate changes

Simon Schüpbach[1], H. Fischer[1], S.O. Rasmussen[2], A. Svensson[2], D. Dahl-Jensen[2], J.P. Steffensen[2] and J.W.C. White[3]

Owing to their outstanding temporal resolution, ice cores are well-suited to investigate rapid climate transitions during the last glacial period. They show that the climate system underwent dramatic reorganization on annual-to-decadal time scales during the Dansgaard-Oeschger events.

Snow falling on the central parts of polar ice sheets is compressed to firn by the weight of the overlaying snow, eventually turning to ice through sintering and recrystallization (Herron and Langway 1980). The isotopic composition of the snow deposited on the surface (a proxy for the local condensation temperature) and impurities (such as aerosols and dust particles) are preserved in this process. In addition, air is trapped in bubbles during the transition from firn to ice, and can be extracted to study, for example, past greenhouse gas concentrations. Accordingly, the top 50-120 m of an ice sheet consists of porous snow and firn, which allows the air to circulate between the surface and the top of the firn column, while diffusive processes dominate further down the firn column (Fig. 1). Once the transformation from firn to ice is completed, the air is trapped in the ice, and the age distribution and composition of the air in the bubbles are no longer changed.

In the firn column, thermal and gravitational diffusion leads to isotopic fractionation. The isotopic composition of the gas trapped in the ice can thus be used as a temperature proxy during fast temperature changes at the surface of an ice sheet, e.g. by analyzing the $^{15}N/^{14}N$ ratio ($\delta^{15}N$) of nitrogen gas (Huber et al. 2006; Kindler et al. 2014; Severinghaus et al. 1998).

Through the mixing of air in the firn column, the air entrapped in the ice is considerably younger than the surrounding ice matrix (Fig. 1). This age difference is usually denoted as Δage, and is responsible for the uncertainties when investigating the phasing of events during fast climate transitions. Δage depends mainly on snow accumulation and the firn temperature, such that low snow accumulation and low temperatures cause large Δage, and vice versa. Therefore, maximum Δage values are observed in Antarctica e.g. in the Vostok ice core during the Last Glacial Maximum about 20'000 years ago (Δage of approx. 5000 years), while in Greenland Δage values are considerably lower (up to 1400 years during the Last Glacial Maximum).

Dansgaard-Oeschger events

During the last glacial period, North Atlantic climate was not stable. The cold stadial periods were interrupted by warmer interstadial periods of durations from 100 to several thousand years. The interstadials, also called Dansgaard-Oeschger (D-O) events, generally show a common shape in time - at the beginning, temperature increases rapidly, and subsequently decreases first slowly, then abruptly to reach stadial values again (Fig. 2a). Other climate parameters mimic this pattern. This Northern Hemisphere temperature pattern is linked to Antarctic temperature by means of the bipolar seesaw (Stocker and Johnsen 2003). This concept proposes that a reduced Atlantic Meridional Overturning Circulation (AMOC) leads to heat accumulation in the southern hemisphere (Southern Ocean) until temperature increases rapidly in the north, whereafter temperature decreases again in the south (EPICA Community Members 2006).

Due to their outstanding temporal resolution and well-constrained chronologies throughout the entire last glacial period, Greenland ice-core records are perfectly suited to investigate fast climate variations in the North Atlantic region (e.g. Huber et al. 2006; Steffensen et al. 2008), while CH_4 synchronized Antarctic ice cores can be used to reconstruct mechanisms which link both hemispheres during past abrupt climate changes through the bipolar seesaw (EPICA Community Members 2006).

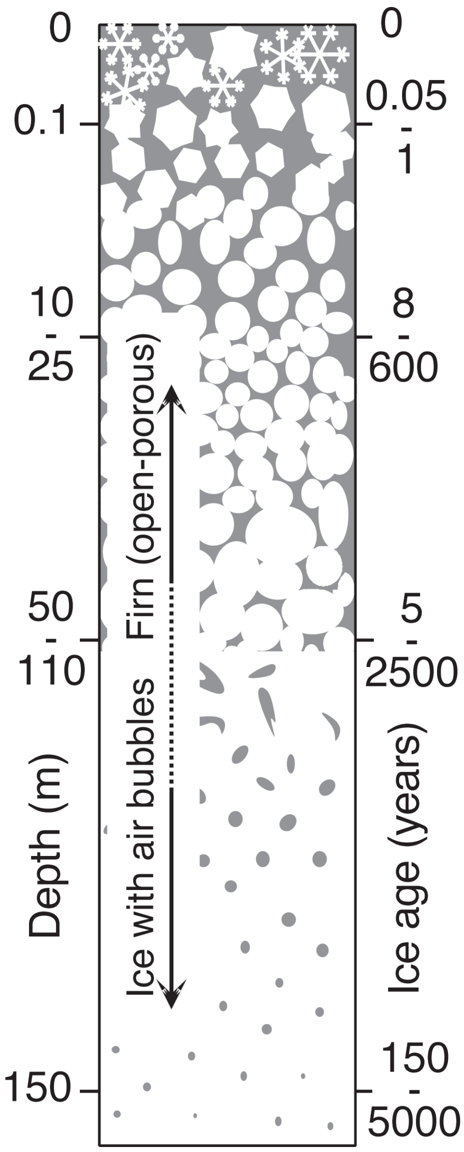

Figure 1: Schematic of the firn column with typical ranges of depth and age. Adapted from Schwander (1996).

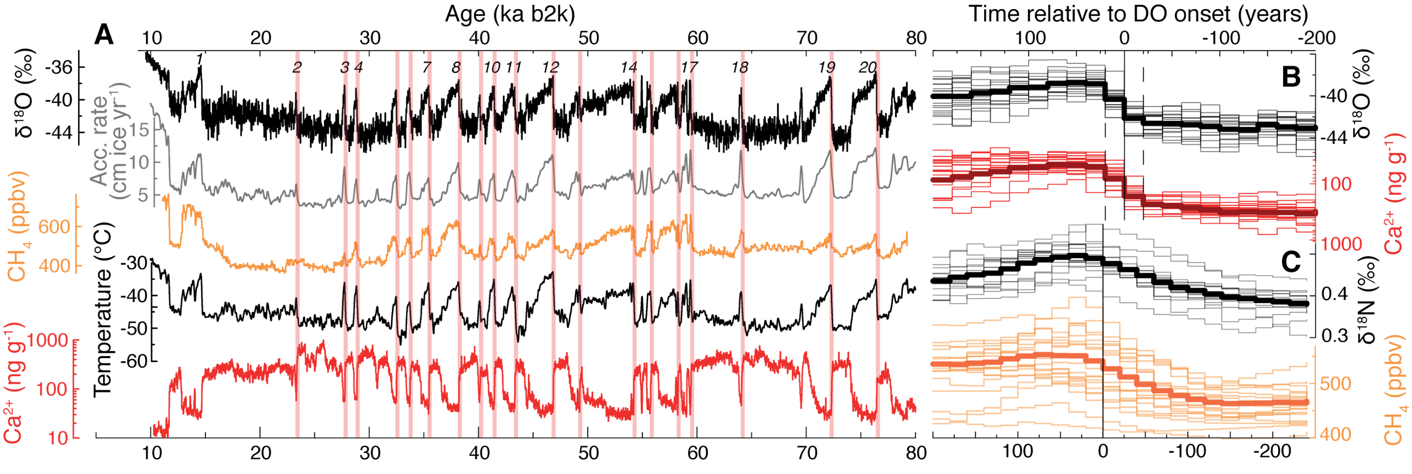

Figure 2: (A) From top to bottom: Glacial NGRIP records of $\delta^{18}O$ (Rasmussen et al. 2014), accumulation rate (Kindler et al. 2014), atmospheric CH_4 concentration (Baumgartner et al. 2014), $\delta^{15}N$-derived temperature (Kindler et al. 2014), and Ca^{2+} ice concentrations (Rasmussen et al. 2014). Italic numbers indicate D-O events. Red shades indicate the D-O onsets used in the stack on the right side. All records are plotted on the GICC05modelext age scale (Rasmussen et al. 2014; Seierstad et al. 2014). **(B)** Stacks of $\delta^{18}O$ and Ca^{2+} at the rapid onsets of D-O events 2-20. A relative time of 0 years corresponds to the onset as defined by Rasmussen et al. (2014), negative time means older ages, positive time means younger ages. **(C)** Stacks of the rapid D-O onsets of CH_4 concentration and $\delta^{15}N$ (proxy of temperature change).

Duration and rates of change during D-O onsets

In Figure 2b, we stack $\delta^{18}O$ and Ca^{2+} at the onsets of D-O events 2-20. It is evident that the changes in $\delta^{18}O$ and Ca^{2+} are equally abrupt between stadials and interstadials. The transition from stadial to interstadial conditions of $\delta^{18}O$ takes place within 1-2 steps of the 20-years-resolution record. Within the data resolution, no significant lead or lag of Ca^{2+} relative to $\delta^{18}O$ can be observed. The mean duration of the climate transition for Ca2+ is also in the order of 40 years. Within these four decades, Ca^{2+} concentrations decrease by one order of magnitude, and $\delta^{18}O$ increases by 3.8‰ on average.

The Ca^{2+} record is primarily reflecting changes in dust source conditions, most likely from Central Asian desert regions (Biscaye et al. 1997; Svensson et al. 2000), and transport effects. Thus, changes in Ca^{2+} concentration indicate reorganizations of wind fields and atmospheric circulation patterns at regional to hemispherical scale. The close relative timing of $\delta^{18}O$ and Ca^{2+} changes indicates that the rapid changes in Greenland atmospheric dust loading and in $\delta^{18}O$ may be linked to the same large-scale circulation changes.

Gas concentrations stored in ice cores change more slowly than $\delta^{18}O$ and Ca^{2+} because they are well mixed in the atmosphere and have residence times of a decade (CH_4) or more (e.g. CO_2 and N_2O). Due to gas diffusion in the firn column and the slow bubble enclosure process, fast changes of atmospheric gas concentrations are further smoothed in ice cores (Fig. 2c). Huber et al. (2006) calculated an average duration of $\delta^{15}N$ increase of 225±50 years for D-O events 9-17. $\delta^{15}N$ is controlled by the width in the age distribution of the air enclosed in the ice and by the slow heat conductance in the firn column, which gets rid of the thermal diffusion signal. From the stack of D-O 2-20, we calculate a mean temperature jump of 10.1°C, and a mean CH_4 concentration increase of 70 ppb (Fig. 2c). The increase of atmospheric CH_4 concentration at the onset of a D-O event shows a slight lag of approximately 50 years, relative to the temperature increase recorded in $\delta^{15}N$ in line with the findings of Huber et al. (2006). A direct comparison of gas parameters and ice parameters is difficult, because Δage uncertainty (50-100 years) is comparable to the observed differences of the start of the increase.

The durations of the fast D-O onsets discussed above can be translated into rates of change in CH_4 concentrations and temperature. If we assume that $\delta^{18}O$ documents the temporal change in surface temperature at the ice-core site (approx. 40 years; e.g. Steffensen et al. 2008) and take the $\delta^{15}N$-derived average temperature increase of 10.1°C, this results in an average temperature increase of 2.5°C/decade. Fig. 2c shows that the increase of CH_4 is slightly faster than $\delta^{15}N$. Assuming a rise time of atmospheric CH_4 concentration of about 30 years and an increase of 70 ppb, this results in an average rate of change of 23 ppb/decade, however, delayed by a few decades relative to the temperature increase. Comparing these values with modern rates of change (temperature: 0.15°C/decade (global) and 0.46°C/decade (Arctic), last 40 years; CH_4: 48 ppb/decade, last 30 years) shows that Greenland temperature increased considerably faster at the onsets of D-O events than modern temperature does, but modern atmospheric CH_4 concentration is increasing substantially faster than it did during D-O events. This stresses the strength of the anthropogenic CH_4 perturbation in recent decades compared to the most severe natural CH_4 changes, and at the same time illustrates how fast earth climate system variations can occur under glacial boundary conditions.

AFFILIATIONS
[1]Physics Institute and Oeschger Centre for Climate Change Research, University of Bern, Switzerland
[2]Niels Bohr Institute, University of Copenhagen, Denmark
[3]INSTAAR, University of Colorado, Boulder, USA

CONTACT
Simon Schüpbach: schuepbach@climate.unibe.ch

REFERENCES
Baumgartner M et al. (2014) Clim Past 10: 903-920
Biscaye PE et al. (1997) J Geophys Res 102: 26765-26781
EPICA Community Members (2006) Nature 444: 195-198
Herron MM, Langway CC Jr. (1980) J Glaciol 25: 373-385
Huber C et al. (2006) Earth Planet Sc Lett 243: 504-519
Kindler P et al. (2014) Clim Past 10: 887-902
Rasmussen SO et al. (2014) Quat Sci Rev 106: 14-28
Schwander J (1996) NATO ASI Series I 43: 527-540
Seierstad IK et al. (2014) Quat Sci Rev 106: 29-46
Severinghaus JP et al. (1998) Nature 391: 141-146
Steffensen JP et al. (2008) Science 321: 680-684
Stocker TF, Johnsen SJ (2003) Paleoceanography 18, doi:10.1029/2003PA000920
Svensson A et al. (2000) J Geophys Res 105: 4637-4656

A paleo-perspective on the AMOC as a tipping element

Stephen Barker[1] and Gregor Knorr[2]

Ocean circulation within the Atlantic is capable of changing rapidly, with important consequences for global climate. Evidence from various climate archives suggests that abrupt transitions in the past were preceded by systematic behavior that could have provided early warning indicators.

The Atlantic Meridional Overturning Circulation (AMOC) redistributes heat, salt and carbon as part of the global thermohaline circulation. Major changes of the AMOC would have global impacts and, as a potential tipping element (Lenton et al. 2008), it is a focus for future projections. The IPCC (2013) concluded that it is very unlikely that an abrupt transition or collapse of the AMOC will occur during the next century for the scenarios considered. However, it is not clear that, under realistic forcing conditions, the complex models used for future climate scenarios are capable of producing the abrupt changes that occurred relatively frequently during the last glacial period (Valdes 2011).

Paleo evidence for abrupt change

Temperature records obtained from Greenland ice cores provided the first convincing evidence of past abrupt climate change (Fig. 1). The Greenland records revealed repeated transitions (the so-called Dansgaard-Oeschger, D-O, oscillations) between cold, stadial conditions and warmer interstadial conditions, with extremely fast (decades or less) shifts between these states (NGRIP members 2004). These alternations are one expression of a global system, capable of driving major changes in components ranging from ocean temperatures to monsoon rainfall. Massive ice-rafting events across the North Atlantic (Heinrich Events, HE) during some stadial phases (HS events) were associated with particularly cold conditions across the North Atlantic (Shackleton et al. 2000) and suggest the existence of three distinct climate "states" during glacial times.

The ocean's role in rapid climate change

It has long been argued that D-O and Heinrich variability involved changes in the AMOC and many attempts have been made to test this using paleodata. On a basin scale, water mass tracers, such as benthic foraminiferal $\delta^{13}C$ and Cd/Ca ratios and seawater Nd isotopes, suggest a reduction in the ratio of northern versus southern deep water end-members in the Atlantic during northern cold events, particularly those associated with H-Events (Shackleton et al. 2000). On a regional scale, variations in the transport of North Atlantic Deep Water have been reconstructed using a variety of methods including sediment composition, grain size and magnetic analysis (Kissel et al. 2008). These studies suggest a systematic link between high-latitude climate change and variations in deep ocean circulation, even for non-Heinrich stadial events. They suggest a reduction in the deep overflows emanating from the Nordic Seas during cold events, implying a decrease in the production of deep waters through open ocean convection north of Scotland. Concomitant variations in wintertime sea-ice cover across the Nordic Seas have been proposed as an effective means of explaining the very large changes in temperature observed across Greenland associated with D-O transitions (Li et al. 2010).

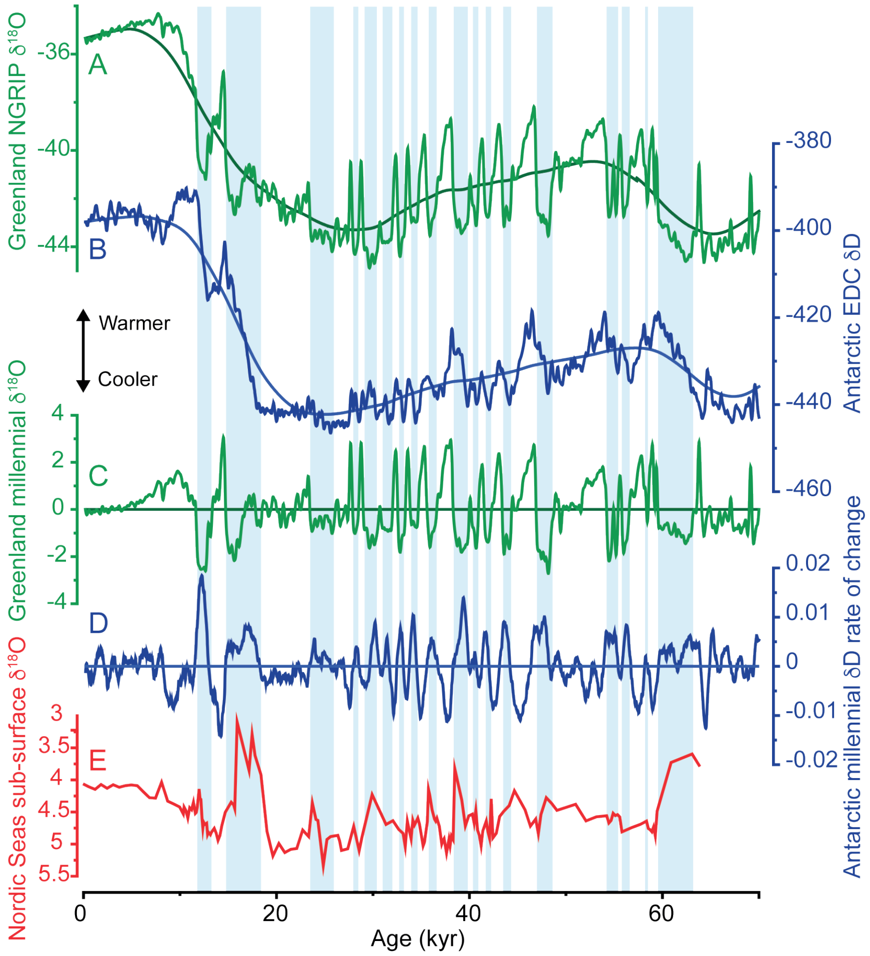

Figure 1: Abrupt climate change over the past 70 kyr. The blue bars indicate stadial events. **(A)** Greenland temperature proxy record showing the abrupt D-O transitions (NGRIP members 2004). Orbital component is a 7 kyr running mean. **(B)** Antarctic temperature proxy record showing a more gradual behavior (Jouzel et al. 2007). **(C)** Millennial-scale component of Greenland temperature. **(D)** Rate of change of Antarctic temperature showing systematic warming during Greenland stadials and cooling during interstadials (Barker et al. 2011). **(E)** Proxy record showing sub-surface warming in the North East Atlantic during stadial events (Ezat et al. 2014).

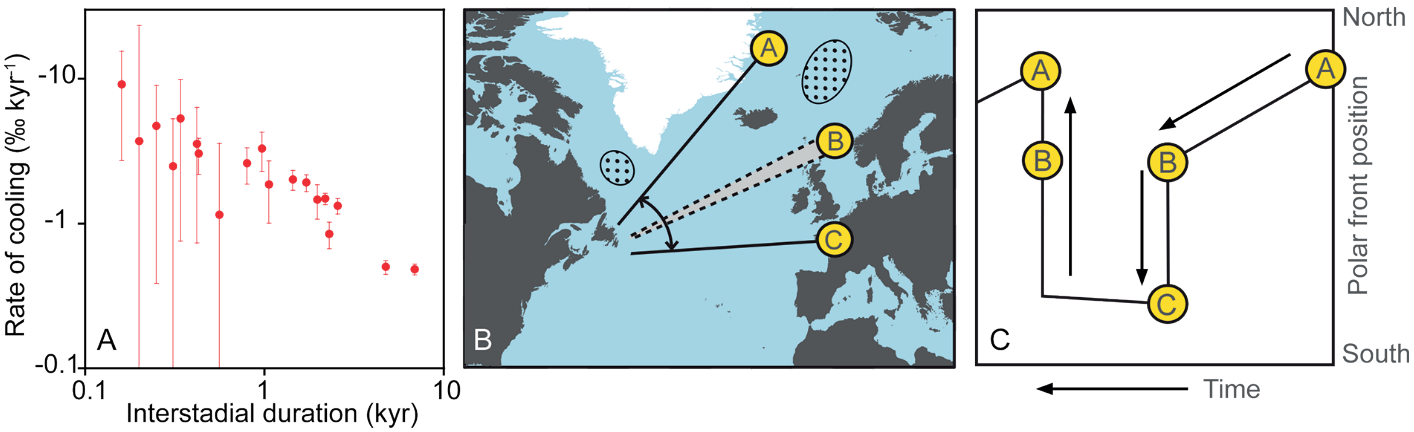

Figure 2: Gradual cooling during an interstadial precedes the abrupt transition to stadial conditions. **(A)** The rate of cooling (defined here as the rate of change in $\delta^{18}O$) during a Greenland interstadial is related to its duration. **(B)** Cartoon showing the approximate migration path of the North Atlantic polar front associated with D-O transitions. Stippled areas show approximate locations of modern deep convection. Position A represents interstadial conditions with convection north of Scotland. Stadial conditions are represented by point C with deep convection restricted to south of Iceland. **(C)** Temporal evolution of the polar front position across a D-O oscillation. From point A, gradual cooling pushes the polar front southwards. On reaching threshold point B, an abrupt southward migration of the polar front occurs with the transition to stadial conditions (point C). It can be seen that a faster rate of cooling between A and B would result in a shorter interstadial. The return to warm conditions is essentially synchronous across the North Atlantic. Modified after Barker et al. (2015).

The AMOC as a tipping element

The magnitude and speed of D-O transitions qualifies as abrupt climate change, yet the nature of the transitions and whether they are "predictable" in some way is debated. Abrupt transitions could be the result of a gradual change in forcing applied to a system containing a threshold (tipping point) or of a large and abrupt change in forcing applied to a system with or without a threshold. In the former case, we could expect "early warning" indicators of the abrupt change as a result of "critical slowing down" as the threshold is approached. A decrease in system resilience close to the bifurcation point would be reflected by an increase in variance and autocorrelation that could be detected given a well-resolved time series of a relevant system parameter. No early warning would be expected for a system without a threshold, or in a system forced through a threshold by a large and rapid change in forcing.

Statistical studies using the Greenland temperature records have produced contrasting results, with early warning being undetected (Ditlevsen and Johnsen 2010) or weakly present (Cimatoribus et al. 2013). Yet there are other reasons to suspect that D-O transitions are the result of gradual forcing through a critical threshold and are not merely stochastic in nature.

The abrupt transitions from interstadial to stadial conditions over Greenland are preceded by gradual cooling during interstadial times (Figs. 1,2). Barker et al. 2015 have argued that this cooling is related to a gradual southward migration of the North Atlantic polar front, giving rise to a diachronous transition to polar conditions across the North Atlantic, and leading to an abrupt descent into stadial conditions once a threshold is crossed (Fig. 2b,c). Such a threshold is also implied by the Greenland temperature records themselves, which reveal an inverse relationship between the rate of cooling within an interstadial and the duration of that event (Fig. 2a).

The abrupt transitions from stadial to interstadial conditions, as recorded by the Greenland temperature records, reveal no systematic behavior prior to these transitions. However, using the Greenland temperature records, one cannot differentiate between HS events and non-H stadials even though North Atlantic records suggest much colder conditions during HS events (Shackleton et al. 2000). This can be explained by the insulating effect of sea-ice across the Nordic Seas but implies that the Greenland temperature records are not optimally suited for detecting early indications of impeding interstadial transitions. In contrast, the Antarctic ice core records suggest a continuous build-up of heat across the Southern Ocean throughout all stadial events (Jouzel et al. 2007; Fig. 1d). Moreover, the "Antarctic signal" is not restricted to the remote Southern Hemisphere but can be detected around the Earth as a globally pervasive signal (Barker and Knorr 2007). Furthermore, gradual global warming (that could be the incidental by-product of stadial conditions; Fig. 1) could itself lead to an abrupt strengthening of the AMOC beyond some threshold (Knorr and Lohmann 2007), suggesting that early warning of abrupt warming transitions may be detectable given the right record.

Prone to instability

The ubiquitous cooling observed throughout interstadial periods, leading ultimately to an abrupt transition to stadial conditions (Barker et al. 2015), suggests that whether or not the interstadial mode of AMOC is dynamically stable, its very existence necessitates a transition back to a stadial mode. Equally, if the build-up of heat during stadial conditions (Jouzel et al. 2007; Ezat et al. 2014) is the ultimate cause of an abrupt switch back to interstadial conditions, it could be argued that neither state is truly stable. Thus, the D-O oscillations may be an inevitable consequence of glacial climate, rather than the consequence of random external perturbations. Indeed, the Antarctic temperature record documents the continuous redistribution of heat throughout stadial and interstadial periods alike (Jouzel et al. 2007; Barker et al. 2011; Fig. 1). According to this metric, the AMOC only ever experiences quasi-equilibrium during full interglacial and full glacial conditions (Barker et al. 2011). Thus from a paleo perspective it appears that abrupt transitions in the AMOC can occur in response to gradual change, even if that change is a product of the AMOC state itself. State-of-the-art climate models should be tested to reproduce this sensitivity to learn more about abrupt climate transitions in the past and place more robust constraints on future predictions of AMOC stability.

AFFILIATIONS

[1]School of Earth and Ocean Sciences, Cardiff University, UK

[2]Alfred Wegener Institute, Bremerhaven, Germany

CONTACT

Stephen Barker: BarkerS3@cardiff.ac.uk

REFERENCES

Barker S et al. (2015) Nature 520: 333-336

Barker S, Knorr G (2007) PNAS 104: 17278-17282

Barker S et al. (2011) Science 334: 347-351

Cimatoribus A et al. (2013) Clim Past 9: 323-333

Ditlevsen PD, Johnsen SJ (2010) Geophys Res Lett 37, doi: 10.1029/2010GL044486

Ezat MM et al. (2014) Geology, doi:10.1130/G35579.1

IPCC (2013) Climate Change 2013: The Physical Science Basis. Cambridge University Press, 1552 pp

Jouzel J et al. (2007) Science 317: 793-796

Kissel C et al. (2008) Paleoceanography 23, doi:10.1029/2008PA001624

Knorr G, Lohmann G (2007) Geochem Geophys Geosyst 8, doi:10.1029/2007GC001604

Lenton TM et al. (2008) PNAS 105: 1786-1793

Li C et al. (2010) J Clim 23: 5457-5475

NGRIP members (2004) Nature 431: 147-151

Shackleton NJ et al. (2000) Paleoceanography 15: 565-569

Valdes P (2011) Nature Geosci 4: 414-416

Identifying and anticipating tipping points in lake ecosystems

Peter G. Langdon[1], J.A. Dearing[1], J.G. Dyke[1] and R. Wang[2]

Tipping points are large and potentially irreversible changes in a system. They have been extensively studied in lake ecosystems. This article describes how we can identify past and predict future tipping points and their impacts for lake management.

Lake ecosystems are changing rapidly under growing anthropogenic pressure, with many moving from one functioning state to another across poorly understood thresholds. These changes can be termed regime shifts, which we define as any substantial reorganization of a complex system with prolonged consequences. The cusp between states can be represented as a tipping point or critical transition, where a small perturbation may be sufficient to move the system from one state to another.

These abrupt, discontinuous changes feature internal processes and feedback loops which reinforce the new state, as in a fold bifurcation (Fig. 1). Consequently, being able to warn of an approaching tipping point before it is reached may allow for policies to be put in place in time.

Lake systems can be complex. But if we assume that the system can occupy more than one stable state, for example oligotrophic "clear water" or eutrophic "turbid water", then we can formulate simple mathematical models of how different drivers, such as nutrient loading or water-level change, cause the system to transition from one state to another. Such an approach is well established and early warning signals (EWS) or impending tipping points have been formulated for a range of natural and social systems (Scheffer 2009). Much of the original evidence and theory for tipping points and EWS has come from analyses and models of lake ecosystems, but more recently there has been a focus on the analysis of lake sediments (e.g. Wang et al. 2012).

As a lake ecosystem approaches a tipping point, it loses resilience. Models and laboratory experiments suggest that in this condition an ecosystem takes more time to recover from perturbations, a phenomenon known as critical slowing down (CSD). CSD is more likely a source of EWS in systems where the external impacts are relatively small. Where the impacts are large, the lake may flip temporarily in and out of an alternate state, before ultimately settling in the alternative state – a phenomenon known as flickering. In lake ecosystems where external drivers constitute high levels of noise, flickering is a more likely source of EWS than CSD (Scheffer et al. 2012).

While the formulation of EWS is mathematically straightforward, there are a number of challenges in observing them in a real world context. For example, EWS require analysis of the rates of change of certain variables. This requires measurements taken over short intervals from long and highly resolved datasets that are sometimes not available. Furthermore, some studies have shown that regime shifts can arrive without warning (Hastings and Wysham 2010) and that EWS can arise as false positives in any model regardless of critical transitions (Kéfi et al. 2013). Additionally, many mathematical models used to define complex dynamics are low-dimensional simplifications of reality, which risk omitting the very complexity that characterizes the real-world systems. Research priorities include observing or reconstructing EWS signals in time series from real-world lake systems so that relevant theories may be tested and the underlying mechanisms explored.

