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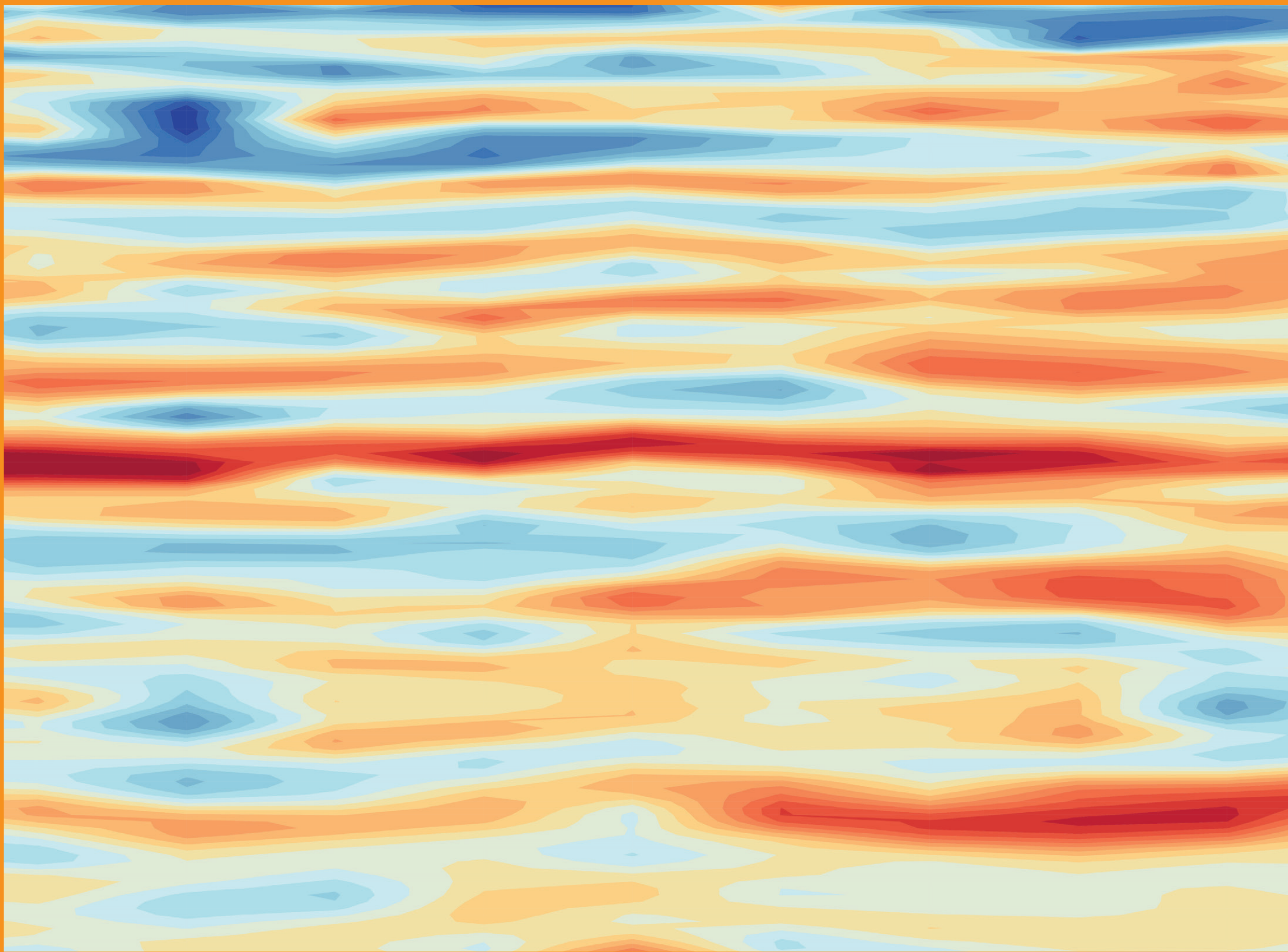

CENTENNIAL TO MILLENNIAL CLIMATE VARIABILITY

EDITORS
Michel Crucifix, Anne de Vernal, Christian Franzke and Lucien von Gunten

PAGES futurearth

News

PAGES at EGU 2018
Eight PAGES working groups/Integrative Activities have sessions at the General Assembly 2018 of the European Geosciences Union in Vienna, Austria, from 8-13 April 2018. Session abstracts are due 10 January 2018.
http://pastglobalchanges.org/calendar/upcoming/127-pages/1738-egu-18

New SSC members and co-chair in 2018
PAGES welcomes two new Scientific Steering Committee members to the organization on 1 January 2018. Zhimin Jian (Tongji University, China) and early-career researcher Emilie Capron (University of Copenhagen, Denmark) were elected from many outstanding candidates. They replace outgoing members Sheri Fritz (co-chair), Liping Zhou and Janet Wilmshurst. We take this opportunity to thank Sheri, Liping and Janet for their six years of service. Mike Evans now joins Willy Tinner as co-chair and we also welcome him to the role.

New data guidelines
PAGES has updated its data guidelines. PAGES continues to facilitate the development of community-based, data-intensive synthesis products, and promotes data stewardship within its constituency. Several widely used databases have been developed by PAGES-sponsored activities and many others are under construction.
http://pastglobalchanges.org/my-pages/data/data-guidelines

PAGES 2k Network Phase 3
Several new PAGES 2k Phase 3 projects have been announced or have a new website presence. Do you have an idea for a project focusing on paleoscience in the past 2000 years? New projects can be proposed at any time.
www.pastglobalchanges.org/ini/wg/2k-network/projects

Guest scientists at PAGES IPO
Professor Giri Kattel worked on various Aquatic Transitions working group projects in October and meet with local scientists in his field. Currently a Visiting Professor under the CAS-PIFI program in Nanjing, China, Kattel is working on paleolimnology, resilience and climate change in upland and lowland lakes and floodplain systems in China. He will return to The University of Melbourne, Australia, in January 2018.
http://pastglobalchanges.org/news/1822-guest-kattel-17

Scott St. George, Associate Professor in the Department of Geography, Environment and Society at the University of Minnesota, USA, gave talks in Bern and Zürich during his two-week stay in Switzerland in November, focusing on Floods Working Group and 2k Network topics. He can't quite believe how much PAGES has influenced his career.
http://pastglobalchanges.org/news/1844-guest-st-george-17

Former co-chair claims D-O-uble delight
PAGES congratulates former co-chair Hubertus Fischer on being awarded the 2018 Hans Oeschger Medal, which will be presented at the EGU 2018 General Assembly in Austria in April, and the Willi Dansgaard Award, which was presented at the AGU Fall Meeting in New Orleans, USA, in December 2017. Fischer, who finished his tenure with PAGES at the end of 2016, topped the nominees for outstanding achievements in ice research and/or short term climatic changes (past, present, future). We believe it is the first time someone has won both awards within one year and have appropriately named it the D-O-uble (as Dansgaard-Oeschger events are often abbreviated as D–O events).

Suggest a new working group or apply for meeting support*
Propose a new working group http://pastglobalchanges.org/ini/wg/new-wg-proposal or apply for workshop support by 19 April 2018 http://pastglobalchanges.org/my-pages/meeting-support *This round of meeting support is only open to current PAGES working groups. The next open call for workshop support will be in the second half of 2018.

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
If you have problems updating your details, we can help. Contact pages@pages.unibe.ch

Upcoming issue of Past Global Changes Magazine
Our next magazine will be on past land cover and land use. Contact the LandCover6k working group or the PAGES office if you are interested in contributing.
http://www.pastglobalchanges.org/ini/wg/landcover6k/intro

Calendar

EcoRe3: Resilience, disturbance, functional traits
8-9 May 2018 - Salt Lake City, Utah, USA

First PEOPLE 3000 workshop
14-18 May 2018 - San Rafael, Argentina

LandCover6k: European land-use at 6000 BP
21-23 May 2018 - Barcelona, Spain

GPWG2: African Fire History and Fire Ecology
20-22 July 2018 - Nairobi, Kenya

INQUA-PAGES: Impacts of sea-level rise
26-29 August 2018 - Utrecht, The Netherlands

Joint PALSEA2-QUIGS workshop
24-27 September 2018 - Galloway, USA

GEOTRACES-PAGES: Trace elements
3-5 December 2018 - Aix-Marseille, France

www.pastglobalchanges.org/calendar

Featured products

2k Network
Five new papers were accepted to the 2k phase two synthesis special issue "Climate of the past 2000 years: regional and trans-regional syntheses" of *Climate of the Past*.

Global Monsoon
The much-anticipated second synthesis product from PAGES' former working group. P. Wang et al. address driving mechanisms of global monsoon (GM) variability and outstanding issues in GM science (2017, *Earth Sci Rev* 174).

LandCover6k
L. Furong et al. estimate relative pollen productivity for plant taxa characteristic of human-induced vegetation in ancient cultural landscapes in eastern China (2017, *Veg Hist Archaeobot* 26). L. Marquer et al. combine pollen-based REVEALS estimates of plant cover with climate, anthropogenic land-cover and dynamic vegetation modeling results (2017, *Quat Sci Rev* 171).

OC3
E. Sikes et al. published "Enhanced $\delta^{13}C$ and $\delta^{18}O$ Differences Between the South Atlantic and South Pacific During the Last Glaciation: The Deep Gateway Hypothesis" (2017, *Paleoceanography* 32).

QUIGS/PALSEA2
B. Otto-Bliesner et al. published "The PMIP4 contribution to CMIP6 – Part 2: Two interglacials, scientific objective and experimental design for Holocene and Last Interglacial simulations" (2017, *Geosci Model Dev* 10).

VICS
Huge media interest surrounded the paper from J. Manning et al. that suggests volcanic eruptions, climate change and the absence of summer flooding caused upheaval in ancient Egypt (2017, *Nat Comm* 8). M. Toohey and M. Sigl describe a new reconstruction of volcanic stratospheric sulfur injections and the associated aerosol optical depth (2017, *Earth Sys Sci Data* 9)

Cover

Color plot representing variations along depth/time (vertical) and space (horizontal) of oxygen isotopic composition in snow trenches in Dronning Maud Land (from Münch et al. 2017, featured in Laepple et al., p. 140 of this issue).

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Centennial climate change: The unknown variability zone

Michel Crucifix[1], A. de Vernal[2] and C. Franzke[3]

Power spectra of paleoclimate records show that climate variability exists at the centennial timescale. There is no variability gap, as previously thought. Photo credit: Anne de Vernal.

Arguably, centennial variability has been the forgotten orphan of climate dynamics theory. In a 1990 paper titled "Three basic problems of palaeoclimate modelling", the late Barry Saltzman presented the centennial timescale as a zone with a variability gap – a demilitarized zone, separating people interested in weather from those interested in the slow evolution of climate.

Saltzman was putting forward an idea that has, until recently, deeply penetrated our paradigms of climate modeling. General circulation models generate weather. A so-called "climate snapshot" is often an average of the generated weather over a few centuries or so. At the other extreme, the dynamics of ice ages are simulated with models which do not include weather variability. We know today that this separation is no longer tenable. There is centennial variability, which seamlessly connects weather to the great ice ages.

The study of centennial variability is thus important for gaining a complete understanding of climate variability. It is important because a deep knowledge of the causes and the amplitude of climate variations at the centennial timescale is needed to properly put anthropogenic climate change and future climate projections into context. Beyond decadal mean temperature, we are concerned about trends and changes in the occurrence of extreme events, changes in ocean circulation and changes in quasi-oscillatory regimes such as ENSO.

All of this may occur at the centennial scale. But studying centennial variability is also important for those who are interested in the slowest timescales, as centennial dynamics may influence the timing and speed of phenomena such as glacial inceptions and deglaciations. For example, sea-level fluctuations during interglacial periods are now known to have been larger than previously believed.

We are thus left with the difficult task of quantifying the amplitude of centennial variability and to understand its causes. Some of the challenges bear on the experts in the collection and analysis of paleoclimate data. Examples taken from marine records, sea ice and tree rings highlight the unfinished path still to accomplish to separate climate from non-climate variability in paleoclimate records. We should thus be wary of naive and superficial interpretations of power spectra. On the other hand, explanations for the causes of centennial variability generate their share of heated debates.

As we know, the climate system is complex enough to generate its own internal oscillations, like the El-Niño Southern Oscillations or Dansgaard-Oeschger events. There is no reason not to have such modes in the centennial band. Dijkstra and Von der Heydt (p. 150) provide one such example.

Besides, variability emerging from the chaos of atmospheric and oceanic motion may also propagate upwards and downwards throughout the frequency spectrum to produce what we know as the background spectrum. There is a controversy as to whether the background is mainly generated by linear processes of accumulation and relaxation of fluctuations, or whether it involves non-linear dynamics at a deep level, akin to turbulent processes, which are by nature intermittent and "spiky". A wise and well-informed use of statistical modeling will be helpful to instruct the debate.

The PAGES working group "Climate variability Across Scales (CVAS)" has been established for these reasons, and brings together experts in time series analysis and nonlinear geophysics with paleoclimate and data scientists.

Finally, we need to pay more attention to the external forcing of climate change. We still know little about the centennial variability of solar forcing or about possible changes in volcanic activity at this timescale. Ice-age modelers are, however, too familiar with the idea that even weak external forcing may combine with internal dynamics to generate large amplitude response.

With the urgency of anthropogenic climate change, we have to do everything possible to make sure we have a good grasp on centennial dynamics. We are not there yet. However, we hope that this special issue will more widely spread discussions about this topic and increase interest in centennial variability.

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Why is scaling important?

Christian L.E. Franzke[1] and Naiming Yuan[2]

Scaling is an emerging concept for understanding climate variability on all timescales. Here, we introduce the concept of scaling and discuss its importance for climate studies. We also discuss possible mechanisms for the emergence of scaling in the climate system.

One of the most intriguing facets of the climate system is that it exhibits variability on all timescales, e.g. convective activity on an hourly timescale, synoptic weather systems on a daily timescale, large-scale teleconnection patterns with timescales from intra-seasonal to interannual, the coupled atmosphere-ocean system with variability on decadal and centennial timescales and then there are the timescales associated with the ice ages. This variability on different timescales is not arbitrary as discovered by Harold Edwin Hurst (1880-1978). Hurst was a hydrologist and investigated the long-term storage capacities of reservoirs (Hurst 1951). He was interested in estimating the optimal height of a dam so that the water level in the reservoir is consistently high enough to always allow a sufficient amount of water to flow out of the reservoir. By examining the water-level fluctuations in reservoirs, he discovered a relationship between the variability and the timescale over which the variability is estimated. This relationship is now called the Hurst effect, which describes among others the property that the variability over short timescales has a smaller amplitude than over long timescales. The Hurst effect has since been discovered in many other climate variables like temperature, precipitation and tree rings (Hurst 1951).

What is scaling?

Time series which are displaying the Hurst effect have an intriguing property: they remain statistically similar if one zooms in or out (Fig. 1a-b). Scaling is thus related to the notion of fractality (Mandelbrot 1983; Feder 2013), and is mathematically encapsulated by the following equation:

$$F(n) \propto n^{H} \qquad (1)$$

where n denotes the window size over which the amplitude of the fluctuations (*F*) is computed. The exponent *H* is then visualized by plotting the logarithm of *F*(n) against the logarithm of n. When doing so *H* corresponds to the slope of the corresponding regression line.

We now show that the Hurst effect may emerge from two different effects: (i) existence of correlations between distant points in time and (ii) long-tailed distribution of the amplitudes of the data of interest.

The first effect indicates that even far away points in time are still relatively strongly correlated; in other words, the serial correlation of a time series decays very slowly. Furthermore, for the scaling effects related to the temporal evolution of time series, the above scaling equation (Eq. (1)) indicates that the knowledge of high-frequency variability allows one to predict the low-frequency variability of a time series.

To highlight this point we now compare a scaling time series with a short-memory time series in Figure 1 by applying one of the most often used statistical models of climate variability – the auto-regressive process of first order (AR(1)). This is a short-memory process that has a typical auto-correlation timescale. On longer timescales this process acts like independent white noise and the time series values on those timescales become uncorrelated. This is illustrated in Figure 2. There we display a fluctuation analysis of an AR(1) process and a long-memory process. On long timescales the AR(1) process becomes uncorrelated with a slope of 0.5 (compare the fluctuation analysis (black line) with the line with a slope of 0.5 (blue line)). While for the long-memory process (red line), the slope is 0.75 (green line), indicating long-lasting serial correlations. Even very far apart points in time are still correlated, in contrast to a short-memory process.

The contribution related to the probability distribution of the values of a time series is also illustrated in Figure 1. There we display a white noise (uncorrelated values), heavy-tailed distribution (α-stable) in both the typical linear-linear (Fig. 1c) and log-log scalings (Fig. 1d). For α=2 the distribution is

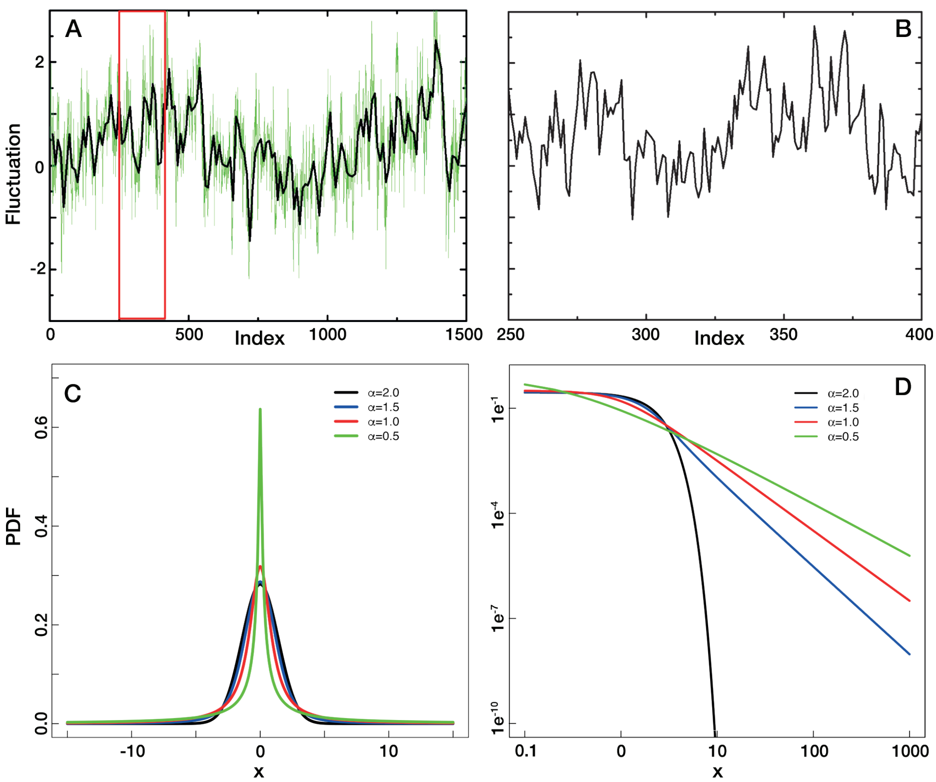

Figure 1: (A-B) Time series with scaling behavior. (A) A time series with scaling behavior and (B) shows the portion in the red box of (A). After zooming in, time series in (B) shows similar pattern as the time series in (A). **(C-D)** Probability distribution function of an alpha-stable distribution (C) with linear and (D) logarithmic axis scaling.

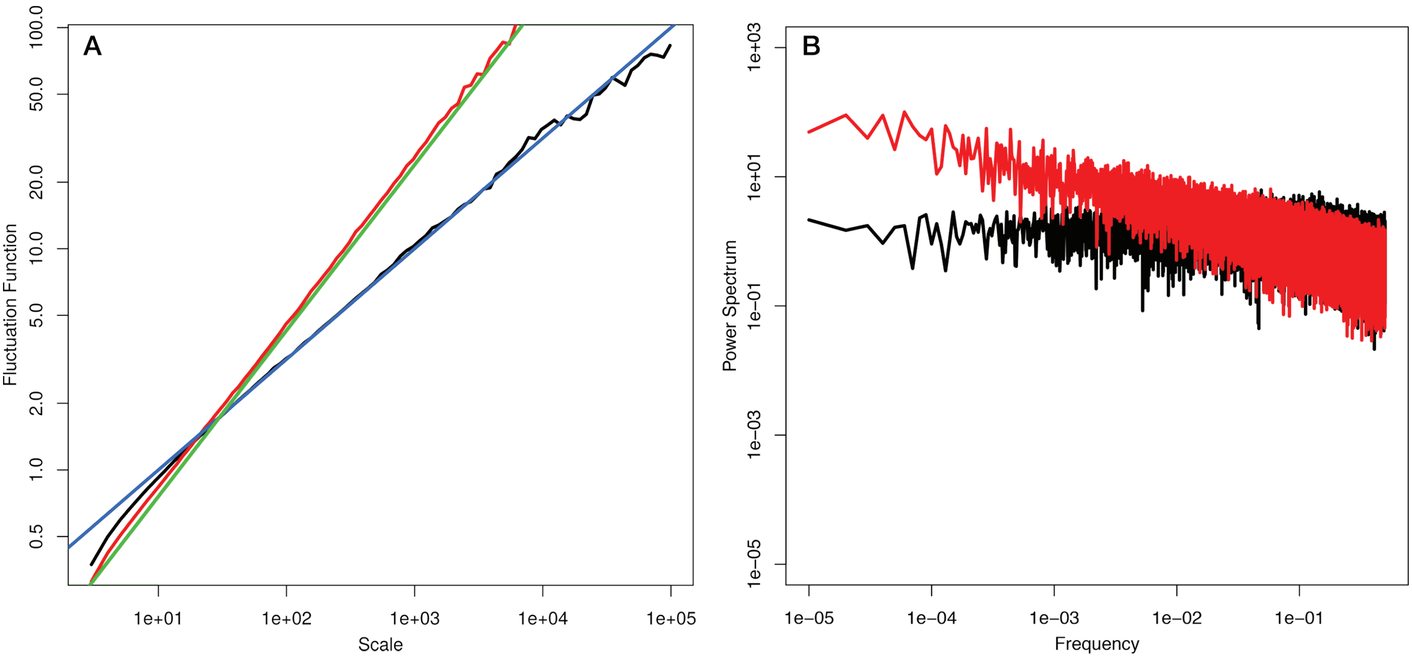

Figure 2: (A) Fluctuation functions for AR(1) process (black line) and scaling model (red line) with regression lines with slopes of 0.5 (blue line) and 0.75 (green line). **(B)** Power spectrum of AR(1) process (black line) and scaling model (red line).

the Gaussian distribution with an exponential decay of the probability density function (PDF) while for $\alpha<2$ it has a power-law decay. The probability for very large events decays more slowly for smaller α values. Hence, extreme events are much more likely to occur for PDFs with a power-law decay of their tails. Heavy-tailed distributions have been shown to be relevant, for instance, for the modeling of the Dansgaard-Oeschger events (Ditlevsen 1999).

Combining the two contributions to the Hurst exponent (i) long memory and (ii) power-law distributed jumps, the Hurst exponent can be written as:

$$H = J + \frac{1}{\alpha} - \frac{1}{2} \quad (2)$$

where J denotes the long-memory parameter that determines how fast distant points in time decorrelate, and α is the tail exponent of the PDF (e.g. Franzke et al. 2012). Thus, both effects can contribute to the observed behavior.

What are the implications of scaling?
The long-memory property of many observed climatic time series has consequences for the robust detection of trends. Because long memory leads to the persistence of the time series, long deviations from the mean state are very likely. This can lead to the appearance of apparent trends; so-called stochastic trends (See Fig. 1 of Franzke 2012). Long-memory processes can lead to apparent trends over relative long periods of time even though these trends are not caused by external forcings like increasing greenhouse gas concentrations. These stochastic trends have to be distinguished from deterministic trends which are caused by external forcing.

The presence of long memory in the climate system represents a challenge for the detection of trends in climatic time series. Most trend studies just consider a short-memory process like an AR(1) even though most climate time series also have the long-memory properties (Bunde et al. 2014; Ludescher et al. 2016). This leads to bias in trend detection. In those cases, one is much more likely to assign a trend to be statistically significant even though it is not (Ludescher et al. 2016). Long memory increases the uncertainty of the trend estimates, but on the other hand the true trend could be much larger than under the short-memory assumption.

The long-memory property also induces clustering of extreme events. Long memory leads to long-term quasi-cycles and stochastic trends, i.e. large values are likely followed by large values and vice versa. This tendency also leads to the fact that extremes are likely followed by other extremes and that there will also be long periods when no extremes will occur. This, in turn, leads to the clustering of extreme events in data, which may be used for the development of early warning systems of extreme events.

Long-memory property is also relevant for climate prediction. The stronger the long memory is, the better predictability we may have. Accordingly, using the scaling in climate, it is possible to design climate-prediction models from the perspective of climate memory.

What are the physical mechanisms of scaling?
Since the long-memory property in the climate system is counterintuitive, it is important to identify the underlying mechanisms which cause scaling in the climate system. The superposition of short-memory processes can lead to the emergence of scaling (Granger 1980). This idea is based on the fact that the climate system is composed of many sub-components with different typical time-scales (atmosphere, ocean, cryosphere, etc.) and we then observe their superimposed effect in our measurements. Franzke et al. (2015) show that regime behavior due to nonlinear dynamics can also lead to scaling behavior.

