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PAGES news

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El Niño-Southern Oscillation

Editors:

Pascale Braconnot, Chris Brierley, Sandy P. Harrison, Lucien von Gunten and Thorsten Kiefer

Beyond just beautiful - Tridacna *spp. are faithfully recording paleoENSO variability. These giant, long-lived bivalves are reef dwelling organisms characteristic of the Indo-Pacific region. The presence of symbionts provides the multitude of colors commonly observed in* Tridacna *spp.*

p. 72-79

Mini section on data assimilation

Inside PAGES

Celebrating 20 years

In this issue we celebrate 20 years of PAGES news. You can read our paleobibliographic analysis on the next page, and take a trip back in time and enjoy the first ever copy of PAGES news from 1993. A reprint is included in this issue as an insert (it was much smaller then).

Communications update

PAGES has now joined the Twitter-sphere. Follow us to get all the latest news: @PAGES_IPO. You can also subscribe to our new YouTube channel: Past Global Changes, and of course, we've still got the Facebook fan page: PAGES Past Global Changes.

Staff update

Welcome to our two new staff members: Nicole Wegmüller (Finance and Office Manager) and Leonie Goodwin (Communications and Project Officer).

PAGES OSM and YSM

The Open Science and Young Scientists Meetings continue to resonate. We recently uploaded videos of seven plenary talks with the accompanying PowerPoint slides and some short video montages to our YouTube channel: Past Global Changes. You can also read reports on the YSM activities written by the participants, starting on page 89.

PAGES umbrella programs

The transformation of the landscape of Global Environmental Change programs is taking shape. The new Future Earth program has now established a Scientific Committee and an Interim Secretariat with an Interim Director. You can check the names of the personnel on the Future Earth website (www.icsu.org/future-earth) and keep informed via their media, including a newsletter and a blog. Our current umbrella program IGBP has decided to sunset by the end of 2015. The PAGES SSC has decided that over the next two years PAGES should join the Future Earth network, while at the same time continuing to collaborate with other organizations.

IGBP Scientific Committee in Bern

In April, PAGES, together with ProClim and the Oeschger Centre, hosted the IGBP Scientific Committee Meeting in Bern. IGBP SC members came together from around the globe to discuss potential synthesis projects, IGBP's legacy and how best to transition into the new integrated Future Earth super-program in the coming years.

Support for meetings

During its meeting in June, the PAGES SSC granted support for a total of ten scientific and educational meetings. The next deadline for applying for PAGES meeting support is 20 September 2013. Support can be sought for workshop-style meetings relevant to PAGES Foci and Cross-Cutting Themes. The three eligible categories are PAGES Working Group meetings, workshops with a training or education focus, and an open call for other workshops that are relevant to PAGES science. Application guidelines and forms can be found on the PAGES website > My PAGES > Meeting Support.

Guest scientists

We are pleased to welcome two guest scientists to the PAGES office this summer: Gisela Winckler from the Lamont-Doherty Earth Observatory, US and Bernd Zolitschka from the University of Bremen, Germany. Among other things, they are working alongside PAGES staff to edit upcoming editions of PAGES news. You can learn more about our Guest Scientists and the work they are doing on the PAGES website > People > Guest Scientists.

Introducing the new mini section

We hope you enjoy our first Science Highlights mini section; in this issue it focuses on Data Assimilation. The new mini section format will feature 4-5 articles focusing on a specific topic, and might appear more regularly in future issues depending on demand.

Upcoming newsletters

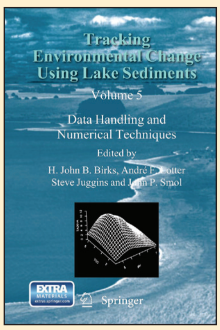
The next two issues of PAGES news will focus on dust and on annual recorders of the past. While the dust issue is already closed, suitable articles for the annual recorders issue are still welcome. Contributions should explore the question of how natural archives with annual resolution are approaching the temporal resolution of instrumental records. Submissions should be discussed with Bernd Zolitschka (zoli@uni-bremen.de) and be submitted before the 15th of September. As always, you are invited to submit Science Highlights, Program News, and Workshop Reports for the Open Section of PAGES news. Author guidelines can be found on the PAGES website > My PAGES > Newsletter.

New on the PAGES Bookshelf

Tracking Environmental Change Using Lake Sediments, Volume 5
Data Handling and Numerical Techniques

Editors: H. John B. Birks, André F. Lotter, Steve Juggins, John P. Smol

Springer, 2012



Another volume in the "Development in Paleoenvironmental Research Series", this book is the first of its type to cover the full range of modern data-analytical and statistical techniques used in paleolimnology and paleoecology. It features numerical and statistical techniques, such as exploratory data analysis, error estimation, clustering, ordination and modern statistical learning techniques. It also includes case studies on human impact, lake development and climate change.

20 years of PAGES news

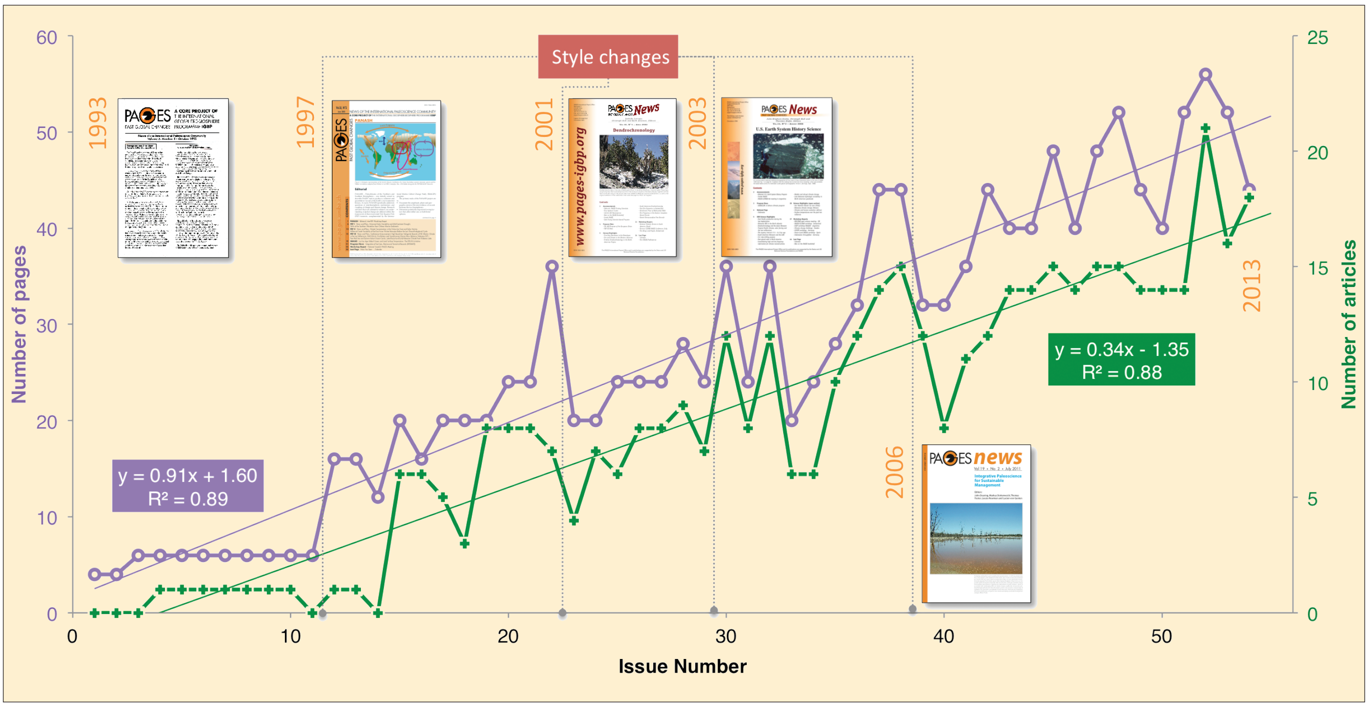


Figure 1: Paleobibliographic analysis of PAGES news.

The four-page insert included in this issue is a copy of the first ever PAGES news created 20 years ago in Spring 1993. We thought this milestone provided an opportunity to reflect on how far PAGES news has come in that time, but also how many of the issues discussed in our first newsletter still remain pertinent today.

A quantitative paleobibliographic analysis reveals the steady growth of PAGES news in the last 20 years. We found evidence of five distinct stylistic eras and observed that the number of pages in each issue has increased 12-fold from four in 1993 to around 50 in current issues (Fig. 1). Likewise there is a strong correlation between the number of pages and the number of science highlights articles (r^2= 0.92; $P<0.01$), with early issues usually containing one article and more recent issues 15±2. If this trend continues over the next 20 years, PAGES news will be a daunting 100 pages thick and feature 35 articles by the year 2033!

Hans Oeschger, the first chair of PAGES, observed in his introduction to the first issue that global change research is advancing at a remarkable pace, and many of the issues he highlighted back in 1993 are still relevant today. An improved understanding of past global change is crucial for evaluating present environmental conditions and for creating predictive climatic models. Paleoclimatic and paleoenvironmental data have the unique ability to provide detailed insights into ecosystem responses to climate change at different time scales, which can inform future policymaking.

We hope you enjoy a little trip back in time via our first issue. And for anyone thinking about replying to the Call for Title Suggestions advertisement on the last page: Although we have happily stuck to the "unimaginative title" PAGES news for 20 years, we are, of course, still open to your suggestions for improvement.

PAGES Calendar

Paleofire data synthesis using R
02 - 06 Oct 2013 - Besançon, France

Holocene Circum-Arctic Peatland Carbon Dynamics
12 - 16 Oct 2013 - Bethlehem, USA

PALSEA 2013 Workshop
21 - 24 Oct 2013 - Rome, Italy

Joint PAGES 2k & PAST2k-PMIP Workshop
04 - 06 Nov 2013 - Madrid, Spain

Ramsar Wetlands: Ecological Character
06 - 08 Nov 2013 - Queenscliff, Australia

PMIP Ocean Workshop 2013
04 - 06 Dec 2013 - Corvallis, USA

Age Models, Chronologies, and Databases
13 - 16 Jan 2014 - Belfast, Northern Ireland

PAGES Focus 4 workshop
03 - 07 Feb 2014 - Leuven, Belgium

www.pages-igbp.org/calendar/upcoming

Editorial: El Niño-Southern Oscillation - observations and modeling

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The El Niño-Southern Oscillation (ENSO) is one of the major climate phenomena affecting our global environment (Figs. 1 and 2), but current understanding of ENSO is limited. Instrumental records are too short to allow us to document its spectrum of variability and there is little knowledge of how variability alters with changes in the climate mean state, for example with anticipated global warming.

In the PAGES news issue "Paired perspectives on global climate change" (2012), Amy Clement highlighted some important issues about the decadal variability, predictability and modeling of ENSO with global warming. As pointed out by Julien Emile-Geay in the same issue, paleoclimate data are a valuable resource to improve our understanding of these issues, even though the past does not provide direct analogs for the future. Analyses of high-resolution paleoclimate indicators and the possibility of long simulations with the same climate models used for future climate projections offer new opportunities for improving our understanding of ENSO. One of the foci of the working group on climate variability in the 3rd phase of the Paleoclimate Modeling Intercomparison Project (PMIP3; Braconnot et al. 2012a) is to foster the synthesis of high-resolution data and the development of new data-model comparison methodologies to examine changes in ENSO.

The future of ENSO research

The suite of papers presented in this newsletter is one outcome of the PMIP workshop on "Tropical climate variability with a focus on last millennium, mid-Holocene and Last Glacial Maximum" which took place in the south of France in September 2011 and was co-sponsored by PAGES (Braconnot et al. 2012b). The articles provide an overview of high-resolution records and modeling studies that can be regarded as a basis for future ENSO research. Individual contributions address how one can extract ENSO-relevant climate information from tree rings, corals, giant bivalves, or shells, and how modeling can be used to test explicit hypotheses to improve the interpretation of paleoclimate records as well as to infer the mechanisms of climate change. The articles also illustrate some fundamental questions that need to be addressed in preparing multi-proxy reconstructions of past ENSO behavior and in analyzing paleoclimate modeling results. We consider these studies to be the first step towards a comprehensive evaluation of whether climate models incorporate the right physics and feedbacks to reproduce the diversity of ENSO events.

Pulling the pieces together

An exciting development, showcased in this special issue, is that many different types of records exist that

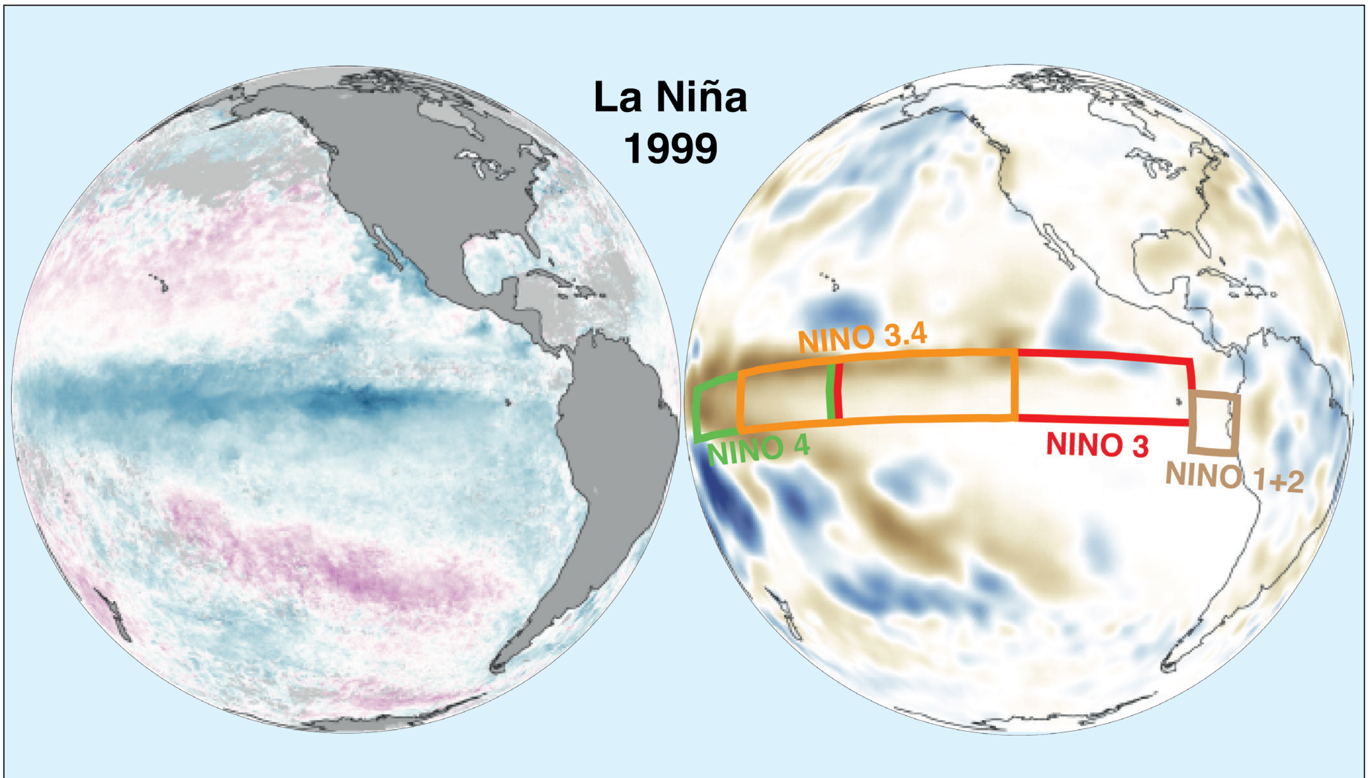

Figure 1: La Niña event of 1999. Left: Positive (purple) and negative (blue) sea surface temperature anomalies. Right: Positive (blue) and negative (brown) rainfall anomalies (mm). The four El Niño regions referred to in the following articles are depicted in the right panel. Images from NASA.

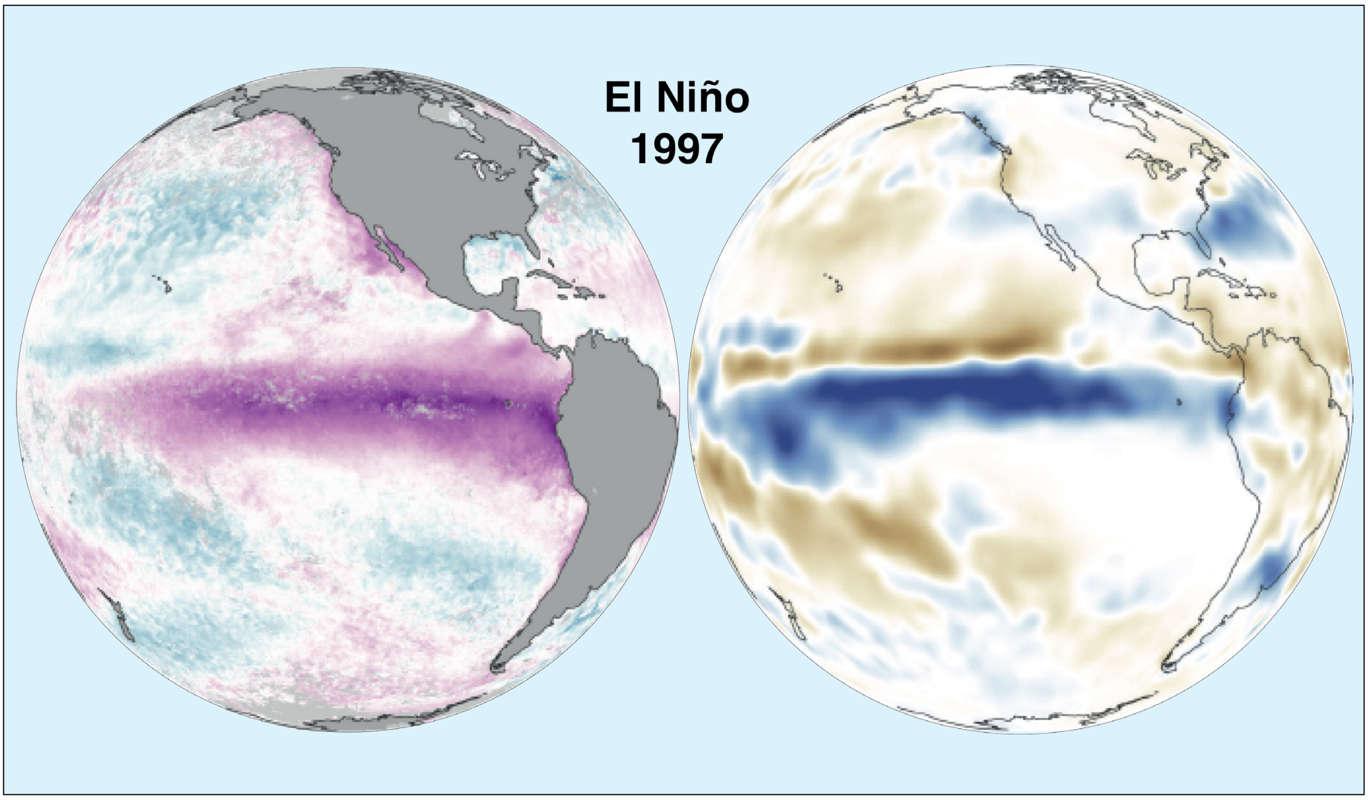

Figure 2: El Niño event of 1997. Left: sea surface temperature anomalies. Blue: negative, purple: positive. Right: Rainfall anomalies (mm). Brown: negative, blue: positive. Images from NASA.

document short term climate variability (see Elliot et al. p. 54 and Carré et al. p. 56) and that pooling information from multiple types of records provides a pan-tropical picture of ENSO. The contributions here and in other recent papers (e.g. Cobb et al. 2013), demonstrate that the process-level understanding of individual records has improved over recent years (see Elliot et al. p. 54 or McGregor et al. p. 52). This includes the recognition that it is rare for paleoclimate records to reflect a single climate variable (e.g. temperature or salinity) or aspect of climate variability (e.g. seasonal phasing or magnitude changes in mean frequency or in extremes). The challenge now is to find ways to synthesize the disparate aspects of the records and to take advantage of the wider range of information available to provide an overview of ENSO variability (see Russon et al. p. 62 or Thompson et al. p. 60).

Modeling improvements

A second important development is the improvement in modeling capacity and analytical approaches. Coupling between different components of the climate system is notoriously difficult and this poses problems for simulating aspects of the climate system, such as ENSO, that are primarily driven by the coupling between the ocean and atmosphere (see Capotondi et al. p. 58 or Lazareth et al. p. 66). Nevertheless, with improved model physics, increased spatial resolution, more routine incorporation of tracers (e.g. isotopes) and biogeochemistry, and the ability to run much longer simulations, state-of-the-art models are increasingly yielding important insights into ENSO. Model simulations show that ENSO displays non-stationary behavior in space and time, including the strength of ENSO teleconnections (Capotondi et al. p. 58, Merkel et al. p. 68). The simulations imply that the ENSO phenomenon has to be decoupled into different components, such as mean state, hydrology and teleconnections that change independently depending on the forcing (see Braconnot et al. p. 64). The lessons learned from models and their integration with observations pose ambitious challenges to the interpretation of the ENSO-relevant signal in paleoclimate records (Russon et al p. 62, Brierley p. 70, Lazareth et al. p. 66).

Towards data and model integration

It is a pivotal time for the ENSO community. We see a real need for new activities. First and foremost, there needs to be a more integrated approach to combining data and modeling for hypothesis testing. To facilitate this, the community needs to synthesize more primary data across regions and realms. This will allow us to capitalize on the improvements in process understanding that are emerging from both data analyses and modeling experiments. The other requirement is developing statistical and analytical tools that combine the two sources of information (data and model outputs) to disentangle the evolution of mean state, seasonality, and interannual to decadal variability. To develop these approaches and tools, we see a need for a dedicated activity within the PAGES and PMIP communities that brings together the full range of expertise. This is the only way to answer the fundamental questions about the relationships between the background climate state, the seasonal cycle and ENSO variability.

Selected references

Full reference list online under:
http://www.pages-igbp.org/products/newsletters/ref2013_2.pdf

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Myanmar monsoon drought variability inferred by tree rings over the past 300 years: linkages to ENSO

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A new tree-ring record of teak from Myanmar yields information about past tropical monsoon rainfall variability, including sustained drought conditions, and climatic effects of the El Niño-Southern Oscillation (ENSO), dating back nearly four centuries.

Extreme climatic conditions linked to the Asian monsoon and modulated by the ENSO system, such as droughts and floods, severely impact human populations. In 2008, Cyclone Nargis caused >138,000 fatalities and more than an estimated 10 billion US$ in economic damage. However, our knowledge of monsoon climate and ENSO-related impacts remains limited, not the least due to sparse paleoclimatic information. Such information is especially scarce for Myanmar, which is directly impacted by the effects of the monsoon but where even instrumental climate records and related studies of monsoon climate dynamics are rare. Much of the country experiences pronounced wet and dry seasons linked to the seasonality of the monsoon. Myanmar rainfall correlates significantly with indices of ENSO and Indian monsoon rainfall (e.g. All India Summer Monsoon Rainfall and Core Indian Rainfall), although these relationships are spatially and seasonally variable and not very well understood. Myanmar's location in the transition zone between the South Asian and East Asian monsoon systems results in a particularly complex spatial pattern of precipitation variability.

Asian Monsoon dendroclimatology

Gleaning additional information on the long-term climate variability of Myanmar and greater monsoon Asia relies on records from natural or historical paleoclimatic archives. Tree rings are often ideal as they can yield precisely dated, annual time series, also referred to as "chronologies", dating back centuries to millennia. Studying tropical tree rings poses considerable difficulties because of the lack of pronounced seasons at low latitudes where monsoonal rainfall occurs, and the associated obstacles in identifying tree species that can be dated for dendrochronology. Nevertheless, much progress in chronology development has been made in recent years that now allows us to reconstruct past climate in tropical Asia from tree rings (e.g. Cook et al. 2010, Monsoon Asia Drought Atlas MADA; Buckley et al. 2007, 2010; Ummenhofer et al. 2013).

The MADA tree-ring dataset was analyzed for past changes in the Palmer Drought Severity Index (PDSI) and thus provided evidence for major droughts and wet events in Southeast Asia (e.g. Indonesia, Thailand, and Vietnam). However, in the case of Myanmar, tree-ring data coverage is still exceedingly sparse and represents a sizeable gap in paleoclimate information of monsoon Asia. Here we present a new record for Myanmar that can be incorporated into the MADA network.

Myanmar teak

Teak (*Tectona grandis*) is one of the tree species that has been used most successfully

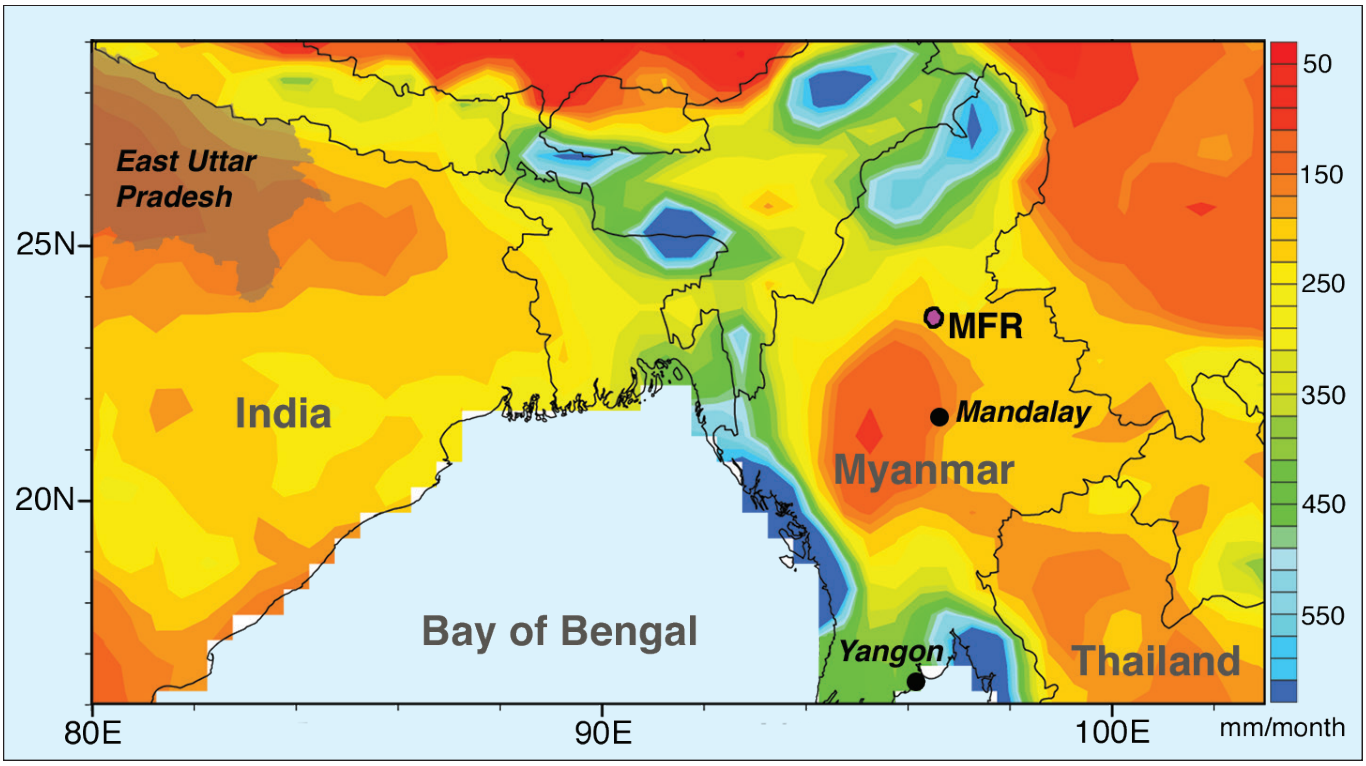

Figure 1: Map of Myanmar and adjacent southern monsoon Asia. Pink dot is Maingtha Forest Reserve (MFR) teak tree-ring site north of Mandalay. Background shows monthly Global Precipitation Climatology Centre rainfall data for the period 1951-2007, averaged for May–October when the majority of Myanmar annual rainfall occurs. The figure shows the lower mean rainfall in central Myanmar (modified from D'Arrigo et al. 2011).

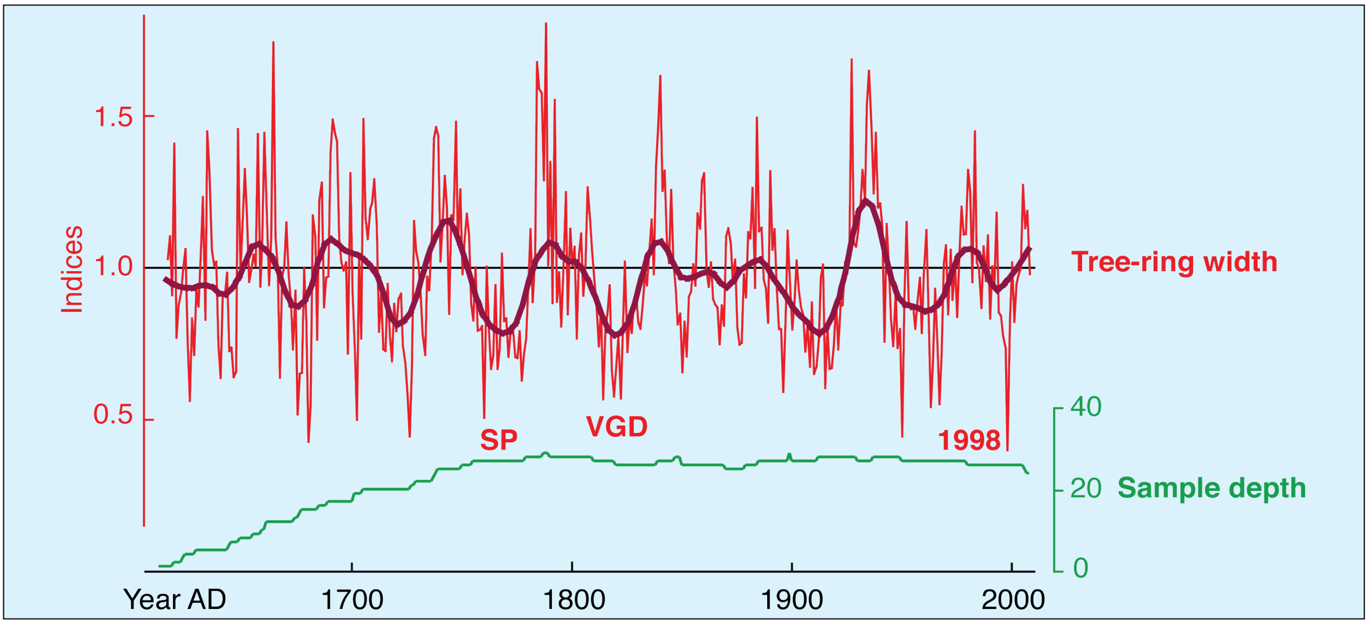

Figure 2: Tree-ring width chronology of teak (in dimensionless indices or values) for central Myanmar, spanning 1613-2009 AD, with sample depth (number of individual tree samples). Sample depth is near its peak over much of the chronology, gradually declining prior to the middle 1700s. Plot labels time of Strange Parallels (SP) drought in the 1700s (Buckley et al. 2007, 2010), the late Victorian Great Drought (VGD), and narrow ring at time of 1997-98 "El Niño of the Century" (modified from D'Arrigo et al. 2011).

for tropical dendroclimatology. It is endemic to Myanmar, but due to its great commercial value it is now rapidly disappearing across the country. Our new ring width chronology of teak for the Maingtha Forest Reserve is one of the first high-resolution proxy records that were developed for Myanmar (Figs. 1 and 2; D'Arrigo et al. 2012). It is based on 38 individual series from 20 living trees and spans the years 1613-2009 AD. Teak growth at the site is positively correlated with rainfall and PDSI variability over Myanmar, during and prior to the May-September wet monsoon season. Accordingly, the Maingtha Forest Reserve record reveals past variability of Myanmar hydroclimate.

Monthly correlations between the Myanmar teak ring-width chronology (Fig. 2) and instrumental PDSI (1950-2003 AD) were computed for the region overlapping our teak site (15-25°N, 95-105°E), for the period, from the year prior to the current year of radial growth to the current year. Statistically significant (95% level), positive correlations were found for the months concurrent and just prior to the wet monsoon season, from around April to August. Correlations with PDSI are strongest when averaged over May and June ($r = 0.32$, $n = 54$), reflecting the importance of moisture availability for teak growth in central Myanmar around the time of monsoon onset. Comparison with local monthly station rainfall records (e.g. for Mandalay and Yangon) further confirms that teak growth in central Myanmar is controlled by moisture availability.

This teak record also correlates significantly with larger-scale climate indices, including those for core Indian rainfall and ENSO. With the IITM All-India monsoon rainfall index, correlation for May-Jun is $r = 0.36$ ($p < 0.01$, $n = 57$). Correlations are stronger using the core northeast Indian monsoon rainfall index, which represents the region of India opposite the Bay of Bengal from Myanmar (23°N, 76°E). Averaged over Jan-Jun (1950-2006), the correlation is $r = 0.46$ ($p < 0.001$). For East Uttar Pradesh, a subdivision of this core region, the correlation is 0.47 since 1950 (Jan-Jul, $p < 0.001$, $n = 57$); and $r = 0.29$ over the maximum common period ($p < 0.001$, $n = 136$; 26°N, 82°E).

The Myanmar teak chronology correlates negatively with Niño-3 SST (Jul-Aug, $r = -0.27$, $p < 0.05$, $n = 60$). This is consistent with the tendency for positive Niño-3 SSTs, as during El Niño warm events, to be linked to drought conditions and decreased teak growth over southeast Asia, due to the eastward migration of the Walker circulation. Notably, Myanmar teak growth in the year 1999, following the so-called "El Niño of the Century" of 1997-1998, is the lowest of any year on record (Fig. 2). The year 1998 also shows the lowest annual rainfall value for central Myanmar. Myanmar teak growth is also below average during the Strange Parallels drought (Fig. 2) found across southeast Asia in the 1700s. The late Victorian Great Drought was associated with a major ENSO warm episode (1876 to 1878) and is perhaps the most spatially pervasive and severe drought in the MADA tree-ring data set for monsoon Asia (Cook et al. 2012; Buckley et al. 2007, 2010).

The potential of the new Myanmar record

Our new teak tree-ring width chronology from central Myanmar, one of the first paleoclimate records published for this country, is significantly and positively correlated with local and regional precipitation as well as with larger scale indices of Indian monsoon core rainfall, particularly over northeastern India. The Myanmar teak records also correlate negatively with Niño-3 SST, consistent with the tendency for El Niño warm events to be linked to drought over Southeast Asia, as they were following the pronounced 1997-1998 warm event. Thus, this teak record reflects not only local conditions, but also the large-scale strength of the circulation of the Asian monsoon-ENSO system. The timing of the inferred drought conditions coincides with megadroughts identified elsewhere in southeastern Asia, including Thailand and Vietnam (Buckley et al. 2007, 2010), and which are attributed to variability in the tropical Indo-Pacific climate system and the Intertropical Convergence Zone. Overall, our results indicate much potential for generating reconstructions of monsoon climate dynamics for Myanmar and the wider region from tree-ring data.

Note

MADA dataset available online at the NOAA Paleoclimatology website, International Tree-Ring Databank (ITRDB).