Empirical examples

Previous research shows that over the past 150 years many lakes have experienced regime shifts in their ecosystems through the effects of atmospheric pollution (acid rain from coal and oil fired power stations) or farming in the drainage basins (nutrient runoff from fertilizer applications) on water quality, and while some have since recovered to their former conditions many have not (Battarbee et al. 2014). While many

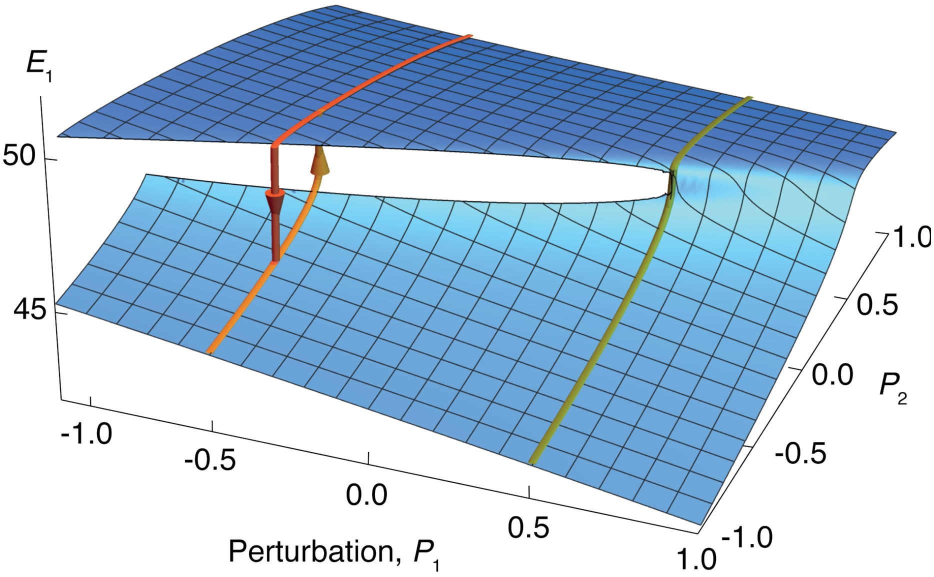

Figure 1: A simple model of a bi-stable system (Weaver and Dyke 2016). The diagram shows how the magnitude of perturbations (P1 and P2) acting on an environmental variable (E1) can lead to smooth, easy to reverse changes in the value of E1 (yellow line) or abrupt critical transitions with hysteresis loops (orange and red lines).

studies have been undertaken on lake ecosystems in an attempt to identify transitions in state, relatively few have focused on detailed assessments of changes in resilience prior to transition, or attempted to identify EWS prior to a tipping point. Indeed, identifying characteristics of a tipping point, as opposed to more gradual shifts, remains a challenge for lake ecosystem research.

Shallow lake eutrophication typically results in a transition from benthic to pelagic community dominance that may or may not result in an overall shift in algal production. The drivers may be either top-down, such as significant changes in fish populations, or bottom-up through enhanced nutrient loading, or a combination of both. Evidence from temperate studies suggest that changes from clear water plant-dominated systems to turbid, eutrophic systems take 10-100s of years (Sayer et al. 2010). These changes could be interpreted as flickering between states, as the resilience drops and positive feedback loops strengthen. The final stage of settling into the alternative state would be an abrupt transition but further research is required to test these ideas.

Deeper lakes that stratify can also react to change through top-down or bottom-up processes. Some modeling work on instrumental and paleolimnological data has suggested that deep stratified systems do show nonlinear transitions between alternate attractors (Seekell et al. 2013). Other experiments on test lakes (with controls) in Michigan have manipulated the food web over a four-year period by steadily increasing the top predators to the ecosystem to turn the lake from turbid to clear water. All directly measured variables on the manipulated lake showed changes in variability (EWS) a year prior to the completion of the transition (Carpenter et al. 2011; Seekell et al. 2012). The tipping point appears to happen much faster than in shallow lakes, likely due to the speed and magnitude of the drivers (annual vs multi-decadal timescales). Can these effects be upscaled to a whole ecosystem? Batt et al. (2013) compared ecosystem productivity against measured drivers for the same manipulated and control lakes. They found no changes in variance, a typical EWS identified in modeling experiments, but they did define a "first day of alarm" that signifies an up-and-coming tipping point.

Other work on deeper lakes has focused on how increased nutrient loading can enhance internal nutrient recycling in a positive feedback cycle through hypolimnetic oxygen depletion. At Erhai Lake, China, diatom data showed a significant tipping point in 2001 using both equal and non-equal increment sediment samples. Monitored water quality and algal data before and after 2001 allowed reconstruction of the two stable states and the hysteresis effect predicted by bifurcation theory (Fig. 2). Time series analyses of sediment data suggested the presence of EWS in the form of increased variance a few decades before the transition (Wang et al. 2012; Doncaster et al., in press).

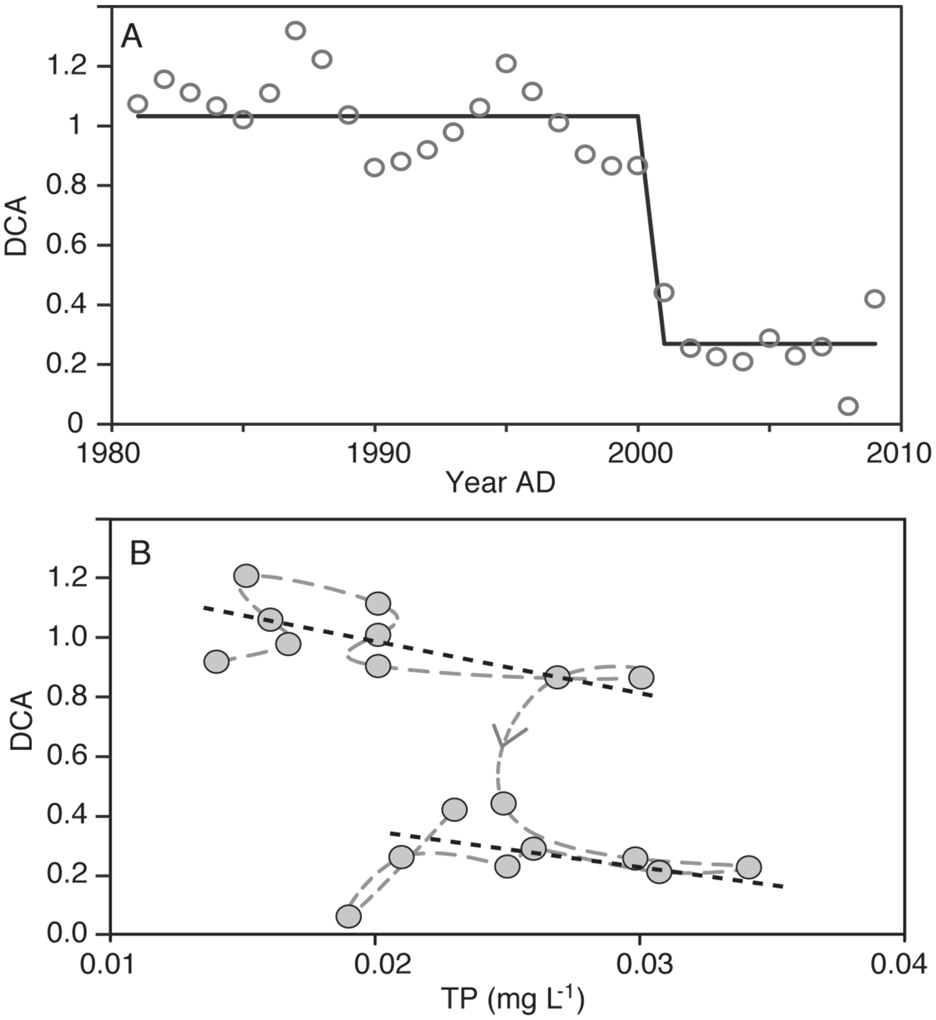

Figure 2: Regime shift, tipping point and alternative stable states at Erhai lake, Yunnan, China (after Wang et al. 2012). **(A)** Student's t-test on sequential analyses of diatom DCA data from deep water sediments which indicates a clear tipping point in 2001 from mesotrophic to hypereutrophic states. **(B)** Phase-space plot of instrumental measurements of total phosphorus (TP) from 1992-2009 plotted against changes in diatom state response (DCA axis 1 scores). The plot shows the two alternative states, the upper state (1992-2001) and lower state (2001-2009) occurred across TP values 0.02-0.03 mgl^{-1}, which is equivalent to 50% of the whole TP scale: this finding is strong evidence for alternative states and hysteresis.

Future challenges

We do not yet understand why tipping points occur in some lakes and not others, nor are we able to identify EWS with confidence. There is much scope for more empirical data collection and analyses targeted at the detection of tipping points and EWS in lake ecosystems. More data will improve our modeling approaches and advance theoretical developments. Paleolimnological data offer great potential in these respects especially where time-series of sub-decadal ecological processes can be resolved at equal increments. Significant advances in identifying and anticipating tipping points in lakes and other systems are not only possible but eagerly awaited by the wide scientific community.

AFFILIATIONS
[1]Geography & Environment, University of Southampton, UK
[2]Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China

CONTACT
Peter G. Langdon: P.G.Langdon@soton.ac.uk

REFERENCES

Batt RD et al. (2013) PNAS 110: 17398-17403

Battarbee RW et al. (2014) Ecol Indic 37: 365-380

Carpenter SR et al. (2011) Science 332: 1079-1982

Doncaster CP et al. (in press) Ecology, doi: 10.1002/ecy.1558

Hastings A, Wysham D (2010) Ecol Lett 13: 464-472

Kéfi S et al. (2013) Oikos 122: 641-648

Sayer CD et al. (2010) Freshwater Biol 55: 500-513

Scheffer M (2009) Critical Transitions in Nature and Society. Princeton University Press, 400 pp

Scheffer M et al. (2012) Science 338: 344-348

Seekell DA et al. (2012) Ecosystems 15: 741-747

Seekell DA et al. (2013) Theor Ecol 6: 385-394

Wang R et al. (2012) Nature 492: 419-422

Weaver IS, Dyke JG (2016) Earth Syst Dyn Discuss doi:10.5194/esdd-6-2507-2015

Multi-decadal climate variability as triggers of societal regime shifts in Japan

Takeshi Nakatsuka

The PAGES Asia2k summer temperature reconstruction since 800 CE is providing valuable insights into Japanese history. We demonstrate that multi-decadal temperature variability is closely associated with famines and warfare in Japan, resulting in significant societal changes.

Japanese historians have frequently remarked that climate may have had a significant impact on historical events, but have not reached a consensus on the mechanisms of change. A major challenge has been the use of different paleoclimate data based on a range of natural proxies, which were sometimes incorrect or contradictory to one another. In many instances, time series of past climate were arbitrarily selected by historians to support specific arguments. Of particular concern has been the inclusion and recognition of low-quality paleoclimate data for the robust analysis of climate and history relationships in Japan.

The Asia2k reconstruction

The PAGES 2k Network has successfully reconstructed annual changes in continental temperature by integrating many climate-sensitive proxy data over the past 2000 years (PAGES 2k consortium 2013). The strategy to use available datasets with strict selection criteria has helped make more reliable reconstructions. As part of this effort, the Asia2k Working Group has compiled more than 200 tree-ring chronologies beginning before 1600 CE over a wide region in Asia (east of 70˚E), enabling the development of yearly summer temperature variations in individual grid points since 800 CE. Crucially, an average East Asia summer temperature reconstruction has been generated across all 2° grid points north of 23˚N (Cook et al. 2013). Although the original tree-ring chronologies are mainly distributed in inland cold regions, such as Tibet, Himalaya and Mongol, the reconstructed temperature variation corresponds well to the summer temperature index during early modern Japan (Fig. 1A) estimated from documentary records of climate disasters (Maejima and Tagami 1986). Because tree-ring based temperature reconstructions have typically been limited to the last 500 years in Japan, the new Asia2k paleo-temperature data enables us, for the first time, to elucidate climate and history relationships at annual time scales for medieval and ancient Japan before 1500 CE.

Apparent coincidence to Japanese history

Multi-decadal variability in the East Asia summer temperature appears to have been enhanced during the 12-15th centuries in medieval Japan, and was associated with numerous famines and wars which culminated in the Sengoku period, characterized

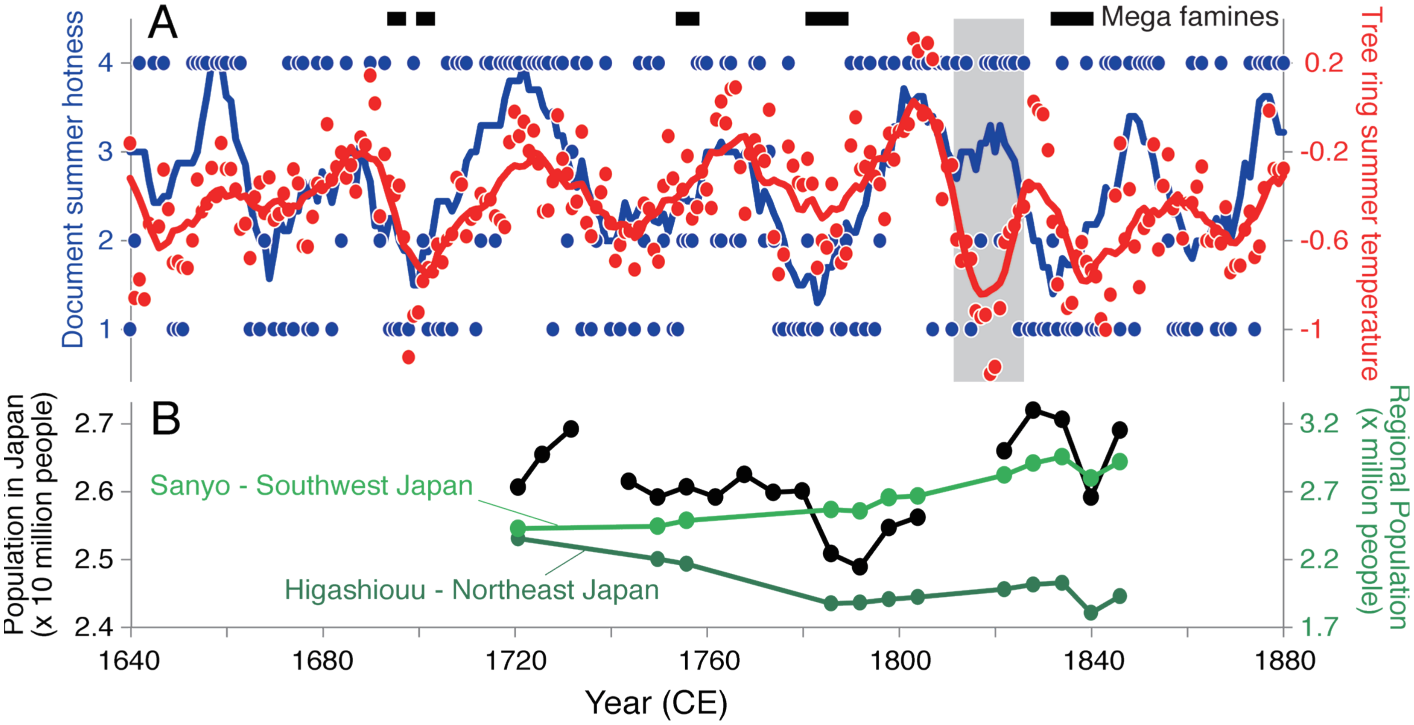

Figure 1: (A) Tree-ring based East Asia summer temperature reconstruction (red; Cook et al. 2013) and document-based Japanese summer hotness estimation (blue; Maejima and Tagami 1986) during 17-19th centuries. Solid circles and thick curves show annual and 11 years running mean values, respectively. Except for the extremely cold winter of 1820 CE (gray shade), both time-series parallel one another closely. Upper black thick lines indicate occurrence of mega famines in northeast Japan. **(B)** Populations in Japan (black solid) and two regions (green).

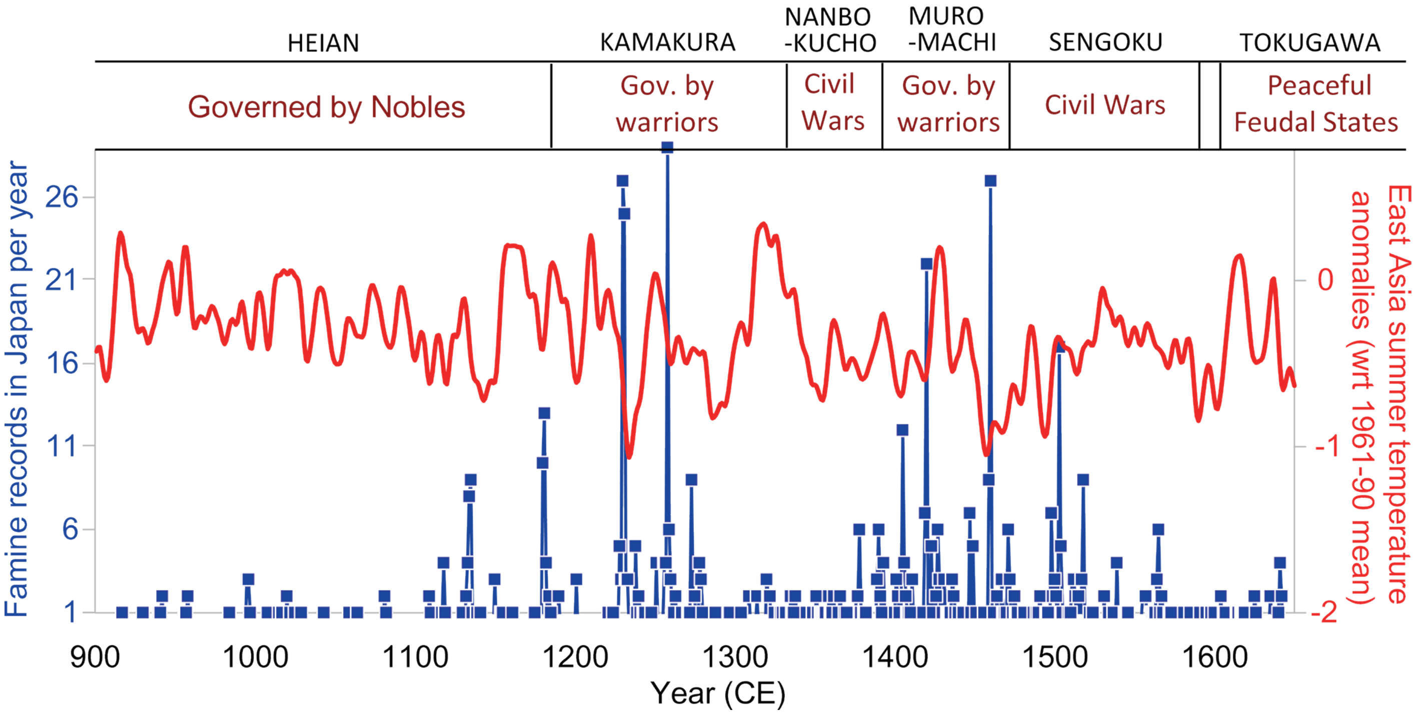

Figure 2: Number of documentary records of famine per year in Japan (blue; Fujiki 2007) and 11-year running mean of East Asia summer temperature (red; Cook et al. 2013). Upper panels define key historic periods (black: name of era; brown: political characteristics).

by near-constant warring states and societal unrest in the 16th century (Fig. 2). The comparison between temperature and historical events demonstrates that abrupt cooling after 10-20 years of long warmth often caused famines characterized by unprecedented numbers of deaths (Fig. 2) and sustained periods of warfare. Because pre-modern Japanese societies were based on rice paddy cultivation, the increase in rice yields during the warm period might have led to overpopulation, resulting in a society poorly prepared for the following cold period and the inevitable decline in agricultural yields. An example is the Kangi mega-famine in 1230-1231 CE, caused by the abrupt drop in summer temperature after several decades of unprecedented warmth from the middle of the 12th century. Another example is the Kansho famine of 1459-1460 CE, which led to the Onin war (1467-1477 CE), the destruction of the capital city Kyoto, and ultimately led to Japan becoming an aggregate of warring states. Overall, multi-decadal temperature variability from the 12-15th centuries appears to have resulted in many serious societal disturbances, with political government led by nobles during periods of relatively stable climate, followed by civil wars and warrior leadership during subsequent climate instability. It therefore seems that temperature variability was a major driver of societal regime shifts.

The cause-and-effect relationship between multi-decadal climate variability and societal responses can also be observed in the early modern period (17-19th centuries; Fig.1). During the bi-decadal warmth around 1720 and 1800 CE, rice yields rose and population increased even in cold northeast Japan, where rice normally grew poorly under average climate. Local people in northeast Japan became involved in the national rice market, selling excess rice and raising capital to support the finance of local lords and improve the living standard of peasants. These sustained warm conditions thus made adaptation to abrupt cooling difficult, tragically resulting in famines. When the climatic situation changed and famines occurred, the people in Japan started to rebel against the Tokugawa government. Although the Tokugawa government suppressed rebellions at that time, the frequent famines in northeast Japan led to geographical balance change in population and economy (Fig. 1B), leading to a "stronger" southwest region and the reformation of government in 1868 CE conducted by the people from the southwest Japan.

Paleodata for historical studies

The above-mentioned examples for the apparent coincidences between climate changes and historical events in medieval and early modern Japan are, however, special cases. In fact, modes of societal responses to climate change differed depending on the region and period they took place. Abrupt cooling in medieval Japan often caused famines, but we cannot find many indications of famines during the 14th century in historical documents (Fig. 2). While famines directly resulted in war in the late 15th century, they did not cause war in the 13th century. In some feudal domains of northeast Japan during the 18th century, local lords could save people from starving, even when a famine, due to crop failure, killed several hundred thousand people in total over northeast Japan (Fig.1).

As a result, we find there are many lessons embedded in history of societal adaptability to climate change. To date, however, historians have been limited in their ability to critically assess past societal responses to climate changes, because previous studies on human history have not had access to robust paleoclimate data such as that generated by Asia2k. Crucially, we can now learn from past societal struggles to overcome climate disasters by precisely comparing paleoclimate data with the enormous historical and archeological evidence available in Japan. Our results suggest this is a promising way for the promotion of new inter-disciplinary studies between humanity and natural sciences, contributing to the strategy of Future Earth. In Japan, an inter-disciplinary research project "Societal adaptation to climate change: Integrating paleoclimatological data with historical and archaeological evidences" (www.chikyu.ac.jp/rihn_e/project/H-05.html) is now ongoing, to take advantage of the full potential of paleoscience.

AFFILIATIONS

Research Institute for Humanity and Nature, Kyoto, Japan

CONTACT

Takeshi Nakatsuka: nakatsuka@chikyu.ac.jp

REFERENCES

Cook ER et al. (2013) Clim Dyn 41: 2957-2972

Fujiki H (2007) "Chronological Table of Medieval Climate Disaster" (in Japanese)

Maejima I, Tagami Y (1986) Geog Rep Tokyo Metro Univ 21: 157-171

PAGES 2k consortium (2013) Nature Geosc 6: 339-346

Simple tipping or complex transition? Lessons from a green Sahara

Sebastian Bathiany[1,2], M. Claussen[2,3], V. Brovkin[2], M. Scheffer[1], V. Dakos[4] and E. van Nes[1]

The history of the Sahara provides an example for our changing perspective on abrupt change in the Earth system. The emerging concepts can help us to understand past transitions and assess potential future tipping points.

Little does the monotonous and hostile environment of today's Sahara Desert tell us about its colorful past. However, climate and vegetation reconstructions reveal that several thousand years ago, parts of the Sahara resembled a flourishing garden with extensive vegetation and lakes (Jolly et al. 1998). This green Sahara was only the most recent of many green episodes in North Africa's history. The most important driver of these landscape transformations was the permanent change in the Earth's orbital parameters (Kutzbach 1981). When the distance between Earth and Sun is smallest during boreal summer, the larger solar irradiation intensifies the West African monsoon and thus increases rainfall.

While it is obvious that rainfall is beneficial for vegetation, climate models indicate that vegetation can also enhance rainfall. First, the dark vegetation absorbs more sunlight than the bright desert and provides energy for convection (Charney et al. 1975). Second, the evaporation from vegetation and lake surfaces feeds the water back into the atmosphere (Rachmayani et al. 2015). Vegetation and rainfall are therefore linked in a self-amplifying process, a positive feedback. The stronger this feedback, the more abrupt the transition from a green Sahara to a desert (Fig. 1).

Whereas orbital parameters change gradually over thousands of years, model results (Claussen et al. 1999) and a dust record from the Atlantic (de Menocal et al. 2000) suggested a quite rapid vegetation loss at the end of the green Sahara. This seemed to support the view of a switch from a green state to a desert state, a natural climate catastrophe comparable to a chair suddenly tipping over when it is slowly tilted. Such tipping points have been found not only in atmosphere-vegetation models (Brovkin et al. 1998), but also in simple models representing ocean circulation, Arctic sea ice, ice shields, savannah and lake ecosystems, and the East Asian and Indian monsoons.

Tipping points in a world of complexity

Each tipping point in the simple models mentioned above results from a positive

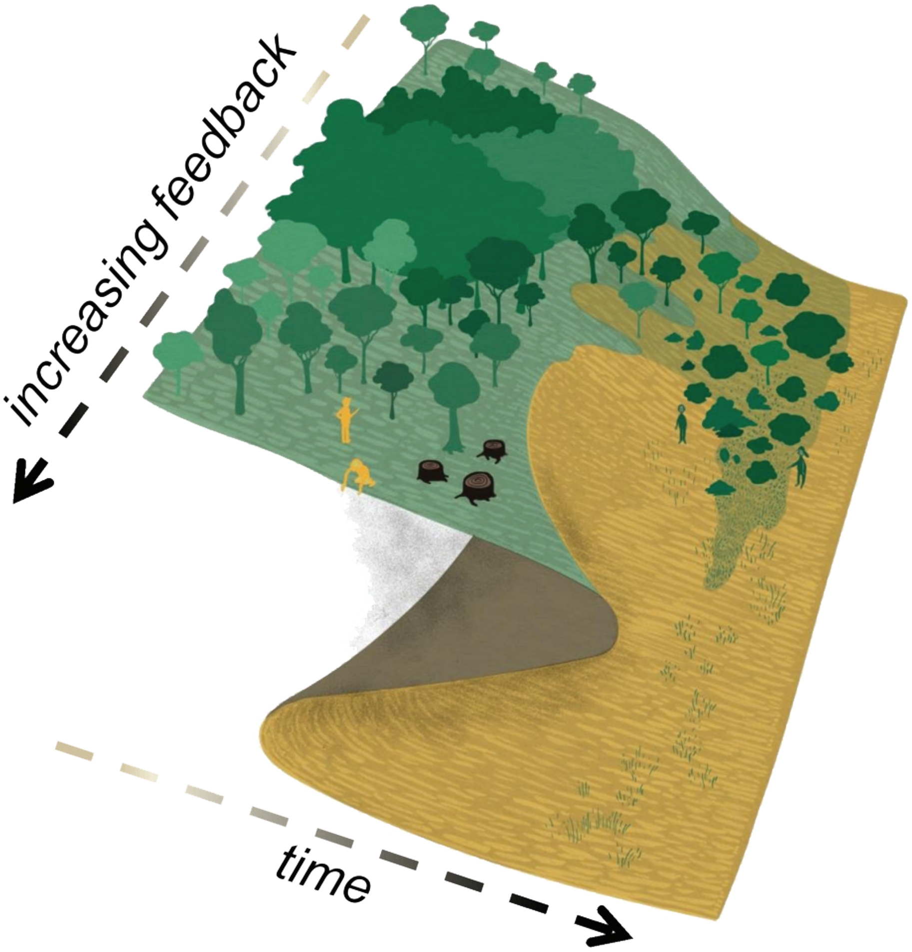

Figure 1: Stability landscape of green Sahara and desert. The larger the atmosphere-vegetation feedback, the sharper the transition between the two states. From: Model Calendar 2015, designed by Elsa Wikander at Azote, funded by the Beijer Institute of Ecological Economics and the Stockholm Resilience Centre.

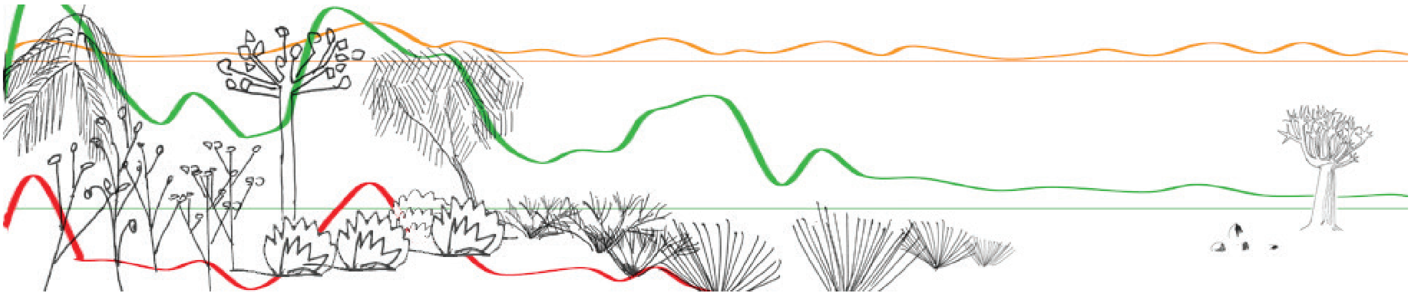

Figure 2: Idealized abundance of East Saharan plant types from 6000 to 3500 years ago (from left to right) with Acacia (orange), Poaceae (green) and tropical plant taxa (red). Pollen records after Kroepelin et al. (2008), drawing by Dominique Donoval, Max Planck Institute for Meteorology, Hamburg.

feedback. However, in reality, the rate of a transition is not a question of feedbacks alone. For instance, fast fluctuations in the weather permanently perturb the vegetation and other slow components of the Earth system. These fluctuations thus superimpose an otherwise smooth transition and can either make it more gradual or even more pronounced (Liu et al. 2006).

Moreover, there are reasons to believe that the spatial heterogeneity of the land surface tends to make transitions smoother on large spatial scales (Brook et al. 2013). Indeed, different records from the Sahara, such as pollen reconstructions from northern Chad (Kroepelin et al. 2008; Fig. 2), suggest a spatially inhomogeneous transition to today's desert and a gradual decrease in rainfall. Theoretical modeling studies confirm that if different locations are only weakly connected or very dissimilar, every location changes with its own timing, and transitions tend to be gradual on large scales (van Nes and Scheffer 2005). Even in the case of a uniform climate, vegetation still consists of different plant types with different moisture requirements, promoting a gradual change in vegetation composition instead of a singular vegetation dieback (Claussen et al. 2013; Fig. 2).

It is therefore quite clear that the Sahara Desert was not born in one synchronized tipping event. Nonetheless, the case of the green Sahara reminds us that we also need to take spatial interactions into account, because the winds and currents in the atmosphere and ocean couple different locations. Naturally, this connection tends to be strongest between adjacent places since properties like water and energy are transported from one place to the next. But large-scale circulation features like the African monsoon or the ocean's overturning circulation can also couple locations very far from each other. Strong links in the network of interactions can synchronize transitions and promote abrupt change far from the origin of its occurrence. An abrupt climate change at a single location may thus trigger a domino effect of climate changes at different locations. The question is therefore not only whether tipping points exist but also whether there are local hotspots where a system is particularly vulnerable (Bathiany et al. 2013).