ACKNOWLEDGEMENTS
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How scaling fluctuation analysis transforms our view of the climate

Shaun Lovejoy

Applied to numerous atmospheric and climate series, Haar fluctuation analysis suggests a taxonomy with four or five scaling regimes that contain most of the atmospheric and climate variability. This includes a new "macroweather" regime in between the weather and climate.

On scales ranging over a factor of a billion in space and over a billion billion in time, the atmosphere is highly variable (from planetary scales down to millimeters, from the age of the planet down to milliseconds). This is usually conceptualized in a "scale-bound" framework famously articulated by M. Mitchell (1976) and that focuses on specific phenomena operating over narrow ranges. At first this served to develop simplified mechanisms and models but today, problems are usually solved using full-blown general circulation models (GCMs) and these have wide-range scaling, power law variabilities. By construction, GCMs respect these spatial and temporal scale symmetries.

In the following brief overview, I describe the wide-range scaling view made possible (and necessary) by modern models and paleo-data, and helped by new nonlinear geophysics analysis techniques.

We now know that Mitchell was wrong by a factor of perhaps as much as a quadrillion (see Fig. 1a for details); the great bulk of the variability is in the background spectral continuum (Wunsch 2003) that Mitchell considered to be no more than a series of shallow flat "steps": Gaussian white noises and their integrals.

The continuum can be divided into four or five scaling regimes (Fig. 1) in which mean absolute temperature fluctuations ΔT vary with timescale Δt as $\Delta T \approx \Delta t^H$ (for Gaussian processes, there are other equivalent definitions of H, see Franzke and Yuan, this issue). From fast to slow, these regimes alternate in the sign of H from weather, macroweather, climate, macroclimate and megaclimate (this is a proposed taxonomy, the macroclimate regime is very short and may be better considered as a broad quasi-oscillatory regime). When $H>0$, the temperature "wanders", it appears unstable. When $H<0$, successive fluctuations tend to cancel, so that as the period Δt is increased, temperature averages converge, they appear to be stable. Such scaling regimes arise whenever the dominant dynamical processes respect a temporal-scale invariance symmetry. An important feature is that scaling processes generally exhibit long-range statistical dependencies implying potentially huge memories that can be used for prediction.

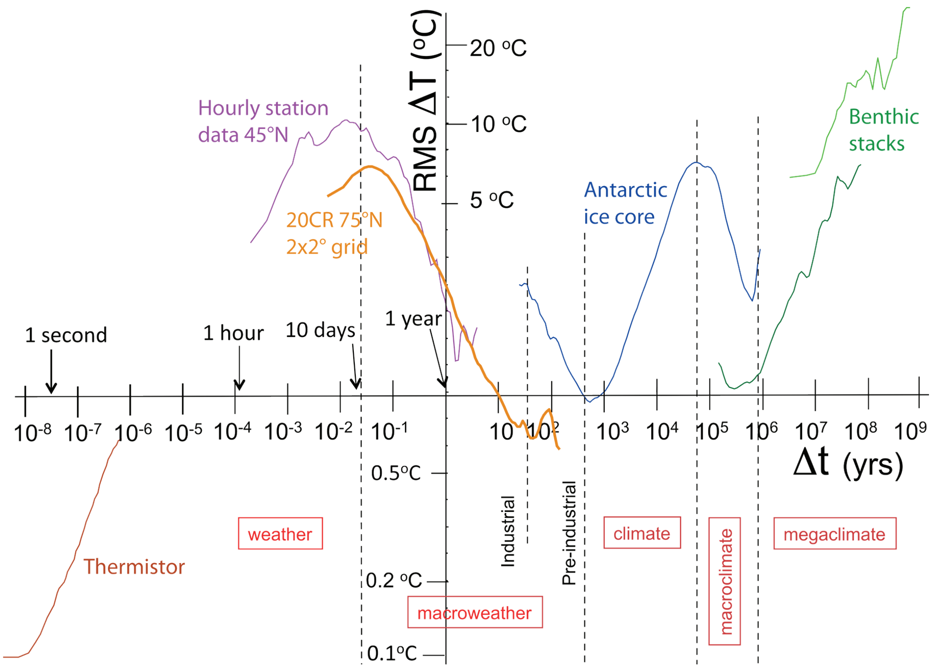

Figure 1: The root mean square (RMS) Haar fluctuation showing the various (roughly power law) atmospheric regimes, simplified and adapted from Lovejoy (2015) where the full details of the sources are given. The dashed vertical lines show the rough divisions between regimes; the macroweather-climate transition is different in the pre-industrial epoch. The high-frequency analysis (lower left) from thermistor data taken at McGill at 15Hz was added. The thin curve starting at 2 hours is from a weather station, the next (thick) curve is from the 20th century reanalysis, the next, "S" shaped curve is from the Epica core. Finally, the two far right curves are benthic paleo temperatures (from "stacks"). The quadrillion estimate is for the spectrum, it depends somewhat on the calibration of the stacks. With the calibration in the figure, the typical variation of consecutive 50 million year averages is ±4.5°C (Δt=10^8 years, RMS ΔT = 9°C). If the calibration is lowered by a factor of ≈3 (to variations of ±1.5°C), then the spectrum would be reduced by a factor of 3^2. On the other hand, the addition of the 0.017s resolution thermistor data increases the overall spectral range by another factor of 10^8 for a total spectral range of a factor ≈10^{23} (for scales from 0.017s to 5x10^8 years).

This simple scaling picture took a long time to emerge. At first, this was because paleo data were limited and our views were scale-bound. Later, it was because analysis techniques were either inadequate (e.g. when fluctuations were quantified via differences or from autocorrelations), or were simply too difficult to interpret (most wavelets and detrended fluctuation analysis), or when using spectral analysis whose interpretations can be very sensitive to "spikiness" (Fig. 2) and has lead to numerous ephemeral, spurious claims of oscillations.

The situation is clarified by the systematic use of simple-to-interpret Haar fluctuations $\Delta T(\Delta t)$. Over the interval from time t to t-Δt, (i.e. at scale Δt), $\Delta T(\Delta t)$ is simply the absolute value of the average of the series $T(t)$ over the first half of the interval (from t-Δt to t-$\Delta t/2$) minus the average over the second half (from t-$\Delta t/2$ to t). When typical absolute fluctuations decrease with scale ($H<0$), H quantifies the rate at which anomalies decrease as they are averaged over longer and longer timescales. Conversely, when $\Delta T(\Delta t)$ values increase with scale Δt ($H>0$), H quantifies the rate at which typical differences increase. Haar fluctuations are useful for processes with -1<H<1 and this encompasses virtually all geoprocesses. Historically, Haar fluctuations were the first wavelets, yet one does not need to know any wavelet formalism to understand or

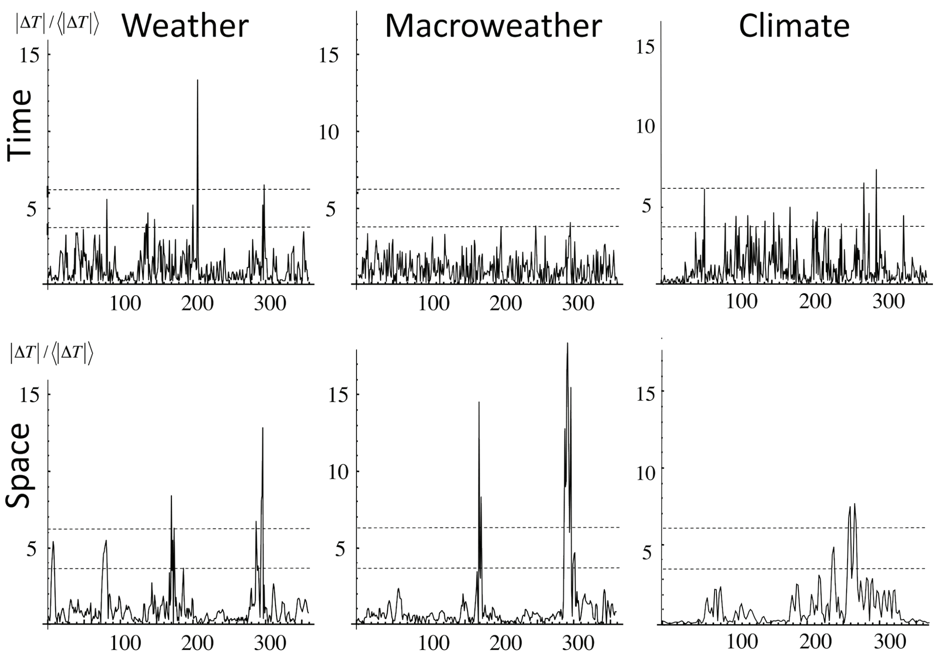

Figure 2: A comparison of the "spikiness" (intermittency) in time (top) and space (bottom), of weather, macroweather and climate series and transects. The graphs have 360 points and show the absolute differences between consecutive values normalized by their means. Each graph has two parallel dashed lines; the lower one corresponds to a Gaussian probability of 1/360, the level of the expected maximum value. The upper dashed line corresponds to a (Gaussian) probability of one in a million. While the spatial intermittencies (bottom) are strong, the temporal intermittencies are nearly absent from the macroweather series (upper middle). Adapted from Lovejoy (in press). **Upper left**: Hourly temperature data from 1-15 January 2006, from a station in Lander Wyoming. **Upper middle**: 20C Reanalysis (20CR) from 1891-2011; each point is a four-month average, the data are from a single 2x2° grid point over Montreal, Canada (45°N). **Upper right**: GRIP (75°N) paleo temperature degraded to 240-year resolution (the present to 86400 years before present, left to right). **Lower left**: ECMWF reanalysis for the average temperature of 21 January 2000, along the 45°N parallel at resolution of 1° longitude. **Lower middle**: The same as at left but for the temperature averaged over the month of January 2000. **Lower right**: The 45°N 20CR temperatures, averaged since 1871.

use them. Although the second-order Haar fluctuations (the mean of $\Delta T(\Delta t)^2$) have the same information as the spectrum, the latter was sufficiently difficult to interpret that the "background" was badly misrepresented.

The timescales of the transitions from one regime to another have fundamental interpretations. For example, the inner scale τ_{dis} for weather is the dissipation scale and the outer scale is the typical lifetime of planetary structures: $\tau_w \approx$5-10 days, itself determined by the energy rate density (W/kg) due to the solar forcing (Lovejoy and Schertzer 2010). The next regime, "macroweather", is reproduced by weather models (either GCM control runs or the low-frequency behavior of stochastic turbulence-based cascade models). Without external forcings, averages converge to a unique climate so that macroweather continues to arbitrarily large timescales. However, at some point (τ_c) external forcings and/or slow internal processes become dominant, there is a transition to the climate regime. In the industrial epoch $\tau_c \approx$20 years; in the pre-industrial epoch, $\tau_c \approx$centuries to millennia (Huybers and Curry 2006, see Fig. 1).

A key goal for PAGES' Climate Variability Across Scales (CVAS) working group is to clarify the spatial (and epoch to epoch) variability and origin of τ_c: it is not obvious that either solar or volcanic forcings are sufficient to explain it. It seems likely that slow processes including land-ice and/or deep ocean currents may be needed. At Milankovitch scales, *H* again changes sign and even larger scale (megaclimate) regimes (far right in Fig. 1) has *H*>0 again.

The scaling has consequences. For example, hiding behind seemingly ordinary signals, there is often strong intermittency; "spikiness". This is visually illustrated in Figure 2 which compares the absolute changes of series (top) and transects (bottom), normalized by their means. Also shown are the expected levels of the maxima for Gaussian processes (bottom dashed lines), and the levels expected at a probability level of one in a million (top dashed lines). One can see that with unique exception of macroweather in time, the signals all hugely spiky. This "intermittency" has two related aspects: extreme jumps (non-Gaussian probabilities) with the jumps themselves clustered hierarchically: clusters within clusters. As anyone familiar with spectral analysis knows, these jumps have large impacts on the spectra; they generate random spectral peaks that can be highly statistically significant when inappropriate – yet standard - Gaussian statistical significance tests are used. In climate applications, they are regularly responsible for ephemeral claims of statistically significant periodicities.

If the process is scaling, then in general the clustering is different for each level of spikiness, requiring a hierarchy of exponents. For example, typical fluctuations near the mean are characterized by the exponent C_1 (technically, C_1 is the fractal codimension of the typical spike sparseness). Similarly, the probability of an extreme fluctuation ΔT exceeding a threshold *s* will be a ("fat-tailed"), power law probabilities $Pr(\Delta T>s) \approx s^{-q_D}$ for the probability of a random fluctuation ΔT exceeding a fixed threshold *s*. q_D is another exponent; starting with Lovejoy and Schertzer (1986), q_D has regularly been estimated as ≈5 (weather and climate temperatures). Depending on the value of q_D, extreme fluctuations occur much more frequently than would classically be expected. They are easily so extreme that they would spuriously be considered "outliers". Such events are sometimes called "black swans" (Taleb 2010) and it may be difficult to distinguish these "normal" extremes from tipping points associated with qualitatively different processes, although either might be catastrophic.

A key objective of CVAS is to go beyond time series, to understand variability in both space and space-time. In the weather regime, the spatial *H* exponents are apparently the same as in time. This is a consequence of the scaling of the wind field and of the existence of a well-defined size-lifetime relationship (Lovejoy and Schertzer 2013). However in macroweather – to a good approximation (verified empirically as well as on GCM and turbulence models) – one has "space-time statistical factorization" so that the joint space-time statistics such as the spectral density satisfies $P(\omega,k) \approx P(\omega)P(k)$ and the space-time relationship can be quite different than in weather (Lovejoy and Schertzer 2013). This is important since – without contradicting the existence of teleconnections – it statistically decouples space and time, transforming the GCMs "initial value" problem into a much easier to handle stochastic "past value" (but fractional order) macroweather forecasting problem.

The systematic application of nonlinear geophysics analysis and models-to-climate data has only just begun. CVAS will help take it to the next level.

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Scaling of global temperatures explained by linear energy balance models

Kristoffer Rypdal and Hege-Beate Fredriksen

Scale invariance of natural variability of global surface temperatures is often interpreted as a signature of nonlinear dynamics. However, the observed scaling can be adequately explained by linear energy balance involving subsystems with different response times.

The analysis of instrumental data and proxy reconstructions of global mean surface temperature (GMST) reveals higher variability on longer timescales than expected, provided we assume that the surface temperature responds as if it were a body with a heat capacity corresponding to the mass of the ocean mixed layer. The power-spectral density of the temperature variability of such a body, driven by the stochastic forcing from atmospheric weather systems, should have the shape of a Lorentzian distribution; a flat spectrum for low frequencies *f*, and a power-law spectrum $P(f) \sim f^{-2}$ for high frequencies. The transition between the two regimes would be at a transition frequency $f_\tau = (2\pi\tau)^{-1}$, where τ is the exponential decay time (the time constant) for a perturbation of the equilibrium temperature. The stochastic process that exhibits such a spectrum is sometimes referred to as red noise. The actual observed spectrum tends to follow the power-law $P(f) \sim f^{-1}$, which is called pink noise or 1/*f*-noise. This power-law scaling has been demonstrated for Holocene climate in a large number of papers, and Rypdal and Rypdal (2016a) also found such a spectrum for the background noise in $\delta^{18}O$ of Greenland ice-core records during the last glaciation by eliminating the sudden transitions between warm and cold periods that have been found in ice-core data at that time. Thus, the observed power-law scaling does not comply with the Lorentzian spectra of simple linear energy balance models (EBMs), and a popular explanation has been nonlinearity in the response. Nonlinearity, however, offers no real explanation of the scaling of the background GMST variability until a nonlinear theory of the GMST spectrum is in place, and at present it is not. Our objective in this article is to show that a linear EBM may explain the observed spectrum, provided some plausible additional physics is added. For this purpose, we need to give a brief description of how such models work.

Energy balance models and their linearization

First it should be mentioned that EBMs of the GMST often contain nonlinearity in the form of a temperature dependence of the surface albedo due to the snow and ice cover. Such models exhibit multiple fixed points, bifurcations with sudden transitions, and hysteresis. An excellent review of such models was given by North et al. (1981), where also the description of internal variability in the global temperature is introduced through stochastic forcing terms. For a climate system far from tipping points, however, the traditional EBMs exhibit a stable fixed point, and for moderate perturbations of this energetic equilibrium the equations of energy balance can be linearized. This linearization of the GMST response is supported by general circulation models (GCMs). Linearity of the temperature response in GCMs has been extensively studied over the last two decades, and the majority of studies find only weak nonlinearities in the global response. For instance, Rypdal and Rypdal (2016b) demonstrated, by analyzing millennium-long data sets from the Norwegian Earth System Model (NorESM), that linearity of the response prevails (Fig. 1).

The one-box model and the exponential response to forcing

An exponentially decaying response function derives naturally from the simplest

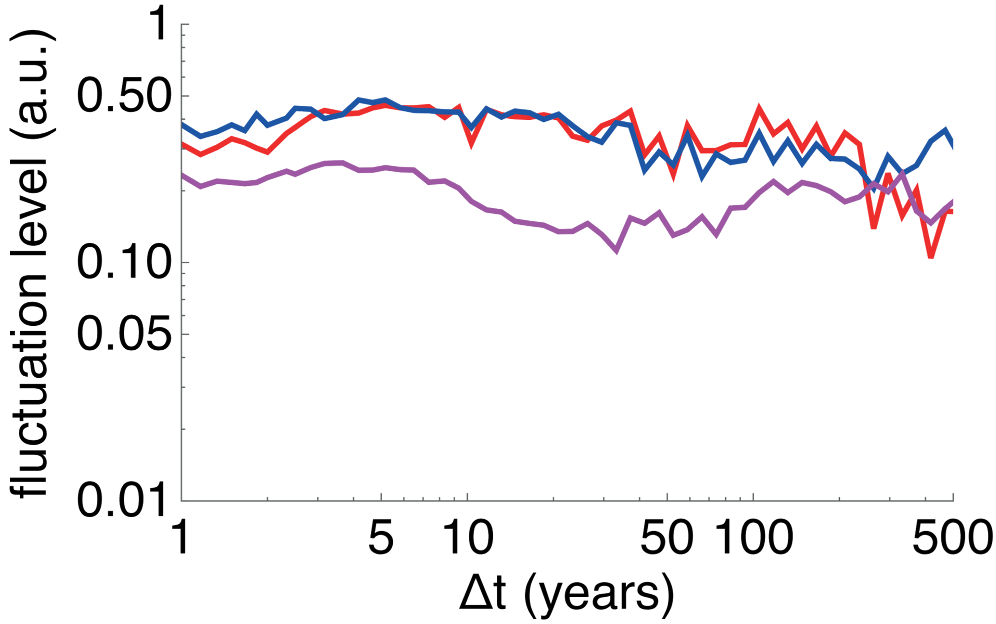

Figure 1: Fluctuation levels of GMST (in arbitrary units) obtained in the NorESM model as a function of timescale Δt. Red: Fluctuation level of GMST response to the sum of volcanic and solar forcing. Blue: The same for sum of responses to volcanic and solar forcing. The overlap of the curves suggests linearity of the response. Magenta: The same for control run, reflecting fluctuation level of internal variability.

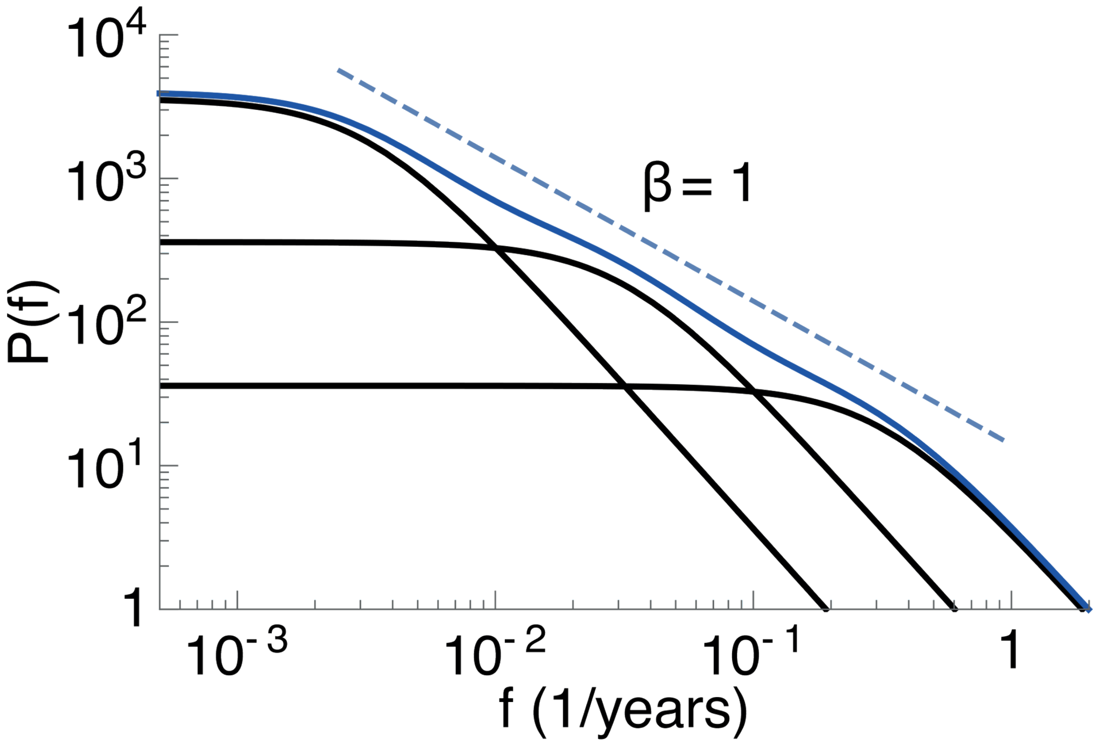

Figure 2: Temperature fluctuations described by a multi-box model can be written as a sum of the outputs from the one-box model with different response times. Here we use τ_1=0.5, τ_2=5 and τ_3=50 years, and each black curve shows the spectra as given by Eq. (1). The sum of these is the blue curve, well approximated by the power law $P(f)\sim f^{-1}$ (dashed line).

conceivable model of the GMST response to forcing; the zero-dimensional, linear energy balance equation; $C\,dT/dt=F-\lambda T$. Here T is the surface temperature anomaly and F is the perturbation of radiation flux density (the forcing) giving rise to T. In general, the forcing has a deterministic and a stochastic component, the latter representing the influence of the chaotic variability of atmospheric weather systems. CT is the change in heat content per square meter in a vertical column when GMST changes by T, hence C represents the effective heat capacity per unit area of this system, which is dominated by the heat capacity per unit area of the upper few hundred meters of the oceans. The model neglects the heat exchange between this layer and the deep ocean, and in this respect, it is based on the same assumptions as aqua-planet GCMs. The term $-\lambda T$ represents the change of flux density of top of atmosphere longwave outgoing radiation in response to the temperature change T, and is corrected for fast feedback processes. If F results from an abrupt change of forcing, then T will eventually relax to a new equilibrium state $T=SF$, where the parameter $S=\lambda^{-1}$ is the equilibrium climate sensitivity. The time evolution of the relaxation can be written as $T(t)=FS[(1-\exp(-t/\tau)]$, with time constant τ=CS. By Fourier transforming the one-box model we obtain the Lorentzian spectrum,

$$P(f)=|\tilde{T}(f)|^2=\frac{|S\tilde{F}(f)|^2}{1+(2\pi f\tau)^2} \qquad (1)$$

where $\tilde{T}(f)$ and $\tilde{F}(f)$ are Fourier transforms of $T(t)$ and $F(t)$, respectively. From this relation, one observes that the response on timescales longer than the time constant τ is simply obtained by multiplying the forcing by the sensitivity S, while the response on fast timescales ($f>f\_T$) is weaker due to the thermal inertia. If the forcing grows rapidly, the temperature, and hence the radiation-loss term $-\lambda T$, will grow more slowly and the climate system will accumulate heat until a new thermal equilibrium is attained. This delayed warming is what is referred to as "the warming in the pipeline".

Multi-box models and the power-law response

It has been known for several decades that atmospheric-ocean GCMs exhibit climate responses on separated timescales, i.e. there is more than one time constant involved in the response. A simple two-box generalization of the one-box model allows for heat exchange between the upper mixed layer of the ocean and the deep ocean, and the general response to a forcing starting at time t = 0 can be written as a convolution integral $T(t)=\int_0^t G(t-t')\,F(t')\,dt'$, where the response kernel is a superposition of two decaying exponential functions with different e-folding times τ_1 and τ_2. Geoffroy et al. (2013) estimated the parameters of a linear two-box energy balance model by data from runs of a large number of GCMs with step-function forcing and linearly increasing forcing, respectively. They found a very good fit to the simulated global temperature. Rypdal and Rypdal (2014) demonstrated that an excellent fit to global instrumental temperatures and Northern hemisphere temperature reconstructions over the last two millennia could be obtained by replacing the superposition of exponentials by a power-law function $G(t)\sim t^{\beta/2-1}$ with $\beta\approx1$. If $F(t)$ is assumed to be a white noise representing the stochastic forcing, the resulting internal GMST-variability exhibits a spectrum $P(f)\sim f^{-\beta}$ similar to the observed one. Fredriksen and Rypdal (2017) showed that there is a correspondence between this power-law scaling and the spectra obtained from the linear box models by developing a formalism of N boxes exchanging heat with each other (Fig. 2). In fact, they obtained spectra reminiscent to those obtained from observations and GCMs by restricting the model to three boxes, suggesting that scaling observed in GMST is a result of linear energy exchange in a system with multiple response times.

