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PAST GLOBAL CHANGES
MAGAZINE

30 YEARS OF PAGES: PAST - PRESENT - FUTURE

EDITORS

Hubertus Fischer, Sherilyn Fritz, Michael N. Evans and Sarah Eggleston

SPECIAL SECTION

Highlighting the future of past global change research

EDITORS

Stella Alexandroff, Madelyn Mette, Tamara Trofimova and Alicja Bonk

PAGES

News

6th Open Science Meeting and 4th Young Scientists Meeting

The new dates for the OSM and YSM in Agadir, Morocco, in 2022 have been announced: The YSM will be held 15-17 May, the OSM icebreaker 17 May, the OSM 18-21 May, and all excursions start 22 May. The OSM and YSM are PAGES' premier events and provide an invaluable opportunity to bring the international past global change community together to share, discuss, learn, and plan for the future. The Local Organizing Committee will keep an eye on COVID-19 developments, and further announcements will be made mid-year: pages-osm.org/

New PAGES website

The PAGES website is currently being revamped and upgraded, with the launch set for mid-2021. We hope you enjoy a more interactive and modern experience, and would love to hear your thoughts about the new design. Email your feedback to pages@pages.unibe.ch

PAGES SSC announcements

On 1 January, PAGES welcomed Scientific Steering Committee (SSC) member Zhimin Jian as the new SSC Co-chair. Zhimin takes over from Mike Evans, who has been a PAGES Co-chair since 2018. We thank Mike for his leadership and guidance and look forward to his continued input as an Executive Committee (EXCOM) member. Zhimin joins Willy Tinner as Co-chair and joins Willy, Mike, Katrin Meissner, Liping Zhou, and Marie-France Loutre on the EXCOM team.

Launch of *Past Global Changes Horizons* magazine

The first issue of *Past Global Changes Horizons* was released to much fanfare in April. This 60-page magazine is designed for teenagers and young adults but is relevant for all. The 18 easy-to-understand articles and comics explain how past global changes can help us understand potential future climate and environment scenarios. Hard copies can be ordered, too. All details: pastglobalchanges.org/products/pages-magazines/pages-horizons

PAGES webinars

Ariane Burke from the PAGES-affiliated Hominin Dispersals Research Group presented "The impact of climate change on the structure of human populations during the Last Glacial Maximum (LGM) in Western Europe: implications for biological and cultural evolution." Access the recording on PAGES' YouTube channel: youtu.be/5iNx6XV_mf4

Felix Riede and Phil Riris from the Knowledge Action Network on Emergent Risks and Extreme Events (Risk-KAN), a joint initiative of Future Earth, IRDR, WCRP, and WWRP, presented the group and how PAGES scientists can be involved. Access the recording on PAGES' YouTube channel: youtu.be/5tauO-pglrA

New working group

The Human Traces working group focuses on the long legacy of pre-Anthropocene human impacts and aims to address the knowledge gap about spatial and temporal variations in early human impacts, with the overarching goal to create a global synthesis of human traces in geologic archives. Find out more and join its activities: pastglobalchanges.org/human-traces

New data scholarship for PAGES working groups

This year, PAGES has implemented a new opportunity for current and recently sunsetted PAGES working groups. The Data Stewardship Scholarship was created to assist our working groups in collating and storing FAIR (Findable, Accessible, Interoperable, and Reusable) data. All details: pastglobalchanges.org/science/wg/data-stewardship-scholarship

Deadline for new working groups and workshop financial support

The next deadline to propose a new PAGES working group or to apply for financial support for a meeting, workshop or conference is Monday 20 September 2021. All details: pastglobalchanges.org/my-pages/introduction

Help us keep PAGES People Database up to date

Have you changed institutions or are you about to move? Would you prefer to receive an electronic copy rather than a hard copy of our magazine? You can update your account preferences easily here: pastglobalchanges.org/people/people-database/edit-your-profile. If you have access difficulties, we can help: pages@pages.unibe.ch

Upcoming issues of *Past Global Changes Magazine*

Our next magazine, guest edited by Pascale Braconnot, Paul Valdes, and Katrin Meissner, focuses on activities within the Paleoclimate Modelling Intercomparison Project (PMIP) in celebration of its 30th anniversary. Although preparations are well underway, if you would like to contribute please contact our Science Officer: sarah.eggleston@pages.unibe.ch

Calendar

PALSEA: Ice-sheets and solid-Earth processes
13-15 September 2021 – Palisades, NY, USA

Human Traces: 2nd workshop
21-29 September 2021 – Online

QUIGS: Glacial Terminations
21-23 September 2021 – Cassis, France

PEOPLE 3000: Human-environment feedbacks
September or October 2021 – Arica, Chile

ACME: Towards reliable proxy-based reconstructions
October or November 2021 – Helsinki, Finland

C-PEAT: Joint PAGES-INQUA workshop
Late 2021 – Bangkok, Thailand

Due to COVID-19 disruptions, these events are not guaranteed to take place in person. Check for updates here: pastglobalchanges.org/calendar

Featured products

CRIAS
The group released an online climate-history art exhibition titled "Weathered History: The Material Side of Past Climate Change": artsandculture.google.com/exhibit/weathered-history/hwJiMeBlg6zDLg
Three papers in the group's *Climate of the Past* special issue are now available: pastglobalchanges.org/products/13159

C-PEAT
Julie Loisel et al. review the main agents of change of peatland carbon stocks and fluxes in *Nature Climate Change*: pastglobalchanges.org/products/13149

CVAS
An online seminar series ran from November 2020 to March 2021. Access all recordings on the CVAS Playlist on PAGES' YouTube channel: youtube.com/playlist?list=PLSaCdvmD4wMLH_QfoKHyc5n4d-0_KBHDL

Floods
Scott St. George et al. published the comment piece "Paleofloods stage a comeback" in *Nature Geoscience*: pastglobalchanges.org/products/13148

LandCover6k
Kathleen Morrison et al. present a hierarchical classification of land-use systems designed to be used with archaeological and historical data at a global scale: pastglobalchanges.org/products/13236

PALSEA
Five articles have been published in the working group's special issue "WALIS – the World Atlas of Last Interglacial Shorelines" of *Earth System Science Data*: pastglobalchanges.org/products/13120

Cover

We've taken some editorial liberties to celebrate our 30th anniversary by using an image from the biggest gathering of PAGES' scientists which happened at the 5th Open Science Meeting in Zaragoza, Spain, in May 2017.

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For she's a jolly good fellow: Happy Birthday, PAGES!

Hubertus Fischer[1], S. Fritz[2] and M.N. Evans[3]

In a human life, reaching 30 years is usually a notable milestone. The teething troubles are long behind us, the endless school days are over, perhaps a university degree is in our pocket, there are no parents to tell us what to do and what not to do, and, if we're lucky, we have a stable income and a career underway. It is the time where we feel that we have achieved something important and that our actions have an impact.

As with all analogs, this one has its limits, but having edited this special 30-year anniversary issue of the *Past Global Changes Magazine* (which contains articles that look at the past, present, and future of PAGES from various perspectives), we feel that 30 years is not such a bad age for PAGES either. Born as an idea of a few visionary and influential climate scientists 30 years ago (see: overbearing parents above), PAGES has overcome obstacles and growing pains, developing from a small structure into a vibrant interdisciplinary body, and has certainly left its mark on the climate research landscape.

Of course, some boundary conditions have always governed what the PAGES objectives were, but within this framework PAGES has been a leader in filling a void in climate and sustainability research. PAGES members have synthesized observations and reconstructions from paleoclimatic archives, in conjunction with models, to identify processes and changes in the Earth system, and use them to put the present and future climate into context.

Thirty years may also be the age where we realized that growth may not just be in the vertical direction but may also proceed sideways, and that we have to exercise more and make a greater effort to stay fit than we did in previous years. Certainly, the sphere of scientific questions and the composition of the community of PAGES has grown oblate over the years. PAGES is now a community of almost 5500 subscribers, 15 working groups, and more than 500 active working group members. The last PAGES Open Science Meeting in Zaragoza, Spain, drew a crowd of nearly 900! So yes, PAGES has grown both in length and girth, but its vast science output shows that it has never been fitter. The articles in this issue, a sample of working groups combined with a series of articles by the PAGES Early-Career Network, attest not only to the excellent output and the imprint left by PAGES on Earth Sciences, but also to the promise of more from the next generation of PAGES leaders.

Success does not necessarily always follow growth and experience, but we are optimistically looking into the future. With a stable financial background secured for the coming decade, it is essentially up to the PAGES members to fill its science plan with new, innovative ideas, science questions and paleoscience perspectives, and insights relevant for the challenges that lie ahead for mankind in terms of climate change, biodiversity loss, and a sustainable use of natural resources. Looking at the many early-career researchers who are carrying PAGES forward and infusing PAGES with new ideas (as shown in the series of articles in the section "Highlighting the future of past global change research" in this magazine), there is little to worry about.

As is common when celebrating such a round anniversary, there is always someone standing up to give a sometimes mildly funny and often too-long speech on behalf of the person celebrating the jubilee. We don't want to be that someone, so we had better stop here. But as is also customary in these cases, we cannot resist toasting PAGES:

"To the next 30!"

And why not?!

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Figure 1: PAGES also celebrated reaching adulthood at the PAGES 3rd Open Science Meeting in Corvallis, OR, USA, in 2009 (Image credit: Nick Rackebrandt).

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A 30-year multi-proxy reconstruction of PAGES' history

Thorsten Kiefer[1] and Marie-France Loutre[2]

At its core, the mission of the Past Global Changes project has remained remarkably consistent over 30 years, fostering interdisciplinarity and international collaboration to better understand and predict environmental change. The hows and whos, however, have evolved dynamically as challenges and opportunities changed over time.

Thirty years of history is a good reason for PAGES to celebrate but also to reflect on the timeliness of the endeavor. On the 20th anniversary of PAGES, one devil's advocate asked whether it wasn't time to wrap up and make room for something new. At the time, we considered the idea (only very briefly). Today, although 10 years older, PAGES is still as youthful and dynamic as ever, though in different ways. From paleoecology we know that for long-term survival and success of a species, a society or an ecosystem is required to evolve with the changing ambient conditions. The same appears to apply to international organizations in the dynamic landscape of research and innovation.

In this article, we reconstruct key indicators of the history of PAGES. As the current and previous director of PAGES, we have access to accumulated direct observations from over 15 years. Unfortunately, this reaches only halfway back to the inception of PAGES in the year 1991 CE. The history beyond direct observations therefore relies on reconstructions based on proxy data from historical documents and anecdotal evidence. As with any good paleoscientific work, we base our interpretations on occasionally patchy, potentially biased, and uncertain evidence to generate a coherent conclusion.

Science

The PAGES newsletters of the early 90s reveal that the initial focus was on pushing paleoscience research internationally, with members of the Scientific Steering Committee (SSC) advocating the paleoscience areas for which they were globally recognized pioneers. This led seamlessly into sharing the results and the excitement of existing paleoscientific projects and programs with the global PAGES community by endorsing major ongoing paleoscience initiatives, such as ice-core work in Greenland (GRIP, GISP2) and continental deep drilling (ICDP).

The first Science Plan, published in 1994, formally cast this emerging structure into an array of focus areas that has largely continued to mark the scope of PAGES to today. The focus areas became home to emblematic, big programs that attracted attention, presumably also funding for individual projects, and certainly engagement of researchers across areas of the globe that had so far collaborated only sporadically. The Science Plan was designed to foster this with global programs, such as Paleoclimate and Environments of the Northern and Southern Hemispheres (PANASH), with its three meridional Pole-Equator-Pole (PEP) transects, or the International Marine Past Global Change Study (IMAGES), with its game-changing paleoceanographic sediment-coring campaigns.

Figure 1: Examples of popular publication formats through time (Kroepelin and Odada 1994; Markgraf 2001; Marlon et al. 2008; Gonzalez Arango et al. 2015; PAGES2k Consortium 2017).

In the late 2000s it became apparent that the formerly dynamic PAGES programs might become stale after many years of existence and occupy resources that could otherwise be used for new developments. This led to the establishment of a rolling system of working groups with a limited lifetime, initiated by the community, and quality-checked by the SSC. Each group proposes final goals and outcomes in its initial proposal, thus allowing PAGES to evaluate its progress over the course of three to six years, then declare victory, sunset the working group and head for new shores. The move towards a faster-spinning machine, fueled by the innovative ideas coming from the community, resulted in the creation of more than 40 working groups since 2006 and accelerated the continuous innovation cycle that may well contribute to PAGES' youthful appearance to this day.

Another striking evolution of PAGES relates to the kind of primary scientific publications resulting from PAGES' activities (Fig. 1). The pioneers of PAGES loved to produce pretty reports that were quick to flick through, appealing to look at, and a pleasure to read. The next generation produced hard-cover books that summarized copious amounts of information, suitable also to take pride of place on every paleoscientist's bookshelf. With the dawn of the new millennium, however, reports and books were abandoned, as peer-reviewed scientific papers rose in popularity: succinct, quality-validated, citable, downloadable, and increasingly career-relevant for the authors. Several community papers in high-profile journals have contributed to raising the profile of PAGES' approach to generate excellence through global collaboration.

While the regard for academic papers remains high to this day, a competitor (or complement) recently entered the stage in the form of databases and data products, such as those on the climate of the past 2000 years, paleofire, and speleothems. This nicely converges back to a vision of PAGES' pioneers for global data sharing through comprehensive paleoscience data centers. It will be interesting to see what product formats will characterize PAGES' next decade.

Community

The centerpiece of PAGES today is uncontestably its global community of active researchers and other experts. They believe in the power of collaboration to drive forward their field of science with passion, recognizing that the energy and creativity of the community accelerates their individual research objectives.

In its inaugural days, PAGES was driven by world leaders in the still-young disciplines of paleoclimatic and paleoenvironmental science. They had the scientific standing and the exciting research projects at their fingertips to raise a strong profile for the newly founded PAGES project. In the late 90s and early 2000s, PAGES created entry points for participation by paleoscientists from different disciplines worldwide. Since the late 2000s, all members and followers of the paleoscience community can propose and, if successful, run a working group to contribute to the advancement of paleoscientific understanding and capacity.

Finally, over the last decade, the PAGES community witnessed a spectacular diversification, not only scientifically and geographically, but also by achieving healthy balances

Figure 2: Logos of all five PAGES Open Science Meetings that have taken place so far and of the one to look forward to in 2022.

of gender and across the career spectrum. The early-career researchers, specifically targeted with a first Young Scientists Meeting (YSM) in 2009, are today a driving force in PAGES through regular YSMs, our own Early-Career Network, and a seat on the SSC.

Once every few years the PAGES community gathers at the Open Science Meeting (OSM). Meetings during the years 1998, 2005, 2009, 2013, and 2017 were held in London, Beijing, Corvallis, Goa, and Zaragoza (Fig. 2). Writing this article during the pandemic years 2020/21, it is not without melancholy that we recall many in-person paleoscientific exchanges with international colleagues at those locations. If you need something to look forward to, mark your calendar with the upcoming OSM in Agadir, Morocco, from 15-21 May 2022!

Communication

Probably the most visible and continuous expressions of how PAGES, and indeed the world, has evolved over the last three decades are our means of communication. To get a sense of how long PAGES has been around, consider that it existed for several years without a web presence – unthinkable today, but the norm back in the early 90s. It

Figure 3: Different designs of the PAGES website since its establishment in 1997.

was not until 1997 that PAGES' first website went live, initially hosted by NOAA, then soon afterward by the University of Bern. Since then, the website has been the main point of reference for information and a resource for PAGES products. Figure 3 invites you to travel through different times of web design and to enjoy the brand-new website that was launched to celebrate PAGES' 30th anniversary.

Another extremely important PAGES outlet is its magazine. *PAGES news* was launched in 1993 as a compact four-page leaflet, printed and mailed to subscribers (Fig. 4). Since then, it has grown considerably in size and scope, including more and more information about PAGES' scientific activities and findings. In April 1997, for the first time, a thematic focus was published in *PAGES news*, emphasizing the activities going on within two of the three PEP Transects and soliciting article contributions from experts within the PAGES community. The concept of an appealing in-house publication with a core of scientific articles that are sometimes even cited in peer-reviewed papers has persisted ever since. In 2014, PAGES took the obvious step to rename its publication into what it had actually become, a magazine-style publication with relevance not only for the PAGES project but with recognition in the field of paleoscience and beyond: *Past Global Changes Magazine*, impossible to miss in its bright orange design, was born.

With the rise of electronic mail, PAGES moved the spread of network information such as upcoming events, deadlines, and activities from the printed *PAGES news* to the much faster medium of email. In 2001, the first PAGES e-news was sent out, making sure that subscribers received information about opportunities well before the deadlines. What seemed fast at the time is slow today. Since PAGES entered the social media world in 2010, information is shared also as decentralized, real-time updates and interactive exchanges via Twitter and Facebook – but fear not, recent polls have revealed that a critical mass of paleoscientists still appreciates their information spoon-fed in menu format and many even still appreciate reading the magazine on good old paper. Therefore, PAGES will continue with the e-news and magazine hardcopies into its fourth decade.

It is always the ultimate commendation when figures from the magazine are used in conference presentations and education. From 1994 to the early 2000s, PAGES offered its most iconic figures for copying or printing as overhead slides, and until 2016 all magazine figures were downloadable as PowerPoint files. While content-extraction software has now made separate provision of figures redundant, everyone should continue to feel welcome to use material from the PAGES website and *Past Global Changes Magazine* extensively for free (with an enthusiastic reference to PAGES, please[1]).

[1]To use material published by PAGES, please be sure to follow the CC-BY guidelines: creativecommons.org/licenses/by/4.0/

Figure 4: Stepwise evolution of the layout of *Past Global Changes Magazine*, formerly known as *PAGES news*.

Behind the scenes

Two more factors have been essential for the long life and success of PAGES. First, the generous long-term funding by the National Science Foundations of Switzerland and the US, substituted in 2019 by the Academies of Sciences of Switzerland and China, provided the necessary cash resources. With this foundation, PAGES was able to develop its science agenda and structure as described above to constantly improve the organization. (For more information on the history of funding and the players behind it see Fischer et al. this issue.)

Second, as the authors of this retrospective and as executive directors who cumulatively escorted PAGES through more than half of its lifetime, we pay tribute to the staff of the PAGES International Project Office. Under the guidance of five different executive directors, approximately 40 staff members have supported projects, liaised with the community, edited newsletters, created websites, updated content, administered finances, disseminated information, and contributed in many other ways to the establishment of PAGES as an efficient program with a dedicated mission and a friendly face.

To date, PAGES has almost 5500 subscribers: around 500 attend workshops each year, about 200 co-author articles in *Past Global Changes Magazine* each year, and almost 900 were at the last OSM in Zaragoza in 2017. With this crowd, the future of PAGES is bright! The 30-year anniversary offers an opportune moment to look back with humble pride and look forward with vivid anticipation.

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Past Global Changes: 30 years of paleoscience to help save the planet

Hubertus Fischer[1], S. Fritz[2] and A. Mix[3]

Without the reconstruction of past global changes and the knowledge of the processes that control them, future long-term alterations in components of the Earth system cannot be reliably predicted. Over the last three decades, PAGES has dedicated its work to provide this information to the global science community.

Early visionaries

In 1972, the Club of Rome published its first report on "The Limits to Growth" (Meadows et al. 1972). It received substantial public attention and raised awareness that our use of global natural resources at an ever-increasing speed is not sustainable and that planetary boundaries set limits to economic growth. At the same time, more and more scientists across the globe engaged in quantifying the ongoing human impacts on climate and the environment, improving our understanding of the Earth system, and implementing these processes in Earth system models to predict Earth's future evolution. In the decades following the Club of Rome report, the International Council for Science (ICSU) and the International Social Science Council (ISSC) initiated four global programs to organize the huge task of global change research: the World Climate Research Programme (WCRP), quantifying physical changes in the climate system; the International Geosphere-Biosphere Programme (IGBP), studying changes in biogeochemical cycles; DIVERSITAS, concentrating on changes in biodiversity; and the International Human Dimensions Programme (IHDP), addressing the impact of these changes on human societies and their well-being.

Some early visionaries from the paleoclimate field immediately realized that documentation of contemporary changes alone was not sufficient to assess the impact of human interference with the Earth system, particularly because many components of the system act on timescales much longer than the era of direct scientific observations (which are typically limited to a few decades or, in some cases, a few centuries). Some examples of such long-timescale components include glaciers and ice sheets, natural biogeochemical cycles, ecosystems and food chains, or ocean circulation. Most importantly, these are also all components that are crucial for the robust long-term prediction of climate, greenhouse gas forcing, and ecosystem response. Moreover, they are key to assessing the impact of anthropogenic changes on human well-being, which is affected by processes such as sea-level rise, water supply/desertification, heat waves and other extreme events, ecosystem structure and function, or agriculture.

Among the early visionaries in the early effort to incorporate paleoperspectives into global change studies were John A. (Jack) Eddy, a US solar scientist, and Hans Oeschger, a Swiss climate physicist (Fig. 1), who together chaired a special IGBP working group on "Techniques for Extracting Environmental Data from the Past". This working group met for the first time in 1988 in Bern, Switzerland, and included a "who's who" of paleoclimate researchers at that time. It was not an easy feat to assemble all those illustrious names in one room and to glue them together to work towards a common goal, but Oeschger and Eddy succeeded. Only a year later, an even larger workshop was organized in Snowmass, Colorado, USA. Those were the "good old times" when all participants were paid to attend, and it certainly helped in bringing the brightest "paleominds" together. The Snowmass workshop led to the report "Global Changes of the Past" (Bradley 1989) and may be regarded as the birth of PAGES, the IGBP Core Project on Past Global Changes. PAGES was officially launched two years later in 1991, with the goal to use the paleorecord to inform the global-change debate on long-term changes, processes, and risks in the Earth system.

An achievement just as impressive as bringing a large part of the paleocommunity together within PAGES was that Eddy and Oeschger managed to convince both the US National Science Foundation (NSF) and the Swiss National Science Foundation (SNF) to jointly fund the endeavor, including a dedicated project office in Bern. Unfortunately, Jack Eddy had to step down for personal reasons soon after the inauguration of PAGES, but Herman Zimmerman, program manager at the NSF, was so convinced of the PAGES cause that he stepped in with great enthusiasm as PAGES Co-Director, together with Hans Oeschger, and also spent a significant amount of time in Bern to help run the office.

The first PAGES Science Plan (PAGES Scientific Steering Committee 1994) was structured both geographically and temporally along three pole-equator-pole (PEP) transects. It concentrated on the last 2000 years and multiannual to decadal variability, as well as the longer timescale of the last glacial/interglacial cycle. This was a structure that "still makes my head spin", said Herm Zimmerman recently. Despite, or likely also because of, this multidimensional structure, a large part of the paleoscience community immediately joined this endeavor, helping to make PAGES an IGBP showcase.

With a spirit of being open to all participants, PAGES soon provided unrivaled integrated datasets as well as new insights into the Earth system that could not have been achieved without paleoscience and the large-scale syntheses that PAGES facilitated; a modus operandi that continues today. It is fair to say that the long timescales of change that are central to the work of PAGES are

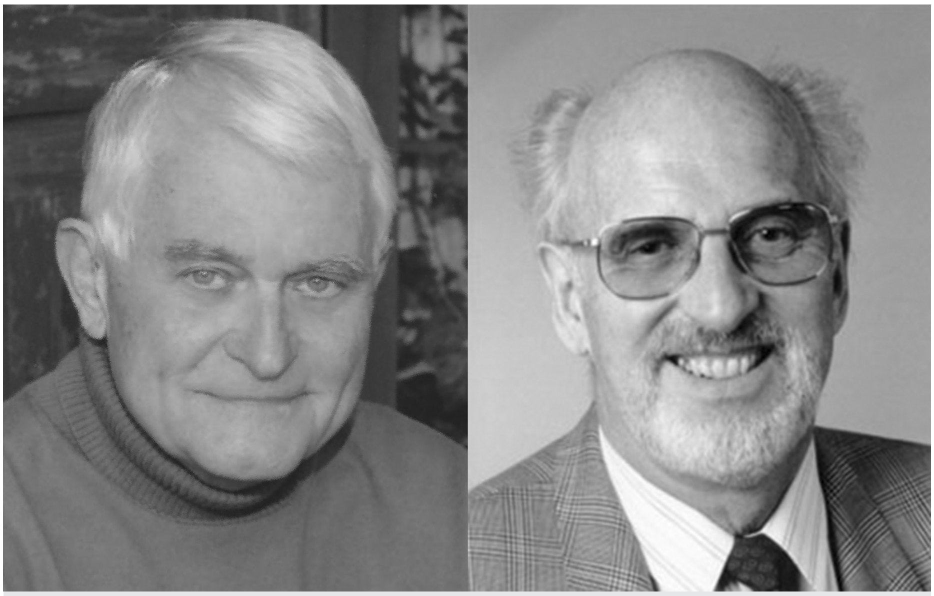

Figure 1: The two early PAGES visionaries Jack Eddy (left) and Hans Oeschger (right).

also at the heart of the notion developed in IGBP that we live in the time of "The Great Acceleration" (Steffen et al. 2015), as many of the Earth system trends displayed in the IGBP Great Acceleration Plot (Fig. 2) could not have been quantified without paleoresearch. The long-term changes in the Earth system caused by humans in the course of the (late) Holocene are also the reason for the ongoing discussion to define this time as a new geological era, the so-called "Anthropocene", where geological evidence is overprinted by human actions.

The success of PAGES and especially of its innovative working groups clearly demonstrated that the whole is greater than the sum of its parts and that interdisciplinarity is key for producing the new knowledge required to assess global change from a paleo perspective. The roughly 1000 PAGES contributions that can be found today in the PAGES product database attest to the sustained timeliness and constant community-driven input that defines the success of PAGES. These products include a large number of contributions to *Past Global Changes Magazine*, reports, science plans, and information and outreach materials, but also about 400 peer-reviewed articles, of which more than 10% have been published in some of the highest-ranking journals in Earth and climate science.

The science objectives evolved over time, responding to new facets and dimensions of global change research, as reflected in the ternary diagram (Fig. 3) of the latest science plan (Kiefer et al. 2015). This plan focused the PAGES working groups within the three poles of "climate", "environment" and "humans", thus making PAGES more flexible, multi-dimensional, and responsive to the most pressing global change questions. Not only the science portfolio but also the services provided by PAGES have grown immensely over the years. This encompasses products both for the public and the paleoscience community (*Past Global Changes Magazine* articles, working group meetings, Open Science Meetings, etc.), and with the dedicated Young Scientists Meeting and the Early-Career Network, PAGES is now the home for early and senior paleoscientists alike (see Kiefer and Loutre, this issue, for more details).

The Mid-PAGES Transition

With climate-change science becoming increasingly mature and climate and environmental issues increasingly pressing, the call for more integrated and solution-oriented climate research became louder. In 2001, a first attempt was initiated to cross the borders between the four ICSU/ISSC programs (WCRP, IGBP, DIVERSITAS, and IHDP), through the so-called "Earth System Science Partnership". ESSP tried to provide an umbrella for cross-topical exchange and collaboration, but unfortunately never had the necessary traction to integrate these large, individually well-oiled science machines. In particular, the social science realm, which is a crucial element for transferring Earth system science into policy-relevant and actionable science, did not receive the attention that was proportionate to the ever-growing global disaster humankind was and still is heading towards.

Accordingly, ICSU and ISSC (which in the meantime had joined to form the cross-disciplinary International Science Council) decided to redefine from scratch the way global change science was organized. The authors of this article participated in this painstaking process, spending many a day at transdisciplinary conferences, and workshops, in discussion groups, and writing a large number of reports, statements, and countless emails. The goal of all this activity was to design a programmatic structure of global change research that would encourage interdisciplinary collaboration and involve stakeholders outside of science in the research design, while at the same time enabling core projects, such as PAGES, to continue providing the crucial science basis without which educated political decisions cannot be made.

The result of this process was the global sustainability program Future Earth, which became the umbrella organization of PAGES after IGBP officially ended in 2015. The transition of PAGES to Future Earth was a learning process for all. For Future Earth, whose motivation was to support political action with scientific information, it was not immediately clear how a project like PAGES could become policy relevant, because

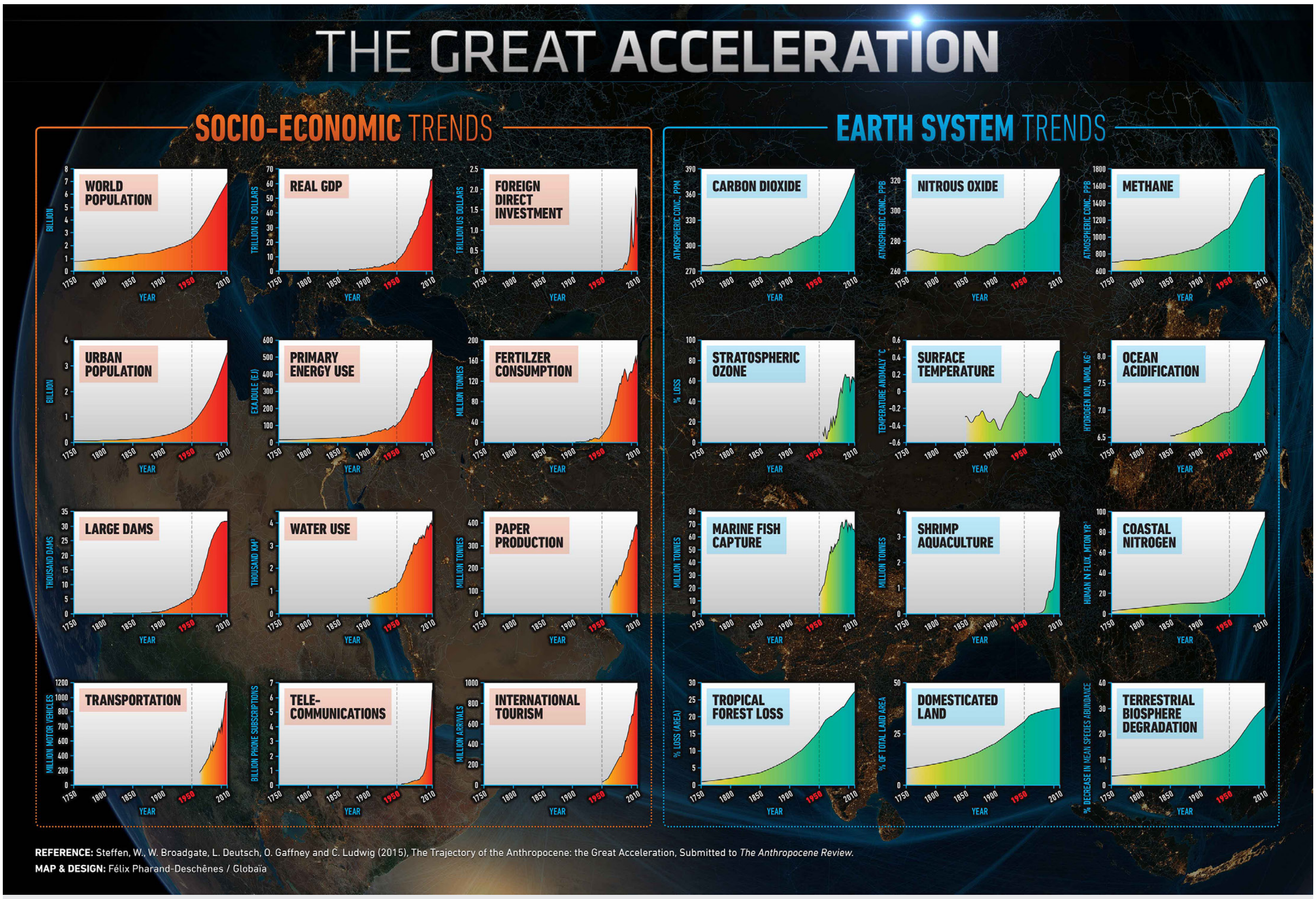

Figure 2: The great acceleration plot showing the rapid changes in socio-economic (left) and Earth system parameters (right) over the last 150 years (Steffen et al. 2015).

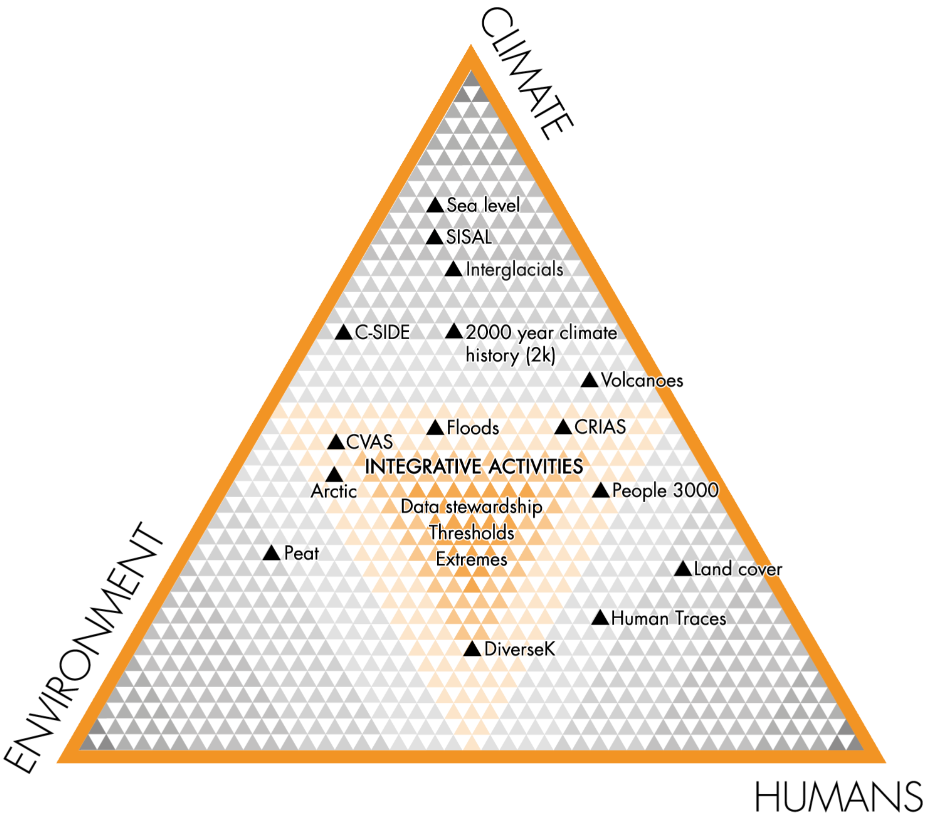

Figure 3: The PAGES ternary diagram showing the current PAGES working groups and their main focus in the three dimensional "phase space" of climate, humans, and the environment.

PAGES looks at time periods where humans were just one of many species on this planet and did not yet have comparable means to alter the entire Earth system. Eventually, understanding among the different fields and views assembled under Future Earth improved, helped along by PAGES' continuous delivery of first-class scientific products. For PAGES, the struggle at the beginning was with the concept of co-design, i.e. engaging the large range of stakeholders in PAGES' science. However, it is fair to say that by continuously scrutinizing its approach with respect to co-design and policy relevance, PAGES was able to focus even more attention on its initial goal of helping to solve global change issues.

Financial glaciation/deglaciation

PAGES had the privilege of being able to concentrate on scientific endeavors and breakthroughs, while the US and Swiss funders through their steady support provided the stability needed to initiate, establish, and nurture an international interdisciplinary network, including expansion of scientific connections and capacity in the developing world. Since the NSF and SNF only fund competitive grants, this naturally meant that PAGES had to earn its financial support by regularly submitting proposals that provided an account of previous achievements, explained the plans going forward, and justified the resources requested. While proposal writing increased the stress levels of the PAGES directors and co-chairs every four years, especially in the immediate presence of a deadline, this funding model and its inherent obligation to convince reviewers and funders clearly contributed to maintaining the excellence of PAGES over three decades.

The continuing success of these proposals in a highly competitive funding landscape attests to the quality of PAGES' work.

Another long-term supporter of PAGES was and is the University of Bern, which handles the accounting and human resources management of the PAGES International Project Office (IPO). In 2009, former PAGES co-chair Heinz Wanner also convinced the university to physically host the IPO. Sharing office space with the Technical Support Unit of IPCC Working Group I during its AR5 assessment cycle and, to this day, with the Oeschger Centre for Climate Change Research of the University of Bern, provides immeasurable opportunities for synergies and joint activities to promote (paleo) climate science.

Potentially related to the PAGES transition from IGBP to Future Earth, the last five years of PAGES' history were also a time of financial insecurity, and it was not clear if or how long PAGES would survive. After 25 years of US and Swiss funding, questions about the sustainability of this funding arrangement were raised by both the NSF and SNF. The issue on the Swiss side was not financial but only an organizational one, and since 2019 the Swiss funding has been provided by the Swiss Academy of Sciences. On the US side, NSF officials were afraid that the substantial PAGES funding would exacerbate increasing demand for their funds, with a view that PAGES' funding was in competition with individual investigator projects. Accordingly, NSF asked PAGES to secure funds from other programs and from other nations and organizations, to diversify the funding platform. While this request was justified, it was not easy to implement quickly, and this sadly led to the end of sustained US NSF funding in 2018.

But PAGES would not be PAGES if it were not able to mobilize its international science network and develop new funding channels. Convincing a national funder to support an organization such as PAGES is not as simple as we all wish it could be, because typical funding streams are usually not targeted at such a hybrid between a research project and an international science-facilitating organization such as PAGES. However, in 2019, the Chinese Academy of Sciences, which through a long line of PAGES Steering Committee members had always followed and supported the progress of PAGES, stepped in to provide a share of the funding. Thus, with joint funding from the Swiss Academy of Sciences and the Chinese Academy of Sciences for the next eight years, at levels similar to those in prior years, the PAGES story can continue.

Whether it continues to be a success story, however, is not so much a matter of the funding or its sources. More importantly, PAGES' success is crucially dependent on all of us who read this article: on the new generation of outstanding early-career scientists who bring novel ideas to PAGES and are highly motivated to do their own science but also be active in representing science in the public arena; on the senior scientists, to constantly realign and redefine PAGES to keep it at the forefront of global change research and to funnel paleoscience information into the highest policy levels; and, last but not least, on the dedicated team at the International Project Office in Bern, who commit their time and energy to providing paleoscientists with the best support possible to continue interdisciplinary paleoresearch to help save the planet.

ACKNOWLEDGEMENTS

We are immensely grateful to Herm Zimmerman, Ray Bradley, and Malcolm Hughes for their engaging stories and anecdotes about the early days of PAGES (which not all made their way into this article) . Great thanks also to Heinz Wanner and Christian Pfister for some Swiss perspective of past PAGES changes.

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Looking forward

Michael N. Evans[1], W. Tinner[2], Z. Jian[3], B. Vannière[4], S. Eggleston[5] and M.-F. Loutre[5]

The future of PAGES is in the construction of a more global and diverse paleoscience community, expansion of links with other, complementary initiatives, and in the support of community-driven science. PAGES should challenge itself with bold new initiatives, lean administration, a smaller carbon footprint, and open and inclusive activities, with the central theme of time threaded through the effort.

What will the PAGES community do in its next phase? May we borrow your crystal ball? Our view of PAGES is, at best, educated guesswork but is informed by the trajectory that is evident in the timeline of PAGES' activities, achievements, support over the past 30 years (Fig. 1), as well as recent initiatives. The future may also be reflected in the new science and organizational diagram that we present here and which replaces the venerable PAGES triangle (adopted in 2015), and, before that, the science plan and implementation strategy of 2009 (Fig. 2).

Science

With its unique perspective and focus on the element of time within Earth system dynamics, the PAGES community will continue the development of process understanding by the integrated analysis of experiments, observations, and reconstructions (What

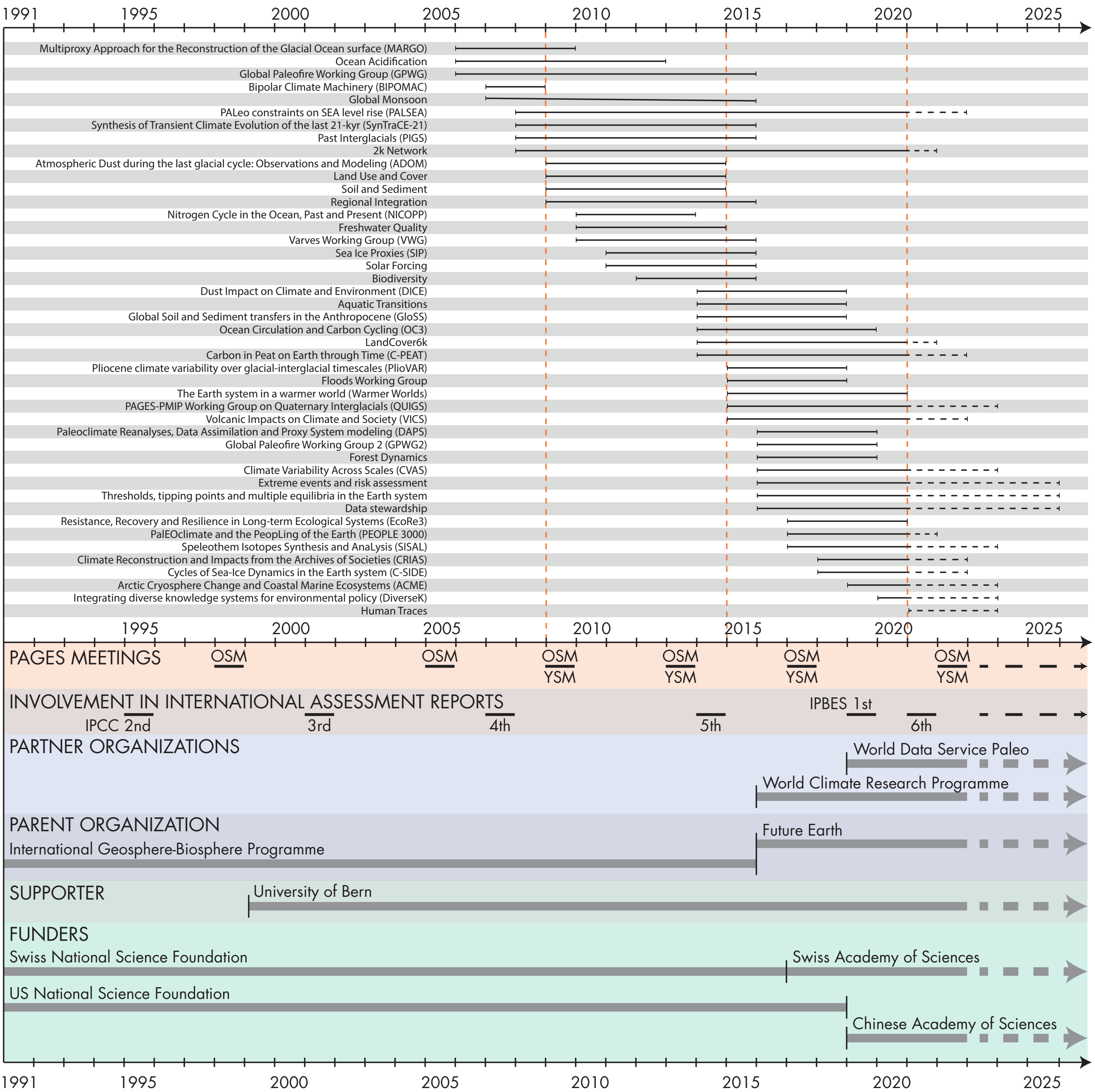

Figure 1: Timeline of PAGES' research themes, working groups, contributions to other global research activities, and funding. Vertical lines represent structural transitions.