Finally, neither climate feedbacks nor spatial interactions are required to obtain abrupt change on a local level. First of all, ecological systems can have tipping points of their own (Scheffer et al. 2001), and many physical and biological systems have intrinsic thresholds, like the freezing temperature of water or the wilting point of plants. Secondly, a shift in the position of sharp spatial gradients or circulation patterns can cause abrupt change at a particular location. For example, the gradual spatial shift of the vegetation distribution may locally be seen as a sudden desertification. Abrupt change in paleorecords like the dust record by de Menocal (2000) could thus be interpreted to result from a shift in the desert boundary or the wind direction.

An uncertain future

In the light of all these mechanisms at play, the reconstructions from the Sahara leave room for interpretation. Has the Sahara taken its green secret to the grave? And are tipping points only a Fata Morgana, caused by oversimplified models? Research on other potential climate tipping points indicates that this may be true. So far, comprehensive climate models cannot convincingly answer the question if large-scale climate tipping points are ahead in the near future (Drijfhout et al. 2015). However, there is evidence that abrupt climate changes happened in the Earth's history. The potential damage such events may cause, and the large uncertainty of their occurrence, require us to assess the risk of future abrupt change by improving our scientific understanding.

The crucial questions of this assessment are the same as for the Sahara. What is the balance of the relevant feedbacks? How homogeneous is the system and are there strong spatial connections? What is the interplay between fast variability and slow system components, and what can we learn from the variability? Are there natural thresholds which promote or prevent abrupt change? As the physical or biological processes differ in each case, answers may depend on which potential tipping point is considered. Bridging the gap between the world of tipping point concepts and the world of process understanding will therefore be key to scientific progress. The green Sahara provides an example for this challenge. Even though its decline was overall more gradual than previously thought, it remains a fruitful case study to explore the above questions. Insofar, the green Sahara has not turned to dust, but flowers in a greater context.

AFFILIATIONS

[1]Department of Environmental Sciences, Wageningen University, The Netherlands
[2]Max-Planck-Institute for Meteorology, Hamburg, Germany
[3]Meteorological Institute, University of Hamburg, Germany
[4]Center for Adaptation to a Changing Environment, ETH Zürich, Switzerland

CONTACT

Sebastian Bathiany: sebastian.bathiany@wur.nl

REFERENCES

Bathiany S et al. (2013) Earth Syst Dynam 4: 63-78
Brook B et al. (2013) Trends Ecol Evol 28: 396–401
Brovkin V et al. (1998) J Geophys Res 103: 31613-31624
Charney J et al. (1975) Science 187: 434-435
Claussen M et al. (1999) Geophys Res Lett 26: 2037-2040
Claussen M et al. (2013) Nat Geosci 6: 954-958
de Menocal P et al. (2000) Quat Sci Rev 19: 347-361
Drijfhout SS et al. (2015) PNAS 112: 5777-5786
Jolly D et al. (1998) J Biogeog 25: 1007-1027
Kroepelin S et al. (2008) Science 320: 765-768
Kutzbach JE (1981) Science 214: 59-61
Liu Z et al. (2006) Geophys Res Lett 33, doi:10.1029/2006GL028062
Rachmayani R et al. (2015) Clim Past 11: 175-185
Scheffer M et al. (2001) Nature 413: 591-596
van Nes E, Scheffer M (2005) Ecology 86: 1797-1807

The domestication of fire as a social-ecological regime shift

Reinette Biggs[1,2], W.J. Boonstra[1], G. Peterson[1] and M. Schlüter[1]

Social-ecological regime shifts involve large, often abrupt, reorganizations in interlinked social and ecological systems. The domestication of fire illustrates how physiological and social changes enabled humans to start actively controlling fire, dramatically reshaping the environment and society itself.

While many changes to the environment occur gradually in response to changing conditions, some changes occur abruptly and may be difficult or impossible to reverse. Examples of such changes have been documented in terrestrial, aquatic, marine and climate science, as well as in archeology and psychology, at timescales ranging from paleo records to contemporary observations (Scheffer 2009; also see www.regimeshifts.org). In this article, we briefly introduce the notion of social-ecological regime shifts, namely abrupt shifts that involve components of both social and ecological systems.

What is a social-ecological regime shift?

There is growing interest in social-ecological regime shifts, which we define as a substantive change in the structure and function of interconnected social-ecological systems (SES). Such shifts are associated with a reconfiguration of dominant feedback processes and typically arise from a combination of gradual changes in underlying conditions and a large external shock (Biggs et al. 2012; Fig. 1). Although the shift itself may take decades or centuries, it is usually abrupt relative to the duration of each regime. Social-ecological regime shifts are important as they often have substantive impacts on the ecosystem services and benefits people obtain from SES, and often occur unexpectedly.

While studies have addressed regime shifts in ecological, and to some extent, social systems, there has been limited work on shifts in coupled SES. As with the broader emerging area of SES studies, it is still unclear how social-ecological regime shifts can be most usefully conceptualized and analyzed. Currently, the notion of social-ecological regime shifts can refer to: (1) shifts that arise from ecological dynamics (e.g. eutrophication) and consider the social and economic impacts of these changes; (2) shifts that arise from social dynamics (e.g. introduction of new legislation) and their consequent environmental effects; and (3) cases where the actual shift itself arises from the interaction of social and ecological processes (e.g. harvesting of common pool resources). The latter is perhaps most interesting as it may account for shifts that cannot arise from either social or ecological dynamics, but only occur due to the interaction of these components (Lade et al. 2013).

The concept of social-ecological regime shifts may differ somewhat from that of ecological regime shifts in terms of the type of changes it helps explain. Rather than focusing on the potential for systems to flip "back and forth" between alternate regimes (e.g. clear vs murky water lakes), it may be more useful in explaining "punctuated" change over time – i.e. periods of relatively rapid change that separate longer periods that are relatively stable, but quite different from one another in terms of SES structure and function. The inclusion of social dynamics, which enhances memory, learning, and anticipation in SES, amplifies the role of history and path dependence, reducing the reversibility of shifts. The domestication of fire illustrates this dynamic very clearly.

Domestication of fire as a social-ecological regime shift

Learning how to control fire dramatically changed how humans interacted with each other and their natural environments. Fire domestication appears to have become widespread among hominins by some 300-500 thousand years ago (Sandgathe et al. 2011). Researchers have argued that this marks the start of the

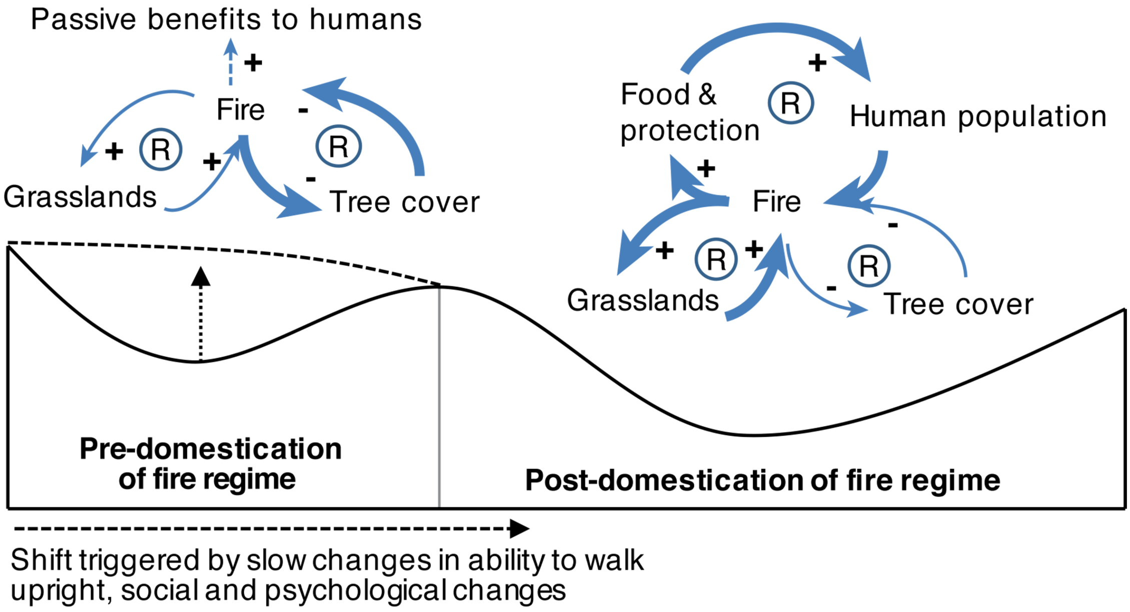

Figure 1: Simplified schematic of the shift in dominant systemic feedback processes associated with the domestication of fire and increased global abundance of grasslands. Bold arrows depict dominant feedbacks shaping social and ecological dynamics in the different regimes; R depicts reinforcing feedbacks.

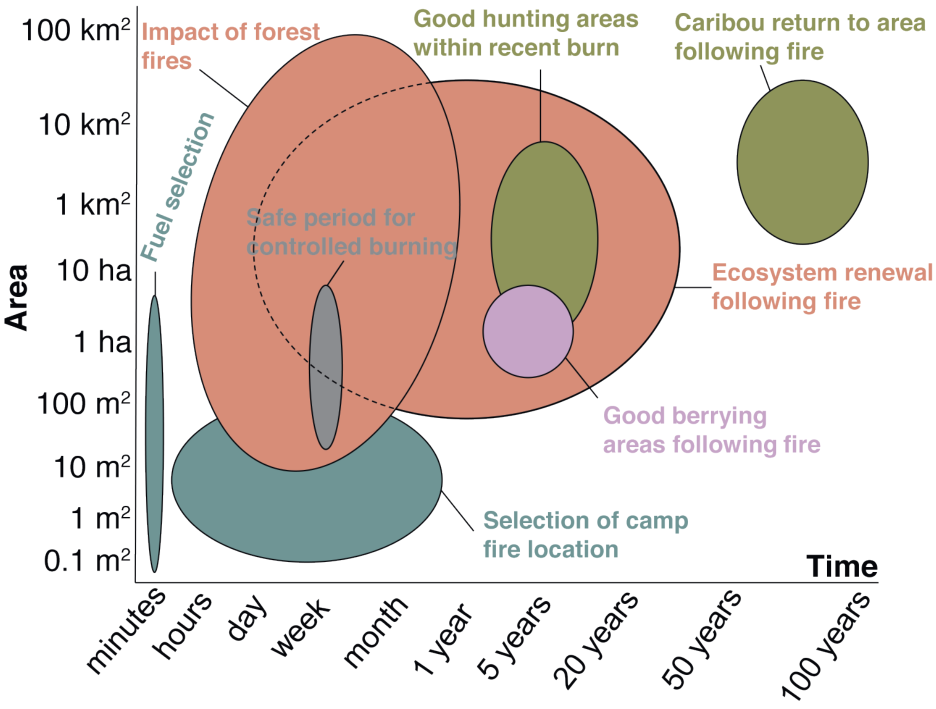

Figure 2: Spatial and temporal dimensions of knowledge related to fire use and its impacts held by Anishinaabe elders in Ontario, Canada, and the areas of expertise they require. Modified from Miller and Davidson-Hunt 2010.

Anthropocene and humanity as an Earth-transforming species (Glikson 2013).

The domestication of fire involved a shift from a long period in which hominins only passively enjoyed the benefits of fire, to a situation where they actively controlled its use (Goudsblom 2015). Researchers believe that active control of fire required physiological changes, in particular the ability to walk upright, which enabled people to use sticks to transport fire and supply it with fuel. However, social and psychological changes were also crucial: obtaining fire from wildfires, and handling and maintaining it required effort, observation, patience, anticipation and social negotiation (Twomey 2013). Before hominins could actively control fire, these social and mental skills had to become part of a learned repertoire of shared ways of thinking and doing (Goudsblom 2015; Sandgathe et al. 2011; Fig. 2).

The domestication of fire changed human demography and social interactions, and fundamentally restructured the ways in which hominins interrelated with their environments. On-site fires in hearths were used to cook food, which greatly expanded the range of foods that hominins could eat and preserve (Wrangham 2009). On-site fires also helped fend off large hominin predators such as saber-toothed cats, drive off mosquitoes and poisonous animals, harden and bend tools, and provide a source of warmth and light. They could also be used for signaling. Off-site burning in the wider landscape similarly helped hominins improve their access to food and make predators more visible. Burning of the landscape was also important for clearing vegetation, driving and attracting animals, clearing pathways, waterholes and campsites, signaling, asserting rights, warfare, ritual activities, and for aesthetic pleasure and entertainment (Scherjon et al. 2015).

Anthropogenic burning of the landscape was typically patchier, and more extensive and intensive than wildfires, and in time reshaped entire ecosystems (Bowman et al. 2011). This impact is most clearly expressed in the increasing global abundance of grasslands after the domestication of fire (Pyne 2013). Control of fire also changed the balance of power between hominins and the species they competed with for food (including other hominin groups), or that preyed on them. Anthropogenic burning of landscapes may have contributed to the mass extinction of large animals during the Pleistocene (Rule et al. 2012). The use of fire therefore radically changed the ecological niche of (early) humans (Odling-Smee et al. 2003).

This example illustrates how ecological, social and psychological changes reinforced one another to produce far-reaching changes, that not only permanently reshaped ecosystems and human society, but also the relationship between humans and nature (Fig. 1). This massive systemic reconfiguration has been argued to have set the stage for further large-scale social-ecological regime shifts. Changes involved in the domestication of fire spurred other social developments such as the creation of language, development of tools, population growth, enculturation (the learning of socially learned habits, routine and norms), and social distinction (Twomey 2013) that created the possibility for further radical innovations in time, most notably the domestication of plants and animals for agriculture (Burton 2009).

Conclusion

Social-ecological regime shifts are important from both a scientific and a policy perspective, as they provide a conceptual framework for understanding non-linear change associated with restructuring of coupled SES. Over shorter time horizons, social-ecological regime shifts often have large impacts on the functioning of ecosystems and society, and therefore on human wellbeing. Furthermore, such shifts usually occur unexpectedly and are often difficult or impossible to reverse, making them difficult for society to cope with or adapt to.

Over longer time horizons, social-ecological regime shifts may have far-reaching effects, fundamentally restructuring the relationships between people and nature and the long term trajectory of global change. The potential for such radical transformative change suggests that, in the context of the tremendous sustainability challenges society faces today, we should consider more deeply how shifts to more sustainable societies could unfold. The diverse, interconnected set of changes involved in the domestication of fire suggests that a transition to more sustainable societies is unlikely to involve only the development of new technologies and legislation that reduces environmental impacts. Instead, such technological and institutional changes are likely to fundamentally reshape both society and the environment in time, and transform the relationship between people and nature in ways that are difficult to foresee.

AFFILIATIONS

[1]Stockholm Resilience Centre, Stockholm University, Sweden

[2]Centre for Complex Systems in Transition, Stellenbosch University, South Africa

CONTACT

Reinette Biggs: oonsie.biggs@su.se

REFERENCES

Biggs R et al. (2012) In: Hastings A, Gross L (Eds) Encyclopedia of Theoretical Ecology. University of California Press, 609-617

Bowman DMJS et al. (2011) J Biogeogr 38: 2223-2236

Burton F (2009) Fire: the spark that ignited human evolution, University of New Mexico Press, 246pp

Glikson A (2013) Anthropocene 3: 89-92

Goudsblom J (2015) Fire and Civilization [In Dutch: Vuur en Beschaving], Van Oorschot, 295pp

Lade S et al. (2013) Theor Ecol 6: 359-372

Miller MA, Davidson-Hunt I (2010) Hum Ecol 38: 401-414

Odling-Smee FJ et al. (2003) Niche construction: the neglected process in evolution, Princeton University Press, 488pp

Pyne S (2013) Fire: Nature and Culture, Reaktion Books, 207pp

Rule S et al. (2012) Science 335: 1483-1486

Sandgathe DM et al. (2011) PNAS 108: E298

Scheffer M (2009) Critical transitions in nature and society, Princeton University Press, 400pp

Scherjon F et al. (2015) Curr Anthropol 56: 299-326

Twomey T (2013) Camb Archaeol J 23: 113-128

Wrangham R (2009) Catching fire: how cooking made us human, Basic Books, 320 pp

Squeezing a rainfall record out of desert sand dunes

Abi Stone[1,2]

Pore moisture within desert sand dunes provides a novel archive for paleomoisture availability. Hydrostratigraphies are produced from variations in chemical tracers in a vertical profile. The applicability has been demonstrated in drylands in five continents and three examples are given here.

Reconstructing past rainfall fluctuations in drylands is challenging. The deposition of sedimentary archives, such as sand dunes, are mediated by a number of factors, of which changing moisture availability is just one. Former river courses, and former lakes fed by rivers, often record changes imported from a climatic zone outside their dryland location (exogenous systems). Speleothems are restricted to limestone terranes and tend to be discontinuous records in drylands. Isotopic records within hyrax middens have growing potential, but are also spatially restricted to areas with rock-ledge habitats. Therefore, developing further proxies capable of recording changes in moisture availability is extremely valuable for dryland Quaternary environmental reconstruction.

Chemical tracers within sand dune pore moisture offer a novel additional proxy for paleomoisture availability. When and where this moisture moves downward, fluctuations in its chemical signature with depth can be utilized to establish a record of changes to moisture availability through time, based on the transport of a signal built up in the near-surface zone (Fig. 1). The resolution and timescale of the preserved hydrostratigraphy depends on the rate of moisture movement and the thickness of sediment (Stone and Edmunds 2016). Applications over a range of timescales are briefly explored to demonstrate the utility of this approach.

Basis of tracer technique

Pore moisture in sand dunes above the water table is described as the unsaturated zone (USZ) of the hydro(geo)logical cycle. It is in this USZ that hydrostratigraphies can be reconstructed, based upon variations in chloride concentration in pore moisture. The chloride signal is established in the near-surface recycling zone, and this inherited signal is then transmitted vertically in the moisture that is infiltrating through the sediment, so that a depth-based profile of samples represents a temporal record (Fig. 1).

The input of moisture at the surface from precipitation contains solutes, including chloride. The long-term average concentration of this input can be established empirically, and varies between regions as a function of continentality. The chloride input gets modified in the near-surface zone by evapotranspiration, which removes water and enriches the chloride concentration, and by mixing (Fig. 1). Below the zone of recycling, moisture moves downwards, and movement is closest to homogenous in sand-rich sediments containing some finer-fraction sediment (e.g. Gehrels et al. 1998). This means that the concentrations of chloride in pore-moisture at sequential depths are a record of a climatically driven process in the zone of recycling before being transmitted down to that depth. The record can be read as low(high) chloride concentrations recording high(low) moisture availability. A certain degree of smoothing of the record will have occurred in the recycling zone, including smoothing variations between individual rainfall events.

Records of land-use changes and precipitation

USZ hydrostratigraphies can be used to quantify increases in moisture flux through sediments as a result of land-use change. In southwestern Australia, clearance of native eucalyptus vegetation increased recharge rates from ~0.1 mm yr^{-1} under intact vegetation to 2.5-8.5 mm yr^{-1} and 3.8-28.0 mm yr^{-1} under pasture and cereal cropped land respectively (Cook et al. 1994). This is demonstrated clearly in the hydrostratigraphy by a vertical displacement of a single subsurface chloride peak in cleared sites compared to intact sites.

The influence of artificial irrigation can also be investigated. In the Thar Desert, northwest India, multi-decadal length hydrostratigraphies demonstrate a recharge rate under irrigated cropland of 18-98 mm yr^{-1} as compared to 2.7-5.6 mm yr^{-1} in a non-irrigated dune (Scanlon et al. 2010).

Over timescales of a few hundred years, the potential of USZ hydrostratigraphies as proxies for precipitation has also been demonstrated. For example, a 108-year-long

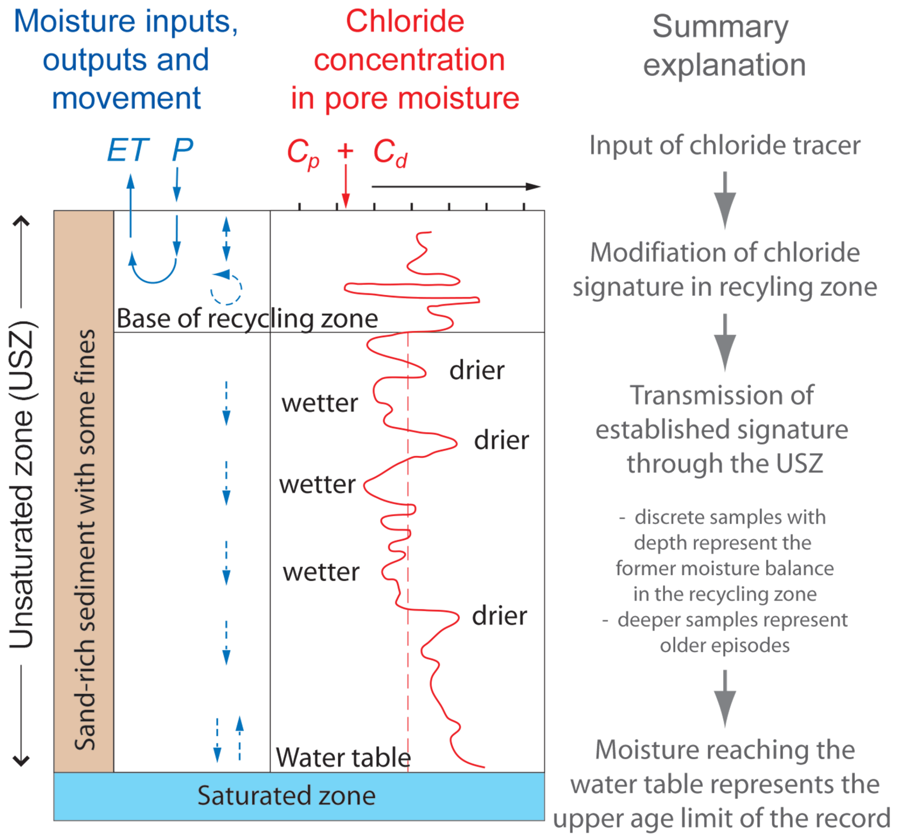

Figure 1: Schematic diagram to demonstrate the basis of the unsaturated zone hydrostratigraphy approach (P is precipitation, ET is evapotranspiration, C_p is concentration of chloride in precipitation and C_d is concentration of chloride in dry deposited material), modified from Stone and Edmunds (2016).

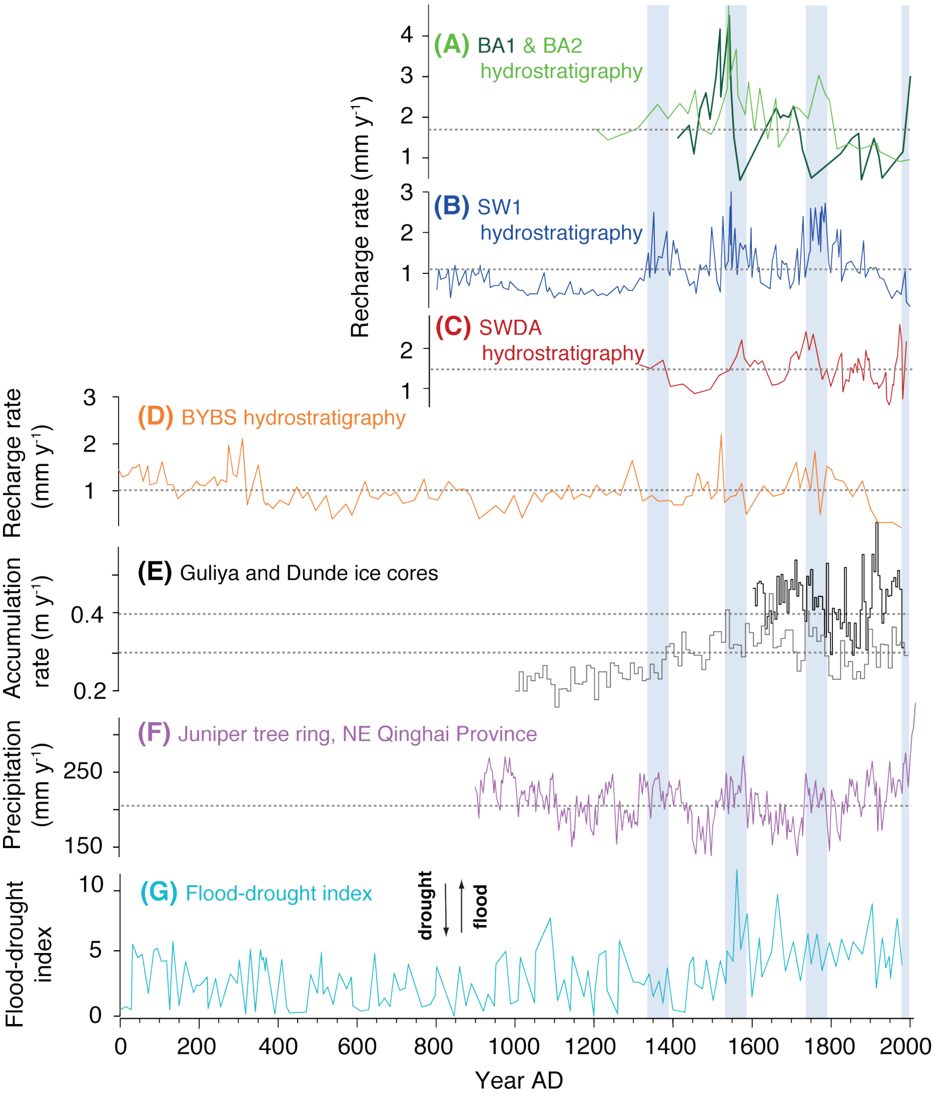

Figure 2: Paleohydrologic records from five USZ hydrostratigraphies from the Badain Jaran desert **(A)** BA1 (solid line) and BA2 (dashed line) near Baoritelegai (Ma and Edmunds 2006), **(B)** SW1 near Sayinwusu (Ma and Edmunds 2006), **(C)** SWDA near Lake Sayinwsus (Gates et al. 2008), **(D)** BYBS near Lake Bayan Bur (Ma et al. 2009) and **(E)** Dunde (black line) and Guliya (gray line) ice-core accumulation rate (Thompson et al. 1997), which are ca. 400 km and 2000 km from the Badain Jaran desert. **(F)** Juniper tree-ring growth record from the NE Qinghai Province, China (Sheppard et al. 2004), which is ca. 500 km south of the Badain Jaran desert. **(G)** drought-flood index for China from historical documents (Zhang and Crowley 1989), modified from Stone and Edmunds (2016). The blue shaded vertical lines highlight where at least two hydrostratigraphies and two or more of the supporting proxy archive record wetter than average conditions.

hydrostratigraphy from Louga, Senegal correlates well with both a local precipitation record and Senegal River flow data, and records the 1970s Sahel drought and the 1940s dry period (Edmunds and Tyler 2002).

Records of climatic change in central Asia

Arguably the most significant development for dryland Quaternary environmental reconstruction using this approach comes from the decadal-scale resolution, multi-millennial length hydrostratigraphies from mega-dunes within the Badain Jaran desert in China (e.g. Ma and Edmunds 2006; Gates et al. 2008; Ma et al. 2009). The longest is a 30 m record spanning 2050 years, with four others >500 years. Comparisons with independent paleohydrological proxies for northern China have been made, which highlight wetter intervals in this region around 1350-1400, 1550-1600 and 1750-1800 and after 1990 (Fig. 2A-D). The three earliest wetter intervals are supported by above-average values for precipitation reconstructed from Juniper tree-ring growth records from the northeast Qinghai Province (Sheppard et al. 2004) and the middle phases are also phases of above-average ice-core accumulation in the Guliya ice core (Thompson et al. 1997) and above-average wetness in the flood-drought index (based on historical documents) (Zhang and Crowley 1989). However, the overall correspondence is not perfect, with some larger incursions in the other proxies not appearing in the USZ hydrostratigraphies, suggesting some regional complexity in paleohydrology in this region.

Reconstructing long-term dryland aridification

Initially driven by a motivation to assess whether the deep USZ in the semi-arid western United States might safely store nuclear waste without contaminating groundwater, more than a dozen hydrostratigraphies record an aridity trend through the Late Glacial and into the Holocene (e.g. Scanlon 1991; Phillips 1994; Tyler et al. 1996). The majority of profiles place this shift at around 16,000 to 13,000 years ago. There is one 240 m thick hydrostratigraphy at the Nevada nuclear test core than contains an earlier cycle from higher recharge to greater aridity during Marine Oxygen Isotope Stage (MIS) 5 (Tyler et al. 1996).

Conclusions and outlook

The unsaturated zone (USZ) in dryland environments is a novel and valuable archive, providing a direct paleomoisture proxy, where the enrichment of chloride acts as a tracer for the balance between precipitation and evapotranspiration. The sand-rich sediments required for this approach cover a portion of drylands where it is extremely challenging to reconstruct hydrological variations over the Quaternary, owing to poor preservation of biological material and a scarcity of water-lain sediments and speleothems.

Further development of modeling approaches that incorporate transient fluxes of water and tracer input concentrations (Ginn and Murphy 1997) will continue to reduce uncertainties within USZ hydrostratigraphies. Studies must routinely verify the suitability of the sediment texture at a site-by-site basis and avoid sediments that experience a very heterogeneous vertical flow of water.

USZ hydrostratigraphies have proven potential within drylands (Stone and Edmunds 2016). Depending on the thickness of the USZ sediment and the rate of moisture infiltration, hydrostratigraphies can record low-resolution trends in humidity-aridity over deglacial timescales, a decadal-resolution paleomoisture proxy for the last two millennia or quantify changes in moisture flux in sediment resulting from anthropogenic land use change.

AFFILIATIONS
[1]School of Environment Education and Development, The University of Manchester, UK
[2]School of Geography and the Environment, University of Oxford, UK

CONTACT
Abi Stone: abi.stone@manchester.ac.uk

REFERENCES

Cook PG et al. (1994) Water Resour Res 30: 1709-1719

Edmunds WM, Tyler SW (2002) Hydrogeol J 10: 216-228

Gates JB et al. (2008) Holocene 18: 1045-1054

Gehrels JC (1998) Hydrolog Sci J 43: 579-594

Ginn TR, Murphy EM (1997) Water Resour Res 33: 2065-2079

Ma J, Edmunds WM (2006) Hydrogeol J 14: 1231-1243

Ma J et al. (2009) Palaeogr Palaeocl 276: 38-46

Phillips FM (1994) Soil Sci Soc Am 58: 15-24

Scanlon BR (1991) J Hydrol 128: 137-156

Scanlon BR et al. (2010) Hydrogeol J 18: 959-972

Sheppard PR et al. (2004) Clim Dyn 23: 869-881

Stone AEC, Edmunds WM (2016) Earth-Sci Rev 157: 121-144

Thompson LG et al. (1997) Science 276: 1821-1825

Tyler SW et al. (1996) Water Resour Res 32: 1481-1499

Zhang P, Crowley TJ (1989) J Clim 2: 833-849

Top-class, new generation sediment coring on Research Vessel *Marion Dufresne*

Denis-Didier Rousseau[1], H. Leau[2], Y. Réaud[3], X. Crosta[4] and M. Calzas[3]

Over the last 20 years, the PAGES-endorsed IMAGES program (International Marine Past Global Change Study, http://www.images-pages.org/) supported 18 sea-going expeditions onboard the 120-meter-long Research Vessel *Marion Dufresne*. This vessel, operated by the French Paul-Emile Victor Polar Institute, was equipped with an in-house-developed, unique sediment coring facility, called CALYPSO, which allowed for the retrieval of high-quality, long marine cores at sites of high sedimentation rates. The vessel currently holds the world record for the longest marine core ever retrieved - 64.5 m. These cores enabled the comparison of marine and ice-core records at the same resolution for the first time, and tremendously improved the understanding of past oceans dynamics.