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Inferring past climate variations from proxies: Separating climate and non-climate variability

Thomas Laepple[1], T. Münch[1,2] and A.M. Dolman[1]

The statistical properties of climate variability are often reconstructed and interpreted from single proxy records. However, variation in the proxy record is influenced by both climate and non-climate factors, and these must be understood for climate inferences to be reliable.

Before interpreting the temporal variability in any climate proxy record we first need to study the reproducibility of the measured signal. One way of doing this is to compare variations in nearby records that were subject to the same history of the target climate variable, such as local temperatures. In simple terms, features that appear only in individual records most likely represent non-climate variability, whereas those that reproduce across multiple proxy records potentially represent variations in climate. Such a comparison provides an upper limit on the climate information contained in the record.

Reproducibility is a necessary but not sufficient condition for a reconstructed signal to be inferred as climatic in origin. Spatially coherent variability can also be caused by environmental changes independent of the variable of interest. For example, changes in ocean circulation might cause large-scale changes in water masses that affect the preservation of marine climate proxies and thus the recorded signals. One way to overcome this is to compare the record to independent estimates of variations in the target variable; either from instrumental records such as weather stations, or from independent climate proxies that record the same target variable. Performing such comparisons in the frequency domain allows for a more detailed characterization of the proxy system: in particular, it highlights the timescales at which the signal is preserved rather than obscured by noise and where it might be reliably interpreted as climate.

The procedure outlined above is idealized, and may in many cases be unrealistic due to limitations in resources such as cost, manpower, or replicate proxy material. However, advances in the collection, processing and analysis of the proxy material now make it often feasible to obtain the volume of data required to carry out such analyses.

Oxygen isotope records on the Antarctic Plateau

Here we give an example of the first steps of this approach for the isotopic composition of water archived in firn and ice at the drilling site of the EPICA Dronning Maud Land ice core (EDML) at Kohnen Station on the Antarctic Plateau.

Isotopic variations in ice are usually interpreted as a proxy for local air temperature at the location of snowfall. However, in reality, many processes influence the signal,

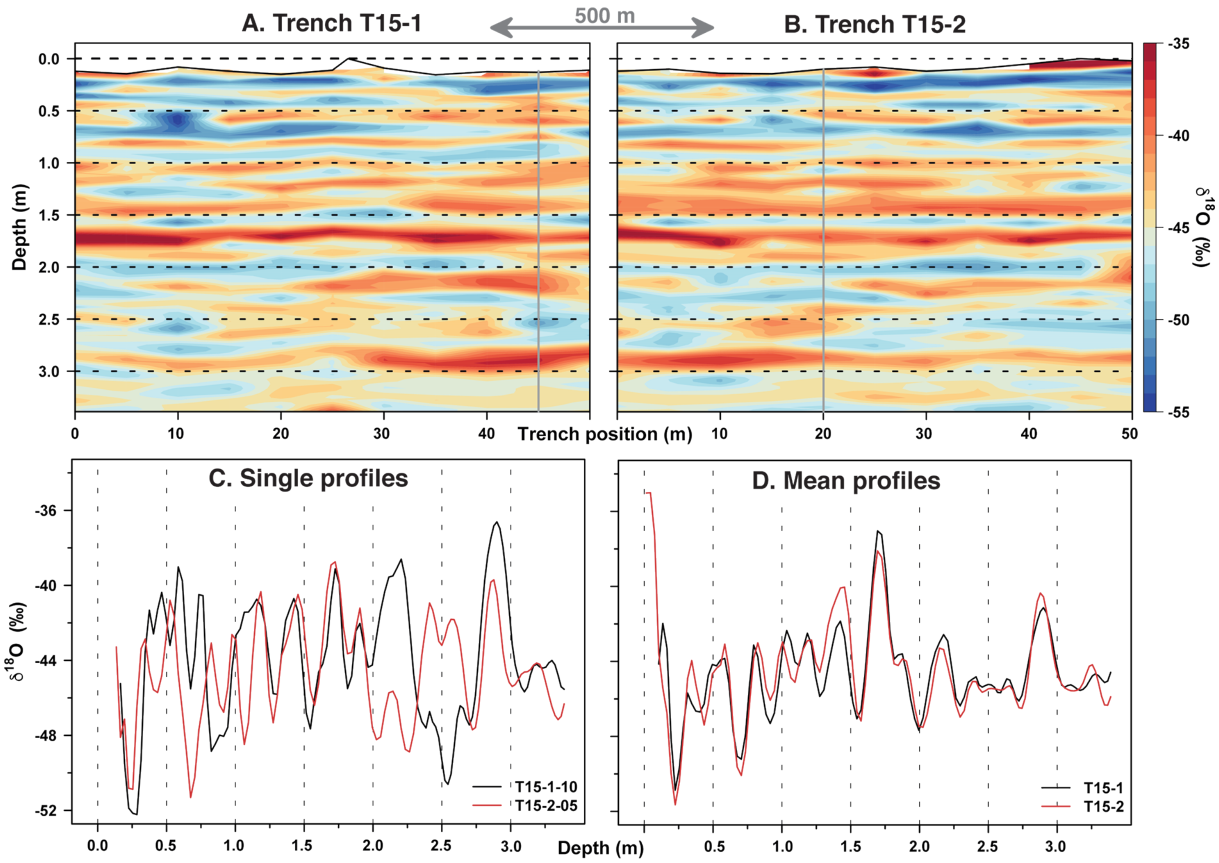

Figure 1: The oxygen isotope records of the snow trenches T15-1 and T15-2 from the EDML site. Panels **(A)** and **(B)** show the isotope variations in each trench as two-dimensional color images; panel **(C)** the comparison of two selected individual isotope profiles (the positions marked as vertical lines in (A) and (B)); and panel **(D)** the comparison of the mean profiles obtained by averaging across the individual profiles of each trench. Figure modified from Münch et al. 2017.

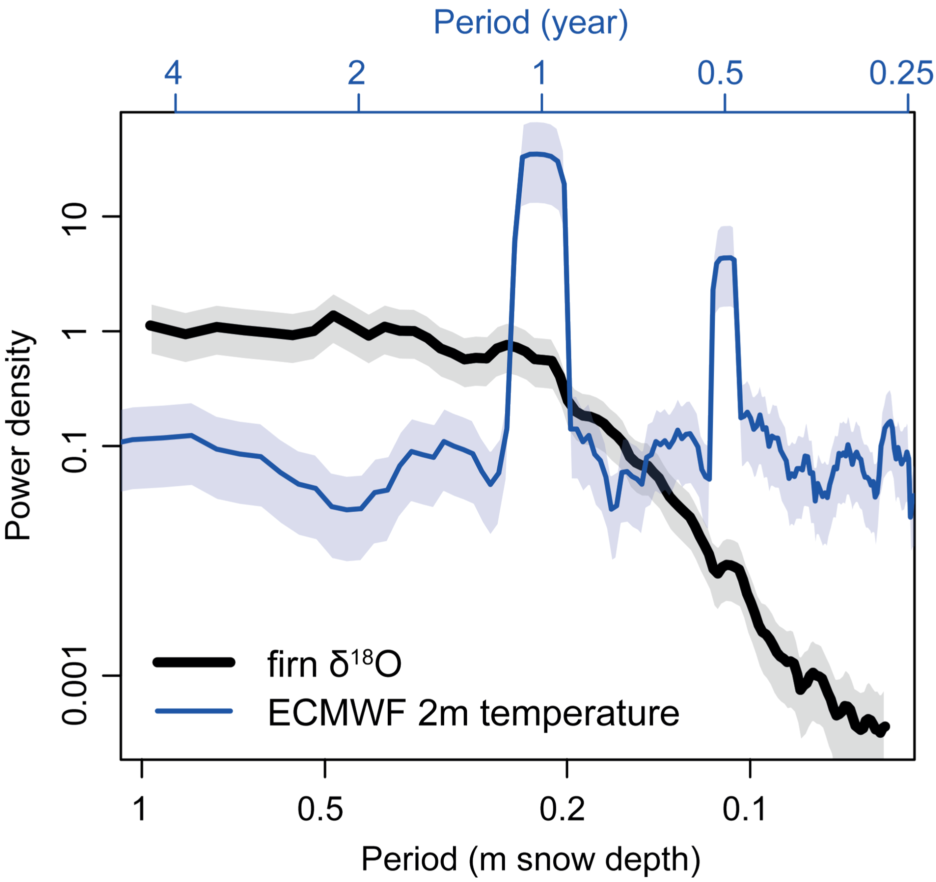

Figure 2: Power spectra of the $\delta^{18}O$ variations from the snow trench data (average spectrum across 22 3.4 m deep trench profiles, black) and of the monthly 2 m air temperatures (1979-2016) from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (blue) at EDML. The horizontal and vertical scales are aligned assuming an accumulation rate of 22 cm snow per year and using the modern spatial $\delta^{18}O$ to temperature relationship of 0.8 ‰ K^{-1}, respectively. For details on the spectral analyses see Laepple et al. 2017.

starting with the evaporation source of water and including depositional and post-depositional effects (Casado et al. this issue). Indeed, previous studies have shown that the reproducibility of isotope profiles is poor on monthly to multi-decadal timescales for low-accumulation sites such as EDML (< 100 mm w.e. a^{-1}; Karlöf et al. 2006). Thus, when interpreting isotope records it is essential to quantify the proportion of variability which is related to the target variable versus that of the other sources.

Spatial and vertical isotope variability

We extended the concept of replicate coring by analyzing the horizontal and vertical variations of snow density and isotopic composition at EDML in several 50 m long and 1–3 m deep snow trenches. Isotope and density profiles were sampled at 0.2 to 5 m intervals along the wall of each trench which allowed us to create two-dimensional images that characterize the proxy variations from the centimeter to the hundred-meter scale (Laepple et al. 2016; Münch et al. 2016, 2017; Fig. 1).

Looking at the isotopic composition, we found visible layers that indicate a representative signal but also show significant horizontal variability (Fig. 1A, B). Consequently, the mean correlation (r) between any two individual vertical profiles separated by more than 10 m (equivalent to comparing two normal firn cores) was just 0.5, but between the two trench-averaged vertical profiles the correlation was much higher (0.9; Fig. 1D). We could explain the observed spatial variability by a simple model describing the local stratigraphic noise as a process with a horizontal decorrelation length of ~1.5 m (Münch et al. 2016). This model provides an upper bound on the reliability of seasonal to interannual-timescale climate reconstructions from single firn cores for our study site. It further shows that averaging several vertical profiles, separated by distances greater than the decorrelation length, will reduce the noise and produce a signal that is representative over a scale of at least 500 m (Fig. 1D). Similar studies are needed and are ongoing at other sites to create a mechanistic model of the stratigraphic noise, or to parameterize the noise as a function of the depositional parameters (Fisher et al. 1985).

The power spectra of proxy versus climate

At EDML, the dominating surface temperature signal is the annual cycle: its first two harmonics explain 95% of the monthly variance in the last 40 years (ERA interim reanalysis, Dee et al. 2011). Comparing the power spectra of the instrumentally observed temperature signal with that recorded by the oxygen isotopes in the trenches shows the fundamental difference between the records (Fig. 2). On scales shorter than annual (less than ~0.2 m snow thickness), the oxygen isotopes show less variability than the temperatures. This is expected since firn diffusion dampens small-scale isotopic variability (Johnsen et al. 2000). In contrast, for interannual variations (greater than ~0.3 m snow thickness), the isotopic variability is around one order of magnitude higher than that of temperature. Also of note is that the annual cycle and its harmonics are largely missing in the isotope record. Both findings can be explained by precipitation intermittency (Persson et al. 2011), interannual variations in snow accumulation and snow redistribution which corrupt and alias the seasonal cycle, shifting its power to lower frequencies (Laepple et al. 2017). One should therefore avoid a direct interpretation of the spectrum of variability in isotope records in terms of temperature signals.

Outlook and implications for other proxies

Using the example of oxygen isotopes of water at the EDML site, our analysis demonstrates the need to consider the reproducibility of proxy records. Since the analysis was restricted to the top 3.5 m of firn, it applies to seasonal and interannual-scale variations. To determine the implications for centennial to millennial-scale climate reconstructions, the temporal correlation structure of the noise has to be known at those scales, therefore we are currently extending our analysis to deeper firn and ice cores. A simple comparison with the local instrumental temperature record demonstrated the fundamentally different nature of the isotope and temperature signals on seasonal to interannual timescales. While the deviations are not unexpected given our knowledge of precipitation intermittency, redistribution and firn diffusion, they caution against a simplistic interpretation of the spectrum of variability in proxy records. Similar studies for other archives, such as sediment cores, would be useful and would assist and improve the interpretation of climate variability derived from proxies (Laepple and Huybers 2013). In addition, they would provide a much-needed test bed for proxy system models that take a mechanistic approach to the same problem (Dee et al. 2015).

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Temporal scales and signal modeling in dendroclimatology

Joël Guiot

Tree rings are demonstrably good proxies for temperature or precipitation at timescales less than a century. Reconstruction based on multiple proxies and process-based modeling approaches are needed to estimate the climate signal at lower frequencies.

Paleoclimatological proxies "represent records of climate that were generated through physical, chemical and/or biological processes. Reconstructions of climate rest on attempts to turn this around in order to get back to the climate information" (Hughes et al. 2010). In most cases these reconstructions are obtained as chronological series, which are characterized by a time resolution depending on the sedimentation or growth processes. These processes act as a low-pass filter and determine the resolution of the climatic signal. Here, I focus specifically on tree-ring series.

Pre-processing of tree-ring series

Tree-ring series reproduce annual variability of the climate with relatively good reliability, but tree growth is the result of numerous complex processes. Hence, like all biological proxies, tree rings record a combination of several climate variables. At low frequencies, the signal is affected by an age-related trend, which includes both geometrical and physiological factors. During its young phase, the tree builds its architectural model and leaf system, and then reaches its reproductive maturity with a progressive increase of biomass production. This is the physiological component of the trend. Afterwards, the tree leaf area stabilizes, and a fairly constant quantity of xylem is distributed along a circle of increasing diameter. This is the geometry factor. Other low-frequency effects may occur during the tree's lifespan, such as competition variations, changes in nutriment availability and carbon concentration in the atmosphere, fires, infestations, diseases, or genetic variability – and climate changes. All these factors result in a complex combination of low and mid frequency signals, which should be understood and modeled to produce indices for climate reconstructions.

The classical approach, called the standardization, consists of detrending tree-ring time series before calibration with meteorological time series. Numerous methods exist, but it is difficult to distinguish the low-frequency signals related to climate from other factors (Cook and Kairiukstis 1990). The standardization produces indices, which are defined as the ratio between the raw tree ring and a theoretical model of (low-frequency) growth, either calculated by nonlinear functions, smoothing, autoregressive models or a function based on the biological age of the tree (Briffa and Melvin 2011). The latter method is complex and needs a large number of replicated series for the same species. No method is perfect and some of them reduce the low-frequency signal excessively, while others introduce spurious low-frequency variations. For these reasons, climate reconstructions tend to be biased, with either too little or too much low-frequency variability.

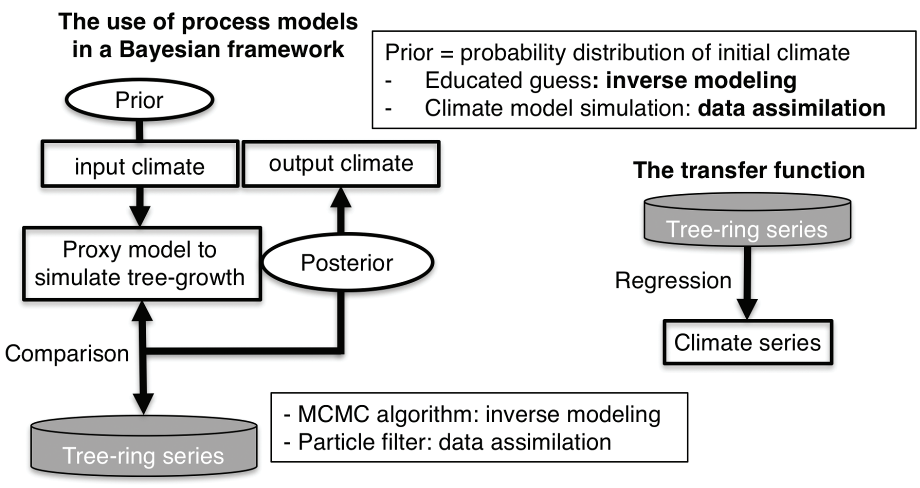

Figure 1: Diagram of the process-based approach and comparison with the standard transfer function. In the process-based approach, the initial probability distribution of the climate (needed to initiate the iterations) may be given by educated guess, as it is done with the class of methods called inverse modeling, or by simulation of climate models, as it is done with the class of data assimilation methods. The standard transfer function uses the tree-ring series as input and the climate as output. The stream is opposite to the causal relationships.

Climate reconstructions

Climate reconstruction consists of calculating a regression between climate series and tree-ring series on the period where both are available (usually the last century) and to extrapolate the regression, also called transfer function, to tree-ring series of previous centuries. These reconstructions may be affected by the so-called "divergence problem". From the 1970s, the tree-ring series no longer appears to be correlated with summer temperature, especially in the high latitudes and in some cases in the high elevations (D'Arrigo et al. 2008). The correlation shifts towards the summer precipitation or other climate factors. The shift may be caused by a change of limiting factors (climate becoming warmer, trees are lacking water), an effect of CO_2 fertilization, air pollution, soil composition change (increase of nitrate), or insolation. This induces a calibration bias: if the transfer function is calibrated on the most recent period (after the 1970s), it should not be used to estimate climate variations before the 1970s. This problem triggered some worries about the value of the climate reconstructions.

Despite these risks of biases, and likely because of them, numerous statistical reconstruction methods have been introduced after the pioneer paper to deconvolve the climatic signal (Fritts et al. 1971). Tree rings are indeed an interesting material for statisticians because the time series have annual resolution and they are also well replicated (a site tree-ring series is based on 20 to 50 cores).

The climate signal calibration is often based on multiple regression, but the low-frequency signal may differ depending on the stationarity of the time series, on the calibration period, the use, or not, of the principal components, the rescaling

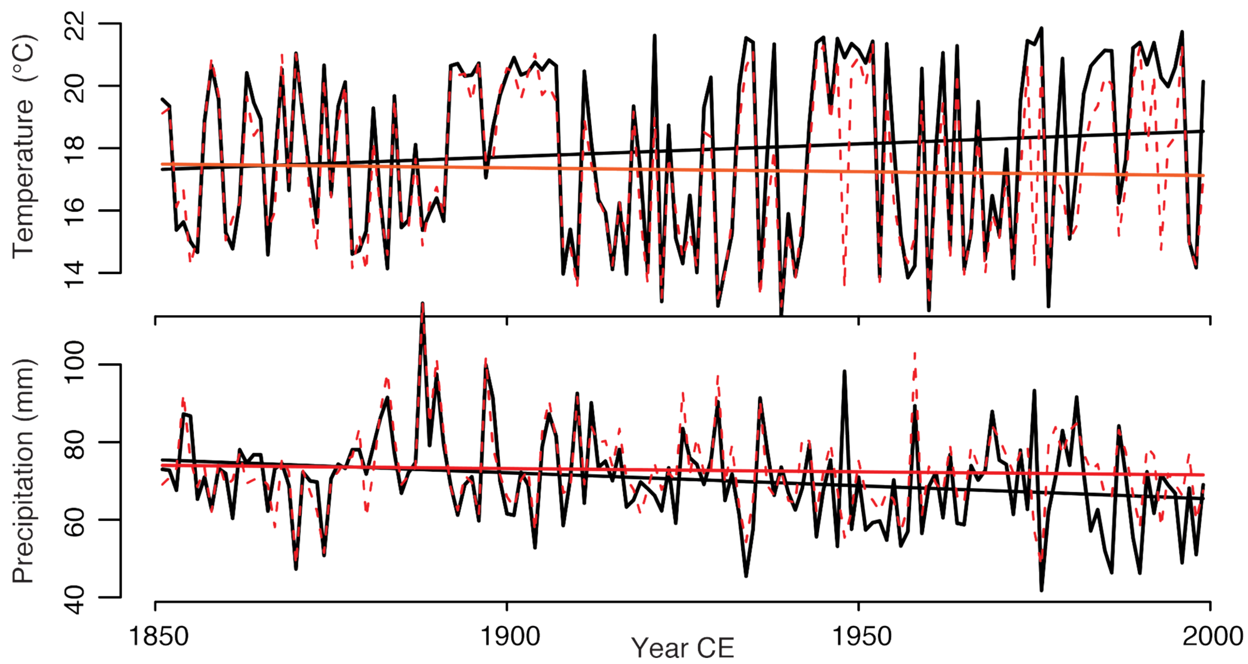

Figure 2: Summer temperature and precipitation reconstructions at Fontainebleau, France, obtained from the inversion of the multiproxy biophysical model MAIDENiso (Boucher et al. 2014), i.e. the MAIDEN model with an isotope simulation module. Red curves are obtained when the inversion is forced by CO_2 fixed at preindustrial levels (280 ppmv) and black curves are obtained from increasing values of CO_2 from 280 ppmv in 1850, 320 ppmv in 1960 to 360 ppmv in 2000. Straight lines with corresponding colors represent the trends. Adapted from Boucher et al. (2014).

done after the calibration and other variations (Bürger et al. 2006). Pseudo-proxy method is an interesting method to study the behavior of the reconstruction method. It consists (i) in generating proxy series from climate model simulation to which are added white noises of progressively increased variance, (ii) in calibrating the reconstruction method on the pseudo proxy series, and (iii) analyzing the performance of the method in function of the noise variance. A difficulty is that these pseudo-proxies should mimic as best as possible the physics of the proxies used (Christiansen and Ljungqvist 2016).

Other variables may be measured on tree rings and used for estimating past climates. They have not the same biases but can have others. The tree-ring maximum density has proved to be quite useful to reconstruct the summer temperature and seems to be free of age-related trends (Briffa et al. 1992). Oxygen isotopes ($\delta^{18}O$) in cellulose is a potential means to reconstruct variables related to water (Saurer et al. 1997). Stable carbon isotopes ($\delta^{13}C$) record the balance between stomatal conductance and photosynthetic rate, dominated at dry sites by relative humidity and soil water status, and at moist sites by summer irradiance and temperature (McCarroll and Loader 2004).

Moberg et al. (2005) proposed to use both pollen data and tree rings to reconstruct Northern Hemisphere average temperature. Pollen data are robust on low frequencies, so that they could help improve the quality of the low-frequency part of the signal. This application used a wavelet analysis. A similar approach has been used by Guiot et al. (2010) for gridded temperature in Europe, using a method of spectral decomposition. A calibration is done separately in the low-, medium- and high-frequency bands with the appropriate proxies.

Process-based approaches

Finally, one may model the formation of the record by representing explicitly the chain of physical and biological processes which lie between the climatic information and the observed signal. Such a model may be used in "forward mode", forced by climatic or other environmental data (Fig. 1). It may also be inverted to estimate climate from observations, as in the MAIDEN or VS-light models (Boucher et al. 2014; Tolwinski-Ward et al. 2014). The inverse problem is solved with a Bayesian method, which estimates the posterior probabilistic distribution of the climate parameters providing the observed tree growth. When the processes generating the low-frequency discrepancies are included in the model, it is possible to clear the climate reconstruction from the corresponding biases, such as the CO_2 effect. This process is illustrated in Figure 2. Scenario A1 (black) forces the inversion with true values of CO_2 concentration while scenario A2 (red) forces the inversion with constant CO_2 concentration (280 ppmv). Both reconstructions are highly correlated in the high-frequency domain. When the CO_2 effect is not taken into account (A2), the temperature reconstruction has no linear trend (the differences are not significant for the precipitation). As this temperature trend is also recorded in the observations (not shown here), it is important to take into account the CO_2 effect to obtain better reconstructions in the low-frequency domain. Another approach based also on process models, which seems also promising, is data assimilation, in which proxy data are used in conjunction with model runs (Acevedo et al. 2016; see also Fig. 1).

Conclusion

In conclusion, tree-ring series have an excellent time control and an annual resolution, and are good proxies for temperature or precipitation variations (depending on their geographical position and species) at sub-century timescales. At lower frequencies, literature is extensive on the difficulties coming from (i) the standardization procedure (age-related factors), (ii) the selection of model relating tree growth and climate, and (iii) the calibration of the model itself. Proposed solutions are based on multiproxy approaches, use of appropriate treatment of low frequencies, and, finally, mechanistic tree-growth models.

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Variability of Arctic sea-ice cover at decadal to millennial scales: the proxy records

Anne de Vernal

Sea-ice observations cover only a few decades, making proxy reconstructions a necessity to document natural variability. Proxy data suggest resilient sea ice in the Canadian Arctic, but large variations in seasonal extent in the Pacific Arctic and subarctic Atlantic.