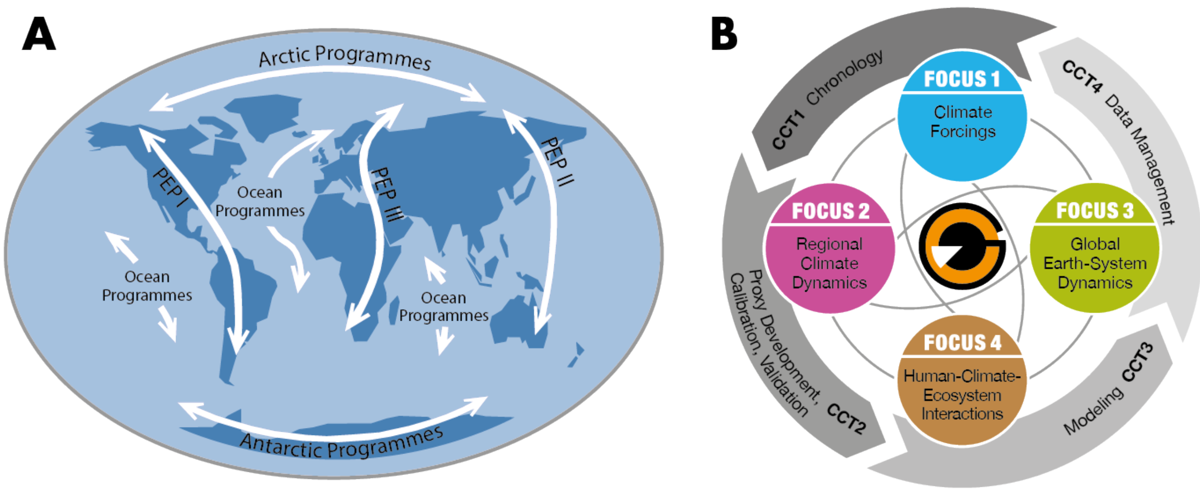

Figure 2: PAGES' scientific structure **(A)** 1994–1998; **(B)** 2009–2014 (2015–2021: see Fischer et al. this issue, Fig. 3).

happened? What is possible? How likely is it?) with simulations (Why did it happen? Can it be generated from known processes? How likely is it?). What mechanisms are most consistent with observations, reconstructions, and available simulations that arise from a variety of different experimental designs? Leveraging the increasing precision and accuracy of multivariate data streams and increasingly realistic Earth system simulations, we see PAGES' working groups moving from analysis of global means to regionally resolved patterns. We see renewed focus on moisture dynamics and integrated tracers, climate services, the understanding of ecosystem dynamics, and the ways in which the oceans, atmosphere, land surface, ice, biosphere, and human activities are transiently coupled on timescales of decades to centuries (Fig. 3). These initiatives are already happening. All are useful contributions that enable forecasting of Earth system changes over the extended time horizon of the next ca. 500 years.

Support

PAGES is extremely fortunate to have had dedicated, continuous support over the past 30 years, including from the US and Swiss National Science Foundations, the Swiss and Chinese Academies of Sciences, and the University of Bern. The effect of steady funding has been cumulative, helping to increase PAGES' momentum, as can be observed in the rise in the number and diversity of supported products. In the next 30 years, PAGES may seek more diverse international support to become deeply rooted on all continents through various national funding instruments. It is up to all scientists involved in PAGES' activities to explore new funding possibilities, such as those currently provided by the Swiss and Chinese Academies of Sciences, in their countries of residence, to secure and promote PAGES' future prosperity.

Figure 3: PAGES' proposed new science diagram (2021–). Concentric circles represent the building blocks of PAGES, which at its core is composed of working groups and integrative activities within PAGES' scope. Their research supports partner programs, informs strategies for sustainability, and provides outreach opportunities. The arrow represents the integration of information and learning that propels the paleosciences forwards and provides context for future projections.

Mission

PAGES' objectives[1] continue to center on the natural sciences but evolve toward inclusion of social-science perspectives, with continued support for climate, ecosystem and land use reconstructions to discover past processes and mechanisms of environmental and societal dynamics. PAGES' working groups will continue to provide quantitative forcing and long-term data for model validation. To further strengthen the societal perspective, PAGES fosters the development of working groups that seek to more fully integrate social-science disciplines and societal archives, including those from Indigenous records, and of climatic events and their impacts. For example, we might begin to understand the reasons underlying the human imprint on the environment, and this might support the development of the element of time in integrated assessment simulations (Beckage et al. 2018). With input from practitioners, the potential for paleo-informed policy should improve. This trend is evident in the scope of integrative activities on warm state climates and societal risks associated with thresholds and extreme events.

Activities

PAGES will continue to be community-driven, with the support of its lean, efficient, and productive International Project Office. This includes even more global collection, dissemination, and synthesis across spatial and temporal scales, for phenomenologically meaningful regions and dimensions (e.g. patterns within and across elements in Fig. 3) by means of Open Science Meetings[2] and clustered meetings, in which multiple working groups convene to consider shared interests and opportunities, such as the Topical Science Meetings.[3] Although we acknowledge that personal contacts are at the heart of international science, we anticipate that meetings will become more and more internet-enabled, and virtual, to reduce their carbon footprint. This will enhance the goals of building a community, but also improve accessibility, which is especially important for an increasingly global PAGES.

It remains a challenge to make PAGES a truly global and diverse community, and to improve the representation of that community in its leadership. Emerging initiatives include visiting fellowships designed to mentor and support African and Latin American scientists; bias training and measures to enable us all to feel safe and welcomed at PAGES Open Science Meetings; web-enabled, recorded, and close-captioned meetings and webinars; and in-person workshops held in a more diverse set of locales. We must lead more in these regards, because it has been the community which has not only created awareness of problems, but also contributed ideas and initiatives to improving PAGES for all.

Further activities will continue to follow FAIR (findable, accessible, interoperable and reusable) practices in the curation and stewardship of paleodata, metadata, and code compilations. This will be achieved through the use of public repositories, advanced databasing technologies, webinars, and partnerships with associated and complementary global research networks such as the NCEI[4], Neotoma[5], Linked Earth[6], PANGAEA[7], Future Earth[8], and WCRP.[9] An achievable goal in the coming decades is the development of self-updating repositories that contain not only raw observations but also dynamic chronologies, reconstructions, and version-tracking code bases, which are indexed to associated direct observations and simulations of phenomena of interest.

Perhaps PAGES' most consequential future activities will be in the development of early-career scientists. Many of us can recall a pivotal PAGES "moment"; for one of us (MNE), it was observing a 2011 2k Network meeting, and leaving an hour or so later with the mandate to start Ocean2k. The PAGES Early-Career Network (ECN[10]) has recently formalized the interests and needs of emerging paleoscientists, and its dynamic, virtual community is a model for future working groups. PAGES' Scientific Steering Committee (SSC[11]) now encourages working groups to actively engage ECRs in their leadership, and includes an ECR representative on the SSC; this has improved its vision and creativity. PAGES' ECRs and workshop organizers have long integrated outreach activities, such as public events, but we envision a clear need to connect more directly with the public who supports our research and is interested in the science and consequences of global change. To this end, *Past Global Changes Horizons* (Fig. 4), a magazine for anyone interested in paleoscience, is designed to communicate and educate.

Prospects

The ultimate goal of PAGES will remain its interest in three challenging global problems: climate change, biodiversity loss, and the sustainability of ecosystems and societies. To succeed, PAGES will need an even better integration of observations and reconstructions with process-based dynamic models to further understand long-term Earth system processes and how they impact sustainability. Additional effort will be needed to train new generations of paleoscientists and transfer knowledge from the PAGES community to the public and to decision-makers. And PAGES has an opportunity and important role to fulfill as its parent body, Future Earth, evolves. Future Earth's organization is becoming increasingly flat, simple, and representative, reflecting the wide range of ideas present in the community. Within that community, we imagine that PAGES will find synergies with other Future Earth Global Research Projects, such as AIMES[12], BioDISCOVERY[13], GMBA[14], IHOPE[15], SOLAS[16], MRI[17], the Emergent Risk and Extreme Events Knowledge Action Network[18], and partners such as WCRP.[9] PAGES can provide observations and modeling of what is possible on the seasonal to multi-million-year timescales that bracket those over which anthropogenic Earth system forcing are likely to be expressed. PAGES can also place concepts of risk, adaptation, resilience, and sustainability of societies within the context of what human civilizations have already managed, and the mechanisms by which they have either succeeded or failed. How might we learn from those past global changes, challenges, successes, and failures? Future global changes may not repeat past global changes, but perhaps they rhyme with them (Wittreich 1987; Gould 1988).

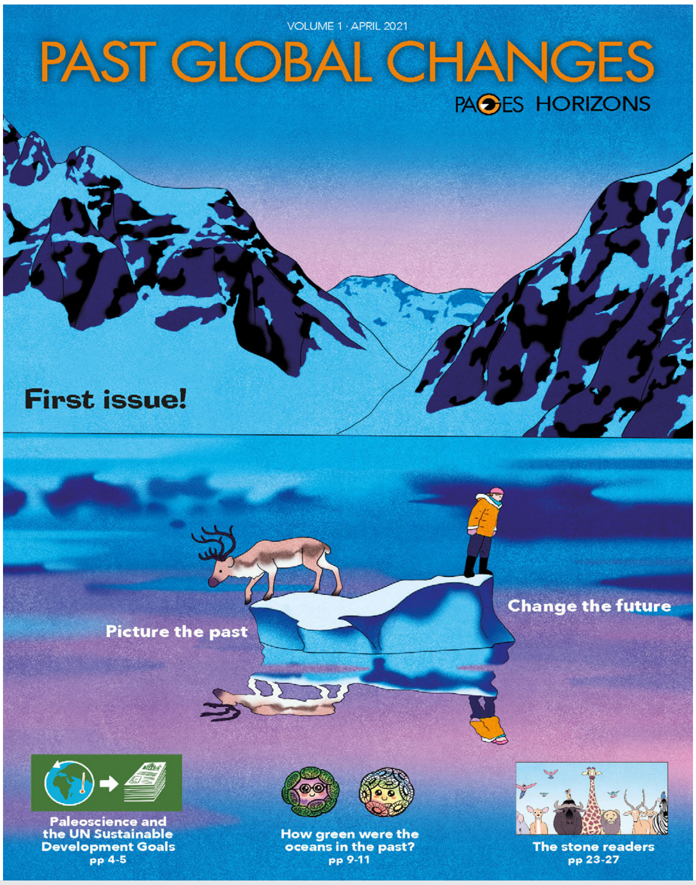

Figure 4: The first issue of PAGES' new magazine for anyone interested in paleoscience, *Past Global Changes Horizons*, was published in April 2021.[19]

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[17]https://www.mountainresearchinitiative.org
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SynTRACE-21: Synthesis of Transient Climate Evolution of the last 21,000 years

Zhengyu Liu[1], B.L. Otto-Bliesner[2], P.U. Clark[3], J. Lynch-Stieglitz[4] and J.M. Russell[5]

SynTRACE-21 initiated a comprehensive data-model comparison of the transient evolution of global climate during the last 21,000 years; this comparison improved our understanding of global and regional climate changes and also raised new challenges to both models and proxy data.

Background

The large magnitude of climate change over the last 21 thousand years (kyr), documented by an extensive array of well-dated paleoclimate records, has made this period one of the best paleoclimate targets for testing climate-model estimates of climate sensitivity and the ability of models to simulate abrupt climate change. Model-data comparisons have remained a challenge, however, because model simulations of global climate are usually limited to hundreds of years while proxy records that span the entire interval are limited in their spatial coverage.

To address these issues, model-data comparisons have traditionally used the "snapshot" strategy in which data representing a specific time slice (e.g. 21 kyr before present (BP), 6 kyr BP) are portrayed on a map for comparison to climate-model results for that time slice. This strategy greatly improved our understanding of global climate changes that are driven by external forcing to the coupled ocean-atmosphere system, notably orbital forcing, greenhouse gasses and ice sheets (COHMAP Members 1988), but it has several limitations.

From the data perspective, uncertainties in age models influence the map reconstruction, transferring uncertainties from the time domain to the space domain. From the perspective of mechanisms, while the snapshot strategy can be used to study the near-equilibrium surface responses, it cannot be used to study the response associated with the slow components of the climate system, such as the deep ocean, nor internal climate variability, such as the millennial-scale climate events and abrupt changes of the last deglaciation. The coarse temporal resolution between successive snapshots also makes it difficult for the snapshot approach to identify the complex temporal phasing relations between different climate events and thus assess mechanisms of climate change at regional and global scales.

Given these issues, the paleoclimate community recognized the importance of performing transient climate-model simulations that allow us to compare the results to the evolution of climate change recorded by data timeseries. In particular, such simulations should be conducted with synchronously coupled atmosphere and ocean components, as any asynchrony in the model, such as an acceleration in the forcing or a model component, will distort the response of the temporal evolution of the slow components, notably the deep ocean, and can thus only be used approximately for the quasi-equilibrium response of surface ocean and the associated climate variability to external forcing.

The rapid advance in high performance computing over the last decade has now made it possible to simulate the transient climate evolution on multimillennial timescales in state-of-the-art, synchronously coupled ocean-atmosphere models. Here we summarize the SynTRACE-21 project, in which the Community Climate System Model 3 was used to simulate the transient climate evolution of the last 21,000 years (TRACE-21) and promote model-data comparison. The model has a 3.75-degree horizontal resolution for the atmosphere, a variable resolution

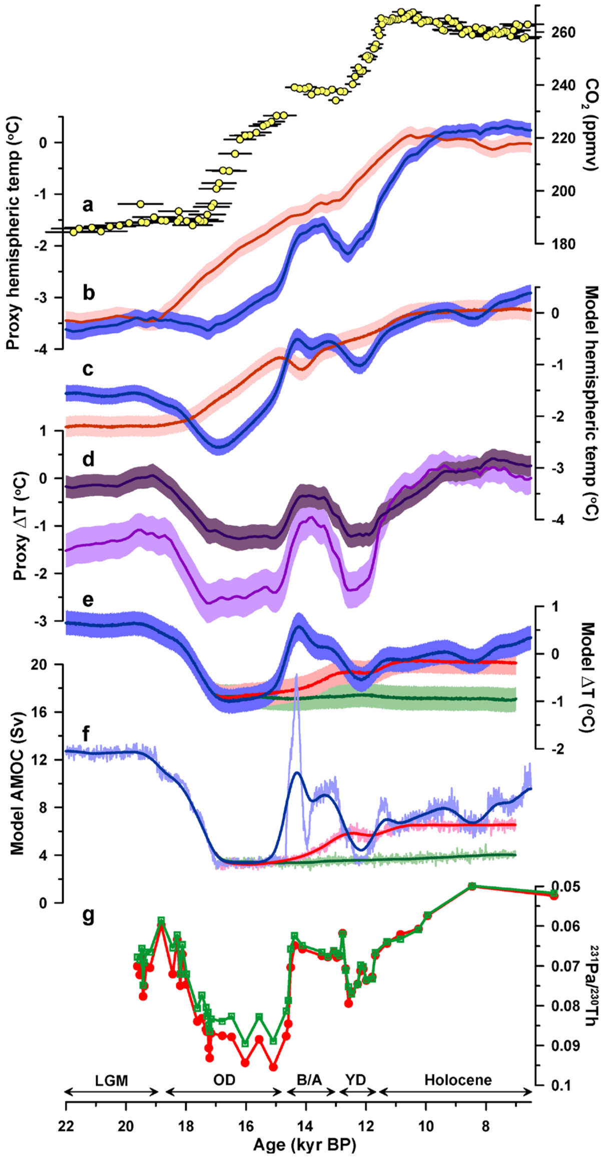

Figure 1: Hemispheric temperatures. **(A)** Atmospheric CO_2 concentration. **(B)** Northern Hemisphere (blue) and Southern Hemisphere (red) proxy temperature stacks. **(C)** Modeled Northern Hemisphere (blue) and Southern Hemisphere (red) temperature stacks from the TRACE simulation. **(D)** Northern Hemisphere minus Southern Hemisphere proxy temperature stacks (dark purple). North Atlantic minus South Atlantic region proxy temperature stacks (light purple). **(E)** Modeled Northern Hemisphere minus Southern Hemisphere temperature stacks in the TRACE (blue), CO_2 (red) and ORB (green) simulations. **(F)** Modeled AMOC strength in the ALL (blue), CO_2 (red), and ORB (green) simulations. **(G)** North Atlantic sediment core OCE326-GGC5 $^{231}Pa/^{230}Th$. Temperatures are given as deviations from the early Holocene (11.5-6.5 kyr BP) mean. Figure reproduced with permission from Shakun et al. (2012).

from ~3.6 degrees at high latitude to ~0.9 degrees in the ocean (Yeager et al. 2006).

Supported jointly by PAGES, the US National Science Foundation, the US Department of Energy, the US National Center for Atmospheric Research, and Brown University, SynTRACE-21 was led by a steering committee of US-based modelers (Z. Liu, Univ. Wisconsin-Madison; B. Otto-Bliesner, National Center for Atmospheric Research) and data developers (P.U. Clark, Oregon State Univ.; J. Lynch-Stieglitz, Georgia Tech.; J. Russell, Brown University) and ultimately involved dozens of scientists around the world. After two US NSF-funded community workshops in Madison, WI (2008), and Boulder, CO (2009), two PAGES workshops were held: the first at Timberline Lodge, Mt. Hood, OR (9-13 October 2010), and the second in Providence, RI (3-7 November 2012), with several other meetings coordinated with other projects and conferences.

SynTRACE-21 outcomes

Using changing insolation, proxy data of greenhouse gas forcing, reconstructions of ice-sheet size and coastline, and an assumed history of freshwater water forcing in the North Atlantic, Liu et al. (2009) first simulated the transient climate evolution of the coupled atmosphere-ocean-terrestrial vegetation system for the last 21 kyr in a baseline experiment (TRACE-21). This experiment, along with additional sensitivity experiments, was then used for comparison with data and for understanding the mechanism of the response.

<u>Global temperature changes</u>

The deglacial evolution of global climate from the Last Glacial Maximum (LGM, ~21 kyr BP) to the early Holocene (~11 kyr BP) presents an outstanding opportunity to combine TRACE-21 simulations with data to better understand the transient response of Earth's climate system to major climate forcing factors. The forcing factors include the changes of the external forcing associated with the Earth's orbit, the ~80 ppm rise of atmospheric greenhouse gases (GHG), as well as internal forcing of continental ice sheet and meltwater inputs to the ocean that result in changes in the Atlantic Meridional Overturning Circulation (AMOC). A major effort has been made by the paleoclimate research community to characterize these changes through the development and synthesis of well-dated, high-resolution records from the deep and intermediate ocean as well as from the continents, as summarized in Clark et al. (2012). The synthesis indicates that the superposition of two leading modes of climate change explains much of the variability in regional and global climate during the last deglaciation, with a strong association between the first mode and variations in greenhouse gases, and between the second mode and variations in the AMOC.

Shakun et al. (2012) further reconstructed the global surface temperature (largely sea-surface temperature) from proxy records and compared the evolution of the reconstructed global and hemisphere mean temperatures (Fig. 1). They found that global surface temperature is correlated with and, furthermore, generally lags CO_2 during the last deglaciation. The TRACE-21 simulation indicates that the large deglacial warming is caused by the large response of annual mean temperature to increasing GHGs, and the agreement with the data suggests comparable climate sensitivity in the model.

Differences between the respective temperature changes of the Northern and Southern Hemispheres parallel variations in the strength of the AMOC reconstructed from marine sediments. Consistent with the TRACE-21 simulations, these observations support the conclusion that an anti-phased hemispheric temperature response to the AMOC superimposed on globally in-phase warming driven by increasing CO_2 concentrations can explain much of the temperature change during the last deglaciation (Fig. 1).

Marcott et al. (2013) extended the annual global surface temperature reconstruction through the Holocene (~11–0 kyr BP; Fig. 2). The reconstruction showed that deglacial warming continued into the Holocene with temperatures plateauing in the early to mid-Holocene for global and hemispheric average temperatures, followed by a cooling of ~1°C through the middle to late Holocene. This Holocene cooling trend in annual mean global temperature, however, is physically puzzling.

Under the dual forcing of a declining residual ice sheet and rising atmospheric CO_2, transient climate-model simulations, including TRACE-21, exhibit a warming trend in the Holocene, in contrast to the reconstructed late-Holocene cooling in proxy data (Fig. 2; Liu et al. 2014a). The Holocene cooling trend in the data is more consistent with a response to summer insolation in the Northern Hemisphere and tropics, and thus may be attributed to a summer seasonal bias of the temperature, as simulated in models.

This potential summer bias, however, can't explain the data cooling trend in the Southern Hemisphere, potentially indicating model shortcomings in the representation of certain feedback processes. Overall, TRACE-21 has improved our understanding of the mechanism of major global climate changes and, furthermore, has stimulated studies on the potential biases both in the model and data interpretation (e.g. Marsicek et al. 2018).

<u>Regional hydroclimate changes</u>

Comparisons of TRACE-21 with terrestrial proxy data also provided insights into mechanisms of regional hydroclimate changes over the last 21,000 years. For example, Otto-Bliesner et al. (2014) studied climate change during the last deglaciation in Africa (Fig. 3). Proxy data show that wet conditions developed abruptly ~14,700 years ago in southeastern equatorial and northern Africa and continued into the Holocene. The abrupt onset and coherence of this early African Humid Period, however, has been challenging to understand, because changes in seasonal insolation forcing in the southern

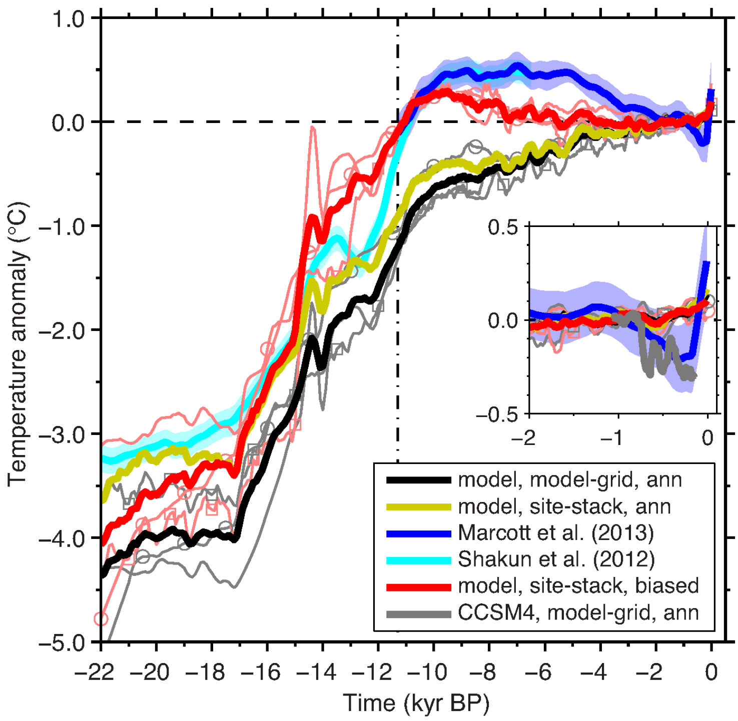

Figure 2: Evolution of the global surface temperature of the last 22,000 years: the reconstruction of Marcott et al. (2013) (blue) after 11.3 kyr BP and Shakun et al. (2012) (cyan) before 6.5 kyr BP, the model annual global temperature averaged over the global grid points (black) and the model seasonally biased temperature averaged over the proxy sites (red). The models are CCSM3, FAMOUS, and LOVECLIM, with the ensemble mean in heavy, solid lines and individual member in light, thin lines (LOVECLIM and FAMOUS marked by circles and squares, respectively). Each temperature curve is aligned at 1 kyr BP. The ensemble mean model annual temperature averaged over proxy sites is also shown (yellow); its similarity to the model grid average demonstrates the insensitivity of the temperature trend to the average scheme. The insert shows the expanded part after 2 kyr BP, with the addition of the last millennium experiment in CCSM4 (grey), which is forced additionally by volcanic aerosol and solar variability. Figure from Liu et al. (2014a).

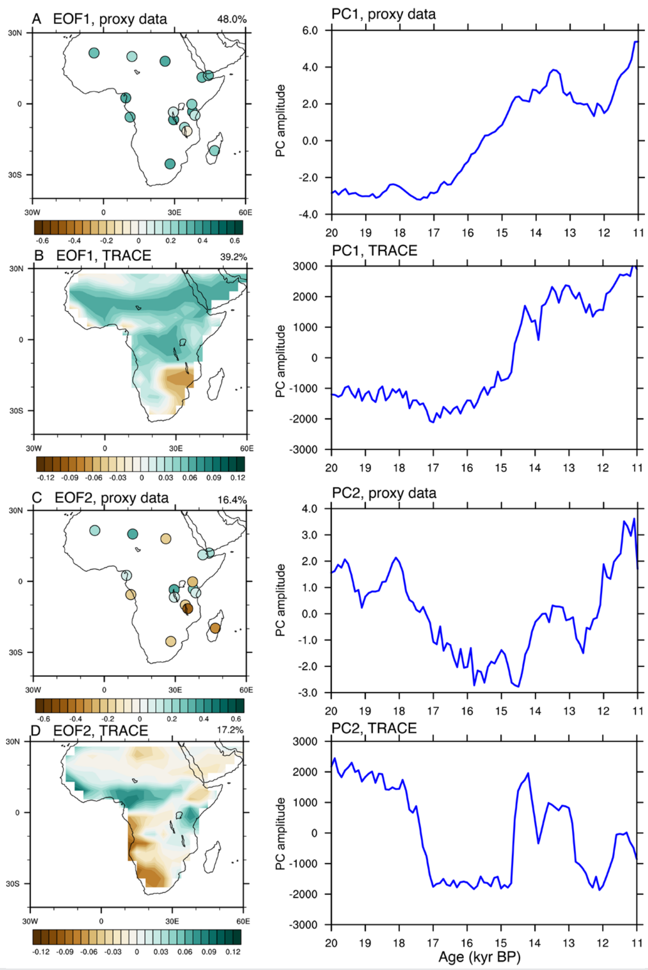

Figure 3: African hydroclimate for the deglacial period 20 to 11 kyr BP. EOF1 and PC1 of **(A)** proxy data for moisture availability and **(B)** TRACE annual precipitation (millimeters per year). EOF1 explains 39.2% and 48.0% of the total variance of model precipitation and proxy data, respectively. **(C)** and **(D)** same as **(A)** and **(B)** except for EOF2 and PC2. EOF2 explains 17.2% and 16.2% of the total variance of model precipitation and proxy data, respectively. Model results and proxy records are interpolated to the same 100-year resolution. Figure reproduced with permission from Otto-Bliesner et al. (2014).

tropics should weaken the austral monsoons (Otto-Bliesner et al. 2014).

Comparing the data with TRACE-21 simulations shows that a meltwater-induced reduction of the AMOC during the early deglaciation suppressed precipitation in both regions (Fig. 3). Once the AMOC was reestablished, wetter conditions developed north of the equator in response to high summer insolation and increasing GHG concentrations, whereas wetter conditions south of the equator were a response primarily to the GHG increase.

The TRACE-21 simulations have provided similar constraints for a number of other studies of regional precipitation. For example, Liu et al. (2014b) investigated the relationships between deglacial evolution of the East Asian Summer Monsoon (EASM) and oxygen isotope records from speleothems. The $\delta^{18}O$ records document a series of isotopic changes that vary coherently across the Asian monsoon region. This change is difficult to interpret as a response to local precipitation, which tends to change at regional scales.

Comparing the data with TRACE-21 simulations shows reasonable agreement between the speleothem $\delta^{18}O$ records and southerly monsoon winds, demonstrating that the data can record large-scale changes in the EASM. The subtropical monsoon circulation exhibits a continental-scale response due to global climate forcing associated with insolation and AMOC, as well as atmospheric teleconnections. The $\delta^{18}O$ values, however, are altered by changes in the upstream source region, as well as local precipitation changes. Thus, despite the inherent computational limitations in model resolution and complexity, the TRACE-21 simulations provide insights into the paleoclimate proxies and large-scale monsoon dynamics.

Perspective

TRACE-21 has now been widely used by the paleoclimate community, ushering in a new era of seamless model-data comparison of transient climate evolution and abrupt climate changes from seasonal to orbital timescales, from regional to global spatial scales, and from the atmosphere to the deep ocean (e.g. Marsicek et al. 2018; Kaufman et al. 2020).

SynTRACE-21 has also built upon earlier data-model comparisons in demonstrating the effectiveness of this approach for improving our understanding of the mechanisms responsible for the climate evolution recorded by the data, as well as in identifying potential shortcomings in models and data. The model-data comparison of transient climate evolution has also stimulated further studies on the stability of the climate system, such as the AMOC, in the past, as well as for the future (Liu et al. 2017).

With the continued development of high-performance computing and improvements and increase in the number of proxy records, paleoclimate research will further benefit from new model-data studies beyond SynTRACE-21. First, for a direct comparison with the observed proxy variables and model variables, models need to be improved to include paleo proxy tracers, such as stable isotope ratios in foraminifera and other geochemical tracers (Brady et al. 2019). Second, model resolution should be improved so that detailed regional conditions at the location of the proxy data can be better simulated, e.g. IsoROMS (Stevenson et al. 2015) and the isotope-enabled model WRF (Moore et al. 2016).

One ultimate objective of combining data with models is the data assimilation of paleo proxies in advanced climate models, which requires further improvement of the estimation of the uncertainty of the proxy records as well as models (Tierney et al. 2020). These assimilation products will not only provide dynamically consistent reanalyses of the state of past climate, but may also help to constrain parameters and processes in future generations of Earth system models, thus further enhancing our ability to predict the future response of Earth's climate to GHG emissions.

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Global climate goes regional, and vice versa: Reflecting on 14 years of the PAGES 2k Network

Nerilie Abram[1], D. Kaufman[2], H. McGregor[3], B. Martrat[4], O. Bothe[5] and H. Linderholm[6]

For the past 14 years, the PAGES 2k Network has brought together a large, interdisciplinary community to better understand pre-industrial climate and give context to recent human-caused climate change.

The past 2000 years of Earth's history provides a critical context for understanding climate variability and change. This is a period where climate changes occurred as a result of well characterized natural climate forcing, as well as unforced internal variability, and has now transitioned into a climate that is strongly forced by human factors. It is also a period where a range of paleoclimate proxy records, often with annual or better resolution, can be used to build up a comprehensive spatial understanding of our climate system. Recent step changes in computing capabilities now allow for ensembles of millennial-length climate-model simulations with which researchers can test and improve our knowledge of the climate system. All of these factors provide a rich scientific backdrop for the work of the PAGES 2k Network.

The 2k Network is one of the longest running working groups of PAGES. Now in its 14th year, the 2k Network has generated more than 54 journal articles, two major paleoclimate databases for temperature and hydrology reconstructions, and around 40 *Past Global Changes Magazine* articles, while fostering an open and collaborative work environment with an emphasis on FAIR data stewardship principles (Wilkinson et al. 2016).

Evolution of the 2k Network

When the 4th Assessment Report of the Intergovernmental Panel on Climate Change was released in 2007, it stated that "*Palaeoclimate information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1,300 years*" (IPCC 2007, p. 9). This was a finding that specifically related to the Northern Hemisphere, due to the low density of available proxy records from the Southern Hemisphere and tropics, and where questions remained over statistical reconstruction methods and the suitability of different proxy records.

A *Past Global Changes Magazine* article in 2005 highlighted the opportunities that dense networks of high-quality natural and documentary archives offer for moving beyond global average, or Northern Hemisphere average, temperature reconstructions (Wanner 2005) to resolve spatial patterns of climate variation. This effort coincided with an interest in testing the increasingly smaller-scale climate information being simulated by new generations of climate models. Wanner posited that "*the complex dynamical processes leading to past and future climate and environmental change can only be understood if we also acquire insight into the regional dynamics.*" This, through the LOTRED (Long-Term Climate Reconstruction and Dynamics) approach, set in motion the beginnings of the PAGES 2k Network.

The first phase began in 2008, with the goal of assembling paleoclimate records over specific regions and using these to produce continent-scale temperature reconstructions. The work initially involved eight regional working groups covering each continent and its surroundings (including an Arctic2k group). Later, an Ocean2k working group was also established to collate paleoclimate data from the world's oceans. Each group used their own expertise to assess the suitability of paleoclimate records and the best methods for combining these proxies into continent- or ocean-basin-scale temperature reconstructions.

The second phase involved trans-regional projects that brought together the datasets compiled across the regional working groups to answer specific scientific questions about the timing and inter-hemispheric variability of natural and anthropogenic climate changes over the past 2000 years. Phase 2 also included efforts to unify and test the statistical methods of reconstructing climate, and assembled a global paleoclimate temperature database with best practices of data management and accessibility. Work of the regional working groups also continued with efforts to develop hydroclimate reconstructions and resolve spatial patterns in climate changes. A major product of Phase 2 was a special issue of *Climate of the Past* titled "Climate of the past 2000 years: regional and trans-regional syntheses". This special issue also focused on putting into practice open-access data stewardship principles (Kaufman et al. 2018).

Phase 3 of the PAGES 2k project has seen the conclusion of some trans-regional projects as they achieved their goals, and the development of new project groups under the 2k Network banner. These project groups are community-led projects that are working towards the Phase 3 goals to: (1) build further understanding of climate variability, modes and mechanisms, (2) improve reconstruction methods and reduce uncertainties, and (3) assess proxy-model agreement.

Highlights of 2k Network research

The first major synthesis of the PAGES 2k Network showed that across seven reconstructed continental regions, all experienced a long-term cooling trend during pre-industrial times over the past 2000 years (PAGES 2k Consortium 2013). Long-term cooling of the global ocean also characterized the last 2000 years (McGregor et al. 2015; Tierney et al. 2015). Reconstructed long-term pre-industrial cooling is robust across different reconstruction methods, is consistent with last millennium climate model simulations, especially for the Northern Hemisphere

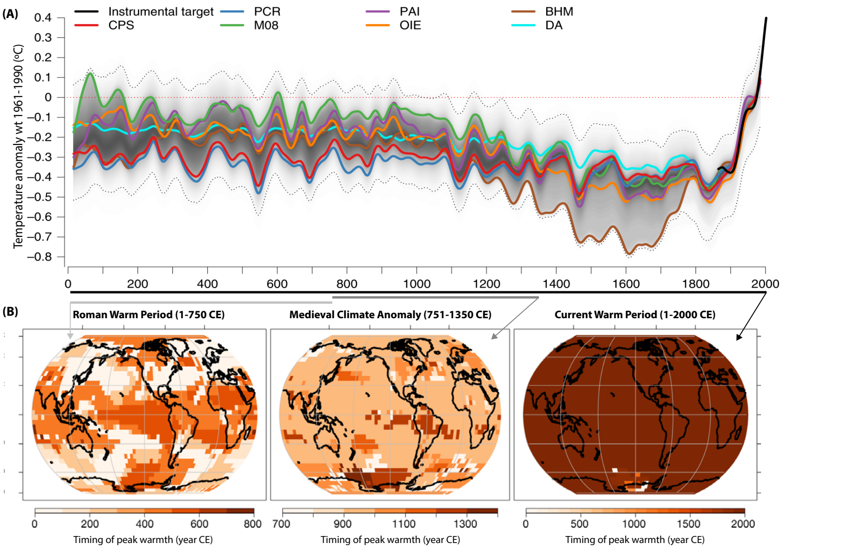

Figure 1: (A) Reconstruction of global mean temperature over the last 2000 years using multiple methods demonstrates the unprecedented rate of current warming. **(B)** Spatially resolved temperature reconstructions demonstrate that warm periods prior to the current warming were not globally synchronous. Modified from PAGES 2k Consortium (2019) and Neukom et al. (2019).

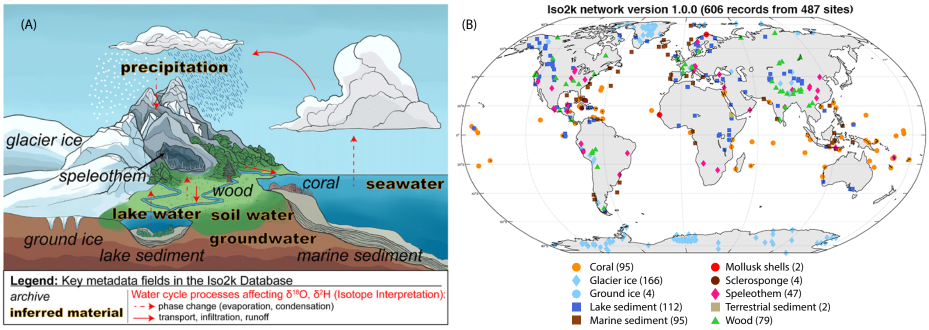

Figure 2: (A) Schematic illustration of the global water cycle and key metadata fields in the Iso2k database, and **(B)** spatial distribution of isotope records in the Iso2k database. Adapted from Konecky et al. (2020).

(PAGES 2k-PMIP3 group 2015), and is thought to be largely a response to accumulated volcanic forcing of pre-industrial climate (McGregor et al. 2015). Multidecadal fluctuations over the past 2000 years have a coherent magnitude and timing between global temperature reconstructions and appear to also be attributable to volcanic forcing during pre-industrial times (PAGES 2k Consortium 2019). Spatial reconstructions of this temperature variability have now found that there were no warm or cold periods during pre-industrial times of the past two millennia that occurred at a global scale (Neukom et al. 2019; Fig. 1).

The onset of industrial-era warming began in the mid to late 19th century in all ocean and land areas except Antarctica (Abram et al. 2016), i.e. earlier than can be assessed based on historical observations alone. Sustained warming began first over Northern Hemisphere land masses and in the tropical oceans, and was delayed in the Southern Hemisphere possibly due to Southern Ocean circulation processes, but this delayed southern warming onset is not currently reproduced by climate,model simulations. The 20th century warming interval is the only time in the past millennium when both hemispheres have experienced contemporaneous warm extremes (Neukom et al. 2014), and the second half of the 20th century has the largest global warming trends (at timescales of 20 years or longer) of any time in the past 2000 years – highlighting the unprecedented character of recent human-caused warming compared with natural climate variability in the past (PAGES 2k Consortium 2019).

The work behind these research highlights has led to, or been enabled by, the most well documented and extensive database of temperature sensitive proxies of the past 2000 years published to date (PAGES 2k Consortium 2017). The community-sourced database gathered 692 records from 648 locations, including all continental regions and major ocean basins, and is shared in the Linked Paleo Data (LiPD) format (McKay and Emile-Geay 2016) with options provided for accessing the database in multiple coding languages. A similar effort has now also resulted in a comprehensive global database of water isotope ($\delta^{18}O$ and δD) proxies for investigating variability and trends in global hydroclimate (Konecky et al. 2020; Fig. 2).

Ongoing work within the 2k Network seeks to resolve natural versus anthropogenic trends in the global hydrological cycle, and linkages between the marine hydrological cycle and the terrestrial hydrological cycle. Several reconstructions have emerged over the past few years that shed new light on regional hydroclimate, including precipitation in Antarctica (Thomas et al. 2017) and Australia (Freund et al. 2017), the evolution of the Southern Annular Mode and its teleconnections (Dätwyler et al. 2018), and drought in Scandinavia (Seftigen et al. 2017). Regional studies also highlighted the problem of spatial gaps in hydroclimate data, which are obvious in the Southern Hemisphere (Nash et al. 2016; Gergis and Henley 2017), as well as parts of the Northern Hemisphere, including the Arctic (Linderholm et al. 2018). Others highlighted the importance of historical documents for our understanding of past hydroclimatic changes and their societal impacts (Guevara-Murua et al. 2018; Gil-Guirado et al. 2019).