References

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Coral microatoll reconstructions of El Niño-Southern Oscillation: New windows on seasonal and interannual processes

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***Porites* coral microatolls show δ^{18}O signal reproducibility and fidelity comparable to more conventional coral growth forms. Longer-lived and fossil microatolls, which grow in suitably flushed environments, contain δ^{18}O signals that can significantly extend instrumental records of the El Niño-Southern Oscillation.**

Porites corals are the most commonly used genus for reconstructing El Niño-Southern Oscillation (ENSO). This hermatypic coral is found in all tropical reef environments (Veron 2000) with a variety of growth forms. Climate reconstructions of a century or more have been obtained from the most common, dome-shaped *Porites* growth form, whereby the colonies, beginning from the substrate, grow outward and upward towards the ocean surface (Knutson et al. 1972). Domed structures, however, are not the only *Porites* growth form.

Coral microatolls

Porites coral microatolls are found on shallow reefs where reef topography enables individual colonies to grow up to the average spring low tide level. Further upward growth is limited due to exposure of the upper coral surface at low tide (Stoddart and Scoffin 1979). At this point, the coral then grows laterally, resulting in a flat-topped discoid growth morphology termed "microatoll" (Fig. 1).

Coral microatolls can live for decades to many centuries (McGregor et al. 2011a), are distributed broadly across the Indo-Pacific region (Scoffin and Stoddart 1978), and their preservation potential is particularly high due to the possibility for rapid burial beneath sand and coral rubble through storm ridge or beach deposition. Microatolls provide information about past water levels, from which sea level, climatic, or tectonic histories have been derived (Natawidjaja et al. 2004; Sieh et al. 2008; Smithers and Woodroffe 2001; Taylor et al. 2008, 1987; Woodroffe and McLean 1990; Woodroffe et al. 2012; Zachariasen et al. 1999). Microatolls also have the advantage of sampling a narrow depth range over long periods of time, which is desirable when reconstructing depth-dependent, ENSO-related variables, such as sea surface temperature (SST) and sea surface salinity (SSS), together with changes in ocean dynamic height, in the tropical Pacific.

Studies of domed *Porites* show that there can be significant differences in skeletal δ^{18}O on the sides and tops of the corals and this is equally a concern for laterally-growing microatolls (e.g. Cohen and Hart 1997; McConnaughey 1989). However, testing of δ^{18}O variability within and between *Porites* sp. microatolls living on reef flats around Kiritimati (Christmas) Island in the central Pacific ocean, demonstrates no significant differences between δ^{18}O records from different growth orientations within a single microatoll, or between records from microatolls in different reef settings (McGregor et al. 2011b). Moreover, δ^{18}O records from microatolls and from conventional domed *Porites* from elsewhere on the atoll (Evans et al. 1998b; Nurhati et al. 2009) also show similar patterns and magnitude of variability. Together, the results show that *Porites* microatolls can be used interchangeably with dome-shaped corals to reconstruct tropical climate variability.

ENSO and δ^{18}O in modern microatolls at Kiritimati Island

Kiritimati Island is optimally located (Evans et al. 1998a) for reconstructions of ENSO. The island lies within the dry equatorial zone of the central Pacific, and in the NINO3.4 index region where SST variations define ENSO events (Bjerknes 1969; Ropelewski and Halpert 1987). In this region El Niño events result in marked positive SST anomalies of up to 3°C in the boreal winter, whereas La Niña events produce negative SST anomalies of 1-2°C (Wyrtki 1975; Fig. 2a). Rainfall also shows a dominant ENSO signal with higher annual precipitation during El Niño years.

Porites microatolls from Kiritimati register these climatic variations. Variations in a composite (stacked) monthly microatoll δ^{18}O record spanning the years 1978-2007 show a strong inverse correlation of r = -0.71 with SST and records major El Niño events (McGregor et al. 2011b; Fig. 2a). This is similar to findings for domed-*Porites* from Kiritimati where 70% of the variance is shared with SST (Evans et al. 1999). The stacked microatoll δ^{18}O record

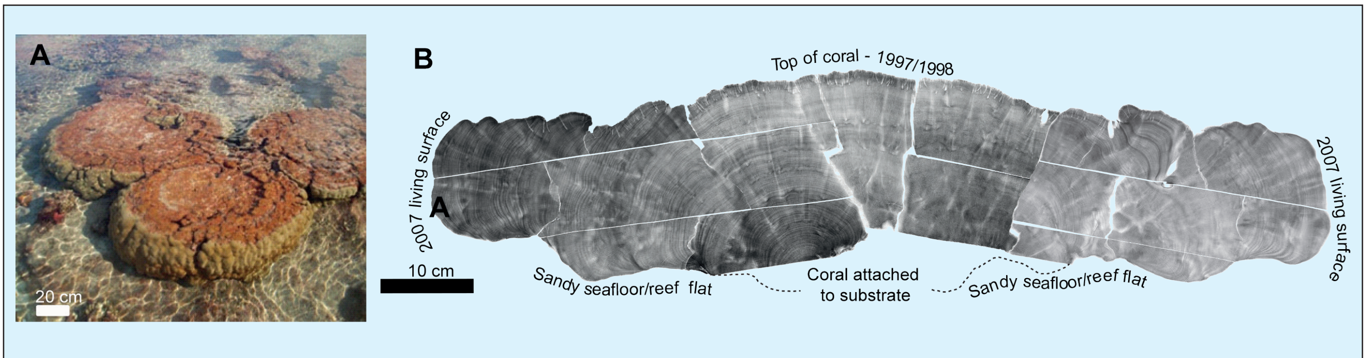

Figure 1: Porites *coral microatoll image and X-radiograph.* ***A)*** Porites *coral microatolls on a reef flat at low tide.* ***B)*** *Positive X-radiograph cross- section through a* Porites *microatoll. Dark and light bands are the high and low-density bands, respectively, that form as the coral grows. Starting from the center, the coral grows upwards until further upward growth is constrained by exposure during the minimum low water level (in this case, 1997/1998). Lateral growth then ensues resulting in a discoid microatoll structure. The location of the living surface in 2007 when the coral was collected is indicated. Dashed lines indicate the outline of coral pieces not X-rayed.*

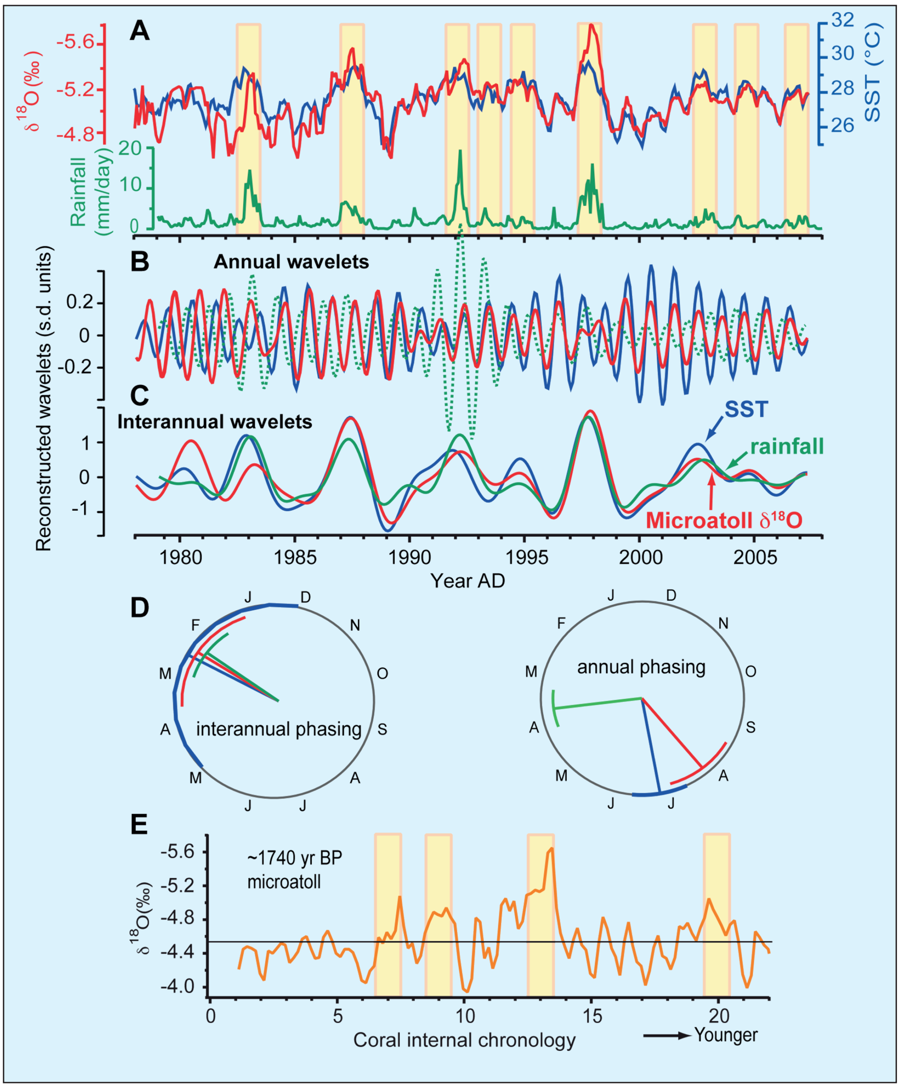

Figure 2: Variability of Kiritimati Island records. ***A)*** *Comparison of the stacked microatoll δ¹⁸O record (red line) with Kiritimati SST (blue line) and monthly rainfall (green line). The stacked δ¹⁸O is a composite of three microatoll records from Kiritimati. The microatoll δ¹⁸O record is strongly anti-correlated with Kiritimati SSTs (r = -0.71) and is sensitive to El Niño events (yellow bars).* ***B)*** *Annual-scale and* ***(C)*** *interannual-scale wavelets for the stacked microatoll δ¹⁸O (red, y-axis inverted), SST (blue), rainfall (green).* ***D)*** *The circular phase plots show the calendar month (and 95% confidence intervals) when, on average, the wavelets in B) and C) reach their maximum value. In general the microatoll δ¹⁸O record tracks SST variations. The rainfall is in phase with the SST and coral δ¹⁸O data at the interannual scale, but is out of phase at the annual scale.* ***E)*** *Profile of a δ¹⁸O microatoll from Kiritimati dated at ~1740 yr BP, placed on a new floating age scale (unpublished data) that shows El Niño events (yellow bars) similar to those of the past few decades. Black horizontal line is the mean δ¹⁸O. Figure modified after McGregor et al. (2011b), and Woodroffe and Gagan (2000). SST and rainfall data from ERSSTv3b (Smith et al. 2008) and GPCPv2 (Adler et al. 2003), respectively.*

also corresponds with anomalously high rainfall years (Fig. 2a); annual mean coral δ¹⁸O values of less than -5.3‰ are found only in years when total annual rainfall is above 1800 mm. In addition to local SST and rainfall, the microatoll δ¹⁸O signal is also negatively correlated with both SST and precipitation amount over a broad area of the equatorial Pacific (McGregor et al. 2011b). Since most of the covariance between δ¹⁸O, SST and precipitation is due to ENSO, the spatial correlations reflect the characteristic ENSO pattern.

ENSO and seasonal cycle variance patterns

Understanding ENSO annual and interannual cycle variance and interactions can provide important information on ENSO processes (Guilyardi et al. 2009). ENSO variance is recorded in the stacked microatoll δ¹⁸O record. The record (Fig. 2b,c) tracks SST variability at interannual (ENSO; 53% of the δ¹⁸O variance) and annual timescale (14%), consistent with existing analyses of instrumental tropical Pacific SSTs (Chiu and Newell 1983). Changes at annual and interannual scales at Kiritimati are reminiscent of the climate signal of the eastern equatorial Pacific (Chen et al. 1994; Mitchell and Wallace 1992).

ENSO events occur irregularly every 2-8 years, yet individual events show a distinctive SST pattern tied (or "phase-locked") to the seasonal cycle, such that El Niño SST anomalies peak during the boreal winter (DJF). The interannual component of SST and rainfall records for Kiritimati Island show maxima in February, as does microatoll δ¹⁸O (Fig. 2d). At the annual scale, the microatoll δ¹⁸O, which peaks in July-August, varies predominantly in-phase with SST, rather than with rainfall. The annual maximum in Kiritimati rainfall occurs in March-April, due to the position of the Intertropical Convergence Zone (ITCZ) (An and Choi 2010; Horel 1982; Mechoso et al. 1995; Waliser and Gautier 1993). That the microatoll δ¹⁸O tracks SST at the annual and interannual scale is important; SST variations in the NINO3.4 Index region are used to define ENSO variations. Accordingly, microatoll δ¹⁸O from the NINO3.4 region, such as Kiritimati Island, can be used to reconstruct past ENSO variations at multiple timescales.

ENSO signal in fossil microatoll δ¹⁸O

Fossil *Porites* microatolls, which were growing in well-flushed environments, offer opportunities to reconstruct tropical SST and ENSO variability beyond the limits of the instrumental record. Initial studies confirm reduced ENSO variability during the middle Holocene (Woodroffe et al. 2003). Individual ENSO events in the late Holocene (Fig. 2e) however, appear at least as intense as those experienced in the past two decades (Woodroffe et al. 2003). One particular El Niño event from 1740 yr BP (Fig. 2e) shows a negative δ¹⁸O excursion to ~5.6‰, which suggests substantial addition of ¹⁸O-depleted rainfall (Woodroffe and Gagan 2000). The stronger ENSO in the late Holocene may represent tighter coupling in the Pacific between the more southerly ITCZ, the east Pacific cold tongue and the Southern Oscillation, which could amplify ENSO precipitation variability and associated teleconnections. Such a scenario is consistent with terrestrial paleoclimate records indicating a marked increase in El Niño activity from ~3000 yr BP. We are undertaking further analysis of fossil coral microatolls and their annual and interannual variability to test this scenario.

Note

Data are archived at WDC-paleoclimatology http://hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1:4336223539645946::::P1_STUDY_ID:12278

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Giant clam recorders of ENSO variability

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Giant clam stable isotope profiles from Papua New Guinea faithfully record all the major El Niño events between 1986 and 2003, thus illustrating the usefulness of this archive to reconstruct past ENSO variability.

Considerable uncertainty remains about the response of the El Niño-Southern Oscillation (ENSO) to future climate scenarios (Merryfield 2006). Reconstructions of past changes in seasonality and ENSO from natural archives have a key role in providing information for understanding both the full range of variability and the sensitivity of ENSO to changes in climate boundary conditions. Geochemical time series extracted from skeletons of annually banded reef-building corals and mollusks constitute powerful records in this regard. A number of exciting recent studies have illustrated how clams (i.e. bivalves) can be used in paleoenvironmental studies (e.g. Sano et al. 2012; Wanamaker et al. 2012).

Here we specifically illustrate the usefulness of one bivalve species, *Tridacna gigas* (Fig. 1) as a natural archive for paleo-ENSO. Massive *Porites* spp. corals and *Tridacna* spp. clams are both reef-dwelling, aragonite secreting organisms. Their annual bands can be subsampled and analyzed to derive profiles of oxygen isotope ratios ($\delta^{18}O$) which have been shown to reflect the combined effects of regional sea surface temperature (SST) and sea water $\delta^{18}O$ from which they precipitate their aragonite structures (Tudhope et al. 1995; Welsh et al. 2011). Time series of $\delta^{18}O$ in modern and fossil corals collected in northern Papua New Guinea in the heart of the Western Pacific Warm Pool have been used to reconstruct ENSO variability for short windows of time over the past 130 ka (Tudhope et al. 2001). These records are however extremely rare because of the tendency for the porous *Porites* skeleton to undergo diagenetic alteration during periods of subaerial exposure. An advantage of *T. gigas* is that they have relatively impervious and finely layered shells that inhibit infiltration of ground waters that would lead to the diagenetic processes of dissolution, recrystallization and precipitation of secondary calcite. Finally, while coral $\delta^{18}O$ show an isotopic disequilibrium, *Tridacna* spp. precipitate their shells in isotopic equilibrium. This provides the possibility to more accurately quantify past changes in absolute SST and see water $\delta^{18}O$.

Figure 1: Photo of a live Tridacna gigas *from Heron Island.* T. gigas *are reef dwelling mollusks which have symbiotic algae living within their mantle. Valves are 50 cm from end to end. Photo K. Welsh.*

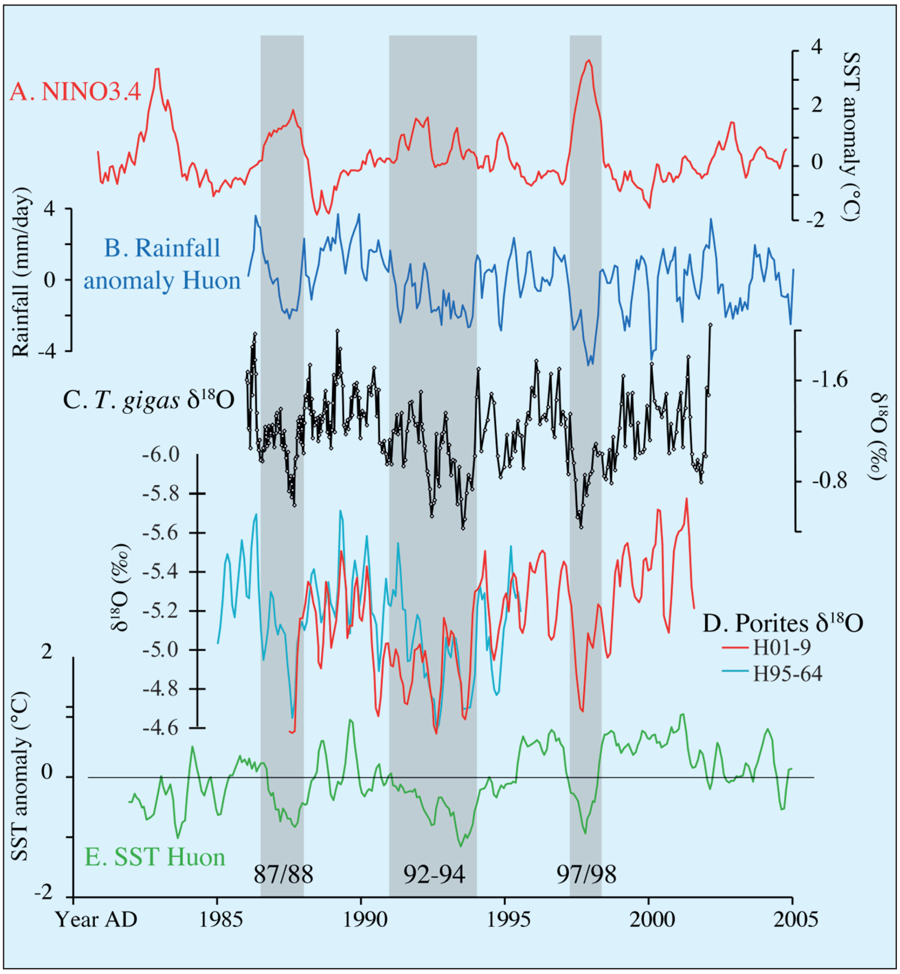

Figure 2: Comparison of T. gigas *$\delta^{18}O$ profile with ENSO index, local temperature and rainfall data.* ***A)*** *NINO3.4 index,* ***(B)*** *3pt smoothed monthly rainfall anomaly (mm day^{-1}, NASA/GPCPV2) for 146.25°E, 6.25°S,* ***(C)*** T. gigas *$\delta^{18}O$ record,* ***(D)*** *Porites $\delta^{18}O$ profiles and* ***(E)*** *3pt smoothed monthly SST anomaly (from IGOSS) for the same grid box as the rainfall data. Y-axes of the $\delta^{18}O$ are inverted. The shaded bands indicate El Niño events.*

Calibration

To illustrate the potential of *T. gigas* as paleo-ENSO recorders, we obtained a high-resolution $\delta^{18}O$ profile from a modern specimen that we compared to modern *Porites* coral $\delta^{18}O$ profiles and an ENSO index. Samples were collected from three localities along the Huon Peninsula in northern Papua New Guinea. Profiles of $\delta^{18}O$ were obtained by subsampling the annual growth bands using high precision microdrilling devices. The age of the coral and bivalve $\delta^{18}O$ profiles were obtained independently (i.e. they were not tuned to one another) by counting the annual growth bands when visible and using the $\delta^{18}O$ maxima and minima to position the warmest and coolest months. The *T. gigas* $\delta^{18}O$ profile covers the period 1986-2002 and the *Porites* $\delta^{18}O$ records cover the period 1987-2001 (Fig. 2). Average SSTs at the Huon Peninsula are around 29°C with an annual range of 0.5-1.5°C in monthly means. The predicted equilibrium skeletal annual average $\delta^{18}O$ is -1.6‰. Therefore, our results confirm that *T. gigas* precipitate their shell close to isotopic equilibrium as has been shown previously (e.g. Aharon et al. 1991).

Comparison of bivalve and coral profiles

A striking feature is the high degree of resemblance between the coral and bivalve records despite their geographic separation of approximately 30 km and their average $\delta^{18}O$ offset of ~4‰ (Fig. 2). Profiles correlate in detail on the seasonal and on the interannual levels. This correlation is particularly interesting given that paleoclimate archives obtained from coastal areas characterized by strong SST and salinity gradients can potentially be significantly influenced by the local micro-environmental hydrography. Our results clearly show that corals and clams record large-scale regional patterns. Furthermore, the good correlation between $\delta^{18}O$ coral and bivalve profiles remains constant although measurements have been obtained from different carbonate secreting organisms with fundamentally different biological controls on carbonate formation and different growth rates.

Giant Clams as recorders of ENSO events

In northern Papua New Guinea precipitation and temperatures are coupled on seasonal and interannual timescales. El Niño periods are associated with lower than average SST and drier conditions, whereas La Niña periods are associated with higher than average SST and wetter conditions. The associated changes in see water $\delta^{18}O$ and SST will thus have cumulative effects on shell $\delta^{18}O$, which will become more positive during El Niño and more negative during La Niña phases. The comparison of the ENSO index with the *T. gigas* and *Porites* $\delta^{18}O$ records shows that each El Niño event is recorded in the shell and coral profile by isotopic shifts of around 1.0 to 1.2‰ toward more positive values (Fig. 2) reflecting the combined influence of lower temperatures and decreased rainfall. During the El Niño phase of the Southern Oscillation, the region experiences relative drought and slightly reduced SSTs (~-0.2 to -0.5°C anomaly, see Fig. 2). These factors combine to drive skeletal $\delta^{18}O$ to heavy values, with SST explaining about 30-50% of the skeletal $\delta^{18}O$ range.

Take away message

We show that shells of *T. gigas* can be used to produce multi-decadal climatic records, hence providing a valuable resource for investigating changes to the frequency and strength of ENSO events in the past. The excellent reproducibility of clam and coral $\delta^{18}O$ profiles illustrates the strength of using these archives to reconstruct large-scale hydrographic changes.

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Reconstructing ENSO in the Eastern Tropical Pacific from short-lived marine mollusks

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Shells of mollusks from offshore Peru were analyzed to reconstruct variability of the seasonal cycle and ENSO. The data provide insights into past changes in ENSO-related interannual variability in the Eastern Tropical Pacific and in the spatial structure of ENSO.

The focus of much paleoclimate work on ENSO has been on records spanning multiple decades, such as those derived from corals. Such long records are, however, relatively rare, especially in the Eastern Tropical Pacific. This important limitation for studying past changes in the spatial pattern of ENSO activity can be compensated for by obtaining records from a larger number of shorter-lived organisms. In this case, information about past climate is not available as a continuous record, but is compiled to extract climate statistics.

Carré et al. (2013) recently presented a technique that responds to the critical need for quantitative estimates of tropical marine interannual variability. This technique uses the shells of marine mollusks that live for 1-4 years, and thus allow us to reconstruct the seasonal range of sea surface temperature (SST). These data can then be compared to coral records and GCM outputs. The technique of using marine mollusk shells shares similarities with the approach of coral studies in that it produces floating windows of climate record at a very high, often monthly, resolution. It also shares similarities with the approach of analyzing many foraminifera shells individually from the same sediment layer (Koutavas et al. 2006; Leduc et al. 2009) in that paleoclimate statistics are estimated from a random sample. Isotopic records in mollusks enable independent reconstructions of the seasonal cycle. This approach is valid for any coastal mollusk species that faithfully records at least one annual SST cycle, and therefore opens up new opportunities for direct, quantitative paleo-ENSO reconstructions in the Eastern Tropical Pacific, using either archeological shell middens or uplifted fossil shell banks from Peru.

ENSO characterization in the Niño1+2 region

SST variability on the Peruvian coast is largely dominated by ENSO-related interannual variability. The amplitude of the annual cycle (ΔT) on the coast is also clearly related to the Niño1+2 index, with larger amplitudes during El Niño and smaller ones during La Niña. As a result, the variance of the annual cycle amplitude, Var(ΔT), on the Peruvian coast over any period of time is an indicator of ENSO variance generally in the Niño1+2 region (Fig. 1a).

Oxygen stable isotopes ($\delta^{18}O$) in marine shells from central and southern Peru primarily reflect SST variability since seawater $\delta^{18}O$ is not significantly affected by freshwater input and evaporation (Carré et al. 2013). *Mesodesma donacium* shells grow continuously throughout the year and record the full annual cycle of coastal SST in Peru over a window of 1 to 4 years at a monthly resolution (Fig. 1b). Modern shells (n=13) collected during the late 20th century provide a random sample cumulatively providing about 25 years of statistics that faithfully reproduces the skewed distribution of ENSO

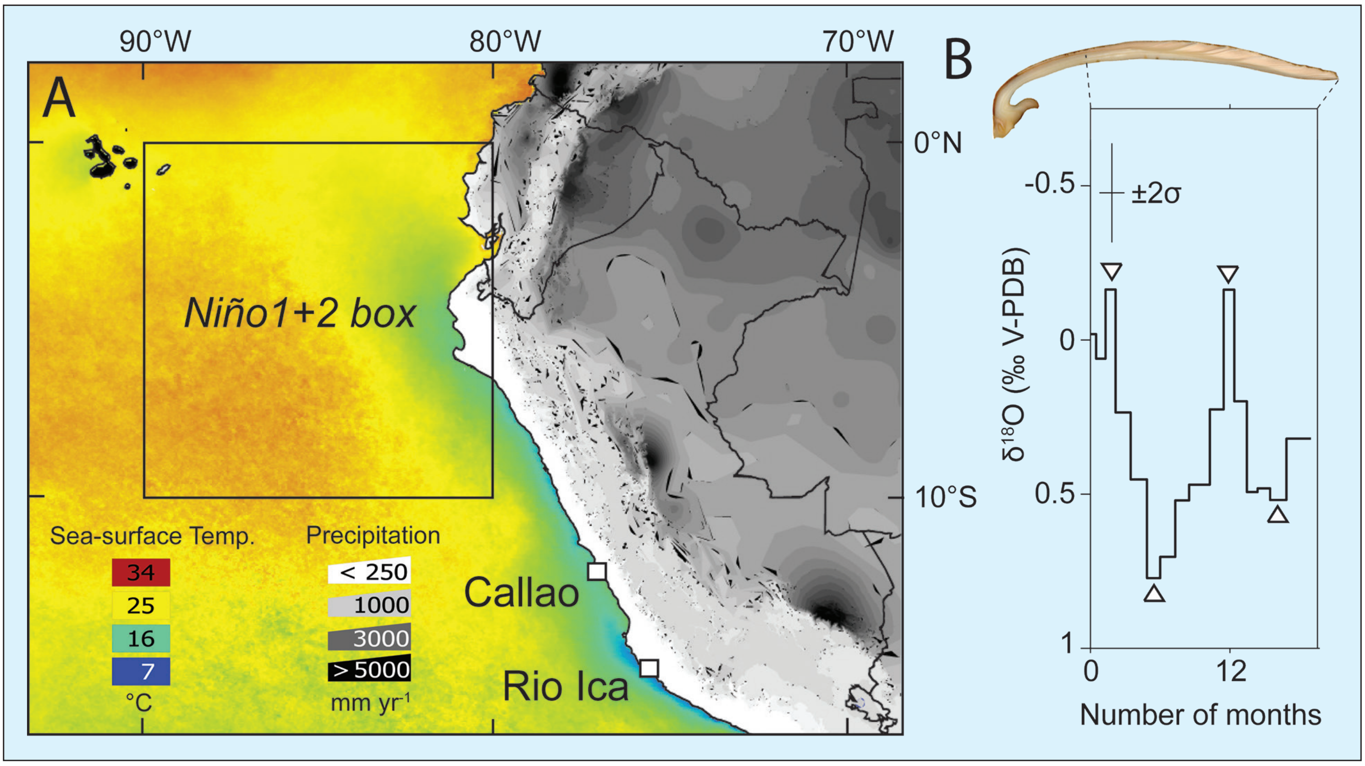

Figure 1: ***A)*** *Annual mean SST and precipitation for the 1950-2010 period. Location of the Niño1+2 region in the Eastern Tropical Pacific and the Peruvian localities mentioned.* ***B)*** *Polished section of a* M. donacium *shell, and the associated* $\delta^{18}O$ *plotted on a time scale. The shell was continuously sampled so that every data point integrates about one month. The chronology was determined using shell growth lines. Triangles indicate seasonal extrema used for the calculation of seasonal amplitudes ΔT.*

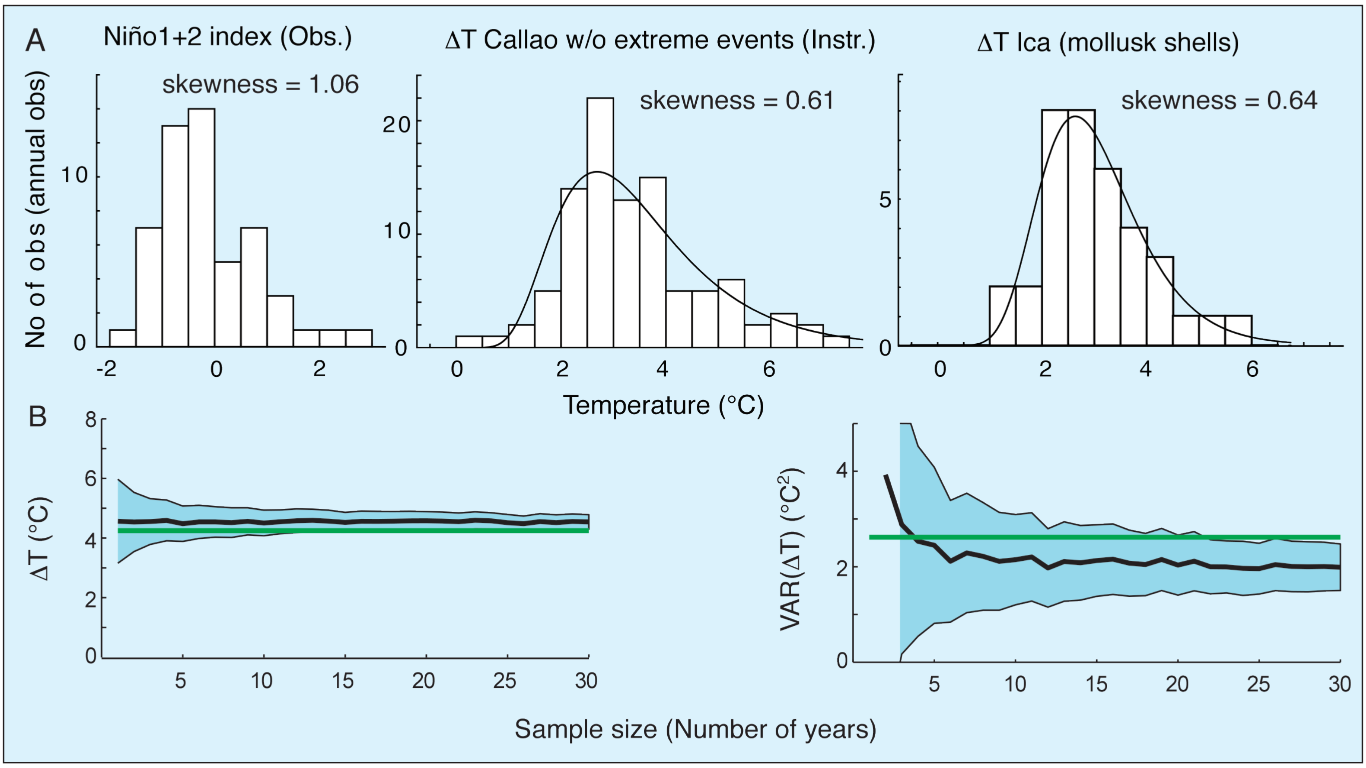

Figure 2: ***A)*** *Distributions of annual Niño1+2 index from 1950 to 2002, seasonal ΔT values in Callao, Peru from 1950 to 2002 excluding extreme El Niño events in 1982-83 and 1997-98, and ΔT values calculated from a modern sample of* M. donacium *shells from Ica, Peru.* ***B)*** *Results of Monte Carlo simulations undertaken to estimate the uncertainties of mollusk-derived paleoclimate reconstructions. Plots show the true value (green), the ensemble average value (black line), and the standard error (blue area) vs. the sample size, for the reconstruction of the mean and variance of ΔT.*

anomalies of this period in Callao, Peru and in the Niño1+2 region (Fig. 2a). It should be noted that the extreme warm events of 1982-83 and 1997-98 are not recorded in the data as the exceptionally warm conditions induced mass mortality in the mollusks. However, such events are so extraordinary even at the millennial scale (Rein 2007) that they are arguably not representative of ENSO (Takahashi et al. 2011). The mollusk shells are complementary to rainfall-related archives as they are sensitive to variability in the marine manifestation of ENSO while rainfall-related archives are more sensitive to occasional catastrophic events induced by the atmospheric anomalies of extreme ENSO events (Rein 2007).

Estimating the reconstruction uncertainties

Estimating reconstruction uncertainties is a necessary challenge in paleoclimate studies if meaningful comparisons with GCM simulations are to be made. To estimate the reconstruction error, we used an in situ instrumental time series and simulated the reconstruction process (forward proxy model). This was done by randomly extracting short time samples and adding different types of noise to them representing uncertainty sources (such as analytical error, random growth breaks, or temperature tolerance). Iterating this process thousands of times provides an estimate of systematic biases (the mean value of the error population) and of the standard error (the standard deviation of the error population) (Fig. 2b). This shell sample yields thus an estimate of mean annual temperature with a precision of ±0.4°C, of ENSO variance with a precision of ±30%, and of ENSO skewness with a precision of ±0.3. This procedure can also be used to evaluate the relative contributions of error sources, and improve our understanding of the proxy (Carré et al. 2012). This sample will be used as a modern reference to normalize past reconstructions, minimize systematic biases due to the archive or to local effects, and allow meaningful comparisons with coral records and climate simulations.

Discriminating Central from Eastern Pacific modes in the past

Capotondi et al. (2013, this issue) present some recent developments in our understanding of ENSO diversity. Two types of El Niño events, Central Pacific events and Eastern Pacific events, have been defined by the location of the maximum SST anomaly (Ashok et al. 2007). Because of their significantly different impacts, the question of the evolution of ENSO in both the past and future, should now also address the variable contribution of Central Pacific and Eastern Pacific ENSO events. In the Niño1+2 region, in the far Eastern Pacific, Eastern Pacific and Central Pacific modes can be distinguished by the shape of their SST distributions. The Eastern Pacific mode is characterized by positively skewed SST distributions while the Central Pacific mode produces a symmetric distribution.

Such a change in ENSO asymmetry has been noted since the 1990s (Yeh et al. 2009; Boucharel et al. 2011; Dewitte et al. 2012). La Niña cold events generate negatively skewed SSTs in the Niño1+2 region. The ENSO anomaly distribution obtained from the modern Peruvian shell sample faithfully reproduces the positive skewness of the late 20th century ENSO, even without recording the most extreme ENSO events (Fig. 2a). Fossil mollusk shell samples from Peru could therefore potentially be used to track past changes in the frequency of Eastern Pacific and Central Pacific events, and provide novel insights into the relationships between ENSO modes and the mean climate.