Sea ice is an important component of the climate system as it is responsible for Arctic amplification through ice-albedo feedbacks and because it controls the exchanges of heat and gas at the ocean-water interface. Sea-ice formation and melt vary in response to incoming energy and depend upon stratification and thermal inertia in the upper water layer, which are functions of salinity. They also vary in space in relation with surface-ocean and atmospheric currents that form pack ice in convergence zones and redistribute sea ice in subpolar seas.

Satellite observations of Arctic sea ice are continuous since 1979. They show large variations of Arctic sea-ice extent at intra-annual timescales, from summer (September ~6.3±1.1 10^6 km^2; see limit in Figure 1) to winter (March ~15.5±0.5 10^6 km^2), which represent about 60% of the change in the coverage (see http://nsidc.org/data/seaice_index). Beyond seasonal variation, a multidecadal decreasing trend is recorded, with a larger change in summer (13.3% per decade) than winter (2.7% per decade). The decrease in summer sea-ice extent is correlated with the rise of surface air temperature (r^2~0.63). However, the sea-ice decline is non linear and could result, at least in part, from internal variability (Swart et al. 2017). Longer-than-satellite time series are therefore needed for a proper assessment of trends and to document the full range of sea-ice variability under natural forcings and feedbacks.

Reconstructing past sea ice

The development of time series covering centuries to millennia is a challenge. Among approaches used to document past sea ice, one consists of the compilation of historical archives such as ship logs, diaries and any sea-ice-related observations (e.g. ACSYS 2003). Available information encompasses a few centuries and mostly covers the subarctic North Atlantic where human populations have settled. It illustrates variations in seasonal extent of sea ice in areas located along the winter-spring sea-ice edge, with multidecadal variations, for example in the Barents Sea (Vinje 2001), or the secular trend since the 19th century, for example off Iceland (Lamb 1977). The data also show clear regionalism, which point to complex dynamics of the seasonal sea ice and prevent spatial extrapolation from isolated sites.

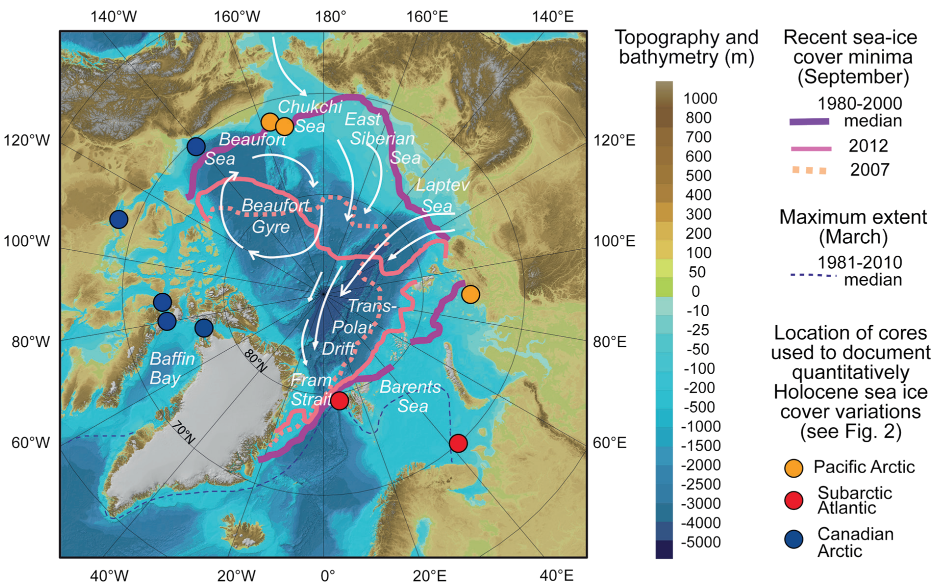

Figure 1: Map of the Arctic Ocean with limit of minimum sea-ice-cover extent (mean from 1980 to 2000; minima of 2012 and 2007), main currents paths (white arrows) and location of cores used to illustrate the circum-Arctic sea-ice-cover variations during the Holocene (Fig. 2).

Another approach to reconstruct Arctic sea-ice extent uses its relationship with climate to derive time series based on the analysis of annually resolved climate-related data from tree rings and ice cores of circum-Arctic regions (Kinnard et al. 2011). This approach allowed for the development of a comprehensive 1400-year record of late summer Arctic sea-ice extent, which suggests natural variability ranging mostly from ~9 to 11 10^6 km^2 (Kinnard et al. 2011). The set of data is, however, heterogeneously distributed with very rare data points from the Russian Arctic, which is the most critical region with respect to the recent decline in sea-ice cover.

Most studies to document past Arctic sea ice on a long timescale use biogenic proxies from marine sediment cores, based on the assumption that sea ice controls environmental conditions such as light, temperature and salinity, thus playing a determinant role on species' distribution, primary productivity and biogenic fluxes to the sea floor (de Vernal et al. 2013a). Microfossils routinely recovered in marine sediments, such as ostracods or foraminifers, were used as paleoceanographic tracers, but their relationship to sea ice is indirect (e.g. Cronin et al. 2010; Polyak et al. 2013). Among marine microorganisms yielding microfossil remains, diatoms and dinoflagellates appear to be more directly related to sea ice as they include taxa associated with sea ice. For example, some diatom species blooming in spring sea ice produce organic biomarkers (IP25), providing direct indications on sea-ice occurrence (e.g. Belt et al. 2007). Many IP25 time series have been produced since 2007, but the curves remain qualitative in the absence of calibration (e.g. Belt and Müller 2013; Stein et al. 2017). Quantitative estimates of sea-ice cover were proposed from transfer functions based on the calibration and the application of modern analogue techniques. In particular, regional data sets of diatom distributions in the surface sediments were used to quantitatively estimate spring sea-ice concentrations from transfer functions, notably in the eastern Baffin Bay (Sha et al. 2014). Hemispheric-scale databases of dinoflagellate cyst populations

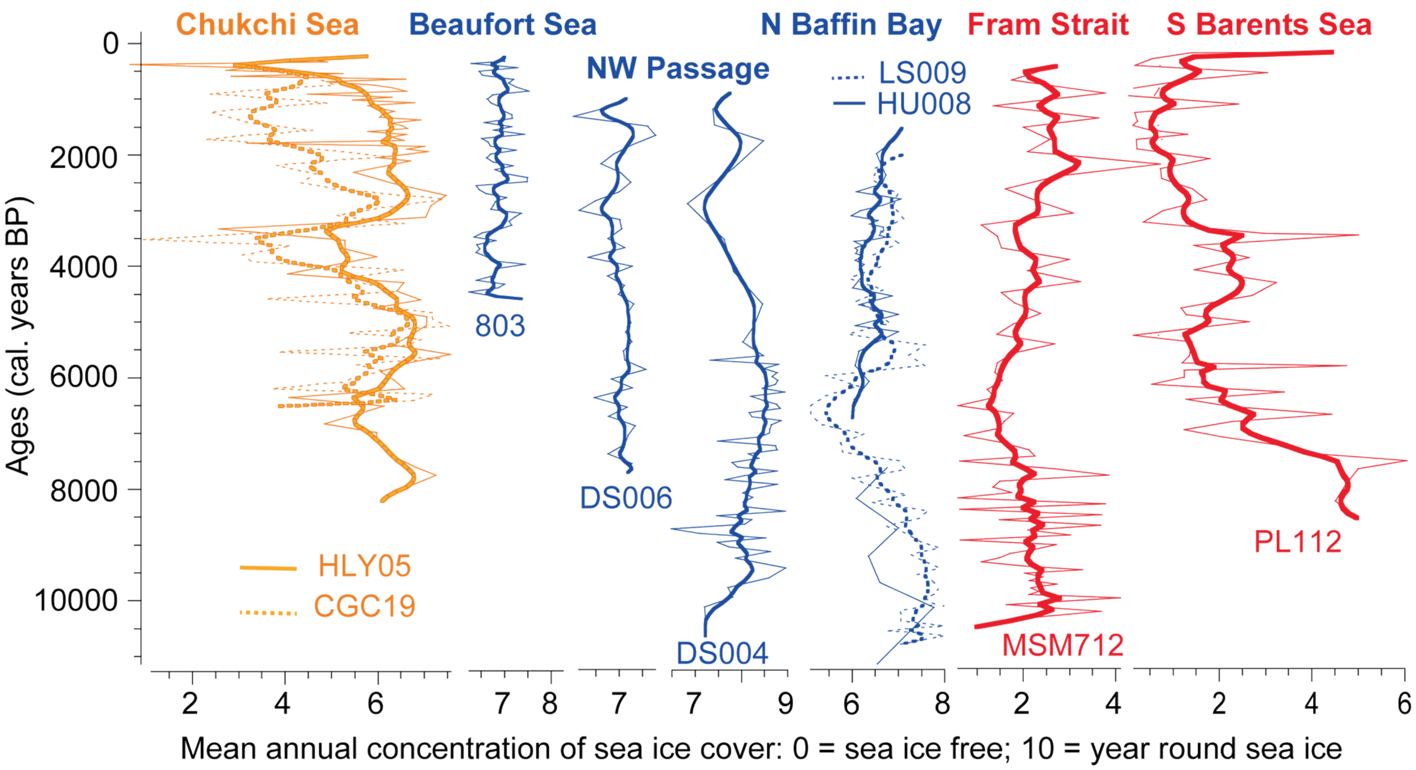

Figure 2: Reconstructed sea-ice cover versus ages during the Holocene. The thin lines correspond to estimates and the thick lines are the smoothed values, which better illustrate millennial-scale variations.

allowed the application of modern analogue techniques for quantitative reconstructions of seasonal sea ice at many sites in the Arctic and subarctic seas (de Vernal et al. 2013b; See examples in Fig. 2).

The limitation of marine sea-ice proxies

Regardless of the approach, the marine-based sea-ice records suffer from several caveats:

(1) The temporal windows of proxy-data. A sediment slice (1 cm usually) may represent decades to centuries or millennia, depending on sedimentation rates (mm per year to cm per thousand years) and bioturbation. This is problematic in the central Arctic Ocean where accumulation rates are particularly low.

(2) The "modern" relationships between the proxies and sea ice are defined from the comparison of surface sediment samples and recent observations, which usually do not encompass the same time window. This is an important source of errors when calibrating transfer functions and applying modern analogue techniques.

(3) Each record has first a local to regional value. The spatial distribution of marine-core records of past sea ice is not dense enough for extrapolation at the scale of the Arctic Ocean and subarctic seas. The rarity of quantitative sea-ice estimates in the Russian Arctic, where the largest variability is presently recorded, is a critical issue.

(4) Year-round ice-free conditions and seasonal sea ice can be assessed from many proxies, but perennial or multiyear sea ice is more difficult to reconstruct. One ostracod taxon parasite of sea-ice nematode was used to assess multiyear sea ice in the central Arctic (Cronin et al. 2013), but perennial ice cover is usually deduced from negative evidence (nil productivity of primary producers).

Circum-Arctic sea ice during the Holocene

Despite limitations, the marine data provide clues on sea-ice cover variations with time windows ranging from decades to centuries, thus yielding smoothed records. At the scale of the Holocene, proxy-data suggest limited variations in general, with likely resilient perennial sea ice in the central Arctic Ocean, but greater variations in the seasonal sea ice as expressed in terms of spring sea-ice concentration (Sha et al. 2014) or number of months of sea ice (de Vernal et al. 2013b) in the Arctic and subarctic seas which are within the limits of winter sea ice. In other words, the variability of sea-ice cover as reconstructed from marine proxies illustrates more the seasonality of its extent and concentration than the actual changes in the Arctic-wide extent of sea ice. The amplitude of local changes during the mid- and late Holocene seems to be mostly comprised within the range of interannual variations as recorded during the last decades. At some sites, variations from a dominant mode to another (low to high sea ice) is recorded with a pacing ranging from multidecadal to millennial scales that may, however, depend upon the time resolution achieved by the analyses. The records based on a standardized quantitative approach, allowing comparison at the circum-Arctic scale, show limited changes and persistent sea ice in the Canadian Arctic, but large-amplitude changes closer to the Pacific and Atlantic gateways (de Vernal et al. 2013b; Fig. 2), where inter-basin exchanges (freshwater and heat fluxes) seem to result in a higher variability in sea ice cover. They also suggest diachronous, if not opposite, changes in the western (Pacific) Arctic versus eastern (Atlantic) Arctic at millennial scales, which might well illustrate shifts from dominant Arctic dipole pattern (Wang et al. 2009) to strong polar vortex leading to more stable Arctic sea-ice cover.

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On the limits of climate reconstruction from water stable isotopes in polar ice cores

Mathieu Casado, A. J. Orsi and A. Landais

Ice core water stable isotopes are a favored proxy to reconstruct past climatic variations. Yet, their interpretation requires calibration from other proxy records and is affected by various processes which alter the signal after it has been imprinted.

The isotopic composition ($\delta^{18}O$, $\delta^{17}O$ and δD) of snow is linked to the condensation temperature because of fractionation associated with distillation from the evaporation site to the precipitation site (Dansgaard 1953). Over large ice sheets, ice is preserved for thousands of years (EPICA 2004) and, thus, analyzing the isotopic composition of the successive layers provides continuous, high-resolution indicators of past climatic variations.

A classical way to retrieve temperature from isotopic composition is to use the spatial relationship between $\delta^{18}O$ of surface snow and surface temperature (e.g. Lorius and Merlivat 1975, for Antarctica). However, one should keep in mind two main limitations when using such a method. First, it assumes that the spatial relationship between $\delta^{18}O$ and temperature is a good surrogate for the temporal relationship between $\delta^{18}O$ and temperature although this link is known to change with time. Second, post-deposition processes affect the snow stratigraphy and the isotopic composition of the snow after precipitation. In the end, the produced time series are also modulated by variable depth-to-time transfer function due to accumulation variations, ice thinning and diffusion.

Resolution and noise

The local accumulation is a determining factor for both the extent of an ice-core record and the maximal resolution that can be achieved. As the ice thickness is capped between 3 and 4 km, depending mainly on the geothermal flux and the topography, it is necessary to choose a site with low accumulation to obtain an ice record spanning several glacial-interglacial cycles (Fischer et al. 2013).

For sites with low accumulation, the snow is exposed at the surface for a long time. Hence, the initial precipitation signal is modified by local post-deposition processes (Ekaykin et al. 2002) due to snow-air interactions, such as the impact of metamorphism, wind and surface roughness, and diffusion. It prevents proper recording of the signal at the intra-seasonal and seasonal scale for sites with accumulation lower than 8 cm ice equivalent per year (Münch et al. 2016).

Deeper in the firn, diffusion smooths the isotopic composition time series, erasing part of the climatic signal (Johnsen 1977). This limits the interpretation of ice-core records at timescales smaller than a few decades.

Finally, for longer timescales (and thus deeper in the ice), the varying depth-to-age transfer function affects the spectral properties of the isotopic composition. The first limitation is the accumulation rate itself, which decreases during glacial periods as a thermodynamic response to temperature decrease. The temporal resolution also gets lower with depth due to ice thinning. As illustrated in Figure 1, the number of years per meter globally increases with the depth of the record, from roughly 20 years per meter at the top of the core at Dome C, up to 1400 years per meter for glacial periods at the bottom. Overall, the variability found in single ice-core records combines both the climate variability and several signatures of the archiving process itself.

Isotope to temperature calibration

The calibration of $\delta^{18}O$ to temperature can be tested against independent temperature time series, such as borehole measurements at the ice-core site. These

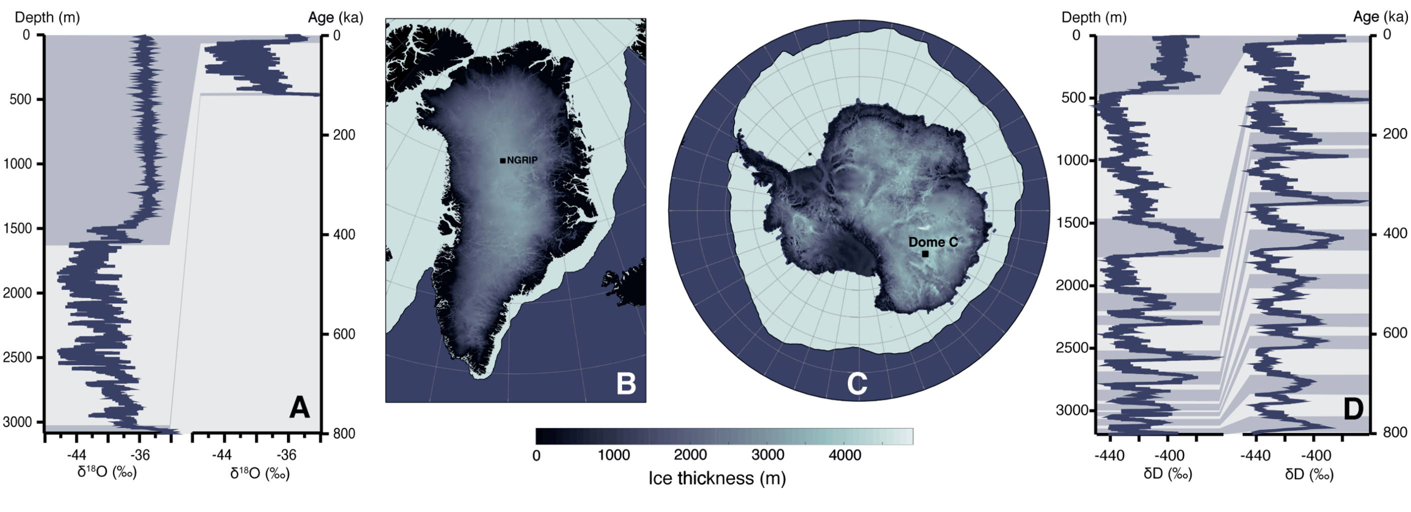

Figure 1: Greenland and Antarctic ice-core sites. **(A)** Isotopic signal from the NGRIP ice core. **(B)** and **(C)** maps of ice thickness in Greenland and Antarctica, respectively. **(D)** isotopic signal from the Dome C ice core.

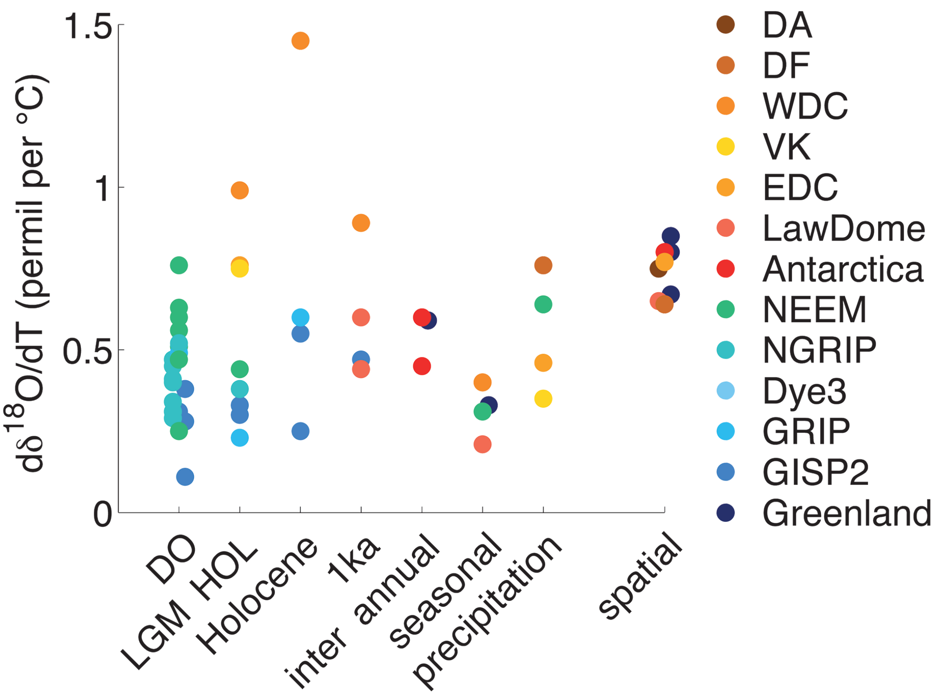

Figure 2: Slopes between isotopes and temperature for different locations and timescales.

measurements performed in Greenland have suggested that the use of the spatial slope (measurements made through space) to estimate the amplitude of the temperature change between the last glacial maximum (LGM) and present-day underestimates by a factor of two the true amplitude of the temperature change (Cuffey et al. 1994). Jouzel et al. (2003) also showed using simulations that the temporal slope (measurements made through time) linking isotopic composition to temperature is less steep than the spatial one and that it does not remain constant over time. This large variability can be due to differences in the large-scale atmospheric circulation, vertical structure of the atmosphere, the seasonality of precipitation, modification of location, or climatic conditions in the moisture source regions.

To take into account the changes in processes involved in the formation of the isotopic signal, calibration of the isotopic paleothermometer is realized through different methods. Weather station data are used at the seasonal and interannual scale, borehole temperature measurements are used at the scale of the recent anthropogenic warming (Orsi et al. 2017) or for the LGM-Holocene transition, and isotopes of nitrogen and argon can be used during abrupt warming events in Greenland (Guillevic et al. 2013). Isotope-enabled climate models can also be used to infer the isotope-temperature relationship with a direct control on the timescale and on the period: for instance, Sime et al. (2009) highlighted that for warm interglacial conditions, the isotope-temperature relationship can become non linear whereas it is not the case for cooler (glacial) conditions.

The ensemble of slopes $\delta^{18}O$ versus temperature found in the literature (Fig. 2) shows, at all timescales, a large span of values ranging from 0.2 to 1.5‰ $°C^{-1}$ which differs from the mostly constant spatial slopes. From this compilation, it is clear that neither the seasonal temporal slope nor the spatial slope, which are the most direct to measure, can be used to calibrate the relationship for longer time periods. For instance, work on Dansgaard–Oeschger events (abrupt warming events during glacial periods typically spanning from decadal to centennial scales) showed that, even for events of a similar timescale, at the same site, the scaling is not preserved (Guillevic et al. 2013). This shows that a more complex framework than simple linear regression to temperature is necessary to interpret the isotopic signal.

These variations in the temperature sensitivity need to be properly taken into account before stacking cores from different sites, or computing power spectra, as the respective amplitude of different spectral peaks of $\delta^{18}O$ variability may include more than one driver (climatic or not).

Conclusions

If water isotopes from ice-core records are insightful tools to reconstruct past climates, there are fundamental limits to their power of reconstruction.

First, the resolution of the ice-core record is not constant in time, due to changes in the accumulation rate, thinning due to ice flow, post-deposition processes, and diffusion of the water isotope signal in snow and ice. Spectral properties of ice-core water isotopes time series are thus affected. For instance, for low accumulation sites, such as those found on the East Antarctic Plateau (below eight cm per year, ice equivalent), multi-decadal resolution at best can be extracted for the isotopic signal, even for recent periods, whereas in Greenland, where larger accumulation is found, seasonal cycles can be retrieved for the last 1,000 years from ice-core records.

Second, the relationship between isotopes and temperature is not constant in time and space. As a result, different methods should be applied to calibrate the isotopic paleothermometer: e.g. borehole temperature for glacial-interglacial transition (millennial scale) or $\delta^{15}N$ for rapid climatic variations (decadal to centennial scales).

These observations call for a more careful use of isotopic records when these timeseries are used for general inferences about the climate system (e.g. Huybers and Curry 2006), keeping in mind the variety of processes involved in the archiving of the climatic signal in the snow isotopic composition. Several approaches can help to clearly identify the transfer function leading to the isotopic signal from ice-core records: isotope-enabled global climate models are the way forward to refine the relationship between precipitation $\delta^{18}O$ and temperature (Sime et al. 2009), and field studies (Casado et al. 2016) can help evaluate how this signal is modified after the deposition and how the isotope-to-temperature relationship is altered at the seasonal and interannual timescales. Finally, using proxy system models can help quantify the impact of archival processes on the climate signal (Evans et al. 2013).

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Centennial- to millennial-scale sea-level change during the Holocene and Last Interglacial periods

Robert E. Kopp[1], A. Dutton[2] and A.E. Carlson[3]

An increasing number of studies reveal regional or global sea-level instability during interglacial periods, belying a traditional assumption of stability. Sea level may have undergone multi-meter-scale variability during the Last Interglacial period, and decimeter-scale variability in the late Holocene.

The scientific community has traditionally considered sea level to be more variable during glacial periods, subject to abrupt millennial-scale changes in climate and glacial dynamics than during warm interglacial periods, thought to be characterized by comparatively stable sea levels. That paradigm is now shifting. Recent reconstructions suggest that sub-millennial, multi-meter-scale oscillations in sea level occurred during the Last Interglacial period and that decimeter-scale variability occurred during the mid to late Holocene in both relative- and global mean sea level.