After 20 years of existence, both the coring system and the vessel were upgraded (Fig. 1) in an initiative funded by the French government to provide the scientific community with top-notch technological marine support for the new generation of coring tools. The new coring equipment, developed within the CLIMCOR project (http://climcor-equipex.dt.insu.cnrs.fr/?lang=en), provides the chance to collect high-quality oceanographical data as crucial complements for paleoclimatic data.

The objective is to routinely retrieve 75-meter-long, undisturbed sediment cores in any water depths to adequately address the scientific targets highlighted by international scientific programs. To achieve this, a specially designed DYNEEMA synthetic cable, with controlled minimum elasticity, has been developed to drastically reduce the sediment disturbance upon coring of the top meters of the core, which was the main flaw of the previous coring system. The first sea trials, operated in November 2015, show that when the corer is triggered just above the seabed at a water depth of 4500 m, the elastic rebound of the cable has been strongly reduced from 16 to 9 meters. This elastic rebound is due to the sudden release of the corer weight that was set to five tons for this test. This minimized elastic rebound should now guarantee undisturbed sediment recovery down to 4000 m water depth.

Other technical improvements lead to better control of the operation with a suite of pressure and acceleration sensors on the corer head and the triggering system, and software (e.g. CINEMA software developed by Ifremer; Bourillet et al. 2007; Woerther et al. 2012), allowing a detailed monitoring of the coring operation, increased safety of the operation both for the personnel and instrumentation, an optimization of ship time, and a larger choice of environment-data collection during the coring process, including detailed information on the degree of preservation of the recovered sediment sequence.

During its midlife refit, the vessel was adapted to suit this new long-core challenge. Scientific deck equipment, such as the coring winch and associated frame, the hydrological winch and the deployment system were upgraded. The coring handling equipment capacity was increased to 45 tons SWL (Safe Working Load) and the ship bulwark was modified to allow easier and safer deployment of a 75-meter-long corer.

Figure 1: Research Vessel *Marion Dufresne* in dry dock during her complete refit (photo by Damen Shiprepair Dunkerque).

Finally, a new suite of acoustic sensors was integrated on board the vessel, including KONSBERG EM122 and EM710 multibeam echo-sounders and a SBP 120-3 sub-bottom profiler. This equipment provides the highest image quality of the seabed and upper sediment, allowing an accurate survey of the coring targets. A new Ultra Short Base Line system (USBL Posidonia) was integrated to accurately locate the various corers on the seabed.

Due to the massive investment through the "Investissements d'Avenir" French national program, the refitted *Marion Dufresne* offers brand new and top-class coring equipment, able to collect up to 75-meter-long continuous sequences of undisturbed sediments at water depths as deep as 4500 m, which is available to the international paleoceanographic and paleoclimate communities for upcoming exciting and stimulating expeditions.

AFFILIATIONS

[1]Ecole Normale Supérieure, LMD, Paris, France
[2]French Polar Institute Paul Emile Victor, Plouzané, France
[3]CNRS, National Institute for Earth Sciences and Astronomy, Paris, France
[4]Bordeaux University, EPOC, Pessac, France

CONTACT

Denis-Didier Rousseau: denis.rousseau@lmd.ens.fr

LINKS

http://climcor-equipex.dt.insu.cnrs.fr/
http://www.cnrs.fr/
http://www.institut-polaire.fr/
http://www.agence-nationale-recherche.fr/investissements-d-avenir/

REFERENCES

Bourillet J-F et al. (2007) 6th International Conference on Offshore Site Investigation and Geotechnics: Confronting New Challenges and Sharing Knowledge. Society of Underwater Technology, London, UK

Woerther P et al. (2012) Improving in piston coring quality with acceleration and pressure measurements and new insights on quality of the recovery, INMARTECH 2012, Texel, the Netherlands

Unprecedented coring performance with the upgraded Research Vessel *Marion Dufresne*

Aline Govin[1], N. Vázquez Riveiros[1], Y. Réaud[2], C. Waelbroeck[1] and J. Giraudeau[3]

The MD203 ACCLIMATE expedition was the first coring cruise onboard the Research Vessel *Marion Dufresne* since her midlife refit in 2015 (Rousseau et al. 2016). Taking place in March 2016 in the South Atlantic Roaring Forties and Howling Fifties, this cruise provided a full-scale exercise to test, in rough sea conditions, the latest generation of sediment coring equipment.

To illustrate the unprecedented quality of long sediment sequences taken with the improved giant CALYPSO piston corer, we compared two deep-water cores collected ~13 km apart on the South African margin (Fig. 1): (1) core MD02-2587 taken in 2002 with the former coring facilities and (2) core MD16-3510 recovered with the new coring facilities.

The similarity of downcore sediment reflectance changes measured on board confirmed that both cores record the same climatic and environmental events (Fig. 1A-C). However, the 2002 core is stretched by up to 30% compared to the 2016 core, meaning that, for a similar core length, the 2016 core goes further back in time. Also, the 2002 core exhibited signs of coring deformation marked by bent dark layers, which, in contrast, are straight in the 2016 core (Fig. 1B). The absence of sediment stretching and deformation in the 2016 core thus highlighted the unprecedented quality of this ~45-meter-long core taken at ~4400 m of water-depth with a recovery rate higher than 94%!

Sediment stretching and deformation were known features of giant piston cores taken with the former R/V *Marion Dufresne* coring facilities (Skinner and McCave 2003). They were due to the elastic rebound of the cable, which, after the sudden release of the corer weight, caused the upward acceleration of the piston and hence over-sampling of the sediment.

Three major modifications of the R/V *Marion Dufresne* coring facilities, in addition to the modernized winch and gantry, led to the outstanding quality of sediment cores recovered during the ACCLIMATE cruise. First, the use of a specially designed DYNEEMA synthetic cable, with a controlled minimum elasticity, strongly limited the elastic rebound of the coring system. Second, the systematic use of the CINEMA software (Bourillet et al. 2007; Woerther et al. 2012), which specifically simulates the elastic rebound prior to coring operations, to optimize the corer settings according to the site's specificities (e.g. water-depth, corer configuration), further contributed to minimize sediment disturbances during coring. Finally, the implementation of pressure and acceleration sensors on the core head and the triggering system, and the injection of this data in the CINEMA software, allowed for a detailed monitoring of coring kinematics, in particular of the piston behavior. This approach led to a thorough understanding of the coring procedure and gave detailed information on the degree of preservation of the recovered sediment sequence.

The upgraded R/V *Marion Dufresne* is the sole research vessel able to collect up to 75-meter-long continuous sequences of undisturbed sediments at water depths as deep as 4500 m. The improved sediment coring facilities now yield cores of outstanding quality, which will provide indispensable high-resolution records to unravel past ocean and climate dynamics.

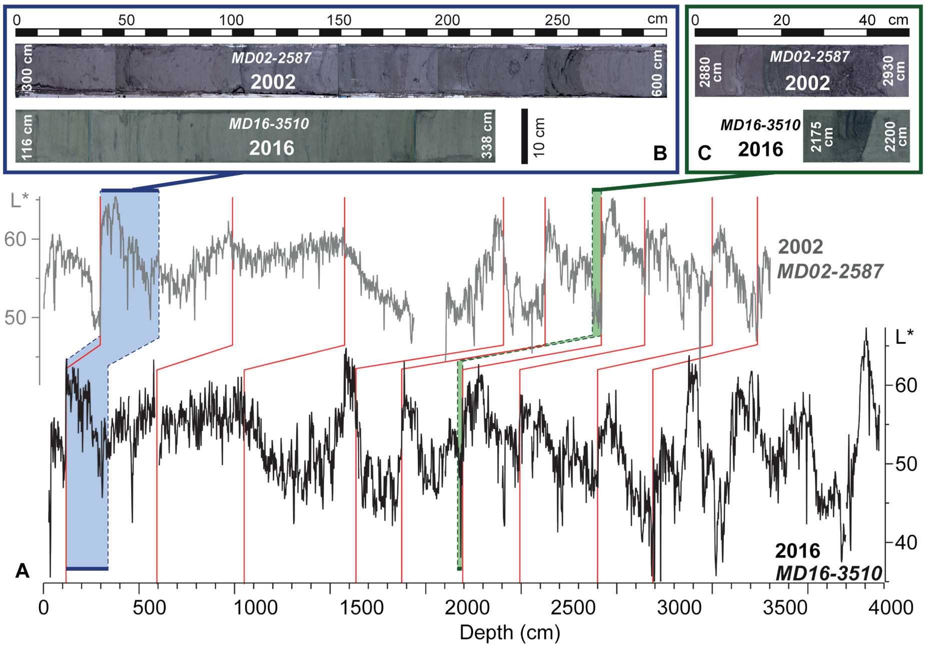

Figure 1: Comparison of cores MD02-2587 (35°17.7'S, 29°22.2'E, 4468 m) and MD16-3510 (35°21.38'S, 29°14.78'E, 4435 m) collected in 2002 and 2016, respectively, at the same South African margin site. **(A)** Downcore reflectance (L*) changes in both cores on their respective depth-scales. Red lines highlight conspicuous color changes synchronous in both cores. The 2002 core is stretched compared to the 2016 core. **(B)** Core photographs of the same time period (blue area) covered by 300 and 222 cm of sediments in the 2002 and 2016 cores, respectively. Dark layers are straight in the 2016 core, while bent in the 2012 core. **(C)** Core photographs of the same turbiditic event (green area). The characteristic downward coarsening of turbiditic sediments is stretched in the 2002 core. These features illustrate the absence of sediment stretching and deformation in the 2016 core, in opposition to the 2002 core.

ACKNOWLEDGEMENTS

This is a contribution to the ACCLIMATE ERC project funded by the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement n° 339108.

AFFILIATIONS

[1]Laboratoire des Sciences du Climat et de l'Environnement, Université Paris Saclay, Gif sur Yvette, France
[2]National Centre for Drilling and Coring, Centre National de la Recherche Scientifique, Brest, France
[3]Environnements et Paléoenvironnements Océaniques et Continentaux, Université de Bordeaux, Pessac, France

CONTACT

Aline Govin: aline.govin@lsce.ipsl.fr

LINKS

http://climcor-equipex.dt.insu.cnrs.fr/
http://www.sea.acclimateproject.eu/

REFERENCES

Bourillet J-F et al. (2007) 6th international conference on Offshore Site Investigation and Geotechnics: Confronting New Challenges and Sharing Knowledge. Society of Underwater Technology, London, UK

Rousseau D-D et al. (2016) PAGES Mag 24: 26

Skinner LC, McCave IN (2003) Mar Geol 199: 181-204

Woerther P et al. (2012) Improving in piston coring quality with acceleration and pressure measurements and new insights on quality of the recovery, INMARTECH 2012, Texel, the Netherlands

New PAGES working group on floods

Bruno Wilhelm[1], S. B. Wirth[2] and J. A. Ballesteros-Canovas[3]

Inland floods are among the most destructive natural hazards causing widespread loss of life, damage to infrastructure and economic deprivation. Robust knowledge about their future trends is therefore crucial for the sustainable development of societies worldwide. Ongoing climate warming is expected to lead to an intensification of the hydrological cycle and to a modification of the frequency and magnitude of hydro-meteorological extreme events. However, climatic projections for the future occurrence of precipitation extremes are still uncertain. The reason for this challenge is primarily the complexity of the variation in precipitation patterns at a regional scale and a limited temporal and spatial coverage of instrumental data capturing precipitation extremes and floods.

Records of past floods from lacustrine, fluvial and marine sediments, tree rings, speleothems, and historical documents provide a comprehensive overview of the variability of floods during warm and cool climates of the past. With the help of these paleo-flood records, we can significantly improve our understanding of the physical processes controlling the occurrence and magnitude of floods under varying past, present and near future climate states.

Therefore, bringing together researchers from the growing community investigating past flood events worldwide is timely. A survey conducted in June 2015 by Wilhelm and Wirth, with support from PAGES, confirmed the need and interest in a Floods Working Group. The objective is to coordinate and synthesize results on the natural variability of floods under different climate conditions and in different regions of the world, plus offer an ideal platform to promote collaboration.

The leaders and the scientific committee defined four major goals for the first three-year period of the working group:

(i) Share best practice of methodologies used by the various research communities working with sediment records, tree rings, speleothems, instrumental data and more. The objective is to improve the quality of the flood records and to reduce uncertainties, for example in the detection of events and in the dating precision.

(ii) Intensify efforts for determining the magnitude of past floods reconstructed from natural archives via calibration with historical and instrumental data. Information on past flood magnitudes will highlight the importance of flood reconstructions for stakeholders and future flood-risk estimations.

(iii) Establish a database of published datasets on past floods. The goal of this open-access database will be to improve the visibility of existing paleo-flood data and to enable their intercomparison.

(iv) Test and identify optimal statistical tools for the analysis of flood frequency, occurrence of extremes, and the comparison of datasets.

A very important goal of the Floods Working Group during this first phase is also to promote interdisciplinary collaboration and discussion between flood scientists as well as specialists in the fields of hydrology, statistics, climate dynamics and modeling. This network will become particularly important to examine and model atmospheric processes and hydrological conditions leading to extreme floods.

We expect important links with the PAGES-endorsed Varves Working Group (http://pastglobalchanges.org/ini/end-aff/varves-wg/intro), since varved lake sediments provide high-resolution and well-dated flood records. We also anticipate strong links with the PAGES 2k Network (http://pastglobalchanges.org/ini/wg/2k-network/intro) as the density of flood data is high for the past 2000 years.

The Floods Working Group met for the first time at the "Cross Community workshop on past flood variability" in Grenoble, France, 27-30 June 2016. This workshop was held to gain an overview of the different kinds of flood archives and flood datasets that are available. Another key focus topic was the launch and management of the database, and to discuss visions and ideas of the participants. A report on this meeting will be published in the next issue of the PAGES Magazine.

AFFILIATIONS

[1] Laboratoire d'Etudes des Transferts en Hydrologie et Environnement, University Grenoble Alpes, France

[2] Centre for Hydrogeology and Geothermics, University of Neuchâtel, Switzerland

[3] Dendrolab.ch, University of Bern, Switerland

CONTACT

Name: bruno.wilhelm@ujf-grenoble.fr

LINK

www.pastglobalchanges.org/ini/wg/floods/intro

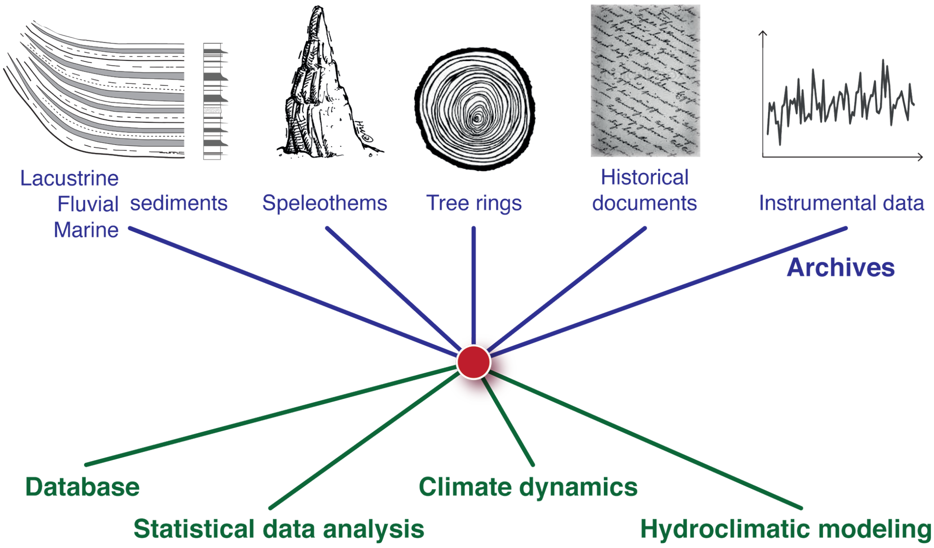

Figure 1: Schematic illustration of the concept and goals of the PAGES' Floods Working Group. Data on past floods will be collected from a variety of archive types, integrated into a database, statistically analyzed, and climatically modeled and interpreted.

Volcanic Impacts on Climate and Society working group

Matthew Toohey[1], M. Sigl[2], F. Ludlow[3], A. N. LeGrande[4] and K. J. Anchukaitis[5]

Volcanic eruptions are an awe-inspiring example of a natural driver of environmental change. At the local scale, erupted lava, ash and gases can have a drastic impact on the environment, with sometimes severe impacts on ecosystems, human health and economies. Global scale impacts can be produced by major volcanic eruptions, like those of Mt. Pinatubo (1991), or Tambora (1815). Such large-scale effects are due primarily to the injection of sulfur into the stratosphere, resulting in the formation of sulfate aerosols. The primary impact of these aerosols is a decrease in global temperature; however, the aerosols can also affect atmospheric circulation and precipitation patterns, leading to complex regional-scale climate impacts. Information on the climate anomalies resulting from volcanic eruptions in the Earth's past therefore provides important insights for understanding the global and regional climate responses to external forcing agents. This in turn informs predictions of future climate change, such as that due to projected increases in anthropogenic greenhouse gases. Volcanically induced climate changes also provide valuable test cases for understanding the impact of climate variability on society.

A wealth of information is available from modern observations of recent volcanic eruptions, however, the number of such events is relatively small. To broaden our understanding of the impacts of eruptions, we rely on other sources, including geophysical records (e.g. tephra layers, ice cores, and climate proxies such as tree rings), as well as archeological and documentary evidence (Ludlow et al. 2013). While there have been great strides forward over recent decades in understanding the role of volcanic eruptions in climate, important open questions remain, and a wide range of interdisciplinary research on this theme is currently underway globally (see PAGES Magazine 23(2), LeGrande and Anchukaitis 2015).

The Volcanic Impacts on Climate and Society (VICS) working group will provide a forum for information exchange between the diverse research communities interested in volcanic eruptions and climate. VICS has three overarching scientific aims:

(1) Improve volcanic radiative forcing reconstructions. VICS will support the reconstruction of next-generation volcanic forcing datasets – focusing first on the past 2000 years, and eventually the full Holocene – and facilitate their use within modeling efforts such as the Paleo-Modelling Intercomparison Project (PMIP). Progress will incorporate improved knowledge of: volcanic sulfate deposition to Antarctica and Greenland (Sigl et al. 2014, 2015), stratospheric transport and deposition of sulfate (Toohey et al. 2013), and the microphysical evolution of aerosols.

(2) Improve understanding of volcanically-induced climate variability. Climate models, proxy-based climate reconstructions and instrumental data don't always agree on the climate impact of major historic eruptions. VICS will support efforts to reconcile different sources of information, fostering collaboration between the proxy, cryosphere, and climate modeling communities; for example, concerning the validation of climate-model simulations. Special emphasis will be placed on the regional and seasonal character of volcanic climate responses and proxy records, the robustness of decadal-scale responses, dynamical responses linked to atmospheric circulation, the role of different boundary conditions (e.g. season and ENSO state), and the roles of eruption frequency versus magnitude.

(3) Improve understanding of societal impacts of volcanic eruptions. VICS will encourage studies into how major eruptions have impacted societies in the past, based on examination of historical, archeological and paleoecological records, and will also aim to develop tools to better frame climate-model results in terms of societal impacts. Such tools will be helpful in predicting societal impacts of major near-future eruptions; for example, there are major uncertainties concerning how a Pinatubo or larger Tambora-magnitude eruption might impact modern economies.

For more information visit the VICS website (www.pastglobalchanges.org/ini/wg/vics/intro), where you can also subscribe to the VICS mailing list.

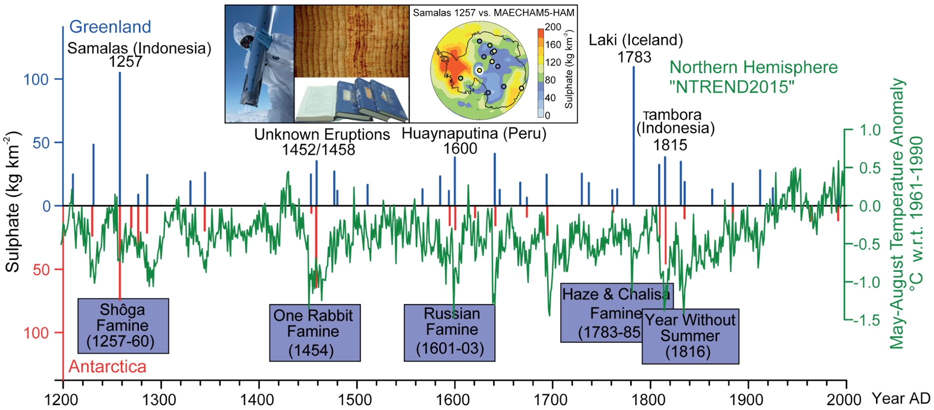

Figure 1: Enhanced atmospheric sulfate burden in the aftermath of large volcanic eruptions as reconstructed from ice cores in Greenland and Antarctica (Sigl et al. 2014, 2015) caused severe summer cooling in the northern hemisphere (Wilson et al. 2016), often associated with crop failures and famines (Puma et al. 2015). Inset suggests archives and tools that can be employed to advance our understanding of the volcanic impact on climate and societies.

AFFILIATIONS

[1]GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
[2]Paul Scherrer Institute, Villingen, Switzerland
[3]Trinity College Dublin, Ireland
[4]NASA Goddard Institute for Space Studies, New York, USA
[5]School of Geography and Development and Laboratory of Tree-ring Research, University of Arizona, Tucson, USA

CONTACT

Matthew Toohey: mtoohey@geomar.de

REFERENCES

LeGrande AN, Anchukaits KJ (2015) PAGES Mag 23(2)

Ludlow F et al. (2013) Env Res Lett 8, doi:10.1088/1748-9326/8/2/024035

Puma MJ et al. (2015) PAGES Mag 23: 66-67

Sigl M et al. (2014) Nature Clim Change 4: 693-697

Sigl M et al. (2015) Nature 523: 543-549

Toohey M et al. (2013) J Geophys Res 118: 4788-4800

Wilson R et al. (2016) Quat Sci Rev 134: 1-18

New Forest Dynamics working group

Jennifer Clear[1,2], R. Chiverrell[3], R. J. DeRose[4], I. Drobyshev[5,6], J. Morris[7] and M. Svoboda[1]

Forest dynamics are driven by an array of disturbances both natural (e.g. fire, windstorms, pathogens) and anthropogenic (e.g. clear cutting, selective logging, slash-and-burn) in origin. Evidence of these events is recorded in sediments (lakes and mires; Fig. 1), dendroecology (tree ring) records, and forestry inventory data. Natural disturbances are fundamental for vital functioning of forest ecosystems, and their impacts (e.g. frequency, severity, spatial pattern) change in response to increasing climatic and anthropogenic pressures. Understanding the disturbance dynamics of the past, present and future is critical research to better inform forest conservation and management (Morris et al. 2015).

The primary aim of the new Forest Dynamics working group is data integration across disciplines, combining the knowledge gained from sediment geochemistry and paleoecology records with that from dendroecology, dendrochronology and monitored forest inventories. Such integration should improve our understanding of forest disturbance dynamics via better proxy calibration and analyses across these different environmental archives. Ultimately, information from these combined resources can contribute to enhance policymaking and land management.

Figure 1: Lake sediment coring in a Spruce bark beetle disturbed catchment at Jezero Laka, Czech Repulic. Photo: Petr Kuneš.

Scientific objectives

The objectives of Forest Dynamics are to: (1) build a spatial geodatabase of reconstructed disturbance histories from the sedimentary and dendrochronological records; (2) combine these disturbance histories by compiling, extrapolating and integrating short-term data onto a common time series; and using well-dated and process-validated calibrated sediment data to extend the knowledge of forest disturbance dynamics from dendroecological to millennial timescales; and (3) assessing the emergent spatial and temporal patterns in forest dynamics related to fire, wind and pathogen disturbances in context of potential shifting drivers of vegetation dynamics (e.g. climate and humans).

Forest Dynamics aims to unite global research communities by linking the multiple temporal scales of paleoecology and bridging the scale difference between sedimentary records and dendroecological records of forest disturbances. Our integrated geodatabase will enable improved interpretation of forest disturbances and help identify limitations in current data coverage. By uniting existing and facilitating new research projects, we aim to improve the spatial coverage and temporal resolution of research into natural and anthropogenically driven forest dynamics.

The Forest Dynamics working group includes an expansive network of international scientists and key participants. We wish to expand our working group and seek global representation from scientists interested in all aspects of forest dynamics (forest succession and development, disturbance dynamics and catchment responses) including tropical, temperate and boreal forests.

Visit the Forest Dynamics website at: http://pastglobalchanges.org/ini/wg/forest-dynamics/intro and join our mailing list to keep up to date with our activities.

Upcoming activities

Workshop (spring 2017 Løvenholm Castle, Denmark) will bring together researchers with interests in forest disturbance (sedimentary geochemists, paleoecologists and dendroecologists) with the aim to bridge the gap between these research communities and produce a comprehensive review paper titled "Mind the gap: challenges and progress in forest disturbance science".

AGU Fall Meeting (12-16 December 2016, San Francisco, USA) - B005 Alteration of disturbance-driven forest dynamics under a changing climate (Session 12625) https://agu.confex.com/agu/fm16/preliminaryview.cgi/Session12625

PAGES OSM (9-13 May 2017, Zaragoza, Spain) - Session 5: Disturbance dynamics across spatial and temporal scales: fire, wind, pathogens and post-disturbance run off as drivers of environmental change www.pages-osm.org/osm/sessions-osm

AFFILIATIONS

[1]Department of Forest Ecology, Czech University of Life Sciences, Prague, Czech Republic
[2]Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, USA
[3]Department of Geography and Planning, University of Liverpool, UK
[4]Rocky Mountain Research Station, US Forest Service, Ogden, USA
[5]Swedish University of Agricultural Sciences, Southern Swedish Forest Research Centre, Alnarp, Sweden
[6]Chaire industrielle en aménagement forestier durable, Université du Québec en Abitibi-Témiscamingue, Rouyn-Noranda, Canada
[7]Department of Forest, Rangeland, and Fire Sciences, University of Idaho, Moscow, USA

CONTACT

Jennifer Clear: jenniferlclear@gmail.com

REFERENCES

Morris et al. (2015) For Ecosyst 2, doi: 10.1186/s40663-015-0057-0

Global Paleofire Working Group phase 2 (GPWG2)

Boris Vannière[1], J. R. Marlon[2] and the GPWG2 Scientific Steering Committee[3]

Understanding the role of human-climate-fire linkages in the past and their influence on the biosphere is key in light of the major fire-regime changes that are occurring on most continents. In the past decade, the GPWG analyzed fire history using the Global Charcoal Database (GCD), and advanced our understanding of the controls and impacts of fire on a wide range of spatial and temporal scales (Marlon et al. 2016). Climate variability had a strong, persistent influence on Late Quaternary trends in fire through its direct impacts on the number and timing of ignitions and fire weather, and through its indirect impacts on vegetation changes and productivity. The complexities of vegetation change and its influences on fire, especially at regional scales and on multi-decadal to centennial timescales, however, remain poorly understood, as do the varied roles of humans (Vannière et al. 2016). The GPWG is therefore launching a new phase – GPWG2 – to more deeply examine the linkages between fires, climate-driven fuel changes, traditional human land uses, modern landscape management, and biodiversity conservation.

GPWG2 will involve fire modelers and stakeholders through projects and workshops, where we will jointly identify questions and approaches that prioritize science in support of sustainability, to provide evidence-based solutions to understanding and managing fire under rapidly changing global conditions. GPWG2 also includes a new focus on crowd-sourced data collection, which is being led by early-career researchers. Throughout Phase 2, we will continue to develop and promote the use of open-source tools, hypothesis testing, and "natural" and model experiments.

Organization and strategy

Three focus groups will address (A) similarities and differences in fire baselines at the biome level; (B) fire risk assessment and management practices to support planning at regional and finer scales; and (C) the role of fire in biodiversity conservation (Fig. 1). These groups will drive our workshop agendas over the next years, and will draw on and intersect with four cross-cutting initiatives. The initiatives, in turn, will provide the data, tools, and infrastructure to support the research of the focus groups. Specifically, the cross-cutting initiatives are:

- Geographic data development for Asia and Africa, particularly to support fire and risk management, which are critical for human livelihoods and the future sustainability of ecosystem services there;
- Syntheses and database development, including the launch of a new user-friendly website and database architecture to support paleofire science broadly (www.paleofire.org);
- Paleofire data-model integration and links with other databases associated with LandCover6k, the European pollen database, Neotoma, LaACER, and more, to support data-model integration and multi-proxy comparisons of fire from ice cores, for example;
- Develop the modern Global Charcoal Database (mGCD), launched during the last GPWG workshop (Harvard Forest, October 2015), and containing surface samples obtained using a standardized protocol, to improve calibration of fire history records and data-model comparisons. This effort will also facilitate the quantification of past changes in fire activity and quantification of uncertainties in reconstructions.

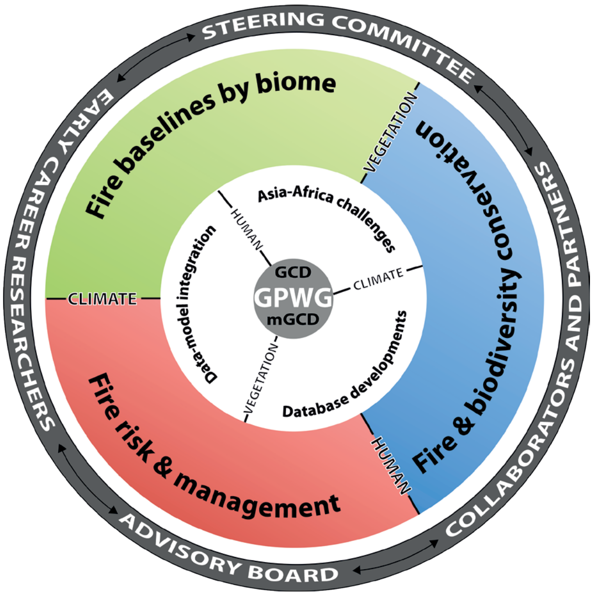

Figure 1: Structure of the Global Paleofire Working Group phase 2 activities.