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Challenges in understanding and modeling ENSO

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Some new exciting directions in ENSO research explore inter-event differences in spatial patterns, teleconnections and impacts, asymmetries between warm and cold phases, and the role of extra-tropical regions in triggering ENSO events. However, large uncertainties remain regarding ENSO projections.

The El Niño–Southern Oscillation (ENSO) is a naturally occurring fluctuation that originates in the tropical Pacific region and affects ecosystems, agriculture, freshwater supplies, hurricanes and other severe weather events worldwide. Over the last thirty years significant progress has been made in improving our understanding of the dynamic processes underlying ENSO, including the ocean-atmosphere feedbacks that are essential to this coupled phenomenon.

The oscillatory nature of ENSO, alternating between El Niño and La Niña events, can be described in terms of the recharge and discharge of warm water to and from the equatorial thermocline ("recharge oscillator"; Jin 1997) or in terms of thermocline depth changes associated with wave propagation ("delayed oscillator", e.g. Suarez and Schopf 1988). These simple paradigms of ENSO as a linear oscillator capture basic dynamical processes; however, they fail to explain differences among events and asymmetries between warm and cold episodes. Moreover, they ignore the important role of stochastic atmospheric phenomena (e.g. westerly wind bursts) and other non-linear effects.

Understanding and predicting the diverse characteristics of El Niño and La Niña events is important since their regional climatic impact can vary heavily depending on the longitudinal location of the SST anomalies. Also, understanding how teleconnections vary depending on the event type is crucial when proxy records are used to reconstruct past ENSO. Hence, exciting new research developments have emerged to address this observed ENSO diversity.

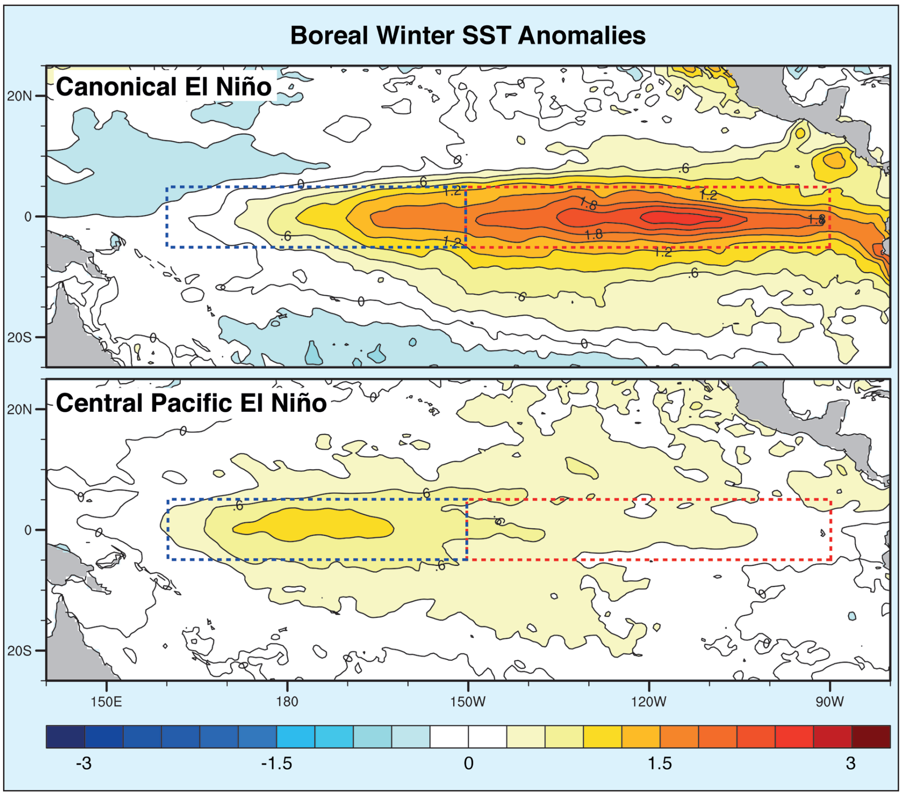

Figure 1: Composite spatial pattern of SST anomalies for the "canonical" ***(top)*** *and "Central Pacific"* ***(bottom)*** *El Niño types (SODA 2.0.2/3) from 1958 to 2007 computed with the approach of Kug et al. (2009). Canonical El Niños are characterized by a boreal winter (DJF) Niño3 index larger than 0.5°C and larger than the Niño4 index (red and blue dashed boxes, respectively), and vice versa for the Central Pacific El Niño (from Capotondi, in press). Observed El Niño events can be described as blends of these two end-member types.*

Understanding ENSO dynamics

The first development is a renewed interest in inter-event differences and the related "El Niño Modoki" debate. Based on a statistical analysis of SST in the tropical Pacific, Ashok et al. (2007) suggested the existence of another type of El Niño, called Central Pacific El Niño (or Date Line El Niño or El Niño Modoki by various authors). They argued that this type of El Niño is not the same as the "canonical" El Niño because its center of action is in the central Pacific instead of the eastern Pacific, as illustrated in Figure 1. It was also suggested that Central Pacific El Niños have become more frequent in recent decades, and their frequency may increase further with global warming (Yeh et al. 2009). Subsequent observational and modeling studies have tried to define the Central Pacific El Niño more precisely or differently (Kug et al. 2009; Kao and Yu 2009). However, as yet no agreement has been reached on the best way to characterize the new Central Pacific-type of El Niño. Some studies have tried to distinguish the central Pacific and eastern Pacific (canonical) warm events based on their underlying dynamical processes, and their relationship with the oceanic mean state (e.g. Choi et al. 2011; McPhaden et al. 2011). A number of other studies dispute the statistical significance of the distinction between the two El Niño types or at least of the increasing occurrence of the Central Pacific variety. They argue either that the reliable observational record is too short to detect such a distinction (Nicholls 2008; McPhaden et al. 2011), or that they have found no trend using other approaches (Giese and Ray 2011; Newman et al. 2011; Yeh et al. 2011). Other authors alternatively suggest to distinguish between other types of El Niño, such as standard and extreme El Niños (Lengaigne and Vecchi 2010; Takahashi et al. 2011). Due to the asymmetric nature of the warm and cold phases of ENSO, Kug and Ham (2011) could not identify analogous distinctions for La Niña, neither in observations nor in the simulations of the Climate

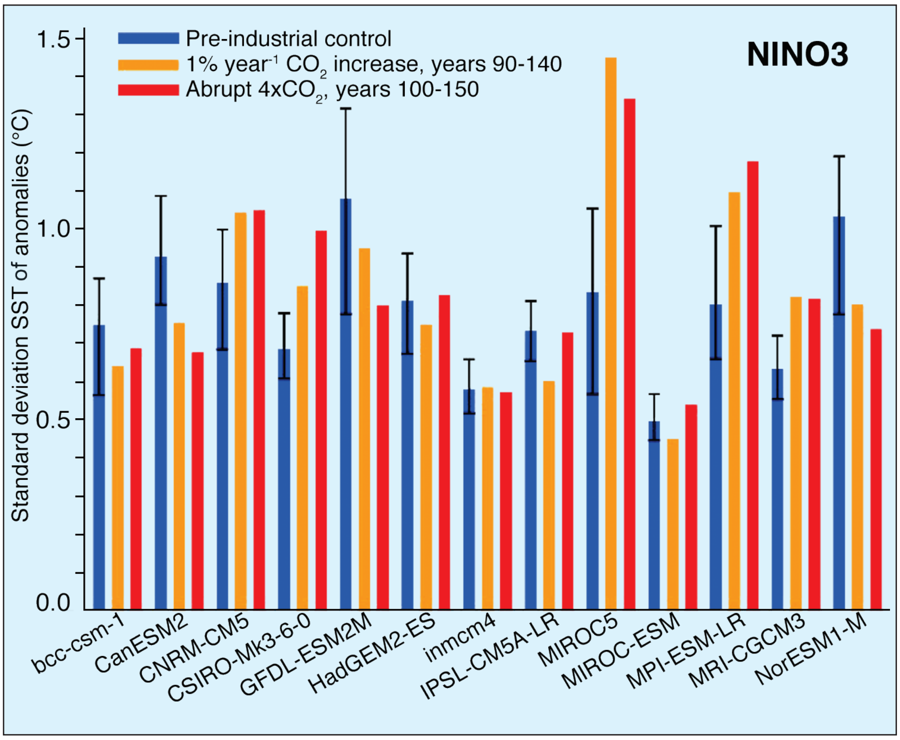

Figure 2: Standard deviation of Niño3 SST anomalies for thirteen CMIP5 model experiments. Blue bars, pre-industrial control experiments; orange bars, years 90-140 from the 1% year^{-1} CO_2 increase experiments; red bars, years 50-150 after an abrupt four-fold CO_2 increase. Model names are given on the x-axis. Error bars indicate the standard deviations over 50-year windows of Niño3 anomalies in the multi-century control experiments. Thus, when the Niño3 standard deviation in one of the CO_2 runs falls outside the error bar, the changes are deemed significant (modified from Guilyardi et al. 2012b). As in CMIP3, this new set of model simulations does not provide a clear trend for ENSO strength in a warming climate.

Model Intercomparison Project version 3 (CMIP3). Due to the large societal relevance of the impacts of ENSO, it is important to predict not only whether an El Niño (or La Niña) event is expected, but if possible which expression the anomaly will take. Fueled by these early studies, new questions are now emerging asking, for instance, if discrete classes of ENSO events emerge from observations, paleoclimate records and model simulations, or if ENSO diversity is better described as a continuum with a few characteristic extremes (e.g. Wu and Kirtman 2005).

Other new lines of research in ENSO diversity include revisiting the relative roles of the ocean and the atmosphere in shaping ENSO (Kitoh et al. 1999; Guilyardi et al. 2004; Dommenget 2010; Clement et al 2011; Lloyd et al. 2011) and exploring the role of regions outside the tropical Pacific in triggering ENSO events (Vimont et al. 2003; Izumo et al. 2010; Terray 2011; Wang et al. 2011). An example of remote influence is the seasonal footprinting mechanism (Vimont et al. 2003): Atmospheric variability originating in the North Pacific can impact the subtropical ocean during winter, and the resulting springtime SST anomalies alter the atmosphere-ocean system in the tropics during the following summer, fall and winter. The diversity of geographical sources and mechanisms proposed may explain the diversity of El Niño events, both in observations and in models.

ENSO in climate models and future projections

Most of our understanding of the representation of ENSO in climate models has been derived from the analysis of the model simulations of the Climate Model Intercomparison Project versions 3 (CMIP3) and 5 (CMIP5). While the models appear to reproduce some of the basic processes and feedbacks associated with ENSO, the details of the SST anomaly patterns as well as the temporal evolution of the anomalies often differ from the observed, and reflect model biases or erroneous atmosphere-ocean interactions (Capotondi et al. 2006, Guilyardi et al. 2009; Guilyardi et al. 2012a). For example, in most of the CMIP3 models, the largest anomalies are located further west along the equator than in observations. Furthermore, in many models ENSO events tend to occur more frequently and regularly than in the real world. While the models keep improving in their simulation of ENSO, no quantum leap was seen in CMIP5 compared against CMIP3 (Guilyardi et al. 2012b).

Over the past few years, new promising methods have emerged, which could improve ENSO simulations, for example by bridging ENSO theoretical frameworks and climate modeling. Resulting innovations include the development of indices that can be used to assess the stability of ENSO in Coupled General Circulation Models (CGCMs), and intermediate models that can be used to predict ENSO characteristics from aspects of the mean state. By focusing on the key processes affecting ENSO dynamics (e.g. the thermocline feedbacks or the wind stress response to SST anomalies), these new approaches have much potential to accelerate progress and improve the representation of ENSO in complex climate models. Not only can these new methods help address the question of whether the characteristics of ENSO are changing in a changing climate, but potentially they can also improve the reliability of centennial-scale climate projections and predictions on seasonal time scales.

Looking forward

At present, we don't know enough about how ENSO has changed in the past (the detection problem) and what caused the changes i.e. the contribution from external forcing vs. that due to internal variability (the attribution problem). Given the much too short reliable observational record (both for ENSO and for the external forcing fields, Wittenberg 2009), the complexity and diversity of the paradigms and processes involved, and the shortcomings of current state-of-the-art models, understanding the causes of ENSO property changes, both in the past and in the future, remains a considerable challenge. For instance Collins et al. (2010) concluded that it is not yet possible to say whether ENSO activity will be enhanced or damped in future climate scenarios, or if the frequency of events will change (Fig. 2). Paleoclimatic and paleoceanographic reconstructions have the potential to initiate the next quantum leap.

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Coral-model comparison highlighting the role of salinity in long-term trends

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We use a simple proxy model to compare climate model simulations and coral records over the 20th century. While models and observations agree that the tropical oceans have warmed, they disagree on the extent and origin of freshening.

The response of the tropical Pacific Ocean to anthropogenic climate change remains uncertain, in part because we do not fully understand how the region has responded to anthropogenic change over the 20th century. Analysis of 20th century temperature and salinity trends is hindered by limited historical data, lack of long-term in situ measurements, and disagreement among coupled general circulation model (CGCM) hindcasts. High-resolution paleoclimate records, particularly the large network of tropical Pacific coral oxygen isotope records, are an alternate means of assessing tropical climate trends. However, these natural archives of past climate are biased by their limited spatial and temporal distribution and their biologically mediated response to climate. By converting native climate variables (e.g. temperature and net freshwater flux) into synthetic ("pseudo") proxy records via an explicit proxy system model ("forward model"), we can directly compare historical climate data and climate model simulations with coral records, and assess biases and uncertainties associated with each.

Pseudocoral modeling

The stable oxygen isotope ratio ($\delta^{18}O$) of coral aragonite is a function of the temperature and the oxygen isotopic ratio of seawater ($\delta^{18}O_{sw}$) at the time of growth; the latter is in turn strongly related to sea-surface salinity (SSS). As direct measurements of $\delta^{18}O_{sw}$ are scarce, we model the expected $\delta^{18}O$ anomalies of corals ($\delta^{18}O_{pseudocoral}$) as a function of sea-surface temperature (SST) and salinity anomalies:

$$\Delta\delta^{18}\mathrm{O}_{\mathrm{pseudocoral}} = a_1\Delta\mathrm{SST} + a_2\Delta\mathrm{SSS}$$

We define coefficient a_1 as -0.22 ‰ °C^{-1} based on the relationship between temperature and the isotopic composition of the skeleton in well-studied coral genera (e.g. Evans et al. 2000). Coefficient a_2 is estimated from basin-scale regression analysis of available observations of $\delta^{18}O_{sw}$ on SSS (LeGrande and Schmidt 2006; LeGrande and Schmidt 2011). Uncertainty in the application of the resulting bivariate model arises from the assumed independence and linearization of a_1 and a_2 and substitution of the second term for a direct dependence on $\delta^{18}O_{sw}$.

We apply this simple forward model of $\delta^{18}O_{pseudocoral}$ to generate synthetic coral (pseudocoral) records from historical observations and CGCM simulations of temperature and salinity (Thompson et al. 2011). When driven with historical climate data, we found that this simple model was able to capture the spatial and temporal pattern of ENSO and the linear trend observed in corals from 1958 to 1990. Modeling pseudocorals with temperature and salinity individually also demonstrated that although warming accounts for the majority of the observed $\delta^{18}O_{coral}$ trend (60% of trend variance), salinity also plays an important role (40% of trend variance). The addition of the SSS term improved agreement between modeled pseudocoral and observed coral $\delta^{18}O$ trends over pseudocoral trends modeled from SST only (Thompson et al. 2011).

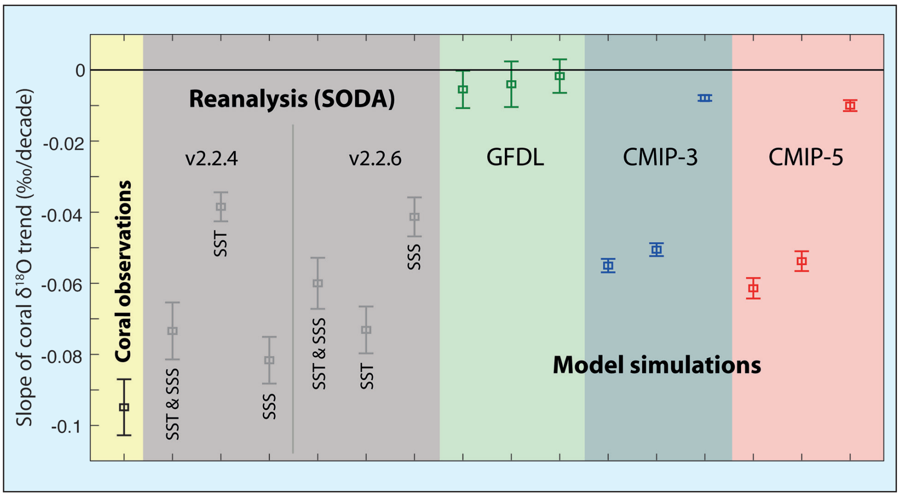

Figure 1: Magnitude of the trend slope (‰ per decade), computed by linear regression through the trend principal component (PC) in corals (far left) and pseudocorals modeled from Simple Ocean Data Assimilation (SODA) 20th century reanalysis (Carton and Giese 2008; Compo et al. 2011), a 500-year control run from the CGCM version CM2.1 of the Geophysical Fluid Dynamics Laboratory (GFDL cm2.1) (Wittenberg et al. 2009), and all CMIP-3 and CMIP-5 model ensembles (average of all models from each modeling group). In each case, $\delta^{18}O_{coral}$ was modeled from SST and SSS (1), SST only (2), and SSS only (3). Error bars depict ± 1 standard deviation of the regression estimate.

20th century trends

When driven with the output from 20th century simulations of a subset of CGCMs from the third phase of the Coupled Model Intercomparison Project (CMIP3) sampled at the coral locations, none of the pseudocoral networks reproduced the magnitude of the secular trend, the change in mean state, or the change in ENSO-related variance observed in the actual coral network from 1890 to 1990 (Thompson et al. 2011). Applying this same approach to the newer (CMIP5) suite of historical climate simulations, we find that large discrepancies still remain in the magnitude (Fig. 1), spatial pattern and ENSO-related variance of the simulated and observed trends. Differences between observed and simulated $\delta^{18}O_{coral}$ trends may stem from the simplicity of our forward model of $\delta^{18}O_{coral}$, biological bias in the coral records, or model-inherent bias in the CGCM SST and SSS fields.

Although we cannot yet completely rule out a non-climatic origin for the amplitude of the observed $\delta^{18}O_{coral}$ trend, previous work highlights biases in simulated salinity fields as a potential source of the observed-simulated trend discrepancy (Thompson et al. 2011). We found that the suite of CMIP3 and CMIP5 CGCMs simulate weak and heterogeneous salinity trends that are indistinguishable in magnitude from that of unforced control runs (Fig. 1). Further, the pseudocoral simulations (Fig. 1) illustrate that the magnitude of the simulated $\delta^{18}O_{coral}$ trend can be less than the sum of

Region	Observed slope	Monthly ModelE2	Annual ModelE2	Decadal ModelE2	ModelE2 at observations
Tropical Pacific	0.27	0.35	0.35	0.36	0.32
South Pacific	0.45	0.33	0.33	0.37	0.30
Indian Ocean	0.16	0.33	0.35	0.35	0.27

Table 1: Slope of the regional δ18Osw-SSS relationship calculated from observations (LeGrande and Schmidt 2006) and the GISS ModelE2 control simulation. Annual and decadal series were calculated by averaging the monthly data at yearly and 10-year intervals.

the individual trends arising from temperature and salinity when the temperature and salinity trends are confounding at the coral sites (as observed for SODA modeled pseudocorals). However, given the limited number of historical SSS observations, much uncertainty remains in the sign and magnitude of the 20th century salinity trend. When forward-modeling pseudocorals with data from two recent versions of an extended reanalysis (SODA v2.2.4 and v2.2.6; Ray and Giese 2012), we found that even the relative contribution of temperature and salinity to the observed pseudocoral trend differs (Fig.1); this discrepancy likely arises from the choice of wind field used in the reanalyses (G. Compo, personal communication). These results suggest a need for improved simulation of moisture transport and additional proxy reconstructions of salinity and $\delta^{18}O_{sw}$ to better understand their relationship and the sign and magnitude of their change.

$\delta^{18}O_{sw}$ vs SSS: insights from isotope enabled simulations

In substituting the $\delta^{18}O_{sw}$-SSS relationship calculated from the limited observational dataset for $\delta^{18}O_{sw}$, our simple forward model assumes that this relationship is not only a valid approximation for $\delta^{18}O_{sw}$, but also that this relationship does not vary significantly through time or within regions. Although this assumption does not likely hold at the millennial timescale (e.g. LeGrande and Schmidt 2011), it may be appropriate for simulating tropical variability during the past century. Here we assess the stability of the $\delta^{18}O_{sw}$-SSS relationship through space and time on monthly to decadal timescales using a control simulation of an isotope-enabled version of the Goddard Institute for Space Studies model (GISS ModelE2, provided by A. LeGrande). In these simulations, the relationship between $\delta^{18}O_{sw}$ and SSS was generally regionally consistent over monthly to decadal timescales (Table 1), suggesting that the substitution of SSS for $\delta^{18}O_{sw}$ is unlikely to impose low-frequency variability on the modeled pseudocorals. However, we find that the slope of the $\delta^{18}O_{sw}$-SSS relationship and its sensitivity to timescale varies within the broad regions of Table 1, particularly between the eastern and western Pacific (Fig. 2). Similar regional variability in the slope of the $\delta^{18}O_{sw}$-SSS relationship was observed in an isotope enabled version of the UK Met Office model (HadCM3; Russon et al. 2013). Additionally, the slopes of the $\delta^{18}O_{sw}$-SSS relationship simulated for the tropical regions in the GISS model were generally higher and more spatially consistent than those calculated from the limited observations (LeGrande and Schmidt 2006; Table 1). If we analyze only model output corresponding to the location and time of observations, the data-model discrepancy is reduced but not eliminated (Table 1). These discrepancies likely arise from the scarcity of paired $\delta^{18}O_{sw}$ and SSS observations as well as from the modeling of precipitation processes, and will be reduced by a combination of continued seawater sampling and model development.

If the current observational dataset underestimates the true magnitude of the $\delta^{18}O_{sw}$-SSS slope, our simple forward model will underestimate the magnitude of the true $\delta^{18}O_{coral}$ trend when a significant freshening is observed. Estimates of uncertainty in the $\delta^{18}O_{sw}$-SSS slope should be incorporated in future work simulating pseudocoral trends. Nonetheless, the salinity trend in CMIP3 and CMIP5 models is weak, and near zero, suggesting that the uncertainty in the $\delta^{18}O_{sw}$-SSS relationship is not likely the source of the difference in the coral and pseudocoral trend magnitude. The presence of a significant freshening in historical observations suggests that this discrepancy is more likely due to an underestimation of the 20th century freshening in the CGCMs.

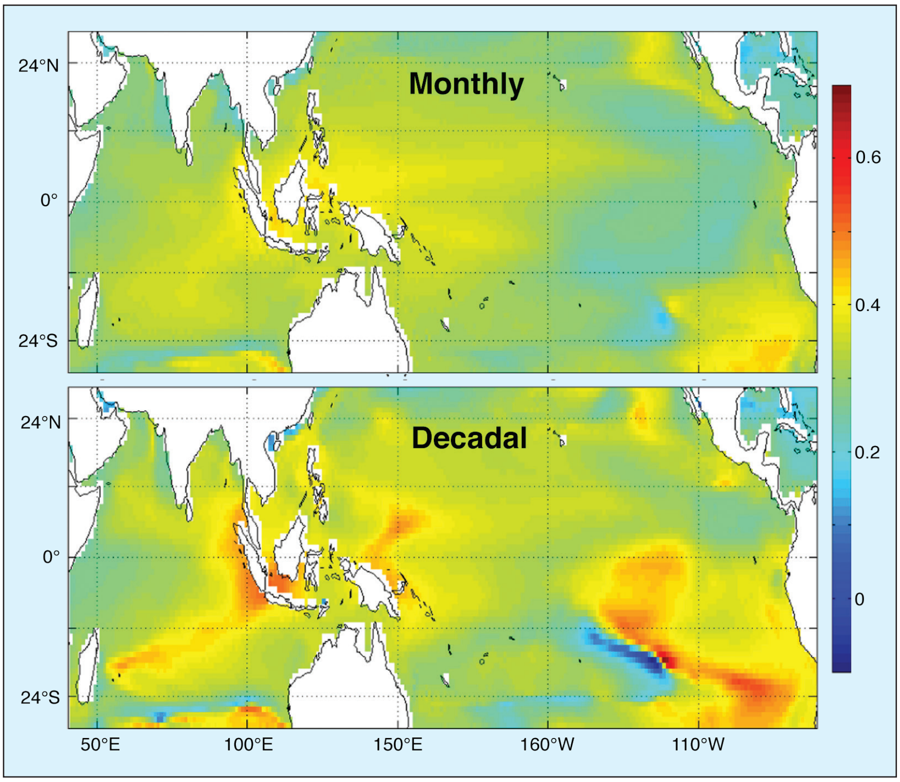

*Figure 2: Slope of the GISS ModelE2 simulated $\delta^{18}O_{sw}$ vs. salinity relationship at each gridbox on monthly **(top)** and decadal **(bottom)** timescales. Decadal series were calculated by averaging the monthly data at 10-year intervals.*

Acknowledgements

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The response of pseudo-corals to ENSO in an isotope-enabled climate model

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Coral stable isotope records provide information on past ENSO variability. However, separating the contributions from variability in ocean temperature and the hydrological cycle to such records remains challenging. Model simulations using water isotope-enabled climate models provide powerful tools to explore this.

The stable oxygen isotopic composition of the aragonite of reef-dwelling corals ($\delta^{18}O_{coral}$) relates to both the temperature, taken here as being the sea surface temperature (SST), and the isotopic composition of the seawater ($\delta^{18}O_{sw}$) in which calcification occurred. The relationship between $\delta^{18}O_{coral}$ and SST, derived from modern calibrations, generally has a slope that is close to the value of -0.2‰ K^{-1} found for inorganically precipitated carbonates (e.g. Gagan et al. 2000; Zhou and Zheng 2003). Some long-lived corals generate sufficiently high growth rates as to allow measurement of $\delta^{18}O_{coral}$ at sub-annual resolution over multiple decades (e.g. Carré et al., this issue). These properties provide a strong basis for using fossil corals $\delta^{18}O_{coral}$ to reconstruct SST variability associated with the El-Niño Southern Oscillation (ENSO) over the Holocene and LGM (e.g. Tudhope et al. 2001; Cobb et al. 2003).

However, $\delta^{18}O_{coral}$ also depends directly on $\delta^{18}O_{sw}$, which is in turn influenced by a range of factors. Some of these factors may be closely coupled to ENSO, such as the local precipitation-evaporation balance, but others relate instead to the integrated hydrological history of the precipitation. In regions with a very active hydrological cycle, where the $\delta^{18}O_{sw}$ contribution is thought to dominate the overall $\delta^{18}O_{coral}$ signal, records have been used to infer past changes in precipitation, rather than SST (Cole and Fairbanks 1990). Fully quantifying the spatial pattern of relative contributions from SST and $\delta^{18}O_{sw}$ to $\delta^{18}O_{coral}$ remains a challenge for interpreting these records.

Limitations of the instrumental record

Instrumental records of $\delta^{18}O_{sw}$ are not available for most coral bearing locations and those that do exist are typically too short to allow robust quantification of inter-annual changes in $\delta^{18}O_{sw}$ (Schmidt 1999; LeGrande and Schmidt 2006). However, the $\delta^{18}O_{sw}$ contribution can be estimated empirically from an instrumental SST record, provided that (1) the ENSO-related $\delta^{18}O_{sw}$ fluctuations relate linearly to those in SST and (2) this relationship remains stationary throughout the period of interest. An example of a case in which the first assumption may be compromised is if the source region for precipitation changes with the magnitude of ENSO events. The second assumption may be compromised if the dominant spatial "modes" of ENSO variability change through time (Yeh et al. 2009; Capotondi et al., this issue). Climate model realizations of the response of $\delta^{18}O_{sw}$ to ENSO fluctuations have the potential to better constrain the validity of such assumptions.

Representing pseudo-corals in an isotope-enabled climate model

Only a few coupled Ocean/Atmosphere General Circulation Models (GCMs) include the additional hydrological cycle processes required to directly simulate water isotope variables such as $\delta^{18}O_{sw}$. Modeling pseudo-coral records based on the use of $\delta^{18}O_{sw}$ proxy variables such as salinity, provide a strategy to avoid this limitation (Thompson et al. 2011, this

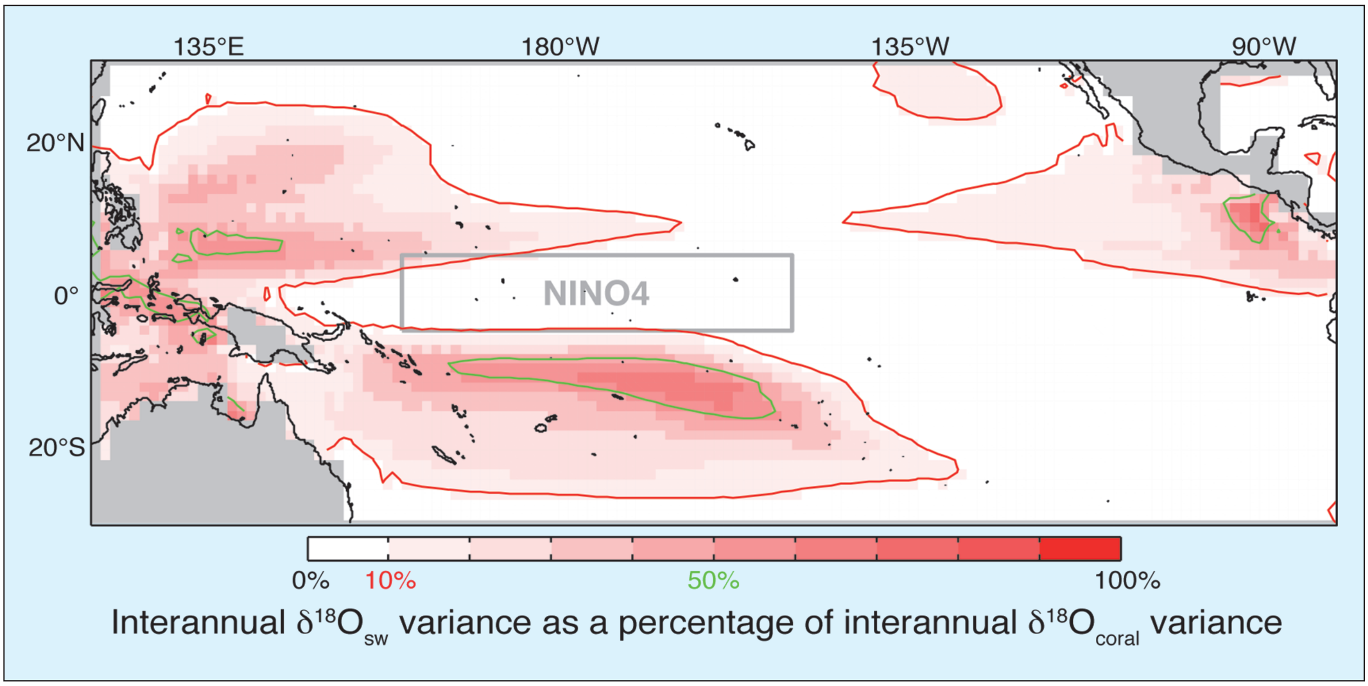

Figure 1: The percentage of modeled interannual $\delta^{18}O_{coral}$ variance accounted for by $\delta^{18}O_{sw}$, assuming a SST - $\delta^{18}O_{coral}$ slope of -0.2‰ K^{-1}. The 10% and 50% levels are contoured in red and green respectively and the location of the NINO4 region is highlighted in gray.

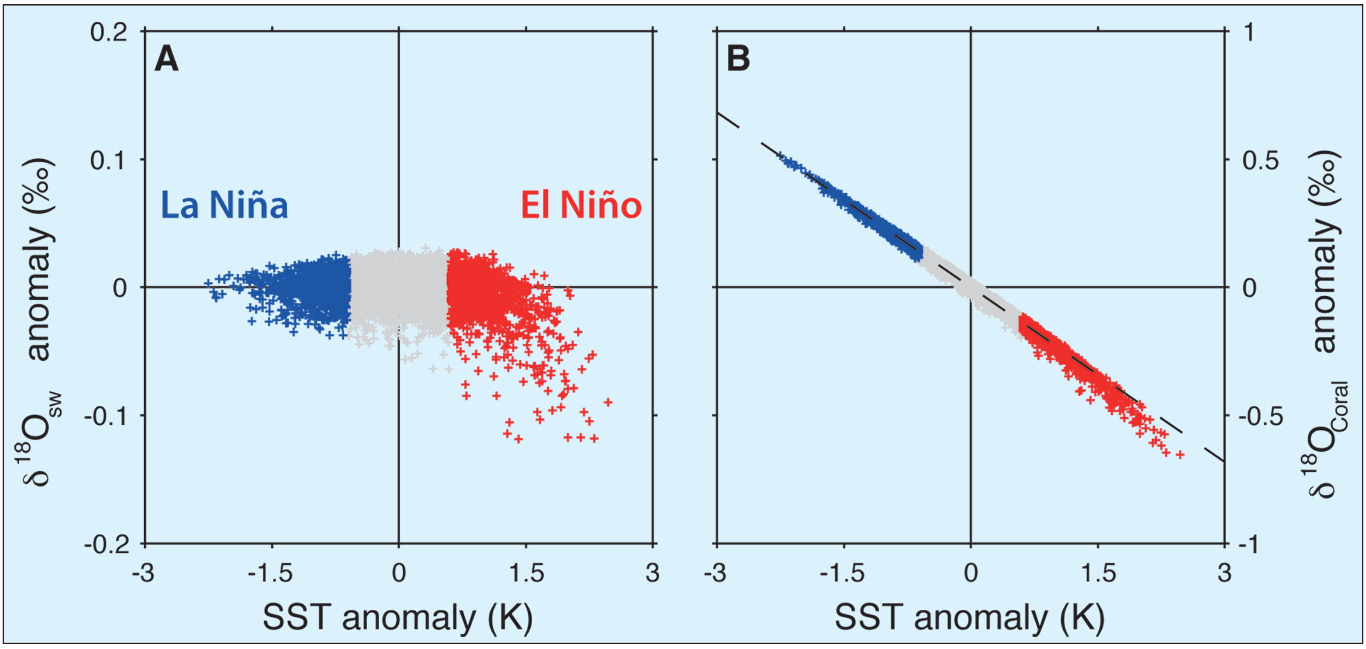

Figure 2: Scatter plots of modeled monthly inter-annual anomaly data within the NINO4 box. ***A)*** *$\delta^{18}O_{sw}$ plotted against SST.* ***B)*** *$\delta^{18}O_{coral}$ plotted against SST, with the assumed slope of -0.2‰ K^{-1} used to calculate $\delta^{18}O_{coral}$ shown as a dashed line. Points are color coded according to their SST anomaly values, such that those lying in the upper and lower standard deviations of the SST data are highlighted red and blue, and are associated with El-Niño and La-Niña events respectively.*

issue). However, work with the isotope-enabled Goddard Institute for Space Studies ModelE-R shows that the slopes of the $\delta^{18}O_{sw}$-salinity relationships may differ when calculated over temporal and spatial patterns of variability (LeGrande and Schmidt 2009). The results presented here are based on a 750-year long pre-industrial control simulation of another isotope-enabled coupled GCM, the UK Met Office's HadCM3 (Russon et al. 2013; Tindall et al. 2009). The inter-annual variability of the tropical climate in HadCM3 is known to be dominated by processes exhibiting spatial and temporal patterns resembling, albeit with significant biases, those of the observed ENSO phenomenon (Collins et al. 2001; Guilyardi et al. 2006). For this study, the water isotope regimes were brought to equilibrium by first running the model for an additional 300 years from an assumed initialization state. The pseudo-coral $\delta^{18}O_{coral}$ field is then calculated directly by inputting the monthly-mean SST and $\delta^{18}O_{sw}$ data for the ocean grid resolution of 1.25° by 1.25° over the tropical Pacific (30°S-30°N and 120°E-80°W) into a linear formulation of the standard isotope paleo-temperature equation, with an assumed $\delta^{18}O_{coral}$ to SST slope of -0.2‰ K^{-1}.