Last Interglacial sea-level variability

The stability of Last Interglacial sea level is still debated, with various reconstructions suggesting between one and four distinct global sea-level peaks (Dutton et al. 2015; Fig. 1). Various reconstructions of local or global mean sea level have interpreted as global mean sea-level oscillations in the order of one to several meters in magnitude, occurring over 1-2 ka (Blanchon et al. 2009; Kopp et al. 2013; Rohling et al. 2008; Thompson et al. 2011). Multiple sea-level peaks have been interpreted from the planktic $\delta^{18}O$ records of the Red Sea (Rohling et al. 2008). However, the uncertain age constraints on marine sediment records make it challenging to assess rates on 1-2 ka timescales, and the age model for this reconstruction has been modified several times (e.g. Grant et al. 2012). Though the potential local sea-level oscillations seen in the Red Sea record are intriguing, similar oscillations seen in the Holocene portion of the Red Sea record are not considered to represent actual changes in global mean sea level, leaving the interpretation of this variability open to debate.

Other reconstructions with radiometric chronologies are primarily derived from fossil coral reefs that grew near the sea surface. Given the limited precision of dating techniques for the Last Interglacial period, the identification of centennial-scale variability may well remain elusive, but it should be possible to resolve millennial-scale changes. The challenge here lies more in the vertical uncertainty related to paleo-water depth of the corals, raising questions as to whether the apparent sea-level variability in some records may be due to variable paleo-water depths or changes in coral ecology rather than local sea level itself. This demands future work to incorporate a more rigorous assessment of coral assemblages and sedimentary features to interpret sea-level variations, along with the fundamental observations of changes in elevation and time recorded by fossil coral archives. However, other sedimentary features, such as erosional or exposure surfaces in these reef sequences, seem to support multi-meter-scale variability during the Last Interglacial period (Hearty et al. 2007). Despite the interpretation of multiple peaks in sea level at several fossil coral reef sites around the globe, the lack of a consensus in the number, magnitude and timing of such oscillations between individual studies and sites complicates a definitive interpretation of a global

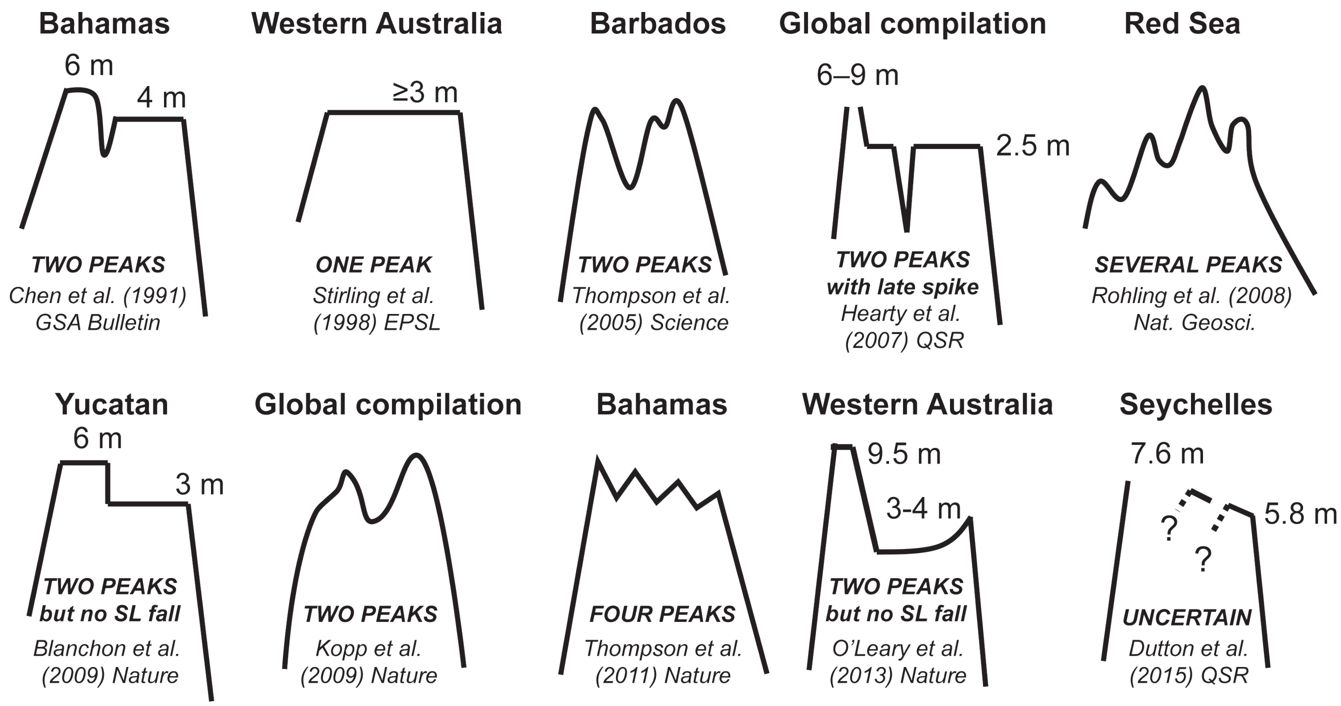

Figure 1: Sea-level reconstructions proposed for the Last Interglacial period (not to precise scale). Different interpretations have been made regarding the number of sea-level peaks, though several suggest evidence for one or multiple sea-level oscillations on millennial timescales.

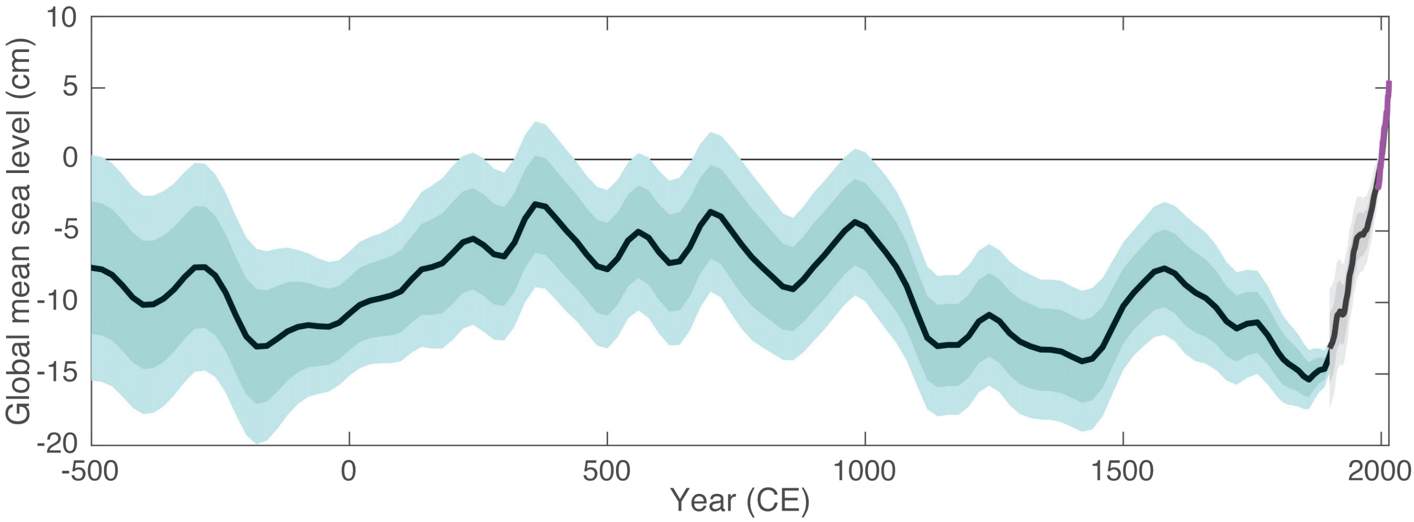

Figure 2: Global-mean sea level over the last 2.5 ka, based on the statistical synthesis of proxy data from Kopp et al. (2016; blue), the tide-gauge-based reconstruction of Hay et al. (2015; grey), and the satellite altimetry record (magenta). Heavy/light shaded regions are 67% and 95% credible intervals.

sea-level history. Nonetheless, numerous fossil reef sites clearly record at least two stratigraphically distinct generations of reef growth. These generations of reef growth often also display significant differences in their post-depositional diagenesis and coral taphonomy that would support the interpretation of a different post-depositional history before the reefs were exposed during the last glacial cycle (Blanchon et al. 2009; Dechnik et al. 2017).

While it is premature to provide a definitive answer regarding the number of sea-level peaks during the Last Interglacial or the rates of sea-level change associated with these millennial-scale sea-level oscillations, the body of evidence points towards a more variable sea-level history than in the Holocene. Of all contributors to sea-level change, only changes in ice sheets seem to have the potential to explain the inferred multi-meter-scale changes. Existing ice-sheet evidence points towards a monotonic retreat of the Greenland ice sheet that can explain only a fraction of the overall sea-level highstand (Colville et al. 2011); data on the Antarctic ice sheet is inconclusive.

Middle to Late Holocene sea-level variability

In general, Holocene sea-level reconstructions have considerably less uncertainty both in time and the magnitude of changes, and hence are more likely to be able to resolve finer details in sea-level changes. Holocene sea-level proxy records are more abundant than in past interglacial stages, and considerable effort has gone into developing standardized databases that enable formal statistical analysis at both regional (e.g. Engelhart et al. 2015) and global (e.g. Kopp et al. 2016) scales.

Following the end of the final wastage of last ice-age ice sheets at ~7 ka, Holocene sea-level rise slowed overall but continued to rise into the late Holocene, reflecting continued retreat of the Antarctic ice sheet (Ullman et al. 2016). In the late Holocene, the highest-precision proxies are derived from salt-marsh sediments and microfossil assemblages, which can yield decimeter-scale vertical resolution and century- or sub-century-scale temporal resolution. Taking advantage of the compilation of well-structured regional and global databases, Bayesian statistical methods have been used to both develop continuous records at individual locations and also estimate the overall spatio-temporal field of relative sea level at regional (e.g. Engelhart et al. 2015) and global scales (e.g. Kopp et al. 2016). Over the last two thousand years, a statistically identified common global sea-level signal exhibits decimeter-scale fluctuations that partially correlate with reconstructed global-mean surface temperature. Notably, a ~0.2°C global-mean surface cooling over 1.0-0.6 ka (Marcott et al. 2013) coincides with a 0.2±0.2 mm a^{-1} global sea-level fall leading into the "Little Ice Age". The division of this sea-level fall between ocean thermal contraction and cryospheric growth is uncertain.

Into the Anthropocene

A significant global sea-level acceleration began in the late-19th century, with a global sea-level rise of 0.4±0.5 mm a^{-1} over 1860-1900 CE (Kopp et al. 2016). At a regional scale, the timing of the sea-level acceleration varies broadly, with emergence above the rate of change due to glacial-isostatic adjustment occurring in the 19th century in some areas and the 20th century in others. In the 20th century, global sea level rose at a rate of about 1.4±0.2 mm a^{-1} (Hay et al. 2015; Kopp et al. 2016) – faster than during any century since at least 2.7 ka (Fig. 2).

The end of the Little Ice Age and the near-synchronous expansion of coal combustion in the 19th century make it challenging to disentangle natural and anthropogenic factors in late-19th and early-20th century sea-level rise. Using the relationship between global mean temperature and global-mean sea level over the last two millennia, Kopp et al. (2016) estimated that, without warming, 20th century global-mean sea level would extremely likely have been limited to -0.4 to +0.8 mm a^{-1} – leaving between 40 and 130% of the observed rise attributable the effects of twentieth-century global warming. The global-mean sea-level signal of warming emerged at the 95% probability level by 1970 CE.

The ~3 mm a^{-1} of global-mean sea-level rise since the early 1990s (Hay et al. 2015) has brought the world outside the realm of late-Holocene experience. With global-mean surface temperature now close to that of the Last Interglacial period (Hoffman et al. 2017), researchers have speculated that the world may be committed to long-term global mean sea-level rise comparable to the Last Interglacial period's 6-9 m peak elevation. Might we also see a return to the enigmatic multi-meter, millennial sea-level dynamism that may have characterized that stage?

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Basic mechanisms of centennial climate variability

Henk A. Dijkstra and Anna S. von der Heydt

Centennial climate variability appears in several long records of climate observables. Understanding the processes responsible for this internally generated variability can be achieved by a combination of more observational data and the definition of falsifiable criteria for specific physical mechanisms.

Indications for variability on centennial timescales are present in several observables of the climate system. Such variability has, for example, been found in a 3,500-year-long Tasmanian summer temperature record (Cook et al. 2000) and in a 4,500-year-long record of the sea temperature near Iceland (Sicre et al. 2008). It is often mentioned that the mechanisms to understand this type of variability are not known. However, several plausible basic mechanisms have been suggested; a mechanism is understood here as a description of a causal chain involving the interaction of well-known processes providing an explanation for the dominant timescale, and possibly a dominant spatial pattern, of variability.

Internal climate variability

Climate variability may arise from changes in the external forcing (e.g. greenhouse gas concentrations, aerosols and solar insolation), but may also originate from internal processes (e.g. instabilities). Examples of such internal variability are the dominant modes of present-day climate variability, such as the El Niño-Southern Oscillation (ENSO) on interannual timescales and the Atlantic Multidecadal Variability (AMV) on multidecadal timescales. When sea-surface temperature (SST) is chosen as the observable, the integration of small fluctuations by the ocean mixed layer generally leads to a red-noise spectrum (where power density decreases with increasing frequency; Hasselmann 1976). Any internal variability such as ENSO is then characterized by a peak above the (red noise) background spectrum and by a particular spatial pattern (Deser et al. 2010).

The mechanisms of ENSO and AMV can be traced back to the amplification of a single pattern due to specific feedbacks. For example, the SST pattern of El Niño is amplified through Bjerknes' feedbacks (stronger SST gradients across the Pacific tropics lead to stronger easterly winds that lead to stronger SST gradients) and is found as a single amplified pattern in Zebiak-Cane's coupled ENSO model. The mechanism of propagation and amplification is related to the same pattern appearing in the mean state of the system, which under strong enough coupling gives rise to an unstable coupled mode with a pattern (Van der Vaart et al. 2000). A very similar single pattern is also found in ENSO simulations using climate models with high-resolution ocean components, having a high degree of variability due to presence of eddies and other small-scale (atmospheric) phenomena. Other types of variability are not related to a single pattern, but arise through the interaction of many patterns possibly having different spatial and temporal scales. Examples of such variability are the zonal and blocked flow transitions in the mid-latitude atmosphere (Charney and DeVore 1979) and the decadal variability of ocean western boundary currents (Shevchenko and Berloff 2015).

Climate variability on centennial timescales

As there is no obvious external forcing on centennial timescales, this variability must arise through internal mechanisms. Such mechanisms can be determined from the analysis of long (multi-century) simulations of global climate models, where the climate forcing may contain the seasonal cycle but no slower components. They cannot be determined solely from observations (proxy or instrumental) because records of the relevant fields are simply not long enough. The observations can hence only be used to falsify the mechanisms proposed from model simulations. Below, we describe two basic mechanisms of centennial variability as derived from such model simulations.

Atlantic surface air temperature variability

The first example comes from a 4,000-year-long simulation carried out with the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model under constant preindustrial forcing (Delworth and Zeng 2012). The observable chosen was the surface air temperature averaged over the Atlantic domain and over the latitudes 20-90°N. This quantity shows dominant variability on centennial timescales, which appears above a red noise background spectrum. In these simulations, the inter-hemispheric heat transport associated with variations in the meridional overturning circulation (MOC) in the Atlantic is responsible for this variability. The variations arise through the advection of salinity anomalies by the MOC, which also determines the dominant timescale in the Atlantic domain surface air temperature.

Can this variability be traced back to the amplification of a single pattern in a more idealized model? Indeed, while investigating instabilities of the MOC in an idealized North

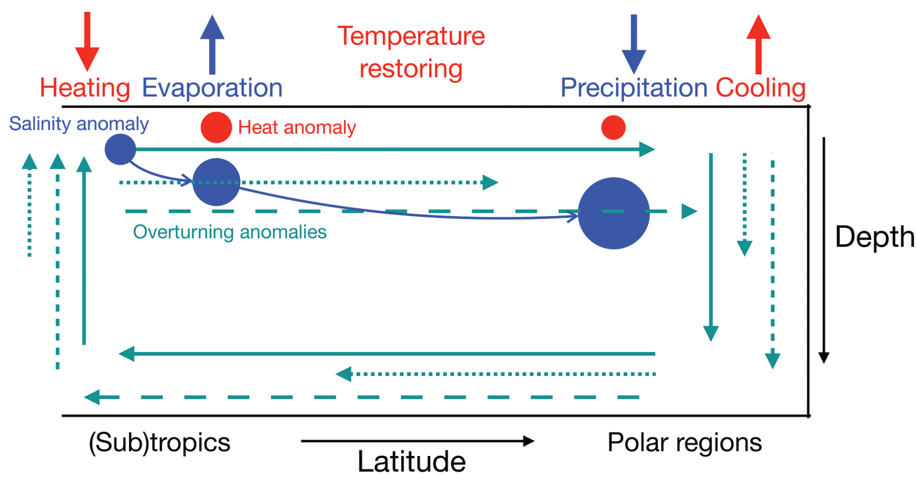

Figure 1: Sketch to describe the mechanism of the Loop Oscillation. A positive salinity anomaly is propagating with the MOC. While it is in the evaporating region, it weakens the MOC, remains longer in this region and hence is amplified. Next, in the precipitating region, it strengthens the MOC, is shorter in this region and is amplified. Moreover, because of different damping of temperature and salinity anomalies, temperature-induced density anomalies appear, which are out of phase with those caused by salinity and hence cause the oscillatory nature of the variability. The timescale is determined by the propagation time of the salinity anomaly over the loop defined by the MOC (details in Sevellec et al. 2006).

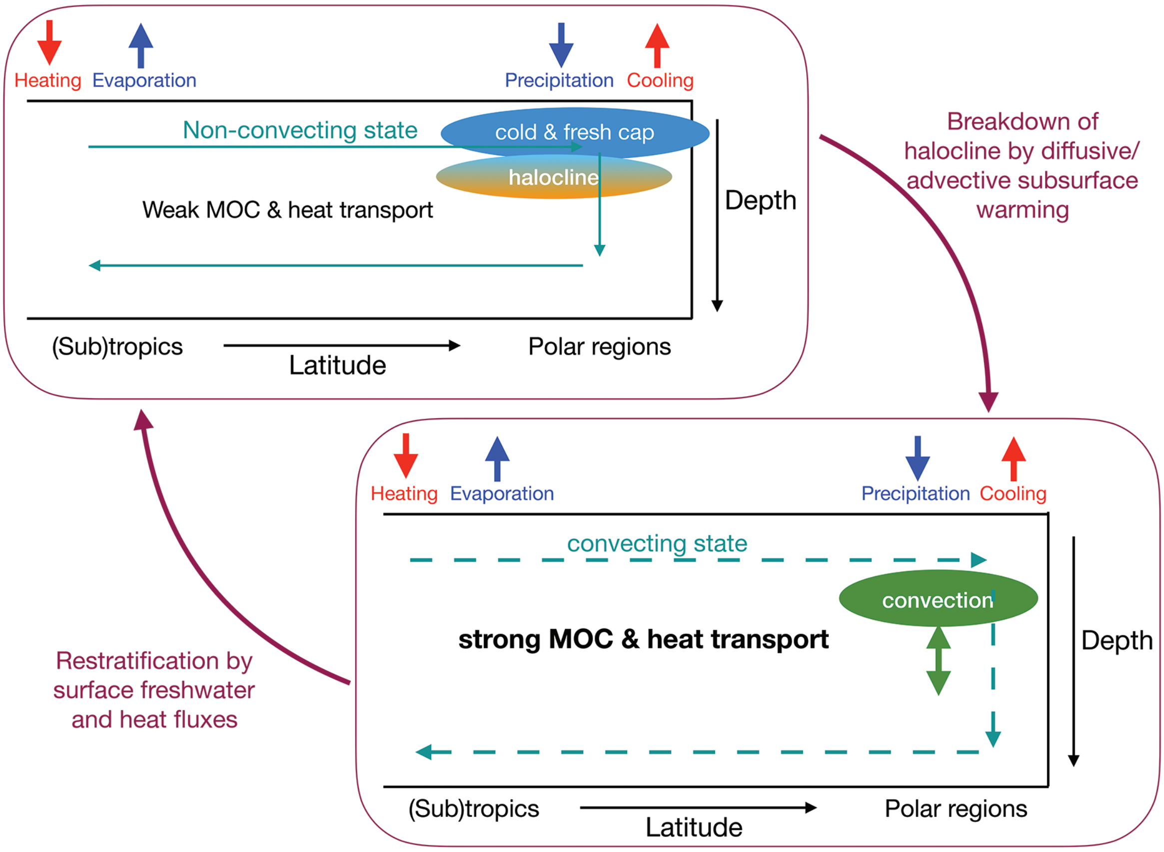

Figure 2: Sketch to describe the mechanism of the Convection-Restratification variability. Starting in a non-(or weakly) convecting state, advective (wind-driven) or diffusive warming of the subsurface ocean causes convection and breaks down the halocline. The convective state increases the strength of the MOC. Through advective and/or diffusive heat and salt fluxes, restratification occurs, which in turn reduces the density at the surface waters eventually causing the transition back to the non-convective state (details in Winton 1995).

Atlantic basin, it was found that buoyancy anomalies, which propagate over the overturning loop can be amplified (Sevellec et al. 2006); such oscillations are called "Loop Oscillations" (or overturning oscillations). The mechanism as deduced from such idealized models is sketched in Figure 1 and described in the caption. Similar patterns were also determined in global ocean models, where the timescale of variability is multi-millennial (Weijer and Dijkstra 2003).

Southern Ocean Centennial Variability

As a second example, we consider the centennial variability which was found in a 1,500-year-long simulation with the Kiel Climate Model (KCM) using present-day constant forcing conditions (Latif et al. 2013). The observable used is the Southern Ocean Centennial Variability (SOCV) index, defined as the zonally and meridionally (from 50-70°S) averaged SST anomaly. The SOCV shows centennial variability above the red noise background. For this type of variability convection in the Weddell Sea is crucial with responses on sea-ice extent and MOC in turn affecting the convection.

Can this variability again be attributed to a single pattern in a simplified model? In this case, this is more difficult and no single pattern in an idealized model has been found causing this type of variability. However, there are idealized models showing the variability caused by transitions between convective and non-convective states. These changes can therefore best be described by "Convection-Restratification" variability; when the restratification takes place through diffusive processes, the variability has been called a deep-decoupling oscillation or a "flush" (Winton 1995). A sketch of the mechanism of the "Convection-Restratification" variability is given in Figure 2 (with a description in the caption). Here the timescale is dependent on the processes restoring the stratification. When this process is vertical, mixing the timescale is millennial (Colin de Verdiere 2007), but when faster processes of restratification are involved, the timescale can decrease to centennial, or even (multi)-decadal (e.g. LeBars et al. 2016).

A way forward

The two mechanisms described above form the basic mechanisms of centennial variability in either the Atlantic or the Southern Ocean. In other model simulations, variants or modifications are found as the atmosphere and sea-ice components are also affected. At the moment, it is difficult to falsify these basic mechanisms by the observational database. It is therefore important that specific falsification criteria for the mechanisms are developed, which can then be applied every time the database of observations is updated. Also, more sophisticated (nonlinear) data-analysis techniques may be needed to look at higher-order statistics than just simple linear stationary statistical measures (Mukhin et al. 2015). An increasing observational database and good falsification criteria of specific mechanisms are the way forward to get more clarity on the processes responsible for centennial climate variability.

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On the importance of centennial variability for ice ages

Peter Ditlevsen[1] and Michel Crucifix[2]

Ice ages are paced by astronomical forcing, but how centennial variability affects their dynamics is still unknown.

A common explanation of ice ages asserts that they result from a chain of responses, which follow and then amplify the effects of the changes in the distribution of incoming solar radiation along the seasons and along latitudes. This is the modern interpretation of the Milankovitch theory. From this perspective, the presence of a 100-ka component dominating the frequency spectrum of proxies for ice ages has often been presented as a puzzle. True, changes in eccentricity modulate the amplitude of precession peaks at a period of about 100 ka, but the spectrum of insolation time series do not contain an amplitude peak at this period. Since the dominant period of response differs from the dominant period of forcing, the feedbacks between components of the climate system must involve some non linearity. It was then observed that the dominance of such non linear feedbacks opens the possibility that ice ages may even arise as a self-sustained cycle. With this possibility in mind, the astronomical forcing is often prudently presented as the "pacemaker" of an internal oscillation rather than a primary "driver".

The SPECMAP days

One of the objectives of the Spectral Mapping Project (SPECMAP) in the 1980s was, precisely, to investigate such dynamics (Imbrie et al. 1992). The methodology consisted of filtering climate records along frequency bands at about 1/20, 1/40 and 1/100 ka^{-1} in order to characterize the amplitudes of different climatic variables, and estimate leads and lags across them.

In parallel, theorists developed and studied small numerical models expressed in the form of time-difference equations representing interactions between climate components such as ice sheets and the carbon cycle. In such reduced models, the relaxation timescales, which encode the typical response time of system components, are generally of several millennia. Hence, by design, these models do not include variability at millennial frequencies, let alone centennial variability. The idea that justifies only focusing on the representation of the dynamics at a given timescale without caring much about faster dynamics is the hypothesis of timescale separation (Saltzman 1990). This is also what Lovejoy (2017) refers to as the "scale-bound view" in this issue. Unsurprisingly, thus, the power spectrum of the output of such time-difference models shows amplitude peaks at periods of ~20, 40 and 100 ka and essentially no power at shorter or longer periods (Fig. 1, the "SM90 deterministic" model).

