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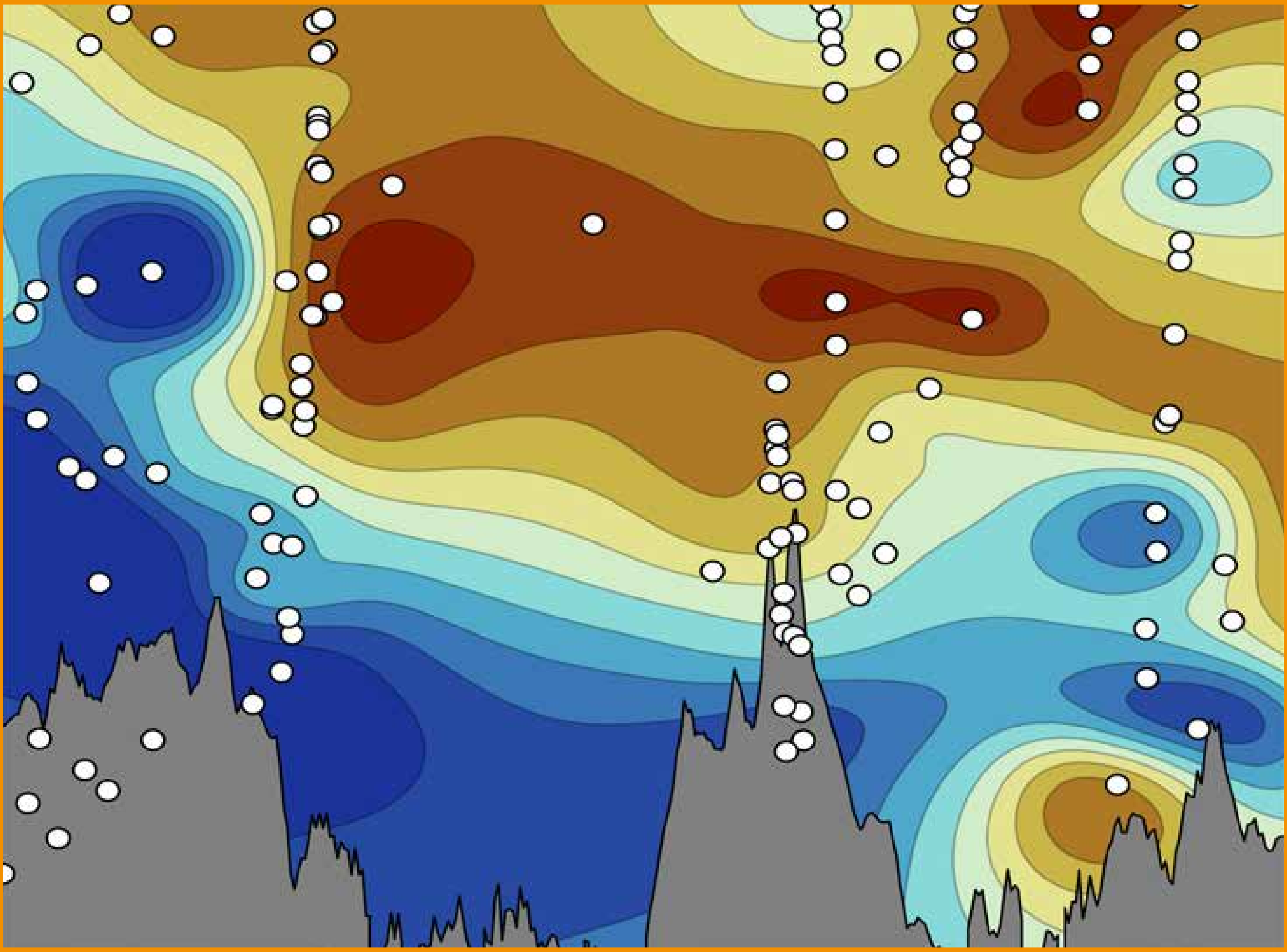
# PAST GLOBAL CHANGES

MAGAZINE



# OCEAN CIRCULATION AND CARBON CYCLING

**EDITORS**

Julia Gottschalk, Xu Zhang, Andrea Burke and Sarah Eggleston

PAGES

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# News

### PAGES SSC and EXCOM news

SSC Members Peter Gell (Australia) and Michal Kucera (Germany) will end their tenure at the end of 2019. PAGES IPO thanks them for their valuable work over the past six years. New members Aster Gebrekirstos (Kenya) and Elena Ivanova (Russia) will join the SSC from January 2020.