Quantifying the $\delta^{18}O_{sw}$ contribution

Modeled inter-annual fluctuations in $\delta^{18}O_{sw}$ vary inversely with those in SST across almost the entire tropical Pacific region such that they combine positively. The fraction of the inter-annual variance of pseudo-coral $\delta^{18}O_{coral}$ that could be accounted for by the inter-annual variance of modeled $\delta^{18}O_{sw}$ is less than 10% (red contour in Fig. 1) across much of the subtropical eastern and equatorial Pacific, but higher in the Warm Pool, South Pacific Convergence Zone, and central American coastal regions. This affirms that the $\delta^{18}O_{sw}$ contribution is indeed important in regions of high precipitation variability (Tudhope et al. 2001; Cole and Fairbanks 1990). Consequently, whilst eastern Pacific pseudo-coral $\delta^{18}O_{coral}$ could be reasonably used as a proxy of SST fluctuations, this is not the case for all locations. However, only in very limited regions does the $\delta^{18}O_{sw}$ contribution exceed 50% (green contour in Fig. 1). Even within the high precipitation regions, there are no locations where one would expect the SST contribution to be negligible. Therefore, interpreting western Pacific corals as solely (or even predominantly) dependent on either temperature or precipitation appears misguided for many locations in the model.

Non-linearity between SST and $\delta^{18}O_{sw}$

The regional relationships between modeled SST and $\delta^{18}O_{sw}$ are not always simple. For example, in the western equatorial Pacific NINO4 region (grey rectangle in Fig. 1), little relationship is seen between modeled SST and $\delta^{18}O_{sw}$ during La-Niña (blue crosses), neutral (grey crosses) and even moderate El-Niño (red crosses) regimes (Fig. 2a). This results in pseudo-coral $\delta^{18}O_{coral}$ values that lie close to the imposed $\delta^{18}O_{coral}$ -SST slope (Fig. 2b). In such situations, the $\delta^{18}O_{sw}$ variability effectively adds (a relatively small degree of) noise to the $\delta^{18}O_{coral}$ record. However, during larger El-Niño events a weak anti-correlation between SST and $\delta^{18}O_{sw}$ becomes evident (lower right quadrant of Fig. 2a), such that for SST anomalies exceeding ~1.5K, a deviation from the imposed slope of the $\delta^{18}O_{coral}$ -SST relationship becomes noticeable (lower right quadrant of Fig. 2b). For large El-Niño events, estimating NINO4 SST directly from $\delta^{18}O_{coral}$ would result in a relative overestimation of the true SST anomaly by over 20%. This effect would complicate attempts to accurately infer the relative magnitudes of the SST anomalies during El-Niño events of different magnitude from proxy records of $\delta^{18}O_{coral}$ alone.

Acknowledgements

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Note

The model data presented here are available upon request from the corresponding author.

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ENSO and changes in the mean state in Holocene simulations

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Simulations suggest that Pacific interannual changes in sea surface temperature (SST) are smaller than SST seasonality, whereas the opposite is modeled for precipitation. Nonstationarity in ENSO patterns may affect the interpretation of past variability changes from climate records.

High-resolution paleoclimate indicators provide a unique opportunity to reconstruct and understand how seasonal climate variability and the El Niño-Southern Oscillation (ENSO) have evolved in the past. However, most climate interpretations of paleorecords assume stationarity, i.e. that the modern relationship between a given climate sensor and ENSO was the same in the past, which might not be true. Therefore, one of the difficulties is to infer how changes in mean state and variability have shaped the evolution of SST and other environmental factors, such as precipitation and wind, in the past. Using a suite of simulations performed with the climate model of the Institut Pierre Simon LaPlace (IPSL-CM4; Marti et al. 2010), we discuss the relative effects of different Holocene forcings on seasonality and interannual variability between the early Holocene and the pre-industrial period.

Sensitivity experiments

Previous simulations and model data comparison have established that long-term changes in insolation affected ENSO variability in the Holocene (Clement et al. 2000; Moy et al. 2002). However, the presence of melting remnant ice sheets in the northern hemisphere during the Early Holocene, may have partially offset the impact of the insolation forcing. In this study, simulations of the Early Holocene and the Mid-Holocene are used to infer how the slow variation of the Earth's orbital parameters affected ENSO variability (Luan et al. 2012). We also conducted a set of sensitivity experiments to examine how meltwater release and the presence of remnant northern hemisphere ice sheets may have impacted ENSO characteristics (Braconnot et al. 2012; Marzin et al. in press). The different model years in the simulations were classified either as El Niño, La Niña, or normal years based on the December-January-February SST anomalies in the Niño3 region (150°W-90°W, 5°S-5°N). Anomalies were only classified as El Niño or La Niña events when they crossed a SST threshold of 1.2 times the standard deviation derived from the pre-industrial SST time series.

ENSO is the dominant mode of SST and precipitation variability in all of the simulations. However, both the pre-industrial and past El Niño event simulations are affected by biases common to most climate models (Zheng et al. 2008). For example, the cold tongue (i.e. the equatorial region in the Pacific with cold SSTs) of normal years penetrates too far west along the equator (not shown), as does the equatorial warming associated with El Niño events (Fig. 1a,c). As a result the horseshoe structure of El Niño's SST and precipitation patterns seen today in the western Pacific is not well pronounced. This discrepancy can lead to misinterpretation when comparing simulated changes with high-resolution coral records from the central equatorial Pacific region (Brown et al. 2008). In addition, simulations of ENSO variability are also damped in the eastern Pacific when compared with modern observations.

Spatial variability of ENSO patterns

Our simulations indicate that over time changes in forcing influence the location and intensity of the maximum SST and precipitation anomalies. In the Early Holocene for example, insolation forcing slightly damps the strength of the peak of the event (Fig. 1) compared with pre-industrial control simulations. In these Early Holocene examples a major reduction is simulated west of the maximum

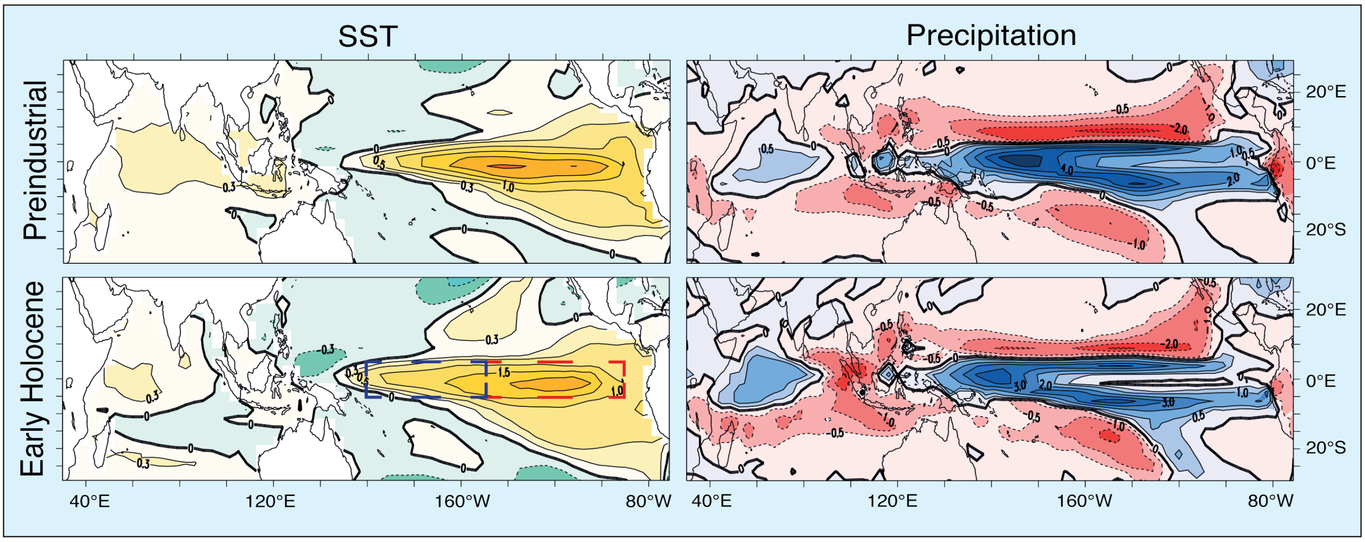

Figure 1: Composite sea surface temperature (SST) anomaly and precipitation anomaly maps during El Niño events as simulated by the IPSL-CM4 climate model for pre-industrial and Early Holocene (9.5 ka BP) climates. The anomalies describe the departures from normal years in each simulation at the peak of the event in December-January. Isolines are plotted every 0.5°C for SST with a refinement of 0.25°C around the 0 line, and every 1 mm d^{-1} for precipitation with a refinement of 0.5 mm d^{-1} around the 0 line. The red and blue dashed boxes in the lower left panel show the Niño3 and Niño4 regions, respectively.

SST anomaly found in the pre-industrial control simulation, and another important reduction occurs on the South-American coast. Figure 1 therefore illustrates that the teleconnections between the different parts of the Pacific basin, as well as between the Pacific and the Indian Ocean, vary depending on the mean climate state. This further suggests that the climatic relationships between regions today are not stationary in time.

Changing seasonality and interannual variability accross time

Insolation forcing also affects the seasonality of SST and precipitation. Changes in the magnitude of the seasonal cycle of precipitation mirror the changes in the seasonal cycle of SSTs.

Figure 2 shows the Early Holocene insolation only simulations (EHnF), and pre-industrial control runs (CTRL) for two regions; the West (Niño4 region; 160°E-150°W, 5°S-5°N), and East (Niño3 region; 150°W-90°W, 5°S-5°N). Compared with the pre-industrial control run, the seasonal cycle of precipitation ("seas" in Fig. 2) was increased in the West (Niño4 region) and decreased in the East (Niño3 region) in the Early Holocene. These precipitation changes follow SST changes (not shown). It indicates that the seasonal variability in insolation was in phase with the SST seasonal cycle in the West and out of phase, in the East. The SST seasonal cycle is further amplified by the east-west asymmetry of cloud feedback and the dynamic response of SST to anomalous westerly winds in the eastern equatorial Pacific (Luan et al. 2012). As a consequence, seasonality had a larger effect on SSTs than do changes in interannual ENSO variability, even in the east Pacific (Braconnot et al. 2012).

With regards to precipitation, we note a reduction of larger absolute magnitude associated with El Niño and La Niña events in both the Niño3 and Niño4 regions when compared with the pre-industrial control runs (Fig. 2). Thus, both seasonality and interannual variability damp the SST and precipitation variations in the eastern Pacific, whereas seasonality enhance and variability damp precipitation in the central Pacific.

Our analyses have implications when interpreting records of past ENSO variability across different regions. In the eastern Pacific, Early Holocene seasonality and interannual SST and precipitation variability are reduced compared with SST and precipitation variability in the pre-industrial run. Therefore climate

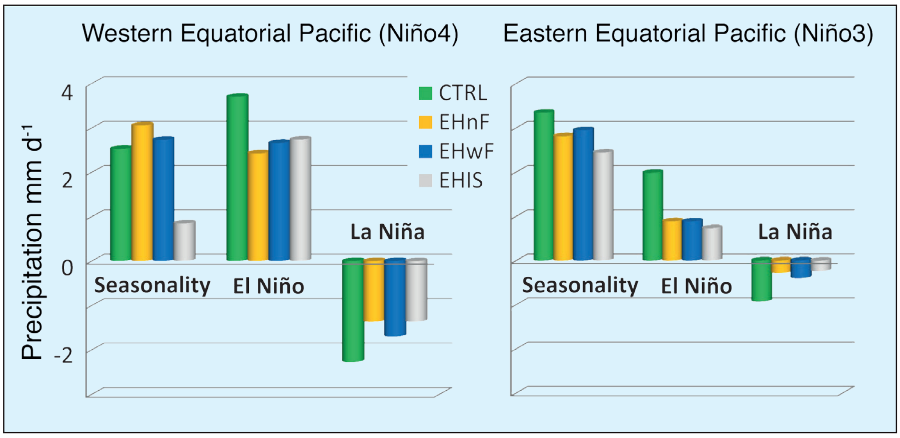

Figure 2: Sensitivity experiments: Diagrams of precipitation (mm d^{-1}) averaged over the Niño3 and Niño4 regions in the Pacific Ocean. Groups of columns show the magnitude of the seasonal cycle and the peak (December) magnitude of El Niño and La Niña events for each of the simulations discussed in the text: pre-industrial (CTRL), Early Holocene (9.5 ka BP, EHnF), Early Holocene with a fresh water flux mimicking ice sheet melting in the North Atlantic (EHwF) and Early Holocene with the presence of remnant Laurentide and Fennoscandian ice sheets (EHIS). See Braconnot et al. (2012) for details on the methodology and statistical significance. The magnitude of the seasonal cycle is computed as the difference between maximum and minimum monthly values at the annual time scale. El Niño and La Niña anomalies correspond to the value at the peak of the event in December.

reconstructions, which are primarily determined by the relative sensitivity of climate sensors to seasonality and interannual variability, must take this into account in their calibrations in order to derive robust reconstructions.

In the central to western part of the basin, changes in seasonality and interannual variability act in opposite directions, and our results suggest that only the natural archives that are sensitive to precipitation would register large ENSO changes in the Early Holocene.

Role of additional forcings

The addition of a fresh water flux in the North Atlantic in the Early Holocene simulations leads to increased interannual variability and a slight increase in seasonality (Fig. 2; EHwF) compared with the simulation in which only insolation is changed (Fig. 2; EHnF). This suggests the fresh water flux partially offsets the changes due to insolation compared with the pre-industrial simulation (Fig. 2). This result is similar to the results of fresh water flux experiments under modern (Timmermann et al. 2007) or glacial (Merkel et al. 2010; see also Merkel et al., this issue) conditions. The presence of ice sheets (Fig. 2; EHIS) in the simulations, leads to a strong reduction in seasonality and a further damping of interannual precipitation variability compared with the insolation-only simulation. Particularly in the western Pacific, the results suggest that the remnant ice-sheets in the Early Holocene may have offset the amplification of precipitation seasonality.

Towards a better understanding

Our results show that the pattern of ENSO anomalies between the east and west Pacific is affected differently by forcings, but that SST variations during the Holocene were predominantly influenced by changes in seasonality driven by the Earth's orbital parameters such as insolation.

Linking the development of an El Niño event with changes in the seasonal evolution of the thermocline depth is a key factor explaining the damping of the simulated ENSO in the IPSL models (Luan et al. 2012). Our sensitivity experiments show that fresh water fluxes partially counteract the insolation-driven seasonal phasing and the melting remnant ice sheets strongly affect the mean thermocline depth and east-west gradient in SSTs (Luan et al. submitted). However, it seems that precipitation and SSTs do not necessarily vary with the same relative strength on seasonal and interannual timescales when subject to the same sensitivity experiments. These findings suggest that a better understanding of the controls and timescales of variability is necessary to interpret paleo-records of past ENSO variability correctly, and that paleo-records should be used with caution to test how well models reproduce changes in ENSO variability.

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A controversial insight into Southwest Pacific mid-Holocene seasonality: from corals to models

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[§]To Guy, in memoriam

"Seasonal amplitude was higher in the Southwest Pacific during the mid-Holocene," say the corals. "It was not," reply the models. "More work is needed," agree the researchers…

In the Southwest (SW) Pacific, the seasonal changes in seawater surface characteristics, such as temperature (SST) and salinity (SSS), are governed mainly by the position and intensity of the South Pacific Convergence Zone (SPCZ) and by the occurrences of El Niño and La Niña events. The SPCZ is a southeast narrow cloudy belt that influences the wind and rain conditions from Papua New Guinea to French Polynesia (Trenberth 1976). During the austral summer, the SPCZ moves southwest whereas during the austral winter it moves north. Consequently, waters in the SW Pacific are generally warmer and less saline during the austral summer, and colder and saltier in winter. At the interannual time scale, the main changes in SST and SSS in the SW Pacific relate to El Niño-Southern Oscillation (ENSO) dynamics, with a periodicity of ca. 2-7 years (Trenberth 1976). During an El Niño event, warm waters of the equatorial West Pacific (the Warm Pool) and connected precipitation migrate toward the central and eastern Pacific. Consequently, the SW Pacific SST decreases slightly while precipitation decreases strongly, leading to higher SSS (e.g. Delcroix 1998). The opposite occurs during La Niña events. Therefore, knowledge of past water characteristics at a seasonal resolution has the potential to provide information on the position and intensity of the SPCZ as well as on the occurrence of ENSO events. Mid-Holocene (6 ka BP) hydrographic proxy data from the SW Pacific are rare. However, this is a key period, characterized by a change in ENSO amplitude that is unfortunately not yet entirely understood.

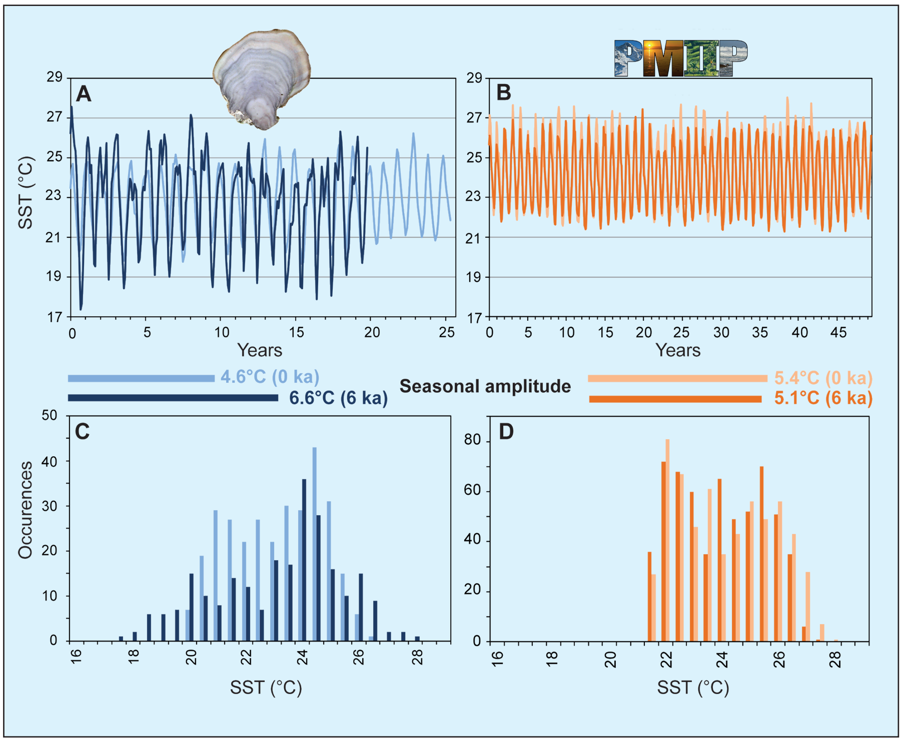

*Figure 1: Comparison between coral (blue) and model run (orange) results in terms of sea surface temperature (SST; °C) characteristics in the New Caledonia region for the present (light colors) and the mid-Holocene (dark colors) situations. **A)** Monthly coral time series from New Caledonia, at present (light blue, Stephans et al. 2004; Stephans et al. 2005) and from a coral fossil from the mid-Holocene (5.5 ka BP, dark blue; Lazareth et al. 2013). **B)** Monthly time series from the CCSM PMIP2-models for the New Caledonia region (160-164°E 20-24°S), at present (light orange) and at the mid-Holocene (6 ka BP; dark orange; Otto-Bliesner et al. 2006). **C, D)** Monthly SST histograms and calculated seasonal amplitude.*

Corals and numerical models: tools to look back in time

Past seasonal data on SST and SSS can be obtained from archives such as massive coral skeletons. The aragonitic skeleton of coral is secreted by polyps over several decades or centuries, at a rate of around 1 cm $year^{-1}$ for massive forms. The chemical composition of skeletal aragonite reflects the properties of the water in which the coral has lived. In tropical areas, studies focus on the massive *Porites sp.* corals. The Strontium/Calcium (Sr/Ca) ratio (Corrège 2006) is a robust proxy for SST in these corals. The stable oxygen isotopic ratio ($\delta^{18}O$) is used, combined with Sr/Ca, to reconstruct the isotopic composition of surface seawater ($\delta^{18}O_{sw}$), which is in turn closely related to SSS (via the evaporation vs. precipitation budget).

Climate models, based on current knowledge of the various compartments of the Earth system, help understand modern climate variability and predict future changes. Climate models with external forcings different to current ones (e.g. different orbital forcings, ice sheets, greenhouse gas concentrations) can be used to simulate past climatic changes. Many model simulations exist for the mid-Holocene (e.g. 19 in the Paleoclimate Modelling Intercomparison Project [PMIP2] database; http://pmip2.lsce.ipsl.fr/; Braconnot et al. 2007). Their main forcing is a millennial-scale change in the seasonality of insolation. For the SW Pacific region, the insolation for January to March was lower than at present while it was higher for August to October.

To gain an insight into SW Pacific mid-Holocene mean climate at seasonal resolution and hence into ENSO characteristics, we studied corals from New Caledonia and Vanuatu which have been dated to 5.5 ka BP and 6.7-6.5 ka

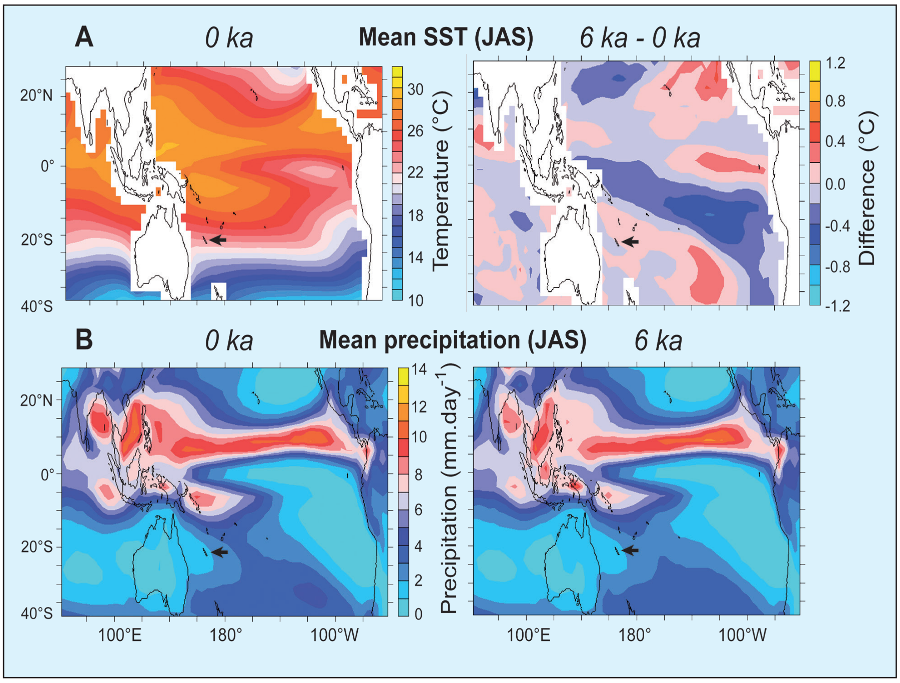

Figure 2: Multi-model mean maps for the winter season (July-August-September, JAS). Six PMIP2 simulations having similar resolution and reproducing correctly the mean seasonal cycle in the New Caledonia region have been used. The arrow points to New Caledonia. ***A)*** *SST multi-model maps at 0 ka (left) and difference (6 ka – 0 ka; right).* ***B)*** *Multi-model mean precipitation field at 0 ka (left) and 6 ka (right). Modified from Lazareth et al. (2013).*

BP respectively. A ~1 cm-thick slab, cut along the axis of maximum growth of the coral colonies, was X-rayed to reveal the annual growth bands. To ensure the skeleton was well preserved, pieces were collected and analyzed for their mineralogy using X-ray diffraction, and for their microstructure using scanning electronic microscopy. If the skeleton preservation was found to be satisfactory, the slab was continuously sampled at 1-mm steps, providing on average one sample per month of coral growth. The samples were then dissolved and analyzed to determine their chemical composition. The New Caledonia coral was too short (~20 years) to investigate ENSO dynamics and as the $\delta^{18}O$ proved to be partly altered, only the SST reconstructed with Sr/Ca will be discussed here.

The 6 ka BP PMIP2 model simulations show a cooling of the tropical Pacific SST (Zheng et al. 2008) and a decrease in seasonal SST amplitude (south of 10°S and between 160-260°E for the South Pacific) related to the insolation change. The results obtained on the New Caledonia coral were compared with the six simulations for which monthly data were available and which correctly reproduced the current SST cycle in the New Caledonia region on four 2° by 2° grid points (164-168°E, 20-24°S).

The SPCZ at 6 ka BP: Where was it located?

In the New Caledonia lagoon, the mid-Holocene SST seasonal amplitude as seen by the corals was higher than nowadays (Fig. 1a). This difference is mainly due to colder mid-Holocene winters. In the New Caledonia region, the histogram of both the modern and mid-Holocene coral-reconstructed SST monthly values (Fig. 1c), and the 0 ka BP model outputs (Fig. 1d) show two modes, corresponding to the positions of the SPCZ in winter (July-August-September, JAS) and in summer (December-January-February, DJF). In the 6 ka BP coral results however, colder temperatures prevail in the winter mode, with a wider distribution. We interpret this as reflecting a more variable position and/or a weakening of the SPCZ during mid-Holocene winters. None of the PMIP2 models for the New Caledonia region reproduce an increase in seasonal SST amplitude in the mid-Holocene and the bi-modality is maintained (Fig. 1d). The models generally follow the insolation change: a warmer winter and a colder summer, leading to reduced seasonality (Fig. 1b).

For the Vanuatu corals, Sr/Ca and $\delta^{18}O$ were measured as proxies for SST and SSS, respectively, and data from the longest colony were used to highlight ENSO characteristics during the early mid-Holocene. The precipitation regime in Vanuatu at 6.7-6.5 ka BP was different from the current one. Fossil corals indicate peaking SSS in summer (DJF) whereas low SSS would have been expected from the reduced summer insolation at that time. Indeed, summer today is accompanied by strong precipitation brought by the southward displacement of the SPCZ. The reconstructed high mid-Holocene SSS suggests that in the SW Pacific at 6.7-6.5 ka BP the SPCZ was located further north than nowadays (Duprey et al. 2012). At that time, ENSO variability was reduced by 20-30% compared to the modern ENSO. It remains uncertain, however, whether the reduced ENSO variability reflects a real trend in ENSO dynamics or if it resulted from a weaker coupling between the precipitation regime and the SPCZ.

Are proxy data and models compatible for 6 ka BP?

While coral records suggest a reduced SPCZ influence in the SW Pacific, possibly from 6.7-6.5 to 5.5 ka BP, the PMIP2 model maps of precipitation reveal only a small shift of the SPCZ towards the northeast and a decrease in associated precipitation during the winter months (Fig. 2b). These small changes, although in the right direction, are, however, not sufficient to simulate an increase in the SST seasonality in the SW Pacific region at 6 ka BP.

The modeled insolation-driven hemispheric change in seasonality is not reflected in the SW Pacific proxy data. This suggests the models have difficulty in reproducing mid-Holocene changes in coupled ocean-atmosphere circulation in this region. This could be due to known model biases in representing the current, and thus also the 6 ka BP, SPCZ, and to the models' large grid size to which the SPCZ seasonal displacement is sensitive. On the other hand, corals are shallow water organisms and the SST and SSS they record may not be valid for open oceans. Clearly, more data and new model runs are needed to understand the amplitude and geographical pattern of western Pacific mid-Holocene changes.

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Interannual variability in the tropical Pacific and associated atmospheric teleconnections during the last glacial period

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Simulations of the climate of Marine Isotope Stages 2 and 3 suggest pronounced ENSO variability during the Heinrich Stadial 1 period when the Atlantic overturning circulation was weaker. Our model results also highlight the nonstationarity of ENSO teleconnections through time.

A well-known example of coupled ocean-atmosphere interaction on interannual timescales is the El Niño-Southern Oscillation (ENSO) phenomenon in the tropical Pacific. Consensus is still lacking about how ENSO will behave under future climate conditions, even in the latest generation of comprehensive climate models (Guilyardi et al. 2012).

Major goals of paleoclimatic research are to provide constraints on the possible range of changes in response to modified boundary conditions and to identify possible feedback and amplification mechanisms in the climate system. In this context, climate models are valuable tools for investigating different climate scenarios that have occurred in the past. Most ENSO studies, however, are limited to the two priority periods specified by the Paleoclimate Modeling Intercomparison Project (PMIP): the Mid-Holocene, and the Last Glacial Maximum (LGM; e.g. Zheng et al. 2008). However, proxy data from the tropical Pacific (e.g. Stott et al. 2002; Leduc et al. 2009; Dubois et al. 2011) suggest that ENSO also changed on millennial timescales, e.g. in association with pronounced abrupt climate changes related to the Dansgaard-Oeschger stadials and interstadials during Marine Isotope Stage 3 (MIS3, 59-29 ka BP).

Modeling ENSO for different glacial climate states

The first modeling studies that addressed MIS3 were limited to intermediate complexity models (e.g. Ganopolski and Rahmstorf 2001; van Meerbeeck et al. 2009; Ganopolski et al. 2010), a regional model approach (e.g. Barron and Pollard 2002), or an atmosphere-only setup (Sima et al. 2009), unsuitable to capture the complexity of ENSO dynamics. Recently, the first simulations of MIS3 climate in a comprehensive coupled climate model were accomplished with the US National Center of Atmospheric Research's CCSM3 model (Merkel et al. 2010). The study used a timeslice approach with a focus on a period of relatively regular Dansgaard-Oeschger variability around 35 ka BP. When 35 ka BP boundary conditions (greenhouse gas concentrations, orbital parameters, continental ice sheet distributions) are prescribed, the model simulates a very weak Atlantic meridional overturning circulation (AMOC) of about 7 Sv, which is much weaker than the preindustrial value of 12 Sv, but also weaker than the ~10 Sv simulated for the LGM. Therefore, we consider the simulated 35 ka BP climate as a stadial climate state. The counterpart of an interstadial climate state is induced in the model by a 0.1 Sv freshwater extraction from the North Atlantic over ~300 model years, thereby forcing a resumption of the AMOC to ~14 Sv.

Our set of experiments also includes a simulation of a Heinrich Stadial 1 scenario. This is set up by imposing a freshwater perturbation of about 0.2 Sv to a simulated LGM ocean state over 360 model years. This is motivated by earlier studies which mimic past Heinrich events by hosing freshwater into the modern ocean and thereby demonstrate that a slowdown of the AMOC may have a pronounced impact on the tropical Pacific (e.g. Timmermann et al. 2007).

One of our major findings was that interannual (about 1.5-8 years) variability in sea surface temperatures (SST) of the eastern tropical Pacific was distinctly increased in our Heinrich Stadial 1 simulation compared to pre-industrial times, whereas variability in our LGM and MIS3 simulations was systematically reduced, albeit only weakly (Fig. 1). Modern ENSO dynamics studies show that stronger ENSO variability is dynamically linked to a weaker annual cycle of SST and to a weaker meridional asymmetry of SST across the equator in the eastern tropical Pacific (Guilyardi 2006; Xie 1994). Our model results show that these relationships also hold for the different simulated glacial climate states. In particular, our Heinrich Stadial 1 simulation exhibits a much weaker north-south contrast in eastern tropical Pacific SST than under

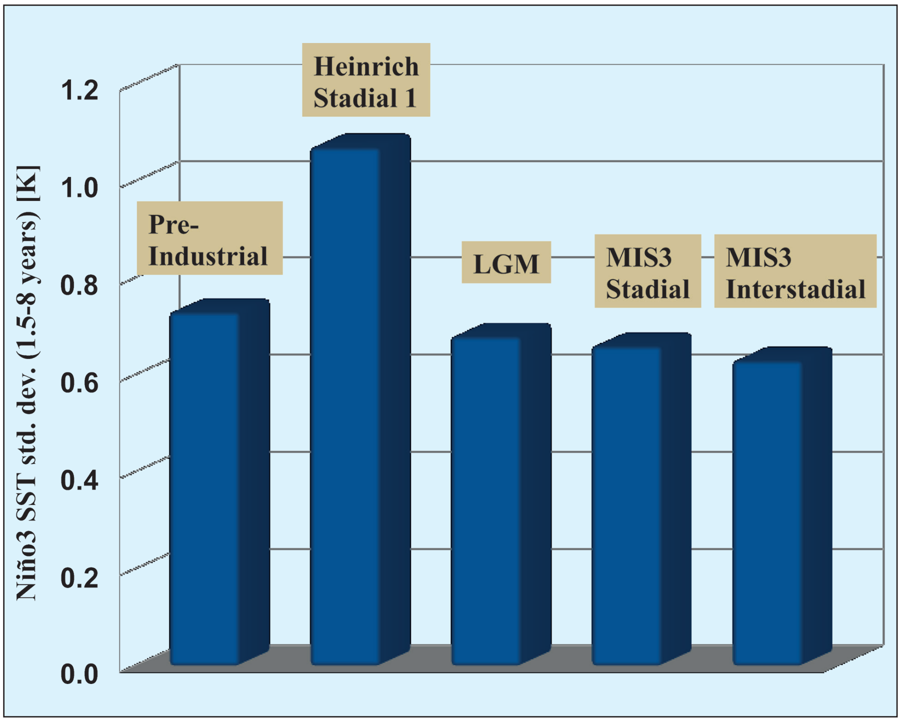

Figure 1: ENSO variability of sea surface temperature in the eastern tropical Pacific (Niño3 region: 150°W-90°W, 5°S-5°N) for different simulated climatic states.