A drunkard's walk

Early on, however, several investigators (e.g. Pisias and Moore 1981) remarked that when the power spectrum of climate variations is plotted on a log-log form, the so-called Milankovitch peaks become almost anecdotal. The visual impression is rather that of a noisy process encompassing slow and fast variability. It turns out that, from the point of view of mathematics, it is not very difficult to construct simple stochastic processes having essentially the same power spectrum as that of the paleoclimatic data. The following model was proposed by Wunsch (2003): Imagine that ice volume may randomly increase or decrease, with a statistical preference for increase (because, say, that the average conditions are colder than in the early Pliocene and favor glaciation). In the parlance of dynamical systems theory this is called a random walk with a drift, perhaps better imaged as "a drunkard's walk". This kind of drifted random walk will unavoidably reach, sooner or later, a threshold which we fix arbitrarily, and at which point we decide that deglaciation occurs.

The two free parameters (drift and threshold) of this model can easily be adjusted to reproduce the broad characteristics of the paleoclimatic deep-ocean sediment record of ice ages. The model spectrum has no scale separation from the high frequencies down to the 100-ka cycle. Milankovitch forcing may then be parsimoniously re-injected either on the drift of the random walk or in a time varying size of the threshold (Huybers and Wunsch 2005).

Two views on ice ages

We thus face two different views on ice ages. In the first view, the modern Milankovitch theory explains ice ages as the result of multiple feedbacks which operate at the timescale of several millennia. Simple deterministic models are the expression of this view and they can be impressively successful at reproducing the broad time evolution of ice age proxies all over the Pleistocene (e.g. Paillard and Parrenin 2004), but they do not reproduce the bulk of the power spectrum.

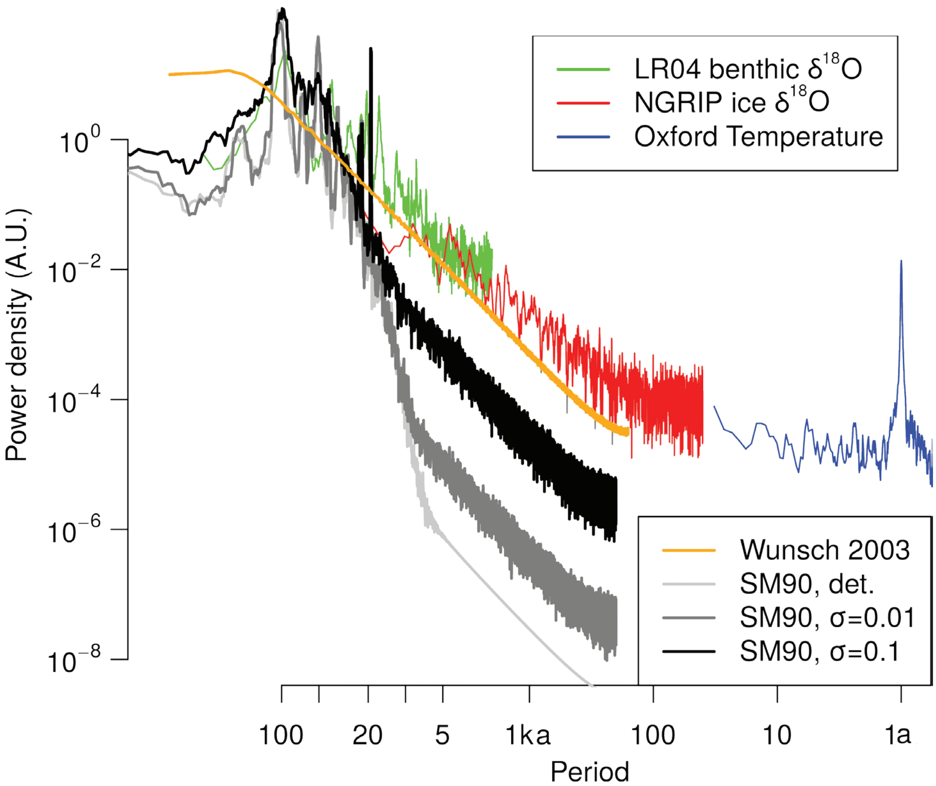

Figure 1: Periodogram of paleoclimatic records: LR04 benthic stack (green), NGRIP isotope record (red), Oxford temperature data adapted from Shao and Ditlevsen (2016; blue), compared to the spectra estimated for the Wunsch (2003) stochastic model (orange), and the Saltzmann Maash 1990 model (thick grey and black, with different levels of added noise; adapted from Crucifix et al. 2016).

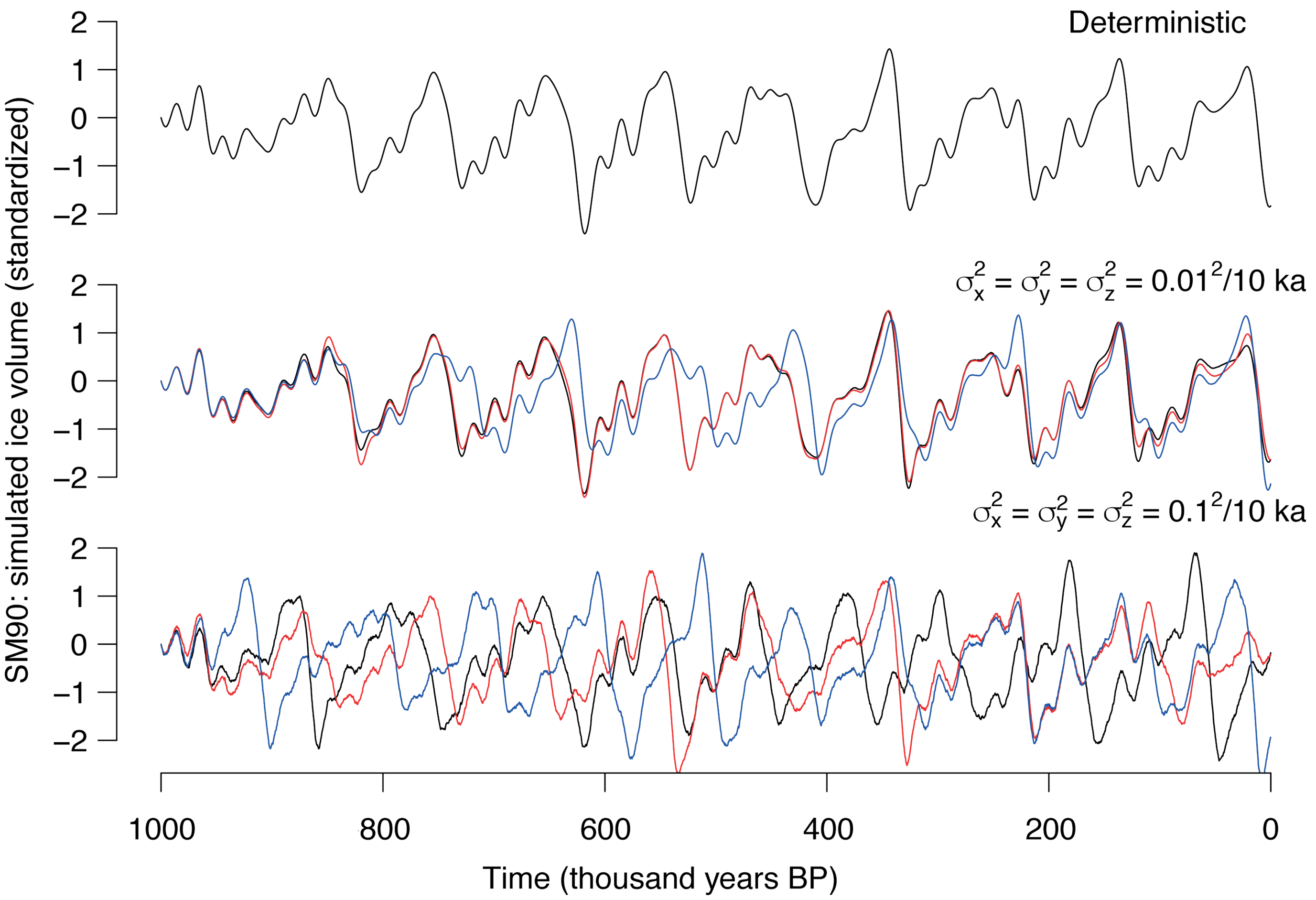

Figure 2: Accounting for background, sub-millennial variability changes our view of glacial cycles. Shown are trajectories obtained with a conceptual, dynamic-stochastic model of ice ages elaborated by Saltzman and Maasch (1990), in **(A)** its deterministic version, and **(B-C)** then modified to include a stochastic diffusion process, of amplitude σ (equations and units in Crucifix et al. 2016). Blue, red and black curves correspond to three possible results of the stochastic process, among an infinity of possibilities. With the highest amplitude noise (C), orbital pacing is considerably weakened.

Models in the same vein, or sometimes even more idealized, have been used to study the phenomenon of synchronization of ice ages on the astronomical forcing, or the mid-Pleistocene transition (Ashwin and Ditlevsen 2015).

In the second view, stochastic dynamics does capture the spectrum (Wunsch 2003; Fig. 2) but a physical theory on the processes that create these fluctuations, determine their statistical properties, and allow them to accumulate over ice-age timescales, is still lacking. Hence neither view can stand alone in offering a complete explanation of ice ages.

There were some attempts to explain the spectrum with a focus on well-identified, non-linear interactions between climate components. Thirty-five years ago, Le Treut and Ghil (1983) proposed a mechanistic model which represented explicitly some fast (sea-ice) and slow (ice-sheet) processes. The model was chaotic; it generated a broad spectrum, but failed to produce a sequence of events that actually resemble ice ages. Another suggestion is to start from a deterministic model and inject a stochastic process in the equations supposed to represent fast atmospheric fluctuations. The strength of the stochastic process can be tuned to bring the power spectrum closer to that estimated from the equations (Fig. 1, black line). The mathematical object built this way is called a stochastic differential equation. As it turns out, in simple models, the stochastic injection tends to ransack the ice-age cycle to the point of making it quite unstable and broadly unpredictable. The sequence of ice ages becomes also much more random (Fig. 2).

Why centennial variability matters

Of course, research on ice ages is increasingly performed with more sophisticated models. Realistic-looking glacial cycles were recently produced with the Earth system model of intermediate complexity CLIMBER (Ganopolski and Calov 2012). Such a model relies on equations which describe well-identified physical aspects of the ocean, ice sheets, atmosphere and carbon cycle, but lack centennial variability. The model therefore exhibits a form of time separation, which is not verified in the data. On the other hand, general circulation models have been shown to produce almost enough centennial variability, but they do not, yet, reproduce glacial cycles. In fact, we do not know whether attempting to represent the full sequence of glacial cycles is a reasonable target. The presence of centennial variability could make them much more random than we think.

For these reasons, centennial variability must be on the agenda of ice-age experts. The relationship between centennial and astronomical variability is largely uncharted, and yet it could still shape our views on the cause of ice ages.

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Regional carbon isotope syntheses from the last deglaciation

Andreas Schmittner[1], G. Martínez-Méndez[2], A.C. Mix[1] and J. Repschläger[3]

Corvallis, USA, 27-29 June 2017

The last deglaciation, which is Earth's climatic transition from the Last Glacial Maximum (LGM, ~21 ka BP) to the Holocene (current interglacial period; ~10 ka BP), is still not fully understood. The associated rise in atmospheric CO_2 and related changes in ocean circulation and carbon storage remain puzzling. Carbon isotopes ($\delta^{13}C$) are influenced by ocean circulation and carbon cycling, including the biological pump and air-sea gas exchange, and preserved in the sedimentary record in fossil shells of benthic foraminifera (unicellular organisms living at the sea floor). The PAGES working group Ocean Circulation and Carbon Cycling (OC3) aims to synthesize benthic $\delta^{13}C$ sediment data globally to reconstruct and understand the mechanism of natural climate and carbon cycle changes with a focus on the last deglaciation.

The current, second OC3 phase focuses on down-core data syntheses in different ocean basins (Fig. 1). Goals of this second OC3 workshop were to discuss the progress and first analyses of the data collection, issues of database structure, scientific questions, and possible publications. Talks presented new modeling results on changes in meltwater fluxes during the last deglaciation, and effects of their spatial distribution on ocean circulation. Model results also explored connections between the Atlantic Meridional Overturning Circulation (AMOC), deep ocean carbon storage and isotope distributions, and atmospheric CO_2. A presentation on age-model uncertainty showed differences of more than 1,000 years depending on the method used to construct the age model (radiocarbon versus oxygen-isotope alignment versus surface-property alignment). Down-core data from the North Atlantic raised the question of northern versus southern sources for reconstructed, very depleted $\delta^{13}C$ and $\delta^{18}O$ deep water (Repschläger et al. 2015; Keigwin and Swift 2017), whereas negative $\delta^{13}C$ excursions in intermediate waters may be explained by changes in the efficiency of the biological pump (Lacerra et al. 2017).

Presentations on Pacific Ocean syntheses showed that the water-mass geometry in the southeast Pacific did not substantially change during the LGM and suggested larger than previously thought mean-ocean $\delta^{13}C$ change during the deglaciation, which may challenge existing interpretations about changes in terrestrial carbon storage. A decoupling of the Pacific from the Atlantic circulation during the LGM was suggested by a comparison of $\delta^{13}C$ depth transects from the southwest Pacific and the southwest Atlantic. The single presentation about the Indian Ocean confirmed earlier studies linking changes in AMOC with monsoonal variations during the last deglaciation. The Indian Ocean and cores from intermediate depths are currently underrepresented in OC3. Presentations on ice-core data included updates to age models and highlighted rapid and coeval changes in CH_4, CO_2 and $\delta^{13}C_{CO2}$, not only during the last deglaciation but also for earlier parts of the last glacial cycle.

LinkedEarth (http://linked.earth; a partner project of PAGES' 2k Network), a new, searchable, open-source, wiki-like platform for paleoclimate data compilation and curation, was introduced to the participants including a tutorial. Participants agreed to use this platform to publish the final OC3 database product.

Discussions noted differing data quality among sediment cores. Since the objective of OC3 is to include all data, it was recommended that information on data quality, including species used, age models and uncertainties, time resolution, and analytical errors, will need to be reported in the database. All data will be quality checked and flagged by multiple scientists according to their regional expertize. Initial groups for the North Atlantic, the South Atlantic, and the Pacific have already been formed. All groups are open to participation from interested colleagues.

OC3 plans to publish three regional syntheses and one global synthesis paper. The next and final OC3 meeting will be in Cambridge, UK, from 13-16 September 2018, preceded by informal meetings at the AGU Fall and Ocean Sciences meetings.

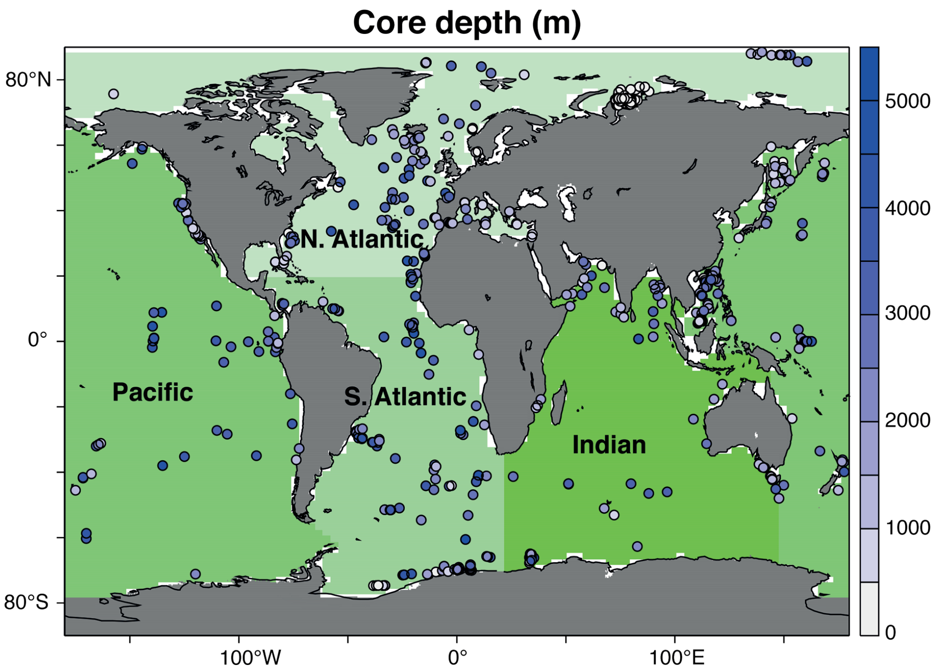

Figure 1: Map of core locations of the current OC3 down-core database. Also indicated are the regions for which different groups will perform syntheses and data quality control.

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Interglacials of the 41 ka-world and the Mid-Pleistocene Transition

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Molyvos, Greece, 28-30 August 2017

A defining feature of the Quaternary is the quasi-periodic expansion and contraction of major Northern Hemisphere ice sheets. Before ~1.25 million years ago (Ma), glacial-interglacial cycles appear symmetric with smaller ice volumes and a period of 41 thousand years (ka, Fig. 1). Between ~1.25 to 0.7 Ma, the Earth's climate underwent a fundamental change, the Mid-Pleistocene Transition (MPT), where the dominant frequency of climate cycles changed from 41 to 100 ka. A full understanding of these modes of variation and the cause of such a change occurring under a relatively similar orbital forcing is still missing. To advance this topic, the third QUaternary InterGlacialS (QUIGS) workshop gathered 29 delegates to review the current science of the 41 ka-world interglacials and the underlying causes of the MPT. The outcome combines information from paleoclimatic archives together with insights from ice-sheet and climate modeling, producing future research directions.

Interglacials of the 41 ka world

Based on published and emerging paleoclimatic records extending beyond the MPT, similarities and differences in 100 ka-world (post-MPT) interglacials were identified. In brief, the 41 ka-world (pre-MPT) interglacials are generally more symmetrical in benthic $\delta^{18}O$ records than post-MPT interglacials (Fig. 1). Interglacial values are similar but the duration of pre-MPT glacial terminations and inceptions can differ. The high latitudes are characterized by warmer oceanic and continental surface conditions during pre-MPT interglacials. While pre- and post-MPT glacial atmospheric CO_2 levels differ, boron isotope-based reconstructions suggest similar interglacial levels (Fig. 1). The relatively high pre-MPT glacial-interglacial CO_2 and sea-level variability is not yet simulated in modeling studies. Pre-MPT interglacials are characterized by a millennial-scale climatic variability but the presence of a bipolar seesaw mechanism at their onset, a key millennial-scale feature of the post-MPT interglacials, cannot yet be assessed.

Sea-level and ice-volume estimates, as well as most reconstructions of more regional climate and environmental patterns during pre-MPT interglacials, have large uncertainties and limited temporal resolutions.

To provide further insights on the nature of pre-MPT interglacials, we encourage future investigations to focus on generating high-resolution datasets across a time slab characterized by typical pre-MPT glacial-interglacial cycles i.e. from Marine Isotopic Stage (MIS) 42 to MIS 46. We hope also that this will generate interest within the modeling community.

The MPT and underlying causes

The MPT, referring both to the change in frequency and intensity of glacial-interglacial cycles between 1.25 and 0.7 Ma, is characterized by multiple events identified in ocean circulation intensity proxies. It is mostly considered to be either driven by (i) an atmospheric CO_2 concentration decline, triggered by weathering or enhanced ocean uptake and storage or (ii) the removal by glacial erosion of thick sediment (regolith), exposing a high-friction crystalline Precambrian Shield bedrock, which increases ice stability, and an attendant change in the ice-sheet response to orbital forcing. Modeling studies have not fully reconciled the "regolith" hypothesis and questions remain over the timing of the regolith removal and the consequent ice-sheet response.

Progression on the causes of the MPT requires obtaining additional CO_2 reconstructions with reduced uncertainties. Boron-derived CO_2 data are coherent with direct CO_2 measurements performed on 1 Ma-old ice samples (Fig. 1) but the drilling of an "Oldest Ice" core back to 1.5 Ma (Fischer et al. 2013) would offer a large increase in confidence about the evolution of the climate-carbon cycle interactions across the MPT.

An article summarizing the ideas about the MPT is being prepared. New data, modeling exercises and ideas emerging from them should appear in the next few years, and QUIGS will return to this topic during its second phase, starting in 2018.

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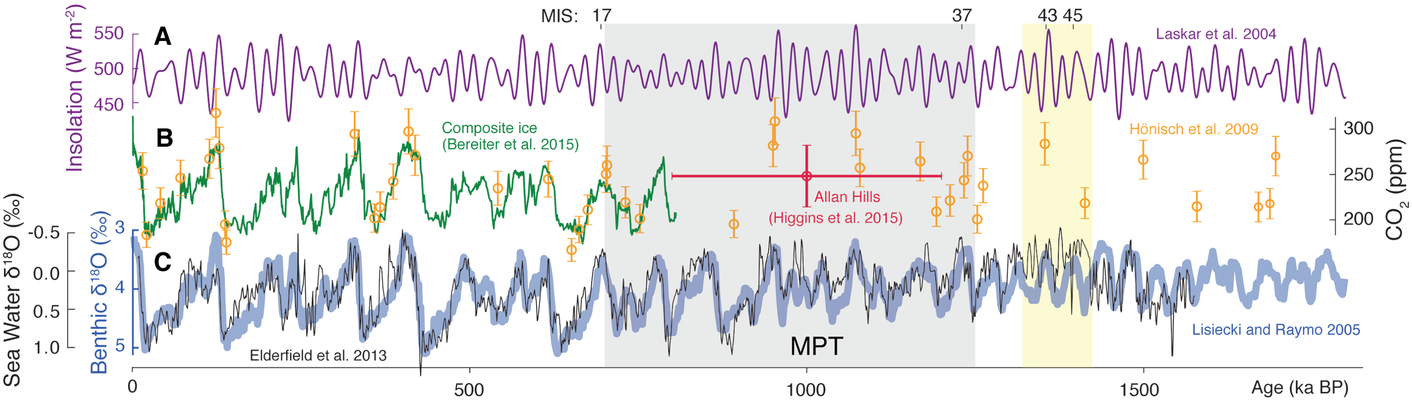

Figure 1: (A) 65°N summer solstice insolation, **(B)** Atmospheric CO_2 concentration, Allan Hills vertical error bars indicate 2σ spread with horizontal age uncertainty, **(C)** Global LR04 benthic stacked $\delta^{18}O$ (blue), ODP1123 seawater $\delta^{18}O$ (black). The MPT and the "typical 41 ka-world" intervals are highlighted in grey and yellow respectively.

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From caves to climate: Creating the SISAL global speleothem database

Laia Comas Bru[1], Y. Burstyn[2,3] and N. Scroxton[4]

First SISAL meeting, Dublin, Ireland, 21-23 June 2017

Speleothem based paleoclimate records have risen in prominence over the last few years as long-term, precisely dated, continental archives of past changes in the hydrological cycle. But these valuable records have yet to make significant contributions to recent big data syntheses. For example, only seven records are included in the standard Palaeoclimate Modelling Intercomparison Project (PMIP) benchmark dataset (Harrison et al. 2014). A synthesis of existing speleothems records has great potential for exploring regional and global-scale past changes in the hydrological cycle, as well as for evaluating the ability of climate models that explicitly simulate water and carbon isotopes to capture hydroclimate variability through data-model comparisons. To address these issues and to increase the impact of speleothem research in general, PAGES' SISAL (Speleothem Isotopes Synthesis and Analysis) working group is creating a systematic global synthesis of speleothem $\delta^{18}O$ and $\delta^{13}C$ records (Fig. 1 and Comas Bru et al. 2017).

Twenty-three SISAL members (including 12 early-career researchers) met for the first SISAL workshop. The meeting took place at the UCD O'Brien Centre for Science at University College Dublin, Ireland, and was coordinated by Laia Comas Bru (University College Dublin, Ireland) and Sandy Harrison (University of Reading, UK). Over three days, workshop participants established the framework for the SISAL database, discussed potential data analysis projects and added entries to the database. On Day 1, speleothem scientists representing all continents (apart from Antarctica) presented reviews of speleothem research and existing records in their regions, and climate and karst/speleothem modelers also introduced how the SISAL database could be used by their communities. These presentations were followed by an interactive introduction to the preliminary structure of the database that was prepared in advance of the meeting by SISAL steering committee members. During this working session led by Kamolphat Atsawawaranunt (University of Reading, UK), participants had the opportunity to test the structure and contents of the database by entering individual data sets and raising any questions or issues. Based on this feedback, Day 2 was dedicated to group discussions where workshop participants deliberated issues such as identifying the essential metadata needed for SISAL's purpose, dealing with ambiguous terminology and ensuring that the database includes the key parameters and information required for assessing age models. Further discussions on data collection strategy and forward planning of analyses served to shape the key points for the group's first scientific papers. Day 3 brought the workshop to a close with a recap discussion on the next steps before SISAL's second meeting in September 2017 (Kaushal and Comas Bru 2017) and developing a timeline for the working group's activities.