A framework has been established for comparing modeled and reconstructed estimates of past hydroclimates in order to quantitatively constrain future hydroclimate risk (PAGES Hydro2k Consortium 2017). Proxy data-model comparisons have shown that northern hemispheric paleodata do not support the intensification of 20th century wet and dry anomalies produced by models (Ljungqvist et al. 2016), and paleodata from Europe further suggest that model simulations may overestimate the risk of temperature-driven droughts in Europe (Ljungqvist et al. 2019). Hydroclimatic perspectives on the Common Era have also been put in a longer context, demonstrating the potential for current weakening of the latitudinal temperature gradient in the Northern Hemisphere to reduce mid-latitude rainfall (Routson et al. 2019).

Future of the 2k Network

Discussions are underway within the community (PAGES 2k Network coordinators 2020) over the future of 2k activities after Phase 3 wraps up at the end of 2021. Throughout the history of the 2k Network, the scientific endeavors have been driven by an organic, grassroots approach. Individuals, often early-career researchers, have brought their ideas, enthusiasm, and leadership to the different activities. As specific projects have been completed, others have sprung up. As researchers have moved on to other priorities, others have joined and renewed the activities and direction of the 2k effort. The 2k Network has produced ground-breaking science, while also building scientific careers and fostering collaborations across an international scientific community.

It is clear that there is momentum within some of the current 2k projects that will continue to yield valuable scientific outcomes beyond 2021. Other 2k projects with important ambitions are still in the early phases. Over the coming months the 2k coordinators will continue the efforts already begun and work with the research community to develop a plan for future 2k research priorities. These include the curation of data products as well as the rescue of existing data sources, building stable bridges between the paleodata and paleomodeling communities, a more holistic 2k view of the climate system that goes beyond temperature, and, finally, using 2k research to provide information that aids society and guides policy decisions.

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PALSEA: 13 years of ice-sheet and sea-level science

Alessio Rovere[1] and Andrea Dutton[2]

We provide an account of the past 13 years of activity of PALSEA, the PALeo constraints on SEA level rise (PALSEA) working group supported by PAGES and INQUA.

Prelude

Sea-level rise due to polar ice-sheet retreat in a warming world is one of the most important aspects associated with future climate change, yet remains challenging to project due to uncertainties in the dynamics of rapid ice-sheet retreat. The geologic record features major, and sometimes rapid, changes in ice sheets and sea level that offer an excellent opportunity to assess the rates, magnitudes, and processes involved in ice-sheet and sea-level change and how they are connected to climate forcing. The PALeo constraints on SEA level rise working group (PALSEA; pastglobalchanges.org/palsea) has developed an interdisciplinary network of paleoscientists who seek to pair the development and synthesis of datasets with geophysical modeling of ice and sea-level proxies. The overarching goal of PALSEA is to improve our understanding of the physical processes involved in ice-sheet dynamics and solid Earth responses, and to provide improved constraints for predicting sea-level rise in the future.

PALSEA started its activities in 2008 after the IPCC 4th Assessment Report: the working group was largely initiated by Mark Siddall, who gathered a group of paleoclimate scientists united by the goal of having a more coordinated role in the 5th Assessment Report. Today, PALSEA is a PAGES working group and an International Focus Group of INQUA (International Union for Quaternary Sciences; https://www.inqua.org). The following is the story of how PALSEA evolved over the past 13 years and its achievements in pushing the boundaries on paleo sea-level and ice-sheet science.

2008–2012: The early years

The first meeting of the newly formed PALSEA group was held 25-29 August 2008 in Bern, Switzerland (pastglobalchanges.org/calendar/past/2008-past/127-pages/1082), and was organized by Mark Siddall, Thomas Stocker, Bill Thompson, and Claire Waelbroeck. It brought together experts from across the community to address how studying past records of sea-level change can add to our understanding of the climate system, and in turn inform future projections of sea-level rise. To foster interdisciplinary discussions, scientists with diverse areas of expertise were invited to attend: Earth and climate modelers, field geologists, and geochronologists. The idea was to facilitate a meeting of these experts, together with a mix of early-career researchers (ECRs), in a friendly and informal environment, to develop new interdisciplinary collaborations. Participants realized the meeting only scratched the surface regarding the various issues on paleo sea-level and ice-sheet reconstructions, some of which were summarized in a review paper (Siddall et al. 2010; Fig. 1).

One year later (21-25 September 2009; pastglobalchanges.org/calendar/past/2009-past/127-pages/1085), at Woods Hole, MA, USA (meeting organized by Bill Thompson, Mark Siddall, and Claire Waelbroeck), the working group met again to discuss the challenges of dating past interglacials. What had initially emerged during discussions at the first meeting became very clear: there was a need to establish a comprehensive Quaternary sea-level database, including standardized descriptions of dated samples and sea-level proxies. This goal would characterize PALSEA activities for the years to come.

The relaxed atmosphere of the first two meetings was in part attributable to the never-written "ground rule" of PALSEA: everyone should leave their ego at the door and should be ready to challenge and be intellectually challenged by others. The emphasis of PALSEA meetings was (and still is) community-building, and PALSEA strives to bring together people who are thinking about the same problem(s) but from different angles and using very different methodologies. Also, PALSEA has always had a strong emphasis on including a large contingent of ECRs.

During the 2010 meeting in Bristol, UK (organized by Glenn Milne, Mark Siddall, and David Richards; pastglobalchanges.org/calendar/past/2010-past/127-pages/1086), three other themes were brought to the table: (1) how to best use paleodata to constrain glacial-isostatic adjustment; (2) how to achieve better integration of archaeological archives of sea-level change in broader sea-level research; and (3) how to use data from past warm periods to better understand the response of sea level to warmer climates. The first theme was dissected into several overlapping topics one year later (24-26 August 2011; pastglobalchanges.org/calendar/past/2011-past/127-pages/1137) at Harvard University in Cambridge, MA, USA (meeting organized by Mark Siddall, Peter Huybers, and Jerry Mitrovica). For three days, the PALSEA community focused on maximum sea levels reached during past epochs, namely the Last Interglacial and the mid-Pliocene, and discussed the geologic evidence for or against rapid sea-level rises or falls in the Last Interglacial and since the Last Glacial Maximum. PALSEA also tackled the issues around the processes that (de)stabilize ice sheets and on the interactions between the cryosphere and the climate system. Last but not least, the PALSEA community started to direct its attention to the implications of paleo sea-level studies on our ability to understand modern ice sheets and sea-level changes.

It was with this focus in mind that the community met 4-8 June 2012 in Madison, WI, USA (meeting organized by Anders Carlson and Mark Siddall; pastglobalchanges.org/calendar/past/2012-past/127-pages/970). This meeting was centered on dissecting the current knowledge on ice-sheet and climate interactions at multiple timescales (Holocene to Pliocene) and in different regions (Greenland and Antarctica). Five years after the first PALSEA meeting, the Madison

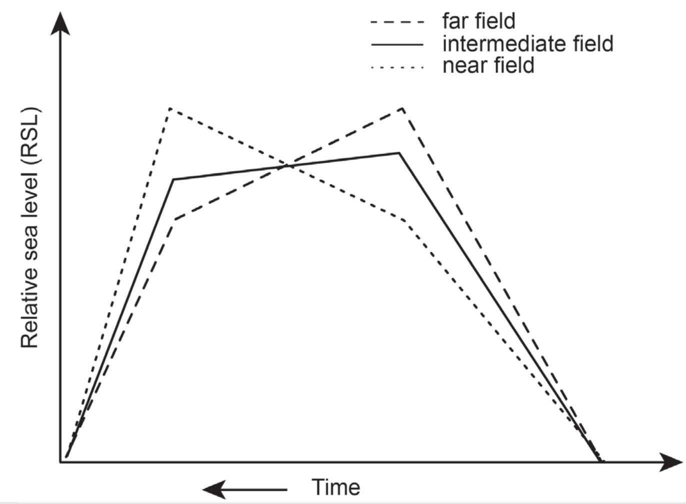

Figure 1: An illustrative sketch of how the relative sea-level record can vary at different sites across the globe across an interglacial sea-level highstand (modified from Siddall et al. 2010). Understanding the links between relative sea level and global mean sea level has been a theme within PALSEA since its inception.

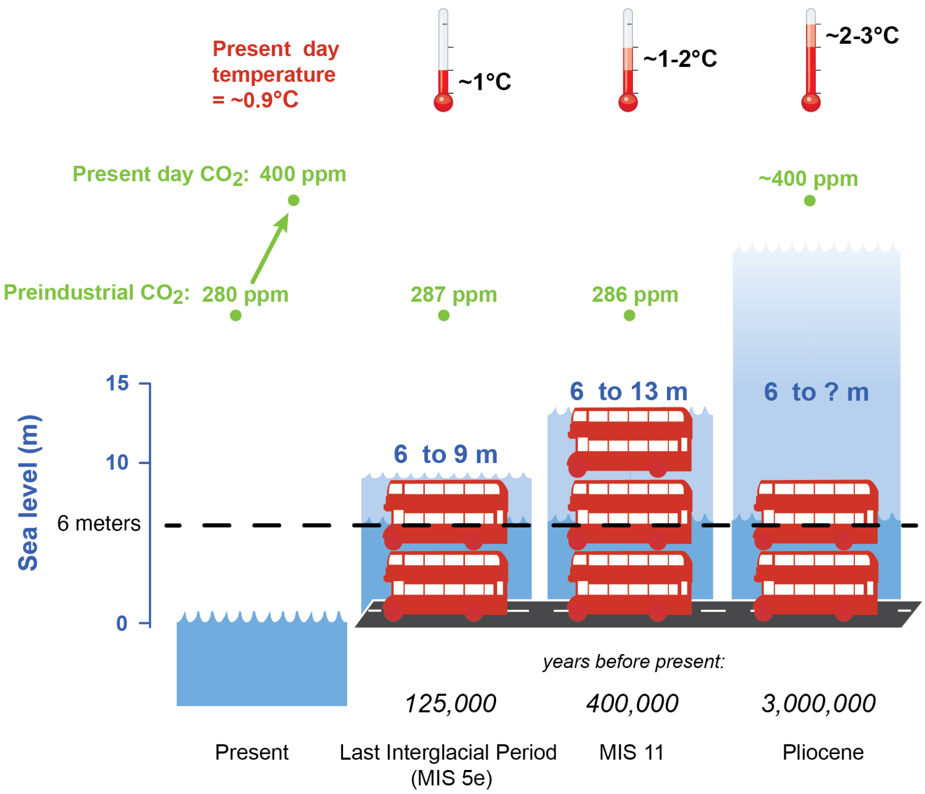

Figure 2: Comparing the magnitude of peak sea level during recent past warm periods. Modified from Dutton et al. (2015).

meeting was also the opportunity for the PALSEA founders to pass the baton to a new leadership team, who would lead PALSEA for the years to come.

The first five years of PALSEA ended with the Madison meeting. During the timeframe 2008-2012, lively discussions at the PALSEA workshops inspired several papers. Among them, an appraisal of ice-sheet responses to past climate forcings (e.g. Carlson and Winsor 2012; Gregoire et al. 2012) and several papers exploring past changes in sea level (e.g. Andersen et al. 2010; Raymo and Mitrovica 2012; Dutton and Lambeck 2012). Within its first five years, PALSEA also benefited from additional funding from the Worldwide Universities Network (WUN) and INQUA, which further enabled the group to support wide and diverse participation, particularly by ECRs. INQUA has remained a devoted supporter of PALSEA since these early years.

2012-2017: Exploring new grounds

The new PALSEA leaders were Anders Carlson, Andrea Dutton, Glenn Milne, and Antony Long. At the group meeting in Rome (21-24 October 2013, organized by Andrea Dutton and Marco Anzidei; pastglobalchanges.org/calendar/past/2013-past/127-pages/853), the community tackled the issue of estimating rates and sources of sea-level change during past warm periods and the Holocene. The workshop included a field excursion where participants had the opportunity to jump into the Mediterranean Sea and snorkel around fish tanks dating back to the Roman age that were often used as common-era sea-level indicators. Additional support was provided to ECRs with the help of CliC, the Cryosphere and Climate project within the World Climate Research Programme (WCRP). One outcome of this meeting was a review paper that summarized the current state of knowledge from an interdisciplinary perspective concerning sea level during past warm periods (Dutton et al. 2015; Fig. 2).

One year later (16-23 September 2014), PALSEA met in a slightly colder, yet equally interesting location. Antony Long and Natasha Barlow organized a workshop in north-west Scotland, in the remote town of Lochinver (pastglobalchanges.org/calendar/past/2014/127-pages/846). Here, the participants had the opportunity to work in a relaxed and informal atmosphere (the meeting was hosted in a lodge, and some participants decided to camp on the lake!), working out the best ways to tackle one of the long-lasting PALSEA goals: documenting paleo sea-level and ice-sheet extent and building sea-level/ice-sheet databases (Fig. 3). The discussions were intense and fruitful, leading to the draft of a paper on strategies and perspectives on sea-level databases that would become, in the following years, a handy guide for those wishing to build new sea-level databases (Düsterhus et al. 2016).

Sea-level and ice-sheet databases have been (and still are) a central topic within PALSEA, mostly due to their importance for the validation of glacial isostatic adjustment (GIA) and ice-sheet models. For this reason, the Scotland meeting was followed by a workshop from 22-24 July 2015 focused on data-model integration and comparison (pastglobalchanges.org/calendar/2015/127-pages/1390; organized by Glenn Milne, Ayako Abe-Ouchi, and Yusuke Yokoyama).

The trio took advantage of the 2015 INQUA conference in Nagoya, Japan, and hosted the workshop at the University of Tokyo. For the first time, a PALSEA conference was held outside of Europe or the US. In three intense days, the problems and opportunities related to using sea-level and ice-sheet data in conjunction with ice and GIA models were discussed for different timescales: the Pliocene, Pleistocene interglacials, and the Holocene.

One of the outcomes of this meeting was the understanding that PALSEA was missing one specific part of the community: scientists working with instrumental records of change. Therefore, for the 18-21 September 2016 meeting in Mt. Hood, OR, USA (organized by Anders Carlson; pastglobalchanges.org/calendar/2016/127-pages/1540), the participation of scientists working with modern sea-level and ice-sheet changes was encouraged. This led to a series of presentations which aimed to stimulate new ideas on the best ways to bridge paleo and modern records, delving mostly into data from the Late Holocene, the Common Era, and the last two centuries. The day before the official workshop start, Nicole Khan (leader of the HOLSEA project, under the umbrella of PALSEA within INQUA; https://www.holsea.org) united several colleagues interested in contributing to a global database of Holocene sea-level indicators. On that day, the group started to define what three years later would lead to the first standardized global sea-level database (Khan et al. 2019). Also the PALSEA team working on Pleistocene sea levels started to work on sea-level databases, with a series of papers dedicated to addressing issues on the data structure (Dutton et al. 2017; Rovere et al. 2016) and releasing a database of dated corals with associated sea-level metadata (Hibbert et al. 2016).

Pleistocene corals took center stage from 6-9 November 2017 in Playa del Carmen, Mexico, for the meeting closing PALSEA's first decade (organized by Andrea Dutton and Paul Blanchon; pastglobalchanges.org/calendar/2017/127-pages/1715). To delve into the issues related to the phasing of ice-sheet and sea-level responses to past climate change, participants explored the fossil reefs exposed at Xcaret, between talks and presentations. The lively discussions were centered on whether these reefs preserved imprints of sea-level oscillations, and how large these changes were. Once more, the possibility to have discussions in the field, among scientists at different career stages and from different backgrounds, proved a winning formula for PALSEA, and a source of inspiration for several new avenues of research. Therefore, it is not by chance that the second five years of PALSEA generated a large number of debates and ideas, which led to more than 80 scientific articles. The problems and advances fostered by PALSEA in its first decade are well summarized in a seminal paper by Dutton et al. (2015), that represents the outcome of several discussions and interactions within the PALSEA community.

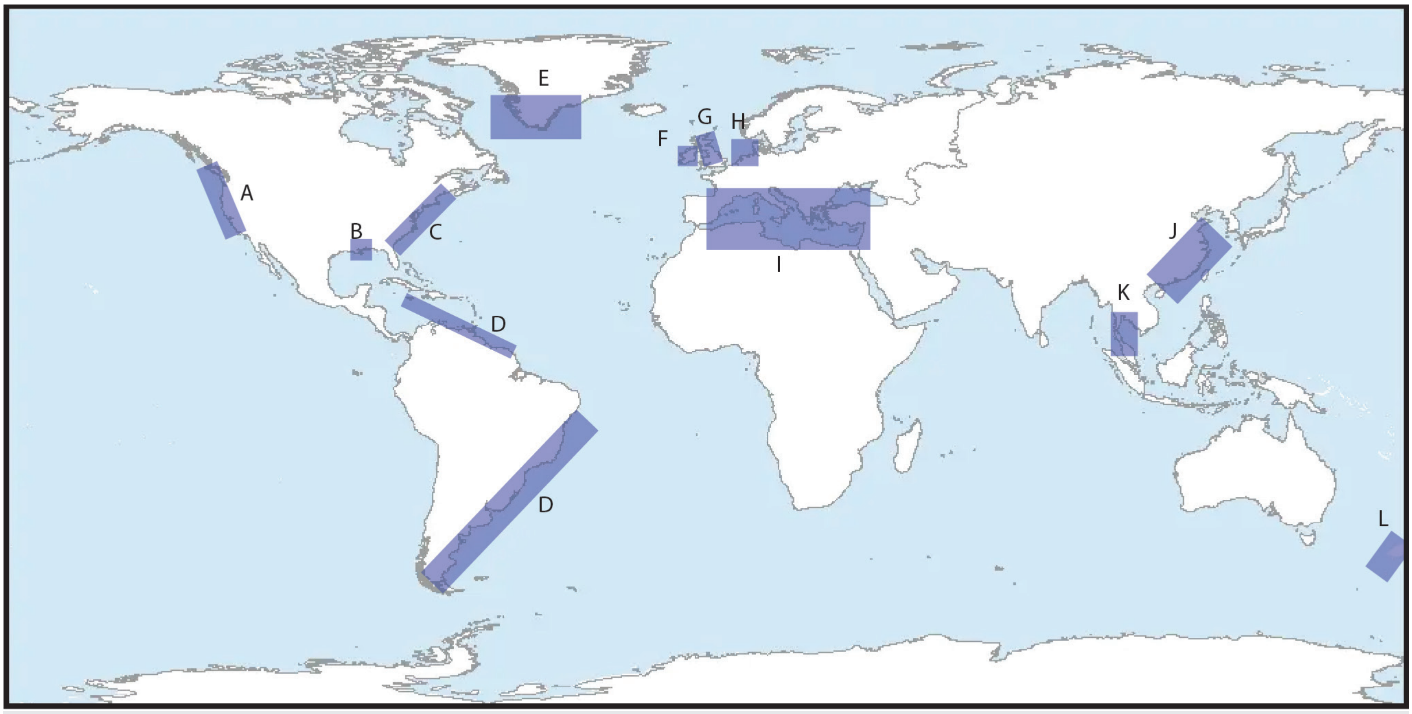

Figure 3: Map showing published regional sea-level databases as of 2014. Modified from Düsterhus et al. (2016).

2018-2020: Going forward

In Mexico, the transition was made to a new leadership, composed of then-ECRs who took part in several PALSEA activities in the previous years: Jacqueline Austermann, Natasha Barlow, Alessio Rovere, and Jeremy Shakun. The first meeting of this new cycle was organized in collaboration with QUIGS (PAGES-PMIP Working Group on Quaternary Interglacials; pastglobalchanges.org/quigs), another long-running PAGES working group. The meeting was held 24-27 September 2018 in Galloway, NJ, USA (organized by Emilie Capron, Robert E. Kopp, and Alessio Rovere; pastglobalchanges.org/calendar/2018/127-pages/1759). The efforts of these two communities were used to define "lessons learned" in these years, resulting in a paper with the self-explanatory title: "Challenges and research priorities to understand interactions between climate, ice sheets and global mean sea level during past interglacials" (Capron et al. 2019). A particularly refreshing aspect of this meeting was the input of new ideas from scientists from the QUIGS community, who had never before participated in a PALSEA meeting.

Given the success of the New Jersey meeting, the 21-23 July 2019 PALSEA meeting in Dublin, Ireland (organized by Natasha Barlow and Robin Edwards; pastglobalchanges.org/calendar/2019/127-pages/1821) also aimed to expand the involvement of those with complementary expertise: several ecologists and geochemists were invited to discuss how to improve proxy-based paleo sea-level reconstructions. Embedded within this meeting was the presentation of the final version of the HOLSEA database (Khan et al. 2019) and the inception of the World Atlas of Last Interglacial Shorelines, an effort to standardize MIS 5e sea-level proxies, that is now underway (Rovere et al. 2020). Some members of the PALSEA community also participated in the INQUA-PAGES ECR workshop on impacts of sea-level rise from past to present (iSLR) in 2018.

The COVID-19 pandemic shocked the world and thwarted plans for the PALSEA meeting in Palisades, NY, USA, in September 2020. The ambitious aim for this meeting was to bring together the Earth and ice modeling communities to define and create a standardized way to share and analyze model results. The meeting was being co-organized with another very active community, SERCE (Solid Earth Response and influence on Cryospheric Evolution), and is currently postponed until September 2021. In order not to lose the possibility to meet and exchange ideas, PALSEA organized a virtual "express" meeting from 15-16 September 2020 (led by Jacky Austermann and Alexander Simms; pastglobalchanges.org/calendar/2020/127-pages/2043). The meeting was held at different times to allow people from different timezones to join. The result was the most well attended PALSEA meeting ever (Fig.4)!

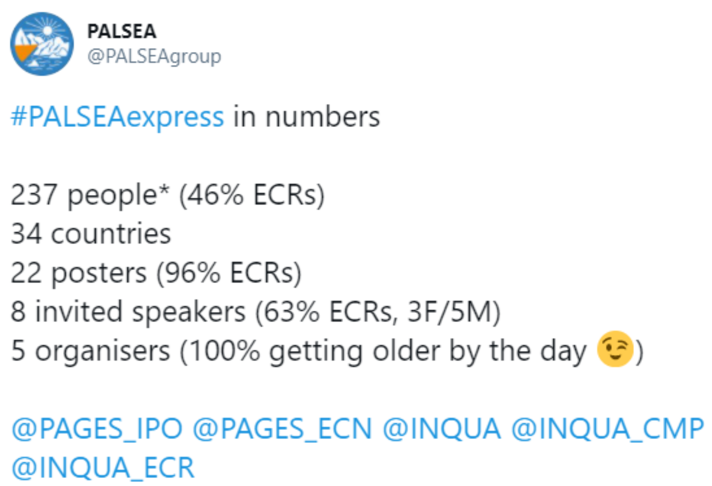

Figure 4: Tweet by PALSEA (@PALSEAgroup) summarizing the numbers of the 2020 virtual meeting.

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Fabulous interglacials: A timeline of the PIGS and QUIGS working groups

Chronis Tzedakis[1], L. Menviel[2], E. Capron[3], B.L. Otto-Bliesner[4], J.F. McManus[5], D. Raynaud[3] and E. Wolff[6]

Part of the scientific rationale for pursuing studies of past interglacials is that they provide a baseline against which to assess the climatic evolution of the current interglacial and the impact of anthropogenic interference. Here, we trace the history of the PAGES working groups on interglacials (PIGS and QUIGS).

Prelude

When we look at the past, our attention is often captured by the allure of the recent (the last couple of millennia) or the shock of the extreme (a planet plunging into an ice age). However, although the past provides no exact analog for the next century and beyond, it is interglacials that provide examples that are most relevant for assessing the current anthropogenic warming, including its influence on the cryosphere and the feedbacks associated with biogeochemical cycles. For that reason, the study of the full range of past interglacials, their climate variability and impacts, their initiation and their ending, are a cornerstone of PAGES' research.

PIGS

On the evening of 30 January 2007, Jerry McManus, Dominique Raynaud and Chronis Tzedakis were talking quietly in a corner of the Captain Kidd bar at Woods Hole Village, on Cape Cod, MA, USA. It had been a good scientific meeting. After two days of talks on Marine Isotope Stage (MIS) 11, the workshop organized by McManus was drawing to a close. In fact, the entire working group on MIS 11, sponsored by the International Union for Quaternary Research (INQUA; inqua.org), was drawing to a close. "Where do we go from here?" the trio asked. "Perhaps we could learn more, if we looked at the whole ensemble of interglacials in a systematic way," said Raynaud. Not entirely clear-headed, they called it "PIGS" for Past Interglacials, and the name stuck (pastglobalchanges.org/science/wg/former/pigs/intro).

They decided to approach PAGES for sponsorship. In its earlier days, PAGES had been focused primarily on the Holocene, but it was now under new management. Paleoceanographer Thorsten Kiefer had recently become the executive director and was possibly amenable to expanding the scope of PAGES to longer timescales. The plan for PIGS was to focus on the last 800 thousand years (kyr), as Antarctic ice-cores were furnishing information on atmospheric concentrations of greenhouse gases over that interval, thereby providing constraints on global boundary conditions. Kiefer was indeed receptive to such a prospect, and later in 2007 a proposal for a PAGES working group on Past Interglacials was accepted by the PAGES Scientific Steering Committee (SSC).

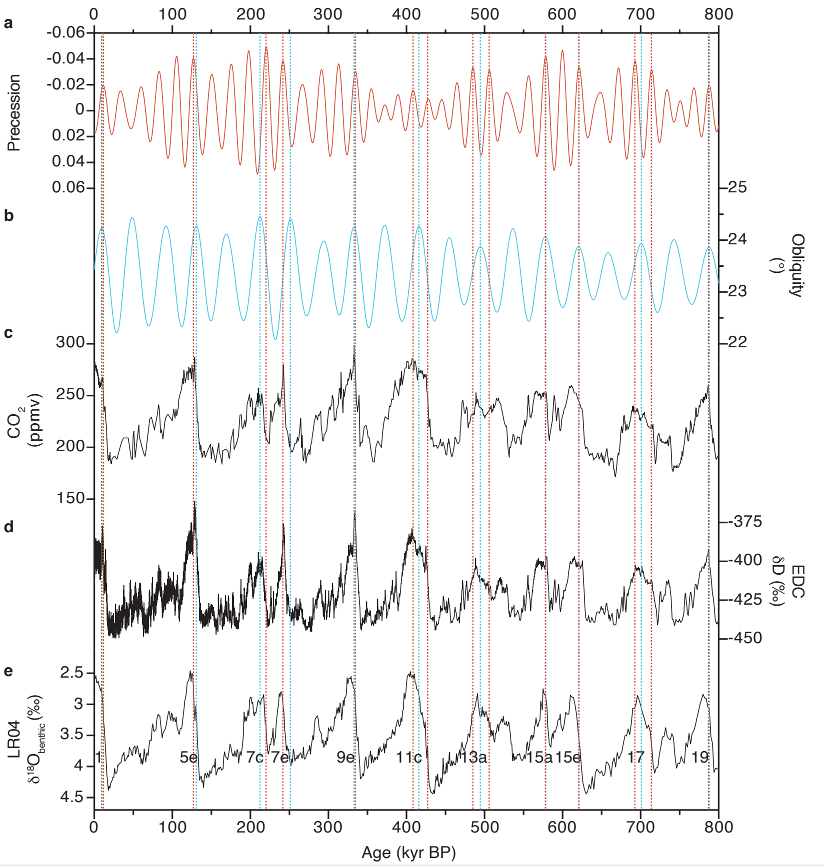

Figure 1: Interglacials of the last 800 kyr. **(A)** Precession parameter, plotted on an inverse vertical axis (Berger 1978). **(B)** Obliquity (Berger 1978). **(C)** Atmospheric CO_2 concentration from Antarctic ice cores (Lüthi et al. 2008). **(D)** δD of ice in the EPICA EDC ice core, Antarctica (Jouzel et al. 2007). **(E)** $\delta^{18}O_{benthic}$ record from the LR04 stack (Lisiecki and Raymo 2005). Marine isotope stages and substages of interglacial status are shown. Vertical dotted lines indicate the timing of precession minima (red) and obliquity maxima (blue). Note the three longer interglacials (MIS 11c, 13a, 17) where precession and obliquity are nearly opposite in phase (Tzedakis et al. 2012). Modified from Tzedakis et al. (2009).

The first PIGS workshop (2-4 October 2008; pastglobalchanges.org/calendar/past/2008-past/127-pages/1024) assessed the then state of knowledge and defined specific priority topics that would form the agenda of subsequent workshops. A PIGS-community progress article (Tzedakis et al. 2009) pointed to the large diversity among interglacials in terms of their intensity, structure, and duration (Fig. 1), but also noted that a general theory accounting for this remained elusive. In essence, an underlying ambition of all PAGES interglacial working groups has been to elucidate some general principles governing this diversity.

The second PIGS workshop (24-27 August 2009; pastglobalchanges.org/calendar/past/2009-past/127-pages/1023) proved a resounding success and failure, in equal measure. Over the course of four days, it showed the full potential of small group meetings (~30 participants), as an interglacial community of like-minded scientists began to form, freely exchanging ideas, showing each other unpublished data, and intensely debating general issues and finer points. A *modus operandi* emerged where community papers would be planned, but otherwise participants were free to pursue their own avenues of research independently, energized by the discussions at the meetings. This caused some consternation at PAGES headquarters, as some papers never formally acknowledged PIGS, although others did (e.g. Mokeddem et al. 2014), but overall the science moved forward. One of the ideas pursued during the meeting was the role of millennial-scale variability as an intrinsic feature of the past five glacial terminations, and plans were made for a PIGS-community paper on this topic. All the initial excitement, however, evaporated a few weeks later, after a brilliant paper on Ice Age Terminations was published by a different group (Cheng et al. 2009), making essentially the same point. The PIGS paper was abandoned.

The third PIGS workshop (20-22 October 2010; pastglobalchanges.org/calendar/past/2010-past/127-pages/1022) focused on interglacial duration and glacial inception. Although estimates of interglacial durations are sensitive to the definition of interglacial conditions in different proxies and archives, it was thought that robust patterns could emerge from a systematic comparison of interglacials. One outcome was a paper (Tzedakis et al. 2012) arguing that the fundamental concept underlying the terminology of an interglacial is that of the sea-level highstand, a measure of integrated global climate effects that lead to the loss of continental ice; by extension, interglacial length was linked to the duration of the highstand. On this basis, it suggested that over the last 800 kyr, the phasing of precession and obliquity influenced the persistence of interglacial conditions over one or two insolation peaks, leading to shorter (~13 kyr) and longer (~28 kyr) interglacials (Fig. 1).

The fourth PIGS workshop (2-5 July 2012; pastglobalchanges.org/calendar/past/2012-past/127-pages/1012) focused on how well we can explain the diversity of interglacials from the forcing and feedbacks and attempted to place interglacials within the wider context of ice-age cycles and the extent to which these are deterministic. A community paper to develop the major themes considered over the course of PIGS was planned, and a follow-up writing workshop brought together the lead authors for each section of the paper at Louvain la Neuve, Belgium, in March 2013. Eric Wolff took up the gargantuan task of editing and putting the different sections together. The landmark paper "Interglacials of the last 800,000 years" appeared in 2016 (Past Interglacials Working Group of PAGES 2016), condensing in 58 pages the then state of knowledge. It proposed that an objective definition of an interglacial is the absence of substantial Northern Hemisphere ice outside Greenland. A corollary of this is the occurrence of more than one interglacial within MIS 7 and MIS 15 (Fig. 1). Thus, interglacials of the past 800 kyr do not occur every 100 kyr, and therefore attempts to predict the onset of interglacials need to account for this irregular return time. The review corroborated the crucial role that millennial-scale climate change (involving rapid changes in Atlantic Meridional Overturning Circulation strength) plays in each glacial termination. It highlighted MIS 5e as the interglacial that experienced the warmest conditions of the last 800 kyr across the globe. Taking a look into the future, the paper concluded that the next glacial inception is unlikely to occur in the next 50 kyr, given the combined effect of the current low eccentricity and high atmospheric greenhouse gas concentrations.

QUIGS

The PAGES-PMIP Working Group on Quaternary Interglacials (QUIGS; pastglobalchanges.org/quigs) arose from an initiative of Bette Otto-Bliesner, who envisaged a more formal connection between the successor to PIGS and the Paleoclimate Modelling Intercomparison Project (PMIP; https://pmip.lsce.ipsl.fr). More specifically, QUIGS would promote a closer collaboration between modelers and the data community to provide expertise on experimental design, data compilations and model-data comparisons, and to assess the relevance of interglacials to understanding future climate change.

With the guidance of PAGES SSC members Hubertus Fischer and Michal Kucera, an ambitious QUIGS working group structure, comprising two three-year QUIGS phases with a one-year gap, was envisaged: in Phase 1, QUIGS would formulate research questions, identify knowledge gaps, and plan how to fill these gaps. In close collaboration with PMIP, it would define model protocols and initiate the model runs and data collection needed. In Phase 2, the working group would return to the research questions identified in Phase 1, with better datasets and new model experiments, ultimately aiming to gain a quantitative understanding of interglacial controls. The four-year return period (between the beginning of Phase 1 and the beginning of Phase 2) would therefore provide the necessary time to complete the tasks.

QUIGS, led by Bette Otto-Bliesner, Emilie Capron, Anne de Vernal, Eric Wolff, and Chronis Tzedakis, was formally approved by the PAGES SSC in May 2015. A little later, Andrea Dutton, Anders Carlson, and Laurie Menviel joined the team.

The first QUIGS workshop on Warm Extremes (9-11 November 2015; pastglobalchanges.org/calendar/2015/127-pages/1520) assessed the current knowledge and research needs on the temporal and spatial patterns of climate forcing, responses, and feedbacks during MIS 5e and MIS 11. Paleorecords and climate model simulations highlighted the need for an improved understanding of the magnitude and drivers of the enhanced warmth during MIS 5e and 11. This led to the definition of model protocols for CMIP6 and PMIP4 Last Interglacial simulations (Otto-Bliesner et al. 2017), and also of surface-climate data benchmarks for high-latitude regions (Capron et al. 2017).

The second QUIGS workshop (18-20 October 2016; pastglobalchanges.org/calendar/2016/127-pages/1592) examined patterns of climate forcing, feedbacks, and responses characterizing glacial terminations. It assessed common features and differences between Terminations I and II (TI and TII), and highlighted the need for improved chronologies and for constraining the size and spatial distribution of ice sheets during the penultimate glacial maximum. This led to an article presenting a protocol for transient simulations of TII (140-127 kyr BP) under the auspices of PMIP4, as well as a selection of records, providing appropriate benchmarks for subsequent model-data comparisons (Menviel et al. 2019).

Our understanding of glacial-interglacial cycles has been built on a large body of evidence from Middle and Late Pleistocene environments, dominated by ~100-kyr ice-volume variations. However, any theory of ice ages remains incomplete if it does not include an adequate description and understanding of the mode and tempo of climate variability during the Early Pleistocene (the so-called "41-kyr world") and the transition into the "100-kyr world" (Mid-Pleistocene Transition, MPT). With this in mind, the third QUIGS workshop (28-30 September 2017; pastglobalchanges.org/calendar/2017/127-pages/1655) explored the characteristics of interglacials of the 41-kyr world and considered causes of the MPT (Ford and

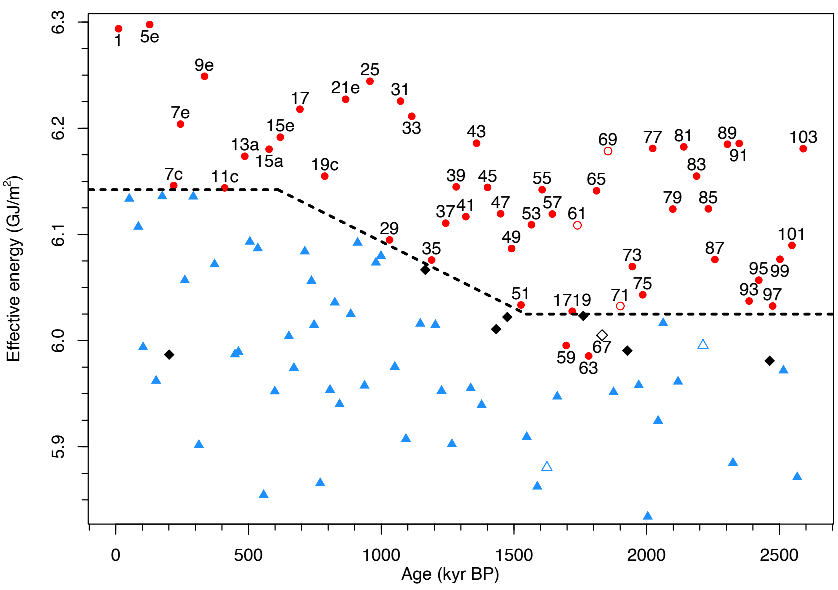

Figure 2: Effective energy for deglaciation (= peak caloric summer insolation + [(time elapsed since interglacial onset) × (discount rate)]) at each insolation peak during the past 2.6 Myr. Each insolation peak is plotted as the onset of an interglacial (red circles), a continued interglacial (black diamonds) or an interstadial (light blue triangles); open symbols correspond to uncertain assignments. The dotted line separates complete deglaciations from incomplete and missed deglaciations; the ramp indicates a gradual rise in the threshold required for a complete deglaciation. Numbers refer to Marine Isotope Stages. Modified from Tzedakis et al. (2017).

Chalk 2020). Despite the emergence of boron-based CO_2 data from marine cores, progress in modeling 41-kyr cycles in sea level and the causes of the MPT requires CO_2 reconstructions with reduced uncertainties. The planned drilling of an "Oldest Ice" core back to 1.5 million years ago (Myr BP) will eventually provide increased confidence on the evolution of the climate-carbon cycle interactions for this period.

One of the outstanding questions identified by PIGS in their final review paper was: "Given the astronomical forcing and the feedbacks that are present, is the occurrence and character of interglacials predictable? In other words, … is it inevitable that we would find ourselves in today's interglacial climate following the same sequence of glacial and interglacials that has occurred?" (Past Interglacials Working Group of PAGES 2016, p. 206). An initial answer to this was provided by Tzedakis et al. (2017), who proposed that an interglacial onset occurs when a peak in insolation exceeds a threshold that decreases with time elapsed since the previous deglaciation, as ice sheets become more unstable. This correctly predicted the deglaciation history during the Quaternary and identified a gradual rise in the deglaciation threshold from ~1.5 Myr BP that led to an increase in the frequency of skipped insolation peaks after 1 Myr BP (Fig. 2). The emergence of longer glacials then allowed the accumulation of larger and increasingly unstable ice sheets. The analysis also showed that the succession of interglacials is not chaotic; the sequence that has occurred is one among a very small set of possibilities, suggesting a degree of probabilistic determinism.

Between Phases 1 and 2, QUIGS and another PAGES working group, PALeo constraints on SEA-level rise (PALSEA), held a joint workshop from 24-27 September 2018 (pastglobalchanges.org/calendar/2018/127-pages/1759). The goal of the workshop was to identify the state of our understanding on the interplay between climate, polar ice sheets, and sea level during past interglacial periods. A position paper identified eight research areas as critical for an improved understanding of climate and ice-sheet responses to astronomical and greenhouse gas forcing, and by extension, responses to conditions similar to or warmer than the pre-industrial climate (Capron et al. 2019).

2019 marked the start of the second phase of QUIGS in which improved datasets and new model experiments are being used to address research questions and knowledge gaps identified during Phase 1. A workshop on "Warm extremes - MIS 5e and its relevance to the future" (1-4 July 2019; pastglobalchanges.org/calendar/2019/127-pages/1910) played a key role in focusing community efforts (model and data) to publish relevant science for the forthcoming 6th Assessment Report of the IPCC. In particular, papers comparing the ensemble of new CMIP6-PMIP4 *lig127k* simulations and proxy reconstructions of surface temperature and sea ice were developed (Kageyama et al. 2021; Otto-Bliesner et al. 2021). The latter paper showed that the model ensemble was able to simulate the reconstructed 127-kyr BP JJA temperature anomalies over Canada, Scandinavia, parts of midlatitude Europe, and much of the North Atlantic (Fig. 3). The exceptions are in the northwestern North Atlantic and Nordic seas, where the marine reconstruction suggests significant cooling (Capron et al. 2017). Potential reasons for mismatches include dating uncertainties, a lingering memory of the H11 event in marine records (Marino et al. 2015), and/or the design of the CMIP6-PMIP4 *lig127k* protocol without meltwater from potential remnant ice sheets over Canada and Scandinavia.

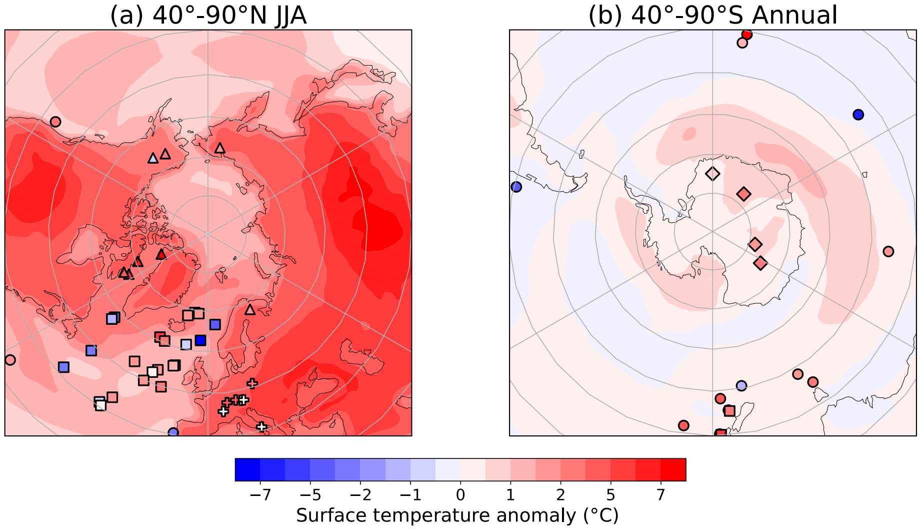

Figure 3: Comparison of results of the CMIP6-PMIP4 *lig127k* simulations and proxy records. High-latitude surface temperature anomaly comparing 127 kyr BP to the preindustrial period from models (ensemble average in colors) and proxies (circles for the compilation by Hoffman et al. (2017); squares and diamonds for marine sites and ice cores, respectively, from the compilation by Capron et al. (2014, 2017); pluses for the compilation of Brewer et al. (2008); and triangles for the Arctic compilation, https://doi.org/10.5194/cp-17-63-2021-supplement): **(A)** 40°-90°N June-July-August, **(B)** 40°-90°S annual. The preindustrial reference is 1850 CE for model anomalies and for the data is 1870–1899. Modified from Otto-Bliesner et al. (2021), courtesy of A. Zhao.