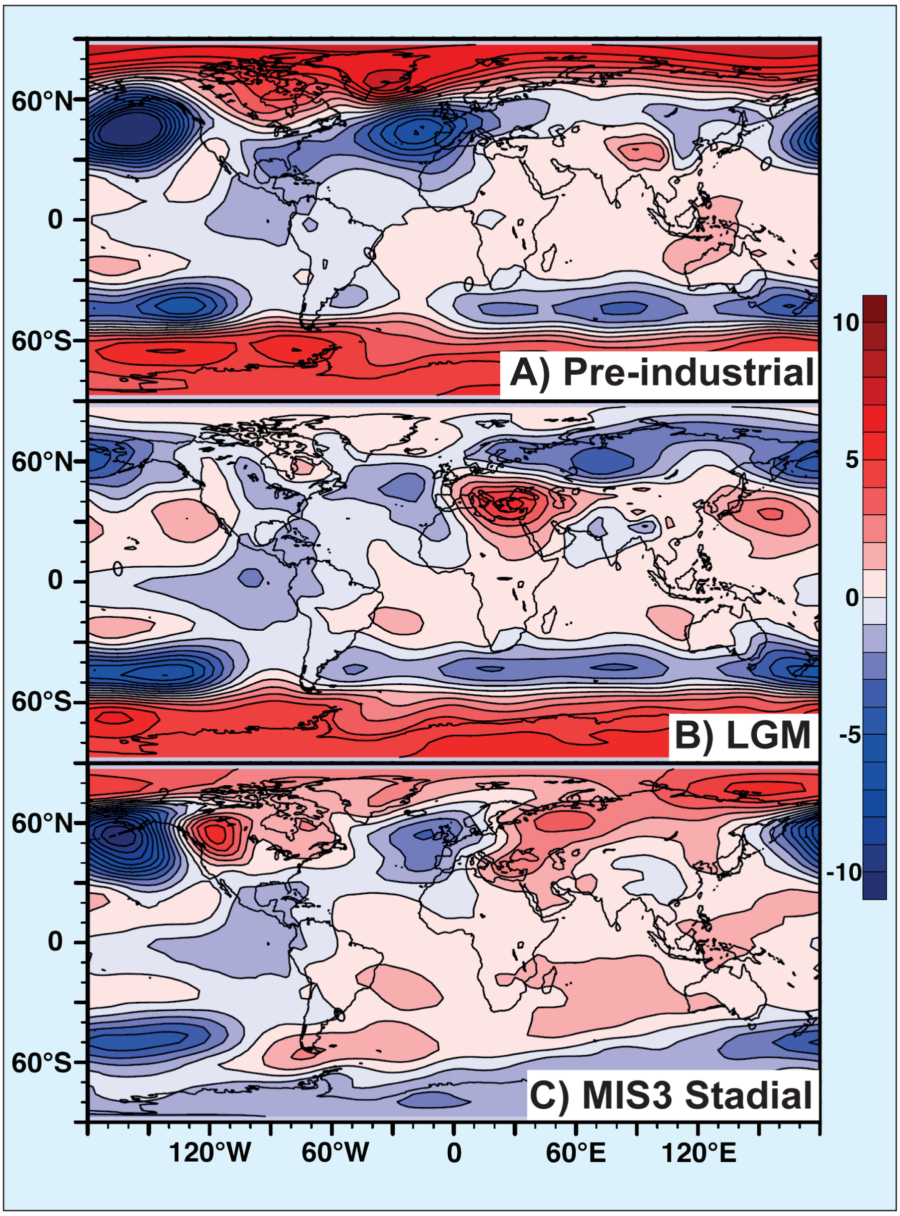

Figure 2: ENSO teleconnections during boreal winter (Dec.-Feb.): El Niño minus La Niña composites of sea level pressure [hPa] for ***(A)*** *pre-industrial control climate,* ***(B)*** *Last Glacial Maximum (LGM), and* ***(C)*** *Marine Isotope Stage 3 (MIS3) stadial climate. Figure modified from Merkel et al. 2010.*

modern conditions. This is attributed to an atmospheric signal communication from the strongly cooled North Atlantic into the tropical Pacific.

Model-data comparison

Further insights into tropical Pacific variability can be achieved through model-data intercomparison. Felis et al. (2012) present findings from a fossil coral retrieved during IODP Expedition 310 near Tahiti. The coral has been dated to Heinrich Stadial 1. Its fast growth rate allows sampling at monthly resolution and provides a unique opportunity to investigate interannual SST variability in the southwestern tropical Pacific during that period. The coral record exhibits pronounced variability at interannual ENSO frequencies during Heinrich Stadial 1, consistent with the basin-wide increase in ENSO variability in our Heinrich Stadial 1-analogue simulation. At the Tahiti location, the coral and the model are also quantitatively consistent, as both suggest a strengthening of interannual SST variability by 20-30% compared to modern conditions.

Modern and past ENSO teleconnections

Modern ENSO is well known for its atmospheric teleconnections of near-global extent. Understanding how teleconnections operate, both in the atmosphere and the ocean, is particularly relevant for the validity of paleoclimatic reconstructions, as they generally assume that atmospheric teleconnection patterns are stable. This may be particularly critical in the interpretation of proxy records not stemming from the core ENSO region. A composite analysis of atmospheric patterns (e.g. of sea level pressure) during all El Niño and La Niña events in the different simulations revealed obvious deviations from the modern spatial distribution of anomalies (Fig. 2). In particular, the teleconnections to the North American continent and the North Atlantic region seem to be strongly altered in terms of amplitude and spatial structure in the LGM and MIS3 simulations. This difference is probably caused by the presence of the glacial continental ice sheets and the glacial cooling of the North Atlantic, which both affect the position of the upper-tropospheric jetstream and atmospheric storm tracks, and thus the tropical-extratropical signal propagation. The typical intensification of the Aleutian low forced by El Niño (Fig. 2a) seems to be present during the LGM but is less pronounced, and the atmospheric bridge to the North Atlantic region seems to be interrupted, as no clear large-scale pattern is simulated there (Fig. 2b). The MIS3 stadial conditions (Fig. 2c) bear more resemblance to the control simulation over the North Pacific, whereas over the North Atlantic, the ENSO influence is clearly reduced, similar to the LGM situation. This points to a complex interplay of atmospheric dynamics with the various forcings in the different climatic states.

The need to learn more about glacial climatic states

In summary, our modeling study confirms that ENSO variability responds to various glacial climatic states. However, ENSO variability does not appear to be linearly linked to the strength of the AMOC. This calls for more detailed analyses, for instance in the form of glacial hosing studies in a multi-model approach (Kageyama et al. 2013). The different roles of the AMOC and the various glacial boundary conditions with respect to their impact on ENSO need to be further disentangled. Likewise, we emphasize that the concept of stationary teleconnections should only be applied to past climatic states with caution as they may be altered by different past boundary conditions and forcings internal and external to the climate system.

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ENSO behavior before the Pleistocene

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The Pliocene was characterized by a weak equatorial sea surface temperature gradient in the Pacific, confusingly reminiscent of that seen fleetingly during an El Niño. Data also show interannual variability in the Pliocene, raising questions about ENSO's dependence on the mean climate state.

The behavior of the El Niño–Southern Oscillation (ENSO) in pre-Pleistocene climates is highly uncertain. This uncertainty is rooted in a fundamental lack of evidence. However, several, recent studies focusing on past warm climates are beginning to address this issue. These studies were motivated by suggestions that the climate of the early Pliocene was a "permanent El Niño" – a term that has led to much confusion. After looking at the new evidence for ENSO, I will discuss the history of the term "permanent El Niño", before suggesting that it should be consigned to history as well.

Pre-Pliocene ENSO

Detection of interannual variability requires paleoclimate indicators that monitor changes over short timescales such as the thickness of varved sediments and isotope ratios in long-lived fossil mollusks or corals. Once a record spanning sufficient years has been recovered, its power spectra can be analyzed for frequencies representative of ENSO. ENSO has been detected during the warm intervals of the Miocene (5.96-5.32 Ma; Galeotti et al. 2010), Eocene (45-48 Ma; Huber and Caballero 2003; Lenz et al. 2010) and Cretaceous (70 Ma; Davies et al. 2011, 2012) from layered deposits or varved sediments showing a strong peak in the 3-5 years range. It has also been seen in the Eocene (50 Ma; Ivany et al. 2011) from analysis of power spectra of carbon isotopes in fossil driftwood and bivalves. All of these analyses have used records gathered in locations far away from the tropical Pacific, such as Antarctica. However, ENSO teleconnections depend on the mean climate state (Merkel et al., this issue) and may therefore have been different in these early warm periods. The plausibility of assumed teleconnections of that time can be confirmed with climate model simulations of the period (Galeotti et al. 2010; Huber & Caballero 2003; Ivany et al. 2011).

Pliocene ENSO

Two studies have found evidence of ENSO-style periodicity during the Pliocene (Fig. 1) from locations in the Tropical Pacific. Oxygen isotope records from fossil corals (MacGregor et al., this issue) from the Philippines show power spectra similar to recent corals, hence likely representing ENSO variability (Watanabe et al. 2011). Analyses of individual foraminifera from the Eastern Equatorial Pacific (Scroxton et al. 2011) find several instances of isotopic compositions outside the range predicted for the present-day seasonal cycle. This has been interpreted as showing an active ENSO cycle. Unfortunately, a foraminifer does not live through an annual cycle (unlike mollusks; e.g. Carré et al., this issue), so changes in the seasonal cycle (Braconnot and Luan, this issue) are a potential source of uncertainty.

Despite the complications associated with each individual study, a picture is emerging in which ENSO is a pervasive feature of past climate. However, a systematic effort will be needed to provide quantitative information from these pre-Pliostocene intervals that could qualify for data-model comparisons.

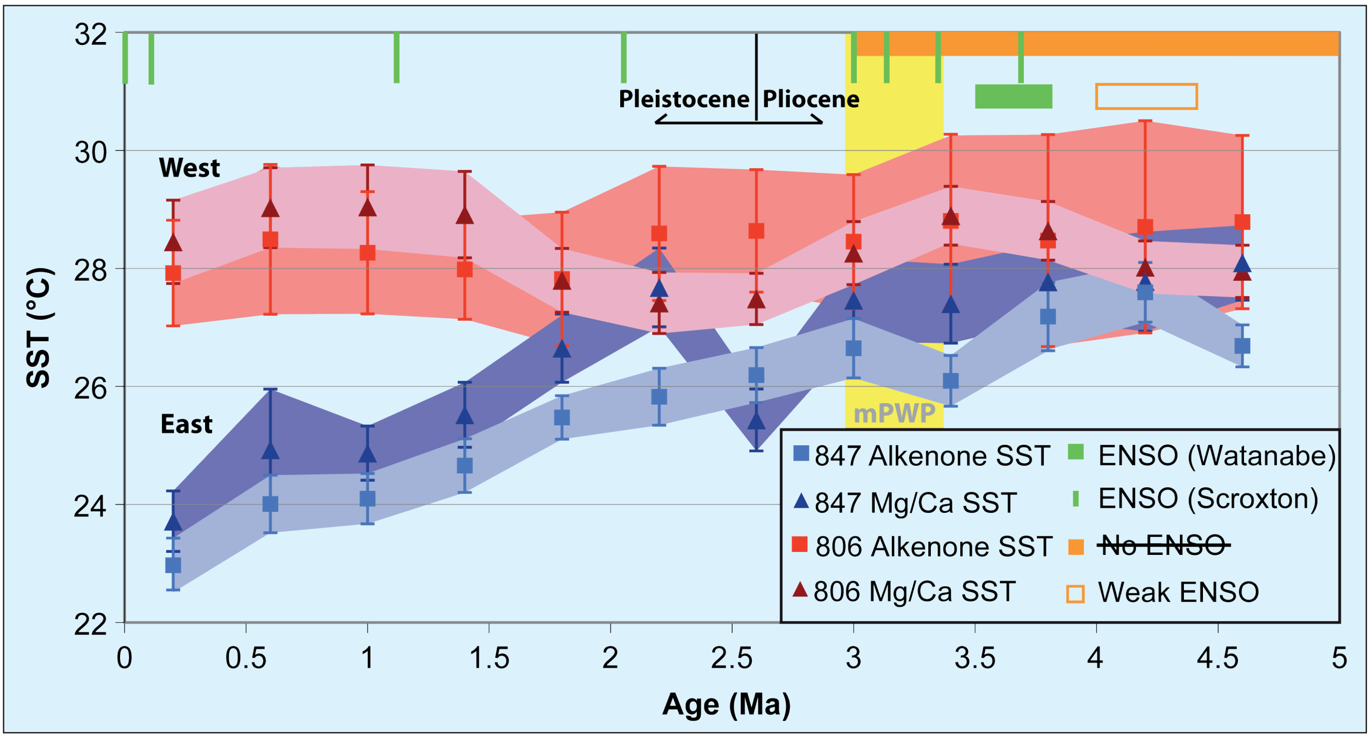

Figure 1: Variation in the Sea Surface Temperature in the Equatorial Pacific over the past five million years. The estimates come from two ocean cores in the West (ODP 806 at 150°E) and the East (ODP 847 at 95°W). Two different types of record are used to reconstruct the temperatures: Mg/Ca (Wara et al. 2005) and alkenones (Dekens et al. 2007; Pagani et al. 2010). The period described as lacking ENSO variability (i.e. the period of the "permanent El Niño") from a mistaken interpretation of Fedorov et al. (2006) is shown in orange. Times with observed ENSO variability, as found by Scroxton et al. (2011) and Watanabe et al. (2011), are marked in green. The time-slab used by PlioMIP and its precursors is marked as "mPWP". Figure modified after Fedorov et al. (2013).

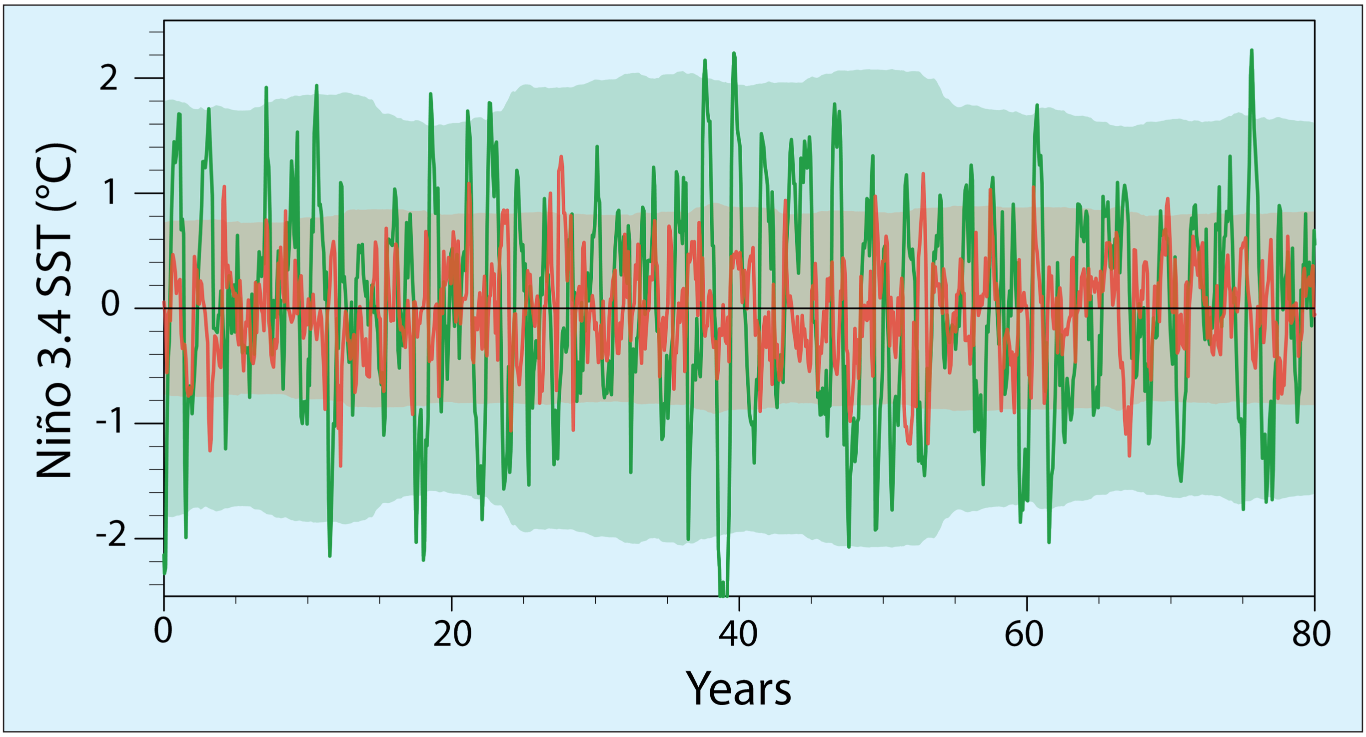

Figure 2: Niño 3.4 SST anomalies in two model simulations; a control (green) and one with an equatorial SST gradient that is approximately halved (red). The shaded area represents four standard deviations from a 30-year running window (Fedorov et al. 2010).

The "permanent El Niño" of the Early Pliocene

One of the factors fuelling the hunt for ENSO in pre-Pleistocene warm climates was the idea that the early Pliocene was in state of "permanent El Niño". Mg/Ca records (a proxy for sea-surface temperatures, SST) from the Western and Eastern Equatorial Pacific (Wara et al. 2005) suggest that no temperature gradient existed along the equatorial Pacific around four million years ago (4 Ma; Fig. 1). Subsequent work shows similar results for the equatorial SST gradient in the early Pliocene. Reconstructions of the SST gradient during older periods need further work, but preliminary data suggest that a reduced SST gradient is not solely a feature of the early Pliocene (LaRiviere et al. 2012) although it may not be a ubiquitous feature of all warm climates (Nathan and Leckie 2009).

An El Niño event (the warm phase of the ENSO oscillation) is characterized by a lack of SST gradient along the equatorial Pacific. Although Wara et al. (2005) emphasized that their Mg/Ca records reflected the mean climatic state, i.e. a change in the long-term average climate rather than a change in interannual variability, they described their observation using the shorthand of "a permanent El Niño". The term was propagated by Fedorov et al. (2006), who used model simulations to examine how such a state could be maintained. They emphasized the similarity between the long-term average state and the conditions seen during recent El Niños. This simile has been read as an assertion that there was no ENSO variability before 3 Ma, although this is not what the authors intended (Alexey Fedorov, personal communication) and is certainly not what is shown by the more recent studies described above.

Equatorial SST gradient and ENSO in models

The mid-Pliocene warm period (3.3-3.0 Ma; marked "mPWP" in Fig. 1) has been the focus of sustained effort by the data and modeling communities, most recently under the auspices of the Pliocene Model Intercomparison Project (PlioMIP; Dolan et al. 2012). This period is one million years later than the minimal SST gradient identified by Wara et al. (2005), but is thought to share similar climate forcings (Fig. 1). Haywood et al. (2007) found ENSO variability in both mid-Pliocene and modern simulations. However, the equatorial temperature gradient of the mid-Pliocene simulation was hardly smaller than in the modern simulation. Subsequent simulations performed with updated boundary conditions (Dowsett et al. 2010), similarly show a lack of strong reductions in the equatorial temperature gradient between the mPWP and the modern day (Haywood et al. 2013) – in comparison with the halving seen in the paleo-observations (Fig. 1).

Attempts have been made to force coupled models to replicate a mean state with a weak SST gradient in the equatorial Pacific. One approach has been to increase the background ocean vertical diffusivity (Brierley et al. 2009), potentially to represent a changed tropical cyclone distribution (Fedorov et al. 2010). These simulations (Fig. 2) appear to show a relationship between equatorial SST gradient and the amplitude of ENSO, but not its period (Fedorov et al. 2010). This result could easily be model dependent, but offers a scenario for a weak ENSO around 4.2 Ma, the time for which proxy data suggest that the SST gradient was very small (open orange box in Fig. 1).

Conclusion

The introduction of the term "permanent El-Niño" in the literature has caused confusion, but it has also motivated paleoclimatologists to look for (and find) evidence of interannual ENSO variability in deep time. The assertion that there was no ENSO variability before 3 Ma, wrongly attributed to Fedorov et al. (2006), is not true. However, the relationship between a Pacific mean state with a minimal equatorial SST gradient and related ENSO properties merits further investigation. We have made progress towards uncovering ENSO behavior on geologic timescales, but there is still a long way to go.

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Mini section on data assimilation

Editors: H. Goosse and A. Paul

Overview of data assimilation methods

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We present the data assimilation approach, which provides a framework for combining observations and model simulations of the climate system, and has led to a new field of applications for paleoclimatology. The three subsequent articles explore specific applications in more detail.

Data assimilation involves the combination of information from observations and numerical models. It has played a central role in the improvement of weather forecasts and, through reanalysis, provides gridded datasets for use in climate research. There is growing interest in applying data assimilation to problems in paleoclimate research. Our goal here is to provide an overview of the methods and the potential implications of their application.

Understanding of past climate variability provides a crucial benchmark reference for current and predicted climate change. Primary resources for deriving past understanding include paleo-proxy data and numerical models, and studies using these resources are typically performed independently. Data assimilation provides a mathematical framework that combines these resources to improve the insight derivable from either resource independently. The three articles that follow describe the current activity in this emerging field of study: transient state estimation (Brönnimann et al., this issue), equilibrium state estimation (Edwards et al., this issue), and paleo data assimilation for parameter estimation (Annan et al., this issue). Here we provide an overview of these methods and how they relate to existing practices in the paleoclimate community.

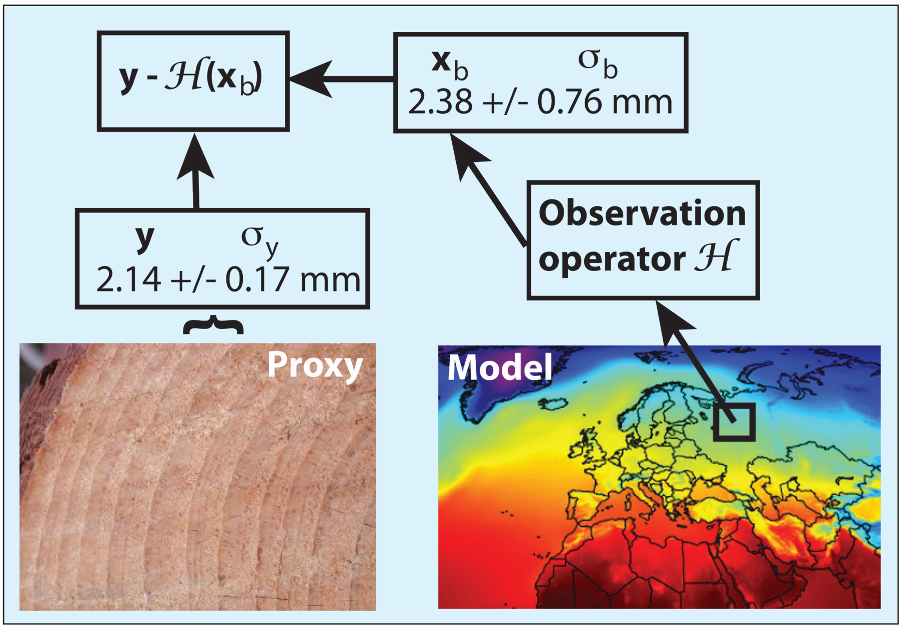

Figure 1: Schematic illustration of how the innovation is determined in data assimilation for a tree-ring example. Proxy measurements are illustrated on the left, and model estimates of the proxy on the right. The observation operator provides the map from gridded model data, such as temperature, to tree-ring width, which is used to compute the innovation. Images credit: Wikipedia.

In weather prediction, data assimilation uses observations to initialize a forecast (Lorenc 1986; Kalnay 2003; Wunsch 2006; Wikle and Berliner 2007). Since the short-term forecast typically starts from an accurate analysis at an earlier time, called the prior estimate, the model provides relatively accurate estimates of the weather observations. Data assimilation involves optimizing the use of these independent estimates to arrive at an analysis (i.e. estimate of the weather or climate state) with a smaller error than the model short-time forecast or the observations.

For Gaussian distributed errors, the result for a single scalar variable (singly-dimensioned variable of one size), x, given prior estimate of the analysis value, x_p, and observation y is

$$x_a = x_p + K\,[y - \mathcal{H}(x_p)] \qquad (1)$$

where x_a is the analysis value. The *innovation*, $y - \mathcal{H}(x_p)$, represents the information from the observation that differs from the prior estimate. This comparison requires a "conversion" of the prior to the observation, which is accomplished by $\mathcal{H}$. For example, in a paleoclimate application, $\mathcal{H}(x_p)$ may estimate tree-ring width derived temperature data from a climate model (Fig. 1).

The weight applied to the innovation is determined by the Kalman gain, K,

$$K = \frac{cov(x_p,\ \mathcal{H}(x_p))}{\sigma_p^2 + \sigma_y^2} \qquad (2)$$

where cov represents a covariance. The error variances associated with the observation and the prior estimate of the observation are given by σ_p and σ_y, respectively. Equation (1) represents a linear regression of the prior on the innovation

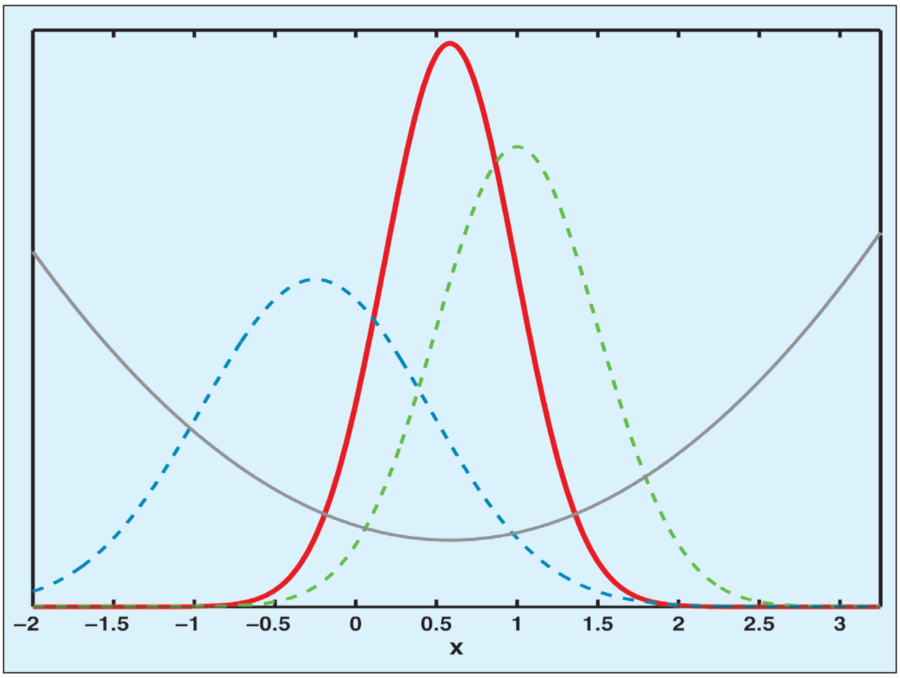

Figure 2: Data assimilation for scalar variable $\mathbf{x}$ *assuming Gaussian error statistics. Prior estimate, given by the dashed blue line, has mean -0.25 and variance 0.5. Observation* $\mathbf{y}$*, given by the dashed green line, has mean 1.0 and variance 0.25. The analysis, given by the thick red line, has mean 0.58 and variance 0.17. The parabolic gray curve denotes a cost function,* $\mathbf{J}$*, which measures the misfit to both the observation and prior; it takes a minimum at the mean value of* $\mathbf{x}_a$*. From Holton and Hakim 2012.*

(the denominator of K is the innovation variance). Equivalently, the Kalman gain weights the innovation against the prior, resulting in an analysis probability density function with less variance, and higher density, than either the observation or the prior (Fig. 2, red solid line, dashed green line and dashed blue line respectively). Generalizing (1) and (2) to more than one variable is straightforward, with scalars becoming vectors and variances becoming covariance matrices (for details see Brönnimann et al., this issue). These covariance matrices provide the information that spreads the innovation in space and to all variables through a Kalman gain matrix.

Application of data assimilation to the paleoclimate reconstruction problem involves determining the state of the climate system on the basis of sparse and noisy proxy data, and a prior estimate from a numerical model (Widmann et al. 2010). These data are weighted according to their error statistics and may also be used to calibrate parameters in a climate model (Annan et al. 2005).

Relationship to established methods

While there are similarities between the application of data assimilation to weather and paleoclimate, there are also important differences. In weather prediction, observations are assimilated every 6 hours, which is a short time period compared to the roughly 10-day predictability limit of the model. However, transient state estimation in paleoclimatology involves proxy data having timescales of years to centuries or longer, which generally exceeds the predictability of climate models, which are on the order of a decade. Consequently, relative errors in the model estimate of the proxy are usually much larger in paleoclimate applications. Hoever, data assimilation reconstruction may still be performed, at great cost savings, since the model no longer requires integration and each assimilation time may be considered independently (Bhend et al. 2012).

Paleoclimate data assimilation attempts to improve upon climate field reconstructions that use purely statistical methods. One well-known statistical approach for climate field reconstruction (Mann et al. 1998; Mann et al. 2008) involves limiting field variability to a small set of spatial patterns that are related to proxy data during a calibration period. Data assimilation, on the other hand, retains the spatial correlations for locations near proxies, which may be lost in a small set of spatial patterns, and also spreads information from observations in time through the dynamics of the climate model. Another distinction between data assimilation and field reconstruction approaches concerns the observation operator, $\mathcal{H}$, which often involves biological quantities of proxy data that have uncertain relationships to climate. Statistical reconstructions directly relate proxy data to the set of spatial patterns, which is essentially an empirical estimate of the inverse of $\mathcal{H}$, and therefore subject to similar uncertainty.

Current and future directions

Research on paleoclimate data assimilation is rapidly developing in many areas. For climate state estimates, a wide range of methods are currently under exploration (see Brönnimann et al., this issue), including nudging climate models to large-scale patterns derived from proxy data (Widmann et al. 2010), and variational (Gebhardt et al. 2008) and ensemble approaches (Bhend et al. 2012). Ensemble approaches involve many realizations of climate model simulations, each of which is weighted according to their match to the proxy data, either in the selection of members (Goosse et al. 2006) or through a linear combination.

Among the important obstacles to progress in paleoclimate data assimilation, some challenges are generic, such as improving the chronological dating quality of proxy records and reducing the uncertainties of the paleoclimate data. Other problems are more specific to data assimilation, such as the development of proxy forward models. Moreover, proxy data typically represent a time average, in contrast to instantaneous weather observations, although solutions that involve assimilating time averages have been proposed to tackle this problem (Dirren and Hakim 2005; Huntley and Hakim 2010). Model bias is also problematic for paleoclimate data assimilation, especially for regions with spatially sparse proxy data.

While the field of paleoclimate data assimilation is still in its infancy, these challenges are all under active research. Merging climate models and proxy data has a bright future in paleoclimate research (e.g. the P2C2 program of the U.S. National Science Foundation), and it is likely that paleoclimate data assimilation will play a central role in this endeavor.

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Transient state estimation in paleoclimatology using data assimilation

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Data assimilation methods used for transient atmospheric state estimations in paleoclimatology such as covariance-based approaches, analogue techniques and nudging are briefly introduced. With applications differing widely, a plurality of approaches appears to be the logical way forward.

Reliable estimations of past climate states are the foundations of paleoclimatology. Traditionally, statistical reconstruction techniques have been used, but recent developments bring data assimilation techniques to the doorstep of paleoclimatology. Here we give a short overview of transient atmospheric state estimation in paleoclimatology using data assimilation. An introduction to data assimilation as well as applications for equilibrium state estimation and parameter estimation are given in the companion papers to this special section (see also Wunsch and Heimbach 2013).

Data assimilation combines information from observations with numerical models to obtain a physically consistent estimate (termed "analysis") of the climate state. It has been hugely successful in generating three-dimensional atmospheric data sets of the past few decades. The "Twentieth Century Reanalysis Project" (Compo et al. 2011) extended the approach as far back as 1871, but there is a limit to further extension, because conventional data assimilation relies on the availability of state observations. Paleoclimate proxies do not capture atmospheric states, but time-integrated functions of states, such as averages, in the simplest case. Therefore, for assimilating proxies, other methods are required than those applied in atmospheric sciences. We briefly present below, three groups of assimilation methods for transient atmospheric state estimation in paleoclimatology: "Classical" covariance-based approaches such as the Kalman Filter or variational techniques; approaches based on analogues such as Particle Filters; and nudging techniques. A schematic view of these methods is given in Figure 1. Note that other methods may be used for the ocean (see Gebbie 2012).

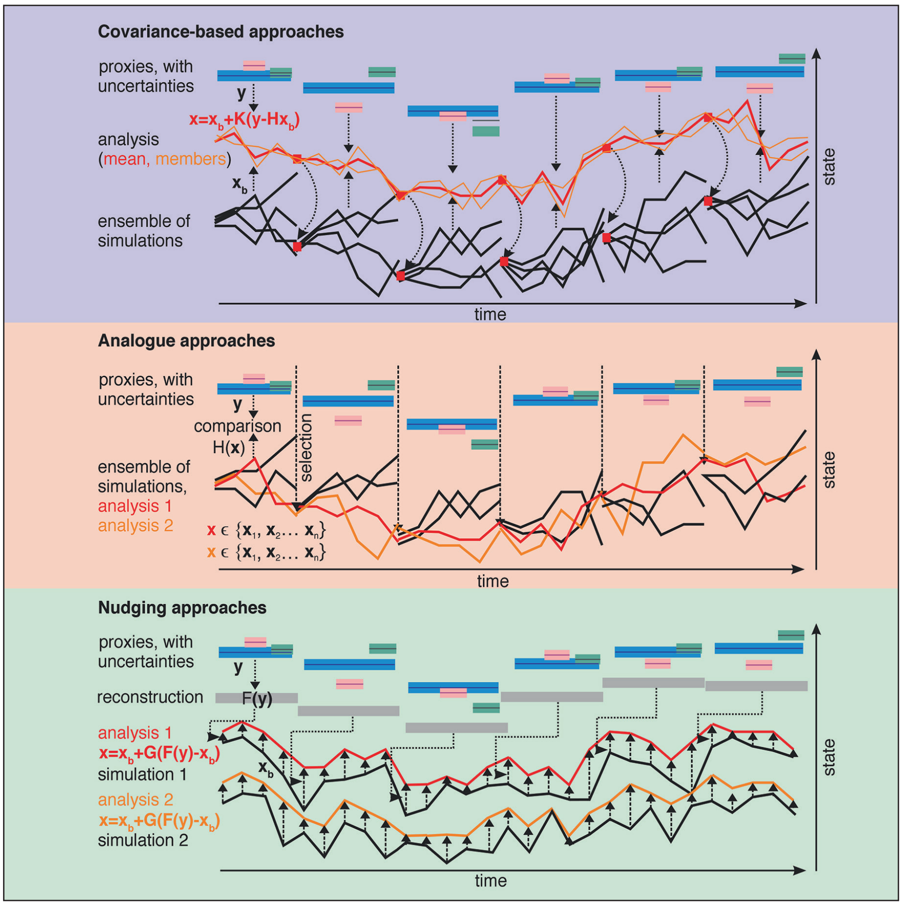

Figure 1: Schematic overview of assimilation approaches. Arrows denote steps in the procedure.

Covariance-based approaches

The assimilation problem can be formulated as a cost function J, assuming Gaussian probability distributions:

$$J(\mathbf{x}) = (\mathbf{x}-\mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x}-\mathbf{x}_b) + (\mathbf{y}-H[\mathbf{x}])^T \mathbf{R}^{-1} (\mathbf{y}-H[\mathbf{x}]) \quad (1)$$

where $\mathbf{x}$ is the analysis, $\mathbf{x}_b$ is a model forecast, $\mathbf{y}$ are the observations (or proxies), H is the observation operator that mimics the observation (or proxy) in the model space, $\mathbf{B}$ is the background error covariance matrix and $\mathbf{R}$ is the observation error covariance matrix (often assumed to be diagonal). The solution to (1) in the classical Kalman form is:

$$\mathbf{x} = \mathbf{x}_b + \mathbf{B}\mathbf{H}^T(\mathbf{R}+\mathbf{H}\mathbf{B}\mathbf{H}^T)^{-1} (\mathbf{y}-\mathbf{H}\mathbf{x}_b) \quad (2)$$

where $\mathbf{H}$ is the Jacobian of H. Variational approaches can be used to approximate the solution. In the Ensemble Kalman Filter (EnKF), $\mathbf{B}$ can be estimated from the ensemble, and each member is updated individually. Normally $\mathbf{x}$ is a state vector. However, Dirren and Hakim (2005) have successfully extended the concept to time averages.

Data assimilation entails that $\mathbf{x}$ serves as an initial condition for the next forecast step. Focusing on the seasonal scale, Bhend et al. (2012) use the EnKF without updating the initial conditions (termed EKF here), which are no longer important on this scale (rather, predictability comes from the boundary conditions, including sea-surface temperatures). This conveniently allows one to use pre-computed simulations. Because $\mathbf{x}$ does not serve as new initial condition, it can be small and can be a vector of averaged model states (e.g. all monthly averages of a season for three variables). H can be a simple proxy forward model, i.e. a time-integrated function of elements of $\mathbf{x}$.