One important decision made during this three-day workshop was the nomination of "regional coordinators", who will liaise with authors publishing on speleothems from a given region and will be responsible for the initial quality control of records. We are confident this approach will enormously help facilitate data entry and also involve a wider group of scientists in the SISAL project, ensuring its success. A complete list of regional coordinators is available on our webpage.

SISAL welcomes paleoscientists interested in the curation of the database and encourages ideas for big data analyses that can be achieved with this new dataset. Those researchers with data to add to the database are encouraged to contact the regional coordinator for the geographic area of their stalagmite record. The first version of the database closes 31 December 2017. For more information about SISAL and how to get involved, go to http://pastglobalchanges.org/ini/wg/sisal

ACKNOWLEDGEMENTS

We would like to thank PAGES, European Geosciences Union (EGU), iCRAG (Irish Centre for Research in Applied Geosciences), Geological Survey Ireland, Quaternary Research Association UK and the University of Reading for their financial support.

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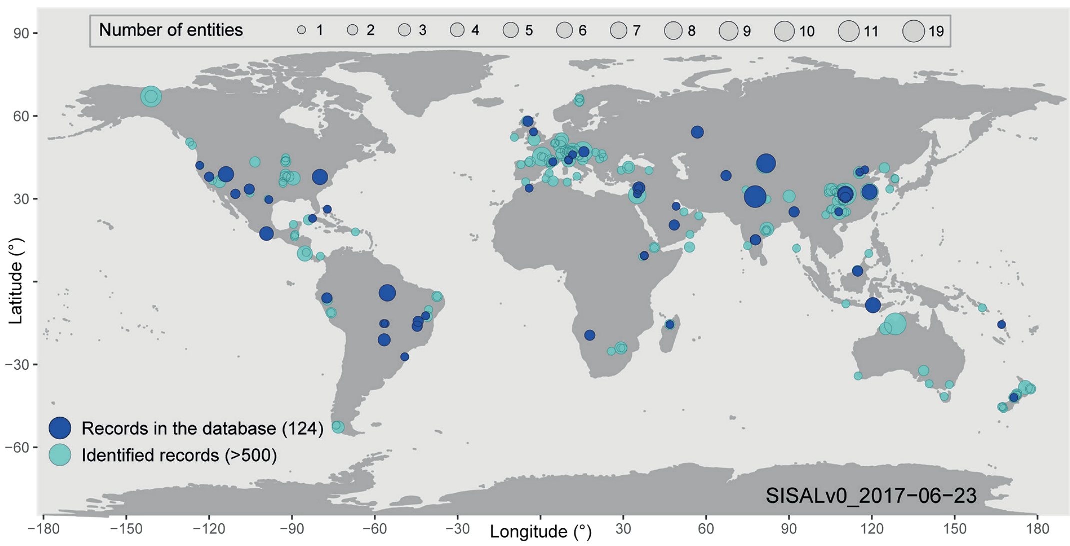

Figure 1: Global map showing the records uploaded to SISAL's database (n=124; dark blue) at the end of the workshop versus the 500+ records identified by SISAL members (cyan).

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Speleothem isotope records for climate model evaluation

Nikita Kaushal[1] and Laia Comas Bru[2]

Second SISAL meeting, Stockholm, Sweden, 20-22 September 2017

PAGES' SISAL (Speleothem Isotope Synthesis and Analysis) working group is creating a systematic global synthesis of speleothem isotopic records (Comas Bru et al. 2017a). Beyond the creation of the database, SISAL also aims to understand and showcase how speleothem data can be used in paleoclimate modeling studies. Data synthesis combined with suitable modeling targets can help reduce uncertainty and improve interpretations in both. Such data-model comparisons can also help refine our quantitative understanding of past climate events and enhance credibility of model projections (Schmidt 2010). At the time of this workshop, we had 208 of ~577 speleothem-based climate records in the database with more records being added every week (see Fig. 1 in Comas Bru et al. 2017b for a global map with identified records). The first version of the SISAL database will be released in early 2018.

Seventeen SISAL members (including eight early-career researchers and six researchers from the PMIP modeling community) met to discuss isotope-enabled model evaluations using the database and how the SISAL database should be made available to end-users such as the paleoclimate modeling community. The meeting took place at the Navarino Environmental Observatory in Stockholm, Sweden, and was organized by a group of SISAL members from different universities. On Day 1, participants presented research on prospects for speleothem-model evaluations targeting specific climate questions, periods and regions. Presentations were also given by stakeholders such as IsoNet (Isotopes for Tropical Ecosystem Studies) and the proxy data synthesis working group of PalMod (www.palmod.de). This was followed by a discussion on the best-practice methods to quantify uncertainties on the age and isotope measurements in SISAL and the most convenient way for modelers to understand and incorporate these uncertainties when using the database. There were subsequent discussion sessions on proof-of-concept exercises using SISAL and existing isotope-enabled simulations. These discussions were formalized through breakout sessions, where tasks were delegated to SISAL members. Throughout the day, we identified gaps in data coverage for key time periods in specific regions.

Day 2 kicked-off designing the contents of the SISAL presentation for the PMIP4 meeting the following week to showcase the major features of the interim SISAL database (Fig. 1). This was followed by a discussion on how to address key questions related to the climate interpretation of speleothem isotopic data using paleoclimate model outputs. Lastly, there were hands-on sessions centered on advancing the first publications emerging from the SISAL database. Sections of the paper describing the database were jointly written by SISAL members in multiple breakout sessions and further papers focusing on specific climate questions were outlined. These outlines will be shared with the wider SISAL community to give it the opportunity to participate in the projects. Day 2 also saw a short presentation on the PAGES working group DAPS (Paleoclimate Reanalyses, Data Assimilation and Proxy System Modelling) to identify possible synergies to emerge from a SISAL-DAPS collaboration. We decided to organize short meetings with both groups at widely attended, large geoscience conferences in 2018 to promote further discussions. Day 3 brought the workshop to a close with a recap discussion on our next steps towards SISAL's third meeting in October 2018 and developing a timeline for the working group's future activities.

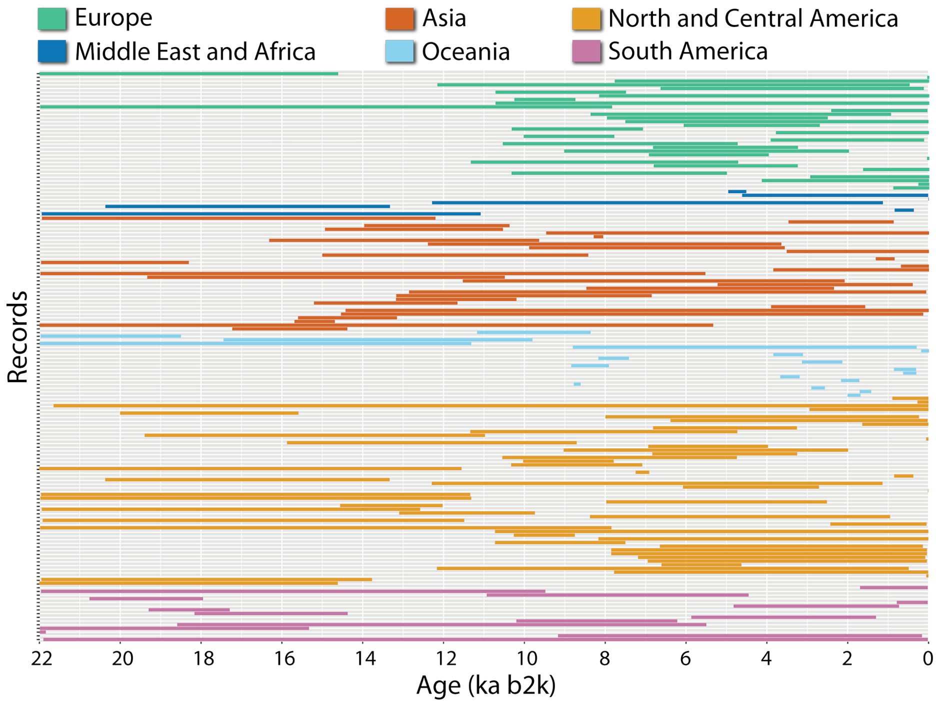

Figure 1: Time coverage of the records (n=208) in SISAL_v0 (September 2017) for different regions: Europe (36-75°N, 30°W-30°E), Middle East and Africa (45°S-36°N, 30°W-60°E), Asia (10-60°N, 60-130°E), Oceania (10-60°S, 90-180°E), North and Central America (10-60°N, 50-150°W) and South America (60°S-10°N, 30-150°W).

SISAL encourages ideas for big data analyses that can be achieved with this new dataset. For more information about SISAL or how to get involved, go to http://pastglobalchanges.org/ini/wg/sisal

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We thank PAGES, the University of Reading, University College Dublin, Navarino Environmental Observatory in Stockholm University, Savillex and John Cantle for their financial support.

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Aquatic transitions in Southeast Asia and Oceania

Keely Mills[1], S. McGowan[2], É. Saulnier-Talbot[3] and P. Gell[4]

Kuala Lumpur, Malaysia, 15-17 February 2017

The first two meetings of the Aquatic Transitions working group, whilst focused on a global agenda, were dominated by members from Europe and North America. Early screening of metadata available from these members highlighted major data gaps in China, South America, Africa, and Tropical Asia. To address some of these gaps, Aquatic Transitions "piggy-backed" on a number of international conferences in China (International Paleolimnology Symposium, Lanzhou, August 2015; INTECOL Wetlands Conference, Changshu, September 2016) to raise our profile and recruit potential members from Asia. This third meeting focused efforts in SE Asia, and welcomed 30 participants (20 from Tropical Asia) to Kuala Lumpur. The group comprised six Aquatic Transitions "veterans", eight established academics with expertise in the region, eight early-career researchers, seven MSc and PhD students, and a stakeholder from the Forestry Research Institute of Malaysia.

Given the new group composition, day one began with introductions to PAGES and Aquatic Transitions, and to what we thought we knew about lake systems in the tropical Asia region, summarizing previously published work (Fig. 1). All participants gave "speed talks", introducing themselves, their research, and the lake systems on which they worked. The afternoon closed with a short lecture on "what is paleolimnology" for those who were less familiar with its use and application.

On the second day, participants rotated between six discussion groups focused on the key topics: SE Asia regional review; Ecosystem services; Linking lakes and drivers; Paleo-problem solving; Lakes as socio-ecological systems; and Freshwater biodiversity. In the afternoon, participants were updated on outputs from the previous Aquatic Transitions meetings (with a focus on populating the UCL-hosted LakeCores database), published papers and those in preparation, and a "Developments in Paleoenvironmental Research" volume that was solicited by Springer. During this session, a number of abstracts were prepared as part of the book proposal – with contributions from early-career members. As part of the database activities, data and publications from the Tropical Asia region were compiled during the meeting (Fig. 1). The day ended with a public lecture hosted by University of Nottingham's Malaysia Campus as part of the Mindset Research Centre lecture series. Three short lectures were delivered by Keely Mills, Nathalie Dubois and Suzanne McGowan under the title "Understanding the Anthropocene using lake sediment records". The talk attracted over 80 attendees and is available as a podcast here: http://mindset.my/content/talk021.html

The final day focused on stakeholders and regional engagement and capacity building. As Aquatic Transitions moves forward, and in an attempt to have our outputs utilized outside academia, it is important to identify key stakeholders. Small groups mapped stakeholder groups, categorizing those who have a high level of interest in our work, and those who have a high level of influence. This was a productive exercise to think more broadly about our interactions when designing research projects for impact. The meeting concluded with discussions on the next steps for Aquatic Transitions – the initial three-year phase ends in December 2017. Community interest was gauged to assess whether we should apply for a second phase to allow us to include more researchers from regions that lack data. Attendees at the Tropical Asia workshop provided excellent support, and it has been agreed that whilst we tie up Phase 1 loose ends, we submit an application in early 2018 for Phase 2. Future workshops in Africa and South America would boost interest and encourage global participation. Finally, regional leaders to help drive Phase 2 forward were identified.

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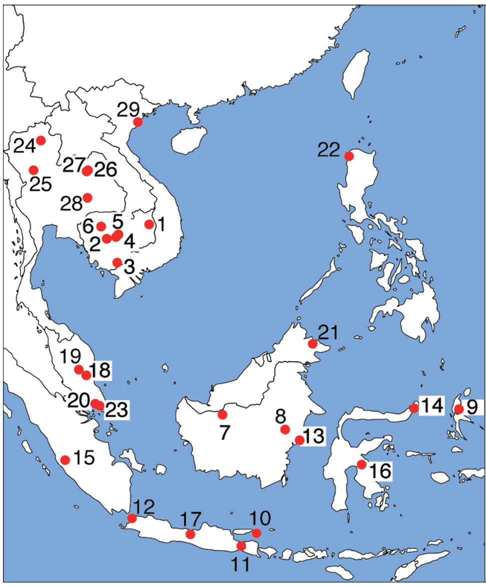

SITES IDENTIFIED - Published Literature

CAMBODIA
1 - Ratanakiri Province
2 - Tonle Sap
3 - Angkor Borei, Mekong Delta
4 - Stung Sen River
5 - Stung Sen River
6 - Angkor

INDONESIA
7 - Lake Pemerak
8 - Kutai Peatlands
9 - Halmahera
10 - Ranu Lamongan
11 - Lake Lading
12 - Rawa Danau
13 - Bau Bau Cave
14 - Lake Tondano
15 - Sikijang Swamp
16 - Lake Matano
17 - Lake near Dieng

MALAYSIA
18 - Tasik Chini
19 - Tasik Bera
20 - Pekan Nanaa
21 - Gomantong

PHILIPPINES
22 - Paoay Lake

SINGAPORE
23 - Nee Soon

THAILAND
24 - Phayao
25 - Nong Thale Song Hong
26 - Kumphawapi
27 - Pa Kho
28 - Mae Nam Mun Valley

VIETNAM
29 - Song Hong (Red River) Delta

Figure 1: During the workshop, we compiled a list of published paleolimnological research from across the south east Asia region. We are now in the process of synthesizing this data into a paper titled "Paleoenvironmental change from SE Asian lacustrine sites".

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TropPEAT Workshop on low-latitude peat-forming ecosystems

David W. Beilman[1], I. Lawson[2] and Z. Yu[3]

Honolulu, USA, 7-9 June 2017

Carbon in peat is one of Earth's single largest, organic, carbon pools. Recent improvements in estimates suggest that low-latitude, carbon-rich peatlands cover 387-657 thousand km^2, hold more than 100 gigatonnes of sequestered carbon (Page et al. 2011; Dargie et al. 2017) concentrated in regional hotspots, and have been the largest component of natural wetland methane emissions globally since the pre-Industrial period (Paudel et al. 2016). Significant strides in research have been made recently (Dargie et al. 2017; Dommain et al. 2014; Sjorgersten et al. 2014), but peatlands globally, and tropical peatlands specifically, remain poorly understood compared to other terrestrial ecosystems.

The C-PEAT working group (see: http://pastglobalchanges.org/ini/wg/peat-carbon), launched in 2014, identified several key subtopics related to global peat carbon including low-latitude peatlands. As part of C-PEAT's Phase 1, 20 experts and working group members came together in early June. Half of the participants were early-career or scientists from developing countries with expertise in understudied tropical regions. Our primary goals were to identify data and knowledge gaps in understanding low-latitude, peat-forming systems and to facilitate new collaborations and studies across geographies and career stages. From the many discussions at the meeting, two main research topics emerged.

Where and how old are low-latitude, peat-forming ecosystems?
A complete and accurate map of tropical peatland distribution remains elusive (Yu et al. 2010) owing to limitations in data, methodology and logistics. As a near-term goal, key regions were identified where high-quality data exists or can be derived for low-latitude wetland distributions. With regional expert input from workshop participants, these are being compiled in a format to serve as validation data for Earth system model simulations (Kleinen et al. 2012).

What are the controls on low-latitude peat carbon formation?
In contrast to cold, high-latitude soils with inherently limited microbial decomposition, tropical peatlands have different organic matter stabilization mechanisms with different vulnerabilities. Discussions of peat formation processes focused on the critical roles of topography (slopes, floodplains), hydroclimatic variability (orographic effects, fog inputs, monsoon climates), the rate and geography of human activities (logging, palm oil, traditional land use), and interactions with other disturbances (flooding, fire) over timescales longer than polar peat carbon (through the Last Glacial Maximum and MIS3). A special issue publication is being planned as a venue for the discussed ideas and research conducted by participants.

A meeting took place at the AGU Fall 2017 Annual Meeting in New Orleans. C-PEAT Phase 2, currently in the planning and proposal stage, would continue activities in low-latitude peatland science.

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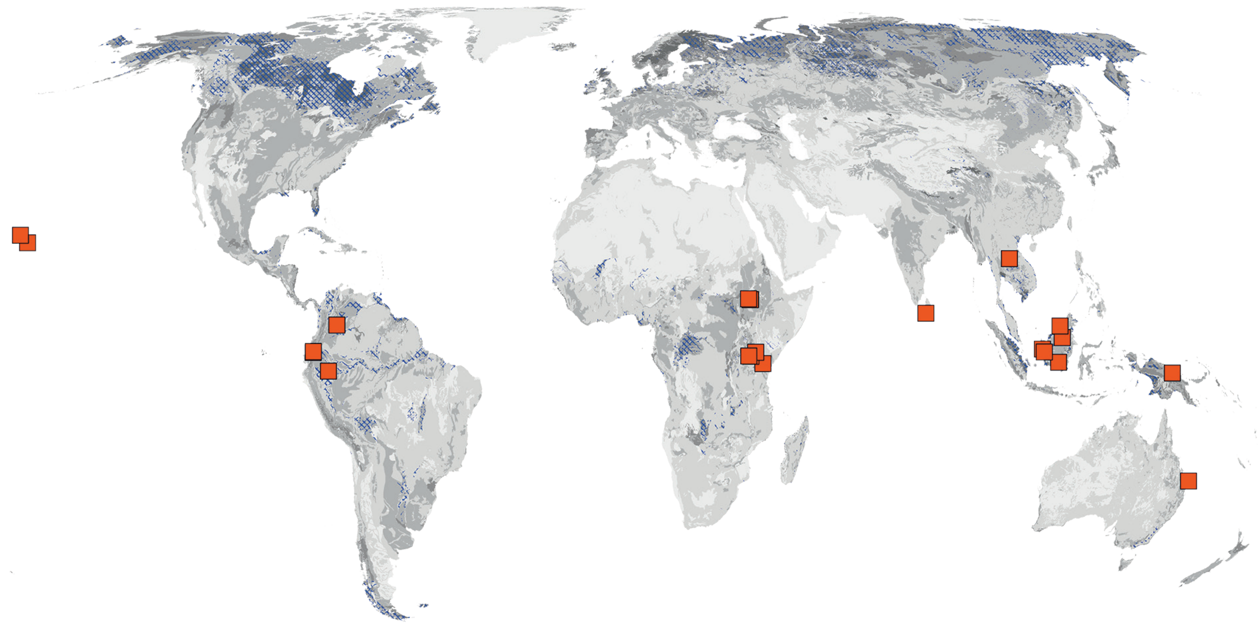

Figure 1: Location of study sites and regions with research results discussed at the TropPEAT workshop (red squares) along with peatland distributions in blue hatching (Yu et al. 2010) and global soil carbon density (<5, 6-10, 11-20, 21-40, >41 kg C m^{-2}; IGBP-DIS) in gray shades.

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PMIP4 contribution to CMIP6

Qiong Zhang[1], J.C. Hargreaves[2], P. Braconnot[3] and M. Kageyama[3]

1st PMIP4 conference, Stockholm, Sweden, 25-29 September 2017

The scientific focus of the Paleoclimate Modelling Intercomparison Project (PMIP) is to understand the response of the climate system to different forcings that have occurred at various periods prior to the historical instrumental record. Climate models are primarily constructed to understand modern climate and predict future climate evolution. These models are developed based on scientific understanding gained from studying the climate of the recent past. Past periods when the climate was radically different provide a useful test of model performance. The quantity of observational information on past climate, based on physical, chemical and biological records, is also increasing, providing more opportunities for quantitative evaluation of models.

PMIP is now in its fourth phase. Five of the PMIP4 experiments are included within the Coupled Model Intercomparison Project Phase 6 (CMIP6), and a number of the PMIP4 working groups are organizing additional experiments covering a broader range of topics (Fig. 1). The results from all of the experiments will provide a substantial contribution to the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6). New analyses will focus on climate sensitivity, changes in the hydrological cycle, physical and biogeochemical feedbacks, climate variability, and the credibility of the climate models which are used for future climate projections.

This first PMIP4 conference brought together 160 researchers from 24 countries. New, in-depth analyses from PMIP3 were presented as well as some first results from the new PMIP4 simulations. All participants gave a short oral presentation so that attendees gained an overview of all the ongoing activities, and to focus discussions at the subsequent poster sessions. A number of new initiatives in data synthesis are underway, and these were given slightly longer oral presentations. Eight speakers from outside the PMIP community gave stimulating, perspective talks. The last day of the conference was devoted to the connection of PMIP4 to CMIP6 and IPCC AR6. For the IPCC AR6, paleoclimate science will be included throughout the report rather than being an isolated chapter. Discussions considered how the key foci of PMIP4 could contribute to the different AR6 chapters where paleoclimate is relevant.

The conference provided opportunities for early-career scientists to develop networks within PMIP. Several of them led activities and discussions, and proposed to (1) have more synergy and interaction between PMIP and PAGES; (2) bring water isotope modeling into PMIP experiments, and make it a standard output; (3) use proxy system models (e.g. PRYSM) for all model-proxy comparisons using PMIP data; and (4) develop a standard approach to synthesize the model and proxy data in the PMIP community, to ensure scientists outside of each respective community can use the data in an appropriate way.

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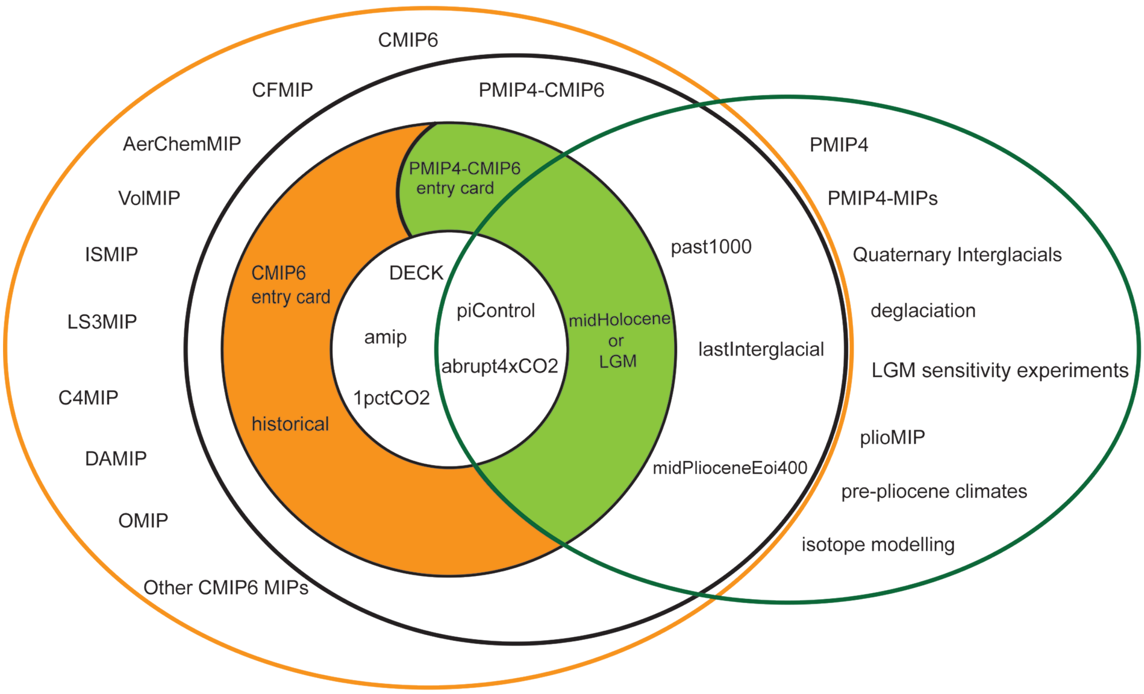

Figure 1: The PMIP4/CMIP6 experiments in the framework of CMIP6, link with other MIPs, and in the framework of PMIP4, with its working groups (Kageyama et al. 2016). The overview and overarching analyses plan for PMIP4 experiments are documented in Kageyama et al. (2016), the series of PMIP4 protocol documents on scientific objectives and experiment design include the two interglacials (Otto-Bliesner et al. 2017), the Last Millennium (Jungclaus et al. 2017), the Last Glacial Maximum (Kageyama et al. 2017), and mid-Pliocene (Haywood et al. 2016).

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The Pollen-Climate Methods Intercomparison Project (PC-MIP)

Basil Davis

Caux, Switzerland, 12-15 June 2017

Fossil pollen provide one of the most widely available sources of proxy climate data for the Quaternary period. Quantitative climate reconstructions from pollen data were first pioneered over 70 years ago (Iversen 1944) and since then the number of different methods has expanded greatly. The PC-MIP workshop was organized with a view to improving collaboration and coordination within the pollen-climate community, to compare and review the main methods currently in use, and to make recommendations for best practice and future development. The first PC-MIP cross-community workshop was attended by 28 researchers from 15 countries, including 14 early-career scientists.