Key components of GPWG2 as a whole, then, are fostering connections among individuals within the interdisciplinary community; promoting strong data practices, including development, access, management, and sharing, among the community; and facilitating the integration of teams, data, and tools to address the questions in fire science at a broad range of temporal and spatial scales. Importantly, GPWG2 is also committed to building capacity in developing countries and to promoting education and training of students and early-career researchers.

Further details on the organization of the working group, coordinators and key participants, and future activities can be found on the GPWG website: www.gpwg.paleofire.org

Upcoming activities

The first workshop on "Fire history baselines by biome" will be near Bordeaux, France, 25-29 September 2016: www.gpwg.paleofire.org/fire-history-baselines-by-biome/ and there will be a follow up workshop on "Central European paleofire research" 5-8 December 2016: www.gpwg.paleofire.org/natural-and-human-driven-fire-regime-and-early-land-cover-changes-in-central-and-eastern-europe/. In 2017 and 2018 workshops are planned in Montréal (Canada), Bern (Switzerland), Eastern Africa and China.

A special issue of Quaternary international about "The fire-human-climate-vegetation nexus" is planned for winter 2016-2017.

AFFILIATIONS

[1]Chrono-environnement, CNRS - Université de Bourgogne Franche-Comté, Besançon, France
[2]School of Forestry and Environmental Studies, Yale University, New Haven, USA
[3]O. Blarquez (Université du Québec à Montréal, Montréal, Canada); D. Colombaroli (Institute of Plant Sciences and Oeschger Centre for Climate Change Research, University of Bern, Switzerland); A.-L. Daniau (Environnements et Paléoenvironnements Océaniques et Continentaux, CNRS - Bordeaux University, Pessac, France); M. Power (University of Utah, Salt-Lake-City, USA); J. Aleman (Yale University, New Haven, USA); D. Hawthorne (Trinity College Dublin, Ireland); C. Courtney-Mustaphi (University of York, UK)

CONTACT

paleofire@gmail.com

REFERENCES

Marlon JR et al. (2016) Biogeosciences 13: 3225-3244

Vannière B et al. (2016) Quat Sci Rev 132: 206-212

Climate Variability Across Scales: from centuries to millennia (CVAS)

Shaun Lovejoy[1] and CVAS Science committee[2]

"Weather is what you get, climate is what you expect". Is it, really? Consider a series of measurements of temperature along the time axis (Fig. 1A). If successive fluctuations tend to cancel each other (Fig. 1B), then averaging over longer and longer intervals smooths the signal; the averages converge more and more to an (apparently) well-defined mean value. However, if slow processes are forcing the system - for example changing the albedo or CO_2 - the system changes constantly, so that this apparently convergent mean slowly varies, and choosing longer and longer periods to estimate it will be of no help. Such systems "wander"; they do not "relax" (Fig. 1C). Whether the system is relaxing or wandering is a matter of timescales: at weather scales or at the multi-millennium (climate) scales, it wanders. Predicting the future thus requires knowledge of the entire history of the evolution of the system.

Therefore, we need to take a fresh look at climate variability and theory, bringing together nonlinear geoscientists and climate scientists to think about effective ways to (i) characterize climate fluctuations and understand their causes and (ii) focus on these aspects when analyzing both climate data and climate models.

This is the objective of the new PAGES working group on “Climate Variability Across Scales: from centuries to millennia (CVAS)”. The group brings people together from both climate and nonlinear geophysics, with expertise in climate, paleoclimate, climate modeling, nonlinear physics, statistics and stochastics. The group’s common research agenda includes a number of themes around the variability of the climate, especially at centennial to multi-millennial scales.

Examples of research that the working group will highlight include: pitfalls while exploiting state-of-the-art paleoclimate data; the origin of long-memory processes; spatiotemporal variability; the gain between forcing and response at timescales of hundreds and thousand years; the carbon budget; atmosphere dynamics at the Last Glacial Maximum; and the role of long-memory processes for seasonal, annual and decadal forecasts, for extreme events and for global warming.

Specific activities include (i) the development of statistical and modeling tools for analyzing and comparing time series and spatial distributions, focusing on centennial and millennial timescales, (ii) the continued development of numerical packages and emphasis of training aspects, through maintained webpages and mini-courses, (iii) preparation of paleoclimate compilations (in both space and time), consistent with respect to their centennial and millennial scale variability, and to properly account for the role of variability in proxy recording on top of climate variability, and (iv) provision of open-source and easy to use software for above data analysis.

The group will hold its first workshop, titled "What do we know about multicentennial, multimillenial variability?"in Hamburg, Germany, from 28-30 November 2016.

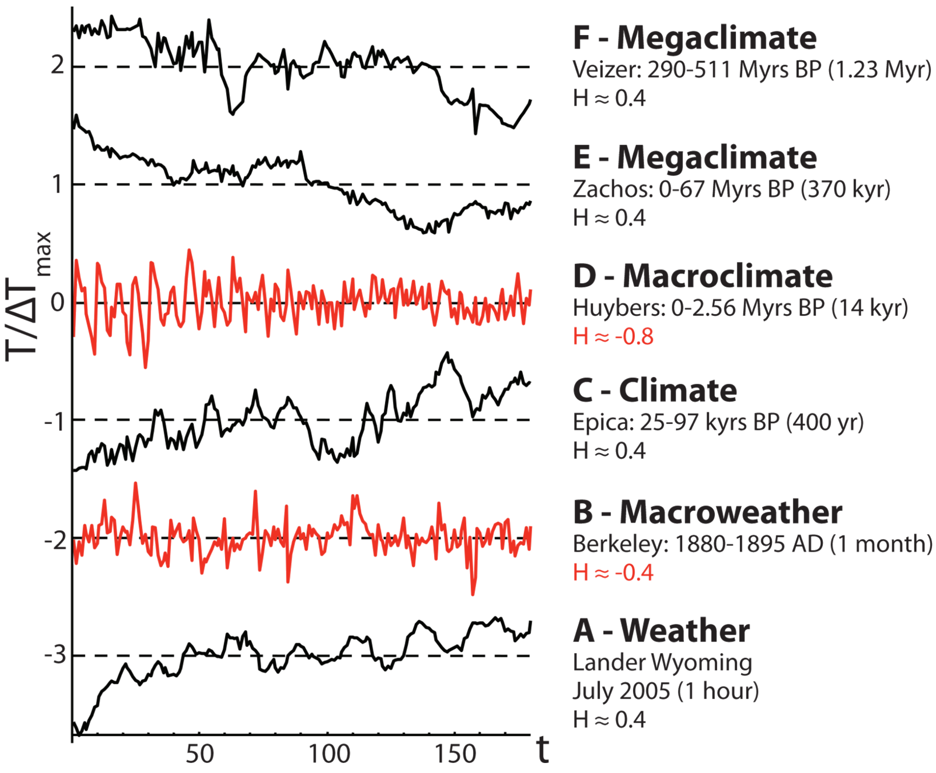

Figure 1: Representative series from each of the five scaling regimes over time periods of seconds to hundreds of millions of years, resolutions indicated in parenthesis with daily, annual detrending (when needed). Starting at the bottom, **(A)** the temperature seems to wander, the difference between two values tends to increase with lag: for the fluctuation ΔT over time interval (lag) Δt, analysis shows that $\Delta T \approx \Delta t^H$ with $H>0$. **(B)** On the contrary, the Berkeley (global, land) series has successive fluctuations that tend to cancel; $H<0$ quantifies the rate. Moving upward, **(C)** the Epica Antarctic $\delta^{18}O$ based paleo series is again “wandering”. **(D-F)** The top three are based on benthic isotopes. Each series had the same number of points (180) and was normalized by its overall range, and was offset by 1 unit in the vertical for clarity. The black curves all illustrate “wandering” cases with $H > 0$, the red, “canceling”, with $H < 0$. This figure is reproduced from Lovejoy (2015) where full details are given.

AFFILIATIONS

[1]Department of Physics, McGill University, Montreal, Canada
[2]www.pastglobalchanges.org/ini/wg/cvas/people

CONTACT

Shaun Lovejoy: lovejoy@physics.mcgill.ca

LINK

www.pastglobalchanges.org/ini/wg/cvas/intro

REFERENCES

Lovejoy S (2015) Climate Dyn 44: 3187-3210

Scale and Scaling in the Climate System

Shaun Lovejoy[1], M. Crucifix[2] and A. de Vernal[3]

Montreal, Canada, 5-7 October 2015

Forty years ago, at the dawn of the revolution in paleoclimate data, it was believed that atmospheric variability essentially consisted of an uninteresting, spectrally flat (white noise) "background", interspersed with periodic and quasi-periodic processes such as the diurnal and annual cycles, the Southern Oscillation and Milankovitch cycles (Fig. 1, bottom). Since then, instrumental and paleo data have shown this picture is wrong by a large factor (Fig. 1, top): the background displays nontrivial "variability across scales" that can be roughly divided into five power law ("scaling") regimes. This state of affairs, underscoring the need for a fresh look at climate variability and theory, motivated this workshop.

The first objective was to get nonlinear geoscientists and paleoclimate scientists to think about effective ways to characterize climate fluctuations, understand their causes, and focus on these aspects when analyzing paleoclimate data; the second was to develop a common research agenda.

The workshop successfully brought communities together with expertise in recent climate (11 participants), paleoclimate (21), climate modeling (9), and nonlinear, statistical and stochastic mathematics (22). Participants, including 14 students, came from Canada, USA, Europe, Asia, and Latin America.

The ice core and marine paleoclimate experts in particular provided an authoritative account of what paleoclimate data can offer (E. Wolff, A. De Vernal), including various pitfalls (M. Kucera). The more applied-mathematics-inclined speakers discussed the origin of long-memory process (C. Franzke), their detection (K. Rypdal), and some difficulties (T. Nielsen). A wide range of timescales was covered from the instrumental periods permitting the study of spatio-temporal variability (H. Frederiksen). We now have enough accurate data to address questions that were previously impossible, such as the gain between forcing and response at timescales of hundreds of thousand years (P. Huybers). Specific physical mechanisms associated with the carbon budget (K. Kohfeld) or atmosphere dynamics at the Last Glacial Maximum (W. Roberts) were discussed. Finally, the value of a good knowledge of long-memory processes was emphasized for seasonal forecasts (R. Hébert), extreme events (S. Innocenti) or global warming (S. Lovejoy).

A number of common research themes emerged around the variability of the climate, especially at centennial to multi-millennial scales. For example, paleoclimate scientists tend to refer to modes of changes called "NAO-like" or "El-Niño like", but how does it actually connect to the interannual modes of variability described by meteorologists? This variability must also be understood from a physical point of view and include the implications for climate change predictions and projections.

The overall result was the creation of a PAGES working group "Climate Variability Across Scales" (CVAS, see Program News article on page 32).

The workshop was co-organized and funded by McGill University and Université de Québec à Montréal. It received additional funding from PAGES and CLISAP (University of Hamburg).

AFFILIATIONS

[1]Department of Physics, McGill University, Montreal, Canada
[2]Georges Lemaitre Centre for Earth and Climate Research, Université catholique de Louvain, Belgium
[3]GEOTOP, Université de Quebec à Montréal, Canada

CONTACT

Michel Crucifix: michel.crucifix@uclouvain.be

REFERENCES

Lovejoy S (2015) Clim Dyn 44: 3187-3210

Mitchell JM (1976) Quat Res 6: 481-493

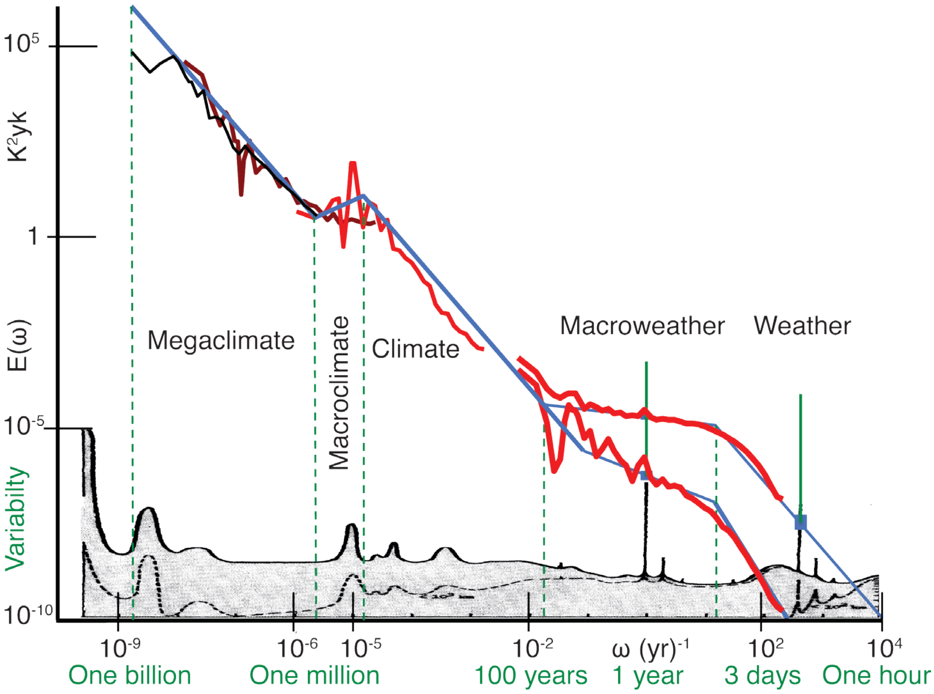

Figure 1: The temperature spectrum ($E(\omega)$) giving the variance per interval of frequency (ω). The bottom (grey) is M. Mitchell's "educated guess" showing the still dominant view of a fairly flat (white noise) "background" interspersed with spikes corresponding to important (quasi-periodic) processes (Mitchell 1976). Top curves are based on instrumental and paleo-data and their range differs from Mitchell's guess by a factor of roughly 10^{15}. In actual fact, the "background" accounts for nearly all the variance, so that the roles of foreground and background must be inverted: Mitchell must be "stood on his head". To a first approximation, the spectrum can be divided into five power law regimes (linear on this log-log plot, blue reference lines). At the far right, there are two nearly parallel instrumental curves corresponding to the spectra of temperatures averaged over the globe (bottom) and over 5°X5° (top). Also shown (green) are the spikes corresponding to diurnal and annual cycles. Adapted from Lovejoy (2015), which has the full details of the data sources.

Paving the road for improved integrative investigations of past Warm Extremes

Emilie Capron[1,2], A. Govin[3], P. Bakker[4], J.S. Hoffman[4], M. Holloway[1,5], G. Moseley[6] and E. J. Stone[5]

Cambridge, UK, 9-11 November 2015

The Last Interglacial (LIG, ~129-116 ka) and Marine Isotopic Stage 11 (MIS 11, ~424-374 ka) stand out as warm interglacials in the context of the last 800 ka (PIGS Working Group 2016). During the first workshop of PAGES' Quaternary Interglacials (QUIGS) working group, a multi-disciplinary group of 31 delegates assessed the current knowledge and research needs on the temporal and spatial patterns of climate forcing, responses and feedbacks during these warm extremes.

Presentations and discussions around recent work (new climate proxies and paleoclimatic records, data syntheses, and climate simulations) outlined known features of the LIG and MIS 11 climates. Overall, the LIG was characterized by sea level 6-9 m higher and warmer temperatures than present-day almost everywhere over the globe. However, peak warmth did not occur synchronously across the globe and it is unlikely orbital forcing explains the observed warmth at all locations. During MIS 11, sea level reached 6-13 m higher than present day and many locations experienced prolonged warmth. Still, the magnitude and drivers of enhanced warmth during LIG and MIS 11 remain unclear.

The workshop also identified current limitations, critical missing datasets and research needs for both interglacials. We need to move toward quantitative estimates of MIS 11 and LIG global warmth and spatio-temporal climate evolutions, via new data compilations and advanced model-data comparisons. Future data syntheses should (1) better assess the seasonality of proxy records to improve interpretation of temperature reconstructions, (2) use robust and coherent chronologies amongst climatic records derived from different archives and a full integration of uncertainties on ages and tracers, (3) better integrate terrestrial records, and (4) be extended to parameters other than temperature (e.g. isotopic tracers). The latter is particularly important, since a number of climate models now have the ability to explicitly simulate climate proxies. Finally, diagnosing unambiguously the state of the Antarctic and Greenland ice sheets during these warm extremes remains a major challenge essential to assess their respective contribution to the recorded higher sea levels.

Setting guidelines for climate simulations to be performed during Phase 6 of the Coupled Model and Ice Sheet Model Intercomparison Projects (CMIP6, ISMIP6) and Phase 4 of the Paleoclimate Model Intercomparison Project (PMIP4) were also discussed. The coordinated CMIP6/ISMIP6/PMIP4 core simulation will be run at 127 ka, which was identified as the most appropriate time interval to determine LIG climate responses and feedbacks to strong insolation forcing (Fig.1). Simulated climate will be compared to data time series between ~128-125 ka to account for delays in climate responses as well as age uncertainties. The 127 ka experiment design will be detailed in a paper to be submitted later in 2016 to the Climate of the Past CMIP6 special issue. Additional sensitivity simulations will be performed within PMIP4 e.g. (1) 127 ka snapshot simulations will investigate the effect of (i) Heinrich event 11 freshwater input and (ii) an early West Antarctic Ice Sheet collapse, (2) a 116 ka snapshot simulation to explore glacial inception processes, (3) MIS 11 snapshot simulations at 416 ka and 409 ka.

The next QUIGS workshop in October (http://pastglobalchanges.org/calendar/upcoming/127-pages/1592-2nd-quigs-wshop) will focus on the timing and shape of glacial Terminations.

AFFILIATIONS
[1]British Antarctic Survey, Cambridge, UK
[2]Centre for Ice and Climate, University of Copenhagen, Denmark
[3]Laboratoire des Sciences du Climat et de l'Environnement, Gif-Sur-Yvette, France
[4]Oregon State University, Corvallis, USA
[5]School of Geographical Science, University of Bristol, UK
[6]University of Innsbruck, Austria

CONTACT
Emilie Capron: capron@nbi.ku.dk

REFERENCES

Bazin L et al. (2013) Clim Past 9: 1715-1731

Dutton A et al. (2015) Science 349, doi: 10.1126/science.aaa4019

Jouzel J et al. (2007) Science 317: 793-796

Lisiecki LE, Raymo ME (2005) Paleoceanography 20, doi:10.1029/2004PA001071

Lüthi D et al. (2008) Nature 453: 379-382

PIGS Working Group (2016) Rev Geophys 54: 162-219

Veres D et al. (2013) Clim Past 9: 1733-1748

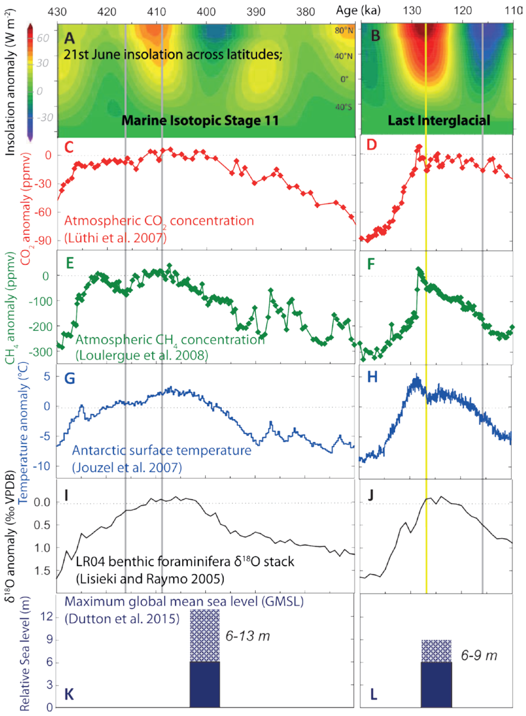

Figure 1: Forcing and climatic records across Marine Isotopic Stage 11 and the LIG. Anomalies for **A-J** are relative to the average value of the last 1000 years, and to present day for **K-L**. Ice core records are displayed in panels **C-H** on the AICC2012 chronology (Bazin et al. 2012; Veres et al. 2012), the LR04 benthic $\delta^{18}O$ curve on its independent chronology (Lisiecki and Raymo 2005). Vertical yellow line indicates 127 ka, the time interval chosen to run the coordinated CMIP6/ISMIP6/PMIP4 core simulation and the vertical grey lines represent the 116, 409 and 416 ka, time intervals for which additional PMIP4 sensitivity simulations will be run. (**K-L**) Maximum global mean sea level (GMSL) relative to present-day, uncertainties remain both in the amplitude (indicated by the shading) and in the exact timing of the GMSL peaks for each interglacial.

Modeling late Pliocene climate variability

Alan Haywood[1], H. Dowsett[2], E. McClymont[3] and U. Salzmann[4]

Leeds, UK, 29 February – 1 March 2016

Thirty members of the PlioVAR working group met to discuss high-resolution proxy records and strategies for new experiments using climate models that will enable an enhanced appreciation and understanding of climate variability during the Late Pliocene.

The workshop began with a series of presentations reviewing high-resolution proxy records for the Late Pliocene. Presentations then focused on previous studies using climate models to predict climate variability during the Pliocene to provide the necessary scientific context for the workshop.

From the presentations and subsequent discussions, a number of key scientific questions and priorities emerged that will provide a focus for activities of the working group and wider scientific community. These include:

1. Characterizing Pliocene "Warm" and "Cold" climate states at a gross level

How does the environment change during warm and cold climate states of the Late Pliocene? How do such variations between warm and cold compare to glacial/interglacial climate variability of the Late Pleistocene? What is the relationship between climate and CO_2 variability during the Late Pliocene and how does this compare to the Late Pleistocene? Going beyond basic reconstructions of temperature, what broader Earth system responses can be linked with climate variability in the Late Pliocene? This will include consideration of ice-sheet behavior, as well as other factors such as dust, which can be addressed using a combined geological data and Earth System Modeling approach.

2. Understanding the M2 "glacial" event

Marine Isotope Stage (MIS) M2 is well represented as a positive isotope excursion in many benthic oxygen isotope records (Fig. 1). The event has been described as the failed onset of Northern Hemisphere Glaciation, but its character and significance remains highly uncertain. Targeted data acquisition will continue to improve our conceptual models of the climate transition into M2, including the difference between the response of the deep ocean and ocean surface. Climate modeling will be used to explore potential constraints on the M2 event using a well-known strategy of fingerprinting. Through a coordinated international effort, single forcing mechanisms of potential relevance to the M2 will be identified and incorporated into new experiments. These include orbital forcing, atmospheric trace gasses, plausible ice-sheet configurations, vegetation response and the importance of specific ocean gateways (e.g. Central American Seaway). The results of these simulations will be compared to available proxy data to determine what forcings, and forcing combinations, allow climate models to more reliably predict regional climate responses for the M2.

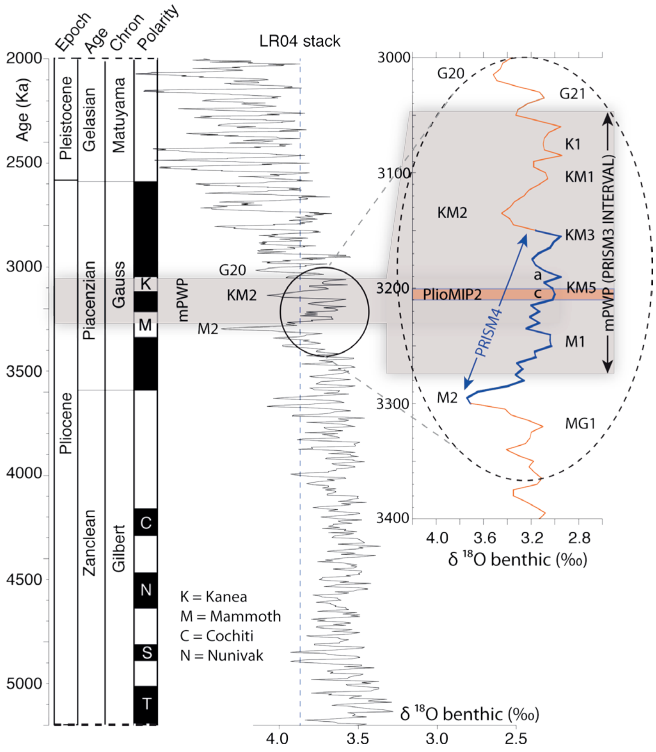

Figure 1: The PlioVAR interval of interest in relation to the long-term climate evolution of the late Pliocene. Shown is the global LR04 benthic oxygen isotope stack and timescale of Lisiecki and Raymo (2005). Vertical dashed line shows present day $\delta^{18}O$ value. The mid-Pliocene warm period (mPWP) or PRISM3 warm interval (3.264-3.025 Ma) is shown by the horizontal shaded grey bar. The inset shows details for the mPWP and position of PlioVAR/PRISM4 and PlioMIP2 focus. Positions of Marine Isotope Stages MG1, M2, M1, KM5, KM3, KM2, KM1, K1, G21 and G20 are provided.

3. Understanding the climate transition from the M2 event to KM5

The transition out of the M2 event is just as enigmatic as the development of the event itself, but it heralded a period of relative climatic stability and equability until the end of MIS KM5 (Fig. 1). The period between M2 and KM5 intersects the warm interval selected for Phase 2 of the Pliocene Model Intercomparison Project (KM5c). Therefore, short high-resolution proxy time series from M2 to KM5 provide an opportunity to contribute towards data-model comparison and model evaluation exercises associated with PlioMIP, enhancing the capabilities of data-model synergy in the future.

PlioVAR is planning additional workshops during the next two years, as well as gathering at future EGU General Assemblies and AGU Fall meetings. Anyone interested in contributing to the project is encouraged to participate. The time, date and location of the meetings will be advertised through the PAGES website and e-news, and the PlioVAR mailing list.

AFFILIATIONS

[1]School of Earth & Environment, University of Leeds, UK
[2]U.S. Geological Survey, Reston, USA
[3]School of Geography, Durham University, UK
[4]Department of Geography, Northumbria University, Newcastle, UK

CONTACT

Alan Haywood: earamh@leeds.ac.uk

REFERENCE

Lisiecki LE, Raymo ME (2005) Paleoceanography 20, doi: 10.1029/2004PA001071

Bridging data and models

Jennifer Marlon

GPWG workshop, Petersham, USA, 27 September - 2 October 2015

The Global Paleofire Working Group (GPWG) met for a final synthesis workshop. The meeting reflected the culmination of five concurrent advances during the past decade, including an increase in wildfire salience globally and thus increased research motivation, the development of the Global Charcoal Database (GCD), the emergence of sophisticated global fire models, and the widespread adoption of open-source tools like the "R" programming language. The convergence of these factors enabled 36 researchers from 11 countries to address questions about fire on many temporal and spatial scales, producing insights that would have been unattainable prior to GPWG's creation.

In anticipation of the workshop, a method for gridding the GCD (Marlon et al. 2016) was developed to facilitate data-model comparisons (Fig. 1). The gridded maps provide new spatial information for specific intervals highlighted in the past millennium. Colored dots on the maps are anomalies that indicate increases or decreases in burning relative to average burning at that same location during the base period (1000-1800 CE). Recent human impacts on fire are particularly evident around the turn of the 19th century in eastern Asia, Australasia, and North America.

The limitation of working with anomalies was a key discussion topic at the workshop, prompting three initiatives aimed at quantitatively calibrating paleofire records. Currently, charcoal particles are measured using very diverse methods (e.g. counts, areas, weights, ratios). Using different quantification methods, coupled with the complexities of charcoal production, transportation, and deposition, limits meaningful comparisons across records from different locations. Standardizing paleofire records to a unitless dimension enables comparisons of relative changes through time, but the loss of units prevents analyses of spatial variability. Approaches using a statistical process model, a modern database of charcoal surface samples, and a series of regional multi-proxy comparisons were each developed to enable modeling of, or quantitative comparisons between, charcoal accumulation rates and independent estimates of area burned from fire-scar, historical, and satellite-based data. These efforts will elucidate the factors controlling charcoal accumulation, and may help to initialize and constrain fire simulations at multiple scales.

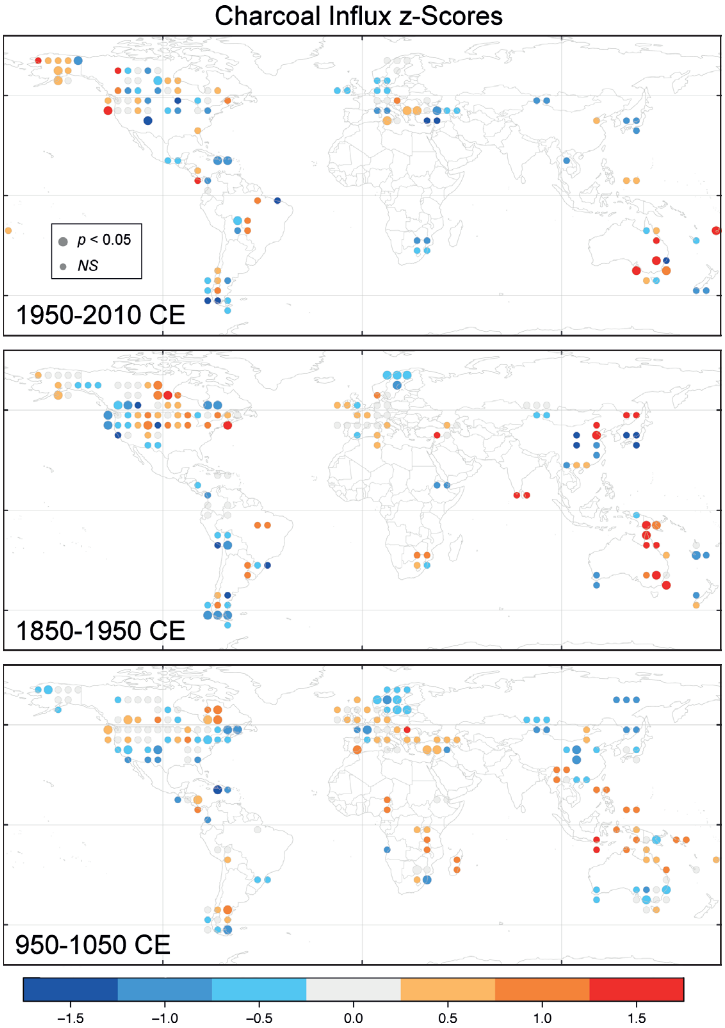

Figure 1: Spatially gridded biomass burning for 1950-2010, 1850-1950, and 950-1050 CE. Charcoal influx anomaly base period is 1000-1800 CE. From Marlon et al. 2016.