Covariance-based approaches are powerful but computationally intensive and can be sensitive to assumptions (e.g. of Gaussian distributions), to the treatment of covariance matrices, or to the behavior of the observation operator.

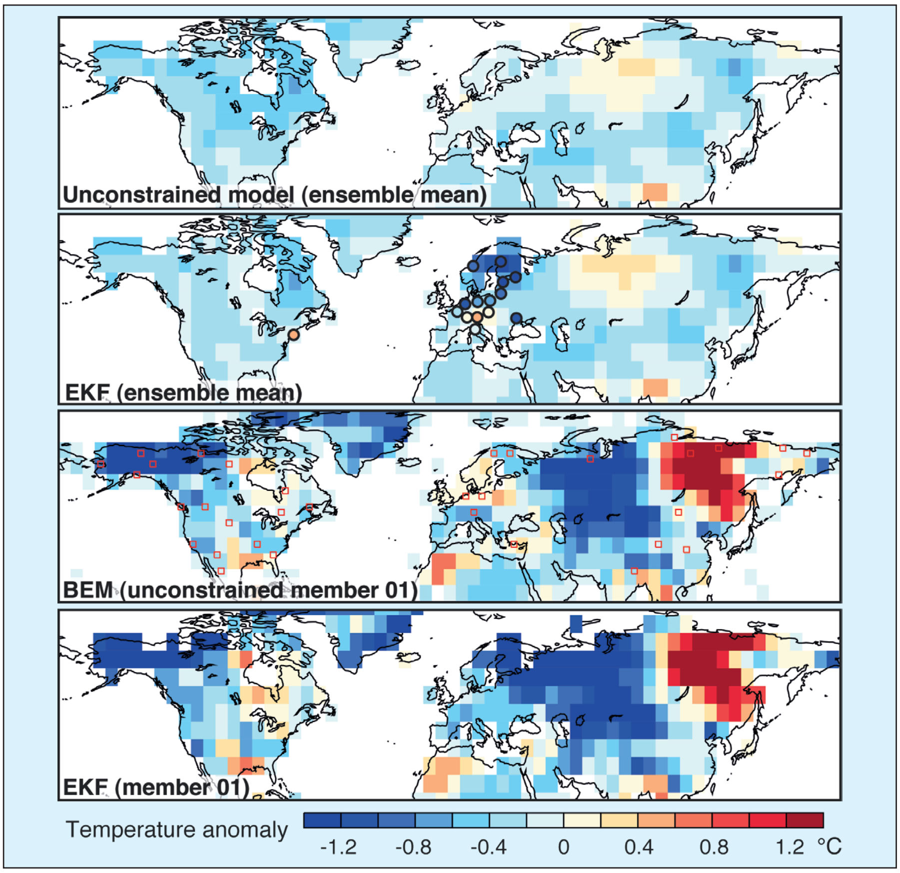

Figure 2: Northern hemisphere temperature anomalies for April to September 1810 (relative to 1801-1830) from the unconstrained ensemble mean, the EKF ensemble mean, BEM (member 01), and the EKF analysis for the BEM member. Circles indicate locations and anomalies of the assimilated instrumental measurements; red squares the locations of tree-ring proxies.

Analogue approaches

Reverting to cost function (1), we can also look for an existing **x**, e.g. by choosing among different ensemble members. The cost function (1) reduces to:

$$J(\mathbf{x}) = (\mathbf{y}-H[\mathbf{x}])^T \mathbf{R}^{-1} (\mathbf{y}-H[\mathbf{x}]) \quad (3)$$

for $\mathbf{x} \in \{\mathbf{x}_1, \mathbf{x}_2, ..., \mathbf{x}_n\}$

New ensemble members are then generated for the next time step by adding small perturbations to **x** and the final analysis is a continuous simulation. The Particle Filter (PF, Goosse et al. 2010) approach uses a distribution of **x** to calculate a weighted sum of cost function contributions to (3).

In the Proxy Surrogate Reconstruction approach (PSR, Franke et al. 2011) and the Best Ensemble Member approach (BEM, Breitenmoser et al., in preparation) pre-computed simulations are used with $\{\mathbf{x}_1, \mathbf{x}_2, ..., \mathbf{x}_n\}$ denoting different slices of a long simulation for PSR or in the case of BEM, the same slice in an ensemble of simulations. The "analysis" in both cases is a sequence of short, discontinuous simulations. In contrast to EnKF, *H* may be non-differentiable (e.g. *H* can be a complex forward model driven by the full simulation output). **R** may be non-diagonal, and **x** may be very large (e.g. six-hourly model output over a 6 month period). However, to reconstruct the state of systems including a large number of degrees of freedom, these approaches require a huge pool of possible analogues (Annan and Hargreaves 2012).

Nudging approaches

Nudging approaches (Widmann et al. 2010) do not explicitly minimize a cost function. The distance between model state and observations is reduced by adding tendencies to (a subspace of) the model state at each time step, similar to an additional source term in the tendency equations. Following our notation:

$$\mathbf{x} = \mathbf{x}_b + G\,(F[\mathbf{y}] - \mathbf{x}) \quad (4)$$

where $F[\mathbf{y}]$ represents the target field (derived using up-scaling method *F* from observations or proxies **y**) in the dimension of the model (sub-)space. *G* is a relaxation parameter.

The Forcing Singular Vectors method (van der Schrier and Barkmeijer 2005) manipulates the tendency equations as well, but adds a perturbation, which modifies the model atmosphere in the direction of the target pattern only.

Examples

Figure 2 shows April-to-September averages of surface air temperature obtained from two assimilations approaches (EKF and BEM) for the year 1810 relative to the 1801-1830 mean. Both approaches are based on the same ensemble of simulations described in Bhend et al. (2012). The ensemble consists of 30 simulations performed with ECHAM5.4 at a resolution of T63/L31 (ca. 2° x 2°), with sea-surface temperatures and external forcings as boundary conditions.

The unconstrained ensemble mean (Fig. 2 top) shows the effect of boundary conditions, here resulting in cooler than average summer temperatures following the large, but not yet localized volcanic eruption in 1809. Anomalies are small and smooth which is typical for an ensemble mean. The EKF analysis was constrained by historical instrumental observations using Eq. (2). The EKF ensemble mean suggests a more pronounced cooling over northern Europe, but over most regions (due to lack of observations) it is close to the unconstrained ensemble mean. BEM was constrained with tree rings from 35 locations. The VS-lite tree growth model (Tolwinski-Ward et al. 2011) was used as *H* and Eq. (3) was minimized. BEM identifies member 01 as the best fitting one. This member exhibits large anomalies in Alaska and Eurasia, but due to the small ensemble size little regional skill is expected (Annan and Hargreaves 2012). For instance, it does not fit well with instrumental observations over Europe. The same member in the EKF analysis (Fig. 2, bottom) shows a better correspondence, but we loose the advantage of having the full 6-hourly model output available.

Limitations and future directions

Paleoclimatological applications are much more disparate than atmospheric sciences in terms of time, time scales, systems analyzed, and proxies used. Therefore, a plurality of data assimilation approaches is a logical way forward. However, all approaches still suffer from problems and uncertainties. Ensemble approaches (PF, EnKF, EKF) provide some information on the methodological spread, which however represents only one (difficult to characterize) part of the whole uncertainty. Further uncertainties are related to model biases, limited ensemble size, errors in the forcings and proxy data. Validation of the approaches using pseudo proxies in toy models and climate models and validation of the results using independent proxies is therefore particularly important. Any approach, however, fundamentally relies on a good understanding of the proxies.

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Best-of-both-worlds estimates for time slices in the past

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We introduce data assimilation methods for estimating past equilibrium states of the climate and environment. The approach combines paleodata with physically-based models to exploit their strengths, giving physically consistent reconstructions with robust, and in many cases, reduced uncertainty estimates.

Those seeking to understand the Earth's past usually take one of two approaches: reconstructing paleoclimate and paleo-environmental states from proxy data derived from natural archives such as ice cores and trees; or simulating them with earth system models that contain theoretical knowledge of physical processes.

Proxy-based reconstructions are based on observations of the real world, but most consider data points independently rather than accounting for correlations in space, time and between climate variables. Therefore they risk being physically inconsistent. Models incorporate aspects of physical consistency, but are imperfect and are tested during development only with present day observations.

Data assimilation produces "best-of-both-worlds" estimates that combine observational and theoretical information while not ignoring their limitations. We discuss data assimilation for estimating past equilibrium states of the earth system such as climate and vegetation. We use the term "paleodata" for measurement-based data: either the observations of proxies or the statistical reconstructions derived from them.

Aims and methods

Equilibrium state, or "time slice", data assimilation is estimation of a snapshot in time during which it is assumed the state variables are not changing. The state estimates may be the primary scientific aim or simply a "bonus" of calibrating model parameters (Annan et al., this issue).

Time slice estimation is a natural starting point in data assimilation because it is more straightforward than estimating a transient state (Brönnimann et al., this issue) and is particularly appropriate if spatial patterns are more important than temporal changes or if the model is computationally expensive. For a given computational resource time slice estimation permits more complete exploration of model uncertainties in parameters, structure, and inputs. Another advantage of a focus on time slices is that for eras studied by the Paleoclimate Model Intercomparison Project (PMIP) relatively large quantities of paleodata and simulations are available. Most data assimilation estimates of equilibrium paleo-states are therefore of the Last Glacial Maximum (LGM: 21 ka cal BP), the most recent era for which annual mean climate is substantially different to the present that also has a long history of study by PMIP.

We use model simulations in paleo-state estimation because models provide links across different locations, times (relevant to transient or multi-state estimation) and state variables. This has two advantages: it helps ensure the resulting state is physically consistent, and it also means we are not limited to assimilating the same variables we wish to estimate. We could assimilate data in one place to estimate another, or assimilate temperature data to estimate precipitation, or assimilate variables corresponding to the outputs of a model to estimate variables corresponding to the inputs. The last are termed "inversion" methods, such as estimating atmospheric variables or terrestrial carbon from paleo-vegetation records (e.g. Guiot et al. 2000; Wu et al. 2007; Wu et al. 2009; Pound et al. 2011) or estimating oceanic variables from paleo-tracer records (e.g. LeGrand and Wunsch 1995; Roche et al. 2004).

Data assimilation requires the following ingredients: paleodata with uncertainty estimates, simulations with uncertainty estimates, and a metric to quantify the dissimilarity, or "distance", between the two. Climate state estimates are obtained by searching for the simulation(s) closest to the paleodata ("optimization") or calculating a weighted combination of the two ("updating").

Distance is usually measured with the standard metric for normally distributed model-data differences, i.e. the sum of squared differences weighted by the uncertainties, though some use ad-hoc or fuzzy metrics (e.g. Guiot et al. 2000; Wu et al. 2007; Gregoire et al. 2010). For non-continuous variables, for example with a threshold, variables must be transformed or a non-Gaussian metric chosen (e.g. Stone et al. 2013).

Optimisation methods search for the simulation with the minimum distance from paleodata. One approach uses numerical differentiation of the model with respect to the parameters, essentially least-squares fitting of a line or curve to one-dimensional data (e.g. LeGrand and Wunsch 1995; Gebbie and Huybers 2006; Marchal and Curry 2008; Burke et al. 2011; Huybers et al. 2007; Paul and Losch 2012). Another approach generates an ensemble of simulations using many different parameter values and then selects the members with the smallest model-data distance ("perturbed parameter ensemble" methods; e.g. Gregoire et al. 2010).

Updating methods combine model and paleodata estimates. Typically the model estimates are generated with a perturbed parameter ensemble, which permits well-defined sampling of parameter uncertainties; the model estimates are reweighted with the model-data distance using Bayesian updating (e.g. Guiot et al. 2000; Wu et al. 2007; Wu et al. 2009; Holden et al. 2009; Schmittner et al. 2011).

Interpretation

Figure 1 illustrates some strengths of data assimilation. The model propagates information from LGM surface air temperature (SAT) reconstructions over land to other regions, and to sea surface temperatures (SST). In this example assimilating SAT reconstructions produces an SST estimate with a warming at the LGM in the northern North Atlantic, which is consistent with the SST reconstructions. Uncertainties are reduced relative to the model estimate

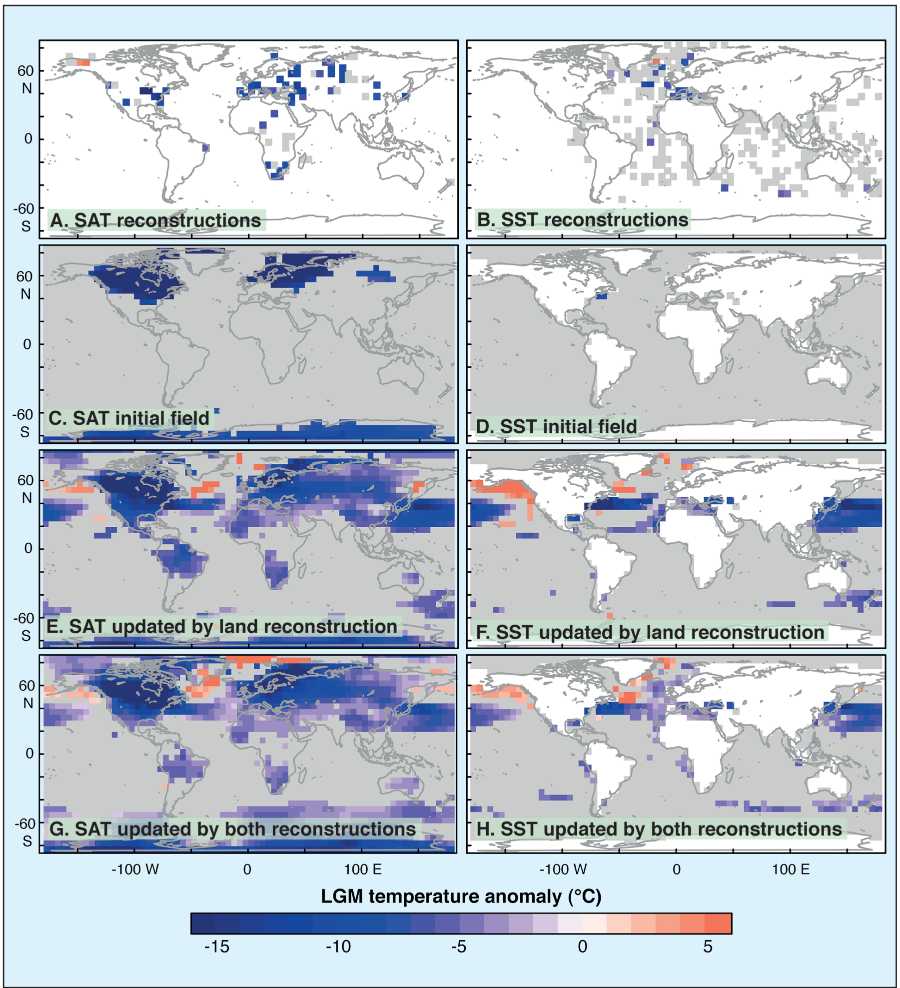

Figure 1: LGM annual mean temperature anomalies from: ***A)*** *surface air temperature (SAT) reconstructions based on pollen and plant macrofossils (Bartlein et al. 2010);* ***B)*** *sea surface temperature (SST) reconstructions based on multiple ocean proxies (MARGO et al. 2009);* ***C, D)*** *simulations from the HadCM3 general circulation model (mean of 17 member perturbed parameter ensemble; Edwards, unpublished data). Data assimilation estimates generated by updating with SAT reconstructions* ***(E, F)****, and both SAT and SST reconstructions* ***(G, H)****. Gray areas indicate regions with low signal-to-noise: magnitude of temperature anomaly is less than 3σ of uncertainty estimates.*

in most locations (grayed out areas are reduced).

How should we interpret assimilated paleo-states? Optimization methods select a single best simulation so the state estimate is physically self-consistent according to the model. But the state estimate from updating methods is a combination of multiple model simulations and paleodata, therefore interpretation requires more care. An ensemble mean anomaly of zero might correspond to a wide spread of positive and negative results; this would be reflected in large model uncertainties. A spatially coherent signal with small uncertainty might emerge from an ensemble after assimilating a single "pinning point" from paleodata; this signal should be physically consistent because it arises from the model physics. Such considerations are common to all multi-model ensemble summaries and reanalyses.

For statistically meaningful results it is essential to use a distance metric grounded in probability theory, i.e. corresponding to a particular distribution of model-data differences ("likelihood function" in Bayesian terms). This might preclude the use of non-standard variables such as biomes.

Data assimilation is a statistical modeling technique and should be evaluated. Testing the method with pseudo-paleodata can help avoid the (literal) pitfalls of finding local rather than global minima in high-dimensional spaces.

Future directions

Data assimilation is a formal method that not only highlights model-data discrepancies but also corrects them. It can be challenging, because it requires a process-based model and reliable estimation of uncertainties for both paleodata and simulations.

For paleodata, difficulties may arise from dating and time averaging. But improvements in estimating reconstruction uncertainties can be made by using forward modeling approaches (e.g. Tingley et al. 2012). These approaches allow greater freedom in specifying the behavior of climate-proxy relationships (such as nonlinearity and multi-modal uncertainties) and enables uncertainties to cascade through the causal chain to allow full probabilistic quantification of the unknown state. Using physically-based forward models for reconstruction, i.e. data assimilation, incorporates information about the relationships between locations, times and variables and therefore minimizes the risk of physical implausibility. The long-term goal may be forward physical modeling of the whole causal chain from radiative forcings to proxy archives (e.g. Roche et al. 2004; Stone et al. 2013).

For paleo-simulations, we do not need models to be complex or state-of-the-art, but we do need to estimate their uncertainties. If they are complex it is difficult to generate their derivatives with respect to the parameters. If they are expensive it is difficult to sample, and therefore to assess, their uncertainties. Thoughtful experimental design with statisticians, and perhaps also statistical modeling of the physical model (known as "emulation"; e.g. Schmittner et al. 2011), can help in this regard. A research priority is to estimate the discrepancy between a model and reality at its best parameter values, and how this varies across different eras. New updating methods are emerging that use the PMIP multi-model ensemble to explore structural uncertainties. For example, Annan and Hargreaves (2013) use the linear combination of ensemble members that best matches the paleodata.

These challenges are worth tackling for the substantial benefits. Information from paleodata can be extrapolated to other locations, times and state variables, and uncertainties are smaller (or at worst, the same) than those of the individual model or proxy-based estimates.

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Parameter estimation using paleodata assimilation

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In addition to improving the simulations of climate states, data assimilation concepts can also be used to estimate the internal parameters of climate models. Here we introduce some of the ideas behind this approach, and discuss some applications in the paleoclimate domain.

Estimation of model parameter values is of particular interest in paleoclimate and climate change research, since it is the formulation of model parameterizations, rather than the initial conditions, which is the main source of uncertainty regarding the climate's long-term response to natural and anthropogenic forcings.

We should recognize at the outset that the question of a "correct" parameter value might in many cases be quite contentious and disputable. There is, for example, no single value to describe the speed at which ice crystals fall through the atmosphere, or the background rate of mixing in the ocean, to mention two parameters which are commonly varied in General Circulation Models (GCMs). Generally the best we can hope for is to find a set of parameter values, which perform well in a range of circumstances, and to make allowances for the model's inadequacies, i.e. structural errors due to inadequate equations and parameterizations. However, inadequacies will always be present no matter how carefully parameter values are chosen: this should serve as a caution against over-tuning.

It may not be immediately clear how one can use proxy-derived observational estimates of climatic state variables such as temperature or precipitation to estimate the values of a model's internal parameters. However, from a sufficiently abstract perspective, the problem of parameter estimation can be considered as equivalent to state estimation, via a standard approach in which the state space of a dynamical model is augmented by the inclusion of model parameters (Jazwinski 1970; Evensen et al. 1998). To see how this works, consider a system described by a dynamical model f, which uses a set of internal parameters θ and propagates a state vector x through time through a set of differential equations:

$$x = f_\theta(x) \qquad (1)$$

We can create an equivalent model g(x, θ) which takes as its state vector (x, θ) (in which the parameter values have simply been concatenated onto the end of the state vector), and propagates this vector through the augmented set of equations

$$\dot{x} = f_\theta(x) \qquad (2)$$

$$\dot{\theta} = 0 \qquad (3)$$

Thus, the existing methods and technology for estimating the state x can, in principle, be directly applied to the estimation of (x, θ), or in other words, the joint estimation of state and parameters.

While this approach is conceptually straightforward, there are many practical difficulties in its application. The most widespread methods for data assimilation, including both Kalman filtering and 4D-VAR, rely on (quasi-)linear and Gaussian approaches. However, the augmented model g is likely to be substantially more nonlinear in its inputs than the underlying model f , due to the presence of product terms such as $\theta_i x_j$ (Evensen et al. 1998).

Further challenges exist in applying this approach due to the wide disparity in relevant time scales. Often the initial state has a rapid effect on the model trajectory within the predictability time scale of the model, which is typically days to weeks for atmospheric GCMs. On the other hand, the full effect of the parameters only becomes apparent on the climatological time scale, which may be decades or centuries.

Applications

Methods for joint parameter and state estimation in the full spatiotemporal domain continue to be investigated for numerical weather prediction, where data are relatively plentiful. But identifiability, that is the ability to uniquely determine the state and parameters given the observations, is a much larger problem for modeling past climates, where proxy data are relatively sparse in both space and time.

Therefore, data assimilation in paleoclimate research generally finds a way to reduce the dimension of the problem. One such approach is to reduce the spatial dimension, even to the limit of a global average. For example, a three-variable globally averaged conceptual model for glacial cycles has been tuned using flexible and powerful methods such as Markov Chain Monte Carlo (Hargreaves and Annan 2002) and Particle Filtering (Crucifix and Rougier 2009). Figure 1 presents the results of one parameter estimation experiment by Hargreaves and Annan (2002).

In the case of more complex and higher resolution models, the problems of identifiability and computational cost are most commonly addressed by the use of equilibrium states. Here, the full initial condition of the model is irrelevant, at least within reasonable bounds, and the dimension of the problem collapses down to the number of free parameters; typically ten at most, assuming many boundary conditions are not also to be estimated. With this approach, much of the detailed methodology of data assimilation as developed and practiced in numerical weather prediction, where the huge state dimension is a dominant factor, ceases to be so relevant.

While some attempts at using standard data assimilation methods have been performed (e.g. Annan et al. 2005), a much broader range of estimation methods can also be used. With reasonably cheap models and a sufficiently small set of parameters, direct sampling of the parameter space with a large ensemble may be feasible. A statistical emulator, which provides a very fast approximation to running the full model, may help in more computationally demanding cases (e.g. Holden et al. 2010).

One major target of parameter estimation in this field has been the estimation of the equilibrium climate sensitivity. This may either be an explicitly tunable model parameter in the case of simpler models, or else an emergent property of the underlying physical processes, which are parameterized in a more complex global climate model. The Last Glacial Maximum is a particularly popular interval for study, due to its combination of a large signal to noise ratio and good data coverage over a quasi-equilibrium interval (Annan et al. 2005; Schneider von Deimling et al. 2006; Holden et al. 2010; Schmittner et al. 2011; Paul and Losch

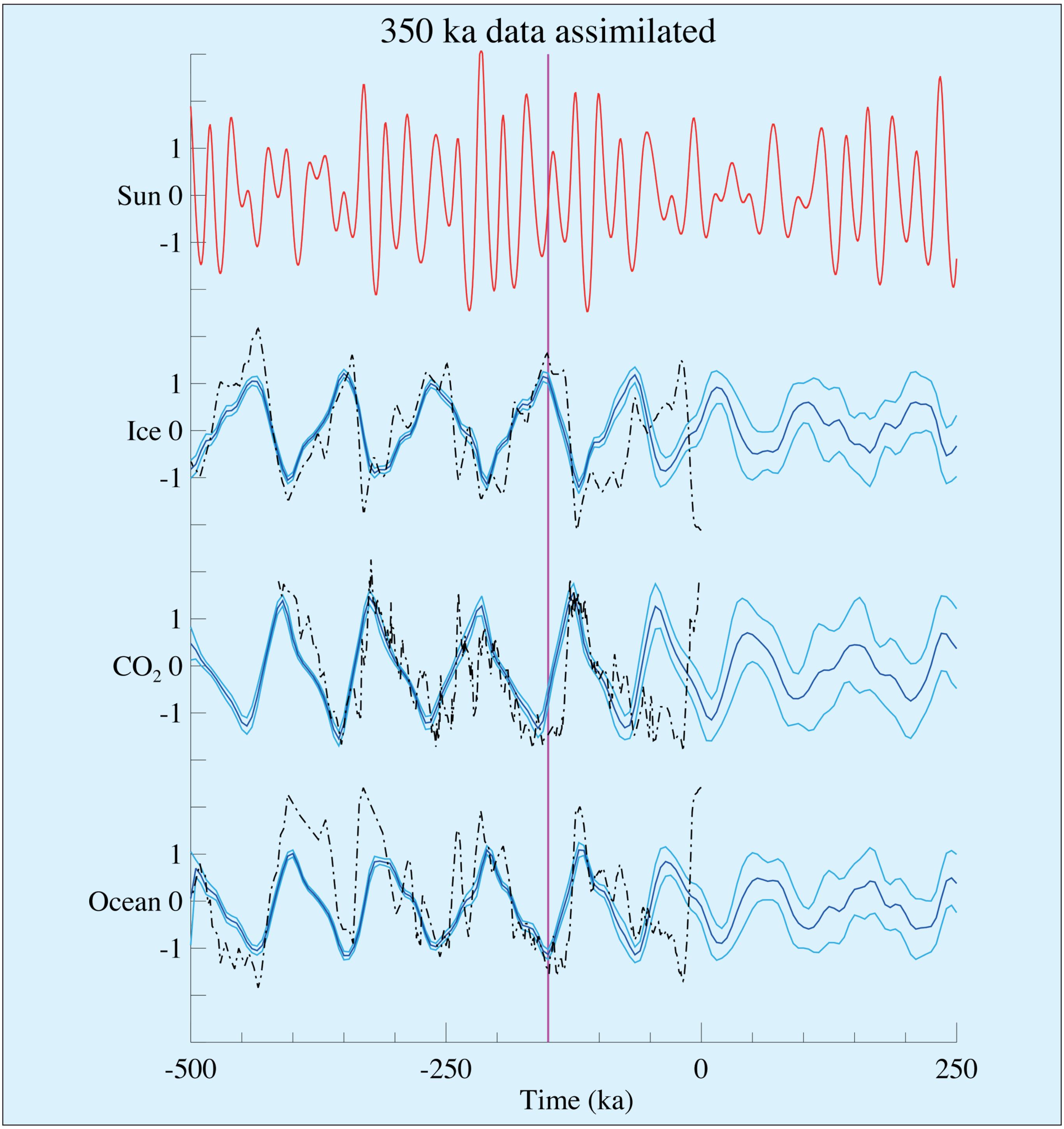

Figure 1: Experiment with 350 ka of data assimilated. The red line at the top is the normalized summer solar insolation forcing at 65°N. The black dot-dashed lines are normalized proxy data from Vostok (ice volume and atmospheric CO_2 concentration) and SPECMAP (deep ocean temperature) cores. Data to the left of the vertical magenta line were used to tune parameters, with the right hand side used as validation of the model forecast, which (over a range of experiments) shows substantial skill for a duration of around 50-100 ka. The dark blue lines show the mean of the ensemble and the light blue lines show one standard deviation of the ensemble. Modified from Hargreaves and Annan (2002).

2012). The methods used for studying the LGM in order to estimate the equilibrium climate sensitivity have covered a wide range of techniques including direct sampling of parameter spaces (with and without the use of an emulator), Markov Chain Monte Carlo methods, the variational approach using an adjoint model, and the Ensemble Kalman Filter. In general, more costly models require stronger assumptions and approximations due to computational limitations.

Approaches which aim at averaging out the highest frequencies of internal variability while still retaining a transient and time-varying forced response may make use of temporal data such as tree rings over the last few centuries (Hegerl et al. 2006). In that case, the spatial dimension can still be reduced, e.g. by averaging to a hemispheric mean. A similar approach was used by Frank et al. (2010) to estimate the carbon cycle feedback.

Paleoclimate simulations provide the only opportunity to test and critically evaluate climate models under a wide range of boundary conditions. This suggests that we need to continue to develop a broad spectrum of methods to be applied on a case-specific basis.

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Impact of climate and sea level change on coastal evolution

Accra, Ghana, 8-12 October 2012

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The third West African Quaternary Research Association (WAQUA) workshop, hosted by the Department of Marine and Fisheries Sciences, University of Ghana, was held at the Institute for Local Government Studies in Accra. The objective of the workshop was to identify how humans adapted to past climatic and sea level changes, and to discuss future adaptation strategies through a multidisciplinary approach.

Twenty-seven scientists from five countries attended the workshop. The inaugural lecture was given by Dr. Thomas Kwasi Adu of the Geological Survey Department of Ghana. He spoke about the causes of sea-level rise and coastal change, and their implications for coastal regions. His lecture stressed the fact that important planning decisions for sea-level rise should be based on the best available scientific knowledge and careful consideration of long-term benefits for a sustainable future. He recommended that decisions on adaptation or mitigation measures should also take into consideration economic, social, and environmental costs.

Sixteen scientific papers were presented and discussed on various topics covering sea level rise, coastal erosion and climate change issues. In particular, the presentations addressed the impact of sea-level changes on coastal tourism development; the linkages between sea-level rise and ground water quality, hydrodynamics, upwelling and biogeochemistry in the Gulf of Guinea; paleoclimatic evidences from the quaternary coastal deposits from Nigeria; dynamics of ocean surges and their impacts on the Nigerian coastline; and the effect of climatic extreme events on reservoir water storage in the Volta Basin in Ghana.

The workshop provided a platform for scientists to share knowledge and information on their respective areas of research. At the end of the presentation sessions, the plenum agreed that research on sea-level rise should be particularly encouraged and that further activities to bring together scientists working in this area should be organized. To stimulate interest and expose students to new methods, regular international workshops or summer schools will be held to bring together students and experts from within and outside the sub-region.

The meeting participants then went on a guided tour of coastal communities along the eastern coast of Ghana. One of them was Keta, a coastal town in the Volta Region that was partly destroyed by sea erosion at the end of the 20th century. Keta is situated on a sandspit separating the Gulf of Guinea from the Keta Lagoon. Due to this double waterfront, the city area is particularly vulnerable to erosion. It is flooded from the ocean front during high tides and from the lagoon front during heavy runoff, especially in the rainy seasons. During devastating erosion events between 1960 and 1980, more than half of the town area has been washed away. The photo (Fig. 1) shows Keta in 1985. Since 1999 more than 80 million US$ have been invested to protect, restore and stabilize the coast of Keta.

The next WAQUA workshop will be held in Senegal in 2014.

Acknowledgements

We express our sincere gratitude to INQUA, PAGES, PAST and the University of Ghana for sponsoring this workshop. We are also grateful to the local hosts, the Department of Marine and Fisheries Sciences, University of Ghana and the Ghanaian Institute of Local Government Studies.

Figure 1: This photo from 1985 shows a section of the Keta town destroyed by sea erosion. Photo by Beth Knittle.

Holocene land-cover change in Eastern Asia for climate modeling

Shijazhuang, China, 9-11 October 2012

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This workshop was held at Hebei Normal University in China, and contributed to the PAGES Focus 4 theme Land Use and Cover (LUC). A major goal of LUC is to achieve Holocene land-cover reconstructions that can be used for climate modeling and testing hypotheses on past and future effects of anthropogenic land cover on climate. Collaborations initiated between Linnaeus University (Sweden; M.-J Gaillard), University of Hull (Britain, Jane Bunting), Hebei Normal University (China; Q. Xu and Y. Li), the French Institute (Pondicherry, India; A Krishnamurthy) and Lucknow University (India; P. Singh Ranhotra) are in line with the goals of Focus 4-LUC and follow the strategy of the European LUC-relevant LANDCLIM project (Gaillard et al. 2010). The aim of these collaborations is to develop quantitative reconstructions of past vegetation cover in India and China using pollen-vegetation modeling and archaeological/historical data together with other land-cover modelling approaches.

The objective of this workshop in China was to initiate the necessary collaborations and activities to make past land-cover reconstructions possible in Eastern Asia. The three major outcomes of the workshop are (i) the building of a large network of experts from Eastern Asia, Europe and USA now working together to understand past changes in land use and land cover in Eastern Asia, (ii) that all existing East Asian pollen databases will be integrated into the NEOTOMA Paleoecology Database by 2014 (coordinated by Eric Grimm, Illinois State University, USA), and (iii) that a review paper will be prepared with the working title "Past land-use and anthropogenic land-cover change in Eastern Asia - evaluation of current achievements, potentials and limitations, and future avenues". It is planned to submit this article this fall. It will include 1) a review of Holocene human-induced vegetation and land-use changes in Eastern Asia based on results presented at the workshop; 2) a discussion of the existing anthropogenic land-cover change scenarios (HYDE, Klein Goldewijk et al. 2010; KK 10, Kaplan et al. 2009) in the light of the reviewed proxy-based knowledge; and 3) a discussion on the implications of these results for future climate modeling and the study of past land cover-climate interactions.

These significant outcomes are the result of three intense days of presentations and discussion sessions. During the lectures, results were presented for historical, paleoecological and pollen-based reconstructions; pollen-vegetation relationships; past human-impact studies; and model scenarios of anthropogenic land-cover changes in the past. Some of the conference was also dedicated to reviewing the state of existing pollen databases and more generally, database building.

Plenary and group break-out discussions focused on more technical aspects such as improving pollen databases, especially for the East Asian region; planning the review paper; and scientific topics such as the use of pollen-based and historical land-cover reconstructions for the evaluation of model scenarios of past anthropogenic land-cover change (Fig. 1), and the integration of model scenarios with paleoecological or historical reconstructions.