The workshop comes at a time of new methodological innovations such as Bayesian statistics, and the rapidly increasing availability of fossil and modern pollen datasets through public pollen databases such as neotomadb.org. At the same time, we are also increasingly asking more from pollen data such as reconstructions from new regions and earlier time periods, seasonally resolved reconstructions, and always better assessment of uncertainties and potential errors.

The workshop

The first half of the workshop focused on general issues related to all or most methods. Background was provided by invited speakers on the history of pollen–climate transfer functions, common criticisms and problems, and alternative perspectives from non-pollen proxies in the marine and terrestrial domains.

This was then followed by breakout groups looking at a variety of issues, including questions related to which climate variables can be reconstructed, non-analogue vegetation and climate problems, modern calibration data, multi-model and multi-proxy approaches, spatial autocorrelation, pollen productivity and long-distance transport. The uniformitarianism assumption was also discussed in relation to novel climates (such as low CO_2 during glacial periods) and the changing influence of human activity, as well as other taphonomic, laboratory and sampling issues.

The second half of the workshop focused on issues specific to certain methods or families of methods. Background was provided by talks on Regression Methods (WA, WA-PLS), Assemblage Methods (MAT, ANN, Response Surfaces), Inverse Modeling, Indicator Methods (PDF, MCR) and Bayesian frameworks (see also Fig. 1). This was then followed by breakout groups to review the various strengths and weaknesses of each method, current and future developments and potential improvements, and the availability of training sets, software and other resources for each method.

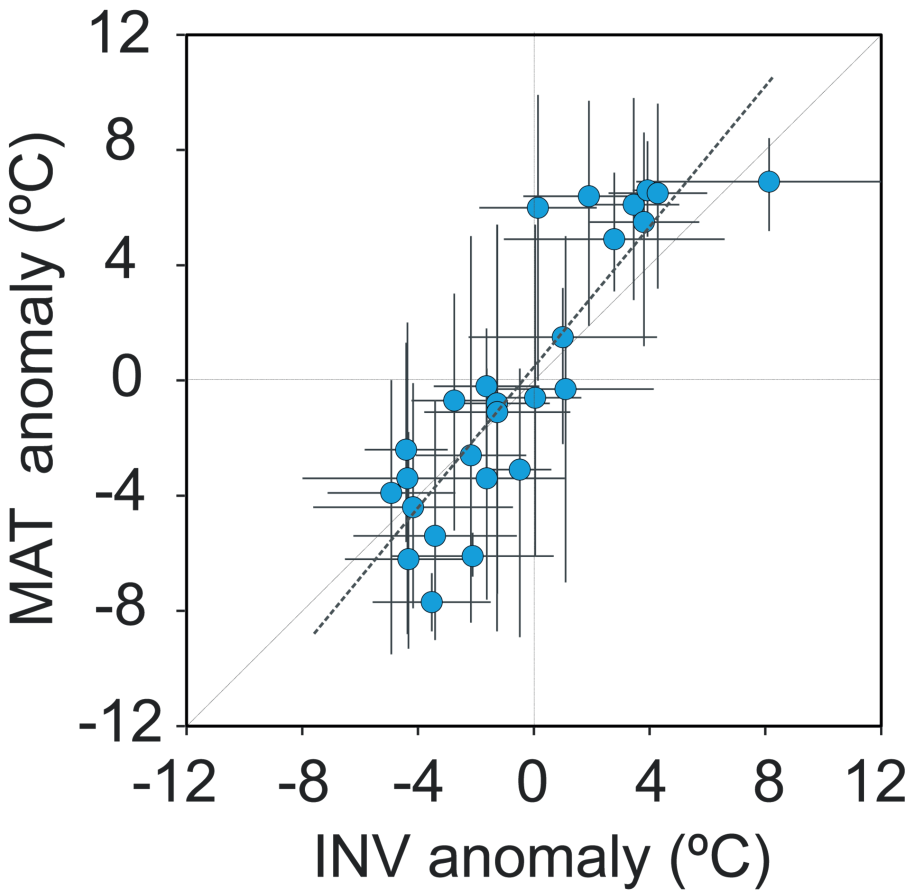

Figure 1: The use of the Modern Analogue Technique (MAT) in the Mediterranean region has been criticized because of potential bias caused by human impact and the possible dominance of precipitation over temperature as a control on vegetation. The Inverse Modeling (INV) method uses a process-based vegetation model to reconstruct the most likely climate to explain a fossil pollen assemblage, independent of the proposed sources of error with MAT. The figure shows a comparison of MAT and INV methods on the same mid-Holocene samples in the region (data from Davis et al. 2003 and Wu et al. 2007). The close agreement between the methods indicates little of the proposed bias in the MAT.

Final discussions included development of standardized fossil and modern pollen datasets that will allow a direct "bench-test" comparison between current methods, as well as providing reference datasets to evaluate future methodological improvements. Datasets have already begun to be selected from different time periods and locations, with a particular emphasis on datasets that can be compared with other proxies.

Future plans

The results of the workshop are currently being condensed into a co-authored manuscript that will be submitted in early 2018. A dedicated PC-MIP website will be online soon to provide a guide to current resources for anyone interested in pollen-climate reconstructions. Further smaller, follow-up workshops are planned to complete the standardized test datasets and bench-test evaluation of current methods.

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Climate dynamics with the Last Millennium Reanalysis

Julien Emile-Geay[1], M.P. Erb[2], G.J. Hakim[3], E.J. Steig[3,4] and D.C. Noone[5]

Boulder, USA, 2-4 October 2017

Paleoclimate data assimilation has emerged as a powerful approach to understand low-frequency climate variations. Paleo data assimilation blends paleoclimate observations with the dynamical constraints of climate models. The third workshop of the Last Millennium Reanalysis project (LMR; a partner project of PAGES 2k) gathered 40 scientists over three days to share the latest advances in data, methods and investigations of climate dynamics made possible by this framework. The workshop, hosted at the National Center for Atmospheric Research in Boulder, was sponsored by the US National Oceanographic and Atmospheric Administration, with support from PAGES.

Steady progress

Recent years have witnessed an explosion of paleo data assimilation approaches[1]. The workshop represented a milestone in moving beyond the inaugural LMR release (Hakim et al. 2016). The latest LMR product has benefitted from the greatly expanded coverage of the PAGES2k Consortium (2017) database, as well as proxy system models that take into account multivariate and seasonal dependencies, particularly for tree rings. Additional gains are enabled by efficient predictive models (Perkins and Hakim 2017). A concerted push by the observational community to develop more widely available water isotope datasets (e.g. Iso2k[2]) offers fresh opportunities to leverage this new technical capability. Paleo data assimilation is agnostic to interpretation, enabling researchers to take advantage of a wider array of paleoclimate observations. The PAGES community is encouraged to continue high-quality syntheses with extensive and standardized metadata annotations, without restricting them to single-variable interpretations (such as whether they are correlated with temperature).

Workshop presentations showed that LMR both reproduces well-established results for the last millennium, such as the hemisphere-average pattern of temperature change, or the thermal response to explosive volcanism (Fig. 1), and provides the opportunity to address new questions. For example, LMR makes it possible to validate dynamical hypotheses for the causes of megadroughts (e.g. Coats et al. 2016), taking advantage of the simultaneous reconstruction of sea-surface temperature, drought indices and geopotential height fields. LMR also provides richer constraints on the climate impacts of volcanic eruptions, assessments of historical drought risk, the dynamics of the Atlantic Multidecadal Oscillation, long-term changes in the Hadley and Walker circulations, and the impact of multidecadal tropical ocean temperature fluctuations on tropical cyclone activity.

A path forward

Discussions at the workshop highlighted several key challenges; addressing them outlines a clear path for further progress. First, while paleo data assimilation enables the reconstruction of nearly any field output by a General Circulation Model, not all can be equally well-constrained or validated. A critical limitation for validation is the lack of homogenous, long-term datasets of the full three-dimensional state of the atmosphere and ocean. Second, there is a need to integrate low-resolution proxy records into paleo data assimilation efforts like LMR, which currently relies almost exclusively on annually resolved records. Blending proxies of monthly to centennial resolution is a new research frontier; the theoretical framework exists (Steiger and Hakim 2016), but urgently needs to be operationalized. Initial reconstructions of the last deglaciation using only marine sediments unveiled promising advances in this regard. Third, proxy system models are key to maximizing the usefulness of paleoclimate observations, but their use still hinges on the availability of high-quality modern observations. Finally, because paleo data assimilation calculations inherit biases from the numerical models they use, purely statistical approaches remain an important complement to the use of dynamical climate models within the assimilation framework.

Building capacity

Beyond the delivery of a multivariate climate field reconstruction, a goal of the LMR project is the release of the underlying assimilation tools. The last day of the workshop featured a "hackathon" designed to enable investigators to run the LMR code (which is open source) and exploit its rich output for their own research. The event helped demystify the "black box" aspects of paleo data assimilation. This exemplified the open-science research model embodied by LMR, and is expected to lead to more stringent validation by a much wider community, as well as unlocking the potential for research applications beyond those considered by the LMR team so far.

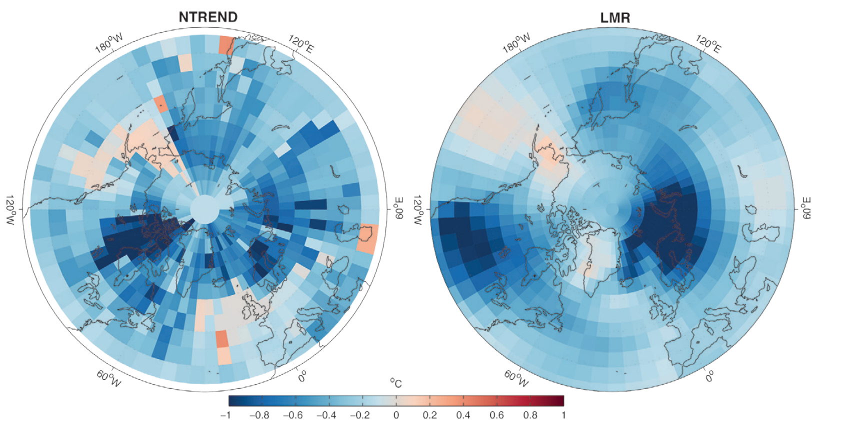

Figure 1: Temperature response to explosive volcanism in two independent temperature field reconstructions, N-TREND (left) and LMR (right). N-TREND (Anchukaitis et al. 2017) reconstructs boreal summer (May-August) mean temperatures using a Point-by-Point regression approach on a temperature sensitive network of 54 tree-ring chronologies across the Northern Hemisphere. Plots show the mean post-eruption temperature anomaly, normalized by the average of the three-year prior to the eruption at each grid point. The 20 eruptions considered here are those equal to or larger than Krakatoa (1883 CE) in the magnitude of maximum global radiative forcing since 750 CE.

LINKS

[1]pastglobalchanges.org/ini/wg/daps/intro

[2]pastglobalchanges.org/ini/wg/2k-network/projects/iso2k

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Paleo-event data standards for dendrochronology

Elaine Kennedy Sutherland[1], P. Brewer[2] and W. Gross[3]

Woodland Park, USA, 10-14 September 2017

Extreme environmental events, such as storm winds, landslides, insect infestations, and wildfire, cause loss of life, resources, and human infrastructure. Disaster risk-reduction analysis can be improved with information about past frequency, intensity, and spatial patterns of extreme events. Tree-ring analyses can provide such information: tree rings reflect events as anatomical anomalies or changed growth patterns at an annual- or even sub-annual resolution (Fig. 1). These centuries-long times series of paleo-events are far longer than historical records.

Dendrochronologists embraced information technology in the 1970s and, over time, developed specialized software using data in formatted, plain-text files. Analytical approaches developed in the 80s and 90s for fire-history analysis (Grissino-Mayer 2001) continue to be used and provide a context to analyze other paleo-events; for example, insect infestations (Speer et al. 2010). The early data structures developed for use in these specialty tools became entrenched and continue to be used today, with some awkwardness and significant limitations. They are inadequate to manage event-related tree-ring data that integrate the disciplines of paleoclimatology, ecology, hydrology, and geomorphology.

With PAGES' support, 15 dendrochronologists[1] from five nations attended a workshop addressing PAGES' Data Stewardship Integrative Activity[2]. The goal was to highlight the commonalities and differences among event indicators and to develop a general data model for dendrochronological-event data. After discussing the commonalities and differences among indicators, we agreed to utilize and expand the Tree Ring Data Standard, TRiDaS (Jansma et al. 2010) as a data and metadata structure to promote best practices of data stewardship. We concurred that a common data management framework would facilitate analysis without dictating software usage.

We summarized event indicators observable in wood anatomy, chemistry, and size variation, and the metadata necessary to describe them. We developed a preliminary list of event types, indicators, and new metadata for TRiDaS, agreeing to adopt existing, vetted metadata definitions (in particular the Forest Inventory and Analysis - FIA[3]) rather than developing new ones. We acknowledged that interoperability with NOAA Paleo, the LiPD format, and LinkedEarth data model (McKay and Emile-Geay 2016) is essential. We agreed to contribute to and to expand the LinkedEarth ontology through the "Trees Working Group" and the NOAA WDS-Paleo ontology, to describe paleo-events, provide a catalogue of current practices, and a list of needed analytical and graphical capabilities. Following these agreements we were easily able to develop a list of products, activities, and outreach efforts that can promote the adoption of these data standards.

In closing, participants agreed that there is sufficient need to merit further development of these concepts with a larger and broader international group. We will seek funding to engage the community in collective crowdsourcing and for the scientific effort needed to create the data framework. In adopting common data standards, this effort can serve the needs of land management and disaster risk-reduction analysis to great societal benefit.

LINKS

[1]http://fhaes.org
[2]pastglobalchanges.org/ini/int-act/data-stewardship
[3]www.fia.fs.fed.us

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Figure 1: A *Larix occidentalis* tree, from western Montana, USA, injured by a 2003 wildfire. Indicators of injury include killed cambium, presence of traumatic resin ducts, resin flooding around the injury, and woundwood rib and scar formation (Smith et al. 2016). Photo courtesy of K.T. Smith; sample prepared and photo taken by K.R. Dudzik, both of USDA Forest Service Northern Research Station, Durham, USA.

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Climate Change: The Karst Record (KR8) conference

Kathleen R. Johnson[1] and Jay Banner[2]

Austin, USA, 21-24 May 2017

In recent decades, speleothems have become increasingly used as paleoclimate archives due to their suitability for precise U-series dating, their fast and continuous growth, their broad geographic distribution, and the fact that they contain multiple proxies which are sensitive to environmental change. The rapid development of speleothem science (Fig. 1) has led, in particular, to major advances in our understanding of past hydroclimate variability. For instance, speleothems have provided detailed records of monsoon variability in Asia and South America, and have improved characterization of global teleconnections in response to orbital- and millennial-scale climate change (e.g. Cheng et al. 2009; Cruz et al. 2005; Wang et al. 2001). However, speleothem geochemical and physical properties reflect a complex, integrated signal of processes in the atmosphere, soil, epikarst, and caves (Fairchild et al. 2006). Robust interpretation of speleothem data, therefore, requires monitoring studies in active cave systems, often in combination with theory and modeling of speleothem processes.

The latest in speleothem-based paleoclimate records, cave monitoring, proxy-development, and modeling studies were presented at the 8th International "Climate Change: The Karst Record (KR8)" conference, which took place at the Jackson School of Geosciences, University of Texas at Austin. The conference, which has been the premier gathering of speleothem scientists since the initial meeting (KR1) in Bergen, Norway, in 1996, brought together 115 scientists from 18 countries for three days of oral and poster presentations (abstracts available at http://sites.uci.edu/kr8conference/scientific-sessions), workshops and field trips. PAGES funding provided travel support for eight early-career scientists, including three from developing countries. The conference was organized around six themes: (1) Cave monitoring and climate proxy development, (2) High-resolution speleothem records, (3) Speleothem records of orbital to millennial scale climate variability, (4) Novel techniques, proxies, and unconventional archives, (5) Modeling in speleothem science, and (6) Speleothem proxy records in an Earth system context. Meeting attendees could choose to attend mid-conference workshops on: (1) Connecting climate models and paleo records, (2) Speleothem petrography, (3) Forward modeling of speleothem isotopes, and (4) Speleothem age modeling. Participants could also select from a variety of field trips to several central Texas cave locations studied by researchers from UT Austin (Banner et al. 2007; Feng et al. 2014; Meyer et al. 2014).

A pre-conference workshop, led by Amy Frappier (Skidmore College), on "Best Practices in Speleothem Science" was attended by 30 scientists. Discussion topics included trends and maturation of speleothem science, strategies for enhancing diversity within the field, and increasing public awareness of speleothem science. Significant discussion focused on strategies for minimizing impacts on cave environments and fostering strong and reciprocal relationships with cave managers and other stakeholders. One sentiment widely shared by attendees is the need for a coordinated effort to create a cave-sample database and archive. Obtaining funding and buy-in from the speleothem community will be necessary to achieve this goal. Finally, there was some discussion of data archiving and speleothem metadata, including participation in community initiatives such as SISAL (http://pastglobalchanges.org/ini/wg/sisal) and LinkedEarth (http://linked.earth). The key outcomes and recommendations stemming from this workshop will be the focus of a forthcoming white paper.

The KR8 conference continued the tradition of previous meetings in providing a forum for the presentation of cutting-edge speleothem-based paleoclimate research, including presentations of new records, detailed cave-monitoring studies, application of new methods and technologies to speleothem science, and strategies for improving interpretation of speleothem records through modeling studies. Furthermore, the meeting provided an excellent opportunity for networking and professional development of young researchers in the highly supportive and collaborative speleothem community. We look forward to the ninth "Climate Change: The Karst Record" meeting (KR9) which will be held at the University of Innsbruck, Austria, in 2020.

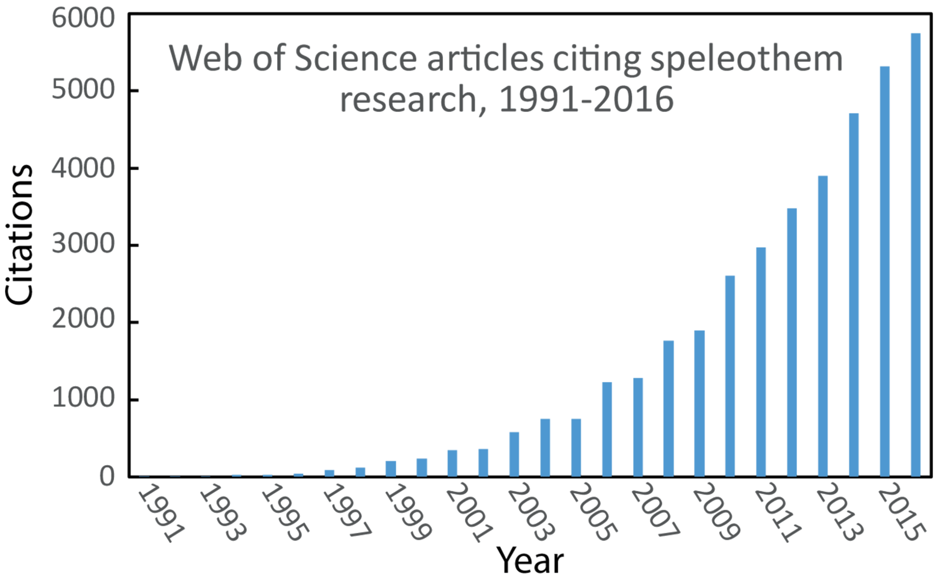

Figure 1: *Web of Science* search results showing the exponential increase in citations per year for articles that include the topics "speleothem" or "stalagmite" and "paleoclimate". This search returns a total of 1,483 articles that have been cited over 41,000 times.

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The Role of Environment in the Socio-Cultural Changes of the Ancient Silk Road Area

Liang Emlyn Yang[1], J. Wiesehöfer[2], H.-R. Bork[3] and M. Hoo[1,2]

Kiel, Germany, 28-29 September 2017

The Silk Road is a modern concept for an ancient network of trade routes that for centuries facilitated and intensified processes of cultural interaction and goods exchange between West China, Central Asia, the Middle East, and the Mediterranean (Elisseeff 2001). The Silk Road flourished when the Han dynasty explored Central Asia around 139 BCE and thrived throughout the Middle Ages and eventually declined under the Islamic and Mongol Empires. There is increasing discussion that climatic and environmental factors may have played a role in fostering economic and socio-cultural changes along the Silk Road and in a broader area (Zhang et al. 2011). Coherent patterns and synchronous events in history suggest possible links between social upheaval, resource utilization, and climate or environment forces (Clarke et al. 2016; Mischke et al. 2017). Such links between climatic, environmental, economic, social, and cultural changes would have manifested themselves differently according to place and time; however, it often remains unclear if and how exactly they affected socio-cultural situations on the ground.

The international workshop "The Rise and Fall: Environmental Factors in the Socio-Cultural Changes of the Ancient Silk Road Area" was held at Kiel University. The Silk Road served as the geographical scope and inspirational concept for the workshop. Nineteen researchers from 12 countries presented topics on the expansion of Ancient China to the west; Central Asia as the key node area of the Silk Road; historical water and agriculture systems; climate and environment disasters in the past; climate links to social evolution; and changes of lake and sea regions from ancient to recent periods. The presentations investigated both perspectives of socio-environmental interactions; it became clear, for instance, that climate change provided better hydrological resources for the golden era of Silk Road trade, and that water withdrawn for human activities resulted in dramatic landscape changes including the near and complete desiccation of large lakes in the arid western part of today's China (Fig. 1). These topics were approached from various disciplinary angles and perspectives, ranging from archaeology, climate change, antiquity, historical geography, agriculture, carving art and literacy. Contributions focused on the middle to late Holocene and covered specific areas along the ancient Silk Road regions.

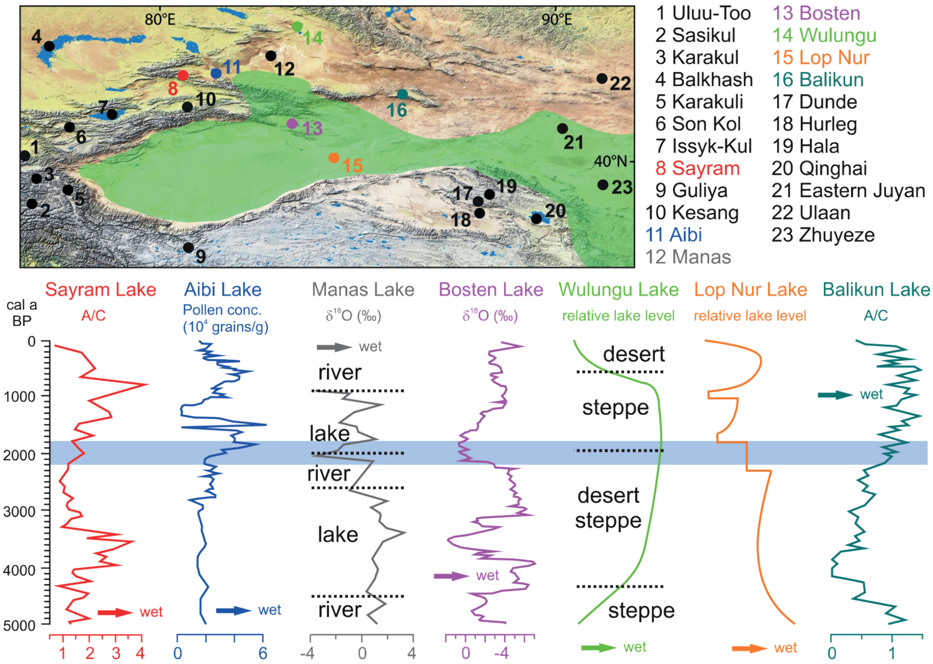

Figure 1: Proxy- and literature-based climate records suggesting massive human-induced landscape changes. The selected curves below the map illustrate wet conditions in specific regions. The green area on the map represents the extent of the Han Dynasty in today's Western China and the blue bar in the graphs refer to its period of occurrence (206 BCE – 220 CE). The Han dynasty is considered as the "golden age" of Chinese history and helped establish the Silk Road. A/C refers to the Artemisia to Chenopodiaceae pollen ratio which is used to differentiate between desert and steppe vegetation. Provided by Steffen Mischke and edited by Liang E. Yang.

The workshop also held a lunch seminar, which discussed joint publication and potential research cooperation. A proceeding book volume, with a proposed title "Socio-Environmental Dynamics along the Historical Silk Road", will be published by Springer. Eighteen full papers from participants have been received for peer review. To share information and to provide an opportunity to those interested in the topic but unable to attend the workshop, additional papers are invited from research groups and experts in the field.

The workshop increased our understanding of the role played by the environment in socio-cultural changes that occurred in the territories along the ancient Silk Roads, and initiated a network of both young and senior researchers to facilitate international connectivity and multidisciplinary cooperation. Moreover, participants expressed great interest in organizing a follow-up meeting and proposed ideas for cooperation in the near future, for instance, nomadic responses to water conditions at the front regions of the Tianshan Mountain.

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