In the midst of the COVID-19 pandemic, a virtual meeting on glacial termination processes and feedbacks was held on 10 and 12 November 2020 (pastglobalchanges.org/calendar/2016/127-pages/1592). Seventy-five percent of the talks were given by early career researchers (ECRs), who presented advances in understanding of deglacial changes in climate, ice sheets, the carbon cycle, and vegetation. Further meetings on terminations and the MPT are planned. A final workshop on one of the most challenging issues, the causes of interglacial intensity, will provide a fitting close to the PAGES interglacial effort.

Coda

Looking back from today's perspective of accelerating global warming, initiating a working group with a specific focus on interglacials appears the obvious thing to have done. But in January 2007, with much attention centered on glacial climate variability, this was not necessarily obvious. From a small group of friends, the PAGES interglacial community grew to involve 69 (PIGS) and 95 (QUIGS) scientists, while ECR participation increased from 10% to over 40%. We are grateful to PAGES, and especially Thorsten Kiefer and Marie-France Loutre, for their encouragement and continued support in this endeavor. It has been a fabulous ride.

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Fire history of an inhabited Earth: Experiences from the PAGES Global Paleofire Working Group

Boris Vannière[1,2], D. Colombaroli[3] and M.J. Power[4,5]

Paleofire research, which was the focus of the PAGES Global Paleofire Working Group over the past 12 years, offers a unique approach to understanding the environmental and social implications of large-scale disturbances associated with changing fire regimes at regional and continental scales.

Recent episodes of destructive fires, seen in media worldwide, have been referred to as "mega-fires" (Williams 2013). In the past decade, nearly every continent has experienced fires of unusual magnitude, calling into question humanity's ability to accept fire as a natural process with which we should coexist (Moritz et al. 2014). Fire scientists are beginning to recognize how humans have been responsible, in many ways, for patterns and consequences of fire occurrence that pervade ecosystems today. Even more critical is acknowledging how our species has progressively promoted conditions for fires to occur over the past centuries and millennia by the sustained conversion of landscapes into fire-prone ecosystems. Humans have become one of the greatest sources of fire while simultaneously creating more fire-prone weather through changing the Earth's climate (Pyne 2015).

Global Paleofire Working Group

Over the past two decades, the number of scientific papers on past fire regimes has increased steadily (e.g. Aleman et al. 2018). Some of these publications were products of an ambitious research project driven by the PAGES Global Paleofire Working Group (GPWG; Power et al. 2008a; Vannière et al. 2016a). Indeed, the long-term perspective offered by paleofire research provides a unique approach to understanding environmental dynamics through time, including the ecological consequences of large-scale disturbances like mega-fires. Such long-term perspectives highlight the multiple factors driving fire regimes and capture the long-lasting effects on ecosystems.

Improving our knowledge of ecological legacies is one of the many opportunities that paleoarchives offer (Whitlock et al. 2010; Power and Vannière 2018). Ecologists have long understood that fire regimes evolve over long timescales, often beyond the ability of modern observations to disentangle forcings and responses, justifying the need for paleofire perspectives. This is most evident in recent trends of increased occurrence of catastrophic fires, emphasizing the critical need to understand and contextualize these transformative processes in the modern world. Interrogating and disseminating knowledge on the history of fire and its role in shaping ecosystems is a fundamental objective for maintaining a habitable Earth where all species may thrive, despite the destructive nature of these fine-scale processes with global consequences.

The GPWG was formally launched in 2008 after several years of collaborative work around the implementation of a global fire history database (Power et al. 2008b; Marlon et al. 2008). The main objective was to centralize a growing volume of fire history data, scattered throughout publications, laboratories and research programs around the world. This unique dataset made novel estimations of millennial-scale changes in biomass burning at global scales possible, as fire scientists began to understand the causes and responses of those changes (e.g. Marlon et al. 2013; Vannière et al. 2016b). This empirically based understanding of fire allowed GPWG to test new hypotheses while evaluating and improving climate models that integrate fire as a key element of the global carbon cycle (Harrison et al. 2018). Additionally, global paleofire data have become a critical resource for estimating the probability of fire occurrence under the constraints of past and future climate change scenarios (Daniau et al. 2012; Lestienne et al. 2020).

The GPWG operated for 12 years in two distinct phases (Power et al. 2008a; Vannière et al. 2016a): GPWG (2008–2015) and GPWG2 (2016–2019). During this time, 18 workshops and congress sessions were organized in 11 countries and 16 cities, bringing together scholars from more than 60 countries (Fig. 1). Based on these scientific meetings, which ranged from day-long to week-long events, more than 50 scientific papers emerged from the new collaborations promoted by the GPWG. *PAGES news* and *Past Global Changes Magazine* published 12 meeting-outcome papers and dedicated a full issue to paleofire research (Whitlock et al. 2010), including topics such as regional paleofire reconstructions, calibration, and data-model comparisons. A full issue of *Quaternary International* reported on the PAGES-GPWG session at INQUA 2015 at Nagoya, Japan (Power and Vannière 2018).

The main objectives of the community workshops were to collectively define priority research areas in paleofire science, to collect data through the sharing of the regional expertise of the participants, to support the emergence of early-career researchers, and to reach out to as many researchers as possible from countries where paleofire research had received limited support.

Data, expertise, and outreach

As the GPWG transitioned from the early community-growth phase into phase two, new challenges and research agendas emerged. During the workshops of the GPWG2 phase, a reflection on intellectual gaps in knowledge and a need for additional collaborative work was carried out with a focus on targeting policy makers and

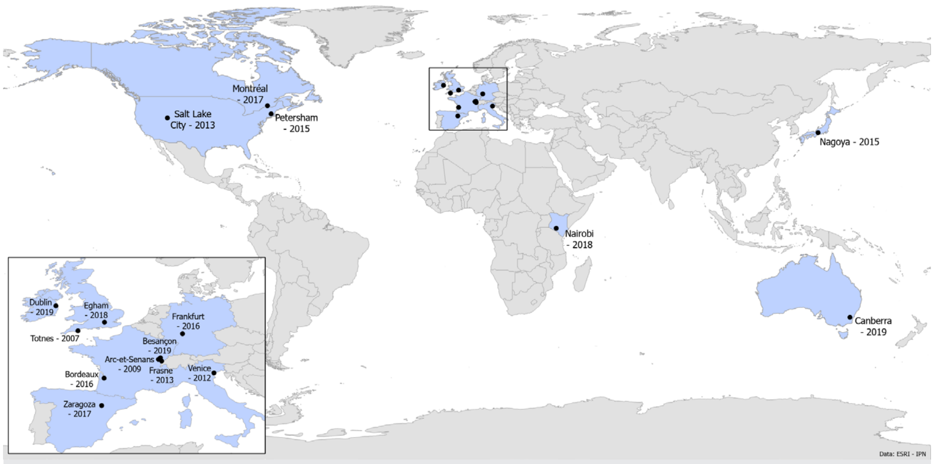

Figure 1: Location of Global Paleofire Working Group workshops and congress sessions over the past 12 years.

environmental managers. The priority for GPWG2 was to apply and transmit scholarly research into action, by emphasizing theoretical reference frames and quantified estimates of biomass burning, and by connecting areas of expertise on long-term environmental processes associated with past and current fire regime changes (Marcisz et al. 2018). One of the long-standing challenges in this community has been the integration of more applied research in communicating with stakeholders. In 2019, the GPWG released a first policy brief (Colombaroli et al. 2019) to identify best practices for sustainable ecosystem management, including how transdisciplinary knowledge (such as paleoecology and Indigenous knowledge) can better inform fire management and policy.

As the paleofire community has evolved, knowledge has been acquired about the drivers and circumstances of fire regimes, the role of anthropogenic fire practices since prehistoric times, and fire ecology on a range of spatial and temporal scales. Translating this knowledge for practitioners has opened new dialogs on sustainable fire risk preparedness. Since fire is viewed by many as a dramatic and dangerous phenomenon, it naturally raises societal fears. Considerable national and local resources are focused on firefighting and suppression policies, which, unfortunately, in the current context of global change, have become insufficient for protecting human populations and the resources we depend on. Moreover, fire was the first of the natural elements – water, earth, fire, and air – to have been significantly altered by our species. Unlike most other elements, fire transcends spatial scales, from the smallest hearth to the largest mega-fires, and operates on all temporal scales, from rapidly changing ecosystems over a few minutes to shaping landscapes over millennia (Pyne 2015).

The large majority of the work and results facilitated by the GPWG are based on the Global Paleofire Database (https://database.paleofire.org). The original goal of the Global Charcoal Database was to integrate all dated, quantitative sedimentary fire-history series (i.e. records of sedimentary charcoal) previously published in the scientific literature. Numerous efforts were put forth to synthesize and compare these fire-history series at regional, continental, and global scales to reconstruct temporal changes in biomass burning (Power et al. 2008b; Vannière et al. 2014).

Fire history, drivers, and impacts

Several key discoveries have emerged over the past decade because of these efforts. The first lesson was that for a very large majority of the world's ecosystems, biomass burning has increased continuously since the Last Glacial Maximum (~21,000 years ago) in response to long-term changes in (1) climate; (2) vegetation, i.e. the amount of biomass available; and (3) human land use. In contrast to the last ice age when the fire signal was very weak in most of the world's ecosystems, the Holocene shows increased spatial heterogeneity in fire activity from one region of the globe to another (Power et al. 2008b).

Figure 2: A slash-and-burn plot in the tropical dry forest of south-Yucatan, Mexico (Image credit: Boris Vannière, 2004).

A second lesson from these efforts was that increasing temperatures is the most important driver of past fire activity. Additionally, abrupt increases in fire activity are linked to intermediate moisture levels that, on the one hand, favor vegetation growth and, on the other hand, can lead to periods of fire-prone drought (Colombaroli et al. 2014; Daniau et al. 2012). For example, during the last glacial-interglacial transition, and at the beginning of the Holocene, a time of maximum solar insolation, many ecosystems on the planet burned regularly, depending on the biomass availability, and in a relatively sustained manner when compared to the modern period (for example Lestienne et al. 2020).

A third lesson has emerged about the role of anthropogenic fire: during the middle and late Holocene, vegetation communities were increasingly modified by human activities; at this time, anthropogenic activities began to override climate as the major player in maintaining and modifying fire regimes in many ecosystems. Evidence from the boreal region (Blarquez et al. 2015), the equatorial region (Colombaroli et al. 2014), the temperate region in Europe (Dietze et al. 2018), and the Mediterranean (Vannière et al. 2016b) supports these findings.

Perhaps the most significant lesson derived from the efforts of the GPWG was that across the planet's biomes and ecosystems, it remains challenging to disentangle natural from anthropogenic drivers of fire and related feedbacks. Similarly, it is still unclear whether vegetation ultimately drives a particular type of fire regime or whether the introduction of fire encourages the expansion of fire-adapted plant formations (Feurdean et al. 2020). However, the emerging collaborative work on these challenges suggests that following a shift in fire regime and/or vegetation composition, a new dynamic balance is established, at least until changes in climate and/or human activities disrupt the system once again.

Lessons from the past

Today, paleofire research suggests that the spatial expression of burning has become more regionally heterogeneous throughout the past 10,000 years, particularly as humans increasingly altered natural fire regimes (Fig. 2). Although the precise timing and regional chronologies of human impacts on fire remain highly variable in space, these findings agree with regional histories of land colonization and cultural changes (Connor et al. 2019). Increasing evidence for regional and even continental-scale human-fire legacies on long timescales are beginning to question old paradigms (Blarquez et al. 2015; Colombaroli et al. 2014).

For example, in Europe, the human footprint on fire regimes extends at least to the beginning of the Neolithic period, i.e. between 9000 and 7000 years ago (Dietze et al. 2018). This may have taken the form of increased fire frequency in exploited ecosystems, which indirectly caused a decrease in the magnitude of large-scale events (extent and intensity). As landscapes became more fragmented, fuel loads were altered and fire regimes were permanently changed from pre-human intervention. (Fig. 3; Vannière et al. 2016b).

Novel fire and vegetation reconstructions are also challenging assumptions regarding biodiversity. It has recently been recognized, for example, that human activities may promote and maintain optimum fire conditions, which in turn maximize plant diversity in ecosystems; in this way, long-term anthropogenic behavior can have a positive impact on biodiversity. For example, in the Iberian Peninsula, Connor et al. (2019) demonstrated that changes in fire regime and vegetation diversity correspond with long-term human-environment interactions beginning as early as 7500 years ago. This new evidence suggests that Neolithic burning promoted vegetation openness and increased woodland diversity ~5000 years and again ~2000 years ago, when intensification and acceleration of the human landscape transformation led to permanent transitions in ecosystem state. In this case, human-driven fires favored open vegetation diversity, disrupted woodland diversity, and meaningfully decreased landscape richness on a regional scale.

During the Holocene, the frequency, size, and intensity of fires may have been much greater or more intense than even the "mega-fires" observed in recent years (Lestienne et al. 2020). The media's portrayal of mega-fires promotes frightening news summaries with discussions of the unprecedented nature of recent events.

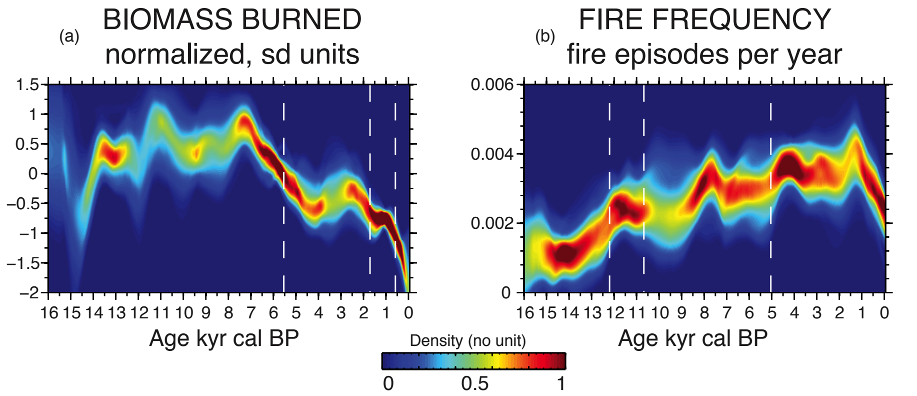

Figure 3: Density distribution of **(A)** biomass burned and **(B)** fire frequency proxies for 16 high-resolution records of south-western Europe (adapted from Vannière et al. 2016b). The colors represent the density of the proxy site-records at each time step; cold (blue and green) colors are indicative of highly dispersed data and thus capture the heterogeneity among sites; hot (yellow to dark red) colors indicate sites with homogeneous responses and thus spatial uniformity. The white dashed lines separate time periods with significant differences in the proxies' mean and variance. Ages are expressed in calibrated kiloyears before present (1950 CE).

Considering the amplitude of past climate changes and the occurrence of hundreds of major cultural transitions around the world, the paleofire community has much to add to these discussions, yet what makes forest fires gain media attention worldwide today is the socio-ecological context in which they occur. The expansion of private and commercial properties and infrastructure into the wild-land–urban interface all but ensures future clashes between large-scale wildfires and an expanding human population. In addition, modern land management and resource exploitation, far removed from traditional land-use systems, has abruptly changed rates of fuel accumulation and fuel structure, often leading to fire-prone conditions in anthropogenic landscapes.

As an example, on the island of Corsica in the Mediterranean Sea, Lestienne et al. (2020) coupled data and models to show that currently, and likely for the first time in the Holocene, the fire regime is constrained by both climatic and anthropogenic factors. Climatic conditions may lead to events similar to the maxima in the paleofire record, but human activities may also increase their frequency. Moreover, these events will take place in very different ecosystems than in the past that are possibly not adapted to such events, therefore posing different levels of risk. At the beginning of the Holocene, summer climatic conditions promoted an extended fire season and large fires in pine forests. About 7000 years ago, climatic conditions became much less favorable for the natural spread of fires, and human land uses explain the recorded fire events. Today, based on the same criteria and markers, it appears that the conditions and length of the summer drought season are reaching levels equivalent to those at the beginning of the Holocene and may exceed them in the coming years. In addition to this, human pressure on ecosystems, as we know them today, is far greater compared to the beginning of the Holocene.

Summary and outlook

Over the past decade, the GPWG has contributed to the international community effort to understand present fire patterns in the context of the long-term changes, with:

- estimates of baseline trends and variability in fire regimes on orbital to decadal timescales and at regional to global spatial scales;
- the online sharing and public dissemination of all fire history data collated at https://database.paleofire.org;
- data-model integration studies that have been used for future projection assessment based on long-term archive observations;
- the different roles of climate, humans, and vegetation as the co-drivers of past fire regimes;
- the development of projects that addressed challenges in conservation, restoration, and biodiversity maintenance under changing climate and land-use conditions;
- the growth and advancement of early-career paleofire scientists; and
- an emphasis on improving the dialog with fire managers and sustainable fire management practices.

Several key challenges remain for the global paleofire community. Many regions of the world remain insufficiently documented in terms of fire history and changing fire regimes through time (for example equatorial Africa and tropical environments). These knowledge gaps require further research to better inform the response to future environmental challenges in terms of how these systems will evolve with management that either includes or excludes policies regarding fire. The paleofire community must intensify efforts to identify knowledge gaps and promote research in critical regions of future change. Stimulating additional paleofire data generation, data synthesis, and novel research are imperative across the following themes:

- Investing in resources to implement new fire-proxy calibration in underrepresented regions, for example by promoting research activities and network building in Asia or Africa;
- A concerted effort of cross-disciplinary integration to promote more diverse knowledge for environmental policy assessment, particularly focusing on local/Indigenous knowledge (Colombaroli et al. 2019);
- Improving our understanding of global fire variability and impacts by integrating the existing fire database (https://database.paleofire.org) with modern observations in a way that can be accessed by other non-specialists, including ecosystem managers and policy makers.

As the paleofire community moves forward, more investment in programs similar to PAGES' recently launched DiverseK working group (pastglobalchanges.org/diversek), which will pursue initiatives related to recent GPWG activities (Colombaroli et al. 2018), is critical. Finally, the PAGES-endorsed International Paleofire Network (https://paleofire.org; Adolf et al. 2020) will make significant contributions toward addressing these challenges in the coming years.

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Obituary: Govind Ballabh Pant (1945–2020)

Rupa Kumar Kolli

Dr. Govind Ballabh Pant passed away suddenly on 18 November 2020. Govind was an outstanding scientist and science leader with a wide range of contributions across the whole climate spectrum, from paleoclimate to future climate scenarios. Govind served as a member of the PAGES Scientific Steering Committee from 1997 to 1999 and played a key role in building and nurturing a strong PAGES community in South Asia.

Govind worked at the Indian Institute of Tropical Meteorology (IITM) in various capacities for more than three decades, including as Director from 1997 to 2005. After his retirement from IITM in 2007, he returned to teaching as a Visiting Professor at the School of Environment and Natural Resources at Doon University, Dehradun, India, and subsequently as a Distinguished Professor in the Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune, India.

Govind's research interests included atmospheric energetics, monsoon dynamics, the ENSO-monsoon relationship, seasonal prediction, climate and climate change, and especially paleoclimatology. He was a fellow of the Maharashtra Academy of Sciences and the Indian Meteorological Society (IMS) as well as the recipient of the K.R. Ramanathan gold medal of the Indian Geophysical Union and an IITM Silver Jubilee award. He was the principal author of two books: *Climates of South Asia* and *Climate Change in the Himalayas*. Along with having served as the President of the IMS and as a member on the editorial boards of many research journals including the *International Journal of Climatology*, he contributed to many national and international bodies in climate science and published numerous research papers in reputed scientific journals.

Govind's international leadership contributions to the International Geosphere Biosphere Programme (IGBP), World Climate Research Programme (WCRP), Intergovernmental Panel on Climate Change (IPCC) and PAGES are highly acclaimed. Govind was associated with the IPCC right from its inception and was the first Indian climate scientist invited to contribute to the First Assessment Report. He continued to support the subsequent assessments and served as the review editor for the Fourth Assessment Report of IPCC WGI in 2007; he received a certificate of appreciation from the IPCC for his contribution to the report when the Panel was awarded the Nobel Peace Prize in 2007. Govind made special efforts to promote these international programs within the Indian scientific community, including through organizing meetings of the governing bodies of PAGES, WCRP and IGBP at IITM. He hosted a PAGES SSC meeting in February 2000, which was attended by the entire PAGES leadership at that time, along with a PAGES workshop on South Asian paleoenvironments.

Trained in tree-ring labs in Tucson and Palisades, USA, under a UNDP fellowship, Govind established the first dendroclimatology laboratory in India at IITM in 1982 and built a multi-institutional team to reconstruct monsoon variations over the past few centuries with an interannual resolution. He passionately nurtured it over the years, and it grew into a leading international leading dendroclimatology laboratory. He also played a pivotal role in bringing the paleoclimatological community closer to the meteorological community, which facilitated a more consolidated view of the entire spectrum of climate variability across India.

Govind published pioneering work in 1981 on the quantitative evaluation of the relationship between the Southern Oscillation and Indian summer monsoon rainfall. His visionary contributions to climate change research at IITM led it to be recognized internationally as an authentic source for global and regional climate change projections. In fact, the seeds for the establishment of the Centre for Climate Change Research at IITM were sown during the implementation of the Indo-UK program of research in which he secured two high-profile projects for IITM.

Govind's international network is far and wide, and he will be remembered more as a dear friend than as a professional collaborator. His sudden passing is certainly a great loss to the climate community, particularly to the dendroclimatic community in India. Govind leaves behind his wife Gita, son Saurabh and daughter Aparna, who played host to many a climate scientist and provided a unique family touch to his collaborations.

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Memories ...

Many thanks to everyone from the PAGES community who contributed their stories and photos from days of yore! Enjoy taking a short walk down PAGES' Memory Lane.

Where it all began ...

Anne-Christine Clottu Vogel, former SCNAT Secretary General

PAGES was indeed launched in 1991, but the strategic meetings leading to the creation of PAGES took place in 1988. Hans Oeschger, the University of Bern, the Swiss National Science Foundation (SNSF) and the Swiss Academy of Sciences (SCNAT) played an important role together with IGPB and ICSU. I remember the very first preparatory session for the launch of PAGES in July 1988, in the "Haus der Universität", because I was invited as an SCNAT representative and as a collaborator of Hans. He was the first co-chair of PAGES (with Herman Zimmerman of US NSF). From the beginning, PAGES was supported in Switzerland due to the personality and fame of Hans, who endorsed its importance. He was also the key to American engagement. It is wonderful that SCNAT and the University of Bern have continued to bring PAGES to life for 30 years with the support of Swiss federal funds. PAGES still has a major scientific role to play at a time when memory and the long term are less considered.

Figure 1: May 1995, in front of the old PAGES International Project Office, on the Barenplatz, Bern, Switzerland. PAGES people in the photo are: Herman Zimmerman (PAGES Co-Director; left), Rosenda Teta (PAGES Secretary; next to Zimmie), and visiting guest scientist Steve Colman (right) (Image credit: Steve Colman).

Figure 2: Workshop participants of the PEP meeting "Late Quaternary Paleoclimates in the Americas", 30 September – 2 October 1993 in Panama City, Panama. A young Marie-France Loutre (second from the left) attended as a PhD student; little did she know at the time that she would return to PAGES 22 years later to join the International Project Office staff as Executive Director!

Workshops fuel publications

Michael N. Evans, PAGES SSC 2016–2021, co-chair 2018–2020

PAGES workshops often reflect hospitality and scientific dedication that transcend their shoestring budgets, and produce results long after they convene. I remember the PAST2K/PMIP3 workshop in Madrid in November 2013, hosted by Laura Fernandez, Elena Garcia and Fidel Gonzalez-Rouco. The workshop began daily with strong coffee and homemade pastries. It included personalized, handmade, reusable nametags, nightly dinners bursting with further discussion at our hosts' favorite local restaurants, and a most memorable facilitated bilingual public outreach event. The discussions fueled at least three subsequent PAGES publications, any number of offshoot collaborations, and great ideas for hosting workshops in a similarly warm and productive way.

Figure 3: Workshop attendees at the memorable Madrid workshop in 2013 (Image credit: Davide Zanchettin).

Table dancers in South Africa
Heinz Wanner, PAGES co-chair 2005–2010

In May 2008, the PAGES SSC and EXCOM held its annual meeting in Cape Town, South Africa, and contributed to the 4th IGBP Congress. After several long sessions, the participants enjoyed a fantastic evening reception in a huge tent in the countryside. After a fine meal, enriched with superb South African wine, several PAGES members met on the dance floor in front of a talented local band. Without any doubt the highlight was reached when prominent PAGES members (precisely said: only men – and not the youngest!) started their show as more or less elegant table dancers, cheered on by the whole IGBP audience.

Figure 4: Who do you think danced on the tables?! PAGES SSC members at the 2008 meeting in Cape Town.

In memory of Mohammed Umer
Pierre Francus, PAGES SSC 2007–2012

The picture is dedicated to the memory of Mohammed Umer who was a member of the PAGES Scientific Steering Committee between 2006 and 2011. Mohammed was not lucky when traveling to SSC meetings. He was seldom in time, and almost never succeeded in arriving at the right place. His luggage was frequently lost. However, eventually, Mohammed always made it to the meetings. His kindness and wisdom will be remembered by many.

Figure 6: Mohammed Umer (1959–2011), PAGES SSC 2006–2011.

Figure 5: Serious science being done at the beachfront during the 4th PAGES OSM in Goa, India.

PAGES defined my research outlook!
Thamban Meloth

My cherished involvement with PAGES was initiated with my participation at the first Swiss Climate Summer School at the beautiful village of Hasliberg in July 1999. I was one of the eight early-career researchers who were generously supported by PAGES and START, under an initiative called REDIE. It was one of the most memorable summer schools I have ever attended. The interactions I had at the school opened up a world of opportunities and cemented my relationship with PAGES. My continued involvement with PAGES meetings and the 2k Network led me to organize the 4th Open Science Meeting in Goa in 2013. What an exotic meeting it was!

Years of collaboration
Lucien von Gunten, PAGES Science Officer 2011–2019

Choosing only one special memory, from the more than eight years I had the chance to work for PAGES, is truly impossible. But what was always present in memorable occasions were the marvelous people, and this feeling that all just came together in a magic PAGES moment. This was regularly the case when different scientific communities met, sometimes for the first time, to work on a common goal. The excitement of the participants at the prospect of all the new opportunities for joint projects unfolding during the meeting was exhilarating and often laid the base for long-lasting collaborations.

Figure 7: Lucien von Gunten attended many memorable workshops and meetings during his time as Science Officer for PAGES.

Long-lasting connections
Antonio Maldonado Castro

In 2005, two Chileans were granted a scholarship by PAGES to attend the 4th International NCCR Climate Summer School in Grindelwald, Switzerland. For me, the experience was unique, even though my English level was not very high, so I could not take full advantage of the experience, but some of the networks I formed there are still in place. Everything that opened my mind to that experience, I wanted others to have, so we organized two courses/workshops in South America, financed by PAGES, focused on students from South America, but bringing world-class researchers to Chile.

Figure 8: Duncan Christie and Antonio Maldonado Castro in the Swiss Alps (Grindelwald). Image credit: Antonio Maldonado Castro.

On the occasion: PAGES' 30th birthday
Michael N. Evans

Probabilities:
Yesterday for what can be:
Not indicative.

Forced change is one thing;
But the climate meanders
On top of that: fact.

Climate system is
Coupled and nonlinear
Add people and stir.

Persistence of risk:
Memory, slow processes.
Cascades and overlays.

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Former co-chairs reminisce about their tenure

What makes PAGES unique?

Bob Wasson (SSC, Vice-chair 1991-1996): My answer to this question lies in the history of attempts to get modernist scientists interested in the paleosciences. I have spent much of my career trying to get historical perspectives into natural resource management. I have had some success, but modernist scientists seem to think that all the history that is needed exists in instrumental records of a few decades in length. And now we have some saying that because of climate change, the past is no longer relevant to the future. This was recently claimed about the extreme bushfires in Australia in 2019/2020 because they are unprecedented. But without a long history how do we know they are unprecedented? And even if they are, histories provide the only means of assessing changes and their causes over sufficiently long periods to capture the full range of variability and which can be used to test forward-looking models.

I was drawn to PAGES because it was different. In traditional Quaternary research the international community was organized within INQUA (https://inqua.org), but to me that organization was valuable only for the paleoscientific community. It was not, as far as I could tell, well connected to modernist science or to decision making. This is where I saw PAGES playing a role, and it has.

Tom Pedersen (SSC, Co-chair 1994–2002): From its outset, PAGES worked hard to embrace connectivity among scientists from all corners of the globe. It reached beyond the more typically dominant Northern-Hemispheric pool of paleoscientists to tap talent in developing countries, particularly in the global south. Plus, it vigorously promoted and encouraged the participation of young developing-country scientists in PAGES-supported research and workshop activities. Such efforts were rooted in a firm two-pronged recognition that the phrase "Global Changes" in the PAGES acronym conveyed importance both geographic AND social. I think the PAGES community saw the need to bring all corners of the planet to the table to map not just paleoclimatic data but also the impacts of both short and long-term climate changes on the evolution of species (including *H. sapiens*).

Julie Brigham-Grette (SSC 2000–2008, Chair 2004–2008): PAGES is unique in bringing together diverse minds, cultures, training, and expertise to the scientific issues, especially documenting how knowledge of past climate change informs the Earth systems' approach to understanding our future. PAGES has unified paleoclimate scientists into a global network, loaded with positive space for collaborations.

Heinz Wanner (SSC, Co-chair 2005–2010): Above all, it is the unique collaboration between enthusiastic scientists of many different disciplines with different interests and different careers: experimentalists and modelers, geoscientists, physicists, chemists, biologists, environmental historians, socio-anthropologists, etc. The format with focused workshops, the edition of white papers and joint publications as well as the organization of field experiments and modeling activities is a great success. An additional strength and success is the inclusion of young scientists from all around the globe. This also guarantees a long-lasting and sustainable collaboration and network.

Without any doubt the high-standard *Past Global Changes Magazine* (earlier called *PAGES news*) brought people together in order to promote new ideas and new projects. The fact that this magazine is usually focused on a specific topic that is addressed by short, high-quality articles arouses the interest of a wide readership.

Hubertus Fischer (Co-chair 2011–2016): For me the uniqueness of PAGES comes from its interdisciplinary and bottom-up nature. It is thanks to the sense of responsibility of the PAGES researchers for safeguarding our planet, paired with their strong curiosity, that they again and again came up with and tackled frontier research questions that are located within the large range of the triangle of climate change, environmental response, and human action. Moreover, most of the working groups and their members have been open to other perspectives from outside their own area of expertise, which made truly new knowledge generation possible. This is reflected by the large range and interdisciplinary composition of the many working groups that PAGES supported over the last 30 years. The large number of new ideas made the life of the PAGES Scientific Steering Committee members easy, as the science plan developed naturally without losing its direction to contribute to the recent global change question. On the other hand, it made the life of the members difficult as they had to choose from a large number of excellent working group proposals to make best use of the limited financial means of PAGES. Looking back at the amount of top-notch science that emerged, its impact on global change knowledge using a rather small amount of money is huge. PAGES has definitely been one of the most successful enablers of science.

Sherilyn Fritz (SSC 2012–2017, Co-chair 2016–2017): PAGES' flexible structure for facilitating community-driven science makes it unique. This structure has allowed PAGES and the PAGES community to adapt, grow, and evolve as the scientific questions and tools of paleoscience have evolved over time.

Figure 1: PAGES Scientific Steering Committee in Naivasha, Kenya, July 2004. L to R: João Morais (IGBP), Carole Crumley, Christoph Kull, Jérôme Chappellaz, Leah Witton, Rick Battarbee, Frank Sirocko, Dan Olago, Julie Brigham-Grette, Peter Kershaw, Rosemarie Otieno, José Martinez, Pinxian Wang, Olga Solomina, Ricardo Villalba, Ashok Singhvi.

Figure 2: PAGES Scientific Steering Committee in Cape Town, South Africa, May 2008. Front (L to R): José Carriquiry, Jérôme Chappellaz, Bette Otto-Bliesner, Heinz Wanner, Cathy Whitlock, Julie Brigham-Grette, Pierre Francus, Eric Wolff; middle: Mohammed Umer, Olga Solomina (IGBP); back: Michael Schulz, Thorsten Kiefer, Ricardo Villalba, Peter Kershaw, Takeshi Nakatsuka, Louise Newman, John Dearing, João Morais (IGBP).

What has been PAGES' most significant accomplishment over the past 30 years?

Bob Wasson: The provision of high quality paleoclimatic records as test beds for global models is one accomplishment. The value of such research has recently been highlighted in Tierney et al. (2020). It is also noteworthy that within a global change program, PAGES has tried to put equal emphasis on climate change and land-use/land-cover change, but often the former won the lion's share of attention. However, I note that in the current science structure humans play an equal role with climate and environment, but I wonder if they really do receive equal attention.

Tom Pedersen: Back in the '90s and early 2000s, I'd say that PAGES' most significant contributions in its first decade were at least threefold:

- PAGES quickly became a "go to" body for scientists from developing countries who sought to contribute to the international community but who had difficulty in finding a pathway in. PAGES helped to open that pathway and in doing so it elevated the importance of developing-country scientific efforts in helping us understand how the Earth has worked.
- In the mid-1990s PAGES set out to produce a high-quality science-focused newsletter which is much more than just a newsletter – it's a freely accessible publication of high quality that presents leading-edge science. While not carrying the heft of a peer-reviewed journal, it does present a plethora of scientific insights to the global community and it does so at no cost to the community. Thus, it's a particularly valuable resource in developing countries. Moreover, it very often gives scientists in those countries a venue for publication that would otherwise be less open to them. There is great value in that, value that continues to this day.

I'll add a wee anecdote here from the mid-1990s. I remember that when we were discussing how best to strengthen what was the *PAGES news* (later renamed *Past Global Changes Magazine*), we agreed that we would never (make that NEVER!) include photographs of SSC members holding wine glasses at some sort of reception at a conference. Other international scientific and social-scientific bodies at that time also produced newsletters, but too often – at least in the view of those of us on the SSC at the time – their lead newsletter page featured a photo of some wine-glass-holding participants that looked like they were at a well-heeled soiree. We agreed that such photos send the wrong message, and we decided instead to put some insightful or thought-provoking scientific image on the front page. That approach was more in keeping with what we saw then as the PAGES philosophy. I think that perspective continues to prevail.

- A major contribution in the early days was the effort to support attendance of young scientists from developing countries at workshops, summer schools and conferences. We put significant resources into that effort and I'd like to think that it helped to launch the careers of young scholars by introducing them to international scientific networks and face-to-face dialog in their fields. I don't have hard evidence to support this contention but I hope it's a fair extrapolation.

Julie Brigham-Grette: PAGES has played a key role in driving shared scientific products that inform the IPCC process. It's important to remember that IPCC assessments did not always have a paleo-rich chapter, but the baseline perspective provided by paleodata spoke for itself. PAGES has fostered the development of syntheses across a variety of both spatial and temporal scales in paleoscience, driving model improvements and collaborative model development. It has also seeded international diplomacy, scientist to scientist, with capacity building and networking in countries where science is not well supported.

Heinz Wanner: Due to the aforementioned collaboration of a broad interdisciplinary community, PAGES was able to ask scientific questions of high significance and interest. With the slogan "exploring the past to understand the future" PAGES launched a number of very successful and projects with high impact. In the early years of PAGES, it was the Pole-Equator-Pole (PEP) initiative. Several joint publications bear witness to the fundamental work within PEP. In recent years, several PAGES projects were very successful and have also had a large public impact, e.g. SynTRaCE-21, Past Interglacials (PIGS), and the PAGES 2k Network.

Hubertus Fischer: The overarching objective of PAGES was and is to shed light on the ongoing anthropogenic climate and environmental changes from a paleo perspective. This is based on the recognition of the early PAGES heroes (such as Hans Oeschger, John Eddy, Herman Zimmerman, and many others) and the PAGES science plans over the last 30 years that many of the Earth system processes act on timescales that are much longer than the direct instrumental record, in particular when it comes to the ocean, ice sheets, and global biogeochemical cycles. Thus, true sustainability research cannot be accomplished without the paleo perspective. Accordingly, I think the largest accomplishment of PAGES is that it was at least instrumental, if not essential, for paleoscience to become a fully recognized and integrated part of climate change sciences over the last 30 years, which made tremendous contributions to our understanding of Earth system processes. Unfortunately, all of this paleo knowledge essentially implies that the Earth system cannot by itself provide sufficient negative feedbacks to the anthropogenic greenhouse gas effect to guarantee a safe operating space for sustainable human action without strong mitigation as well as adaptation measures.

Sherilyn Fritz: PAGES' accomplishments include

- multiple high-impact synthesis products that address broad-scale and important science questions; and
- an increasingly interconnected, diverse, international paleoscience community.

What should PAGES do in its 4th decade?

Bob Wasson:

- Many of the questions PAGES set out to answer will engage international science for years to come, especially in the development of better paleoclimatic records and explanations of their variability. Much progress has been made in producing high-resolution records and this needs to continue, particularly focused on rapid change and extreme events. The latter has direct societal relevance as environmental disasters continue to increase worldwide. But disasters only occur when hazards such as floods and cyclones affect people. This means that social science and human history need to be involved in any work on long records of hazards and the disasters that result when people are vulnerable and exposed.
- The current science structure gives some attention to the links and feedbacks between components of the Earth system. From my experience such an approach requires an analytical framework that obliges individual researchers to commit to a cohesive analysis. If such a framework is not available, all you end up with is juxtaposition of skills with little dynamic interaction. For me system dynamics is the ideal framework.
- It is my view that many in the Quaternary community apply a naïve determinism when correlating societal change with paleoclimatic or, more generally, paleoenvironmental change. The criticism of the idea of societal "collapse" underscores this point, suggesting that transformation occurs when climate change or resource depletion force societal change. For scientists with no training in the social sciences or history, to declare that correlation is causal without serious analysis does our field no favors. Recent ideas about how to analyze relationships between environmental and societal change can be found in an article by White and Pei (2020). PAGES needs to find ways to make this field of research more sophisticated, in the first instance by including social scientists and historians in the SSC.
- While I was associated with PAGES, we tried very hard to fill some of the spatial data gaps, particularly in Africa and Asia, but with limited success. This effort needs to continue.
- If PAGES is to meet its full potential it must be welcoming to social scientists and historians, including, particularly, environmental historians. The current SSC has no social scientists or historians, but I acknowledge that such disciplines have been involved in PAGES activities in the past. But without such voices in the SSC, I suggest that PAGES cannot expect to fully cover its scientific program and therefore realize its full potential.

Tom Pedersen: It might be facile, but I'd have to say, "Stay the course." PAGES has much of which it can be proud. It is justifiably highly regarded in developing countries and it has filled a need that otherwise might not have been filled. There is one other point I'd like to make. PAGES has been continually supported by Switzerland (which I salute). But where is support from other developed countries? Back in the '90s we had a strong ally in the US NSF (Herman Zimmerman) who as program director recognized the value of international networks in science. When he stepped down in 1996, PAGES lost a key ally, and I remember having to deal with NSF program directors after him who, frankly, held provincial views that constrained their willingness to recognize that global-change science was actually, well, global, and not just American. The Americans weren't alone – I had trouble in Canada as well in those days in trying to convince our government to meet the challenge. I'm still embarrassed by that; worse, it hasn't changed.

So, I think a big challenge for PAGES in its fourth decade is to broaden its support base. That will be even more difficult in the post-coronavirus-recovery era, but being difficult doesn't mean progress can't be made. It will require sustained high-level diplomatic effort. That's a big challenge for any SSC but it's one worth pursuing.

Julie Brigham-Grette: Continue with outstanding working groups and focused projects (discovery science) but also don't be afraid to develop a framework for actionable science that others can use for policies. We must also be an international community for change, adapting JEDI principles of justice, equity, diversity, and inclusion.

Heinz Wanner: Let us again focus on exciting (and also longer-term) projects involving proxy people and modelers. The collaboration with the PMIP-CMIP community is important. It makes sense to concentrate on important past time periods that offer insights into key processes of the climate system. We should not be too modest and also launch large projects and programs. Beyond EPICA Oldest Ice (beyondepica.eu) is such a lighthouse project.