Workshop projects focused on human-fire interactions, fire ecology, and fire effects on global atmospheric chemistry and climate. Synthesizing anthropological evidence about human fire-use in traditional societies into a quantitative framework is needed to allow for its integration into global fire models. The current generation of models relies on simple assumptions between population density, fire ignitions, and fire suppression that draw from present-day data. Although modeling necessitates some simplification, synthesizing and incorporating data about cultural fire practices will enable model assessment and improvement not only for paleofire simulations, but also for simulations of past land-cover and land-use changes (e.g. through collaboration with PAGES' LandCover6k working group). Such interdisciplinary research is essential for accurately understanding fire, human, and vegetation coupling with the climate system. The ultimate goal is to use this type of systematic and iterative approach of evaluating past fire activity and paleofire simulations to better contextualize contemporary fire management and understand future fire.

GPWG is continuing its work as GPWG2, with a growing emphasis on using data and models together to address research challenges in ecosystem and climate dynamics, and fire management, among others. Future meetings will be announced through the PAGES' website.

AFFILIATIONS

School of Forestry and Environmental Studies, Yale University, New Haven, USA

CONTACT

Jennifer Marlon: jennifer.marlon@yale.edu

REFERENCES

Marlon JR et al. (2016) Biogeosci 13: 3225-3244

Understanding peat carbon sequestration on Earth

Zicheng Yu[1], D. Charman[2], D. Beilman[3] and J. Nichols[4]

1st C-PEAT workshop, New York, USA, 11-13 October 2015

Peats represent a large, and often active, carbon (C) pool in the land-atmosphere system. At present, these C-rich deposits contain about 600 Pg C, an amount similar to the total C stocks in all living biomass or in the atmosphere. The large size of the peat C pool and its concentration in a number of regions sensitive to climate change and human activities have promoted a heightened interest and increased research in peat C dynamics. Over the last decade, we have learned much about their distributions, histories and controls as a result of site-level, data synthesis, and modeling studies. However, large uncertainties remain in C sequestration rates and stocks, in our understanding of the underlying processes, and in our ability to project their future trajectories. PAGES' C-PEAT (Carbon in Peat on EArth through Time) working group was established in 2014 to coordinate peat C researchers to make important progress on data synthesis and process-level understanding from an integrated, global and Earth history perspective.

The C-PEAT launch workshop focused on three overarching themes: (1) the controls on peat formation (why is there peat?); (2) the estimates of peat C stocks and accumulation rates in Earth history; and (3) the future trajectories of peat C stocks. A total of 52 participants including many early-career researchers from 10 countries attended the workshop. Short presentations were followed by plenary and breakout group discussions. Details on the workshop program and presentations can be found on the workshop webpage (www.pastglobalchanges.org/calendar/all-events/127-pages/1502-c-peat-launch-wshop).

This workshop built on several recent synthesis efforts. The largest peatland region in the circum-Arctic, representing about 90% of global peat C stocks, was the focus of a workshop in October 2013 (Yu and Loisel 2014). A mini-workshop was held in October 2014 on circum-Antarctic peats, including Patagonian peatlands and Antarctic moss peat banks. To complement these efforts, this C-PEAT workshop focused on tropical peatlands, buried peats, deep-time peats and coals, and peat vulnerability (Fig. 1).

The breakout group discussions focused on these topics and the three overarching themes. In particular, a group of tropical peatland researchers discussed the best ways to generate an updated synthesis from tropical peatlands in different regions. Compiling information regarding buried peats under mineral soils or on continental shelves will help identify and quantify "missing" peat C as simulated in some models. A first ever involvement of several deep-time wetland and coal researchers in a peat workshop generated exciting discussions about approaches to estimate equivalent C accumulation rates from deep-time peat and coal deposits. Regarding peat C vulnerability, ideas emerged regarding rapid modern and future loss of tropical peats due to human activities, and potential for new peats in frontier regions, such as the Arctic and Antarctica, in response to a warmer and possibly wetter climate. On the question about why there is peat, we considered that reduced decay of initial organic matter is critical – often achieved by waterlogging (especially in tropical peatlands), by the presence of permafrost (including aerobic peatbanks in the High Arctic and Antarctica), or by cold environmental conditions. Also, recent progress in global peatland modeling (e.g. Stocker et al. 2014) and peat data synthesis (Loisel et al. 2014) will likely lead to more productive data-model comparisons.

During the next couple of years of C-PEAT Phase 1, these topical groups will coordinate and organize focused meetings and workshops to generate synthesis products. We plan a workshop focused on tropical peats in early 2017 and a synthesis workshop, for all C-PEAT members, in late 2017.

ACKNOWLEDGEMENTS

We thank PAGES, INQUA, NSF (Antarctic Earth Sciences grant 1246190) and Lehigh's Department of Earth and Environmental Sciences for financial support, and LDEO for hosting the workshop.

AFFILIATIONS

[1]Department of Earth and Environmental Sciences, Lehigh University, Bethlehem, USA
[2]Department of Geography, University of Exeter, UK
[3]Department of Geography, University of Hawaii at Manoa, Honolulu, USA
[4]Lamont-Doherty Earth Observatory at Columbia University, Palisades, USA

CONTACT

Zicheng Yu: ziy2@lehigh.edu

REFERENCES

Loisel J et al. (2014) Holocene 24: 1028-1042

Stocker B et al. (2014) Geosci Model Dev 7: 3089-3110

Yu ZC, Loisel J (2014) PAGES Mag 22: 41

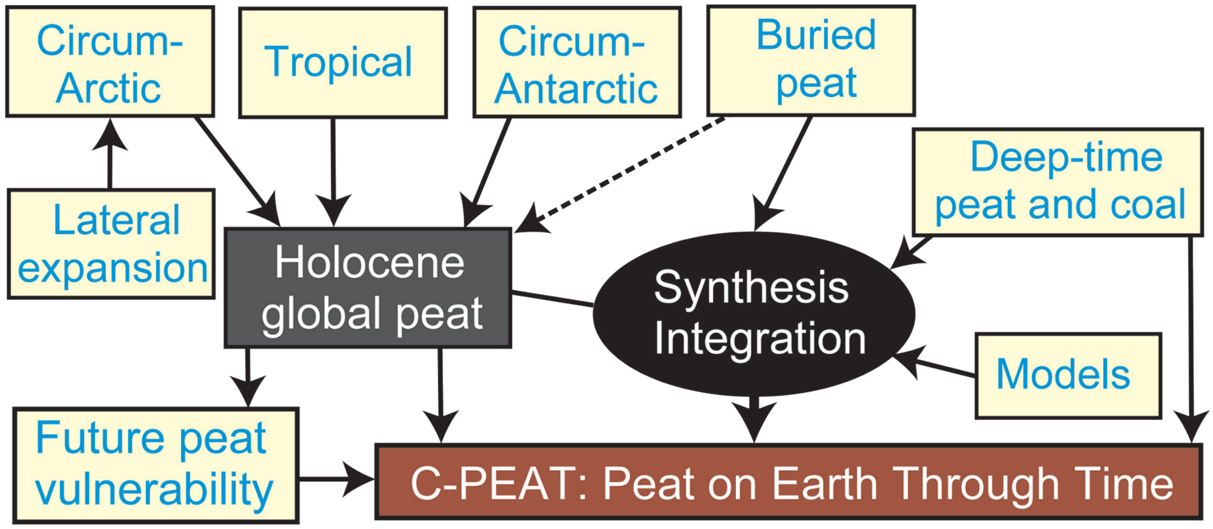

Figure 1: C-PEAT topical groups (yellow boxes) aim to facilitate the synthesis of data and knowledge of global Holocene peat C stocks and accumulation rates from northern, tropical and southern peatlands and their future trajectories, and to improve our understanding of peat accumulation processes and roles in Earth climate system over time through integrating Holocene and deep-time peat data and ideas.

Mapping Human Subsistence in West Africa (1000 BC - AD 1500)

Andrea U. Kay, L.N. Phelps and J.O. Kaplan

Les Rasses, Switzerland, 2-6 November 2015

PAGES' LandCover6k working group aims to better understand the development and present state of global ecosystems as influenced by climate change and humans during the late Holocene. The interdisciplinary working group joins archaeologists with ecosystem modelers and paleoecologists to map land-cover and land-use change over the last 6000 years. This workshop was convened by LandCover6k members who are studying sub-Saharan Africa, a region that has been only superficially treated in most previous large-scale synthesis work, and whose researchers have been underrepresented in international collaborations.

The workshop focused on land-use change during the critical period of the African Iron Age transition (1000 BC-1500 AD) which is marked not only by the spread of agriculture and pastoralism across most of sub-Saharan Africa, but also by the development of modern African climate following the end of the African Humid Period.

The central methodology of LandCover6k is to employ archaeological and paleoecological archives to reconstruct past land cover and land use. Land use is not only influenced by environment but also is a product of historical, cultural, and societal factors that cannot be easily predicted. Kay and Kaplan (2015) therefore proposed a categorization of livelihoods in Iron Age Africa. Each category encompasses the subsistence, trade, technology, and political organization of societies that may be identified in archaeological and historical records. With this classification scheme, we set out to map the occurrence of the livelihood categories in space and time. We decided that a more focused case-study area would facilitate the mapping process, so West and Central Africa were chosen to test this process.

The goal of the ACACIA/LandCover6k workshop was to assemble experienced and early-career researchers who study West and Central Africa. Twenty-four researchers representing 14 institutions in nine countries set out to critique and improve both the existing classification system and a prototype set of maps. Assembling this group – experts in a range of fields including paleoecology, linguistics, archaeology, archaeobotany, archaeozoology, human geography, and modeling – in the same room for a focused discussion of the issues and best practices was the optimal way to address the questions set forth by our project.

The workshop was structured around presentations by participants in plenary, informal discussion sessions, and breakout workgroups. The workgroups were divided between live-editing sessions where we worked on the livelihood maps and a discussion group focused on pastoral systems. One of the first developments to emerge from the plenary discussions was the need to revise the classification system; in some cases, this meant consolidating the existing categories, but also adding new ones. For example, the former category called "Neolithic farmers" has been combined with the "Forager-horticulturalist" category, since the primary difference between the two was the type of crops being used, which is more environmentally than culturally determined. The combined category is now called Small-scale food producers (see Box 1). In addition to the categories revised above, we decided that political entities and their spheres of influence, metallurgical presence/ubiquity/industry, and domestic animal species distributions should be mapped in separate layers, independent of the agricultural categories.

- Hunter-gatherers
- Fishers
- Small-scale food producers
- Settled farmers
- Diversified farmers
- Intensive diversified farmers
- Wetland farmers
- Upland rice farmers
- Pastoralists*
- Industrial production centers*

*to be further revised and defined in future

Box 1: Revised classification scheme for West and Central Africa

Mapping progress was made on several time slices, and a temporary pastoralism polygon (Fig. 1) was put in place until an improved version can be developed. Several plans were made for continued work including office visits in 2016, and collaboration on the publication of the final mapset and a database of African archaeological site data. There was also discussion on the planning of a pastoralism workshop in 2016, where pastoral experts will come together for a critical analysis of basic layers, and to incorporate more specialist knowledge in cultural and subsistence overlays.

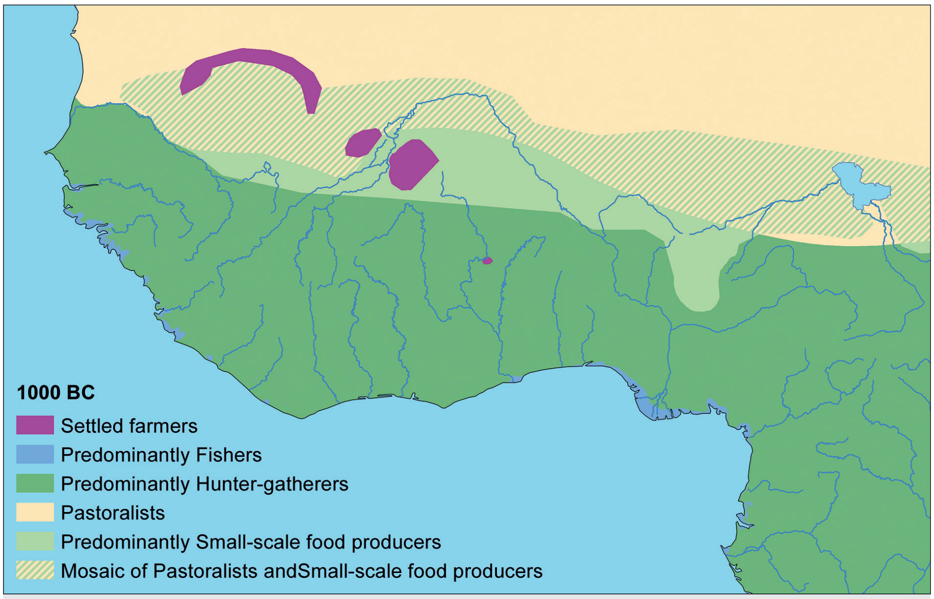

Figure 1: Simplified map of lifestyle category distribution for 1000 BC time slice.

ACKNOWLEDGEMENTS
Funding for this workshop was provided by PAGES and the Swiss National Science Foundation.

AFFILIATIONS
Institute of Earth Surface Dynamics, University of Lausanne, Switzerland

CONTACT
Andrea U. Kay: Andrea.Kay@unil.ch

REFERENCES
Kay AU, Kaplan JO (2015) Anthropocene 9: 14-32

Synthesizing East African land-cover change over the past 6000 years

Rob Marchant[1] and Stephen Rucina[2]

East African LandCover6K, Nairobi, Kenya, 22-23 October 2015

The East Africa LandCover6k workshop brought together over 60 experts from the fields of archeology, archeobotany, linguistics and paleoenvironmental studies to synthesize information on East African land-cover change over the past 6000 years. Through an exchange of ideas, the interdisciplinary group aims to understand directions and drivers of land-cover change, and the interaction with various cultures, technologies, and subsistence strategies across the East African region. The workshop outputs were a series of templates for capturing information on land-use and socioecological change that are currently being populated by the wider community. Ultimately this will lead to a series of land-cover maps for Eastern Africa collated within a review manuscript and harmonized with parallel initiatives from other parts of the African continent. The participants also discussed the utility of East African land-cover-change data for a range of different disciplines, particularly for stakeholders outside of academia concerned with contemporary issues such as resource use and conservation.

The workshop focused on the following questions: (1) What were the dominant land-cover changes during the past 6000 years? (2) What are the key gaps in the archeological and paleoenvironmental records? (3) Were the drivers of land-cover changes natural or anthropogenic? (4) What contemporary questions about human-environment interaction can our data and modeling initiatives help to address?

As one of the core aims of the LandCover6k project is to provide global maps of land cover to feed into climate-model development, Jed Kaplan (U. Lausanne, Switzerland) provided a model-based perspective on land-cover changes in West Africa over the past 6000 years. We then had two overview presentations on the current status and future directions of archeological and paleoecological research in Eastern Africa by Paul Lane (Uppsala U., Sweden) and Dan Olago (U. Nairobi, Kenya) respectively. The workshop then moved to a series of country-specific sessions where current overviews on archeology and paleoecology data were presented as a series of paired talks for Central Africa, Tanzania, Uganda and Kenya.

The second day of the workshop focused on the wider application of land-use data for conservation by Cassian Mumbi (Tanzania Wildlife Research Institute) and Jaqueline Barnard (Kenya Wildlife Service). We then focused on the link to natural resource use, specifically on water by Dickens Odeny (National Water Towers Project, Kenya), Philip Omondi (Kenya Meteorological Department), and carbon by Jennifer Farmer (ALTER Carbon project, Uganda).

Workshop participants then divided into three groups. The first, led by Jed Kaplan, focused on developing a matrix to capture data (stratigraphic, radiocarbon, proxy, artefacts and land use) and meta information (site location, age range covered and environmental setting) that has been subsequently developed and will underpin the synthesis. Rob Marchant led another group on collating information around phases of rapid environmental or technological and land-cover change, particularly looking at the periods around 4000 and 800 years BP. Stephen Rucina led the final group, looking at the spread of archeological data and how this can be used for land-use change study.

The East Africa LandCover6k initiative is currently in the phase of collating data and information behind land use that will be discussed at forthcoming congresses and feed into the wider development of the LandCover6k project.

For more information on the workshop, or to be involved in the East Africa LandCover6k project, please contact Rob Marchant: Robert.marchant@york.ac.uk

AFFILIATIONS
[1]Environment Department, University of York, Heslington, UK
[2]National Museums of Kenya, Nairobi, Kenya

CONTACT
Rob Marchant: robert.marchant@york.ac.uk

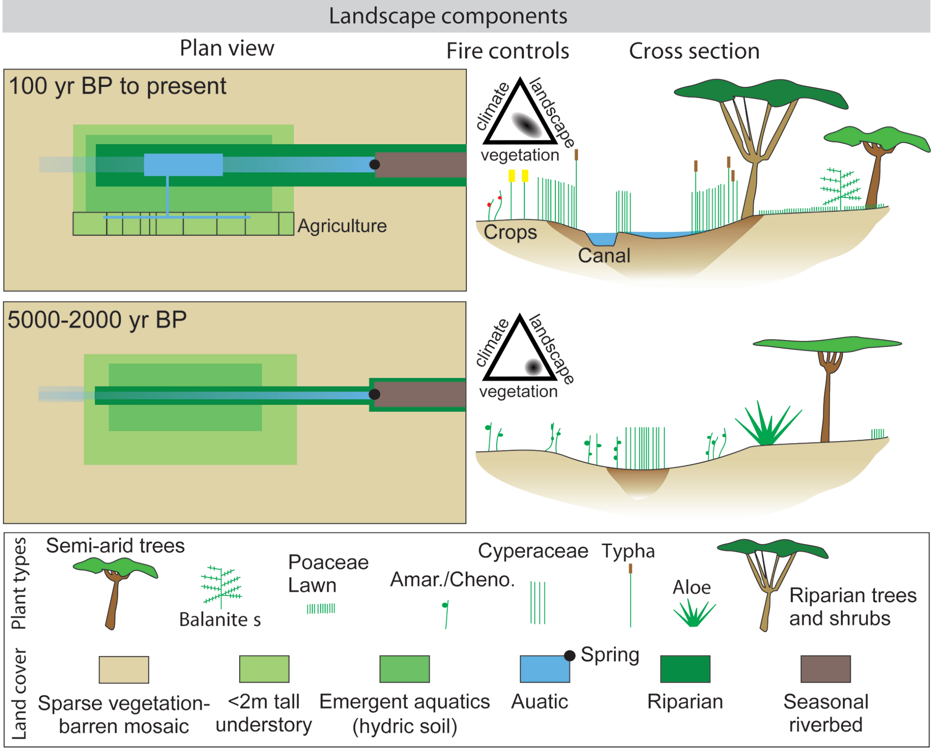

Figure 1: Landscape change inferred from a dated pollen record taken at Esambu swamp, Amboseli, southern Kenya. The mid to late Holocene landscape was characterized by open semi-arid woodland with disjointed fuel connectivity. Through the late Holocene, the catchment was increasingly modified by human activity characterized by channeling water resources and expanding agriculture with fire activity increased.

Land-use classification

Kathleen D. Morrison[1], M.-J. Gaillard[2], M. Madella[3], N. Whitehouse[4] and E. Hammer[5]

LandCover6k workshop, Paris, France, 22-23 October 2015

LandCover6k builds Holocene land-cover reconstructions for the purpose of climate modeling (Gaillard et al. 2015), with a focus on anthropogenic land-cover change (ALCC). Existing ALCC models vary significantly (Gaillard et al. 2010), highlighting the need to evaluate and improve model outputs using paleoenvironmental data, here primarily pollen data. While pollen-based land-cover data provide checks on, or alternatives to, ALCC models, they do not address the causal relationships underlying human modification of environments, which stem from past land-use practices. Land-use practices vary significantly across regions so that, for example, extrapolations from temperate zone cases almost certainly misrepresent the impact of farming in the tropics, or in regions without large animal domesticates (Morrison 2015). Further, similar numbers of people in the same environment practicing different forms of land use will have different effects on vegetation. Because the environmental effects of human population are mediated by land use, they are a challenge to model.

The land-use group (group 6) of LandCover6k integrates and maps historical, archeological and geographic data on human land use over the last ten thousand years. To accomplish this, new modes of data sharing, classification and data management need to be developed. Therefore, the goals of the workshop were to: (1) build this new research community; (2) explain the goals of LandCover6k; (3) develop basic global-scale, land-use categories applicable to the entire project; and (4) evaluate requests from the climate-modeling community for information on past human activities such as burning, tillage, livestock grazing and wood harvest.

Although designed as the first meeting of land-use coordinators for each of the continental-scale groups, the meeting was open to all. Forty-four people from 15 countries attended, including pollen analysts, modelers and representatives from PAGES' Global Paleofire Working Group. The workshop focused on the problem of land-use classification; many existing classifications conflate land cover and land use ("forest", for example, is not a land-use category as people may use forests in diverse ways) and thus cannot be used for this purpose. Our land-use classification is both hierarchical and scalable, with a small number of categories at the highest level, and more in each of the two lower levels. Participants agreed the highest, global-scale level of categories applicable from the early Holocene to CE 1850 will be: (1) no evidence for human land use, (2) foraging (hunting and gathering), (3) farming, (4) pastoralism, and (5) urbanism and/or extractive land use (such as mining or quarrying).

Figure 1: Masinagudi, Tamil Nadu, India. Grazed hill in foreground, tree-bordered fields in middle ground, and forested slopes of the Nilgiri Hills in background. Farmers in this semi-tropical region grow subsistence crops such as rice and pulses as well as spices and other cash crops; nearby forests have been closed for wildlife protection. Prior to the loss of forest access, local farmers practiced forms of agroforestry which maintained denser woody cover. Population figures have not changed significantly, but land-use changes have led to differences in regional vegetation through time (photograph KD Morrison).

Additional subgroups were created, including: (1) separate groups for the CE 1500 and 1850 time windows where strict research separation between historians and archeologists exists, (2) a new group for the Mediterranean and Middle East, and (3) separation of Eastern and Western Europe. Data collection and management issues dictate most of these changes; global-scale synthesis is still planned.

Further details can be found on the LandCover6k website www.pastglobalchanges.org/ini/wg/landcover6k/intro, and the LandUse6k website http://landuse.uchicago.edu/.

AFFILIATIONS

[1]Anthropology, University of Chicago, Chicago, USA
[2]Biology and Environmental Science, Linnaeus University, Kalmar, Sweden
[3]Humanities, University Pompeu Fabra, Barcelona, Spain
[4]Geography, Earth, and Environmental Sciences, Plymouth University, UK
[5]Oriental Institute, University of Chicago, Chicago, USA

CONTACT

Kathleen D. Morrison: morrison@uchicago.edu

REFERENCES

Gaillard MJ et al. (2015) PAGES mag 23: 38-39

Gaillard MJ et al (2010) Clim Past 6: 483-499

Morrison KD (2015) Seminar 673: 75-80

ANTARCTICA2K

Towards a reconstruction of Antarctic climate over the last 2000 years

Barbara Stenni[1,2], M. Curran[3,4], C. Barbante[1,2] and M. Frezzotti[5]

Venice, Italy, 3-4 September 2015

The PAGES Antarctica2k working group met for two days in September 2015 in Italy. Fifty scientists, including PhD and graduate students, coming from 12 countries shared thier expertise in paleoclimate reconstruction methods, dating, ice cores, marine and lake sediments, borehole temperature, polar meteorology and climate modeling. The first objective was to plan two community papers, one focusing on a climate reconstruction using isotopic records from ice cores and other proxy records, the other on a snow-accumulation-rate reconstruction using firn and ice-core records. The second objective was to investigate the possibility to reconstruct the Antarctic sea-ice variability over the past 2000 years using proxy data from both marine sediment and ice cores.

The meteorological observations in Antarctica, a continent one and a half times the size of Europe, started only during the 1957-1958 International Geophysical Year with most of the stations along the coast and only some in the interior. For this reason, Antarctica's past climate is only poorly documented. The interpretation of the isotopic profiles obtained from the ice cores allow to reconstruct the climate at different temporal scales from centuries to glacial-interglacial cycles, and can help fill in this spatial and temporal gap (Jouzel et al. 2007).

However, the snow deposition at the surface in Antarctica is spatially much less homogeneous than the original atmospheric precipitation (snowfall or diamond dust), due to wind erosion and redistribution, sublimation, and other processes during or after the precipitation events. For this reason, reconstructing past precipitation is a challenge.

The group discussed the state-of-the-art paleoclimate reconstructions from the high latitudes of the southern hemisphere. A particular emphasis was given to proxy interpretation and temperature calibration, highlighting the main challenges associated with ice-core water stable isotope records. The key factor controlling the isotopic proxy has been mainly related to temperature variations; however, this is not always straightforward and other processes acting on different spatial and temporal scales may influence this calibration. Early efforts to reconstruct the temperature history of Antarctica over the past 2000 years indicated that, at the continent-scale, Antarctica is the only land region where the long-term cooling trend of the last 2000 years has not yet been reversed by recent significant warming (PAGES 2k Consortium 2013). However, this reconstruction has large uncertainties and masks important regional-scale features of Antarctica's climate evolution.

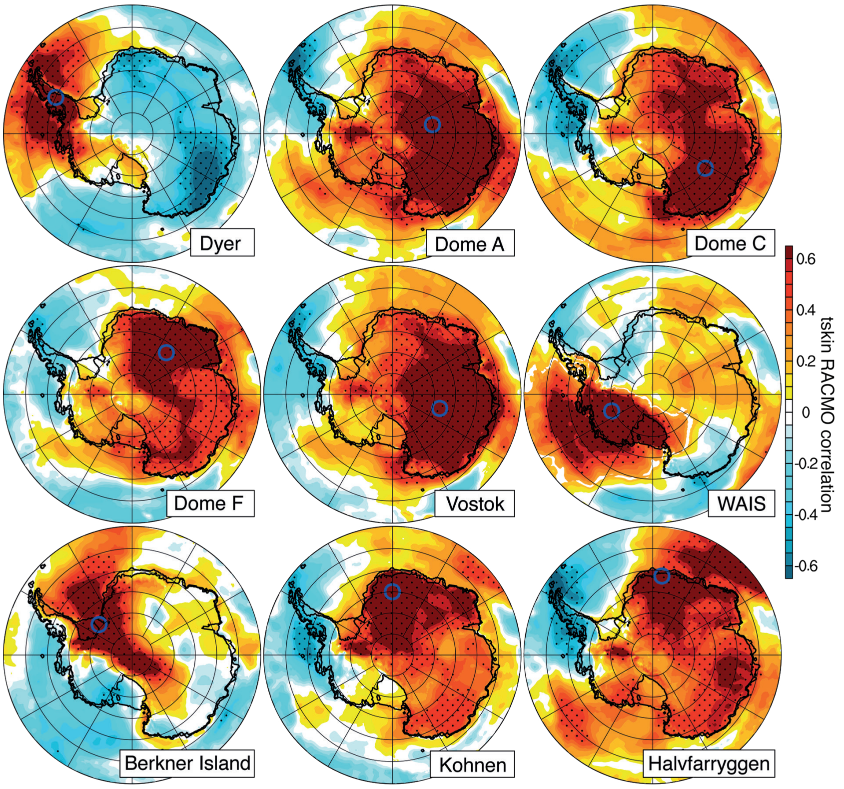

Figure 1: Spatial correlation map (annual values, 1979-2014) of surface temperature for major ice-core drilling sites as simulated by the regional atmospheric model RACMO2.3 at 27 km resolution (courtesy of Melchior van Wessem and Michiel van den Broeke, Utrecht University).

The group decided to expand the paleoclimate database and use new reconstruction methodologies aiming to reconstruct the climate of the past 2000 years at decadal scale and on a regional basis. Seven distinct climatic regions have been selected: the Antarctic Peninsula, the West Antarctic Ice Sheet, the East Antarctic Plateau, and four coastal domains of East Antarctica. This approach, supported by climate-model results (Fig. 1), will be applied to both isotopic and snow-accumulation-rate reconstructions.

The synthesis from ice-core records will be compared and evaluated against proxy data from marine and coastal terrestrial (e.g. lake, peat) records to shed light about possible different patterns between coastal/low-elevation and high-elevation regions in Antarctica. Moreover, a call for sea-ice proxy data has been launched and people within the sea-ice working group are working on implementation of the database.

If you would like to contribute to the current effort, or contribute data, contact working group leader Barbara Stenni.

ACKNOWLEDGEMENTS

The meeting was sponsored by PAGES, PNRA and DAIS (Ca' Foscari University, Venice), under the patronage of SISC.

AFFILIATIONS

[1] Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, Italy
[2] Institute for the Dynamics of Environmental Processes, CNR, Venice, Italy
[3] Australian Antarctic Division, Hobart, Australia
[4] Antarctic Climate and Ecosystems CRC, University of Tasmania, Hobart, Australia
[5] ENEA, CR Casaccia, Roma, Italy

CONTACT

Barbara Stenni: barbara.stenni@unive.it

REFERENCES

Jouzel J et al (2007) Science 317: 793-796

PAGES 2k Consortium (2013) Nature Geoscience 6: 339-346

Comparison of climate reconstruction methods, modeling, and data synthesis approaches

Joëlle Gergis[1], A.M. Lorrey[2], N.J. Abram[3], B.J. Henley[1], S.J. Phipps[4], K.M. Saunders[5] and workshop participants[6]

4th Australasia2k workshop, Auckland, New Zealand, 27-29 October 2015

This workshop, held at the National Institute of Water and Atmospheric Research (NIWA) in Auckland, reviewed research progress and identified potential contributions from the Australasian research community to Phase 2 of the PAGES 2k Network. The workshop included specialists in data collection, data synthesis, climate reconstruction and climate modeling, with increased involvement from lake-sediment and speleothem communities. This multidisciplinary group generated many insightful and collegial discussions that resulted in a highly productive workshop and the establishment of new collaborations.

The presentations showcased developments in data synthesis, climate modeling and new record development. Helen McGregor discussed a low-resolution sea surface temperature composite by the Ocean2k group (McGregor et al. 2015). Nerilie Abram presented the PAGES 2k Consortium effort focused on the onset of Industrial-era warming across oceans and continents. Mandy Freund presented a new Australian precipitation field reconstruction spanning the last millennium.

Hamish McGowan showed a 2100-year temperature reconstruction using a speleothem from New South Wales, Australia. Chris Moy linked high-accumulation lake records from southern South America and the Auckland Islands to changes in the Southern Hemisphere westerly winds. Ben Henley presented an Interdecadal Pacific Oscillation reconstruction from Pacific-wide paleoclimate data using the new Tripole Mode Index (Henley et al. 2015).