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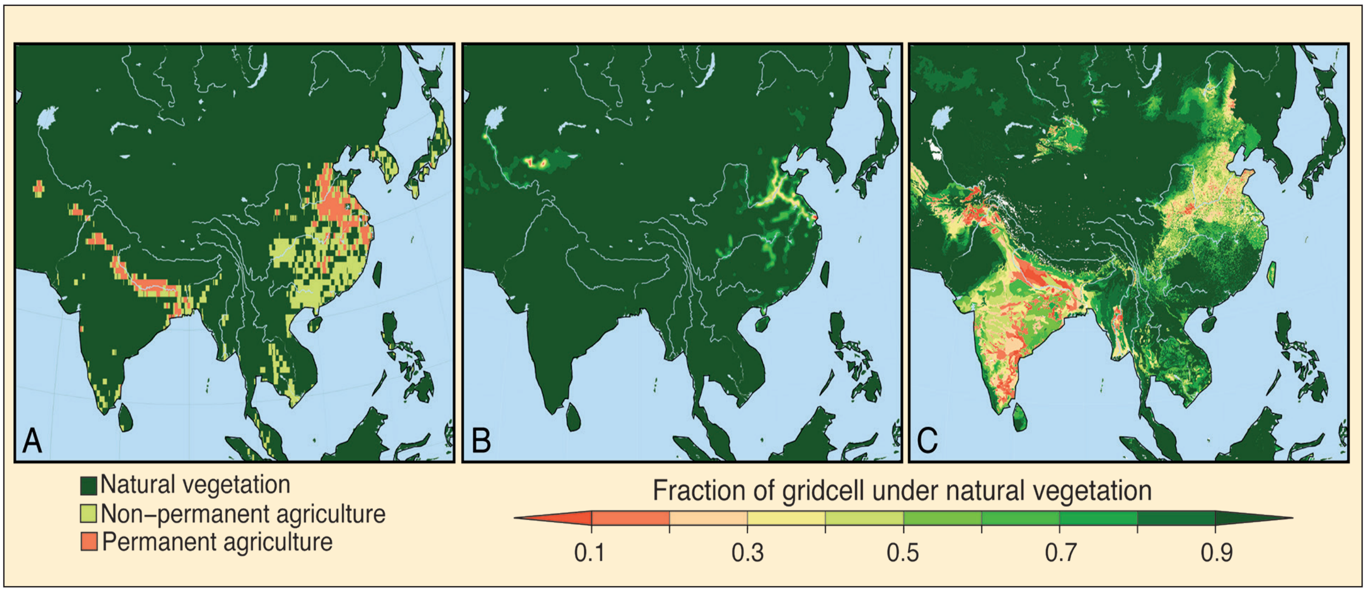

Figure 1: Anthropogenic deforestation in Eastern Asia at AD 1 simulated by three different approaches: ***A)*** *Olofsson and Hickler (2008);* ***(B)*** *HYDE (History Database of the Global Environment) version 3.1 (Klein Goldewijk et al. 2010); and* ***(C)*** *Kaplan et al. (2009). Note the large differences in land-cover between the different models used.*

Palaeo50: The priority research questions in paleoecology

Oxford, UK, 13-14 December 2012

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Paleoecological studies provide insights into ecological and evolutionary processes, and help to improve our understanding of past ecosystems and human interactions with the environment. But paleoecologists are often challenged when it comes to processing, presenting and applying their data to improve ecological understanding and inform management decisions (e.g. Froyd and Willis 2008) in a broader context. Participatory exercises in, for example, conservation, plant science, ecology, and marine policy, have developed as an effective and inclusive way to identify key questions and emerging issues in science and policy (Sutherland et al. 2011). With this in mind, we organized the first priority questions exercise in paleoecology with the goal of identifying 50 priority questions to guide the future research agenda of the paleoecology community.

The workshop was held at the Biodiversity Institute of the University of Oxford. Participants included invited experts and selected applicants from an open call. Key funding bodies and stakeholders were also represented at the workshop, including the US NSF, IGBP PAGES, UK NERC, and UK Natural England.

Several months prior to the workshop, suggestions for priority questions had been invited from the wider community via list-servers, mailing lists, society newsletters, and social media, particularly Twitter (@Palaeo50). By the end of October 2012, over 900 questions had been submitted from almost 130 individuals and research groups. Questions were then coded and checked for duplication and meaning, and similar questions were merged. The remaining 800 questions were re-distributed to those who had initially engaged in the process. Participants were asked to vote on their top 50 priority questions.

At the end of November the questions were grouped into 50+ categories, which in turn were allocated to one of six workshop themes to be chaired by an expert: Human-environment interactions in the Anthropocene (Erle Ellis, University of Maryland, USA); Biodiversity, conservation and novel ecosystems (Lindsey Gillson, University of Capetown, South Africa), Biodiversity over long time scales (Kathy Willis, University of Oxford, UK), Ecosystems and biogeochemical cycles (Ed Johnson, University of Calgary, Canada), Quantitative and Qualitative reconstructions (Stephen Juggins, University of Newcastle, UK), and Approaches to paleoecology (John Birks, University of Bergen, Norway).

Each working group also had a co-chair, responsible for recording votes and editing questions on a spreadsheet, and a scribe. Workshop participants were allocated into one of six parallel working groups tasked with reducing the number of questions from 180 to 30 by the end of day one. This was an intensive process involving considerable debate and editing. During day two, these 30 questions were winnowed down further with each group arriving at seven priority questions. The seven questions from each group were then combined to obtain 42 priority questions. Each working group had a further five reserve questions, which everyone voted on in the final plenary. The eight reserve questions that obtained the most votes were selected to complete the list of 50 priority questions.

Working group discussions were often heated and passionate. Compromises won by the chairs and co-chairs were difficult but necessary. It is important that the final 50 priority questions are not seen as a definitive list, but as a starting point for future dialogue and research ideas.

The final list of 50 priority questions and full details of the methodology is currently under review, and the publication will be announced through the PAGES network.

Acknowledgements

We thank PAGES for generously providing support. We also acknowledge sponsorship from the British Ecological Society, the Quaternary Research Association and the Biodiversity Institute, University of Oxford.

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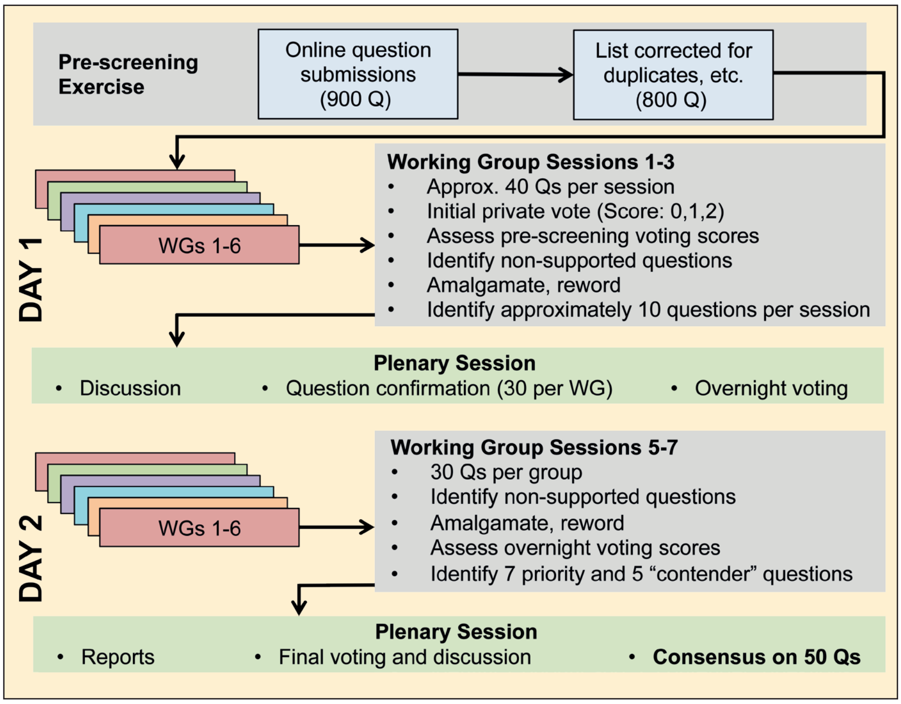

Figure 1: Flowchart of the selection process for the 50 priority research questions.

The Agulhas System and its role in changing ocean circulation, climate, and marine ecosystems

Stellenbosch, Republic of South Africa, 8-12 October 2012

Rainer Zahn[1], W.P.M. de Ruijter[2], L. Beal[3], A. Biastoch[4] and SCOR/WCRP/IAPSO Working Group 136[5]

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This conference was held in recognition of the significance of the Agulhas Current to ocean physical circulation, marine biology and ecology, and climate at the regional to global scale. The conference centered on the dynamics of the Agulhas Current in the present and the geological past; the influence of the current on weather, ecosystems, and fisheries; and the impact of the Agulhas Current on ocean circulation and climate with a notable focus on the Atlantic Meridional Overturning Circulation (AMOC). 108 participants from 20 countries, including seven African countries, attended the conference, of which a quarter were young researchers at the PhD student level. Participants came from the areas of ocean and climate modeling, physical and biological oceanography, marine ecology, paleoceanography, meteorology, and marine and terrestrial paleoclimatology. The Agulhas Current attracts interest from these communities because of its significance to a wide range of climatic, biological and societal issues.

The current sends waters from the Indian Ocean to the South Atlantic. This is thought to modulate convective activity in the North Atlantic. It is possible that it even stabilizes the AMOC at times of global warming when freshwater perturbation in the North might weaken it. But these feedbacks are not easy to trace, and direct observations and climate models have been the only way to indicate the possible existence of such far-field teleconnections to date. This is where marine paleo-proxy profiles prove helpful. They reveal the functioning of the Agulhas Current under a far larger array of climatic boundary conditions than those present during the short period of instrumental observations. For instance altered conditions in the past with shifted ocean circulation and wind fields stimulated Agulhas water transports from the Indian Ocean to the Atlantic, the so-called Agulhas leakage, at very different rates from today's. A number of the paleo-records that were shown at the meeting demonstrated a link between Agulhas leakage and Dansgaard/Oeschger-type abrupt climate changes in the North Atlantic region, suggesting that salt-water leakage may have played a role in strengthening the AMOC and sudden climate warming in the North.

Marine ecosystems were also shown to be measurably impacted by the Agulhas system. Notably, the high variability associated with the prominence of mesoscale eddies and dipoles along the Current affect plankton communities, large predators, pelagic fish stocks, and possibly even facilitate the northward sardine runs swimming against the vigorous southward flow of the Agulhas Current.

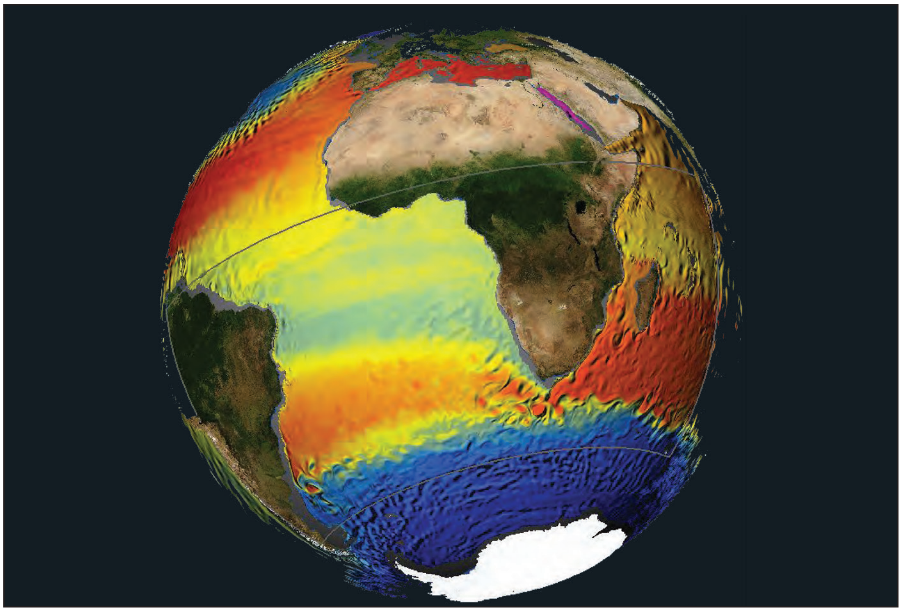

Figure 1: A model perspective of Agulhas leakage and the interbasin water transports between the Indian Ocean and Atlantic. A high-resolution Agulhas model (1/10°, gray box), is nested in a (1/2°) global ocean/sea ice model to simulate temperature and magnitude of currents (see Biastoch et al. 2009).

The meteorological relevance of the Agulhas Current was also demonstrated, for example its role as a prominent source of atmospheric heat and its significance in maintaining and anchoring storm tracks. Among other things, these affect the atmospheric westerly Polar Front Jet and Mascarene High, with onward consequences for regional weather patterns, including extreme rainfall events over South Africa.

The conference developed a number of recommendations; two key ones being that efforts should be made to trace the impacts of the Agulhas leakage on the changing global climate system at a range of timescales, and that sustained observations of the Agulhas system should be developed. Implementing these recommendations would constitute a major challenge logistically and the Western Indian Ocean Sustainable Ecosystem Alliance (WIOSEA) was identified as a possible integrating platform for the cooperation of international and regional scientists toward these goals. This would involve capacity building and training regional technicians and scientists, which could be coordinated through partnerships with the National Research Foundation in South Africa.

The conference was held under the auspices of the American Geophysical Union Chapman Conference series and organized by the Scientific Committee on Oceanic Research (SCOR)/ World Climate Research Program (WCRP)/ International Association for the Physical Sciences of the Oceans (IAPSO) Working Group 136. Additional sponsorship came from the International Union of Geodesy and Geophysics; US NSF; NOAA; PAGES; Institute of Research for Development (IRD) France; and the Royal Netherlands Institute for Sea Research.

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IPICS First Open Science conference

Presqu'île de Giens, France, 1-5 October 2012

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Figure 1: Inside the drilling trench at NEEM, Greenland. The North Greenland Eemian (NEEM) ice drilling is an international project managed by the Centre for Ice and Climate, Denmark, involving 14 nations. In Summer 2010, it recovered ice from the Eemian dating back from 130 ka BP, helping to describe the warming and ice sheet shrinking at a time of unusually high Arctic summer insolation (NEEM community members 2013). Photo: Jérôme Chappellaz.

IPICS (International Partnerships in Ice Core Sciences) is the key planning group for international ice core scientists. Established in 2005, it now includes scientists from 22 nations and aims at defining the scientific priorities of the ice core community for the coming decade. IPICS lies under the common umbrella of IGBP/PAGES, SCAR (Scientific Committee on Antarctic Research) and IACS (International Association of Cryospheric Sciences).

IPIC's First Open Science conference, organized by the European branch of IPICS (EuroPICS), took place in a beautiful setting on the French Côte d'Azur. 230 scientists gathered from 23 nations, with a good mix of both junior and senior scientists present. While most of the participants work on ice cores, a significant number were scientists working on marine and continental records as well as on climate modeling. The sponsorship received from several institutions, agencies and projects, enabled us to invite ten keynote speakers as well as six scientists from emerging countries.

The program followed IPIC's main scientific objectives as outlined in four white papers (www.pages-igbp.org/ipics). Notably, it covered questions of climate variability at different time scales (from the last 2000 to 1 M years), biogeochemical cycles, dating, and ice dynamics. New challenges, such as studying the bacterial content of ice cores, and new methodologies were also the focal point of specific sessions. Over the five days of the conference, all attendees gathered for the plenary sessions combined with long poster sessions. These sessions offered valuable and efficient networking opportunities. The full program can be found at: www.ipics2012.org

Among the various results presented at this occasion, significant information was provided on two big recent projects of the ice core community: the WAIS Divide deep drilling in West Antarctica, and the NEEM deep drilling in North-West Greenland. Ice core projects from outside polar regions were also well represented, with results obtained from the Andes, the Alps and the Himalayas.

The beautiful and peaceful setting of the conference center enabled strong and efficient networking; no doubt, in the future we will see that many new ice core drilling projects had their roots at IPICS' 1st OSC. Proving that ice core scientific outputs remain of prime importance to high-impact journals, the Chief Editor of *Nature* as well as an editor of *Nature Geoscience* attended the full five days of the event.

IPICS' next OSC will take place in 2016. An open call for bids to organize it will be launched in 2013.

Acknowledgements

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Analyzing paleolimnological data with R

Isle of Cumbrae, Scotland, 16-20 August 2012

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Paleolimnology has grown rapidly over the last two or three decades in terms of the number of physical, chemical, and biological indicators analyzed and the quantity, diversity and quality of data generated. Such growth has presented paleolimnologists with the challenge of dealing with highly quantitative, complex, and multivariate data to document the timing and magnitude of past changes in aquatic systems, and to understand the internal and external forcing of these changes. To cope with such tasks paleolimnologists continuously add new and more sophisticated numerical and statistical methods to help in the collection, assessment, summary, analysis, interpretation, and communication of data. Birks et al. (2012) summarize the history of the development of quantitative paleolimnology and provide an update to analytical and statistical techniques currently used in paleolimnology and paleoecology.

R is both a programming language and a complete statistical and graphical programming environment. Its use has become popular because it is a free and open-source application, but above all because its capability is continuously enhanced by new and diverse packages developed and generously provided by a large community of scientists.

This recent workshop, held in the comfortable facilities of the Millport Marine Biological Station, trained researchers on the theory and practice of analyzing paleolimnological data using R. The course was led by Steve Juggins (Newcastle University) and Gavin Simpson (University College London, recently moved to the University of Regina), two of the researchers that have contributed in the development and application of different statistical tools and packages for paleoecology within the R community.

A total of 31 participants from a range of continents (North and South America, Europe, Asia, and Africa), career stages (PhD students to faculty) and scientific backgrounds (paleolimnology, palynology, diatoms, chironomids, sedimentology) enjoyed four long days of training in statistical tools and working on their own data. Initially, participants were introduced to R software and language, tools for summarizing data, exploratory data analysis and graphics. The following lectures and practical sessions focused on simple, multiple and modern regression methods; cluster analysis and ordination techniques used to summarize patterns in stratigraphic data; hypothesis testing using permutations for temporal data, age-depth modeling, chronological clustering, smoothing and interpolation of stratigraphic data; and calculation of rates of change. The final lectures dealt with the application of techniques for quantitative environmental reconstructions. The theory and assumptions underpinning each method were introduced in short lectures, after which the students had the opportunity to apply what they had learned, to data sets and real environmental questions, during practical sessions. There was also time in the evenings for sessions on important R tips, advanced R graphics, special topics proposed by the assistants, and for the students to work on their own data.

The course was conveniently organized just prior to the 12th International Paleolimnology Symposium (Glasgow, 20-24 August 2012), which enabled all of the workshop participants to attend the symposium and encouraged further discussions throughout the following week. PAGES covered travel and course costs for five young researchers from developing countries (Turkey, South Africa, Macedonia, and Argentina) all of who were very grateful for the opportunity to attend.

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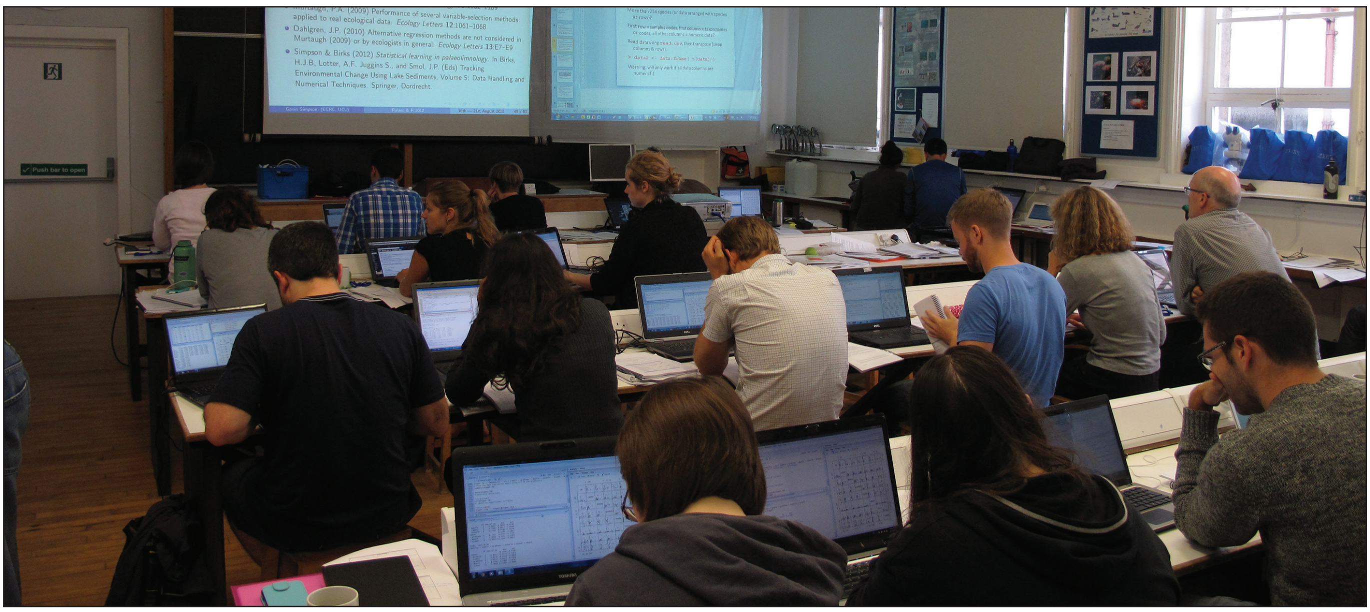

Figure 1: Participants during the R workshop. Photo by S. Juggins.

The Sun and its role in climate change

Workshop of the PAGES Solar Working Group – Davos, Switzerland, 5-7 September 2012

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Better understanding the Sun and its role in climate change is an important but difficult goal. It is important because to properly assess the anthropogenic effect on climate change an accurate quantification of the natural forcing factors is required. But it is difficult because:
(1) natural forcing records are generally not well quantified;
(2) the response of the climate system to forcings is non-linear due to various feedback mechanisms and can only be estimated using complex climate models;
(3) in spite of their complexity models may not comprise all relevant processes and have to be validated, but the instrumental records of climate forcing and climate response are generally too short for this purpose and the data set needs to be complemented by proxy data;
(4) proxy data are derived from natural archives and are only indirectly related to the physical parameters of interest, and their calibration is based on assumptions that may not be fully valid on longer time scales;
(5) instrumental and proxy data reflect the combined response to all forcings, and not only the influence of the Sun. Furthermore, the climate system shows internal unforced variability. All this makes separation and quantification of the individual forcings very difficult.

The main aim of the first workshop of the solar forcing working group was to assess the present state of the art and identify knowledge gaps by bringing together experts from the solar, the observational and paleo-data, and modeling communities.

The workshop was organized jointly with FUPSOL (Future and past solar influence on the terrestrial climate), a multi-disciplinary project of the Swiss National Science Foundations that addresses how past solar variations have affected climate, and how this information can be used to constrain solar-climate modeling. FUPSOL also aims to address the key question of how a decrease in solar forcing in the next decades could affect climate at global and regional scales.

Here are some examples of open questions and problems that were identified in this workshop, and will be addressed in more detail in subsequent meetings:

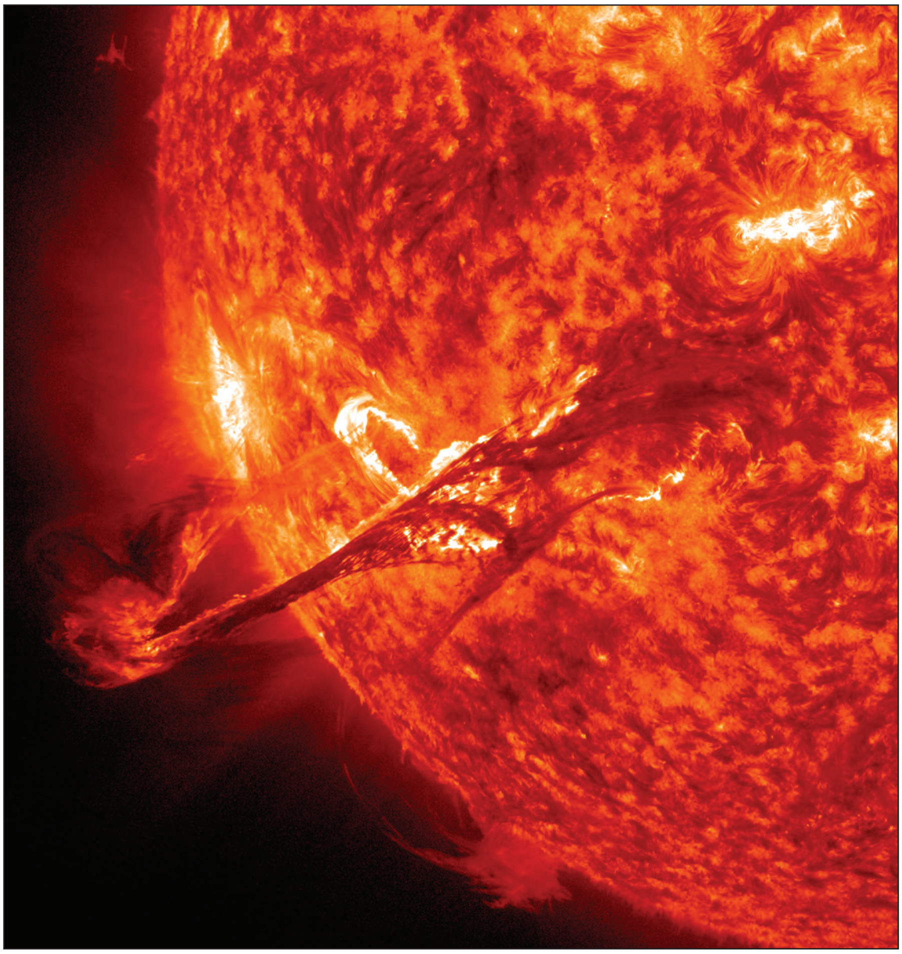

Figure 1: Image of a solar magnetic filament burst. Image by NASA.

• Physical solar models are not yet capable of explaining many observed features such as solar cycles and changes in total solar irradiance (TSI) and solar spectral irradiance (SSI).
• There are still unresolved discrepancies between different composites of TSI based on the same satellite data.
• Semi-empirical models are relatively successful in explaining short-term changes in TSI and SSI on time scales of days to years. However, on multi-decadal time scales input data and instrumental TSI and SSI data for comparison are missing.
• TSI and SSI reconstructions based on proxies suffer from large uncertainties in their amplitudes.
• The most recent minimum, between solar cycle 23 and 24, and probably also the upcoming minimum provide a glance of the Sun at its lowest activity level ever observed during the satellite era.
• UV forcing and possibly also precipitating particles have significant impacts on atmospheric chemistry and dynamics and need to be included in models.
• Detection and attribution of solar forcing is often hampered by volcanic eruptions occurring simultaneously. Strategies to separate solar and volcanic forcings could be to select periods of low volcanic activity (e.g. roman period), to consider regional effects that differ for different forcings, and to look for multi-decadal to centennial solar cycles with well-defined periodicities.

As an opening spectacle to the workshop, a medium-sized flare initiated a long, magnetic filament burst out from the Sun (Fig. 1). Viewed in the extreme ultraviolet light, the filament strand stretched outwards until it finally broke and headed off to the left. Some of the particles from this eruption hit Earth in September 2012, generating a beautiful aurora.

The backbone of PAGES 2k: data management and archiving

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Full affiliations listed here: www.pages-igbp.org/products/newsletters/ref2013_2.pdf

The PAGES 2k Network and NOAA collaborate closely to optimize data compilations, and to build structures to facilitate ongoing supply and dynamic use of data. It is thus an successful example for a large trans-disciplinary effort leading to added value for the scientific community.

The PAGES 2k Network has formed to study climate change over the last two millennia at a regional scale, based on the most comprehensive dataset of paleoclimate proxy-records possible. In 2011, at its second network meeting in Bern, Switzerland (von Gunten et al. 2012) the network formally acknowledged that the envisioned data-intensive multi-proxy and multi-region study must be built on the foundations of efficient and coordinated data management. In addition, the group committed to PAGES general objective to promote open access to scientific data and called for all records used for, or emerging from the 2k project to be publicly archived upon publication of the related 2k studies.

Architects of the home for 2k data

The National Climatic Data Center at the National Oceanic and Atmospheric Administration (NOAA) offered to host the primary 2k data archive. They set up a dedicated NOAA task force to tailor the 2k data archive to the specific needs of the 2k project and to coordinate archiving with NOAA's data architecture and search capabilities. The 2k groups nominated regional data managers to provide input from the users' end.

Over the last two years, the regional 2k data managers have worked closely with NOAA to tailor the database infrastructure and prepare the upload of the 2k data. In addition, they provided expertise to help promote improvements in NOAA's archival of paleoscientific data in general. Since the data managers of the regional 2k groups are spread across the globe, the collaboration was organized around bi-monthly teleconference meetings under the lead of NOAA. In spite of the occasional unearthly meeting hours for some, the interaction between the 2k data and NOAA database groups has worked fruitfully, as the following achievements show.

The 2k database

The paleoclimatology program at NOAA has set up a dedicated 2k project site with subpages for all regional groups (www.ncdc.noaa.gov/paleo/pages2k/pages-2k-network.html). This page was created early in the project to provide the regional groups with a central place to continuously compile datasets considered relevant to their studies.

Populating the database

A two-step approach was applied for entering the 2k data into the database in order to serve demands for both speediness and thoroughness.

First, all records used for the first synthesis article on regional temperature reconstructions (PAGES 2k Consortium 2013) were made available on a "data synthesis products" page dedicated to the paper (hurricane.ncdc.noaa.gov/pls/paleox/f?p=519:1:::::P1_STUDY_ID:14188). This ensured that the records were made publicly available exactly at the time of publication and in a format that will remain identical with the data files supplementing the article. In a second step, all these records are currently being (re)submitted to NOAA with more detailed metadata information than before using a new submission protocol. Additionally, many new and already stored records that were not used for the PAGES 2k temperature synthesis are (re)formatted to the new submission protocol. This will allow improved search and export capabilities for a wealth of records that can currently only be accessed individually.

Improved data submission protocol

The data submission process is a crucial step for the long-term success of a database. On the one hand, it should contain as much relevant information as possible in order to maximize the value of the data. On the other hand, it should remain simple enough to keep the threshold for data providers as low as possible. The NOAA task force and 2k data managers therefore created a substantially revised submission template file. This new protocol allows including more comprehensive information relating to the proxy records, and, crucially, is organized in a structured format that allows machine reading and automated searching for defined metadata information. This is critical in order to maximize the usefulness of the data to other scientists, as it additionally allows them to reprocess underlying features of the records such as the chronology or proxy calibrations.

The new data submission template is also optimized for taking advantage of NOAA's archival structure, which follows international conventions for data description and archiving, and the Open Archive Initiative Protocol for Metadata Harvesting. This allows PAGES 2k data to be visible beyond the NOAA web site.

A new feature of the NOAA-Paleo archive is the search capabilities that allow for project-specific searches by a logical operator (e.g. "PAGES 2K AND Monsoon"). Additional functionalities are planned that will, for example, allow the user to select a subset of proxy data for a region, and generate a single downloadable file of the requested data in NetCDF, ASCII, or Excel™ formats.

2k data management - next steps

In the next phase of the project starting now, the 2k network will work on completing the database of paleoclimate records of the last 2000 years to eventually produce new synoptic climate reconstructions. The proxy records will be collected according to the new NOAA data submission protocol. The prior use of this template during the collection and analysis phases of the project has the following advantages: 1) all records are collected in the same, uniform format allowing for the inclusion of all relevant information, 2) the files are easily computer readable for data analyses, and 3) no additional formatting is required for the subsequent submission to the NOAA-Paleo archive.

For large, data-intensive studies a good data management strategy is crucial. The experience from the PAGES 2k project suggests that setting up a data manager team and involving archivist partners such as NOAA at an early stage of the project is key to handling data efficiently.

This new collaborative data storing effort is only possible thanks to the members of the regional 2k groups who provide their data and metadata inventories with the aim to make the global network of paleoclimate datasets publicly available.

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Updated Latin American Pollen Database: Version 2013 in preparation for NEOTOMA

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The Latin American Pollen Data Base, better known as the LAPD, is an extensive database of pollen from peat and lake cores and surface samples. It covers the areas of Central America, the Caribbean, and South America. The database was launched in 1994 by a research group headed by Vera Markgraf at the University of Colorado, USA, and its management moved to the University of Amsterdam in 1998, where it was hosted by Robert Marchant at the Institute of Biodiversity Ecosystem Dynamics (IBED).

The LAPD started as a website where palynologists were encouraged to share their data. Unfortunately, after the project ended in 2003 no further updates were made to the website and the related database, and the list of pollen data of Latin America quickly became outdated. Recognizing the urgency for an updated LAPD, the group at IBED decided to revive it. Supported by three grants from the Amsterdam-based Hugo-de-Vries-Foundation (Van Boxel and Flantua 2009; Flantua and Van Boxel 2011), Suzette Flantua initiated a search for studies published after 2003. While the exploration for pollen records continues, this new "LAPD 2013" inventory contains 1478 pollen sites throughout Latin America, multiplying by a factor of three the number of sites compared with the last update in 1997 (463 sites). The number of countries represented has increased from 15 to 29.

In the meantime, the "NEOTOMA" database (www.NEOTOMAdb.org) was developed through an international collaborative effort of individuals from 23 institutions. This cyber infrastructure was designed to manage large multiproxy datasets, which makes it easy to explore, visualize, and compare a wide variety of paleoenvironmental data. This is why it was chosen as the primary archive site for the Global Pollen Database. The LAPD data in the 1997-list is now available through NEOTOMA (Fig. 1), and the complete 2013 LAPD inventory with metadata will soon be available through NEOTOMA Explorer (http://ceiwin5.cei.psu.edu/Neotoma/Explorer/).

Although all LAPD data will be incorporated in NEOTOMA, the LAPD database will still exist as an independent entity. There will be a LAPD page within the existing NEOTOMA website which can be used to obtain information on updated pollen sites, the pollen data, and events related to LAPD. It was also proposed to form a Latin American NEOTOMA group of paleoecological researchers to manage the database, and upload and control the quality of the data.

As almost no new data has been contributed to LAPD since 2003, IBED is in the process of digitalizing and uploading their pollen database to make a significant contribution to LAPD and thus stimulate global collaboration, and data input and use by other research groups. The data of the newest pollen sites will be kept on "standby" in an offline database and made publicly available once the related research papers are accepted for publication.

We would like to make researchers aware of the much richer palynological information now available for Latin America and we hope the pollen community will recognize LAPD-NEOTOMA as an important archive, where the original authors are cited and acknowledged to have contributed to the database. We emphasize the great opportunity to promote multidisciplinary research on a continental scale and international scientific cooperation.

We invite anyone with questions, doubts, or relevant information to contact us through Suzette Flantua and to support this global palynological initiative for an improved integration of knowledge and efforts.

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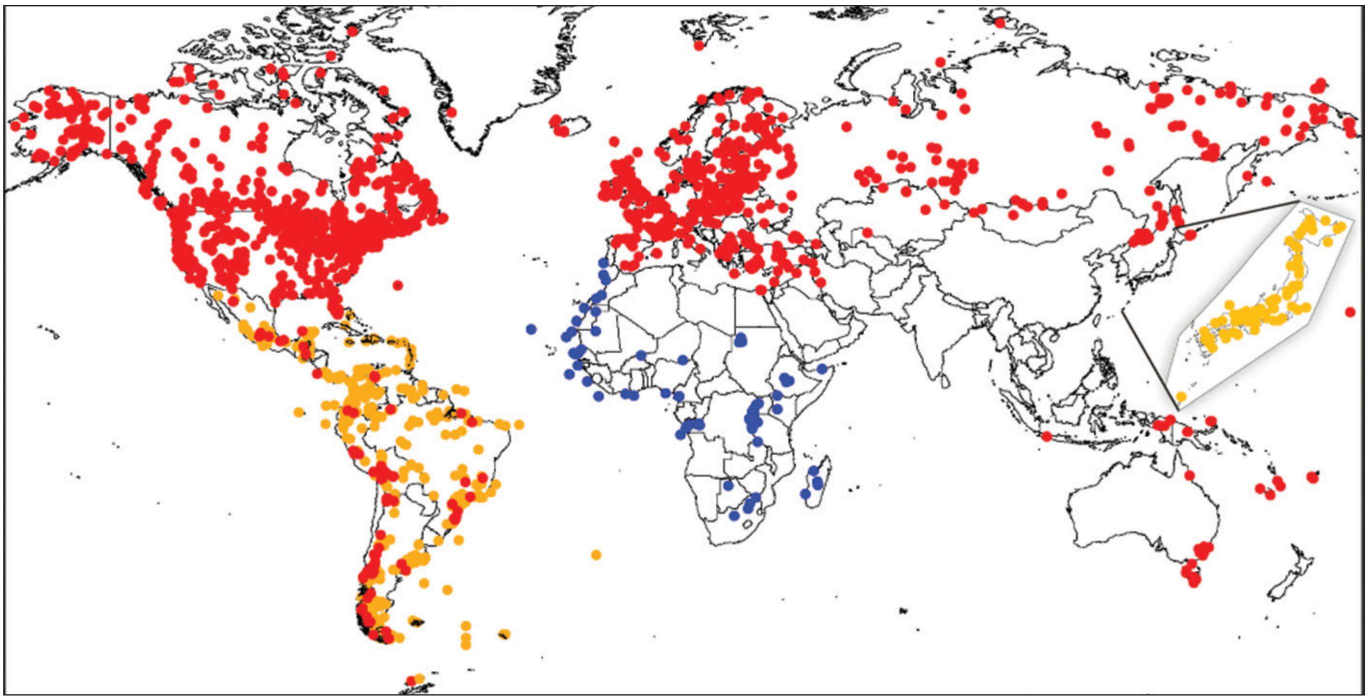

Figure 1: NEOTOMA and LAPD pollen sites. Red dots: existing NEOTOMA database; blue dots: African Pollen Database; yellow dots: inventoried sites for inclusion from Latin America and Japan. (Figure from Grimm et al. 2013).