Hubertus Fischer: This is probably the most difficult question. Of course PAGES could and will continue to produce frontier paleoscience results in the field of climate change research. However, while the ever-increasing need for immediate action to mitigate climate change requires knowledge transfer to practitioners and policy makers, many of the PAGES working groups and experts are strongly rooted in academia and less so in applied science. The challenge for PAGES will therefore be to bridge from its strong roots in natural sciences to its application without losing its scientific credibility. As an example, I point here to climate-related ecosystem changes that are required in forestry and agriculture to warrant a sustainable use of natural resources and ecosystem services. Unfortunately, the paleo knowledge of sustainable ecosystem use is not (always) in line with current practice or apparent economic needs, as long as such ecosystem services and the costs for sustainable use are not included and remunerated. In essence, the challenge for PAGES will be to not lose its scientific strength while at the same time not retreating into the academic ivory tower – a task that is especially challenging for early-career scientists who still have to establish themselves on the science stage. I wonder what instruments PAGES as an organization can offer to build this bridge.

Sherilyn Fritz: PAGES should continue to foster innovative interdisciplinary community-driven science syntheses.

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Figure 3: PAGES Scientific Steering Committee in Cluj-Napoca, Romania, May 2016. Front (L to R): Lucien von Gunten, Hubertus Fischer, Katrin Meissner, Mike Evans, Hugues Goosse. Back: Cristiano Chiessi, Claudio Latorre, Darrell Kaufman, Marie-France Loutre, Dave Carlson (WCRP), Sherilyn Fritz, Asfawossen Asrat, Pascale Braconnot, Blas Valero-Garcés, Lindsey Gillson, Peter Gell, Michal Kucera.

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Highlighting the future of past global change research

Stella J. Alexandroff[1], A. Bonk[2], M.J. Mette[3] and T. Trofimova[4]

Early-career researchers (ECRs) are an important driving force of past global change research and often responsible for the bulk of data production and scientific output. ECRs of today also play a major role in shaping the future of science as they advance in their careers toward leadership positions. It is therefore in the interest of the community to enable ECRs to develop their full potential. Yet, ECRs across the globe tend to work under precarious conditions, lacking visibility, opportunity, and recognition amid an uncertain job market. Ways to support them include setting up networking and collaboration opportunities, providing training, and sharing advice on how to navigate the science world within and outside of academia. In addition, an important effort we can make as a community is to recognize and highlight the value of the work ECRs are doing today.

Over the course of the past 30 years, PAGES has been increasingly proactive in providing opportunities for ECRs. For instance, a large portion of financial support for PAGES' meetings is now designated for ECR attendance, particularly for those from developing countries, to encourage their participation in working groups (WGs). Perhaps the best example to illustrate the efforts by PAGES to support ECRs is the Young Scientists Meeting (YSM). Starting in 2009 and occurring every four years, the YSM brings ECRs from different parts of the world together to provide training and networking opportunities. It was at the third YSM (Zaragoza, Spain, 2017) that discussions about the need for stronger ECR representation within PAGES led to the creation of the PAGES Early-Career Network (ECN). The ECN officially launched in 2018 with the main goals of connecting ECRs to promote the exchange of ideas and skills, and to provide a framework for community support and collaboration.

The articles in this section illustrate advances in past global change research by ECRs active in the PAGES community. The individual contributions were selected in an effort to represent the diversity in scientific scope and geographic distribution of PAGES' members.

The first eight contributions in this section summarize recent developments and findings in original research. Grant and Naish kick things off with a visit to the Pliocene and new estimates for global sea-level variability and ice-volume sensitivity (p. 34). Next, King and Tetzner explain how novel ice-core proxies in the form of marine-sourced organic compounds and diatoms can improve our understanding of sub-Antarctic climate (p. 36). From here, we move to the Northern Hemisphere, where Chaudhary assesses peatland carbon dynamics across the pan-Arctic and its potential effects on climate (p. 38), while Liang et al. share recent advances in eolian processes and landscape dynamics research in Chinese deserts (p. 40). Three contributions present the multifaceted applications of lake sediments – from erosion patterns and flood chronicles in Europe (Rapuc et al. p. 42), to baselines for conservation efforts in Mount Kenya (Omuombo p. 44), to the question of the onset and magnitude of human influence in central Chile (Fuentealba et al. p. 46). Lawman et al. conclude the original data contributions with a look into coral proxy system modeling and the fidelity of tropical Pacific corals as archives of ENSO variability (p. 48).

The final two articles demonstrate excellent ways for ECRs to collaborate and advance their respective research fields. In an elegant metadata analysis, Kaushal et al. assessed the availability of terrestrial Indian paleoclimate records to identify data gaps and list recommendations on how these can be improved (p. 50). In the closing article of this section, Mette et al. describe their experience coordinating a horizon-scanning project in which they defined priority research questions in the field of sclerochronology with input from the research community (p. 52).

For ECRs, it is particularly important to build a track record of international collaborations beyond their own research departments. This can seem like a daunting task for those who have yet to establish a wide research network or access to ongoing projects. Fortunately, PAGES and the PAGES ECN provide organized structures that lend themselves to establishing international science projects. The potential for high-impact and cutting-edge research coordinated and driven by ECRs within PAGES is growing, and will no doubt continue to do so in future generations.

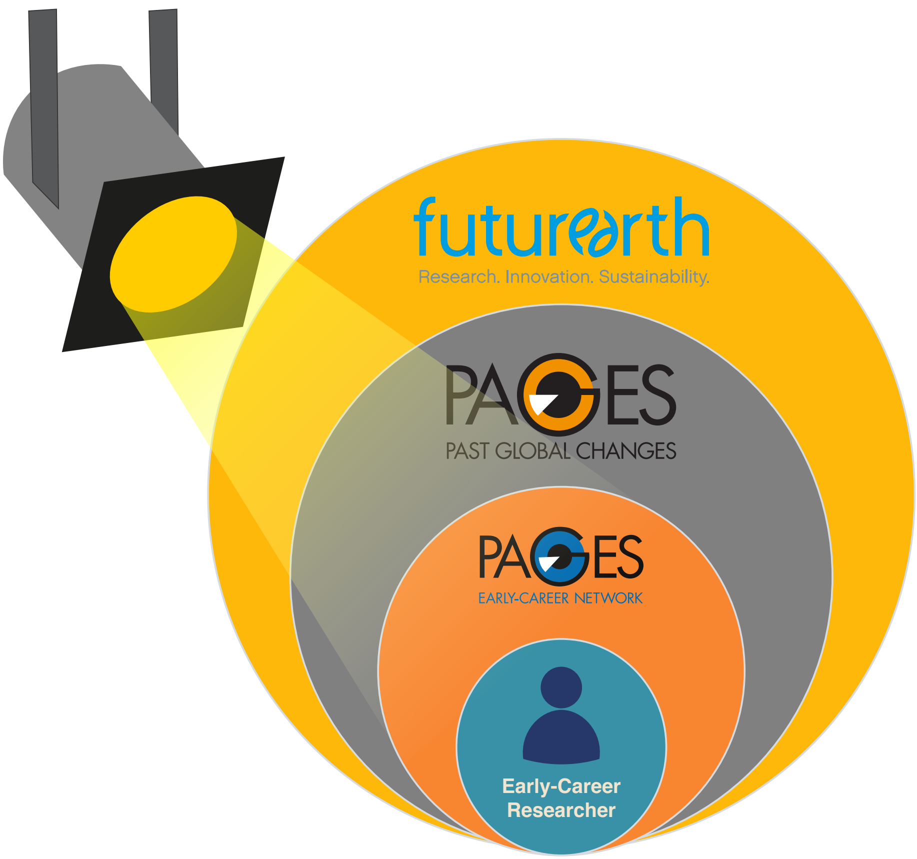

Figure 1: Early-career researchers are an important part of the PAGES community. This special section of the magazine puts a spotlight on their work.

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Pliocene sea level revisited: Is there more than meets the eye?

Georgia R. Grant[1] and Tim R. Naish[2]

We reassess available studies of mid-Pliocene sea level and provide new estimates. The relative amplitude of glacial-interglacial sea-level variability was likely between 6.2 m (16th percentile) and 16.7 m (84th percentile), leading to an average ice-volume sensitivity of 4 m/°C sea-level equivalent.

The mid-Pliocene warm period (MPWP), 3.3–3 million years ago, is the most recent time when Earth's climate reached equilibrium under atmospheric CO_2 concentration of ~400 ppm, with global temperatures 2–3°C higher than during the pre-industrial era (1750 CE; Masson-Delmotte et al. 2013). Sea-level reconstructions for this period suggest peak interglacial sea levels were up to 40 m above present (e.g. Dutton et al. 2015), implying loss of the Greenland, West Antarctic, and marine sectors of the East Antarctic ice sheets, as well as partial loss of the terrestrial East Antarctic Ice Sheet.

Peak magnitude vs relative amplitude

Reconstructions of peak MPWP interglacial sea level are usually reported as global mean sea level (GMSL) with reference to the Holocene. While peak GMSL provides insight into the volume of polar ice-sheet loss and the magnitude of sea-level rise that might be expected because of near-future climate change, it does not capture the full amplitude of glacial-interglacial ice-volume change (Fig. 1), or the full amplitude of sea-level change in response to climate forcing, which may lead to an underestimation of ice volume sensitivity (defined here as the change in sea level equivalent (SLE) of ice volume (m) per 1°C of temperature change). For example, calibrations of the benthic $\delta^{18}O$ proxy of global ice volume and sea level (e.g. Lisiecki and Raymo 2005) place the sea level during many Pliocene glacials below that of present-day, implying larger-than-present ice-sheet configurations at the beginning of deglaciations. This has significant implications for estimating both the amplitude and rate of sea-level rise in response to relatively small amounts of global warming.

We have categorized "continuous" sedimentary sequences used in reconstructing the amplitude of MPWP GMSL into "direct" (e.g. geologic) and "indirect" (e.g. calibrations of foraminifera $\delta^{18}O$ curves; Fig. 1; Fig. 2a). We compare these glacial-interglacial amplitudes with estimates of the peak MPWP GMSL derived from "direct" but "discontinuous" geological remnants preserved in the far field (e.g. paleo shorelines). In addition, we use ice-volume constraints provided by polar continental margin drill cores (Fig. 1; Fig. 2b). Finally, we provide a quantitative reassessment of peak GMSL and the amplitude of glacial-interglacial global sea-level change during MPWP.

Where the uncertainty lies

Many of these peak GMSL estimates have not been corrected for regional deviations due to tectonics, glacio-isostatic adjustment (GIA), or dynamic topography. Deformation of the Earth may cause local sea-level changes large enough to either cancel out or double the amplitude of the ice-volume contribution (Raymo et al. 2011). Although some recent studies have attempted to correct for these regional effects, significant uncertainty remains concerning the role of dynamic topography (Rovere et al. 2015; Dumitru et al. 2019).

Deep-ocean foraminiferal $\delta^{18}O$ records provide one of the most detailed proxies for glacial-interglacial climate variability during the Pliocene; however, the signal is affected by ocean temperature, ice-sheet $\delta^{18}O$ composition and ice volume (Lisiecki and Raymo 2005). Several studies have used Mg/Ca paleothermometry to calibrate benthic $\delta^{18}O$ records (Dwyer and Chandler 2009; Sosdian and Rosenthal 2009; Miller et al. 2012; Miller et al. 2020). Another approach incorporates sill-depth and salinity changes from the Mediterranean to calibrate sea level in a planktic $\delta^{18}O$ record (Rohling et al. 2014), but large uncertainties (>±10 m) remain. On the other hand, sea-level calibrations of the benthic $\delta^{18}O$ record, constrained by backstripped continental margins (sedimentary sequences that have tectonic subsidence and compaction effects removed; e.g. Naish and Wilson 2009; Miller et al. 2012; Miller et al. 2020), are often hampered by the limited precision inherent to foraminiferal paleodepth indicators and the influence of sediment erosion during sea-level lowstands, leading to underestimation of the full amplitude of sea-level change.

In contrast, Grant et al. (2019) derived a continuous but floating sea-level record

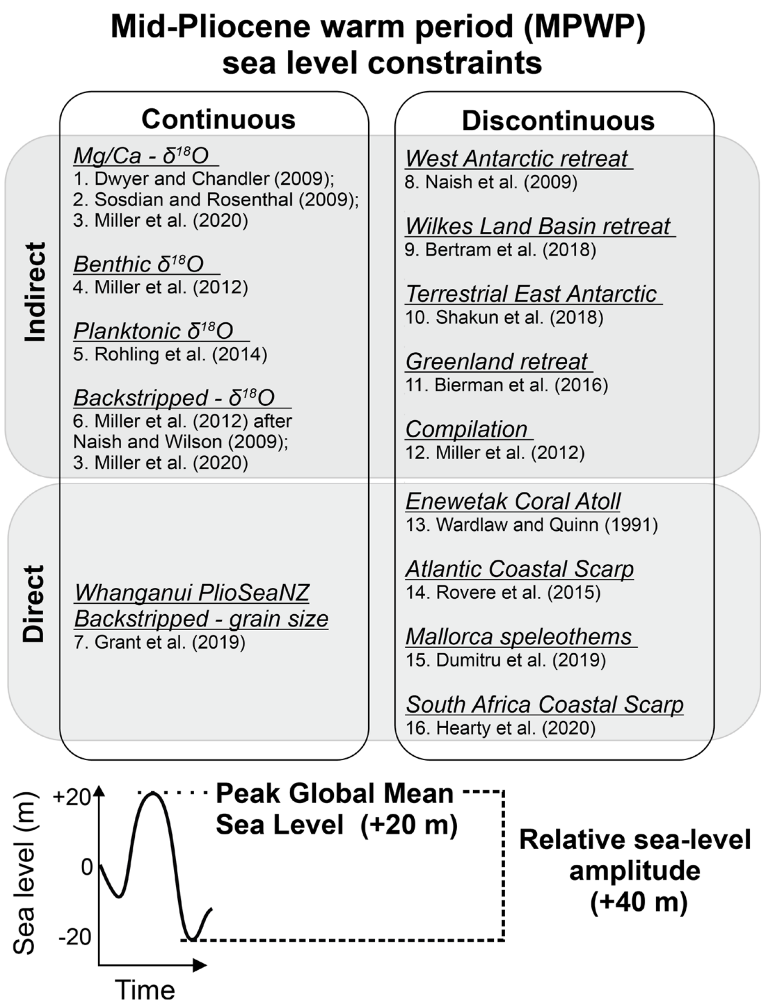

Figure 1: Studies of MPWP sea-level estimates (shown in Fig. 2) are placed into four categories. The schematic sea-level curve illustrates the difference between peak GMSL as a single point referenced to a datum, and relative amplitude of sea-level change over the glacial-interglacial range.

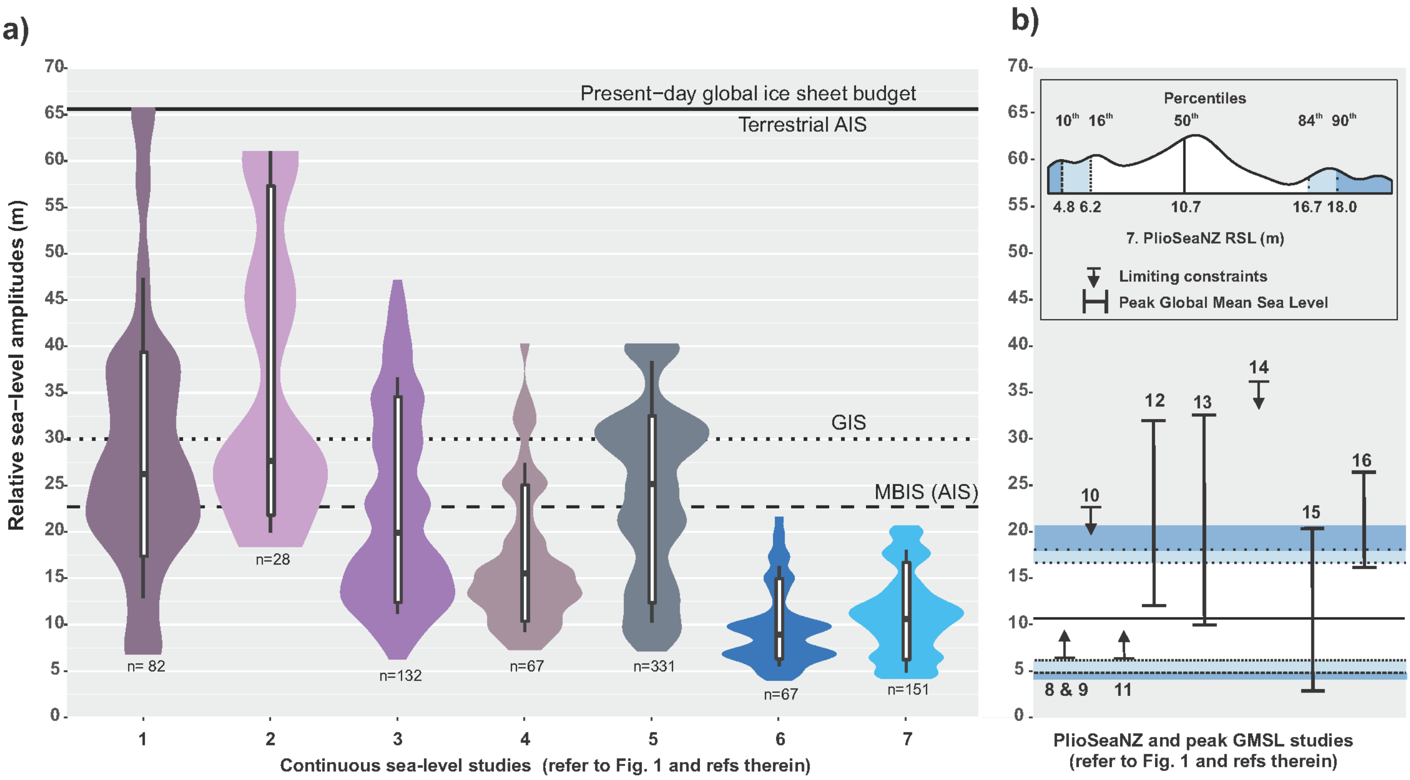

Figure 2: (A) Frequency distributions of relative sea-level amplitudes for continuous studies of the MPWP with box and whisker plots for the 10th, 16th, 50th, 84th, and 90th percentiles with cumulative sea-level equivalent shown for marine-based ice sheets (MBIS) of Antarctic Ice Sheets (AIS), Greenland Ice Sheet (GIS) and terrestrial AIS; and **(B)** *PlioSeaNZ* relative amplitude percentiles shown as horizontal colored bars in comparison to peak GMSL estimates and geologic constraints on ice-sheet contribution to sea level. An R script and R workspace for these plots are available on request from the author. Note that Study 2 only spans part of the MPWP.

for the MPWP termed *PlioSeaNZ* from Whanganui, New Zealand, that is completely independent of the global benthic $\delta^{18}O$ record. It calculates a theoretical relationship between sediment transport by waves and water depth, and applies the technique to grain size in a well-dated, continuous, shallow marine sequence. Water-depth variations obtained in this way, after corrections for compaction, tectonic subsidence, and glacial isostatic adjustment (GIA), yield the full amplitude of glacial-interglacial sea-level variability with precision of ±5 m and are relatively unaffected by dynamic topography.

Revisited estimates

The amplitude of glacial-to-interglacial sea-level change in continuous sedimentary records spanning MPWP (Fig. 1 and references therein) are compared in Figure 2a. The relative amplitude (maximum range) is calculated for a moving 20,000-year window at variable time steps for each record determined by sample spacing in the individual records. The 20,000-year window is chosen to capture the minimum orbital frequency of change. Also plotted are the percentiles (10th, 16th, 50th, 84th, 90th) for the amplitude-frequency distributions.

If these amplitudes are treated as GMSL change above present and the current global ice-sheet budget is considered the potential meltwater source, the sea-level equivalent of marine-based portions (MBIS) of the Antarctic Ice Sheet can account for 22.7 m, the Greenland Ice Sheet contains 7.3 m, and an additional 35.6 m is available from terrestrial sectors of the Antarctic Ice Sheet. Amplitudes >+30 m can only be explained by melting the terrestrial sectors of the Antarctic Ice Sheet, and/or by having more ice on the Northern Hemisphere continents during glacial periods than can be explained by the available geological data (e.g. Thiede et al. 2011). Larger-than-Holocene Antarctic glacial ice volumes cannot be excluded by proximal geological data for every glacial of the MPWP (Naish et al. 2009), but retreat of the East Antarctic Ice Sheet since eight million years ago is precluded by a recent study that found extremely low concentrations of cosmogenic ^{10}Be and ^{26}Al isotopes in the ANDRILL-1B marine sediment core (Shakun et al. 2018).

If all the variability in the *PlioSeaNZ* record was above present-day sea level, then GMSL during the warmest mid-Pliocene interglacial was at least +4.1 m and no more than +20.7 m, with a median of +10.7 m and likely (66%) range between 6.2 m (16th percentile) and 16.7 m (84th percentile; Fig. 2b). This maximum range is consistent with sediment composition from polar continental sediment cores, far-field sea-level reconstructions (Fig. 2b and refs. therein), and ice-sheet model constraints (e.g. DeConto and Pollard 2016). On this basis, we suggest that estimates using a calibration of the deep-sea $\delta^{18}O$ record by Mg/Ca paleothermometry and a sill depth-salinity relationship tend to overestimate the amplitude of global sea-level change during the MPWP.

This range also implies an equilibrium polar ice-sheet sensitivity of 2–8 m of sea-level change for every degree of temperature change, with a mean value of 4 m/°C. This empirical estimate does not consider ice-sheet dynamics, such as a potential stability threshold in the Antarctic Ice Sheet, caused by the loss of ice shelves, which may be crossed at 1.5–2°C of global warming, after which ongoing mass loss may be rapid and non-linear (Golledge et al. 2015).

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Exploring novel ice-core proxies for paleoclimate reconstruction in the sub-Antarctic

Amy C.F. King[1] and Dieter R. Tetzner[1,2]

New ice-core records are being developed from the sub-Antarctic, a region previously lacking in paleoclimate archives. These records capture marine-sourced organic compounds that act as proxies for sea-ice concentration, and wind-lofted diatoms that reflect westerly wind strength.

The sub-Antarctic region is critical to our understanding of past changes in westerly wind strength, sea-ice extent, Southern Ocean biogeochemical cycling, and processes interfacing polar and mid-latitude climate. Yet this region, defined here as southward of the Southern Ocean polar front, is severely lacking in paleoclimate archives. Consequently, our ability to predict future changes in these processes is limited. To answer the need for new climate records, the 2016–2017 Antarctic Circumnavigation Expedition (https://spi-ace-expedition.ch/) collected a suite of shallow (12–24 m depth) ice cores from ice-capped islands and glaciers throughout the Antarctic and sub-Antarctic (Fig. 1). The cores are climate archives for the late 20th century to present day (Thomas et al. 2020). Due to the logistical challenges of accessing such remote islands, several of these cores are the first to have ever been drilled at these sites.

The main objective of the sub-Antarctic ice-core drilling expedition is to "plug the gap" by providing paleoclimate records from the data-sparse sub-Antarctic. The PAGES2k Consortium (2017) highlighted the absence of paleoclimate archives across the Southern Ocean. Their global composite database of 692 temperature-sensitive records from 648 locations provides no spatial coverage in the sub-Antarctic. Improving spatial fidelity of records is another project goal. Ice-core reconstructions of marine-sourced components so far rely on cores from coastal Antarctica. Source regions of marine compounds found in these cores may cover entire ocean sectors (shown in Fig. 1). This means local-scale past climatic changes are not captured.

Alongside the collection of new cores has been the development of a number of novel ice-core proxies, focussing on emissions from the marine biosphere. Sub-Antarctic islands are in areas of marine productivity, therefore sub-Antarctic cores ideally lend themselves to marine-sourced proxies. This article highlights the exciting potential of these new proxies for sea-ice concentration and westerly wind strength, both key drivers in global climate dynamics.

Diatoms as proxies for westerly winds

Diatoms are unicellular algae with siliceous cell walls, found in surface waters worldwide. They are especially abundant in major oceanic water-mass convergence zones, such as the Southern Ocean, where nutrient upwelling leads to high productivity. Diatoms are lifted from the ocean surface into the atmosphere by wind-induced bubble-bursting and wave-breaking processes (Cipriano and Blanchard 1981; Farmer et al. 1993). Once in the atmosphere, they can be transported by strong winds over long distances. In polar regions, airborne diatoms are deposited over ice sheets and ice caps, and incorporated into the ice-core record (Budgeon et al. 2012).

Marine and non-marine diatoms have been found in ice cores from several locations across Antarctica (Kellogg and Kellogg 2005). Diatoms are found throughout the Southern Ocean, but Pike et al. (2008) observed the largest blooms occurred during spring near the Antarctic Polar Front zone, the sea-ice margin, or both. In light of this, Allen et al. (2020) and Tetzner et al. (2021) explored the abundance and diversity of diatoms preserved in Antarctic ice cores, highlighting their potential as proxies of wind strength and atmospheric circulation in the Southern Ocean.

The Peter 1st and Bouvet ice cores (providing climate records for 1999–2017 and 2001–2017, respectively) were obtained from two strategic locations to track changes in the westerly wind belt. Preliminary results from Tetzner et al. (2021), indicate that the Peter 1st ice-core diatom record presents correlations with winds in several locations; a positive correlation ($R > 0.8$, $p < 5\%$) with ERA5-reanalysis wind strength in the westerly wind

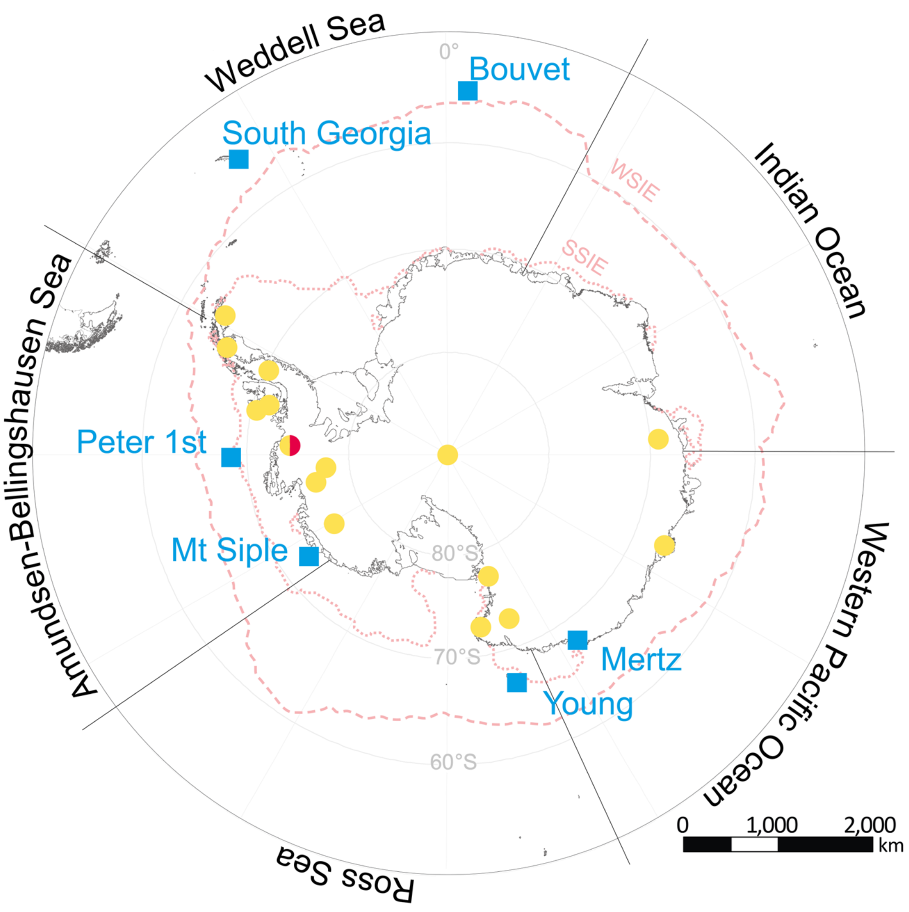

Figure 1: Locations of new sub-Antarctic ice cores (squares), alongside locations of cores previously used for reconstructing sea ice (yellow circles) and westerly winds (yellow/red circle) for the last 2000 years. Winter (WSIE) and summer sea-ice extent (SSIE; source: https://nsidc.org/data/g02135) are included for reference.

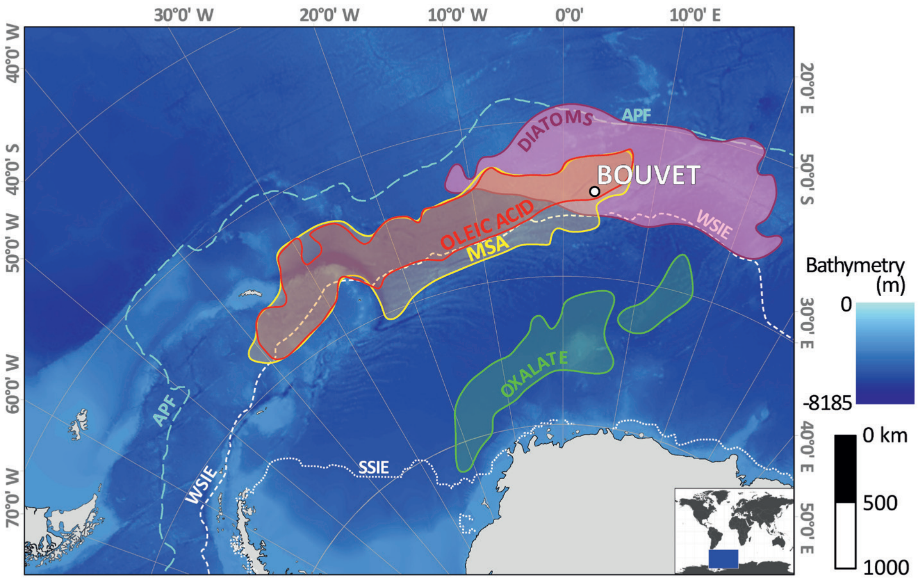

Figure 2: Location of Bouvet with geographical areas where core compound concentrations positively correlate with sea-ice concentration ($R = 0.6$, $p < 5\%$), and area where diatom concentration correlates with westerly winds ($R = 0.6$, $p < 5\%$). Also shown, how these correspond to winter (WSIE) and summer sea-ice extent (SSIE), and the Antarctic Polar Front (APF).

belt north of the Amundsen-Bellingshausen Sea, a positive (negative) correlation with latitudinal winds over the westerly wind belt (Antarctic coastal easterlies), and a positive correlation with offshore winds over the Amundsen Sea. These evidence the imprint of the Amundsen Sea low-pressure center driving the regional atmospheric circulation. Similarly, preliminary results from the Bouvet ice-core diatom record show a positive correlation ($R > 0.7$, $p < 5\%$) with wind strength over the westerly wind belt (Fig. 2). This is supported by a positive (negative) correlation with latitudinal winds over the westerly wind belt (Antarctic coastal easterlies) and a positive (negative) correlation with offshore (onshore) winds over the Weddell Sea. Both indicate that the presence of the Weddell low-pressure center drives the regional atmospheric circulation.

Preliminary results from these ice cores highlight their diatom records as valuable proxies of regional wind strength and atmospheric circulation in the sub-Antarctic region.

Novel organic compounds as sea-ice markers

Organic compounds are emitted from the surface ocean into the atmosphere by biochemical and physical processes. They are infrequently investigated in Antarctic ice-core records due to low concentrations, a lack of current understanding, or both. One established marine organic proxy is methanesulfonic acid (MSA). MSA is an oxidation product of dimethyl sulfide, a chemical compound produced by phytoplankton blooms containing diatoms. Curran and Jones (2000) first proposed that MSA concentration may be interpreted as a sea-ice proxy under the following mechanisms: (1) Antarctic winters with a greater sea-ice extent also have a larger area of sea-ice decay during the following spring melt; (2) This bigger sea-ice break-up zone enhances phytoplankton blooming, and subsequently, production of MSA; (3) Atmospheric transport deposits MSA onto ice caps, incorporating the varying yearly concentrations into ice-core records.

Giorio et al. (2018) discussed a wealth of additional marine organic compounds that show potential for use as paleoclimate indicators. Analytical advances developed by King et al. (2019a), provided a method for analyzing up to 30 of these novel compounds simultaneously in ice samples. King et al. (2019b) subsequently applied these methods, alongside MSA analysis, to the first ever ice core drilled on the sub-Antarctic island Bouvet.

Results of the Bouvet ice-core analyses show a positive correlation ($R = 0.79$; $p < 1\%$) between annual concentrations of MSA and oleic acid, the latter a fatty acid found in diatoms. Further investigation shows that a direct, positive correlation between annual oleic acid concentrations and each year's winter sea-ice concentration is found in a geographical area extending west of Bouvet Island, tracing the margin of maximum winter sea-ice extent (Fig. 2). Back-trajectory analysis (King et al. 2019b) ties the story together: westerly winds transport MSA and oleic acid, from spring blooming events in the sea-ice break-up zone to the west of Bouvet Island to the ice-core site, where they are deposited. Greater concentrations of MSA and oleic acid are emitted, transported, and deposited in years of greater maximum winter sea-ice extent.

The Bouvet ice-core analyses have also produced records of the marine organic compounds oxalate, formate, and acetate. Compound concentrations positively correlate with sea-ice concentration (King et al. 2019b). In contrast to oleic acid and MSA, the correlation exists for summer sea-ice concentration in a region south of Bouvet Island (Fig. 2). A better understanding of the sources of these compounds is required to definitely define the mechanism behind this correlation.

Analysis of the Bouvet core shows great promise for the development of a suite of marine organic sea-ice markers in sub-Antarctic ice cores.

Future directions

Investigation of novel marine-sourced components in ice cores presents new climate proxies in the sub-Antarctic over the past few decades. Organic compound concentrations record variations in sea-ice concentration, and diatoms record westerly wind strength. Thus, diatoms and the fatty acid compounds they produce commonly link records of both emissions and transport of these components. Future work analyzing these components in further sub-Antarctic island cores will allow us to develop these archives throughout the sub-Antarctic, and extend records further back in time. Combining sea-ice proxy records from both marine-sediment and ice cores (Thomas et al. 2019) may provide sea-ice paleorecords of improved accuracy, longevity, and spatial coverage. All of these factors provide the critical context needed for improving future projections of change in the climate-influencing sub-Antarctic region.

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Long-term peatland dynamics and effects of peatland-mediated feedbacks on the climate system

Nitin Chaudhary

The individual- and patch-based peatland-vegetation model LPJ-GUESS was employed to study past and future peatland carbon dynamics across the pan-Arctic. A substantial reduction in peatland sink capacity, expected under rapid global warming, has the potential to trigger important climate feedbacks.

Peatlands are important carbon reserves in the terrestrial ecosystem and cover 3% of the terrestrial land surface area (3.7 × 10^6 km^2; Bridgham et al. 2006, Hugelius et al. 2020). Peatlands store around 400–600 petagrams (10^{15} g) of carbon (PgC) since the Holocene and comprise around 30% of the present-day soil organic carbon pool (Yu et al. 2010; Hugelius et al. 2020). They are also a major source of atmospheric methane emissions (Abdalla et al. 2016). A significant fraction of peatland area coincides with permafrost, affecting carbon accumulation rates and biogeochemical processes (Obu et al. 2019). The majority of northern peatlands started developing 8000–12,000 years ago as a result of the availability of new land surface following deglaciation, warmer climate conditions, higher summer insolation, more pronounced seasonality, elevated greenhouse gas emissions, and higher moisture conditions (MacDonald et al. 2006). However, present-day distribution of soil organic carbon is not uniform across the pan-Arctic region (45–75°N) due to differential peat initiation periods, bulk density values, and changes in dominant plant types (Loisel et al. 2014). Recent advances in field measurements have reduced some uncertainties related to carbon accumulation rates and peat depth across the pan-Arctic (Loisel et al. 2014). However, due to the large extent of peatlands, calculating global and regional estimates directly from field measurements would be difficult. This difficulty can be circumvented by employing peatland models, as these simulate realistic peatland carbon accumulation rates at larger spatial and temporal scales and can further strengthen the recent progress on observing carbon accumulation rates (Stocker et al. 2014; Chaudhary et al. 2017a, b). Understanding long-term peatland carbon dynamics and their controls are crucial for predicting their role in moderating future climate.

Dynamic peatland-vegetation models and long-term carbon dynamics

Dynamic global vegetation models (DGVMs) such as LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator) are used to understand the changes in vegetation, carbon cycle, and climate feedbacks on different temporal and spatial scales. They provide a suitable platform to study long-term peatland carbon dynamics, enabling us to understand the role of peatlands in past and future climate conditions. To this end, a recent study demonstrated a new implementation of peatland and permafrost dynamics with the unique representation of spatial heterogeneity in the dynamic global vegetation model (in LPJ-GUESS; Chaudhary et al. 2017a). This was the first time that any model included dynamic annual multi-layer peat accumulation, freezing-thawing cycles, lateral flow, and spatial heterogeneity in the framework of a dynamic vegetation model (Chaudhary et al. 2017a), and was applied at local to regional spatial scales.

The current model scheme consists of many key variables and interactions controlling the non-linear peatland dynamics (Chaudhary et al. 2018). The relationship between the average rate of peat formation and water table position (Belyea 2009), cyclicity among micro-formations (hummocks and hollows) (Heikki 2002), internal eco-hydrological feedbacks, and multi-directionality (Belyea 2009) that have frequently been observed in many peatland sites can be simulated and explained using this detailed model scheme. The model has been applied in different regions in the Northern Hemisphere and shown to reproduce peat accumulation, permafrost dynamics, and vegetation distribution realistically in several Scandinavian sites (Chaudhary et al. 2017a).

Changes in peatland carbon stocks in the future

Peatlands are severely threatened by ongoing anthropogenic climate warming, and it is expected that many peatland regions will experience significant changes in their

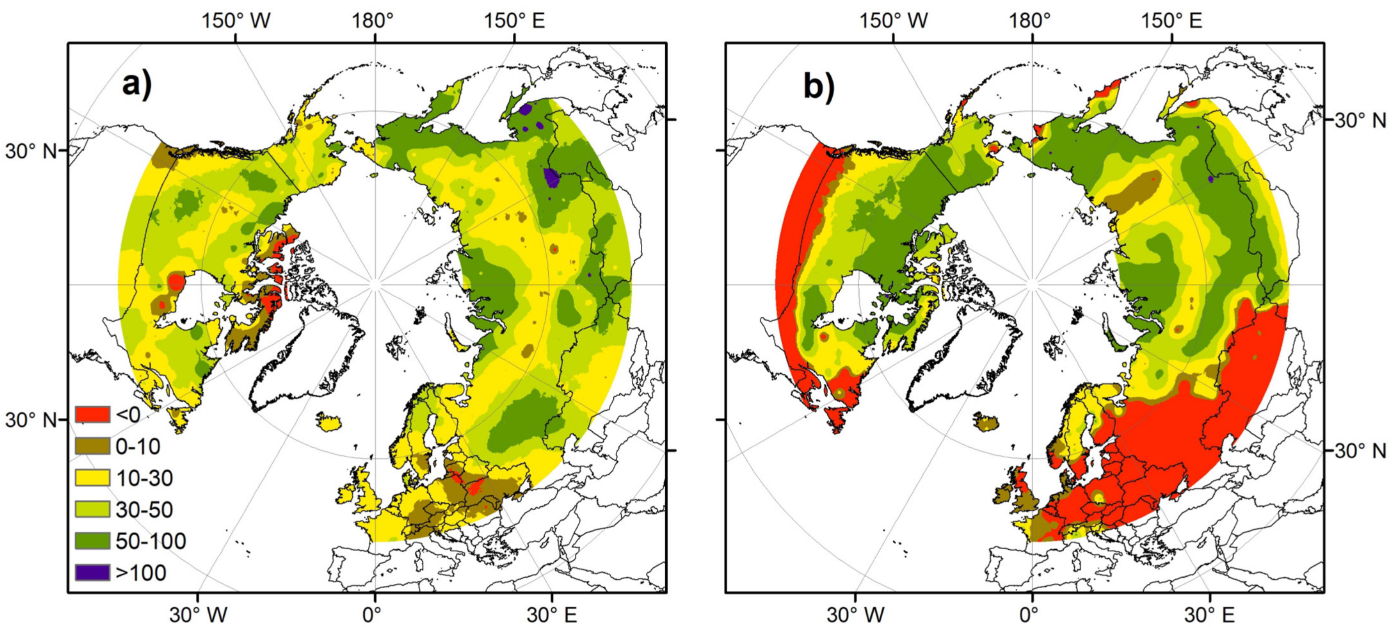

Figure 1: Modeled net peatland carbon accumulation rates (in gC m^2/yr) across the pan-Arctic **(A)** at present (1991–2000) and **(B)** at the end of the century (2091–2100). Positive values indicate carbon sinks, and negative values represent sources of carbon from peatlands to the atmosphere (Chaudhary et al. 2020).