Work connecting proxy data and climate model simulations by Steven Phipps and Duncan Ackerley showcased data assimilation for Southern Hemisphere records using CSIRO Mk3L model simulations, and potential for conducting paleoclimate experiments using the Australian Centre for Water and Climate Research's ACCESS model.

Bronwyn Dixon described the new Australasian "low resolution" database, which includes 536 non-annually resolved records from Australia and Indonesia. The highest quality records were identified and preliminary results presented. Stuart Browning gave a presentation on a new paleoclimate data and climate model-data assimilation method (Browning and Goodwin 2015) to develop a 1000-year reanalysis product called "PaleoR" (http://climatefutures.mq.edu.au/research/themes/marine/paleor/). Following this, Drew Lorrey showcased NIWA's Past Interpretation of Climate Tool (PICT; http://pict.niwa.co.nz), which applies modern analogues from reanalysis data to understand past circulation modes from paleoclimate data (Lorrey et al. 2013). A comparison of results derived from the PaleoR and PICT methods for the 1450-1850 CE period is shown in Figure 1. Lively discussions led by Ian Goodwin considered developing guidelines for future record collection in the Australasian region, framed around understanding regional and hemispheric climate dynamics.

Marcus Vandergoes presented progress developing high-resolution lake sediment records from New Zealand, followed by Krystyna Saunders' precipitation reconstruction from Tasmanian lake sediments based on scanning visible reflectance spectroscopy. An interactive poster session highlighted progress on the climatic interpretation of Western Australian speleothem records by Pauline Treble; a new borehole temperature reconstruction for eastern Australia by Suman Asadusjjaman; sedimentary charcoal records from Pacific Islands by Matthew Prebble; and a new high-resolution Southern Hemisphere westerly winds reconstruction using sub-Antarctic lake sediments by Krystyna Saunders.

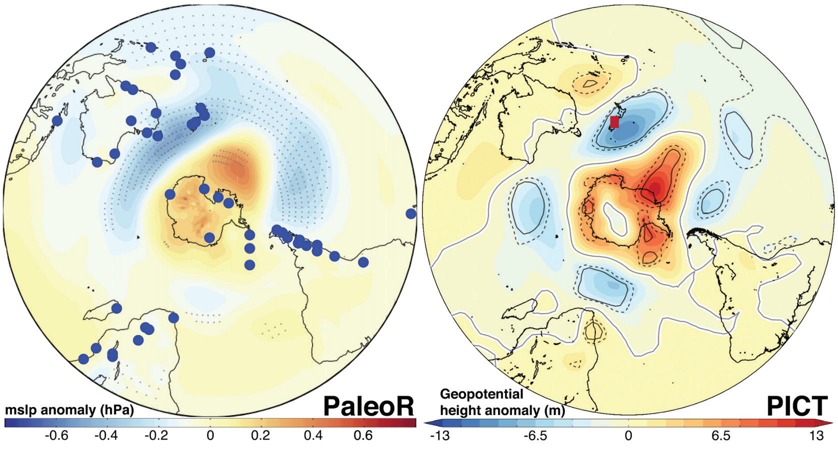

Figure 1: Southern Hemisphere spatial fields for austral summer near-surface atmospheric circulation (1450-1850 CE) based on PaleoR and PICT. PaleoR is based on a diverse range of proxy data from across the globe, while PICT is based on average paleotemperatures from 22 Southern Alps glaciers in New Zealand. Proxy data are independent and derived spatial fields are based on different datasets (PaleoR=climate model; PICT=modern reanalysis). There are broad similarities, along with regional confidence for different parts of the Southern Hemisphere.

There was extensive discussion on regional "best practice" standards for proxy metadata reporting and compatibility with the LiPD framework (McKay and Emile-Geay 2016), existing geochronology protocols, ideas for new record collection that support a new metadata template, and a proposed article on this critical topic.

The workshop identified two contributions on regional hydroclimate synthesis papers, led by early-career researchers Mandy Freund and Bronwyn Dixon, for the planned PAGES 2k synthesis special issue. A proposed table of contents for a regional special issue for *Climate of the Past* was generated to showcase the diversity of new research being developed by the Aus2k community. The proposed submission timeframe is expected to span September 2016 to June 2017. Please contact a steering committee member if you are interested in contributing.

AFFILIATIONS

[1]School of Earth Sciences, University of Melbourne, Australia
[2]National Institute of Water and Atmospheric Research (NIWA), Auckland, New Zealand
[3]Research School of Earth Sciences, Australian National University, Canberra, Australia
[4]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia
[5]Australian Nuclear Science and Technology Organisation (ANSTO), Sydney, Australia
[6]www.pastglobalchanges.org/calendar/all-events/127-pages/1490-4th-aus2k-wshop

CONTACT

Joelle Gergis: jgergis@unimelb.edu.au

REFERENCES

Henley B et al. (2015) Clim Dyn 45: 3077-3090

Lorrey A et al. (2013) Clim Dyn 42: 3039-3060

McGregor HV et al. (2015) Nature Geosci 8: 671-677

McKay NP, Emile-Geay J (2016) Clim Past 12: 1093-1100

Consolidation, finalization and publication of the Euro-Med2k database

Ulf Büntgen[1,2,3], F. Charpentier Ljungqvist[4,5], J. Esper[6], J. Luterbacher[7], S. Wagner[8], J.P. Werner[9] and workshop participants[10]

Hemmenhofen, Germany, 23-25 March 2016

Twelve participants catalyzed interdisciplinary enthusiasm towards consolidation, finalization and publication of the Euro-Med2k database. Two evening guests provided insights into the fascinating interface of archeology and dendrochronology: Oliver Nelle (State Department of Preservation in Baden-Württemberg) and Willy Tegel (Department of Forest Growth, University of Freiburg).

In light of generating strong contributions for the 2k Special Issue in *Climate of the Past*, we discussed the paleoclimatic potential of various high to low-resolution marine and terrestrial proxy archives from the North Atlantic, European and Mediterranean sector. Lead authors for these contributions will be Fredrik Charpentier Ljungqvist (Summer temperature and drought co-variability across Europe since 800 CE), Mary Gagen (European-scale cloud/sunshine reconstructions from the $d^{13}C$ records), Johannes Werner (Reconstructing high and low frequency European temperature and hydroclimatic variations over the Common Era), and Eduardo Zorita (Analysis of cloud feedback in the CMIP5 past millennium simulations). To achieve these goals, Euro-Med2k will further strengthen alliances with Ocean2k (proxies from Mediterranean and North Atlantic sector), Arctic2k (proxies from Fennoscandia including Kola and the Polar Urals), and Asia2k (western Russian Plain, Caucasus and Black Sea region, Altai Mountains).

As another outcome of this workshop, Euro-Med2k expressed strong willingness to maintain its current form and structure beyond 2016. This vision is grounded on a variety of scientific challenges and opportunities associated with the still-growing database.

In addition to the reconstruction of European summer temperatures since Roman times (Luterbacher et al. 2016), Euro-Med2k expanded its perspective towards hydroclimate and compared environmental changes with societal reorganizations.

Ljungqvist et al. (2016) compiled and analyzed 196 moisture-sensitive records to place recent hydrological changes and future precipitation scenarios in a long-term context. They found persistent seesaw patterns of alternating moisture regimes operating throughout the past 12 centuries. Together with an updated compilation of 128 temperature proxy records, the relationship between the reconstructed centennial-scale NH climate variability was assessed and compared to model simulations. While they show reasonable agreement during pre-industrial times, the intensification of the 20th century mean hydroclimatic anomalies in the model simulations, as compared to previous centuries, is not supported by the new multi-proxy reconstruction.

Büntgen et al. (2016) used tree-ring chronologies from the Russian Altai and European Alps to reconstruct summer temperatures over the past two millennia. Unprecedented, long-lasting and spatially synchronized cooling was detected after a cluster of large volcanic eruptions in 536, 540 and 547 CE. This sharp drop in summer temperatures was likely sustained by ocean and sea-ice feedbacks, superimposed on a solar minimum. The interval from 536 to ~660 CE was termed the Late Antique Little Ice Age (LALIA), and should be considered as an additional environmental factor contributing to the establishment of the Justinian plague, transformation of the eastern Roman Empire and collapse of the Sasanian Empire, movements out of the Asian steppe and Arabian Peninsula, spread of Slavic-speaking people and political upheavals in China.

Büntgen and Di Cosmo (2016) enhanced our perception of the environmental conditions under which historical events may have occurred. The sudden withdrawal of the Mongols from Hungary in 1242 CE has generated an array of controversial theories. None of them, however, combined historical reports and natural archives. Documentary sources and tree-ring chronologies reveal warm and dry summers from 1238-1241, followed by cold and wet conditions in 1242. Marshy terrain across the Hungarian plain probably reduced pastureland and decreased mobility, as well as the military effectiveness of the Mongol cavalry, while local despoliation and depopulation caused famine. These circumstances arguably contributed to the determination of the Mongols to abandon Hungary and return to Russia. While overcoming deterministic and reductionist arguments, the new "environmental hypothesis" emphasizes the importance of minor climatic fluctuations on major historical events.

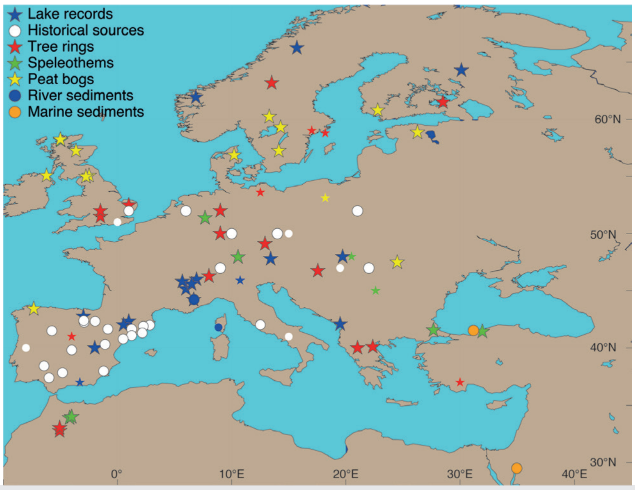

Figure 1: The Euro-Med2k multi-proxy network for hydrological reconstructions. Small, unframed symbols refer to archives for which only metadata exist. Documentary evidence represents larger data assemblages.

AFFILIATIONS

[1]Swiss Federal Research Institute for Forest Snow and Landscape, Birmensdorf, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Switzerland
[3]Global Change Research Centre, Brno, Czech Republic
[4]Department of History, Stockholm University, Sweden
[5]Bolin Centre for Climate Research, Stockholm University, Sweden
[6]Department of Geography, Johannes Gutenberg University, Mainz, Germany
[7]Department of Geography and Centre for International Development and Environmental Research, Justus-Liebig-University Giessen, Germany
[8]Institute for Coastal Research, Helmholtz Centrum, Geesthacht, Germany
[9]Bjerknes Centre for Climate Research and Department of Earth Science, University of Bergen, Norway
[10]List of all workshop participants and group picture here: www.pastglobalchanges.org/calendar/all-events/127-pages/1578-euromed-consolid-meet

CONTACT

Ulf Büntgen: buentgen@wsl.ch

REFERENCES

Büntgen U et al. (2016) Nature Geosci 9: 231-236

Büntgen U, Di Cosmo N (2016) Sci Rep 6, doi:10.1038/srep25606

Charpentier Ljungqvist FC et al. (2016) Nature 532: 94-98

Luterbacher J et al. (2016) Environ Res Lett 11, doi:10.1088/1748-9326/11/2/024001

Data, age uncertainties and ocean $\delta^{18}O$ under the spotlight for Ocean2k Phase 2

Helen V. McGregor[1], B. Martrat[2,3], M.N. Evans[4], D. Thompson[5], D. Reynolds[6], J. Addison[7] and Workshop Participants[8]

1st Ocean2k workshop, Barcelona, Spain, 6-8 October 2015

The oceans make up 71% of the Earth's surface area and are a major component of the global climate system. They are the world's primary heat reservoir, and knowledge of the global ocean response to past and present radiative forcing is important for understanding climate change. PAGES' Ocean2k working group aims to place marine climate of the past century within the context of the previous 2000 years (2k). Phase 1 (2011-2015) focused on constraining the forcing mechanisms most consistent with reconstructed sea surface temperature (SST) over the 2k interval (McGregor et al. 2015; Tierney et al. 2015). The 1st Ocean2k workshop assisted in the transition to Ocean2k Phase 2 (2015-2017), with the workshop goal to develop, coordinate and significantly advance community-identified and -driven activities.

A novel pre-workshop proposal process generated over a dozen ideas for Phase 2, which were then refined at the three-day workshop to three themes of broad interest to the Ocean2k community: metadatabase modernization, quantifying and reducing marine record age model uncertainties, and understanding patterns of global ocean $\delta^{18}O$. In addition, a series of sub-themes with distinct foci emerged.

Metadatabase modernization

Expanding on the crowd-sourced development of the Ocean2k metadatabase (www.pastglobalchanges.org/ini/wg/ocean2k/data), this theme will facilitate submission of datasets to public archives and integrate the metadatabase with the LiPD (McKay and Emile-Geay 2016) and SESAR/EarthChem initiatives (http://earthcube.org/group/marine-annually-resolved-proxy-archives). These initiatives will advance synthesis activities within Ocean2k, PAGES 2k working groups, and with scientists globally.

Age model uncertainties

This theme will apply uniform age model calibration techniques to records in the Ocean2k network, and re-examine their age uncertainties to improve the description of marine climate patterns in space and time through the 2k interval. Preliminary analysis suggests that different techniques can result in age model shifts of ±85 years (4.25% age uncertainty; Fig. 1a-b), making it difficult to identify multi-decadal variability in the marine realm. But, at the centennial scale, a standardized ^{14}C calibration methodology could better constrain the timing of common spatial variability and reduce temporal uncertainty estimates.

Ocean $\delta^{18}O$

Ocean2k Phase 1 identified numerous individual coral and foraminifera SST reconstructions covering some or all of the past 2k, and many of these have associated $\delta^{18}O$ measurements (Fig. 1c). The ocean $\delta^{18}O$ theme will bring these marine SST and $\delta^{18}O$ records together to document the first order spatio-temporal patterns of global ocean $\delta^{18}O$ and investigate the ocean hydroclimate, salinity signals, and circulation changes of the past 2000 years. Results will be compared with realistically forced simulation (isotope-enabled where possible) and the theme will run in conjunction with the PAGES 2k trans-regional project Iso2k.

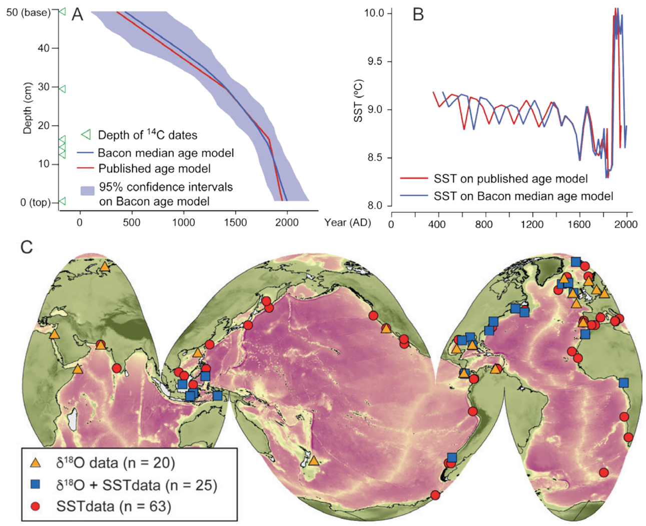

Figure 1: (A) Age-depth relationship for marine core MC-29D from the original publication (linear interpolation between dates, red line; Keigwin et al. 2003), and recalculated (blue line) using the Bacon software (Blaauw and Christen 2011). Age models are based on ^{14}C dates only. **(B)** MC-29D alkenone SST record plotted against the age models from (A). Age models differ by up to 85 years. **(C)** Marine sediment core $\delta^{18}O$ and SST reconstructions in the Ocean2k metadatabase, October 2015 version.

Additional themes

Additional sub-themes will explore the ENSO and teleconnection signals identified in the Phase 1 analysis (Tierney et al. 2015); investigate spatio-temporal AMOC dynamics; synthesize Mediterranean Sea records to investigate North Atlantic influences on the Mediterranean climate for the Little Ice Age and Medieval Climate Anomaly; and evaluate the oceanic response to volcanic forcing seen in proxy and model reconstructions with simulated post-eruption climate features.

Join us

The workshop was the first in-person meeting of the Ocean2k working group after over four years of productive, consensus-driven collaboration (Evans 2015), and we invite you to join the project. See www.pastglobalchanges.org/ini/wg/ocean2k/intro for additional information, or please contact the new overall lead of the working group, Helen McGregor. We thank the CosmoCaixa Natural Science Museum for hosting us and facilitating our successful outreach event, attended by over 100 high school students.

AFFILIATIONS

[1]School of Earth and Environmental Sciences, University of Wollongong, Australia
[2]Department of Environmental Chemistry, Spanish Council for Scientific Research, Barcelona, Spain
[3]Department of Earth Sciences, University of Cambridge, UK
[4]Department of Geology and Earth System Science Interdisciplinary Center, University of Maryland, College Park, USA
[5]National Center for Atmospheric Research, Boulder, USA
[6]School of Earth and Ocean Sciences, Cardiff University, UK
[7]U.S. Geological Survey, Menlo Park, USA
[8]In-person and virtual, www.ocean2k-bcn2015.org/contributions/participants

CONTACT

Helen McGregor: mcgregor@uow.edu.au

REFERENCES

Blaauw M, Christen JA (2011) Bayesian Anal 6: 457-474

Evans MN (2015) "Virtually" Ocean2k, Future Earth

Keigwin LD et al. (2003) Clim Dyn 21: 53-62

McGregor HV et al. (2015) Nature Geosci 8: 671-677

McKay NP, Emile-Geay J (2016) Clim Past 12: 1093-1100

Tierney JE et al. (2015) Paleoceanography 30: 226-252

Hydro2k: Integrating proxy data and models for insights into past and future hydroclimate

Jason E. Smerdon[1], J. Luterbacher[2] and S.J. Phipps[3]

Palisades, USA, 1-3 June 2016

New paleoclimate reconstructions are expanding insights into hydroclimate variability and change during the Common Era (e.g. Cook et al. 2015; Diaz and Wahl 2015). Many last-millennium simulations using fully-coupled climate models are also becoming available (e.g. Fernandez-Donado et al. 2013). Importantly, Phase 3 of the Paleoclimate Modelling Intercomparison Project (PMIP3) included a last-millennium experiment in its protocol, and multiple centers performed the experiment using the same state-of-the-art models used for Phase 5 of the Coupled Model Intercomparison Project (CMIP5). Ensembles of last-millennium simulations (e.g. Otto-Bliesner et al. 2016) are also proposed as part of PMIP4. These developments make the time ripe for expanding our understanding of past hydroclimate variability, while exploring whether climate models simulate hydroclimate in ways that are consistent with the paleoclimate record.

Addressing these emerging themes was the focus of a workshop titled *Comparing data and model estimates of hydroclimate variability and change over the Common Era*, organized jointly by PAGES 2k and the PAST2k working group of PMIP (see Schmidt et al. 2014 and PAGES 2k-PMIP3 group 2015 for outcomes of related past workshops). The workshop included presentations from paleoclimatologists on hydroclimate proxies and their interpretation, climate modelers on current efforts to simulate climate over the Common Era, and from researchers working at the interface of these two areas (see the full agenda and presentation slides at: http://pages2kpmip3.github.io/). The presentations and associated discussions provided an assessment of the state of the science, the challenges associated with hydroclimate comparisons between proxy information and model simulations, and an evaluation of best practices in this emerging field.

Workshop discussions underscored the nascent stage of data-model comparisons over the Common Era generally, and specifically with regard to hydroclimate. Recommendations include the need to account for internal variability and its influence on comparison outcomes. Internal variability will obscure comparisons between proxy reconstructions and climate model simulations, even if they represent both forced changes and internal variability perfectly (Fig. 1). Analyses that go beyond simple time-series associations are therefore strongly advocated, including bootstrapping exercises to evaluate null hypotheses and assessments based on spectral information. The importance of proxy system models (PSMs) was also stressed. When studying decadal and centennial variability, PSMs allow better accounting of the reddening of climatic signals present in some proxy records. For the emerging area of paleoclimate data-assimilation, PSMs also account for the multiple environmental variables often integrated by proxies. Generally, comparison efforts should include as many models as possible, while incorporating the collection of ensemble simulations from individual models. Spatial sampling should be done carefully, keeping in mind that local associations do not necessarily scale regionally or globally (and vice versa). These general points of guidance and the emerging efforts to refine techniques for hydroclimate data-model comparisons will further enhance our ability to evaluate climate models, understand the dynamics of hydroclimate variability and change, and constrain our characterizations of climate risks in the future.

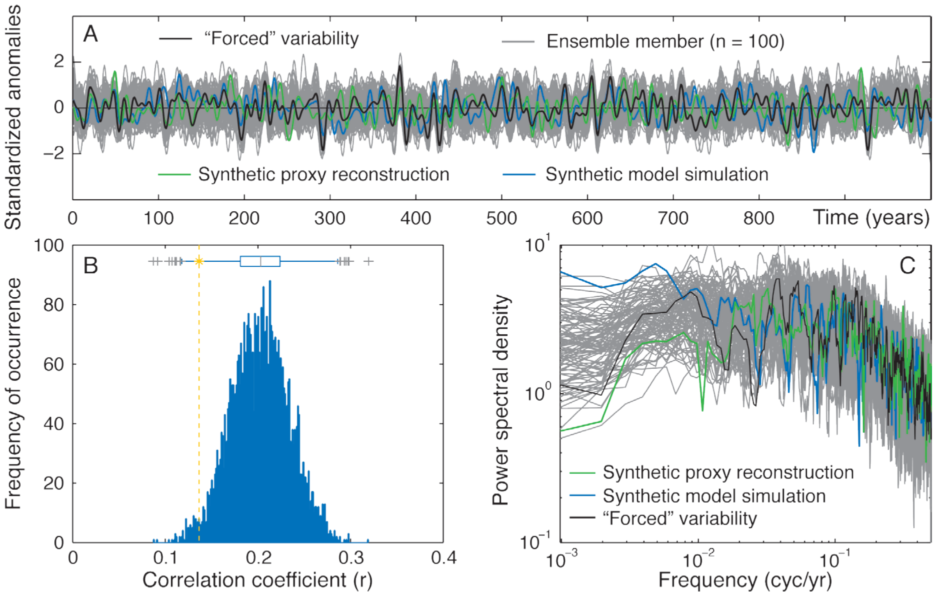

Figure 1: (A) A "forced" signal modeled as an autoregressive lag-1 process (AR(1); $\mu = 0$, $\sigma = 1$, $\rho = 0.3$) and 100 synthetic climate histories constructed by adding the forced series to 100 AR(1) series ($\mu = 0$, $\sigma = 2$, $\rho = 0.3$) to represent internal variability. Two of the ensemble members are highlighted to represent a proxy record and a model simulation that both perfectly sample the forced climate variability while having different realizations of internal variability. All plotted series have been processed with a 10-year lowpass filter. **(B)** The distribution of Pearson's correlation coefficients calculated between each of the grey series in panel (A). The boxplot shows the median, interquartile range and the outliers in grey crosses. The yellow dashed line and star indicate the correlation coefficient calculated between the unfiltered proxy and model series in panel (A). **(C)** The multitaper power spectral density estimates for the forced series and all grey series shown in panel (A).

ACKNOWLEDGEMENTS

This workshop was made possible by PAGES and the Climate Center at the Lamont-Doherty Earth Observatory.

AFFILIATIONS

[1]Lamont-Doherty Earth Observatory of Columbia University, Palisades, USA
[2]Department of Geography and Centre for International Development and Environmental Research, Justus-Liebig-University Giessen, Germany
[3]Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia

CONTACT

Jason Smerdon: jsmerdon@ldeo.columbia.edu

REFERENCES

PAGES 2k-PMIP3 group (2015) Clim Past 11: 1673-1699

Cook ER et al. (2015) Sci Adv 1, doi:10.1126/sciadv.1500561

Diaz HF, Wahl ER (2015) J Clim 28: 4637-4652

Fernandez-Donado L et al. (2013) Clim Past 9: 393-421

Otto-Bliesner BL et al. (2016) BAMS 97: 735-754

Schmidt GA et al. (2014) Clim Past 10: 221-250

Revealing social-ecological systems trajectories to enhance their sustainability

Fabien Arnaud[1], J. Dearing[2], P. Gell[3], K. Walsh[4] and D. Penny[5]

Chambéry, France, 30 May - 1 June 2016

Paleosciences played a crucial role in the societal acknowledgement of humankind's responsibility for global warming. However, while the Earth is simultaneously facing its sixth mass extinction, mainly triggered by human activities and a dramatic rise in human population, it appears more and more obvious that climate is not the sole human-modified system whose dysfunction threatens the security and well-being of humans. Biodiversity loss, soil degradation, the spreading of contaminants, and disturbed nutrient cycles are of particular concern (Steffen et al. 2015). The long-term dynamics of those threats to ecosystems, as well as their impact on ecosystem services, remain largely unknown.

Understanding the complex long-term interactions between human actions, climate and the functioning of social-ecological systems is critical to prepare a safe future (Costanza et al. 2007; Dearing et al. 2015). Addressing these interactions also contributes to the Future Earth Vision 2025 call for new integrated scientific approaches to better understand the complex dynamics of social-ecological systems. In this context, this workshop investigated the potential of paleosciences to create knowledge to help increase the sustainability of human development on Earth.

Scientific contributions and discussions

The workshop was split into three parts with the aim of answering the questions: (1) why, (2) what kind and (3) how to integrate paleodata to better understand complex human-climate-environment interactions? Based on case studies, conceptual advancements were presented. In particular, the attendees debated the interest of transposing the concepts of "safe operating space" and "ecosystem services" to paleostudies. Those concepts could indeed permit the description of the evolution of the environment from a societal point of view with a limited number of descriptors. This point appeared crucial, considering the great diversity of reconstructed variables. Such an approach could provide the foundation for the integration of various proxies from a large variety of disciplines (Fig. 1).

Among the innovative proxies of past changes, DNA and chemical biomarkers appear particularly promising. The integration of archeological and paleoenvironmental data to explain civilization collapses or landscape shaping is of particular interest, but better information systems that combine both the spatial and temporal aspects still need to be developed. Finally, while the ability of models to depict societal-environmental dynamics is getting better, they are still rarely used. Especially at a regional scale, models could be used to connect the local contribution of human practices to global changes and human vulnerability.

Working group perspective

The workshop assembled a new scientific community and generated fruitful and novel discussions. Attendees agreed to submit a proposal for the creation of a new PAGES working group titled "Social-environmental trajectories". The aim of this group would be to promote the development of a scientific community located at the junction of the paleo-, ecological- and human sciences. Based both on proxy reconstructions and ecosystem services-oriented modeling, this group seeks to understand how human practices in the past were successful in the face of global changes over long time periods. Hence the group would ultimately question the resilience of today's societies in the face of global changes, with respect to cultural and natural heritage in particular.

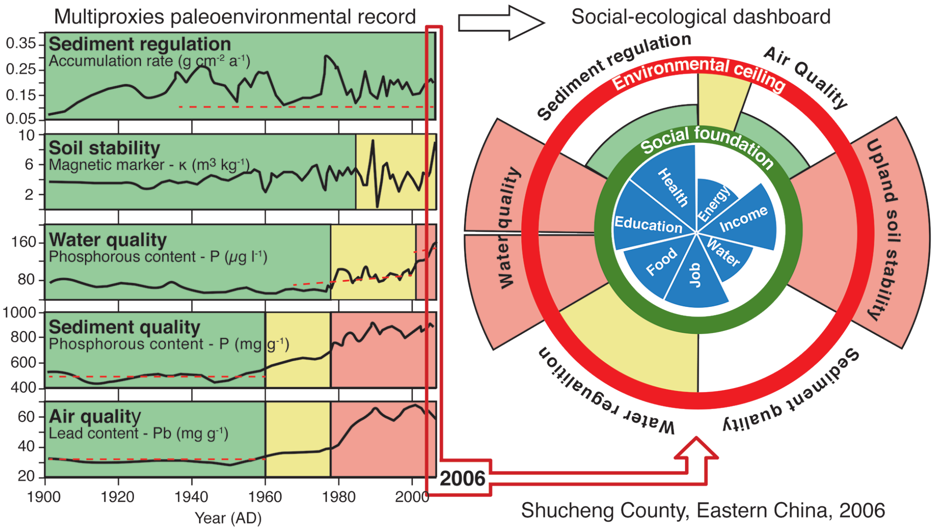

Figure 1: Combination of paleoecological proxies to propose an evaluation of ecosystem functioning and threats of a given region, taking account of its social-ecological trajectories - here for Shuncheng County, China (modified from Dearing et al. 2014). Such an approach combines the concepts of paleo-ecosystem services (Dearing et al. 2012) and safe operating space for humanity (Raworth 2012; Rockström et al. 2009).

AFFILIATIONS
[1]Environment Dynamics and Territories of Mountains (CNRS), University Savoie Mont Blanc, Chambéry, France
[2]Palaeoecology Laboratory, Geography and Environment, University of Southampton, UK
[3]Water Research Network, Federation University, Ballarat, Australia
[4]Department of Archaeology, University of York, UK
[5]Faculty of science, University of Sydney, Australia

CONTACT
Fabien Arnaud: fabien.arnaud@univ-smb.fr

REFERENCES

Costanza R et al. (2007) Ambio 36: 522-527

Dearing JA et al. (2015) Anthrop Rev 2: 220-246

Dearing JA et al. (2014) Glob Environ Change 28: 227-238

Dearing JA et al. (2012) PNAS 109: E1111-E1120

Raworth K (2012) A Safe and Just Space for Humanity, Oxfam Discuss Pap

Rockström J et al. (2009) Nature 461: 472-475

Steffen W. et al. (2015) Science 347: 736

Paleoclimate data standards

Julien Emile-Geay[1] and Nicholas P. McKay[2]

Boulder, USA, 22-23 June 2016

The progress of science can be directly tied to increased standardization of measurements, instruments, and information. Hosted by the US National Centers for Environmental Information (NOAA-NCEI) World Data Service for Paleoclimatology (WDS-Paleo)[1] in Boulder, USA, 40 participants gathered to establish preliminary standards for paleoclimate data. The workshop was primarily supported by the EarthCube-funded LinkedEarth project[2], with auxiliary support from PAGES to ensure international participation.

A common tongue

Building upon the machine-readable Linked Paleo Data framework (LiPD; McKay and Emile-Geay 2016; Fig. 1), the group recognized the need for (i) a structure to organize data and metadata and (ii) a consensual terminology. Group activities highlighted the difficulty to agree upon such terminology, though the conceptualization of Evans et al (2013) emerged as a sound foundation for the structure. WDS-Paleo presented efforts to normalize the terminology used to report observations and their units, for each archive type[3].