A brief report on the 2nd PAGES Young Scientists Meeting in Goa, India

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Back in 2009, PAGES experimented with a different type of meeting for the first time – the inaugural Young Scientists Meeting (YSM) in Corvallis, USA. Recently several 1st YSM alumni worked together with PAGES to build on the success of that inaugural meeting with another YSM. The 2nd YSM took place from the 11-12 February 2013 at the International Centre Goa in India. It brought together graduate students, post-doctoral fellows and early career scientists from around the globe to share their research, network, present and attend workshops and panel discussions designed to address the specific challenges and opportunities facing early career paleoscientists. A total of 79 participants from over 27 countries attended the meeting.

Participants were welcomed by S. Rajan, Director of the National Center for Antarctic and Ocean Research, the Goan host institution. Thorsten Kiefer, PAGES Executive Director, then outlined the rationale behind the meeting and expressed the hope that the YSM would foster multi-disciplinary, international interaction and collaboration amongst the next generation of paleoscientists.

The meeting was structured around seven themes: Climate Forcings; Regional Climate Dynamics; Global Earth-System Dynamics; Human-Climate-Ecosystem Interactions; Chronology; Proxy Development, Calibration and Validation; and Modeling.

Twenty participants gave oral presentations and many others presented posters around each of these themes. A written peer-feedback activity provided presenters with valuable feedback on their presentation and ways to improve. The best presentations received an award, including one year of free online access to the Nature Geoscience journal: Ilham Bouimetarhan (Bremen, Germany) and Vladimir Matskovsky (Moscow, Russia) received prizes for the best oral presentations, and Jesper Björklund (Göteberg, Sweden), Gayatri Kathayat (Xi'an, China), and Timothée Ourbak (Niamey, Niger), for the best poster presentations.

In the keynote talk Alan Mix of Oregon State University reflected back upon his career as a climate scientist, which began during a time of discovery defined by a paucity of data - a stark contrast to the present, with its wealth of data and the commensurate need for new approaches to interpreting it. He emphasized the need for more interaction among paleoscientists and the increased need for more quantitative climate data, which can be better utilized by the modeling community.

The three "The Art of" sessions were a newly framed item in the YSM program and aimed to provide young scientists with practical information about data sharing, reviewing and communicating science (see the following articles).

In "The Art of Sharing Data", David Anderson from the Institute of Arctic and Alpine Research, and National Climatic Data Center, highlighted the importance of sharing data, and in particular, making data publicly available through archiving. He discussed the data-rich world we live in where the sharing and archiving of data can increase the visibility of an individual's research tremendously, and how easy accessibility to datasets will encourage the community to develop new and novel quantitative approaches to interpreting them.

In "The Art of Communicating Science" Gavin Schmidt from the NASA Goddard Institute for Space Studies suggested ways to convey science to different audiences and how to tackle controversies and criticism. He recommended the use of simple language with common examples and as many pictures and graphs as possible, instead of tables and technical jargon.

"The Art of Reviewing" panel included Alicia Newton, Editor of *Nature Geoscience*; Denis-Didier Rousseau, Co-Editor-in-Chief of *Climate of the Past*; Chris Turney, Asian and Australasian Regional Editor for the *Journal of Quaternary Science*; and moderator Alberto Reyes, of Queen's University, Ireland. They fielded many questions from the audience, addressing various topics such as signing reviews vs. double-blind reviews and what editors expect in a good review. It became clear during this session that many YSM participants did not feel their training had prepared them adequately for the peer-review process.

During breakout sessions, participants divided into groups and deliberated on four challenges facing young paleoscientists. More detailed summaries of the breakout and "The Art of" sessions are reported elsewhere in this issue of PAGES news. A key theme emerged across all groups: Many of the big important issues and problems facing early-career paleoscientists are similar the world over and may be dealt with through international efforts. However, just as many are specifically local, and therefore will require local solutions.

There was, of course, plenty of opportunity for social interaction with one another, as well as with the organizers and guests. Communal meals, the icebreaker, and a dinner on one of the famous Goan casino boats featuring a Bollywood show, gave participants an opportunity to bond with each other while enjoying Indian culture and food.

To conclude, participants thanked PAGES for taking the initiative to hold the YSM, and requested such meetings be convened more often. We would also like to gratefully thank the generous sponsors, listed below, whose contributions directly assisted many young scientists travel to and attend the meeting.

Sponsors included: The Ministry of Earth Sciences, Government of India; National Centre for Antarctic and Ocean Research, India; US National Science Foundation; and the Swiss National Science Foundation; Asia-Pacific Network for Global Change Research; System for Analysis, Research and Training; IGBP, Brazil Regional Office; National Oceanic and Atmosphere Administration, USA; National Institute of Ocean Technology, India; Indian National Centre for Ocean Information Services, India; Indian Institute of Tropical Meteorology, India; Oeschger Centre for Climate Change Research, University of Bern, Switzerland; and the International Association of Sedimentologists.

The Art of Communicating Science: traps, tips and tasks for the modern-day scientist

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In a true test of modern-day communication, the participants at the 2nd PAGES Young Scientists Meeting travelled virtually from the 26°C heat of a Goan afternoon to a brisk -2°C morning in New York City to join Gavin Schmidt (NASA, USA) for a lesson in the art of science communication. During this session, Gavin then delved into the nuts and bolts of why scientists are ethically obligated to publicly communicate their science and how communicating it *well* is an increasingly challenging but important aspect of our profession. This article highlights Gavin's tips for effective public communication, some common traps scientists fall into, and tasks or next steps our community needs to take to improve the public's access to accurate, high-quality scientific information.

Despite the general public's interest in science, it is often hard to know where to go for accurate (and understandable) scientific information. In a world of rapid and wide dissemination of knowledge and opinions, it is increasingly important to communicate outside the scientific community. Not only do we have an obligation to communicate broadly, due to the typically high proportion of science funding coming from the taxpayer, but broad communication is essential to avoid misuse or misinterpretations of our work and to slow the propagation of scientific misconceptions.

Crucially, many of the important scientific concepts that need to be conveyed are simply not "news". For example, the physics of greenhouses gases will undoubtedly never make the headlines yet it is a fundamental building block to being literate in the issue of climate change. Communicating these types of facts requires scientists to step beyond traditional avenues of communication. Gavin emphasizes that we, as a community, need to engage with social media and web-based communications, in addition to traditional means of communication (e.g. press releases, interviews and essays). People increasingly rely on the internet as a primary source of information, which means there is a need to provide more accurate and appropriate information online through scientists' blogs, videos, and social media platforms. We need to use this diverse set of tools to not only convey our expertise but importantly, to engage with different audiences.

The challenge of *clearly* communicating the intended scientific message to the public is not insurmountable but requires an understanding of what works and what does not work. Falling into typical science communication traps can quickly turn an interview, article or outreach event into a counterproductive debate or an unintended source of misleading information. Here are some common traps and points on what does not work:

- Avoid talking too much about technical details and avoid technical debates
- Avoid using jargon that you don't take time to explain
- Avoid scientific stereotypes, e.g. arrogance or elitism
- Avoid triggering issues of free speech, data access, and secrecy
- Do not respond poorly to criticism by getting angry or taking it personally
- Always distinguish between personal opinion and scientific consensus
- Try to understand the context in which your statements will be heard or read
- Try to defuse pseudo-debates but do not ignore them
- Avoid sensationalism and over-extrapolated conclusions

In order to get your audience to engage with your science, you have to engage with your audience. Several easy tips that can improve the strength and resonance of your message include:

- Listen to what your audience is interested in or concerned about
- Use imagery and animations. These can often create a deeper connection for the audience (e.g. see Fig. 1)
- Make it personal: use personal, relatable stories that remind people that we are "normal". Personal anecdotes often generate excitement and engagement
- Always remember the big picture and the reasons why you are a scientist
- Be a credible and trustworthy guide and take advantage of the generally held feeling of public admiration towards scientists
- Promote the investigative nature of science
- Provide accessible context outside of the technical literature
- Always underscore what can and cannot be concluded from your work

As mentioned above, we live in an increasingly connected world with growing access to information (and misinformation).

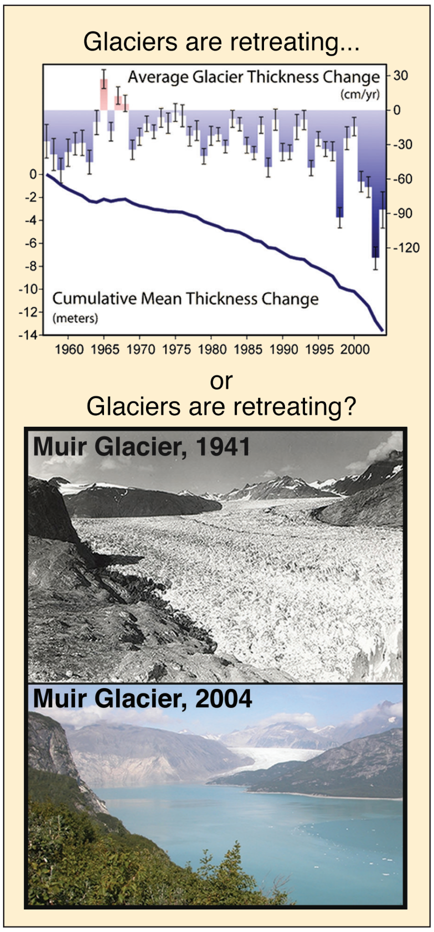

Figure 1: The use of imagery is an effective way to convey messages to the general public. Which illustration would you choose for a public lecture? Image sources: US National Snow and Ice Data Center.

Our collective task is to ensure access to appropriate and understandable scientific information. The key to success relies on a collaborative approach in which we all rally together and begin to communicate the importance of science and the scientific process. En masse we can begin to change the public perception of science, and can contribute to developing a more scientifically literate society. Making use of the above tips, learned from the frontlines of public science communication, can help to initiate this process and move our community in the right direction. Now it is time to get blogging, writing, and tweeting!

For further reading, see Gavin's recommendation: www.skepticalscience.com/docs/Debunking_Handbook.pdf

The Art of Reviewing: Holding up quality in the scientific quality control system

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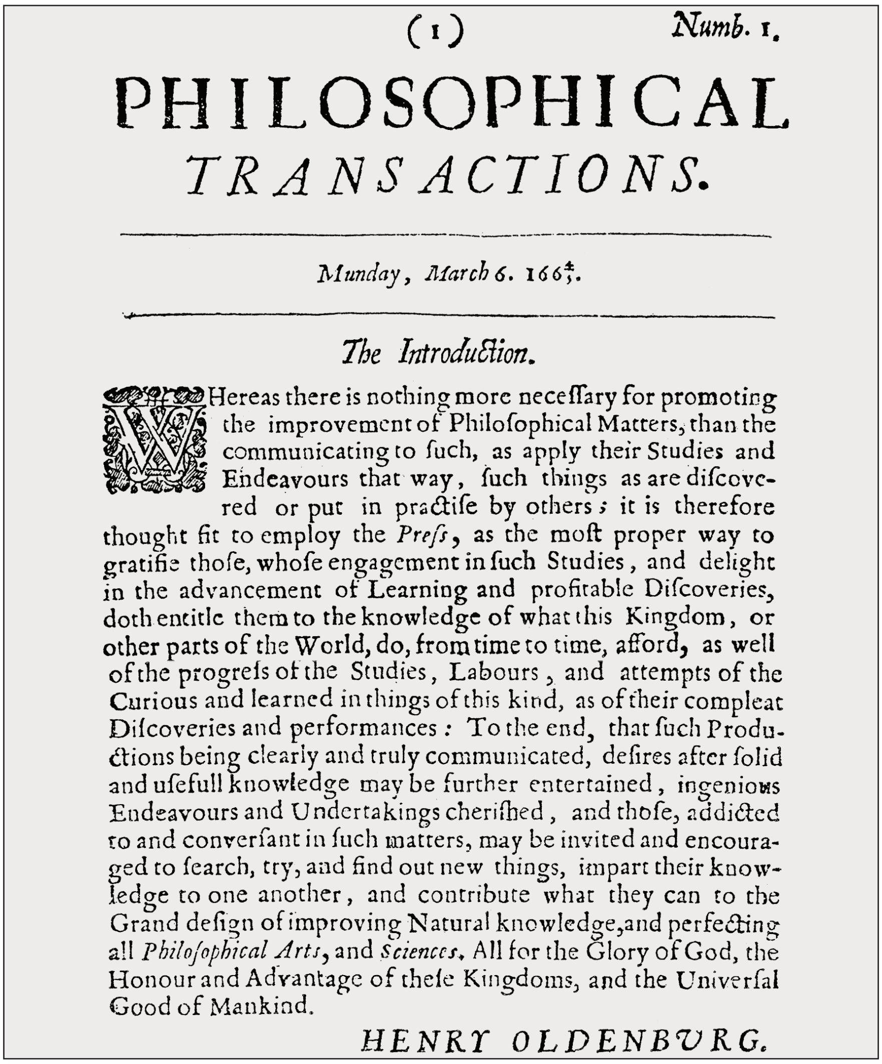
Ever since the publication of the Philosophical Transactions of the Royal Society by Henry Oldenburg (1665, Fig. 1), scientists have acknowledged the importance of relaying research findings to a wider scientific community. Currently, publishing scientific findings in peer-reviewed journals, brands the research work as "credible". These peer-reviewed scholarly articles improve the quality of science and are used as a metric for scientific performance, which is essential for career advancement. The Program Committee of the 2nd PAGES YSM recognized the need to contribute to building capacity in the art of reviewing among young paleo-scientists. To this end, editors from prominent paleoscience journals, namely Nature Geoscience (Alicia Newton), Journal of Quaternary Science (Chris Turney) and Climate of the Past (Denis-Didier Rousseau) were invited to be part of a panel discussion highlighting the aims and process of peer-reviewing.

The discussion commenced with the importance of peer reviewing in science and the responsibility journal editors have to maintain the integrity and quality of science. Accordingly, the nominated reviewers bear the responsibility of scrutinizing the quality and clarity of the scientific content in the manuscript and providing constructive criticism to help authors improve it. From the editor's perspective, feedback on a manuscript should indicate if the conclusions are new, if the study builds upon the existing literature, and above all assess if the evidence presented supports the conclusions.

On the question of "How to differentiate a poor review from a good one?", the panelists' collective reply was: *A good review demands useful and constructive criticism that identifies the strengths and weaknesses of a manuscript and gives recommendations with supporting justifications. As a reviewer, never go by dogmas and don't reject new ideas, if they are supported with data and systematic methodology. If the work is promising, but has not attained its best form, insist that authors take on the burden of more work to justify their novel ideas and research. Always be polite, objective and respectful to the author(s), regardless of whether you recommend the editor accepts or rejects the manuscript.*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Munday, March 6. 166⁴⁄₅.

The Introduction.

Whereas there is nothing more neceſſary for promoting the improvement of Philoſophical Matters, than the communicating to ſuch, as apply their Studies and Endeavours that way, ſuch things as are diſcovered or put in practiſe by others; it is therefore thought fit to employ the Preſs, as the moſt proper way to gratifie thoſe, whoſe engagement in ſuch Studies, and delight in the advancement of Learning and profitable Diſcoveries, doth entitle them to the knowledge of what this Kingdom, or other parts of the World, do, from time to time, afford, as well of the progreſs of the Studies, Labours, and attempts of the Curious and learned in things of this kind, as of their compleat Diſcoveries and performances: To the end, that ſuch Productions being clearly and truly communicated, deſires after ſolid and uſefull knowledge may be further entertained, ingenious Endeavours and Undertakings cheriſhed, and thoſe, addicted to and converſant in ſuch matters, may be invited and encouraged to ſearch, try, and find out new things, impart their knowledge to one another, and contribute what they can to the Grand deſign of improving Natural knowledge, and perfecting all Philoſophical Arts, and Sciences. All for the Glory of God, the Honour and Advantage of theſe Kingdoms, and the Univerſal Good of Mankind.

HENRY OLDENBURG.

Figure 1: Introduction by Henry Oldenburg to the first issue of the Philosophical Transactions of the Royal Society (Oldenburg 1665).

A major issue for editors is finding suitable reviewers, as often the best-known experts in the field lack time. Nevertheless, it is fine to politely turn down the opportunity of reviewing a paper if you lack the time or the expertise the paper demands, or in the event of conflicting research interests. On the other hand, if you agree to do a review, you should keep your word and not decline the responsibility after several months of doing nothing with the manuscript.

The experienced referees on the panel reminded young scientists to be aware of the time pressures involved in reviewing. A thorough review of a paper takes a minimum of two to three days depending on one's efficiency and ability. Anticipating this pressure allows one to set aside ample time to read the paper and let the ideas sink in for a few days, before writing the review. This process helps sharpen one's ideas and thinking on the issues covered in the manuscript.

While it remains important that the authors cite the most recent papers relevant to the study, it is equally important to check if the authors cite the original pioneer works. In case you do not have access to the references the authors cite, you can ask for the papers from the editors rather than provide a poorly informed review.

Therefore, working on the review of a manuscript ahead of the deadline allows time to build initial impressions, verify cited references and reserve sufficient time for constructive feedback, steps that ensure a thorough review. Finally, submitting the report on time also ensures a smooth and efficient evaluation, and makes the new results swiftly available, to the benefit of science overall.

Ethics are a critical aspect in the art of reviewing, and an area in which young reviewers may need to develop. As a reviewer, one has the moral responsibility to put aside one's own research and publication interests, be honest and fair with the authors and consider the interests of the respective journal. The same is true for an editor or reviewer while dealing with conflicting reviews or accepting risky ideas. A test of one's integrity as a reviewer is whether or not you are able to put your name to the review, i.e. disclose your identity.

To ensure the editor can build an adequate assessment of the reviews, it is crucial that the reviewer clearly states which topics are outside his or her area of expertise. This allows the editor to identify additional experts, if needed. One should not shy away from providing detailed reviews, so that a paper can be improved to near perfection. This can include providing grammar and language amendments if possible. However, the main task of a reviewer is to evaluate the science of a study and not necessarily correct the language of the manuscript. Instead of spending time correcting spelling mistakes at the expense of evaluating the scientific content, the reviewer can mention the need for copy-editing to the editor.

Although demanding and time-consuming, reviewing manuscripts provides a unique opportunity to improve one's critical thinking and writing skills, stay updated on cutting-edge research techniques and ensure the quality and integrity of published science. This interactive session on "The Art of Reviewing" brought to light that about half of the ~80 early-career participants had reviewed papers either on behalf of their supervisors or directly for journals; however, most of them had never received formal training in reviewing. Consequently, the young scientists unanimously expressed the wish for formal training in reviewing as part of their doctoral education.

To conclude, the guiding line for a scientist should be "*publish or perish*"! But at the end of this session, we found a new one: "*Peer review: love it or hate it, it's an integral part of every scientist's life.*" (Welsh 2010). So do not panic if an editor picks you to be the chosen one!

Additional information on the art of reviewing is available in published articles, e.g. Smith 1990; Provenzale and Stanley 2006; Rosenfeld 2010, and on these dedicated websites: users.ecs.soton.ac.uk/hcd/reviewing.html; bcl.hamilton.ie/~barak/how-to-review.html; elsevier.com/reviewers/home; councilscienceeditors.org/i4a/pages/index.cfm?pageid=3331

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The Art of Data Sharing: key in future climate science

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At the PAGES Young Scientists Meeting, 11-12 February 2013, in Goa, India, 79 young researchers from around the world gathered to discuss research, to network, and to exchange ideas for the future of climate research. Initiated by a talk on "The Art of Data Sharing" given by David Anderson, head of the World Data Center for Paleoclimatology at the National Oceanic and Atmospheric Administration (NOAA), a lively discussion arose on the benefits and potential of data sharing for future research.

Fortunately, many researchers already upload their data and computer code to an Internet database to be available for future projects. Therefore, a wealth of databases and software exist that are open and easily accessible (see Box 1). These include data from classical proxy archives such as tree rings, ice cores, lake and marine sediments, as well as model output, reanalysis, observations and a multitude

Box 1: Examples of databases, software, and sample repositories.
The number of databases, open-source software and repositories is growing, providing extensive resources for scientists to engage in data-intensive research.

Databases
Pangaea, Data publisher for Earth & Environmental sciences, *www.pangaea.de*
World Data Center for Paleoclimatology, *www.ncdc.noaa.gov/paleo*
Neotoma, A paleoecology database and community, *www.neotomadb.org*
JANUS, Data from the Integrated Ocean Drilling Program, *www-odp.tamu.edu/database*
Core Curator's Database, the Index to Marine and Lacustrine Samples, *www.ngdc.noaa.gov/mgg/curator*
PAGES list of databases, *www.pages-igbp.org/my-pages/data*

Software
Calib, the radiocarbon calibration program, *http://calib.qub.ac.uk/calib*
Analogue, Analogue and weighted-averaging methods for paleoecology, *http://analogue.r-forge.r-project.org*
Singular Spectrum Analysis, A toolkit for spectral analysis, *www.atmos.ucla.edu/tcd/ssa*
Ocean Data View, a software package for the exploration and analysis of oceanographic and other data, *http://odv.awi.de*
KNMI Climate Explorer, an online tool to visualize and analyze climate data with a large ready-to-use database, *climexp.knmi.nl*

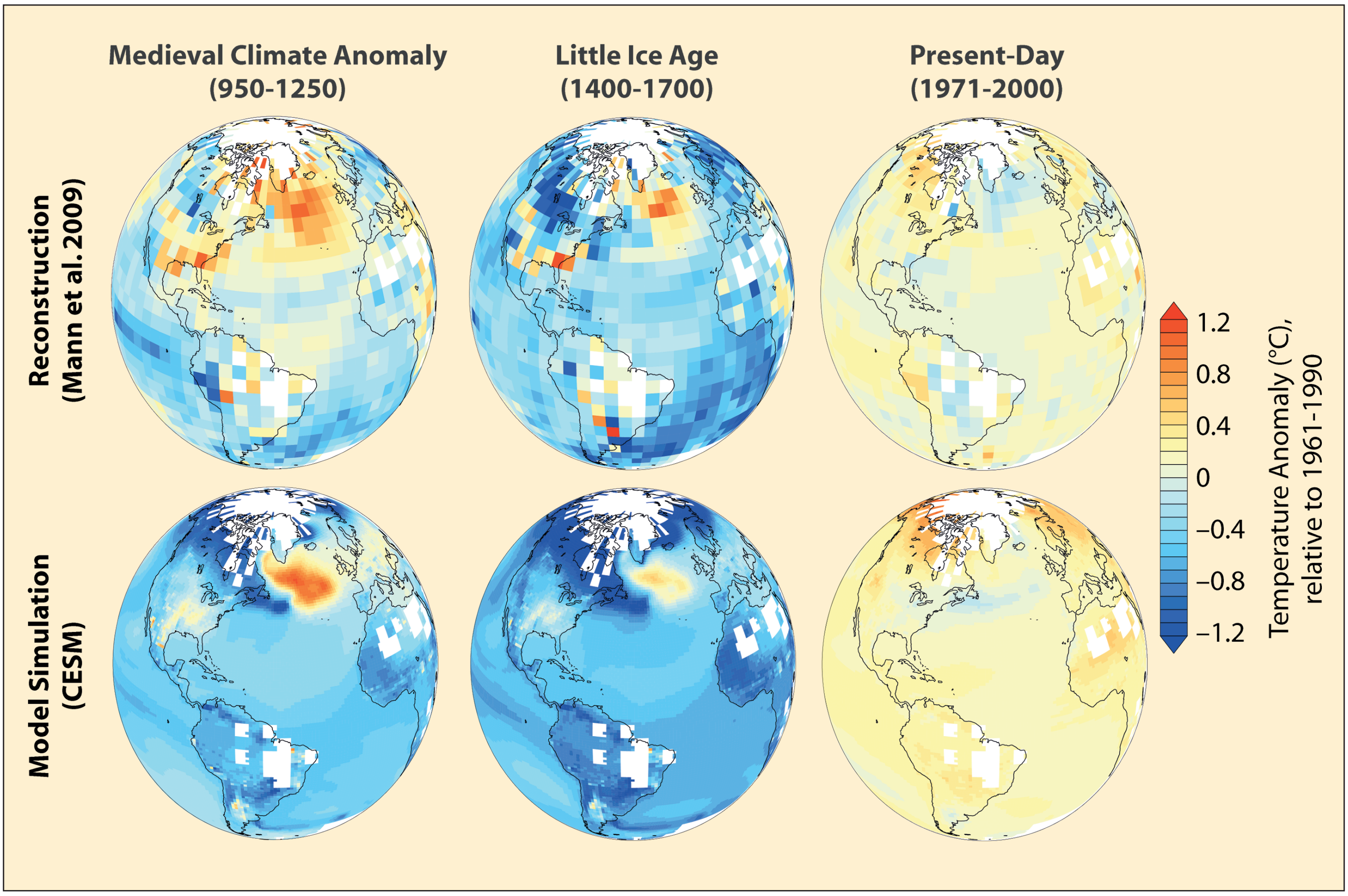

Figure 1: Sharing and combining data and model simulations allows for a better understanding of past climate variability. Temperature anomalies relative to 1961-1990 in a reconstruction (Mann et al. 2009) and a Last Millennium simulation with a comprehensive coupled model (Community Earth System Model). White areas indicate no reconstruction data; the same areas have been masked in the model output for comparability.

of free algorithms, scripts and software packages.

Not only can researchers use these archives to compare with their own new data, but also groundbreaking studies seeing the large-scale picture can result from compiling or reanalyzing existing data sets (e.g. Lisiecki and Raymo 2005; Mann et al. 2008; Andrews et al. 2012). These kinds of data compilation projects are time-intensive. However, when fed back to the database, the resulting data can be highly beneficial for the paleoscience community as it avoids duplication of effort. Data compilation efforts can also be funding-efficient, as some funding agencies have already requested proposals specifically based on that approach. Some general ideas for future compilation-style research include time-slice reconstructions and comparison between transient model simulations and sensitivity experiments conducted by different institutes.

So, why do not all researchers share their data?

The idea of being "scooped" seems to be one of the most important fears preventing researchers from uploading their published data; this seems to be particularly important for young researchers who are working towards establishing their careers and thus cannot afford to not be credited for their work. But in reality, such cases occur rarely and the vast majority of scientists sharing their data experience only benefits from it, including more citations and often even additional co-authorships.

Another barrier to uploading research data seems to be the author's worry about data being misused or misrepresented. Providing detailed meta-information about the data and corresponding error bars greatly reduces the risk of inappropriate use of data. However, the largest hindrance seems to result from confusion about which data repository to use and how to format the data. To this end, many data repositories have helpful "read-me" files and staff support to help with the uploading, so that the researcher hardly has to spend much additional effort.

Some journals and funding agencies are now mandating that authors archive data that appear in publications and discussants at the YSM were united in their hope that this trend towards open access continues.

One way to encourage and credit data sharing in the future could be in the form of a "data citation index". Usually, data compilation studies do not cite every individual data paper that went into the compilation - mainly to prevent the bibliography from exploding. A "data citation index", following the example of the classical citation index for papers, could provide an efficient way of crediting the papers underlying data compilation studies without generating lengthy bibliographies.

With limitless potential for compilation studies to generate truly innovative science and the relative ease of uploading data, we hope many readers consider using these great resources and, of course, helping them to grow.

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Breakout Group A: What should the research questions and priorities in paleoscience be for the next 10 years?

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How can we improve model-based estimates and predictions? How can we improve the production of paleo data? How can we better constrain past rates of change in the Earth system? These questions, among others, were identified as key priorities for future paleoscience during our breakout sessions at the YSM.

We identified that model-based climate sensitivity estimates and the ability to correctly capture climate feedbacks, abrupt transitions, and threshold behavior in models are key to predicting climate and associated changes. Integrated earth-system modeling with improved feedback interactions will be required to study whole-earth system dynamics.

Furthermore, assessing climate model performance requires better datasets of high-resolution proxy reconstructions: We need more high-quality data from under-represented regions. We also need new proxies for several climate variables. Also high on our wish list are solid constraints upon previously unresolved climate system components such as clouds and aerosols. We require better solar and volcanic forcing reconstructions, and we should strive to understand the underlying causes of discrepancies between the different forcing reconstructions available.

To improve the quality of our proxy networks we need to employ replication, high-resolution dating, statistical analysis and multi-proxy approaches in our research. Data uncertainty estimates should always be clearly stated. Process studies and controlled experiments must be used to establish regional calibrations and transfer functions to allow proxy-based reconstructions to capture not only high-frequency climate variability, but also a quantifiable climatic parameter such as temperature or precipitation.

Finally, we need to compile datasets and make them available in a quality-controlled, well-documented and easy-to-use form. Strict formats for "big data" should be employed in a globally acknowledged framework. The field could vastly benefit from larger collaboration with computer software engineers and informatics science to improve efficiency and manageability of earth science datasets.

Breakout Group B: Advocating the relevance of paleo-research to a funding agency or policy maker

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Dear policy makers and funders of science,

We understand your need to base your decisions and investments on stronger arguments of the important role that paleo-research plays in international efforts to understand and emphasize the social, economic, and geopolitical implications of Earth's changing climate. We are also acutely aware of many unanswered questions and substantial uncertainties that currently exist, and always will exist, in paleo-research, as in any other field of science. However, it is now evident that better projections of future climate and environmental change, which form the basis of decisions on national and international greenhouse gas emission policies, require consultation with information from Earth's past.

Repeatedly during its history, Earth's climate has changed abruptly within just a few decades. Climatic variability including changes in the magnitude and frequency of extreme events such as droughts and floods has often had a devastating impact on local societies, and events in the future are likely to bring greater environmental risks as the environment is already subject to substantial stress. Furthermore, due to the increased complexity of modern societies extreme events are likely to become more costly, as recently illustrated by Hurricane Sandy's effect on New York City.

Paleoscientists are undertaking enormous efforts to assess the high complexity of Earth's climate system and gain a better understanding of the general forces controlling global climate change. Integrating local and regional climate information from marine and terrestrial environments all over the world has allowed, for example, the identification of important feedbacks in the climate system; this is crucial if we are to avoid being surprised by abrupt climatic events. The results of this research have helped us to better understand the role human activities play in causing a large part of the changes in the Earth's climate system, namely the significant increase in global temperatures. Moreover, many paleoclimate results are now being effectively assimilated with climate models in order to provide better future projections and predictions of potential impacts likely to affect people in the short-term and in coming decades.

While paleoscientific research is able to highlight some of the environmental risks threatening our planet, much remains to be learned, and this kind of research will still need more financial investment in order to thoroughly examine other scientific questions. While it might not provide direct applications, or solutions for engineering a better future, paleoscientific research makes a substantial contribution to constraining the possible scenarios of future environmental and climatic changes. We encourage you therefore to let paleoscience evidence guide you towards wise decisions on policy and science funding in the context of the high priority challenges facing humanity.

Yours sincerely,
Ilham Bouimetarhan and Hans Christian Steen-Larsen
On behalf of the PAGES Young Scientists 2013

Breakout Group C: Challenges and solutions for enhanced paleoscience communication

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At the 2nd YSM there was consensus among the young international paleoscientists that there is a great need to better develop skills for communicating with different types of non-academic audiences. Clear and effective communication to the public is becoming increasingly important as current and future climatic and environmental changes are frequently a major focus in the media and politics. However, for the paleoscience community there remains the challenge of properly conveying the concept of past change on longer timescales. Facilitating better public understanding of the scientific process is required to break down barriers and have objective discussions, especially regarding the issue of future climate change.

A productive discussion at the YSM about how to address the challenges we face in communicating paleoscience resulted in two potential solutions:

First, as scientists, we need to be proactive in making our research available in our local communities. Creating connections with internet platforms, classrooms, media outlets and other informal science education venues can be highly productive and rewarding, but also difficult and time consuming to develop. To address this problem and to facilitate paleoscience communication, we propose to link with the PAGES scientist database and outline researchers availability for specific outreach activities (e.g. classroom visits, blog articles, Skype calls, laboratory tours, radio interviews). This type of additional database should be communicated through educational networks such as Polar Education International (PEI). The ultimate hope is that this freely accessible database can begin building lasting relationships between the public and local researchers by making it easy for the public to find local scientists. An encouraging example is the Social Media Knowledge Exchange (www.smke.org), which provides a platform for early career scientists in history and archeology to share their research with non-academic audiences.

Second, the current lack of formal training opportunities in science communication is a major obstacle preventing the effective communication of our research. Coursework and other training opportunities, beyond short workshops, are needed to instruct researchers how to effectively and concisely communicate the significance of their research to any audience. In a highly inter-connected world, it is critical that scientists develop an appropriate level of fluency and understanding of how to use communication tools ranging from social media to informal writing.

Ultimately, communicating our scientific results should become a regular and professionally recognized part of the scientific process. Developing the skills to effectively share our science will undoubtedly increase our broader impacts, and PAGES is in a unique position to facilitate this development in the paleoscience community. Already the YSM has stimulated discussion, and we hope that this dialogue can continue in the broader PAGES network to strengthen and broaden our science communication skills into the future.

Breakout Group D: Key educational ingredients to ensure the success of future paleoscientists

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The breakout sessions at the 2nd YSM proved to be an extremely useful exercise that resulted in concrete suggestions for future directions for PAGES and the broader scientific community. The topic of our group was discussed in two subgroups by a total of 21 participants from 12 countries.

One of the key recommendations was that future paleoscience students need better computational skills. In the early days of paleoclimate research, students could turn 50 analyses into a dissertation, but with modern methodological advances, students can now produce hundreds or thousands of geochemical measurements. In addition to expertise in micropaleontology, palynology, organic geochemistry, etc., students need to have the quantitative skills to statistically analyze that data, and effectively put it in the context of a wealth of other paleoclimate archives.

Paleoclimate modelers should have more training in geosciences so that they can better understand the value and limitations of proxy records. Conversely, those generating proxy records need to be capable of understanding and using model results to make proxy-model comparisons.

Students should be encouraged to complete a small research project before opting for a doctoral program so that they can assess their interest as well as aptitude for research. This could be offered as a Bachelor's or Master's dissertation, as is already common practice in some countries, e.g. the USA. This also led to the idea of offering supervisors more incentives (e.g. research assistance or teaching time exemption) for investing time and energy in short-term (i.e. masters-level) research students. Inspired by the panel discussion on peer reviewing, it was also suggested that reviewing should be made a formal part of graduate education.

Over time English has become the single global language bridging international language borders, and thus its knowledge facilitates the effective communication of science. Accordingly, some participants from countries in which English is not the first language did express the need for formal training in reading and writing English. They also wished that some of their science education had been in English.

Earth science is currently not part of the required curriculum in many countries, and the need and importance for elevating earth science education at the primary and secondary school level was expressed. Regarding the much more advanced career stage paleoclimatologists, participants expressed the concern that "paleoclimate" is not as lucrative as mining and petroleum! Although not related to education, the breakout group argued that better incentives and job opportunities will be key conditions to ensure the success of the next generation of paleoscientists.

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