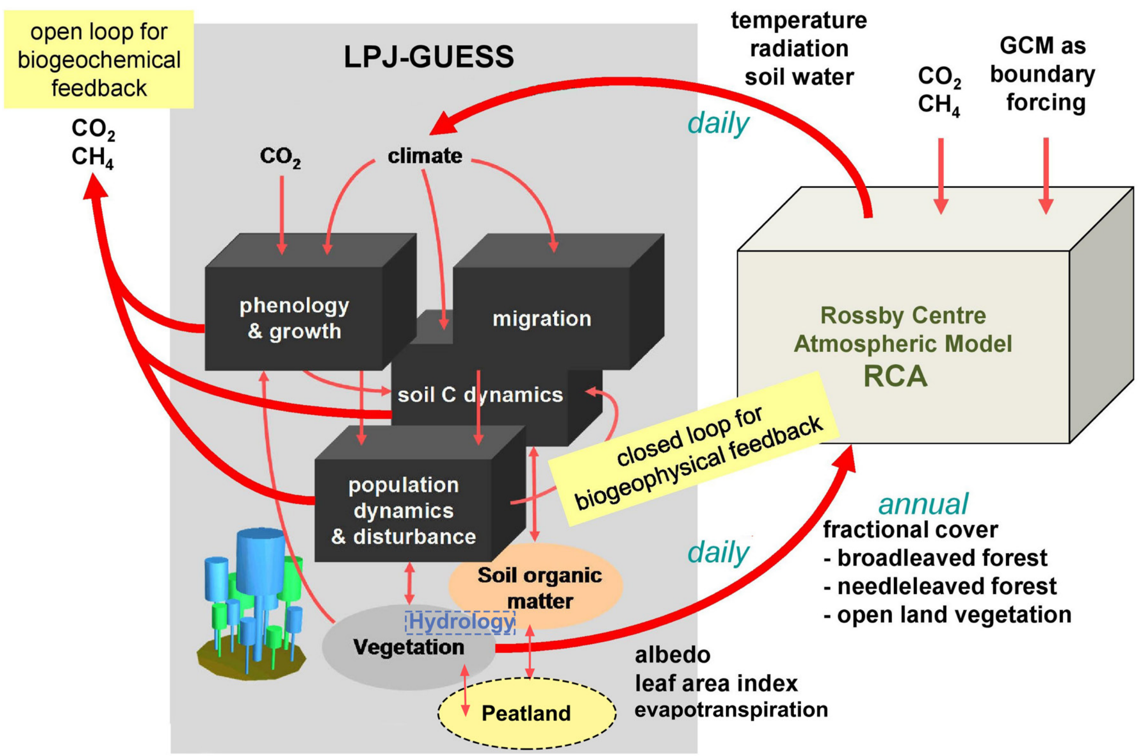

Figure 2: A proposed schematic representation of the regional Earth system model RCA-GUESS.

carbon fluxes in the near future. Subsequent regional (pan-Arctic) studies employing the model described above (Chaudhary et al. 2017b; 2020) found that many peatland regions in Europe, including Scandinavia and Russia, and central and eastern Canada would change from carbon sinks to potential carbon sources in the coming century, while other sites would enhance their sink capacity at other sites (Fig. 1). It was found that permafrost peatlands are likely to accumulate more peat in warmer conditions due to the high level of moisture that results from permafrost thaw, higher precipitation, and elevated CO_2 levels. On the other hand, peatlands that experience reduced precipitation rates and are devoid of underlying permafrost will lose more carbon in the future, particularly peatlands located in the European region and peatlands between 45° and 55°N. Overall, the study showed that peatlands would continue to act as carbon sinks, but their sink capacity will be substantially reduced under rapid global warming (Fig. 1b) in the coming decades.

Peatland-mediated feedbacks

The rapid, ongoing changes in many peatland areas due to climate change have the potential to disturb the prevailing land-atmosphere carbon balance and trigger some pertinent climate-relevant feedbacks. The higher carbon emissions from peatlands as a result of climate warming could result in a positive feedback on climate change, thus amplifying warming (Baird et al. 2009; Frolking et al. 2009). On the other hand, elevated CO_2 concentrations in the atmosphere together with an increase in moisture conditions due to permafrost thawing and higher precipitation rates could promote plant growth and peat accumulation (Loisel and Yu 2013). This, in turn, may enhance the carbon (i.e. CO_2) uptake capacity of many peatlands and would be expected to result in a negative feedback on climate warming. In addition, an increase in the active layer depth or soil moisture due to temperature-driven permafrost degradation and structural collapse of many peatland sites located in cold environments could lead to the formation of wet and water-filled areas (Belyea 2009; Turetsky et al. 2019). This would most likely result in higher methane emissions that would further accelerate regional warming. However, the net effect of all these competing peatland-mediated feedbacks is difficult to study in isolation. For that, an integrated study is required that takes all the critical interactions and feedbacks between peatland carbon cycle and climate into account.

Integrating peatland dynamics in Earth system models

Contemporary Earth system models simulate the state of the atmosphere and biosphere at different spatial and temporal scales and predict their responses and behavior in rapidly changing climate conditions. However, these advanced models currently lack peatlands as a distinct land surface type (Frolking et al. 2009). Due to the absence of a comprehensive representation of detailed peatland and cryospheric processes in any of the current Earth system models, our understanding of these hypothesized peatland-mediated feedbacks on regional and global scales is limited. The peatland dynamics in LPJ-GUESS seem to be reasonable, as the model produces realistic carbon accumulation rates and permafrost distribution at different spatial and temporal scales (Chaudhary et al. 2020). With this peatland extension, the coupled regional Earth system model (RCA-GUESS) will be appropriate for addressing questions related to short-term and long-term effects of peatland dynamics on regional climate (Fig. 2). The model will be employed in the pan-Arctic region to quantify the magnitude, direction, and strengths of peatland carbon-climate feedbacks; these results will then be fed into the land-surface module of the global Earth system model to improve global peatland modeling.

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The enigma and complexity of landscape dynamics in Chinese deserts: From case studies to big data

Peng Liang, H. Li, Y. Zhou, X. Fu, L. Mackenzie and D. Zhang

We analyze the recent progress in eolian surface processes and landscape dynamics in Chinese deserts. These diverse eolian studies, including paleoenvironmental reconstructions, advances in dating techniques, and clarification of sediment provenance, highlight the complexity of desert landscape evolution.

Drylands occupy ~41% of the global land surface and are home to more than two billion people (Reynolds et al. 2007). In recent decades, global warming and intensified human activities have exacerbated the environmental degradation or desertification in drylands, threatening nations' economies and sustainable development. Additionally, deserts are an important yet poorly understood component of the Earth system, with dust released from these regions affecting the global biogeochemical cycle and climate. Early-career researchers (ECRs) at Zhejiang University and elsewhere in China are currently investigating sedimentary archives from the interior of Chinese deserts in the eastern Asian desert belt (Fig. 1) to explore complex landscape dynamics through time.

Paleoenvironmental signals archived in the eastern Chinese deserts

The large semi-stabilized sandy lands in the deserts of eastern China are located near the northern extent of the East Asian summer monsoon (Fig. 1). Stratigraphic sequences from the sandy lands record repeated periods of dune activation and stabilization through alternating eolian (wind-blown) sands and paleosols (buried soils). Dune stabilization processes are usually a landscape response to increased precipitation associated with enhanced summer monsoons, while increased eolian activity and dune activation occurs during periods of drought. These alternating sequences are a direct and sensitive record of past monsoon variability. Yang et al. (2019) found that a dark brown (Munsell soil color 10YR 4/3) paleosol began to develop at 14.5 thousand years before present (kyr BP) and lasted until 2 kyr BP in the Hulunbeier Sandy Land, while stronger pedogenesis (i.e. soil formation) occurred during 9-5 kyr BP. Eolian sequences from the Hunshandake Sandy Land recorded dune stabilization processes from 9.6 to 3.0 kyr BP, though localized eolian events occurred at the same time (Fig. 2). Although the paleolandscape in the eastern sandy lands shows a high degree of spatial heterogeneity, dunes were generally stabilized and eolian activity was suppressed from 7.5 to 3.5 kyr BP in the mid-Holocene (Fig. 2; Yang et al. 2019). These geological records from dune sequences are generally consistent with paleoclimate simulations, which indicate that northern China received higher summer monsoon precipitation during the mid-Holocene than during the pre-industrial period, although the moisture transport pathway is more complex in western Chinese deserts (Feng and Yang 2019).

Spatial heterogeneity of the landscape leads to an unavoidable uncertainty when interpreting geological signals from eolian stratigraphic sequences. Liang and Yang (2016) investigated drivers of landscape heterogeneity at different scales in the Maowusu Sandy Land, northern China (Fig. 1). They found that climate and large-scale agricultural reclamation affect regional landscape patterns in the Maowusu Sandy Land, whereas microtopography and river networks drive landscape heterogeneity at a local scale. The landscape response to declining wind strength in the Maowusu Sandy Land from 1981 to 2016 shows a significantly out-of-step pattern between the western and eastern regions, arising from different regional climates and land-use histories (Liang and Yang 2016), highlighting the complexity of landscape dynamics in drylands.

The eolian processes at the dune scale also play an important role in the interpretation of paleoenvironmental records from dune deposits. The dune stabilization process is assumed to be mainly caused by precipitation-induced vegetation expansion.

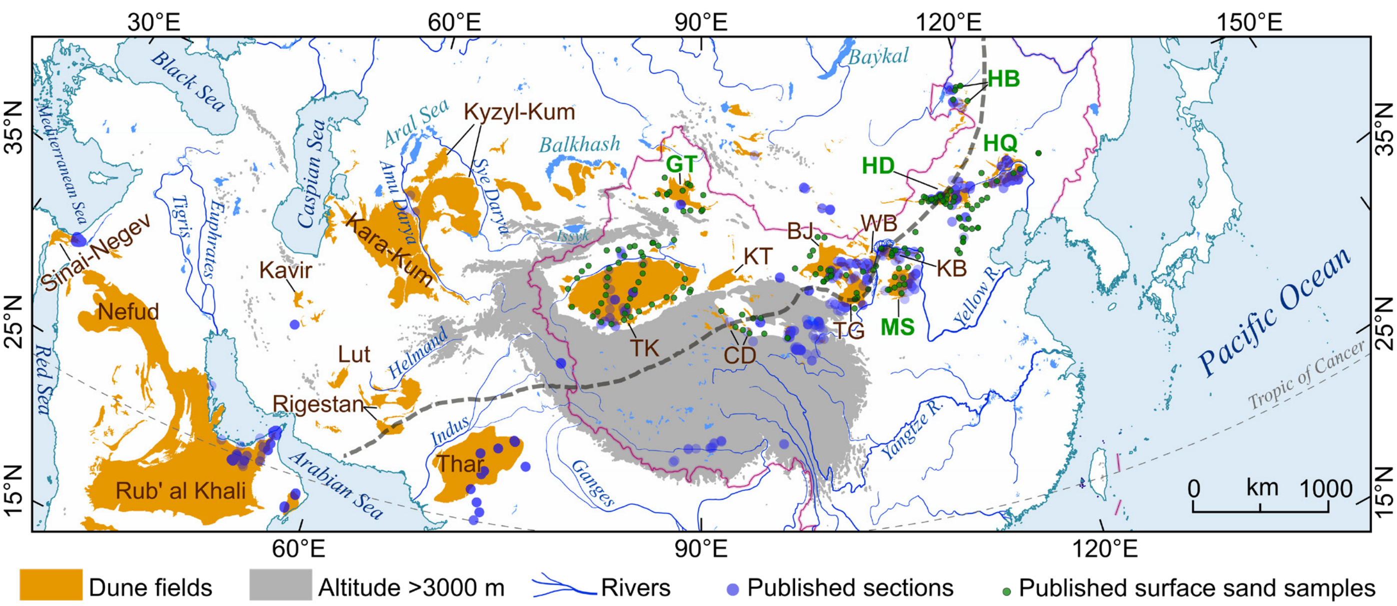

Figure 1: Distribution of Asian deserts, major rivers, and published data in the growing database. The thick dashed line indicates the boundary of the Asian summer monsoon. Active sand seas: Taklamakan (TK); Kumtagh (KT); Chaidamu (CD); Badain Jaran (BJ); Tengger (TG); Wulanbuhe (WB). Semi-stabilized sandy lands: Gurbantunggut (GT); Maowusu (MS); Kubuqi (KB); Hunshandake (HD); Horqin (HQ); Hulunbeier (HB).

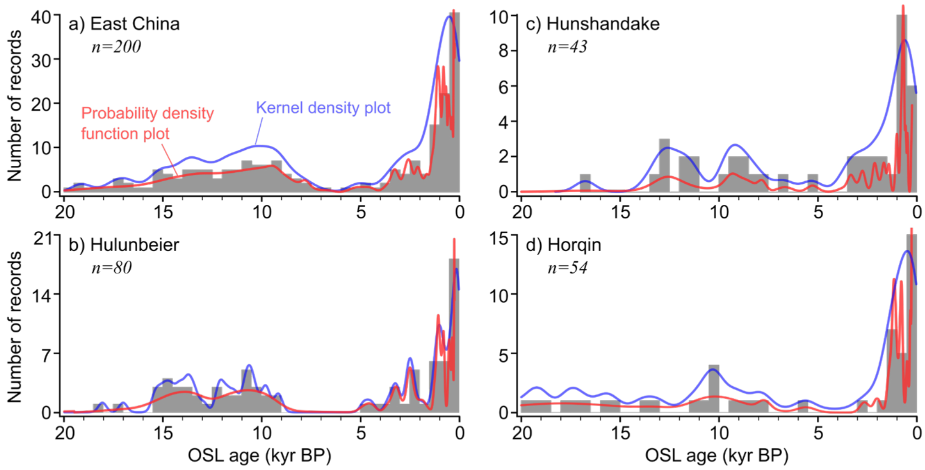

Figure 2: Eolian events represented by the frequency of optically stimulated luminescence (OSL) ages from the eastern sandy lands of northern China. The gray rectangles are OSL age histograms, and the bin size is 0.5 kyr. Data are from Li and Yang (2016) and Yang et al. (2019) with new data added.

However, a new case study investigating the transition from barchan (crescent-shaped sand dune) to parabolic dunes in the Maowusu Sandy Land demonstrated that the reduction of wind strength can lower the sand flux rate and dune height, which allows for vegetation establishment and dune transformation (Zhang et al. 2020). This research suggests that some mismatches between dune activity and moisture variability could be reconciled through a better understanding of past wind regimes.

Improved dating techniques for paleoenvironmental reconstructions

Over the past 20 years, optically stimulated luminescence (OSL) dating has become a well-established Quaternary geochronometer, particularly for eolian sediments, and is arguably the most important tool for desert paleoenvironmental research. A series of luminescence dating procedures for K-feldspar, a ubiquitous mineral in natural sediments, has recently been developed using eolian and fluvial samples from Chinese deserts (Fu et al. 2015; Fu et al. 2018). These techniques considerably extend upper and lower dating limits and improve dating accuracy. The ability to analyze raw luminescence dating data has also been enhanced by a newly developed software "Luminescence Dose and Age Calculator (LDAC v1.0)" (Liang and Forman 2019; https://github.com/Peng-Liang/LDAC), which can maintain, archive, and synthesize basic OSL data, apply appropriate statistical models, calculate environmental dose rate, and render statistically significant final ages. This self-contained tool for luminescence dating allows for inter-laboratory OSL age comparisons and promotes more robust datasets for landscape-dynamics research in drylands and beyond. OSL dating of eolian sands has produced over 300 age records from dunes in China, which were recently compiled as part of the INQUA Dunes Atlas chronologic database (Li and Yang 2016; https://www.dri.edu/inquadunesatlas/). This primary dataset collated by ECRs has helped to build a picture of the eolian history in Chinese deserts since the Last Glacial Maximum, showing that the eolian events identified by the frequency of OSL ages increased during the last deglaciation and late Holocene but are mostly dormant during the mid-Holocene (Fig. 2). However, our understanding of eolian activity at the glacial-interglacial timescale is still unclear due to the lack of well-preserved and statistically meaningful archives older than 20 kyr BP from desert interiors, limiting regional multi-site paleoenvironmental reconstruction (Li and Yang 2016).

Sediment provenance and surface processes

Identifying sediment provenance can yield insights into understanding the complexity of past and present landscape dynamics in deserts. Sediment sources in the Taklamakan Desert, Badain Jaran Desert, Kubuqi Desert, and Maowusu Sandy Land were investigated by combining geochemical compositions of the sand with geomorphic analysis (Hu and Yang 2016; Liu and Yang 2018; Jiang and Yang 2019; Zhou et al. 2020). Results show that the dust fraction (<63 μm) in dune sands from the Taklamakan Desert varies from 0.44% to 21.7% and can be traced to the Kunlun and Tianshan Mountains by their geochemical and sedimentological characteristics. However, the sand particles (>63 μm) were predominantly sourced from the Kunlun Mountains in the south and transported via fluvial processes (Jiang and Yang 2019; Zhou et al. 2020). These results suggest that dust particles within deserts have independent provenance, which is consistent with the low dust-generation potential from sand saltation and wind abrasion found in wind-tunnel experiments (Adams and Soreghan 2020). Similarly, fluvial processes provide sand to the Badain Jaran Desert (Hu and Yang 2016), the Kubuqi Desert, and the Maowusu Sandy Land (Liu and Yang 2018) by transporting loose sediments from nearby mountains to the desert basins. These primary dune-building sediments are then further mixed via local eolian processes (Liu and Yang 2020).

Future work: moving to big data

The aforementioned case studies have greatly enriched our understanding of the landscape dynamics and surface processes in deserts of China and beyond, but a more comprehensive and continental-scale picture is still lacking. Paleoenvironmental reconstructions based on single-site dune deposits or sequences alternating between lacustrine, eolian sands, and paleosols in deserts inevitably contain uncertainties. These uncertainties mainly arise from the spatial heterogeneity of the eolian landscape (Liang and Yang 2016), the episodic/discontinuous eolian sand deposition features with possible eolian erosion (Forman 2015), and the generally non-linear response between eolian depositional processes and climate fluctuations (Yang et al. 2019). A big-data concept incorporating a continental-scale database using the substantial paleoenvironmental records from Chinese deserts could be introduced to overcome these difficulties and complexities. This database is currently under construction (Fig. 1) and will include sedimentary sequences that contain well-vetted geomorphic context information, stratigraphic descriptions, proxies (such as grain size, magnetic susceptibility), and relevant ages. A comprehensive and well-organized database that includes multiple physical and chemical indices of surface dune sand, such as grain size, geochemical composition, and petrology, is also required to advance sand provenance studies. These increasingly large and high-dimensional datasets and data-driven computations are a promising avenue to enhance our understanding of eolian processes and the Earth system from a big-data perspective, especially with the aid of machine learning algorithms. However, more in-depth field studies are still indispensable.

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Human activities disturb lake-sediment records of past flood frequencies

William Rapuc, P. Sabatier and F. Arnaud

Human activities impact erosion and transport processes in catchments, hence disturbing paleoclimate recording. A thorough study of erosion patterns is therefore necessary to disentangle climate and human forcing when interpreting lake sediment-based flood chronicles.

Flood frequencies as a proxy of past extreme precipitation events

In the current context of global climate change, predicting the evolution of precipitation is particularly challenging: an increase of extreme events is expected globally due to the capacity of a warmer atmosphere to hold more water, although regional trends may differ (IPCC 2012). Assessing this requires the acquisition of long-term hydrological datasets (Wilhelm et al. 2019). As flood occurrence and magnitude are linked to precipitation-regime fluctuation through time, the establishment of regional flood chronicles from natural archives could be a key to evaluate the evolution of precipitation regimes on emerged land (Wilhelm et al. 2017).

Of all the natural archives that lend themselves to such reconstructions, lakes are a prime candidate, as they are widely spread across all continents and act as natural sinks, continuously trapping erosion products from an entire catchment over a long period (Wilhelm et al. 2018). Indeed, during flood events, water-transported detrital particles are deposited on the lake bottom in the form of graded layers that differ from the in-lake continuous sedimentation. The identification of these events, by naked-eye observation or using new methodologies (Rapuc et al. 2020), allows scientists to establish flood-occurrence chronicles. In some cases, the thickness and/or the maximum grain size of deposits can be used to assess the intensity of flood events and even decipher past current-flow velocities (Arnaud et al. 2016; Evin et al. 2019). Numerous studies have thus used flood frequency and intensities based on lake sediments to reconstruct hydrological variations through time (Czymzik et al. 2013; Glur et al. 2013; Wilhelm et al. 2018). However, within a given lake system, the amount and physical characteristics of river-borne sediment not only depend on precipitation patterns, but also on the sediment availability, which is a function of soil erodibility and transport processes.

Impact of human activities on erosion and transport processes

Sediment availability and transport processes are forced by both climatic fluctuations and human activities. Consequently, provided that the climatic conditions and methodologies of reconstruction are the same, discrepancies between flood chronicles in the same region should provide evidence of the influence of human activities. The Italian Southern Alps offer an ideal playground for such an experiment. Several lakes in this region have been studied and

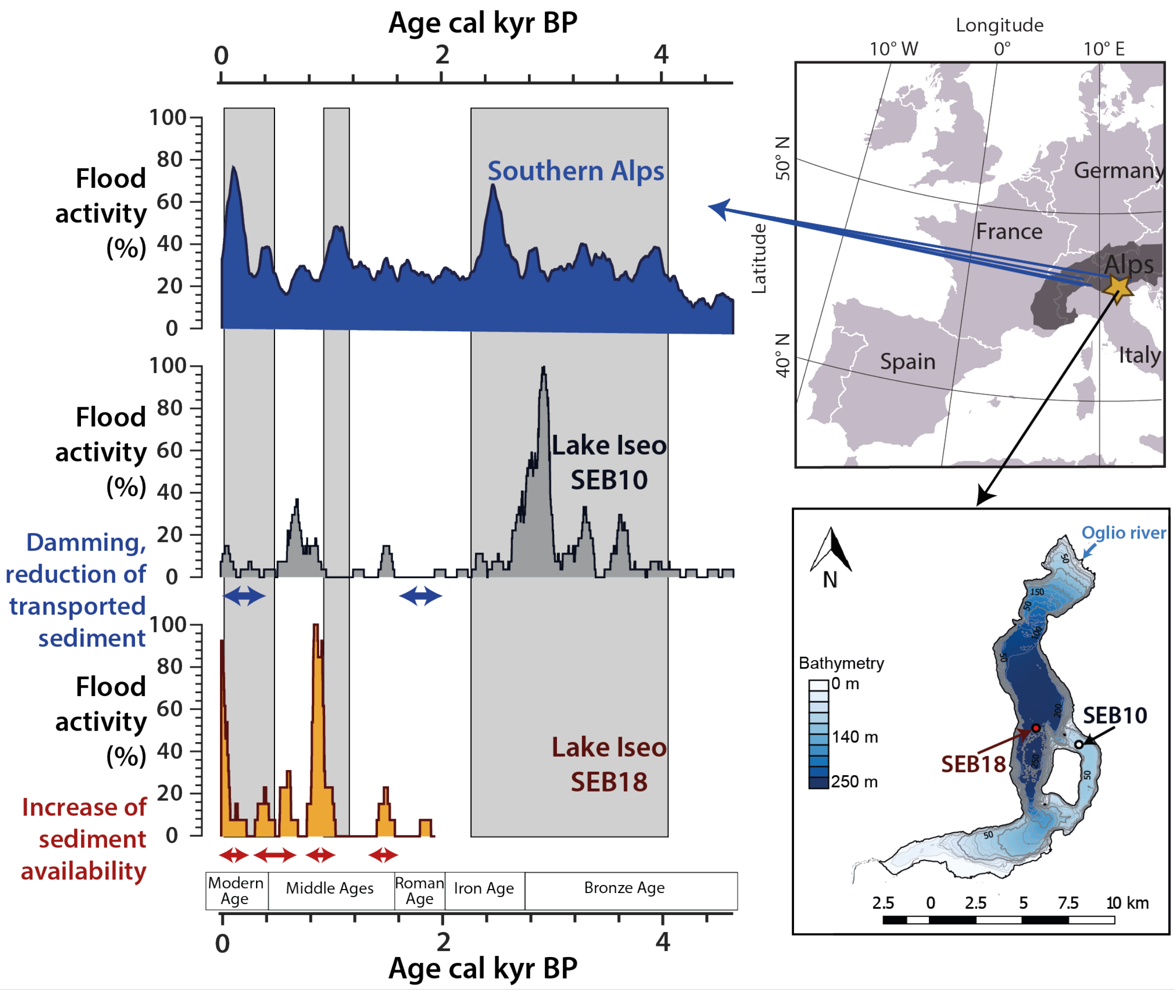

Figure 1: Flood activities modified from the Southern Alps synthesis of Wirth et al. (2013), the SEB10 (Rapuc et al. 2019) and SEB18 (unpublished) sediment sequences from Lake Iseo. Activity is calculated as a ratio of the instantaneous frequency and the maximum frequency measured in the sequence. Gray shading highlights periods of high regional flood frequency.

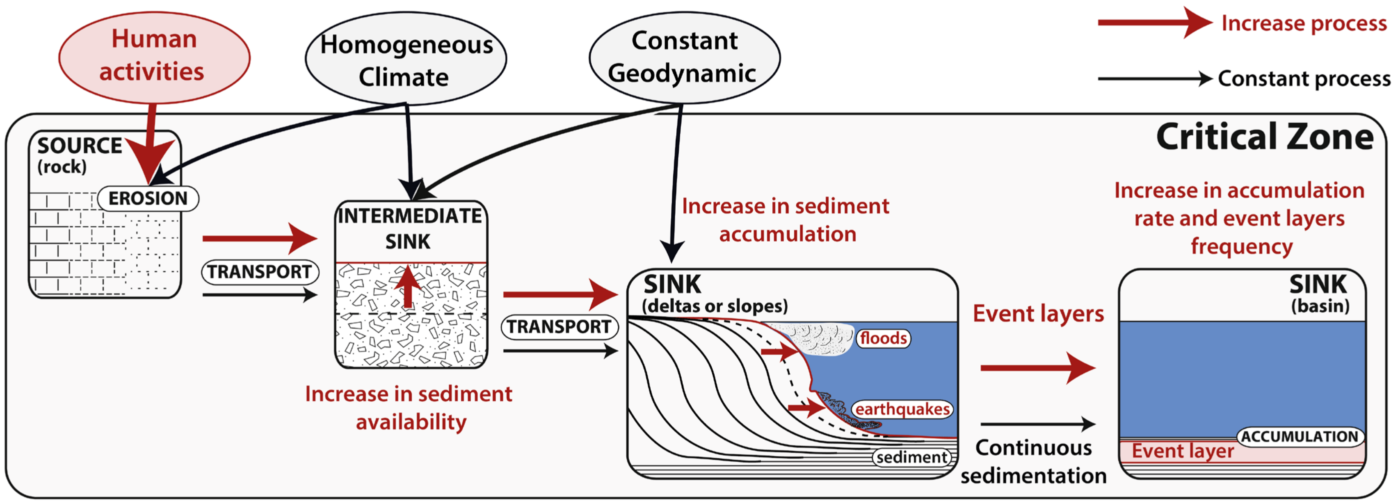

Figure 2: Conceptual model of the Critical Zone erosion cycle in a large catchment and the effects of the three main forcing factors: climate, geodynamics, and human activities.

many flood chronicles have been produced; for example, Wirth et al. (2013) computed a Holocene synthesis of flood frequencies from five lake-sediment sequences from the Southern Alps.

Recently, we produced two flood chronicles from two sediment sequences taken from Lake Iseo, a large perialpine lake. The SEB18 sequence was sampled in the deep basin of the lake, fed by a large catchment (1777 km²). The SEB10 sequence (Rapuc et al. 2019) was retrieved in a shallower basin fed by sediment from a small catchment area (46.5 km²). The SEB10 flood chronicle is consistent with the regional extreme precipitation trend until the Roman Age (approx. 2 cal kyr BP), with an important increase in recorded flood frequency around 4.2 cal kyr BP, reflecting a shift towards wetter climate in Europe (Fig. 1; Wirth et al. 2013). However, the SEB10 sequence differs from the Southern Alps synthesis for periods when human activity is important in the Lake Iseo catchment (Fig. 1). For instance, during the Little Ice Age (LIA, 1300–1860 CE), flood activity in the Southern Alps was high due to a regionally colder and wetter climate, resulting in more frequent precipitation events. However, very few flood layers were deposited in the shallower basin of Lake Iseo at that time. We interpreted that discrepancy as resulting from the anthropization of the main tributaries (streams or rivers flowing into a larger stream or a main stem) through damming, thereby reducing sediment flux to the lake (Rapuc et al. 2019). At that study site, the creation of dams and channels in catchments generally deflected the river flow and trapped sediment upstream, hence reducing the sediment flux to the lake basin and the apparent flood frequency in the lake-sediment record.

A different scenario was documented in SEB18. In this sequence, high flood frequencies are recorded during the Medieval Warm Period (950–1250 CE), and frequencies are lower than expected during the LIA (Fig. 1), in contrast to the regional trend (Wirth et al. 2013; Sabatier et al. 2017). Here, human activity is suspected to have impacted the erosion cycle in the catchment through grazing, agricultural activities, and deforestation, all of which lead to soil destabilization (Fig. 2). When soil erodibility increases and more sediment becomes available, the precipitation intensity necessary to entrain particles from the soil surface decreases (Renard et al. 1991). Hence, even a moderate precipitation event may be recorded as a graded layer in the lake basin, which artificially increases the flood frequency in the sediment record.

The comparison of the SEB10 and SEB18 sequences, taken from different sedimentary basins in the same lake, revealed different lake-sediment responses to the same climate forcing factors (Fig. 1). Moreover, the rise in flood frequency recorded in SEB10 during the High Middle Ages (1000–1250 CE) is delayed by 200 years compared to the SEB18 record. As all other factors are similar at these two core locations, only human-triggered changes in sediment availability or transport processes at the scale of catchment areas can explain these differences.

Summary and future work

Flood chronicles (frequencies and magnitudes) from lake sediments are robust paleoclimatic proxies in the absence of human activity modifying sediment availability in the catchment. However, when human activity affects the Critical Zone (CZ), defined as the reactive skin of our planet at the interface of lithosphere-atmosphere-hydrosphere-biosphere, by increasing erosion, resulting in increased sediment transport and remobilization, the sensitivity of a lake as a natural archive of the CZ dynamic is disturbed. A human-triggered increase in soil erodibility and sediment availability may therefore result in a decoupling of the recorded flood frequency and the regional climatic conditions. Inversely, stream management can result in a drastic decrease of river-borne sediment input. A similar phenomenon may result from other geodynamical processes, such as earthquakes (Rapuc et al. 2018): the sensitivity of a lake to record seismic shaking increases when sediment accumulation in the delta and on lake slopes increases (Fig. 2). To study paleohydrologic or geodynamic fluctuations, the safest way is then to investigate sediments retrieved from high altitude zones (Sabatier et al. 2017). However, large lakes draining large catchment areas offer us the opportunity to observe large-scale precipitation patterns. They are thus valuable resources for reconstructions of past flood frequency when considered together with the three main forcing factors driving erosion patterns and CZ dynamics throughout the Holocene: climate, geodynamics, and human activities (Fig. 2).

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Climate and environmental changes in the Mt. Kenya region

Christine A. Omuombo

Paleo records from Lake Nkunga show that climatic and environmental changes in this region were gradual and subtle during the last millennium. We highlight the importance of sedimentary records in providing a baseline for future conservation efforts on Mt. Kenya.

The last few hundred years have been characterized by increasing anthropogenic utilization of land and land-based resources, resulting in significant changes to the landscape and ecosystems, both in their structure and function. Baseline climate and land-use parameters can be deduced from climate-sensitive lakes with a high degree of reliability (Olago and Odada 2004). Forest cover, in particular, has seen unprecedented disturbances in recent times due to human occupation and modifications in land-use patterns. The overprint of anthropogenic influence on the climate signal is difficult to decipher without clear records of long-term change. Lake sediments within forests are ideal proxy archives to investigate the linkages between natural and anthropogenic factors. In the last millennium, evidence of climate and environmental change from decadal to centennial scales (Tierney et al. 2013; Verschuren et al. 2000) reveal floral and aquatic transformations that can be used as baselines for our decision-making regarding the conservation of our natural resources.

Climate context and human impact during the last millennium over East Africa

During the Late Holocene, East Africa experienced warm and moist conditions (Kiage and Liu 2006), punctuated by two key climatic events: The Medieval Climate Anomaly (MCA; 950–700 cal yr BP) and the Little Ice Age (LIA; 700–100 cal yr BP), observable in proxy records from many sites. The MCA was dry with low lake levels and was synchronous among various sites within a relatively narrow time window. In contrast, the timing of the LIA is highly variable, with the first phase of the LIA corresponding to maximum lake levels due to increased precipitation and the second phase displaying lake-level regressions punctuated by centennial- and decadal-scale droughts (Verschuren et al. 2000). These climatic events coincided with the expansion and settlement of various communities and are therefore difficult to isolate from anthropogenic impacts on the ecosystem responses.

The expansion of trade routes between the interior and the coast of East Africa in the 19th century played a key role in land-cover modification. The spread of domesticated crops from different parts of the world such as East Asia (banana, rice, and cassava) and South and Central America (maize, tomato, and avocado) have been archived in sedimentary records documenting population expansion in the region (Marchant et al. 2018). However, comprehensive datasets describing both the anthropogenic and climate influences on land use only exist for a handful of sites in East Africa, such as lakes Victoria and Naivasha in Kenya.

The Mt. Kenya highlands during the last millennium

Mt. Kenya Forest is a protected area in the East Africa highlands. Several crater and glacial lakes located in different ecological zones of the mountain have been studied to better understand the climatic and environmental signals within their sediments. One of the lakes within Mt. Kenya Forest, Sacred Lake (2350 m asl), hosts the longest records of climate and environmental change spanning the period from 115,000 cal yr BP to present (Olago 2001). During the 20th century the forested catchment areas were converted to agriculturally productive lands for commercial and subsistence farming. As a consequence, an explosion of the human population relying on the utilization of forest-based resources and overuse of arable and pasture lands is an increasing threat to the present-day forest ecosystem.

The first written records of human occupation of the Mt. Kenya region by local communities was about 200 cal yr BP. The extent of their invasion into the montane forest region is not well known (Ndichu 2009); what has been established is that this expansion coincided with periods of conflict

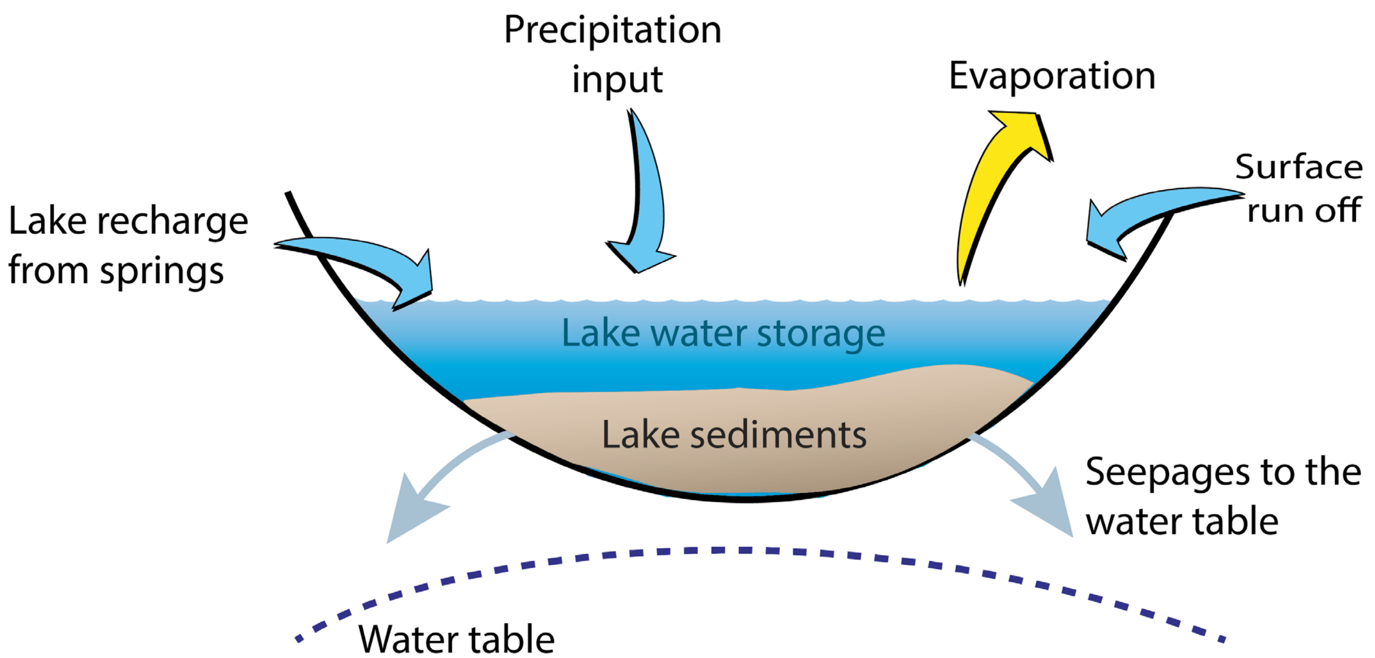

Figure 1: A simplified lake water budget model for Lake Nkunga.

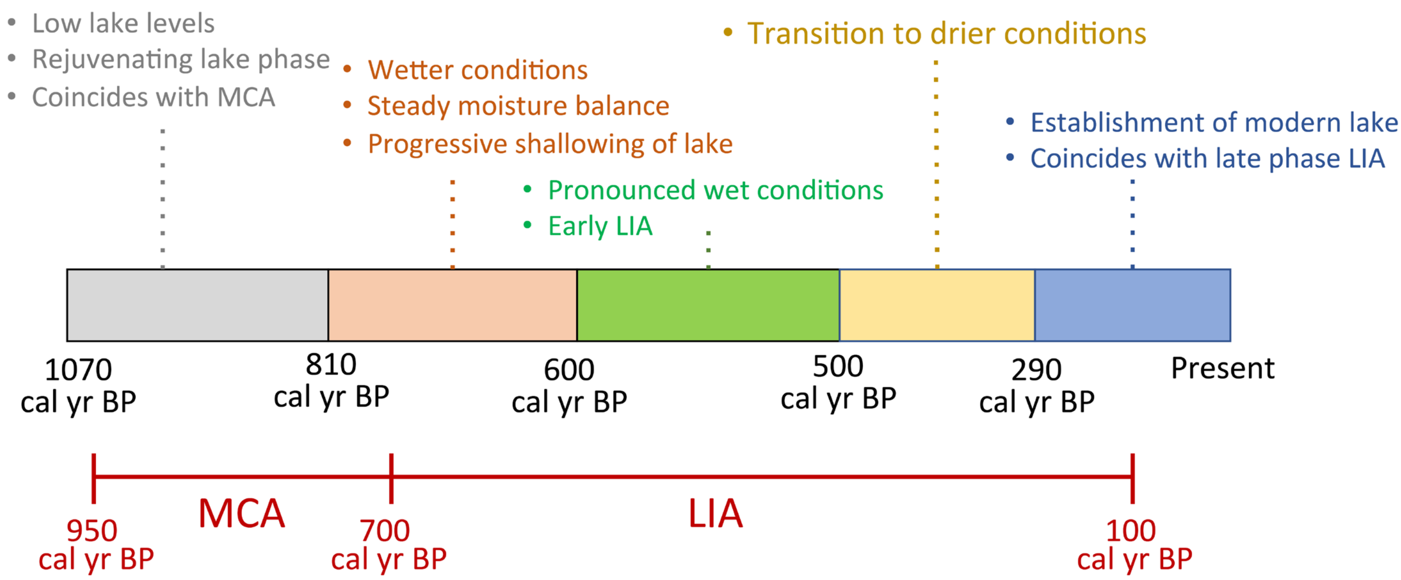

Figure 2: The interpretation of sedimentary archives from Lake Nkunga (sketch not to scale).

over natural resources and civil wars during decadal-scale droughts (Verschuren et al. 2000). Therefore, it is possible that the anthropogenic signal for the last two centuries from this region, detected through the presence of agricultural traces in the sedimentary record, may be overestimated, requiring further analysis to better understand the observed changes.

Lake Nkunga is one of the shallow crater lakes on the northeastern slopes of the mountain located at the equator at 1780 m asl and is located 10 km below Sacred Lake (Omuombo et al. 2020). Previous studies from this lake indicate that sedimentation resumed during the Late Holocene after a hiatus from 30,000–1350 cal yr BP (Olago et al. 2000). The lake has since persisted as a permanent water body archiving sediment over the last millennium. The lake exhibits swamp-like conditions due to its shallow depth (1.9 m on average) and is recharged by precipitation and springs emanating from fissures located at higher altitudes to the east and west and has no known outlet (Fig. 1). We examined a short 89-cm core from this lake and carried out various biogeochemical analyses (mineralogy, magnetic susceptibility, and organic and elemental geochemistry) to decipher the lake responses to climatic and environmental changes during the last millennium (Omuombo et al. 2020).

The hydrological record commences with a warm MCA that coincides with a lake rejuvenation phase and exhibits characteristics signifying a low lake level (Fig. 2). Post MCA, a transition to wetter conditions within the first phase of the LIA is apparent between 600–500 cal yr BP (Fig. 2). Peak sediment influx and the development of swamp conditions (Omuombo et al. 2020) are observed during this time. A relatively stable lake level from 500–290 cal yr BP that has persisted to the present day shows subtle responses to drier conditions. Charcoal particles were visible in the sediments during this stable period, but the link to either anthropogenic or natural fires is yet to be resolved. Anthropogenic influence in our sedimentary record cannot be excluded, even though the first documented human occupation of Mt. Kenya was shortly after this period (ca. 200 cal yr BP). The lake has not changed significantly since 290 cal yr BP, perhaps pointing to the vital role of groundwater recharge from springs located above the lake in stabilizing lake levels.

The role of paleo information in conservation for Mt. Kenya

Lake Nkunga lies at the border of the dry montane forest zone of Mt. Kenya and a human occupation area. It serves as a water source for the villages around it and the wildlife within the Mt. Kenya Forest ecosystem. Recently, concerns were voiced regarding the terrestrialization of the lake due to the presence of reeds and floating mats of water lilies, sedges, and ferns that have restricted access to lake water. While catchment erosion and weathering processes from anthropogenic activities play a significant role in sediment supply in lakes, our record shows that from 290 cal yr BP to present, the sedimentation rate has declined from 0.4 cm/yr to a constant rate of 0.3 cm/yr. The current efforts to reclaim the lake include weed control and the establishment of an ecotourism site through the development of picnic areas, camping sites, and nature trails to increase community income.