Shades of metadata

While more metadata are always desirable, a key discussion focused on distinguishing a set of essential, recommended and optional properties for each dataset. A consensus emerged that these levels are archive-specific (e.g. what is essential to intelligently re-use a dataset is different for a speleothem and a marine sedimentary record). Therefore, the community should coalesce around archive-specific working groups to propose such recommendations. The group also recognized the asymmetry between modern and legacy records (metadata for the latter being inherently more difficult to gather), so what counts as "essential" will be different depending on the age of the study.

A cornerstone of group discussions was to identify what metadata allow to reproduce, cite, and reuse, paleoclimate data. Rewarding data producers emerged as a central theme, thanks in part by presentations on connected efforts on data citations[4], links to scientific expeditions[5], and physical samples[6]. The difficulty to mint data digital object identifiers with the appropriate level of granularity, as well as the current cap on the number of citations in mainstream science journals, were recognized as a major hurdle to crediting data producers; a dialogue with the publishing community should be initiated to remove these hurdles.

Characterizing data records

Part of the drive to enhance the description of paleoclimate data is the need to better communicate their inherent uncertainties. The indirect nature of paleoclimate observations also requires a precise language for their interpretation. This motivated a discussion of a formal paleoclimate ontology, a preliminary version of which was unveiled[7]. Ontologies are formal representations of concepts and their logical connections, and their dividends in other fields were presented. Despite their scientific importance, the concepts of uncertainty and interpretation were found difficult to define unambiguously. However, the group underscored the importance of quantifying how completely these notions are described in the metadata. A multivariate completeness score was proposed[8], allowing users to rapidly evaluate metadata completeness along several dimensions, thus incentivizing best curation practices.

Building consensus

Standards arise by consensus. The group acknowledged the necessity to engage a broad community of paleoscientists, and establish a mechanism to gather their input. The LinkedEarth wiki[9] was designed to facilitate initial discussions by communities of interest, and elaborate recommendations addressing the various issues raised at the workshop. The community engagement process is described at http://linked.earth/community-standards-development/. PAGES will play a key role in this feedback elicitation, and anyone interested in the process should reach out to linkedearth@gmail.com. An official communication from the PAGES IPO about the role of this process in the PAGES Data Stewardship[10] Initiative is forthcoming.

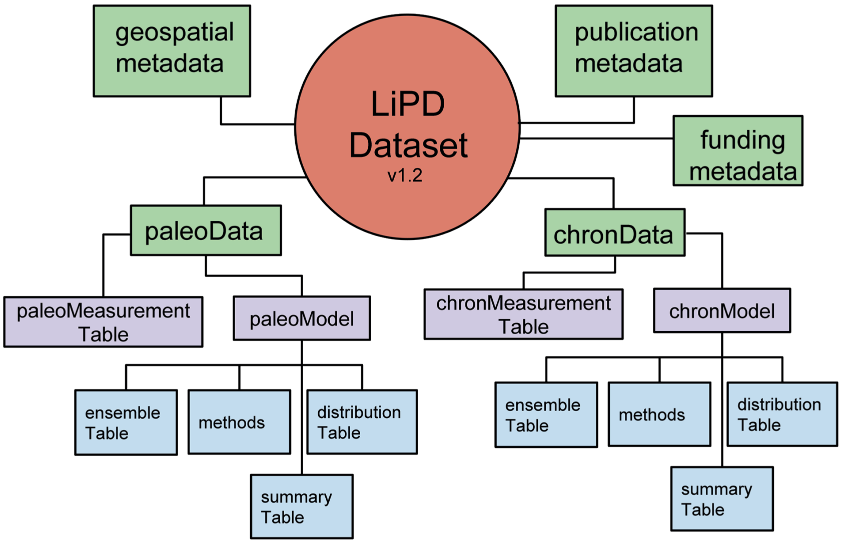

Figure 1: Data and metadata compartments in the current version of LiPD. The format is designed to store, along with several kinds of metadata (location, publication, funding), data tables pertaining to the paleosystem of interest (most often, climate), as well as chronology data, including raw chronological tie points and models based on them.

AFFILIATIONS

[1] Climate Dynamics Lab, University of Southern California, Los Angeles, USA

[2] School of Earth Sciences and Environmental Sustainability, Northern Arizona University, Flagstaff, USA

CONTACT

Julien Emile-Geay: linkedearth@gmail.com

LINKS

[1] www.ncdc.noaa.gov/data-access/paleoclimatology-data; [2] http://linked.earth; [3] https://agu.confex.com/agu/fm15/webprogram/Paper65476.html; [4] www.datacite.org; [5] www.geolink.org; [6] www.geosamples.org; [7] http://vowl.visualdataweb.org/webvowl/#iri=http://linked.earth/ontology; [8] http://wiki.linked.earth/WG_completeness; [9] http://wiki.linked.earth; [10] www.pastglobalchanges.org/ini/int-act/data-stewardship

REFERENCES

Evans MN et al. (2013) Quat Sci Rev 76: 16-28

McKay NP, Emile-Geay J (2016) Clim Past 12: 1093–1100

The European Pollen Database: Research tool and community

Thomas Giesecke[1], J.-L. de Beaulieu[2] and M. Leydet-Barbier[2]

Aix-en-Provence, France, 1-3 June 2016

Open-access paleo databases are of the utmost importance to arrive at a regional, continental, or global understanding of long-term processes and investigate past dynamics of Earth systems. The European Pollen Database (EPD), created alongside the North American Pollen Database more than 25 years ago, serves as the base for numerous analyses of climate, vegetation and land-cover change, while also being an important data repository and educational tool (Fyfe et al. 2009). To function as an up-to-date research tool, the database requires both the submission of new pollen data from the community as well as data stewardship and development of the database. The database is a community-wide effort, but there is an inherent risk of a division between data producers and data users. To overcome this separation and to generate new momentum in the development of the database, we called for an open EPD meeting and training workshop. Co-funded by PAGES, it attracted 126 paleoecologists, at all career stages, from 24 countries.

The meeting consisted of plenary lectures, training workshops, and group and plenary discussions. The lectures illustrated different research fields that use the database, such as climate and land-cover reconstructions (J. Guiot and M.-J. Gaillard), archeology (R. Fyfe), last glacial vegetation change (M. F. Sanchez Goñi), nature conservation (R. Bradshaw), and the postglacial spread of plants (T. Giesecke). Lectures also addressed interactions with the Global Charcoal Database (B. Vannière & D. Colombaroli), problems developing age models beyond the radiocarbon timescale (C. Tzedakis), and the new database infrastructure Neotoma (E. Grimm).

Seven parallel training workshops introduced participants to numerical problems in paleodata analyses and representation: (i) the data management and graphing software Tilia and its interaction with Neotoma (E. Grimm); (ii) the use of the modern surface sample dataset in quantitative reconstructions (B. Davis & M. Zanon); (iii) quantitative vegetation reconstructions using the Landscape Reconstruction Algorithm (P. Kuneš & M. Theuerkauf); (iv) charcoal software and database (B. Vannière & W. Finsinger); (v) working with the EPD using the data analysis software "R" (A. Seddon & J. Chipperfield); and (vi) age modeling (T. Giesecke). Another workshop was dedicated to the identification of non-pollen-palynomorphs (B. Dietre & S. Wolters), which is a field of active development in Quaternary palynology. All workshops were well received by participants, who wished they could be organized on a regular basis.

Group and plenary discussions focused on how to improve the database and make it more accessible to other communities, and we reviewed and simplified the rules and regulations. We also reviewed and reorganized the following EPD working groups:

The Taxonomy working group, coordinated by Steffen Wolters, keeps track of synonym names in the database and is developing a hierarchical system based on morphology. Future activities will include non-pollen-palynomorphs.

The Chronologies working group has produced standardized age models for over 800 sites (Giesecke et al. 2014). Coordinated by Thomas Giesecke, the group aims to provide the same type of models in addition to bayesian age models for the recently submitted sites.

Coordinated by Basil Davis, the Surface Samples working group, which compiled a new European dataset of surface sample data (Davis et al. 2013), will work on expanding this dataset.

The group on Community Outreach is now coordinated by Graciela Gil-Romera. This group will use social media to improve visibility, prepare educational packages for the general public and organize training workshops for the EPD community.

The new Quantitative Tools working group, coordinated by Alistair Seddon, was formed to focus on R and GIS applications. Plus, Petr Kuneš heads up another new group, Former Interglacials, which aims to organize and promote datasets that go beyond the radiocarbon time scale.

Be involved! For further news and information on how to contribute, go to: www.europeanpollendatabase.net

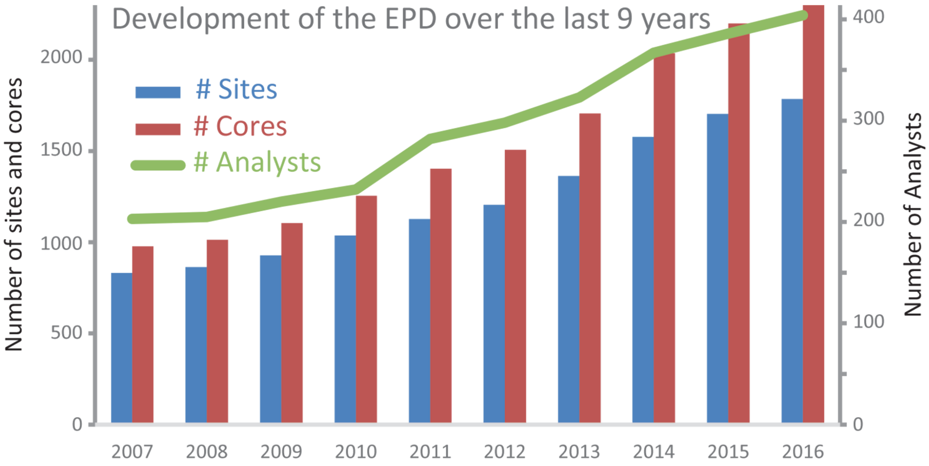

Figure 1: Development of the European Pollen Database since the open meeting in 2007. The number of sites and cores has doubled over the last nine years.

AFFILIATIONS
[1]Department of Palynology and Climate Dynamics, University of Göttingen, Germany
[2]Institut Méditerranéen de Biodiversité et d'Ecologie marine et continentale, Aix-Marseille Université, Aix-en-Provence, France

CONTACT
Thomas Giesecke: thomas.giesecke@biologie.uni-goettingen.de

REFERENCES

Davis BAS et al. (2013) Veget Hist Archaeobot 22: 521-530

Fyfe RM et al. (2009) Veget Hist Archaeobot 18: 417-424

Giesecke T et al. (2014) Veget Hist Archaeobot 23: 75-86

Ice Core Young Scientists workshop

Pascal Bohleber[1], M. Cavitte[2], B. Koffman[3], B. Markle[4], P. Pavlova[5], M. Winstrup[6] and H. Winton[7]

Hobart, Australia, 6 March 2016

Ice Core Young Scientists (ICYS) held a highly successful one-day workshop for early-career researchers (ECRs) in conjunction with the IPICS 2016 conference in Hobart, Australia. Over 85 ECRs attended the event, equivalent to about 40% of the IPICS conference delegation. In addition to providing professional development, the workshop offered a chance for ECRs to get to know each other before the week-long conference began.

The workshop kicked off with a plenary lecture by Nerilie Abram of the Australian National University, asking the question "Why do we need more paleoclimate records from Antarctica?" Nerilie presented research currently in preparation by the PAGES 2k Network, showing that climate models currently do not accurately represent the climate in the Southern Hemisphere. She argued for additional ice-core records from Antarctica and for improved integration of ice-core and other paleoclimate proxy data.

The plenary was followed by a lively panel discussion on the future of ice-core science. Eight panelists shared their views on what and where the next big ice-core project should be, and what major questions the community can try to address using ice cores in the future. Major themes coming out of the discussion included: (a) integrating data from multiple ice cores, such as the work by the PAGES Antarctica2k community; (b) filling in the latitudinal gap of paleoclimate records between the poles and taking advantage of other types of climate proxy records; (c) enhancing the interaction with climate modelers, oceanographers, and biologists using ice cores to answer non-climate questions; and (d) advancing technologies, such as rapid-access drilling and in situ analysis down boreholes. Major questions centered on improving predictions for future climate, especially in regard to sea-level rise, and understanding the role of Antarctica in the climate system. During the IPICS conference closing session, ICYS provided the broader ice-core community with an ECR perspective on the future of ice-core science.

Figure 1: Discussion group "science, family and equality: negotiating the ECR career path".

The ICYS workshop included breakout discussions focused on topics of great importance to ECRs, but which are rarely taught in formal settings. Session topics included "How to get your research funded as an ECR", "Leadership techniques and being a principal investigator" and "Initiating international collaborations". Each breakout group was facilitated by a mid-career scientist who shared his or her expertise and experience in these areas. We were also lucky to have Michael White, an editor at *Nature*, discuss issues around authorship.

Our final plenary session was facilitated by Heidi Roop, of the Science and Society research group at Victoria University of Wellington, New Zealand. Heidi shared insights on how to communicate more effectively with the public. We learned that "knowledge building" efforts, such as having community meetings and developing citizen science initiatives, are most effective in getting the public to understand, appreciate, support, and critically become involved with the science we do. We were able to fold these ideas into short outreach videos, called FrostBytes, which were produced at the end of the workshop. They will serve as a valuable resource for outreach and engagement, and are publicly available on the Climate and Cryosphere (CLiC) website.

PAGES generously supported six travel packages for ECRs from developing countries to attend the workshop. Travel support for ECR attendees was also provided by the US National Science Foundation, the IPICS 2016 conference sponsors, the EPICA Descartes Prize, and the West Antarctic Ice Sheet Divide ice core program. Lunch was kindly supported by CLiC.

This workshop, the first of its kind, successfully built a more cohesive international community of ECRs in ice-core sciences and provided those researchers with information and skills useful to their developing careers – the primary goals of ICYS. Many attendees remarked that simply meeting fellow ECRs before the main meeting improved their conference experience and sense of involvement in the community.

AFFILIATIONS

[1]Climate Change Institute, University of Maine, Orono, USA

[2]Institute for Geophysics, University of Texas at Austin, USA

[3]Department of Earth Sciences, Dartmouth College, Hanover, USA

[4]Earth & Space Sciences, University of Washington, Seattle, USA

[5]Paul Scherrer Institut, Villigen, Switzerland

[6]Centre for Ice and Climate, University of Copenhagen, Denmark

[7]British Antarctic Survey, Cambridge, United Kingdom

CONTACT

ICYS Executive Committee: icecoreys@gmail.com

Using Arctic driftwood at the interface of marine and terrestrial (paleo-)environmental research

Lena Hellmann[1,2], Ó. Eggertsson[3] and U. Büntgen[1,2,4]

Mógilsá, Iceland, 27-30 April 2016

This workshop, on the use of Arctic driftwood as an interdisciplinary paleoenvironmental proxy, was held at the Icelandic Forest Research Institute Mógilsá, northwest of Reykjavik. Twenty-one participants from 10 European and North American countries brought expertise in dendro-sciences, paleoclimatology and paleoecology, as well as archeology, history, oceanography and radiocarbon dating. The aim of the meeting was to build up a driftwood research network, by (1) the organization and coordination of future fieldwork, (2) the joining of forces towards a cross-disciplinary review paper, and (3) the collection of ideas for fundraising and proposal writing to facilitate international collaboration.

A first session on dendro-sciences and paleoecology provided an overview on the achievements of driftwood provenancing and dating, and its potential for reconstructing ocean-current dynamics and sea-ice variations. A second session reviewed proxy-based climate reconstructions for the Arctic, using examples of archeological driftwood research on the effects of wood decaying fungi to ancient wood use and tree-ring dating of archeological driftwood remains. A third session was dedicated to the reconstruction of relative sea-level changes, the effects of shrinking sea ice, the use of paleo-climatic estimates to constrain future climate predictions, as well as the current progress in radiocarbon dating.

Discussions emphasized the urgent need for cross-national sample exchange and free data access.

Finally, all participants agreed on writing an interdisciplinary review article about the current status and future perspective of Arctic driftwood research. The review paper is motivated by the high sensitivity of the Arctic to even small climatic changes going along with short instrumental measurements and a sparse proxy-data coverage for the high-northern latitudes, which again constrains model predictions. Knowledge on past variations in sea-ice extent, ocean-current dynamics, relative sea-level change, biotic dispersal, transport times within the Arctic Ocean and the importance of driftwood for human settlements is scarce.

Figure 1 illustrates the complexity of the driftwood system and proves the relevance of an interdisciplinary research avenue. Arctic driftwood is a unique integral that combines various fields of research within the Arctic region by representing an easily accessible and relatively cheap environmental archive with a huge unused potential that needs to be explored. Existing methods and material from different disciplines of Arctic driftwood research will be provided in the review paper to show the potential of more reliable reconstructions extending prior to the period of instrumental measurements. This paper will further propose the need for Arctic driftwood as a cross-disciplinary proxy archive that can be used to supplement long-term observations and model simulations. The outlook will set priorities for future driftwood fieldwork and research activities, and promote Arctic driftwood as a contribution to multi-proxy approaches for a better understanding of past and present characteristics of the Arctic system.

The workshop created a new strong network of researchers working with this unique proxy archive that will be relevant for the PAGES initiative also in the future. A follow-up meeting on Arctic driftwood research has already been scheduled for May 2017.

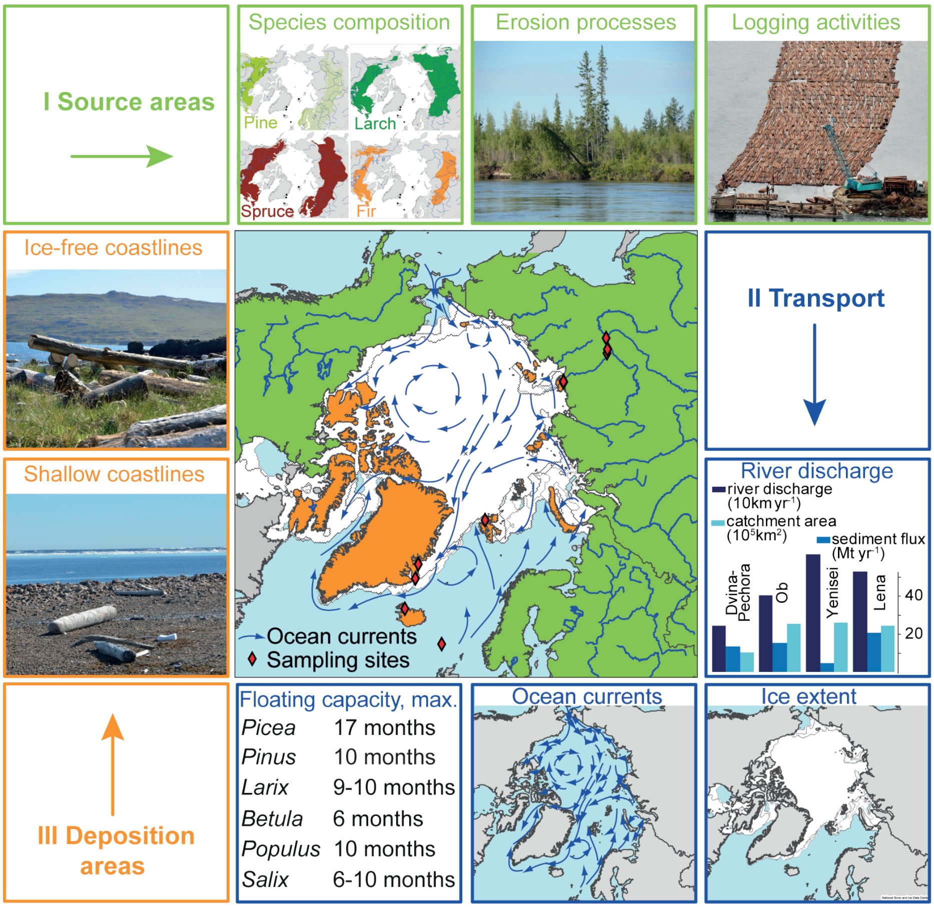

Figure 1: Schematic of the Arctic driftwood system. The amount and kind of driftwood material that starts its way to the Arctic Ocean is determined by species composition, erosion processes and logging activities in the boreal forest zone. How much wood is transported further, and in which direction, is influenced by boreal river discharge, sea-ice extent, ocean currents and the duration of transport, limited by the floating capacity. Deposition sites are generally shallow and ice-free coastlines. Map by the National Snow and Ice Data Center, USA.

AFFILIATIONS

[1] Swiss Federal Research Institute, WSL, Birmensdorf, Switzerland

[2] Oeschger Centre for Climate Change Research, Bern, Switzerland

[3] Iceland Forest Service Mógilsá, Reykjavik, Iceland

[4] Global Change Research Centre AS CR, Brno, Czech Republic

CONTACT

Lena Hellmann: lena.hellmann@wsl.ch

The Atlantic Meridional Overturning Circulation over decades to centuries

K. Halimeda Kilbourne

Boulder, USA, 23-25 May 2016

To make more accurate projections of future climate, we must improve our understanding of Atlantic Meridional Overturning Circulation (AMOC), its drivers and its impacts. Modern oceanographic observations of AMOC have limited record lengths, making it difficult to address important processes with timescales of decades to centuries (Buckley and Marshall 2016). Paleoceanographic data and techniques applied to Earth's recent past have a demonstrated potential to provide information about past AMOC behavior that could address questions about AMOC processes on these timescales and put recent changes into historical context (Alley 2007; Denton and Broecker 2008). Doing so most effectively requires co-ordination and cooperation across traditional disciplinary boundaries.

Two different scientific communities - modern physical oceanographers and paleoceanographers - came together to work on understanding AMOC over decades to centuries. We had approximately 60 attendees from nine countries, including 18 early-career scientists. One third of participants indicated in their meeting applications that they were working on the modern system, half were working on paleoceanographic questions, and the rest defied such simple characterization. During the meeting, it became clear the group represented four communities - modelers and observationalists working on the modern AMOC system, and modelers and observationalists working on the AMOC system of the past. Sometimes the lines were blurry, but there were clear differences in vocabulary, assumptions and scientific priorities. The discussions led to four main recommendations for progressing toward a better understanding of AMOC.

A consistent framework between models and observations

A factor limiting progress is the ability to make valid comparisons between paleoclimate data, model data and modern observations. AMOC in models is often based on the zonally integrated circulation in the Atlantic, and modern observational networks have been set up with this in mind. Paleoclimate proxy records, on the other hand, usually reconstruct an AMOC-related variable such as the vertical mixing in the Labrador Sea. Priority needs to be given to research and activities that move the communities toward a common standard for comparisons between observational and model data.

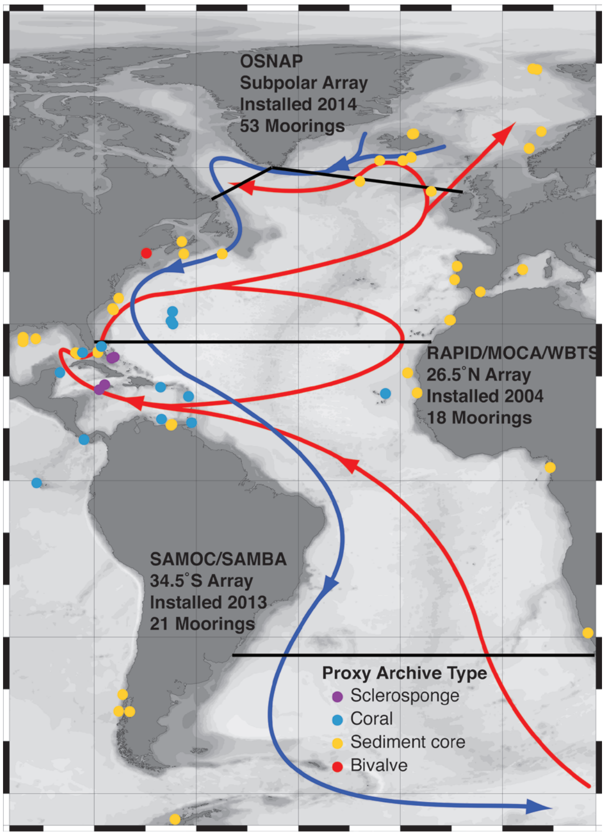

Figure 1: Location of existing paleoceanographic and modern oceanographic AMOC observing systems. Paleoceanographic sites represent the locations of samples/cores with paleotemperature information archived in the PAGES2k proxy temperature dataset version 2.0.0 (PAGES2k consortium, pers. comm.).

A denser network of AMOC and AMOC-related variables

Iterating between observational data and models can be a powerful tool for improving mechanistic understanding of AMOC. Observations tell us how the system behaves and models provide a tool to explore how such behavior arises. Conversely, if different models have different mechanisms, we can use observations to constrain which model might have a more-realistic simulation of the process. The last 1000 years is a key target period because of (i) relatively abundant existing paleoclimate data to provide information about background climate; (ii) reasonably constrained climate forcing variables; (iii) the availability of annual or better resolution proxy archives, and (iv) the potential to overlap with the instrumental record to provide quantitative proxy calibrations. Such data-model comparisons, requiring an improved network of proxy records guided by process-based information from models, can be used to reliably characterize the past behavior of AMOC, including the frequency and amplitude of decadal to centennial variability, as well as the response in associated environmental variables.

Improved understanding and communication of uncertainties

Cross-disciplinary coordination and cooperation could be facilitated if an effort was made to better quantify and report the uncertainties of our research. This issue came up repeatedly in reference to proxy reconstructions and calibrations, data assimilation projects, climate forcing factors used to drive models, and in data-model comparisons.

Encourage coordination between scientific communities

This may be accomplished at the level of individual researchers or larger organizations. Examples of the latter include adding a paleoceanography-specific team to the US AMOC/UK RAPID working groups; reviving something similar to the former PAGES-CLIVAR Intersections program to focus on targeted workshops; and strengthening links between CMIP and PMIP.

AFFILIATION
Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, USA

CONTACT
K. Halimeda Kilbourne: kilbourn@umces.edu

REFERENCES

Alley RB (2007) Annu Rev Earth Planet Sci 35: 241-272

Buckley MW, Marshall J (2016) Revi Geophys 54: 5-63

Denton GH, Broecker WS (2008) Quat Sci Rev 27: 1939-1950

CONTENTS

ANNOUNCEMENTS

2 **News**

EDITORIAL

3 **Tipping Points: Lessons from the Past for the Future**
Chris S.M. Turney, C.J. Fogwill, T.M. Lenton and R.T. Jones

SCIENCE HIGHLIGHTS: TIPPING POINTS

4 **Tipping points in the past: the role of stochastic noise**
Zoë A. Thomas and Richard T. Jones

6 **Tipping ice ages**
Michel Crucifix

8 **The East Antarctic Ice Sheet as a source of sea-level rise**
Christopher J. Fogwill, N.R. Golledge, H. Millman and C.S.M. Turney

10 **Did synchronized ocean warming trigger a deglacial tipping point?**
Summer K. Praetorius and Alan C. Mix

12 **Ice cores: High-resolution archive of rapid climate changes**
Simon Schüpbach, H. Fischer, S.O. Rasmussen, A. Svensson, D. Dahl-Jensen, et al.

14 **A paleo-perspective on the AMOC as a tipping element**
Stephen Barker and Gregor Knorr

16 **Identifying and anticipating tipping points in lake ecosystems**
Peter G. Langdon, J.A. Dearing, J.G. Dyke and R. Wang

18 **Multi-decadal climate variability as triggers of societal regime shifts in Japan**
Takeshi Nakatsuka

20 **Simple tipping or complex transition? Lessons from a green Sahara**
Sebastian Bathiany, M. Claussen, V. Brovkin, M. Scheffer, V. Dakos and E. van Nes

22 **The domestication of fire as social-ecological regime shift**
Reinette Biggs, W.J. Boonstra, G. Peterson and M. Schlüter

SCIENCE HIGHLIGHTS: OPEN SECTION

24 **Squeezing a rainfall record out of desert sand dunes**
Abi Stone

PROGRAM NEWS

26 **Top-class, new generation sediment coring on Research Vessel *Marion Dufresne***
27 **Unprecedented coring performance with the Research Vessel *Marion Dufresne***
28 **New PAGES working group on floods**
29 **Volcanic Impacts on Climate and Society working group**
30 **New Forest Dynamics working group**
31 **Global Paleofire Working Group phase 2 (GPWG2)**
32 **Climate Variability Across Scales: from centuries to millennia (CVAS)**

WORKSHOP REPORTS

33 **Scale and Scaling in the Climate System**
34 **Paving the road for improved integrative investigations of past Warm Extremes**
35 **Modeling late Pliocene climate variability**
36 **Bridging data and models**
37 **Understanding peat carbon sequestration on Earth**
38 **Mapping Human Subsistence in West Africa (1000 BC - AD 1500)**
39 **Synthesizing East African land-cover change over the past 6000 years**
40 **Land-use classification**
41 **Towards a reconstruction of Antarctic climate over the last 2000 years**
42 **Comparison of reconstruction methods, modeling, and synthesis approaches**
43 **Consolidation, finalization and publication of the Euro-Med2k database**
44 **Data, age uncertainties and ocean $\delta^{18}O$ under the spotlight for Ocean2k Phase 2**
45 **Hydro2k: Integrating proxy data and models for insights into hydroclimate**
46 **Revealing social-ecological systems trajectories to enhance their sustainability**
47 **Paleoclimate data standards**
48 **The European Pollen Database: Research tool and community**
49 **Ice Core Young Scientists workshop**
50 **Using driftwood at the interface of marine and terrestrial environmental research**
51 **The Atlantic Meridional Overturning Circulation over decades to centuries**

PAGES
PAST GLOBAL CHANGES

PAGES International Project Office
Falkenplatz 16
CH-3012 Bern
Switzerland

Telephone +41 31 631 56 11
Email pages@pages.unibe.ch
Website www.pastglobalchanges.org
Twitter @PAGES_IPO

Subscribe to PAGES magazine at
www.pastglobalchanges.org/products/pages-magazine

Series Editors
Lucien von Gunten and Marie-France Loutre

Guest Editors
Chris S.M. Turney, Chris J. Fogwill, Tim M. Lenton, Richard T. Jones

Text Editing
Angela Wade

Layout
Lucien von Gunten

Design
sujata design

Parent program
PAGES is a core project of Future Earth.

Sponsors
The PAGES International Project Office and its publications are supported by the Swiss and US National Science Foundations.

Printed on recycled paper by
Läderach AG
Bern, Switzerland

Hardcopy circulation 2450

ISSN 2411-9180