Continued use and future development of Lake Nkunga's forested catchment need to be considered in the context of long-term lake-level changes and internal processes. The lack of a distinct anthropogenic signal from the Lake Nkunga record presents a baseline for the impact of future activities within the lake's catchment. Mt. Kenya Forest provides an important habitat for wildlife in the region, and thus conservation efforts are warranted. Our insights from the paleorecord of lake hydrology suggest that it is indeed important to conserve the forested catchment as a means to sustain the groundwater recharge to the springs that feed the lake. These springs play a critical role in managing the lake water budget (Fig. 1). The integration of paleo information into modern day management of natural resources is lacking despite the availability of such data from several additional sites in East Africa. Better informed governance and management of natural resources, especially during these unprecedented times of changing climatic and environmental conditions, is therefore possible. Consideration of past, present, and future changes could allow for the integration of catchment management policies critical for reaching sustainable development goals.

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A window into the Anthropocene through lake-sediment records in central Chile

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Stable nitrogen isotopes on organic matter from lake sediments in central Chile combined with reconstructions of land-use and cover change show the magnitude of human influence and the onset of the Great Acceleration.

The Anthropocene in central Chile

The Anthropocene has been proposed as a new geological epoch where humankind has become a major driver of the Earth's biosphere and surface processes to an extent that can be readily observed in the sedimentary record (Crutzen and Stoermer 2000). The Anthropocene Working Group of the International Commission on Stratigraphy (https://stratigraphy.org) has recently defined the starting point of the Anthropocene at around 1950 CE, which marks a period of dramatic change in magnitude and rate of the global human activity (the Great Acceleration; Zalasiewicz et al. 2019). However, this date remains a point of contention as agricultural impacts (and associated impacts) have been increasing throughout the Holocene (Ellis et al. 2016; Ruddiman 2019; Zalasiewicz et al. 2019).

Nitrogen, carbon, and phosphorus biogeochemical cycles can all affect primary productivity, and their alteration can cause serious environmental problems such as cultural eutrophication and contamination of terrestrial and aquatic ecosystems. Records of past variations in biogeochemical cycles can help unravel the timing and intensity of the Anthropocene (Wolfe et al. 2013; Zalasiewicz et al. 2019). Humans have had important impacts on the landscape of the Pacific coast of central Chile at least since the Spanish colonial period (16th to 18th centuries). These have been associated with agriculture development, increased fire regimes, and deforestation of native species (Armesto et al. 2010; Gayo et al. 2019). Nowadays, most human impact is related to increasing demands for tree plantations of exotic species (especially *Pinus radiata* and *Eucalyptus globulus*).

We studied two coastal lakes from central Chile to examine the structure and timing of the Anthropocene and the onset of the Great Acceleration. For this, we compared land-use and cover change (LUCC) with stable nitrogen isotopes on lake organic matter ($\delta^{15}N_{om}$) and multiproxy analyses from lake sediments. The Laguna Matanzas watershed (30 km² surface area; Fig. 1b) was mainly occupied by native forest and grassland areas in 1975 CE, but by 2016 CE, tree plantations covered a third of the total area. At Lago Vichuquén, only 1% of the watershed (535.3 km² surface area; Fig. 1c) was covered by exotic tree plantations in 1975 CE; however, these increased up to 66% by 2016 CE.

Watershed-lake dynamics inferred from the sediment record

The Br/Ti ratios in lake sediment from coastal lakes of central Chile are commonly elevated with high organic carbon content, indicating higher lake productivity (Frugone-Álvarez et al. 2017; Fuentealba et al. 2020). Similarly, fluctuations in $\delta^{15}N_{om}$ in lake records have been used as an indicator of changes in paleoproductivity and/or watershed disturbances (Das et al. 2009; Torres et al. 2012).

Historic LUCC in the Laguna Matanzas watershed began during the Spanish colonial period with a Jesuit settlement in 1627 CE and the development of a livestock ranch. After the Jesuits were expelled from South America in 1778 CE, the ranch reached more than 40,000 head of cattle around 1800 CE. During this first period, the watershed-lake dynamics displayed moderate-to-low productivity (Br/Ti; Fig. 2) with elevated sediment input as indicated by our geochemical proxies (Ti; Fig. 2; Fuentealba et al. 2020). Sediment $\delta^{15}N_{om}$ values from the 14th to 19th centuries were relatively high, probably reflecting N inputs from cow manure and soil particles that typically generate higher sediment $\delta^{15}N_{om}$ values (Fig. 2). From the 19th to mid-20th centuries, these overall patterns did not change. The $\delta^{15}N_{om}$ and total nitrogen (TN) values were slightly lower than during the Colonial Period and changes in both were in phase and relatively synchronous.

The implementation of the Chilean Forestry Law Decree of 1931 (DFL n°265) contributed to a strong development of forestry that was coeval with decreased sediment input (low Ti) from the watershed and slightly increased lake productivity (higher Br/Ti). Until the 1970s, the Laguna Matanzas watershed was mostly covered by native forest, and grassland areas were intended for livestock grazing (Fig. 1; Fuentealba et al. 2020). From the 1980s onwards, sediment $\delta^{15}N_{om}$ values decreased, reaching their lowest values in the entire sequence at ca. 2000 CE. During the 21st century, the sediment $\delta^{15}N_{om}$ values increased in tandem with the highest TN values seen in the record (Fig. 2). The increased lake productivity, the sharp change in $\delta^{15}N_{om}$ trend, and the decreased sediment input during the last few decades has been synchronous with the replacement of intensive livestock grazing by intensive agriculture and forestry practices (Fuentealba et al. 2020).

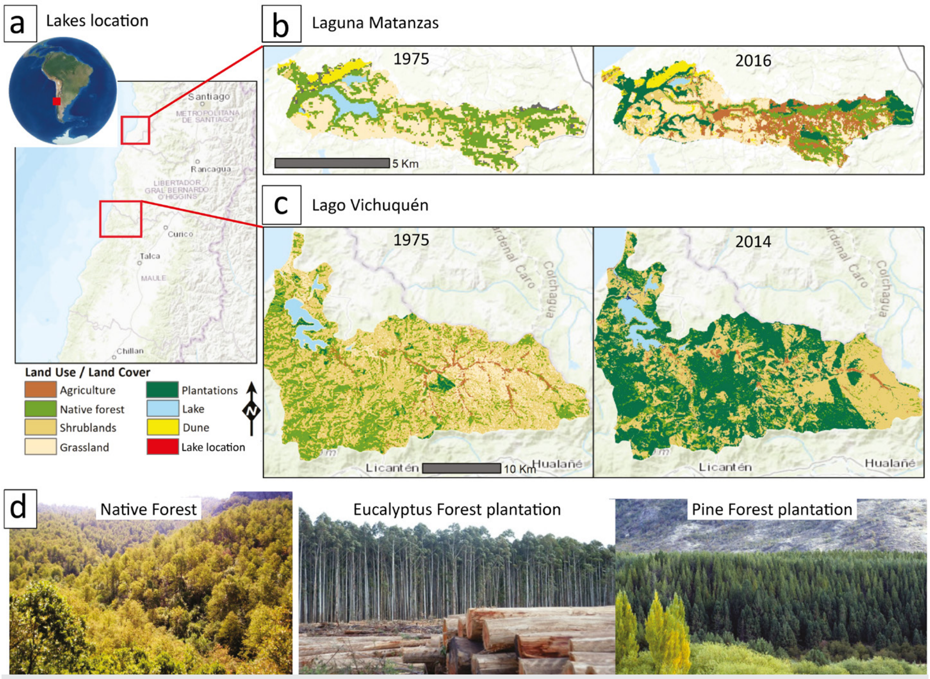

Figure 1: (A) Location of Laguna Matanzas and Lago Vichuquén in South America. **(B)** and **(C)** Land-use and cover changes in both watersheds from 1975 CE and 2014 (Lake Vichuquén) and 2016 (Lake Matanzas) CE (map sources: Esri, HERE, Garmin, World Topographic Map). **(D)** Examples of native forests compared with tree plantations in central Chile.

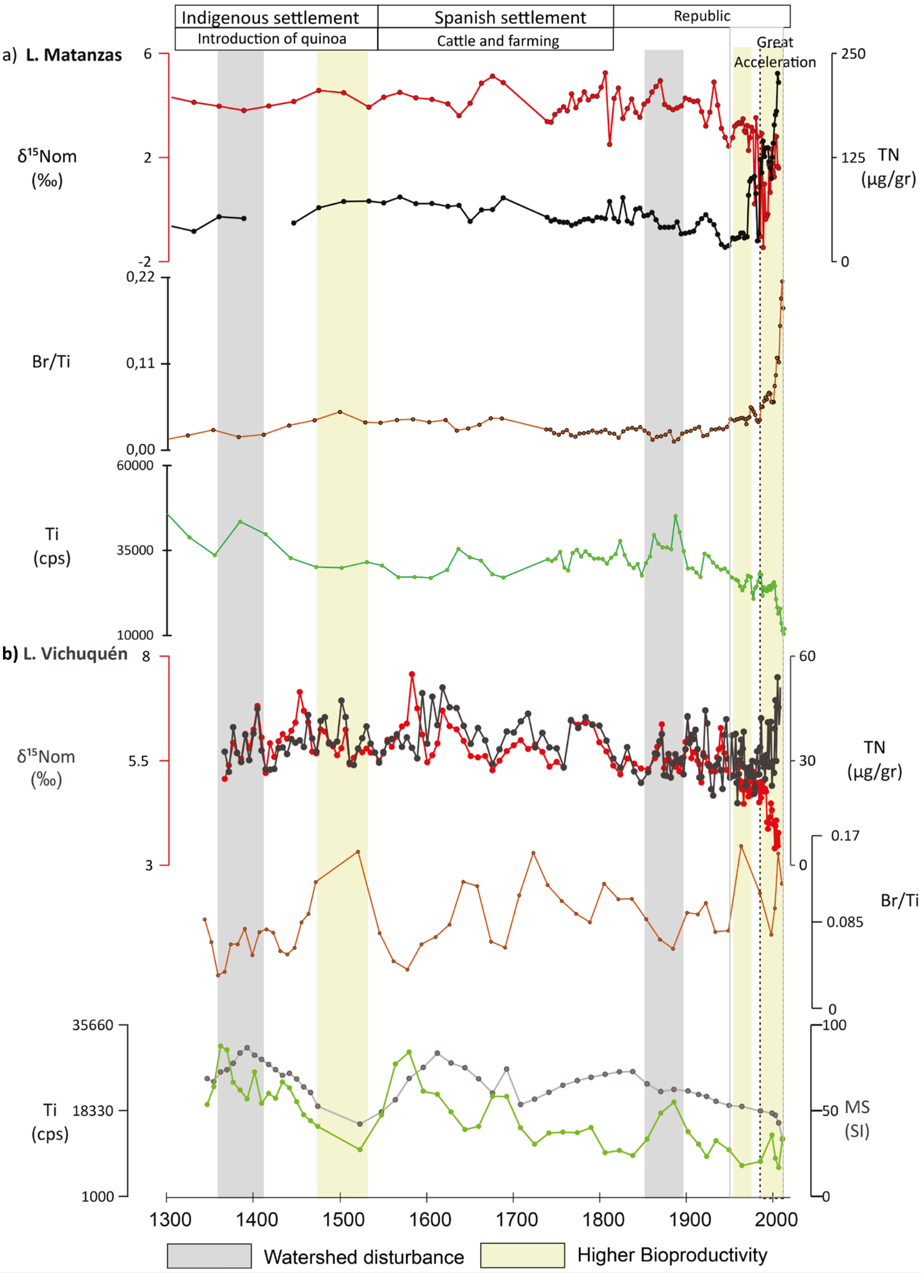

Figure 2: Anthropogenic influences on changes in the N availability and lake productivity during the last six centuries in central Chile (Laguna Matanzas and Lago Vichuquén). Higher sediment $\delta^{15}N_{om}$ values (red line) covaried with the TN (black line), indicating higher lake productivity (Br/Ti) after periods of watershed disturbance (magnetic susceptibility, Ti).

Land use during the colonial period in Lago Vichuquén was characterized by agriculture, cattle ranching, and mining under the Encomienda (feudal) system (Vidal and Ramírez 1985). Historical documents show that before 1580 CE, the Vichuquén watershed was occupied by Indigenous communities dedicated to small-scale farming, extracting wood, and mining activities. The sediment $\delta^{15}N_{om}$ values from this period covary with TN, indicating pulses of enhanced N input from the watershed were likely linked to an increase in land use and sediment input (indicated by changes in magnetic susceptibility and Ti content in Fig. 2).

From the onset of the 19th to the mid-20th centuries, $\delta^{15}N_{om}$ and TN values decreased slightly, most likely related to lowered sediment input from the watershed until the second half of the 19th century. In contrast, the last part of the 20th century witnessed accelerated changes in the watershed as native forests, meadows, and shrublands were quickly replaced by exotic tree plantations (Fig. 1). These changes were synchronous with a major regime shift in the nitrogen cycle as observed by an increase in TN along with lowest $\delta^{15}N_{om}$ values seen in the record.

The $\delta^{15}N_{om}$ lake-sediment record as a tracer of the Anthropocene

Numerous records indicate that the onset of the Great Acceleration in the Northern Hemisphere was around 1950 CE (e.g. Holtgrieve et al. 2011; Rose 2015; Zalasiewicz et al. 2019). However, the timing and magnitude of human activities were likely different between and within the hemispheres. Our results from Laguna Matanzas and Lago Vichuquén show elevated TN concentrations in tandem with the lowest sediment $\delta^{15}N_{om}$ values in the entire record during the 1980s (Fig. 2). Thus, human activities associated with exotic tree plantations clearly had major impacts on the watershed-lake dynamics and nitrogen cycling in central Chile, several decades after the onset of the Great Acceleration. Although nitrogen dynamics respond to limnological processes as well, both lakes crossed a critical threshold, not seen in more than three centuries, during the 1980s due to regional processes associated with national policy changes and government subsidies.

Our study shows that during the historical period in Chile it is not necessarily the presence of human activities *per se* that alters watershed-lake dynamics, but rather the magnitude and intensity of such activities associated with major land-use and cover changes. The increase in tree plantations and intensive agriculture over the last 40 years (since the late 70s and early 80s) has contributed to a shift in sediment input and nutrient transfer to Laguna Matanzas and Lago Vichuquén, affecting productivity in a way that is unprecedented during the last 500 years. Though the Anthropocene and the Great Acceleration have been formally defined globally, we note that local and regional impacts often produce major changes in sedimentary records that are often at odds with these definitions. In the case of heavily populated central Chile, these impacts began with intense activity associated with extensive exotic tree plantations that started in the 1980s, three decades after the beginning of the Great Acceleration.

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Archives of the El Niño-Southern Oscillation: A coral point of view

Allison E. Lawman[1,2], J.W. Partin[2] and S.G. Dee[1]

Proxy system models provide a tool to link paleoclimate proxy data with instrumental observations or climate model output. Recent advances in coral proxy system modeling cement the fidelity of tropical Pacific corals in recording changes in El Niño-Southern Oscillation variability.

Reconstructing ENSO variability using corals

The El Niño-Southern Oscillation (ENSO) is a tropical climate phenomenon that has global impacts on temperature and rainfall patterns. Given its role as the leading mode of interannual variability and the socioeconomic impacts associated with these events, it is of paramount importance to understand how ENSO may change in the future with anthropogenic warming. Tropical climate variability is a source of notable uncertainty in future climate projections (Bellenger et al. 2014; Collins et al. 2010). While simulations provide insight into how ENSO may behave in a warmer world, they often lack critical constraints from physics (Collins et al. 2013), and require independent validation to assess the accuracy of a model's performance. This motivates the study of past ENSO variability during periods when Earth experienced different conditions compared to today's rapidly warming climate.

Corals are a paleoclimate archive well-suited for studying ENSO variability, as they store decades to centuries of sub-annually resolved proxy climate information from the tropics (Fairbanks et al. 1997; Lough 2010). Modern corals serve to calibrate proxies with the instrumental record, while fossil corals provide snapshots of interannual variability during pre-industrial times. In particular, the ratio of strontium to calcium (Sr/Ca) and the oxygen isotopic composition ($\delta^{18}O$) of the coral skeleton are well-established proxies for oceanic conditions. Coral Sr/Ca varies in response to changes in sea-surface temperature (SST), while coral $\delta^{18}O$ jointly records changes in SST and the ratio of the oxygen isotopic composition of seawater to salinity ($\delta^{18}O_{seawater}$/salinity; Corrège 2006; Lough 2010).

Proxy system modeling as a tool to quantify uncertainties

On interannual timescales, corals from the tropical Pacific are influenced by ENSO, local variability, and how the coral itself records climate information. Since corals are widely used to reconstruct paleo-ENSO variability, it is critical to quantify how these factors impact estimates of interannual variability in proxy records. A proxy system model (PSM) is a tool that quantifies sources of uncertainty by mathematically modeling how different processes impact a climate signal that emerges from the proxy data (Dee et al. 2015; Evans et al. 2013). Paleoclimate proxy data is often used to reconstruct climate variables, such as temperature, via empirically determined calibration equations. Alternatively, a PSM can use observed or simulated climate information and generate a forward-modeled time series of what a hypothetical proxy under those conditions would record, i.e. a "pseudoproxy". This calculation translates the climate signal to a proxy signal and considers ways by which the proxy alters the input signal. PSMs thus provide a means to directly compare proxy data and instrumental observations or climate model output *in the same units*.

Coral proxy system modeling work by Thompson et al. (2011) provides an example of a transfer function used to forward model "pseudocoral" $\delta^{18}O$ as a linear combination of SST and $\delta^{18}O_{seawater}$/salinity. This sensor model has since been used for many purposes, including comparing coral $\delta^{18}O$ records with pseudocoral time series generated from instrumental observations and historical climate model simulations (Thompson et al. 2011), and quantifying errors in coral-inferred estimates of ENSO amplitude (Russon et al. 2015) and variability (Stevenson et al. 2013). Our recent coral PSM builds on this and earlier studies by adding new features, called sub-models, into an existing coral PSM framework (Lawman et al. 2020). We use temperature and salinity output from the Community Earth System Model Last Millennium Ensemble (CESM-LME; Otto-Bliesner et al. 2016) to model pseudocoral $\delta^{18}O$ and SST derived from coral Sr/Ca ($SST_{Sr/Ca}$) and quantify how uncertainties associated with assumptions about (1) analytical and proxy-calibration errors, (2) variable coral growth rates, and (3) coral age-depth modeling impact estimates of interannual variability, here defined at the standard deviation of $\delta^{18}O$ and $SST_{Sr/Ca}$ anomalies.

Our results demonstrate that calibration and analytical errors increase estimates of interannual variability in coral geochemical records, whereas variations in growth rates, when combined with certain age modeling assumptions, systematically decrease estimates of interannual variability. When all three sub-models are coupled, we find that such factors can measurably change the standard deviation of $\delta^{18}O$ and $SST_{Sr/Ca}$ anomalies on the order of 10-30% compared to the original, and that the relative importance of each sub-model is specific to individual sites (Fig. 1). We attribute the degree of site-specific changes in interannual variability to the tradeoff between the strength of the interannual signal (ENSO) and the amplitude of the SST annual cycle at a given site.

The PSM is a useful tool for not only quantifying how various coral uncertainties manifest locally at individual sites, but also how they impact a coral's ability to broadly capture changes in ENSO variability. The Niño 3.4

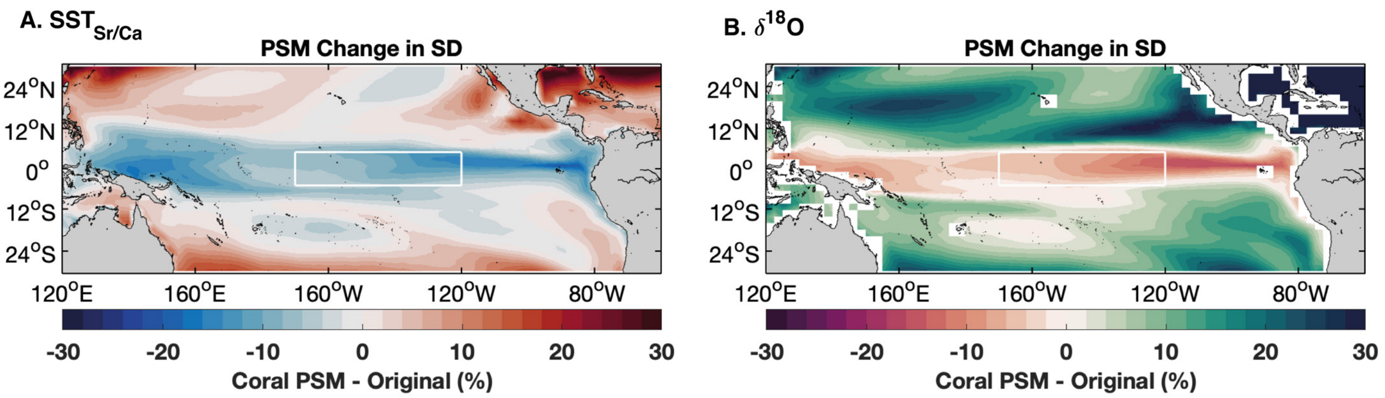

Figure 1: Percent difference in standard deviation (SD) between pseudocoral **(A)** $SST_{Sr/Ca}$ and **(B)** $\delta^{18}O$ anomalies perturbed with variable growth rates, analytical/calibration errors, and the age modeling algorithm (n = 100 realizations), and the original, unperturbed environmental input. The white box outlines the Niño 3.4 region. The model output used here and in Figure 2 is from the CESM-LME 850 control simulation (Otto-Bliesner et al. 2016). Figure reproduced with permission from Lawman et al. (2020).

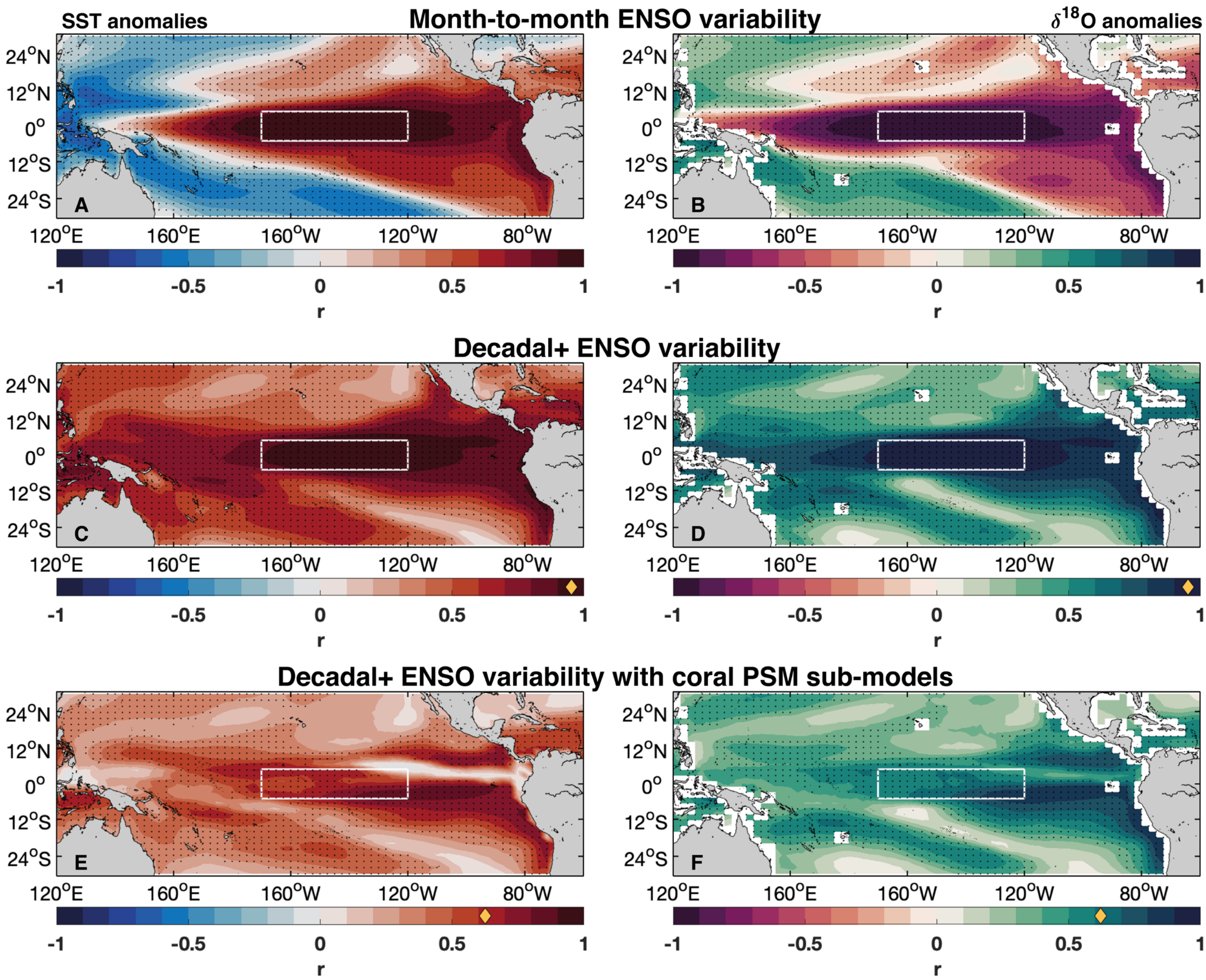

Figure 2: Correlation between Niño 3.4 SST anomalies and values at each grid point. Monthly Niño 3.4 SST anomalies correlated with monthly **(A)** SST anomalies and **(B)** $\delta^{18}O$ generated using the sensor model of Thompson et al. (2011). The 20-year running SD of Niño 3.4 SST anomalies (i.e. decadal+ changes in ENSO variability) correlated with **(C)** SST and **(D)** pseudocoral $\delta^{18}O$ anomalies. The 20-year running SD of Niño 3.4 SST anomalies correlated with **(E)** $SST_{Sr/Ca}$ and **(F)** pseudocoral $\delta^{18}O$ anomalies perturbed by the three coral PSM sub-models. Statistically significant correlations ($p < 0.01$) are stippled. The gold diamond (C-F) indicates the average correlation coefficient for the Niño 3.4 region (white box). Figure reproduced with permission from Lawman et al. (2020).

region has been identified as a "center of action" for ENSO (Fig. 2a-b), and the month-to-month correlation between SST and SST anomalies over this region is a common metric for assessing the ENSO sensitivity at a site. However, fossil corals with absolute age errors on the order of 1% preclude such a precise month-to-month reconstruction back in time. To address this limitation, we investigate how local $\delta^{18}O$ and $SST_{Sr/Ca}$ variability track changes in ENSO variability on decadal and greater timescales (decadal+) using the correlation between the running standard deviation of pseudocoral $\delta^{18}O$ and $SST_{Sr/Ca}$ anomalies with Niño 3.4 SST anomalies (Fig. 2c-d). Although the correlations are, as expected, smaller (Fig. 2e-f) than the original inputs not processed with the three PSM sub-models, the temporal relationship between changes in the pseudocorals and changes in Niño 3.4 SST variability is broadly preserved. Many circum-Pacific locations, particularly those near coral atolls, demonstrate statistically significant correlations with ENSO changes. This highlights the ability of corals from across the tropical Pacific to capture decadal+ changes in ENSO variability.

Future perspectives

Although different processes and assumptions inherent to paleoclimate studies may impact estimates of interannual variability recorded by corals, our recent PSM work highlights the strength of corals in their ability to capture decadal+ changes in ENSO variability. It is most appropriate to compare coral geochemical data with instrumental or climate model output processed through a PSM, as it places the two types of data on a more level playing field. To help facilitate such comparisons, our new PSM sub-models are publicly available to the climate community via a GitHub repository (https://github.com/lawmana/coralPSM). Future work comparing coral geochemical data with climate model observations translated to coral units using a process-based PSM will be a key step toward reconciling differences between models and coral geochemical observations. It is our hope that sharpening our data-model comparisons for the tropical oceans will allow us to refine the implementation of important physical processes in models, thereby reducing uncertainties in future ENSO projections.

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Data-based evaluation of paleoclimate records from the terrestrial Indian region: Opportunities and gaps

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Speleothem, tree-ring, and borehole archives represent the majority of publicly available proxy data from the terrestrial Indian region for investigating local climatic responses to past global circulation changes. Increasing access to data from lake-sediment archives will open new opportunities for climate research in this region.

A case for data

In the last decade, the paleoclimate field has made tremendous progress in the domains of statistical analysis of regional- to continental-scale proxy data (Tardif et al. 2019), numerical modeling (Owen et al. 2018), and data-model comparisons (Comas-Bru et al. 2019) to gain a better understanding of the processes driving climate and to improve future climate predictions. However, these analyses are only possible if data are made available by the initial data generators in supplementary information sections of published articles or in online data repositories. Synthesizing data from these different sources for regional- to continental-scale data analysis then requires further data wrangling, which is estimated to consume 80% of researcher time in some scientific fields (Dasu and Johnson 2003). The NOAA, PANGAEA, and Neotoma repositories and PAGES working groups address this issue by standardizing and, in some cases, synthesizing data. Here, we examine proxy data from the terrestrial Indian region available from the aforementioned sources and suggest the best ways to access data. We show gaps between data that have been measured but are not yet available, which will require an archive-specific, community-based effort. We highlight data that are available and should be considered for future comprehensive data-based analysis.

Distribution of accessible terrestrial Indian paleoclimate data

The terrestrial Indian region has been geographically divided into north, northeast, and peninsular subregions, which have distinct sources of moisture and climates (Fig. 1). Paleoclimate records in databases and repositories are available from speleothem, lake, tree-ring, and borehole archives. North and peninsular India have a high density of paleoclimate records from multiple archives. Northeast India has only speleothem records. Records from the central Indian Indo-Gangetic plain are conspicuously lacking. The geologically oldest proxy records are from speleothems, with the north Indian Bittoo cave record extending intermittently to ~280,000 years before present (Fig. 2). Most of the remaining speleothem records from all three regions cover the last ~30,000 years. Lake records cover the last ~15,000 years, while tree-ring and borehole records cover the last ~500 years.

The NOAA repository hosts the highest number of tree-ring standard-growth index and isotope records, all borehole records (which are part of a single study), and a few speleothem stable isotope and trace element records (Table 1 in the html version of this article). The highest number of speleothem oxygen and carbon isotopic proxy records with standardized data and metadata have been made available by the PAGES working group Speleothem Isotope Synthesis and AnaLysis (SISAL) as sql and csv files. Lake records can be found in the PANGAEA and Neotoma repositories. Many speleothem, tree-ring, borehole, and lake records covering the last 2000 years have been made available by the PAGES 2k Network with extended data and metadata in different formats in the NOAA repository and in FigShare.

Opportunities and gaps

Speleothem oxygen isotopic records provide sub-decadal- to millennial-scale information of past circulation and monsoon conditions from the terrestrial Indian region (Kaushal et al. 2018). They can be used for isotope-enabled climate model-data comparisons to improve our process-based understanding of controls on the monsoon (Battisti et al. 2014) and increase confidence in the ability of climate models to predict future changes (Schmidt 2010). As of yet, only very limited spectral analysis of existing oxygen and carbon isotopic records from the terrestrial Indian region has been performed to identify sub-decadal- and decadal-scale monsoon patterns (Midhun et al. 2020). Similarly, speleothem carbon isotopic and trace element records are increasingly being used to understand past changes in local

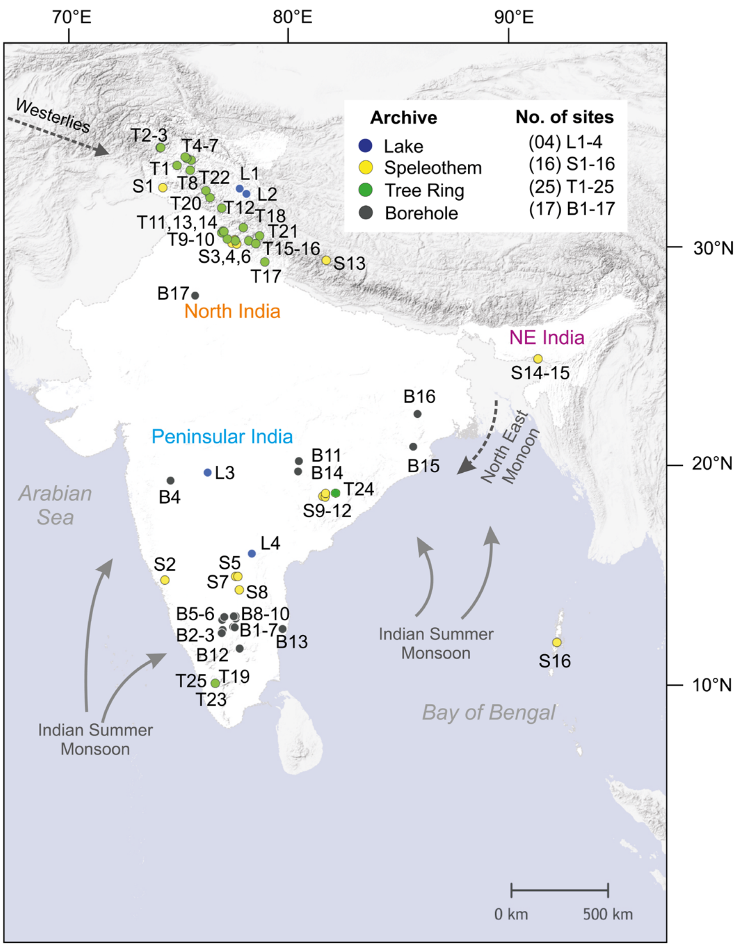

Figure 1: Spatial distribution of paleoclimate records from the terrestrial Indian region available in NOAA, PANGAEA, and Neotoma repositories and made available by PAGES working groups. Detailed information of archives, records and sources are given in the table hosted at https://doi.org/10.5281/zenodo.4292977.

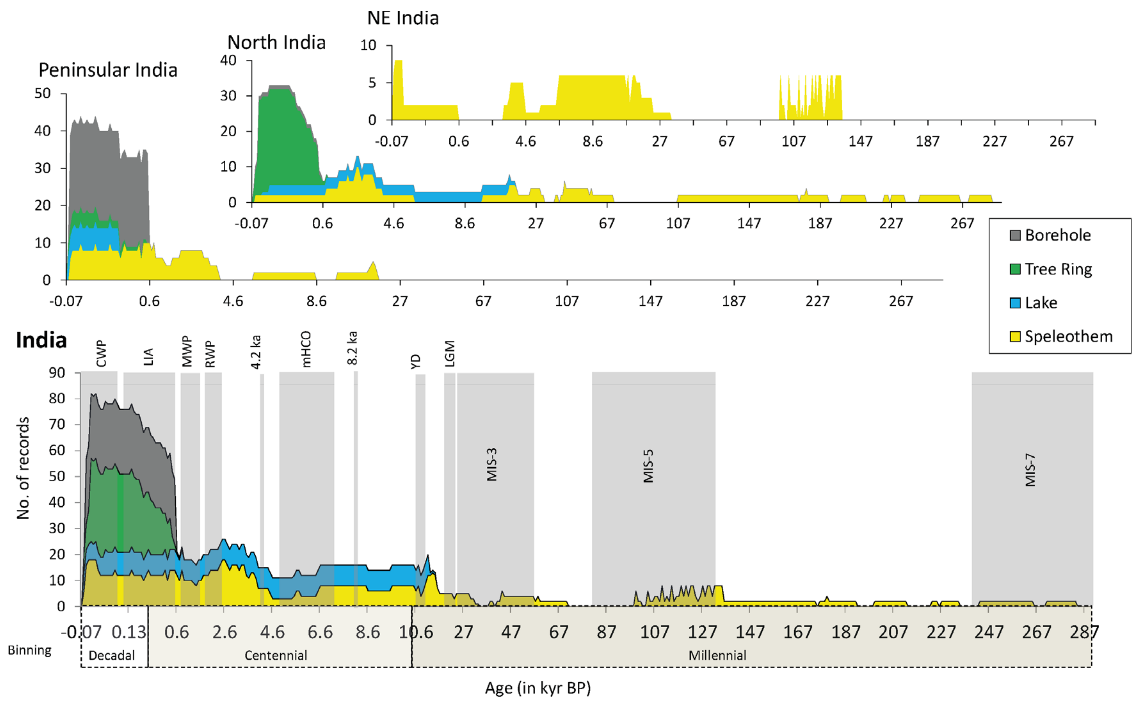

Figure 2: Temporal distribution of paleoclimate records from the terrestrial Indian region. CWP: Current Warm Period; LIA: Little Ice Age; MWP: Medieval Warm Period; RWP: Roman Warm Period; 4.2 ka: 4.2 ka Dry event; mHCO: Mid-Holocene Climate Optimum; 8.2 ka: 8.2 ka event; YD: Younger Dryas; LGM: Last Glacial Maxima; MIS 3, 5 and 7 are Marine Isotope Stages.

climatic and environmental conditions in regions around the globe (Fairchild and Treble 2009; Fohlmeister et al. 2020); however, there are currently few measurements of trace elements or analysis of these proxy data from the Indian region.

Tree-ring growth indices produced from conifer and teak trees provide the highest resolution information of terrestrial climate in India. Tree-ring data are useful for continental-scale reconstruction and analysis of past droughts and temperatures (Cook et al. 2010; PAGES2k Consortium 2017). Millennium-long tree-ring chronologies developed in the terrestrial Indian region (Yadav et al. 2011; Yadav 2013) offer an opportunity to decipher centennial-scale climate variability and to understand prevailing climate during important phases such as the Medieval Warm Period, Little Ice Age, and Current Warm Period. The scarcity of trees with annually resolved tree rings is one of the main reasons for having only a few tree-ring datasets from peninsular India (Fig. 1). A "tree ring" defined based on the seasonality in the isotopic record of trees (Evans and Schrag 2004) could provide the necessary chronology to reconstruct past climate using trees lacking discernible growth rings. Such analysis can be used to decipher past variability in the frequency and intensity of the dry spells during monsoons (Managave et al. 2010), and in simultaneously reconstructing southwest and northeast monsoonal rainfall (Managave et al. 2011).

Lake sediments provide archives of regional to global climate change. Continuous sedimentation allows climatic variability to be assessed over several millennia through analysis of organic (e.g. pollen, carbon isotopes, total organic carbon, lipid biomarkers, diatoms) and inorganic (e.g. grain size, elemental chemistry, environmental magnetism; e.g. Rawat et al. 2015a, b; Sarkar et al. 2015) proxies. India hosts many natural lakes extending from the high-altitude alpine Himalayan regions to the tropical peninsula. Because most Indian lakes are non-varved and receive low sedimentation, they can provide semi-quantitative rainfall estimates only at centennial resolution. More than 76 lake records from India have been analyzed in the literature (Misra et al. 2019); however, as of yet only nine proxy records from four lakes have been made available in databases and repositories. A paleolimnological community-based effort is required to both produce new data from India's many lakes and increase the availability of previously collected lake-sediment records.

Summary

Our analysis suggests that paleoclimate work in the Indian region can be improved by (1) increasing the number and accessibility of lake-sediment records regionwide, (2) generating data from records that extend beyond the last 15,000 years, and (3) generating data from geographically under-represented subregions, such as the central Indian Indo-Gangetic plain. Combining information across the diverse proxy records in the repositories and databases will provide opportunities to assess factors influencing major moisture drivers and mechanisms associated with westerlies and the Asian monsoon system.

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Yadav RR (2013) J Geophys Res Atmos 118: 4318-4325
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LINKS

PAGES2k Consortium (2017):
NOAA: https://www.ncdc.noaa.gov/paleo/study/21171
FigShare: https://figshare.com/collections/A_global_multiproxy_database_for_temperature_reconstructions_of_the_Common_Era/3285353
SISAL database v2.0: researchdata.reading.ac.uk/256/
NOAA repository: https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets
PANGAEA repository: https://pangaea.de/
Neotoma database: https://www.neotomadb.org/
SISAL working group: pastglobalchanges.org/sisal
PAGES 2k Network: pastglobalchanges.org/2k

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An approach to collaboration through horizon scanning in the field of sclerochronology

Madelyn J. Mette[1], T. Trofimova[2], S.J. Alexandroff[3] and E. Tray[4]

Horizon scanning is an exercise which aims to collaboratively identify research priorities within a field. As exemplified by recent work led by members of the PAGES Early-Career Network in the field of sclerochronology, additional benefits include gained experience in collaboration, networking, and knowledge development.

Defining top research priorities within a discipline is a common pursuit toward advancing the state of the art. An increasingly applied strategy, termed "horizon scanning", relies on community-based input and collaboration through surveys and rating systems to develop a combined perspective on important emerging topics and/or persistent challenges in the field (Sutherland et al. 2011). The concepts are then presented as research questions to be addressed within continuing and future work, providing a kind of roadmap for development of the field (for recent examples see Patiño et al. 2017; Sutherland et al. 2020).

Following this objective, four members of the PAGES Early-Career Network (authors of this article; PAGES ECN; pastglobalchanges.org/ecn), recently led a horizon-scanning exercise for the field of sclerochronology. This field encompasses the study of physical and chemical variations in the accretionary hard tissues of organisms, and the temporal context in which they formed. Physical and geochemical proxies from coral, bivalve, and otolith archives, for example, contribute to research questions across ecology, paleoclimatology, archaeology, and other fields. Sclerochronology has experienced significant growth over the past decade, with new methods and applications continually being explored. Because of this, we realized the need and an opportunity to formulate research priorities within our field.

Published as part of a special issue after the 5th International Sclerochronology Conference in Split, Croatia (ISC; June 2019), a manuscript by Trofimova et al. (2020) represents the first peer-reviewed scientific product by the PAGES ECN. The manuscript was strengthened by the significant involvement of 23 additional experts (and coauthors) in sclerochronology. The work can serve as a long-standing resource to be reassessed as the field develops. Completion of the project gives us the opportunity to reflect on the process and its impact on those involved. In this article, we provide a brief description of our process and scientific findings followed by discussion of some of the strategies we used and lessons learned in our approach to collaboration. We suggest that such horizon-scanning projects can provide huge benefits to early-career researchers, especially by giving them increased visibility, allowing them to develop a better understanding of the subject area, and providing them with invaluable experience in international collaboration.

Overall process

The sclerochronology horizon-scanning exercise involved soliciting "high priority" research questions from the sclerochronology community, compiling and categorizing the questions, returning the list to the community in the form of a priority-ranking survey, and, ultimately, presenting the top 50 priority research questions alongside brief descriptions of their context and motivation (Fig. 1). The questions were divided into two broad categories: foundations and applications (Fig. 2). Foundations in sclerochronology include questions addressing knowledge gaps in our understanding of sclerochronological archives. This category was further divided into six subtopics. Applications encompass the use of sclerochronological techniques to address long-standing research questions in other fields. This category was divided into three subtopics. An extra category, Cutting-edge sclerochronology, comprised questions that expert coauthors deemed significant or uniquely important even though the community had not ranked them within the top 50.

Results

While the field of sclerochronology has experienced rapid growth over the past few decades, the top priority questions ranked by the community reveal that there is still significant advancement to be made in building upon our foundational knowledge (i.e. the underlying basis for proxy application). For example, an emergent theme from the Foundations section was the need for a better understanding of the mechanisms behind biological control over biomineralization. Top questions also emphasized the establishment and widespread use of common standards for data management and analysis as an important strategy to enable future work. The large number of questions that were focused on applications, however, suggests the field is developed enough to provide new insights into important topics across the natural and social sciences. Top questions highlighted the precise dating and high resolution (at least annual) attainable from many sclerochronological archives as key advantages to solving long-standing questions in climate science and ecology, in particular. The entire list of highest-ranked questions recognizes the breadth of opportunity within the field of sclerochronology (Foundations and Applications), while also acknowledging novel applications that may have been overlooked in the ranking process (Cutting-edge sclerochronology).

Strategies and lessons learned

The triennial ISC provided a venue to discuss our idea with senior colleagues, gain commitment from collaborators, and establish processes moving forward. Project leaders and invited experts shared and debated feedback on our proposed goals and

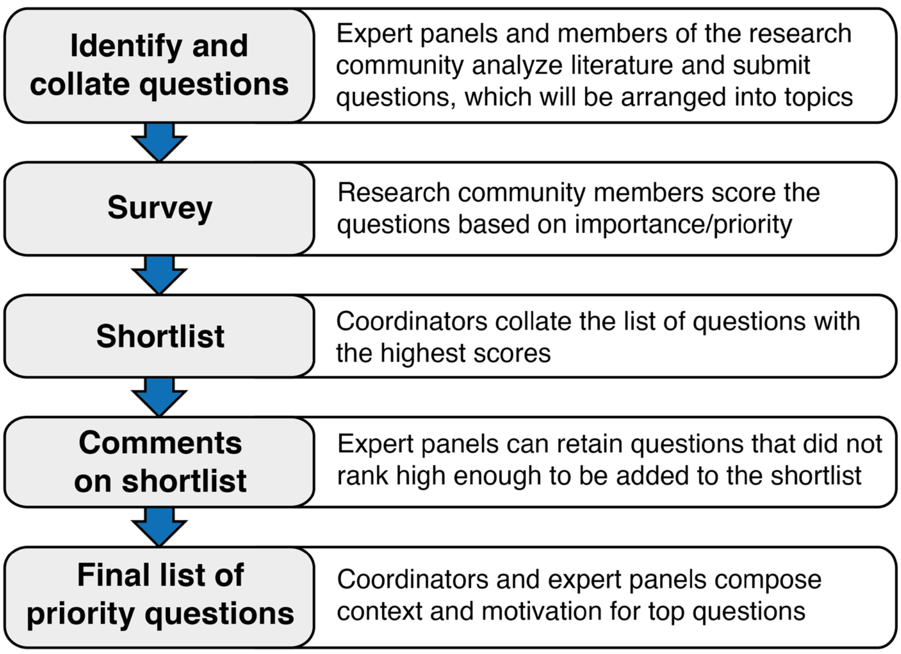

Figure 1: A brief overview of the horizon-scanning process in sclerochronology.

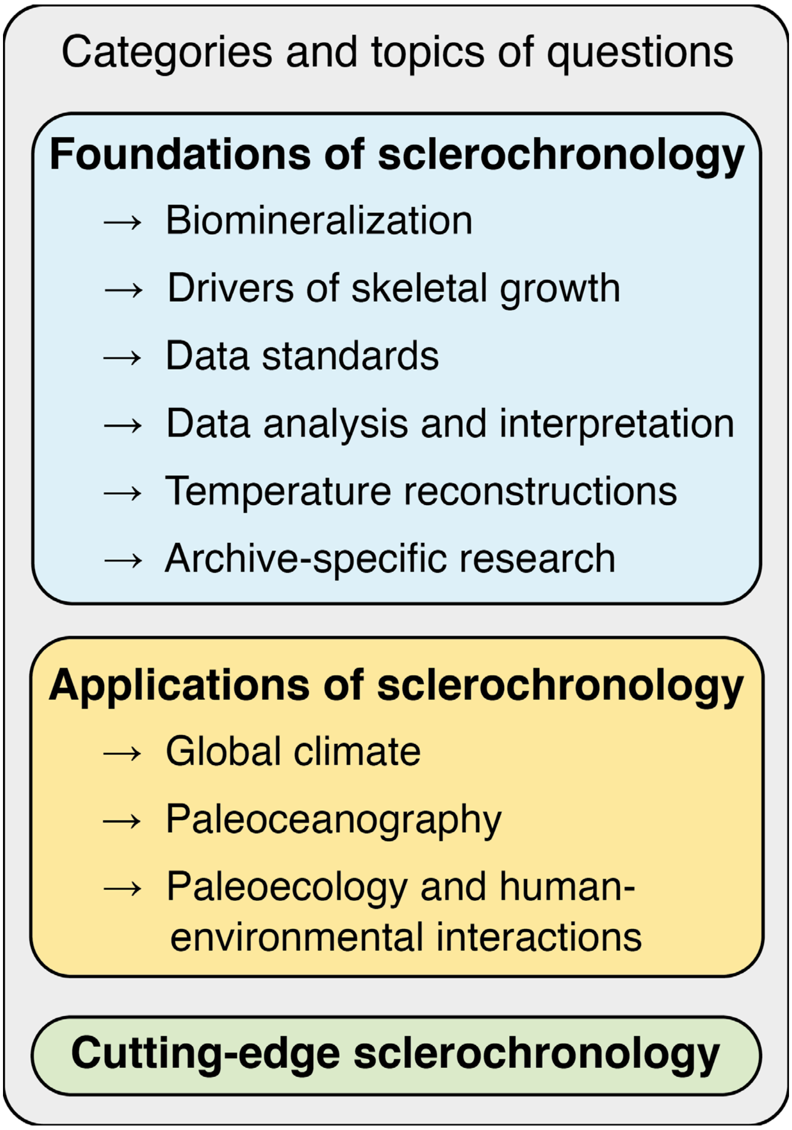

Figure 2: Organization of categories and topics encompassing the horizon-scanning project in sclerochronology, spanning development across foundations and applications of the field. Additional questions retained by expert panels (Cutting-edge) were also presented.

approach. After the conference, the wider sclerochronology community was invited, via email list servers and social media, to submit research questions they deemed important. With 202 initial submissions, deciding how much editorial liberty we should exercise to arrive at a consistent format and use of terminology was a great challenge. Most suggestions required some reformatting in order to be presented on an equal playing field while still preserving their original intent. Providing more clear and strict guidelines during the question submission phase may have alleviated this challenge to some extent.

During our discussions with experts, alternative visions for the article were shared, including the suggestion to present only a handful of broad research "themes" for future work. While we found these suggestions valuable, we were committed to following a traditional horizon-scanning model as exemplified in other fields (e.g. Seddon et al. 2014; Sutherland et al. 2020) as the first such exercise to be performed in sclerochronology. The final list of questions provides ideas for future work and can be pursued as either part or the whole of individual projects.

While research groups independently defining their own research agendas can certainly lead to innovation and progress, a unified research agenda provides an opportunity to cooperatively and more rapidly move the field forward (Sutherland and Woodruff 2009). Furthermore, presenting focused research questions to the community may encourage multiple, reproducible studies on the same subjects, which is essential for reaching scientific consensus. We ultimately received strong and continuous support in this effort throughout the project. Indeed, because we as early-career researchers will inherit the future of the field, we were granted the freedom to follow our vision for contributing to that future.

The broad call to the scientific community resulted in a bias toward some of the most commonly studied archives (bivalves, otoliths), well-represented regions (North Atlantic, Europe), and prevalent research applications (climate science, ecology) presented at the ISC conferences. While an effort was made to properly acknowledge and overcome this bias (see Trofimova et al. 2020 for further discussion), we believe that seeking out the involvement of research groups, more directly and from different fields and regions, could help improve representation across the diversity of sclerochronology, thus providing a more valuable result overall.

We resolved the challenges discussed above through successful international collaboration. Because it was unfeasible to hold virtual meetings with all or even most coauthors, communication to the project team occurred through email and file sharing. The lead authors were primarily responsible for managing questions, discussions, and feedback on two to four subtopics each, followed by review or input on all other subtopics. The coauthors were assigned to expert panels that aligned with their research expertise and tasked with providing feedback on those subtopics. All coauthors had access to one shared document, stored in a cloud, and were given clear instructions on how to use online tools for adding content or providing feedback. This strategy was critical in keeping all authors involved and updated.

Key insights

The collaborative nature of horizon scanning offers an approach which allows early-career researchers, in particular, to significantly contribute to the future of a field. A meaningful byproduct of the exercise was increased visibility, collaborative experience, and knowledge development for those involved. After completion of our horizon-scanning project in sclerochronology, we all felt more equipped to approach multiple subtopics within our field with confidence, having had the opportunity to lead in-depth scientific discussions and help find a consensus among a community of experts. Few other research or training activities could have provided such a comprehensive and rigorous experience. While our project occurred before the COVID-19 pandemic, we recognize that horizon-scanning initiatives may represent prime opportunities to perform large collaborations without the requirement of in-person meetings. The PAGES ECN is well equipped to foster such collaborations through horizon-scanning projects, data compilations, review papers, new research projects, and other pursuits that benefit from broad collaboration.

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DiverseK – Integrating diverse knowledge systems for environmental policy

Daniele Colombaroli[1], M. Coughlan[2], Q. Cui[3], C. Kulkarni[4], J. Mistry[1] and E. Razanatsoa[5]

There is a growing need for more sustainable approaches to tackle future environmental and human livelihood challenges, including biodiversity losses following land-use intensification, and climate impacts under future warmer conditions (Fischer et al. 2018). Conservation plans often lack the full knowledge base to address such challenges (Fig. 1), resulting in conflicts between restoration targets and people's needs. For example, management policies such as fire suppression often contrast with traditional fire-use practices to sustain local livelihoods, or they undermine the key role of disturbance regimes for long-term ecological succession (Coughlan 2013; Kulkarni et al. 2021).

The goal of PAGES' new DiverseK working group is to merge diverse types of local and regional knowledge from science and stakeholders, and to build a more integrative, cross-disciplinary evidence base for better decision-making on environmental and social justice issues. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) only recently adopted a specific framework for Indigenous knowledge (IPBES-5/1), but the role of past legacies and long-term ecological processes are still overlooked in ecosystem management, despite their relevance (e.g. Gillson and Marchant 2014). Synergies between long-term ecology and local/Indigenous knowledge can better support conservation policies to meet landscape conservation targets, for example, by addressing the social-ecological consequences of traditional land management, or identifying the natural and anthropogenic (biocultural heritage) components that maximize biodiversity and resilience in ecosystems (Colombaroli et al. 2019). Such synergies can also help support local communities and other stakeholders as they face the most pressing environmental issues, in ways that are more socially just (Mistry and Berardi 2016).

Scientific objectives

The objectives of DiverseK include methodological advancements, resolution of regional stakeholder-led challenges, and global-scale analyses. We will engage stakeholders in selected areas to foster dialog locally and use our integrated framework to discuss best practices for integration of local knowledge with other disciplines, including fire ecology, paleoecology, and dendroecology. This will provide the ground for a clearer methodological basis for diverse knowledge inclusion, which takes into account ethics and impacts of engagement with local people. Finally, we will focus on areas where conservation targets contrast with the traditional use by local communities and/or the paleoevidence (in terms of baselines, species turnover, community responses, etc.) and identify best management approaches that can be effective in local planning, drawing upon the new integrative knowledge in co-production with stakeholders.

Opportunities for using diverse knowledge systems

The mutual exchange between the scientific and stakeholder communities can provide new opportunities for conservation-based research. For paleoecologists, knowledge of contemporary local practices can aid the interpretation of paleorecords. For local people, in the context of ongoing loss of traditional knowledge, paleoevidence can support local social and environmental-justice struggles. Together, the combination of paleoecology-informed, community-owned and stakeholder-driven knowledge developed from previous collaborations within the former Global Paleofire Working Group 2 (Vannière et al. this issue) can foster dialog between the different disciplines, promoting the inclusion of ecological and socio-cultural disciplines (traditionally separated in academia) and Indigenous knowledge, which represents a key challenge for the science-policy interface (Colombaroli et al. 2019).

Upcoming activities

In the coming year, we plan a series of webinars to involve local communities, academics, and other stakeholders such as protected-area managers, in a process of intercultural exchange to inform environmental management. We welcome participants working at the interface between paleoecology and local knowledge to discuss existing approaches and develop guidelines for best practices.

Visit our website at pastglobalchanges.org/diversek and register for our mailing list to keep up to date with our activities. The working group is also supported by the Leverhulme Wildfires Centre (https://centreforwildfires.org/) and the International Paleofire Network (https://ipn.paleofire.org)

Figure 1: Under warmer conditions and rapid land-use changes predicted for the future, tropical peatlands will require new conservation measures to mitigate the impacts of catastrophic fires (Image credit: Ibnu Fikri).

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HUMAN TRACES

Exploring past human impacts over time and space

Émilie Saulnier-Talbot[1], N. Dubois[2] and J. Boyle[3]

The recently launched Human Traces working group (pastglobalchanges.org/human-traces) aims to bring together scientists from various fields whose work examines archives of anthropogenic activity in the environment. The main goal of the working group is to assemble a shared community resource of Holocene stratigraphic archives optimized to assess drivers and responses to human impacts on the environment and to identify periods of stability and change leading up to the Anthropocene epoch.

In 2019, the Subcommission on Quaternary Stratigraphy voted that the Anthropocene should be treated as a formal chronostratigraphic unit defined by a Global Boundary Stratotype Section and Point (GSSP), to be placed within the 20th century. This vote ended the "Anthropocene" debate, but left the long legacy of pre-Anthropocene human impacts unchanged. Although defining a global "golden spike" has chronostratigraphic value, it may lead to the assumption that all major environmental impacts by human activities are recent. A mid-20th century start to the Anthropocene does not represent the varied history of human activity with regionally asynchronous impacts on the environment that manifested dissimilarly in different parts of the world. Substantial pre-Anthropocene impacts, which can be traced back several thousands of years, and a quantitative understanding of them is essential to managing the planet's resources with the goal of moving towards sustainability.

Lake sediments and other stratigraphic archives such as ice cores serve as long-term records of natural variability and human-induced changes (Fig. 1), making it possible to assess environmental responses to change on various timescales and to link them with either climatic or anthropogenic drivers (Mills et al. 2017). They also allow us to define targets and reference conditions for ecosystem management and conservation, providing a longer-term perspective for recent global changes in the context of the Anthropocene. However, there is still a paucity of long-term environmental regional data, and a global synthesis of human impacts recorded in stratigraphic archives is also lacking.

Scientific goals and activities

Human Traces will focus its scientific activities on collecting and analyzing evidence of the long legacy and build-up of pre-Anthropocene human impacts on the environment with the overarching goal of addressing knowledge gaps about spatial and temporal variations in early human impacts (Dubois et al. 2018). Integral to this work will be the creation of a suitable database of long-term evidence of human impacts from the paleorecord, developed following wide consultation with interested parties.

Activities of the working group will include regular online meetings (every three months) in order to ensure the progress of activities and exchange of information in preparation for in-person workshops. These yearly, if possible, workshops will allow for online participation as well. Meetings and workshops will focus on the identification of the most desirable data types, the collection and quality control of data, database creation, as well as working on crafting of manuscripts based on specific questions relating to various pre-Anthropocene environmental impacts around the world. Summer schools will also be held to foster networking for graduate students, postdocs, and early-career scientists interested in investigating anthropogenic environmental impacts in natural archives at various spatial and temporal scales.

Upcoming meetings and workshops

Our first meeting will be held online in May 2021 (pastglobalchanges.org/calendar/2021/127-pages/2118). An ongoing survey regarding population of the database will be developed and sent out to the PAGES community. The second meeting, focused on the theme: "What is a human impact/trace in a record of broad interest?" and planned for September 2021 (pastglobalchanges.org/calendar/2021/127-pages/2123), will initiate exchanges with other PAGES working groups that also focus on human dimensions: LandCover6k (pastglobalchanges.org/landcover6k), Paleoclimate and the Peopling of the Earth (PEOPLE 3000; pastglobalchanges.org/people3000), and Integrating diverse knowledge systems for environmental policy (DiverseK; pastglobalchanges.org/diversek).

An in-person workshop, specific to lake- and coastal-sediment records, is planned in March 2022, in association with the International Paleolimnology Congress in Bariloche, Argentina, and an interdisciplinary workshop will be held in association with the PAGES Open Science Meeting in Agadir, Morocco, in May 2022. Visit our webpage for more information and to stay up to date: pastglobalchanges.org/science/wg/human-traces/meetings

You can also follow the Human Traces working group on social media!
Twitter: @HTraces
Facebook: facebook.com/HTraces

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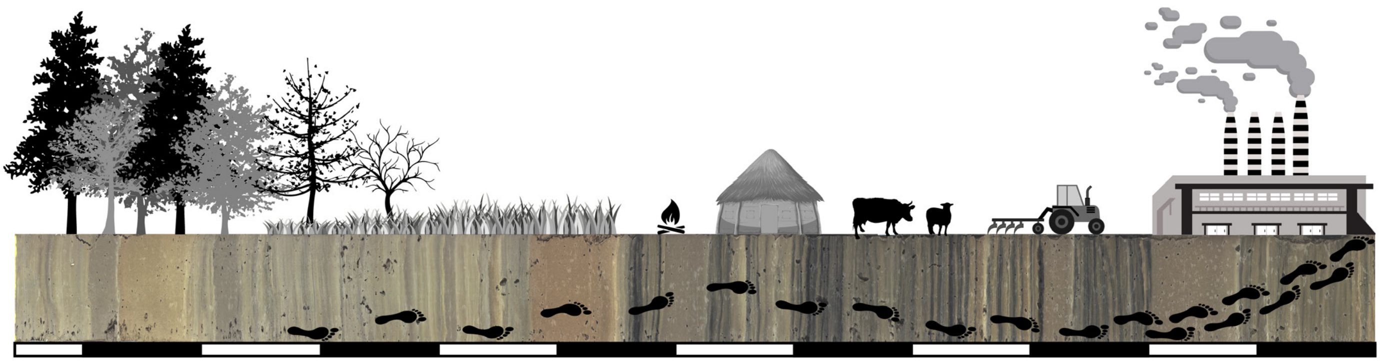

Figure 1: Human traces in sediment archives reflect the history of anthropogenic activities.

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QUIGS

Glacial terminations: Processes and feedbacks

Laurie Menviel[1], E. Capron[2] and R. Ivanovic[3]

Online, 10 and 12 November 2020

The PAGES-PMIP working group on Quaternary Interglacials (QUIGS; pastglobalchanges.org/quigs) and INQUA PALCOM project (https://inqua.org/commissions/palcom) on Terminations Five to Zero (TV-T0) held a virtual meeting on "Glacial terminations: processes and feedbacks" on 10 and 12 November 2020 (pastglobalchanges.org/calendar/2020/127-pages/2054). The meeting focused on the latest data and modeling results on the largest global climate changes of the Quaternary: the glacial-interglacial transitions, also referred to as terminations (Fig. 1).

This first QUIGS-PALCOM virtual meeting, which featured 33 talks, was attended by 70 scientists during both three-hour sessions. The sessions were scheduled so that scientists from across the world could attend at least one session at a convenient time, and the full meeting was recorded. Early-career researchers presented 75% of the talks, thus giving them a great opportunity to present their research to a large group of international experts.

Talks were mainly presented within breakout sessions focusing on (1) deglacial changes in the carbon cycle, (2) deglacial climate and ice-sheet dynamics, and (3) deglacial vegetation dynamics. Most presentations focused on TI (~18–10 thousand years before present; kyr BP) but some also presented results on TII (~140–129 kyr BP) and on older terminations. A few presentations took the broader perspective of the last few million years.

Terminations V to I were interrupted by millennial-scale variability, with a weakening of the Atlantic Meridional Overturning Circulation (AMOC; e.g. McManus et al. 2004; Cheng et al. 2016). New paleo proxy records from the Atlantic Ocean were presented, confirming the occurrence of significant AMOC weakening during TI and TII, while Southern Ocean ventilation was enhanced.

Latest modeling work on Termination I showed that coupled climate models, forced by deglacial ice-sheet evolution and associated meltwater routing, simulate the millennial-scale variability identified in paleorecords, but the simulated timing of these events is not correct. Hence, work remains to better understand the processes involved in the deglacial millennial-scale variability. In addition, some processes currently not taken into account in ice-sheet modeling, such as tidal amplitude and its impact on glacier drainage, could lead to rapid ice-stream deglaciation driven by instability processes.

Talks on deglacial changes in the carbon cycle highlighted the lack of consensus regarding the contribution of the different processes governing the deglacial atmospheric CO_2 concentration increase, i.e. temperature, sea ice, iron fertilization, ocean circulation, and the terrestrial biosphere. Additional proxy records and modeling are still needed.

Discussions mainly focused on (1) the importance of feedbacks during terminations, and particularly the processes leading to the CO_2 rise, given the role of the atmospheric CO_2 increase in the deglacial temperature rise; and (2) the potential misrepresentation of deglacial ice-sheet history, including retention and routing of the meltwater into the appropriate coastal regions, or inappropriate sensitivity of climate models to external forcings.

The meeting highlighted the need to improve our understanding of the deglacial sequence of events, including better constraints on the demise of glacial ice sheets and the associated meltwater routing, the drivers and role of millennial-scale variability, and the processes driving the measured atmospheric CO_2 concentration increase. Additional paleorecords and modeling studies on TII-TV are needed, as they present additional case studies with different climate background and forcing and could thus provide constraints on deglacial processes and feedbacks. TIII (~250 kyr BP) is a particularly interesting case, as changes during this interval are among the fastest over the past 800 kyr, and the millennial-scale dynamics appear to be different compared to other terminations (Cheng et al. 2016; Obrochta et al. 2014).

Robust chronologies for paleoclimatic records are essential in order to decipher the sequence of changes in climate, ice sheets, and the carbon cycle with respect to orbital forcing during glacial terminations. Although more challenging, this is especially true for TII-TV, where radiocarbon dating is not available. Such accurate chronologies are also crucial for robust model-data comparisons.

The joint in-person PAGES QUIGS-INQUA PALCOM TV-T0 workshop "Glacial terminations: processes and feedbacks" is currently scheduled for 21-23 September 2021 in Cassis, France (pastglobalchanges.org/calendar/2021/127-pages/1992). It will focus on understanding whether the deglacial sequence of events influence the following interglacial. The causes for the observed differences between TI and TII will also be discussed in detail.

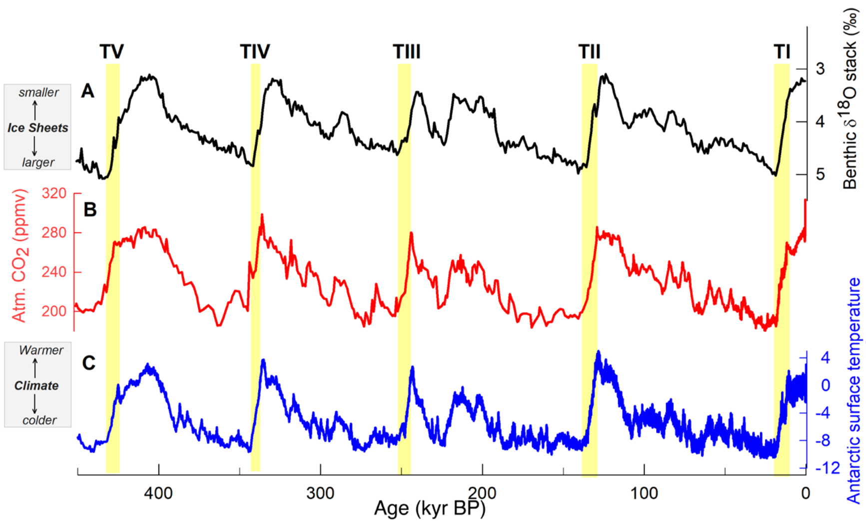

Figure 1: (A) Marine benthic foraminifera $\delta^{18}O$ representing ice-sheet volume (Lisiecki and Raymo 2005); **(B)** Antarctic surface temperature reconstruction from the EPICA Dome C ice core (Jouzel et al. 2007); **(C)** composite atmospheric CO_2 record from Antarctic ice cores (Bereiter et al. 2015). Vertical yellow bars highlight TV-TI.

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PMIP2020 Conference

Jian Liu[1], M. Yan[1], L. Ning[1], P. Braconnot[2] and S.P. Harrison[3]

Nanjing, China, 26-30 October 2020

The Paleoclimate Modelling Intercomparison Project 2020 Conference (pastglobalchanges.org/calendar/2020/127-pages/1947), conducted in a hybrid format at Nanjing Normal University and by Zoom, was the 11th event of the PMIP workshop series initiated in 1991 in Collonges-la-Rouge, France. The major aim of the PMIP2020 Conference was to bring the whole community together once again to discuss progress during the fourth phase of PMIP (PMIP4) since the last meeting in Stockholm in 2017.

Major foci of this meeting were the first results from PMIP4/CMIP6 model evaluations, new ideas on the use of proxy system modeling in PMIP, and reviewing new approaches to reconstruct climate quantitatively for comparison with model simulations. Time was also allotted to other PMIP4 activities, including but not limited to climate transitions, abrupt events, climate variability, and their linkages with changes in climate mean states.

About 300 participants from more than 20 countries attended the conference, with more than 130 presentations (for a selection of results, see Fig. 1). A PMIP overview highlighted new results from PMIP working groups on climate sensitivity, monsoons, sea ice, and ENSO. These studies used results from the Pliocene Model Intercomparison Project (PlioMIP), the Last Interglacial (LIG), the Last Glacial Maximum (LGM), the mid-Holocene, and model-data comparisons.

Four scientific sessions were organized to provide complementary views from all PMIP activities on monsoons, climate sensitivity, transient experiments, and ocean and internal variability. Online discussions of posters and comments on different analyses were designed to identify new results that could fuel new collaborations and feed into the PMIP joint special issue of *Global Model Development* and *Climate of the Past* (pmip.lsce.ipsl.fr/outcome/special_issue). Three keynote speakers (Dr. Yongjin Wang from Nanjing Normal University, China; Dr. Steven Sherwood from University of New South Wales, Australia; and Dr. Marie Kapsch from Max Planck Institute for Meteorology, Germany) gave talks in the monsoon session, climate sensitivity and feedbacks session, and transient session, respectively. The keynote speakers highlighted new scientific advances that should be considered as part of the PMIP4 analysis plan. A discussion of new paleoclimate results that would be relevant to consider in the ongoing IPCC report was also organized with some of the IPCC WG1 lead and contributing authors.

On the final day of discussions, the eight PMIP working group leaders summarized the progress, major findings, and potential future research topics based on the presentations and discussions from the four sessions. Several grand challenges were also proposed by the Chinese paleoclimate modeling community, including (1) glacial ocean tracer modeling, (2) possible changes in equilibrium climate sensitivity with different background climate, (3) evolution of glaciers over the Tibetan Plateau during the glaciation, (4) global climate responses to land-use and cover change (LUCC) since 21 kyr BP, and (5) multiscale climate variability driven by different forcings during the Holocene.

It was suggested that a new working group (named paleo-monsoon) should be initiated, based on wide research interests on paleo-monsoon variability and new research directions made possible by long transient simulations. Some of the scientific goals of the paleo-monsoon working group would be to: improve the understanding of physical processes within global and regional monsoon systems during the past periods (e.g. the last 2 kyr, Holocene, LGM, LIG); differentiate between the contributions from internal variability and external forcings on multi-timescale variabilities of global monsoon systems; and strengthen model-data comparisons on paleo-monsoon systems. This paleo-monsoon working group would be led by Jian Liu, and will help to facilitate collaborations with other MIPs, especially the Global Monsoons Model Intercomparison Project (GMMIP), which focuses on modern and future monsoon variability. Also, the paleo-monsoon working group will help to improve communications between the modeling and observational communities.

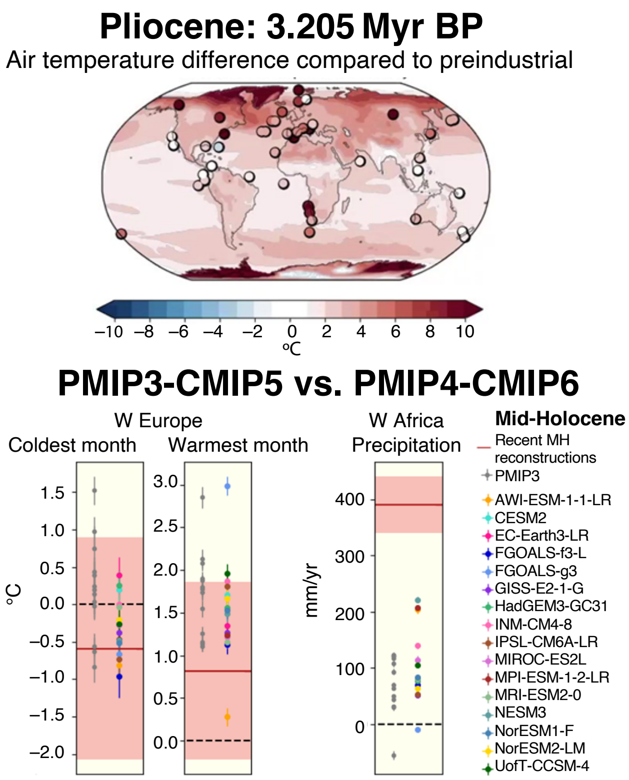

Figure 1: Example of new results from some of the PMIP4-CMIP6 publications for PlioMIP (Haywood et al. 2020; Brierley et al 2020). For more examples, see the PMIP special issue (GMD topical editors 2021).

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Virtual Past Socio-Environmental Systems: An interdisciplinary ECR workshop

PASES workshop organizers*

Online, 9-11 November 2020

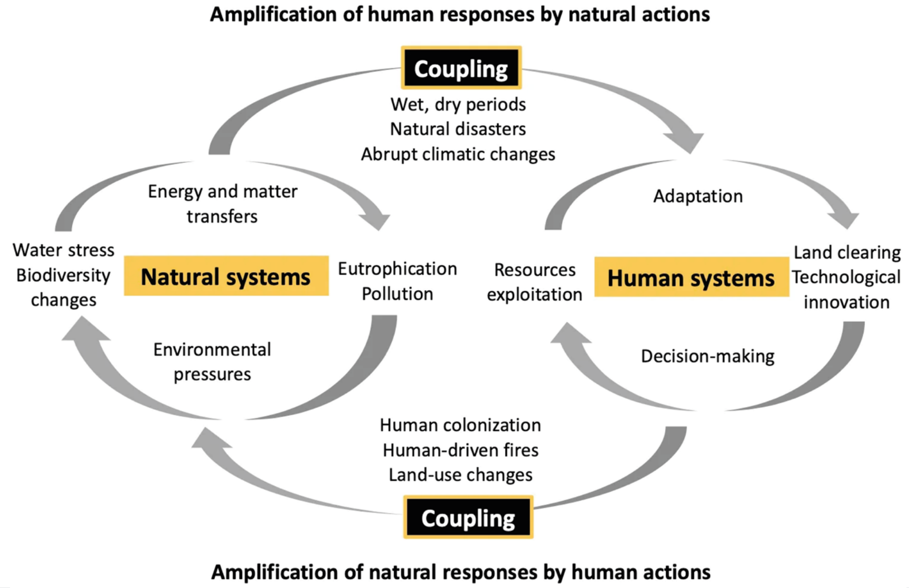

Figure 1: Diagram of an idealized past socio-environmental system showing the coupling between natural and human systems.

Effective interdisciplinary collaboration requires trustful interactions and several iteration cycles throughout the scientific process, from the formulation of research questions to the conclusions. Collaborative research is especially challenging among early-career researchers (ECRs), who usually face cultural and geographical barriers among peers, as well as having less experience of networking. In the paleosciences, although the interpretation of historical and paleoenvironmental records requires cross-fertilization of knowledge, this is usually undertaken within the framework of monodisciplinary investigations. As a consequence, conclusions are often drawn as simple, deterministic (either environmental or human) interpretations. This reductive approach minimizes the complexity of the causal relationships involved in human-environmental systems, especially over longer timescales (Fig. 1). Understanding the interplay between past human societies and the natural systems they inhabited may provide us with sustainability strategies for current and future socio-environmental challenges.

The Past Socio-Environmental Systems (PASES; https://www.pases2020.com; pastglobalchanges.org/calendar/2020/127-pages/2044) workshop was designed as a joint venture between PAGES ECN (pastglobalchanges.org/ecn) and INQUA ECRs (https://inqua.org/ecr) to foster cross-disciplinary collaborations among the next generation of paleoscientists. This workshop was especially designed for those conducting research at the interface of the climate-culture-environment nexus, with experience in proxy-based and modeling records of paleoclimate, archaeology, paleoecology, and human paleodemography.

Without the possibility of meeting in La Serena, Chile, for an in-person workshop due to the COVID-19 global pandemic, the objectives of the virtual PASES workshop were to bring together ECRs who are open to interdisciplinarity, as well as to promote equal opportunities for participants around the world. The online workshop involved 16 presenters and more than 200 attendees from 26 different countries. The workshop included two three-hour sessions on human paleoecology and synthesis of paleorecords. The last day consisted of an open-table discussion with senior researchers reflecting on community-driven paleoscience questions, and a breakout activity to catalyze scientific collaborations among ECRs.

The virtual workshop began with the Human Paleoecology session, introduced by César Méndez's (Patagonian Ecosystems Investigation Research Center, Chile) keynote presentation. Méndez explained the importance of comparative archaeological studies in semiarid regions for understanding human-environmental interactions during the Pleistocene-Holocene transition. Subsequent talks by ECRs gave insights into land-use changes and agricultural practices, the importance of robust chronologies for island colonization processes, and how climate and human pressures can be revealed using sedimentary records in coastal and mountain regions. On day two, keynote speaker Yoshi Maezumi (University of Amsterdam, The Netherlands) spoke about human legacies in the Amazonia through the application of multiproxy evidence from paleoclimatology, archaeobotany, and paleoecology. The following talks by ECRs highlighted the usage of various records (pollen, charcoal, historical archives, bat guano, and ancient eDNA) to tease apart the human and climate drivers explaining past environmental responses. The talks were followed by a lively and interactive Q&A discussion. For attendees who either couldn't attend or wanted to re-watch the presentations, we shared links privately following the workshop.

The final day was dedicated to interactive and collaborative activities. First, attendees participated in the open discussion "ECRs ask, mentors respond", guided by a panel of four senior scientists. These experienced researchers addressed some of the most pressing questions in the field of past socio-environmental systems, which were posed by ECRs during the PASES workshop pre-registration process. Finally, the breakout activity "Pillars of collaboration" had a strong focus on team science, aiming to initiate conversations for genuine interdisciplinary collaboration revolving around boundary objects – elements that any research collaboration should be built upon (question/hypothesis, region, field of study, and methodology) to define a joint problem for past socio-environmental systems' research.

Organizing an international virtual workshop was a significant challenge for the Local Organizing Committee – especially in the midst of a pandemic – and particularly in terms of adapting to different time zones and exploring the myriad of different technical options available to maximize attendance. Altogether, the range of expertise from presenters and attendees led to inspiring discussions that provided scientific foci to build new partnerships and plant the seed for the postponed in-person workshop in La Serena, Chile (planned for November 2022; pastglobalchanges.org/calendar/upcoming/127-pages/1972). For the immediate future, there are virtual PASES networking channels available to encourage active participation and we invite interested ECRs to become involved through the website forum and breakout groups. These virtual workspaces can be a platform for advancement of the PASES outputs, including short articles in the PAGES ECR-led special issue of the *Past Global Changes Magazine*, and a global database comprising well-known case studies characterized by datasets measuring paleoecological proxies, human population and paleoclimatic changes, as well as integrative methodologies.

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*See html version: doi.org/10.22498/pages.29.1.58

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Towards increased interoperability of paleoenvironmental observation data

Oliver Bothe[1], K. Rehfeld[2], B. Konecky[3] and L. Jonkers[4]

Data is an important foundation of scientific progress. It allows us to contrast hypotheses with observational evidence. Sharing and providing data openly have a long tradition in paleoenvironmental research, supported by repositories such as WDS-Paleo[1], PANGAEA[2],and Neotoma.[3]

The 2018 *Past Global Changes Magazine* issue (Williams et al. 2018) "Building and Harnessing Open Paleodata" touches on all the questions from the production of individual records to the reuse of compilations. Common themes were conventions for reporting, for metadata, and for data structures; crediting mechanisms, community as well as external support in data curation and infrastructure; automating processes; and making data more widely usable.

Today, with many new published data compilations (e.g. Iso2k[4], Konecky et al. 2020; SISAL[5], Comas-Bru et al. 2020; PalMod, Jonkers et al. 2020[6], Cao et al. 2020[7]; PlioVAR[8], McClymont et al. 2020), the need for improving reusability and interoperability of data is becoming more pressing. Each of those compilations adheres, to some extent, to the principles of Findability, Accessibility, Interoperability, and Reusability (FAIR; Wilkinson et al. 2016). The creation of such compilations, which includes quality controlling large numbers of original data records, improves the interoperability of available data records and increases the amount of usable data for understanding past environments and assessing uncertainty. But are the syntheses themselves interoperable enough?

Interoperability benefits from common standards about what is reported, using which vocabularies, and in which storage structures (see e.g. Khider et al. 2019). The highlighted compilations still use a variety of vocabularies and metadata elements. They are provided in a number of different formats including LiPD files, a SQL database, and tab-limited text files. Working with multiple compilations requires becoming fluent enough in each of them to write code to harmonize data formats, interact with files, or produce new files.

A harmonized workflow would allow data from different compilations to be used together more efficiently. This in turn would mean that findings could rely on a larger amount of data and better account for uncertainties. In short, we could more reliably establish agreement and disagreement between data sources (including simulation output), and we could obtain more complete pictures of past environments. Standardization of data synthesis products would therefore be a valuable step towards standardization of all paleoenvironmental observation data and towards using all paleoenvironmental data to their fullest, which certainly motivates many PAGES working group activities.

A number of recent initiatives provide key elements of such a toolchain. Curated repositories assist in harmonizing reporting standards, vocabularies, as well as data formats. These repositories cater to a number of research fields with different conventions. Requirements may also differ between the data producers and the data users. Of particular interest for interoperability are the storage conventions and the vocabularies.

In contrast to paleo-observational data, established sharing and access channels as well as utilities provide standardized workflows and a high degree of FAIRness for simulation output. Paleo-observational data standardization efforts can benefit from the experiences of the wider Earth system modeling community. However, harmonizing climate simulation output with tools like the Climate Model Output Rewriter (CMOR[9]) may be more straightforward than harmonizing paleoenvironmental observations. For the latter, we have yet to finish coordinating vocabularies among research communities and may still have to optimize multiple ways of organizing and storing research data before a standard emerges. Finally, we might find that we cannot use one common format but rather that we need a well-designed, automatable, and well-documented set of tools for interacting with multiple community specific standards to create, modify, and update (parts of) files, as well as read files from different formats.

Community engagement is necessary for tools to be adopted for community specific-use cases. Development and maintenance of tools must not depend on individuals and short funding cycles. Community governance as well as technical solutions can ensure sustainable long-term support for standards for reusable and interoperable paleoenvironmental data that maximally serve our understanding of past and future environmental changes. The paleoenvironmental community, as a community of many research communities, has to provide guidance. For this to be established and adhered to, communities as represented, for example, by the PAGES working groups, have to talk to each other, the repositories for paleoenvironmental data, and providers of technological infrastructure. Then, we can tailor standards, formats, and tools to community needs.

PAGES has taken up data stewardship as an integrative activity with relevant structures and cooperations. Thus, PAGES and comparable efforts are in an ideal position to assist sustainable solutions with a long-term commitment, for which the new Data Stewardship Scholarship[10] offered to PAGES working groups may be a valuable stepping stone. Another step can be for PAGES working groups and PAGES governance to instigate and moderate the necessary conversations, e.g. in the form of a virtual data roundtable bringing together all interested parties.

Figure 1: The diverse formats of paleoenvironmental datasets resemble an assortment of gear wheels that do not necessarily work together (Image credit: Laura Ockel, Unsplash[11]).

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CONTENTS

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