The 2020 SSC Meeting will be held in Cape Town, South Africa, from 23-28 March. A one-day symposium will also be included for the local paleoscience community.

### PAGES IPO staff update

Chances are, if you have contacted the PAGES International Project Office (IPO) during the past 16 years, you may have dealt with our Information Systems Coordinator Christian Telepski. At the end of this year, Christian will leave the IPO as the longest serving staff member in the organization's history. PAGES thanks him for all his work and wishes him good luck in his new adventures. In November 2019, Shashika Sedara Hettige joined PAGES as Christian's replacement. He will work with Manuela Roten in our IT department. Find out more here: pastglobalchanges.org/about/structure/international-project-office

### Working group news

Two 2k Network papers were released in tandem in July 2019, garnering worldwide media attention. "No evidence for globally coherent warm and cold periods over the pre-industrial Common Era", published in *Nature*, is in the 99th percentile (ranked 9th) of the 245,560 tracked articles of a similar age in all journals, and "Consistent multidecadal variability in global temperature reconstructions and simulations over the Common Era", published in *Nature Geoscience*, is ranked 60th. Congratulations to all involved. Access both articles here: pastglobalchanges.org/news/all-news-items/9-latest-news/2315

The Arctic Cryosphere Change and Coastal Marine Ecosystems (ACME) working group launched in July. Find out more: pastglobalchanges.org/acme

### PAGES Early-Career Network (ECN)

Pre-registration for the joint PAGES-INQUA ECR Workshop "Past Socio-Environmental Systems" (PASES) from 7-13 November 2020 in La Serena, Chile, is now open (deadline 30 January 2020). The ECN also held its first workshop "Funding starts here - Grant writing for early-career researchers" in May 2019, and has recorded several webinars. All details of ECN activities at: pastglobalchanges.org/ecn

### PAGES-WDS Paleo agreement

In May 2019, PAGES signed a scientific agreement with NOAA National Centers for Environmental Information - Center for Weather and Climate, World Data Service for Paleoclimatology (WDS-Paleo). The interrelated nature of PAGES and WDS-Paleo dates back to our beginnings in 1993.

### PAGES at AGU 2019

The PAGES 2k Network will celebrate 10 years of the "Climate of the Common Era" session at the 2019 AGU Fall Meeting in San Francisco, USA, from 9-13 December. C-PEAT, PALSEA, and OC3 will also conduct sessions, while many SSC members, working-group leaders and ECN representatives will be giving talks. Iso2k project leader Bronwen Konecky and PALSEA working group leader Jacky Austermann will receive ECR Awards. All details: pastglobalchanges.org/calendar/2019/127-pages/1898

### PAGES at EGU 2020

Have you seen the proposed PAGES sessions at the EGU General Assembly from 3-8 May 2020 in Vienna, Austria? We encourage you to submit an abstract by 15 January for 2k Network, ACME, CVAS, Floods, LandCover6k, PALSEA, VICS and more: pastglobalchanges.org/calendar/2020/127-pages/1976

### 6th Open Science Meeting and 4th Young Scientists Meeting

The venue for the 2021 OSM and YSM will be announced in the first half of 2020.

### Help us keep PAGES People Database up to date

Have you changed institutions or are you about to move? Please check if your details are current: pastglobalchanges.org/people/people-database/edit-your-profile If you have problems updating your account, we can help. Contact pages@pages.unibe.ch

### Hard copy or email notification of *Past Global Changes Magazine*

In an effort to reduce our carbon footprint, PAGES would like to know if you would prefer to receive an email notification for future issues of the *Past Global Changes Magazine* instead of a hard copy. If you would like to change, please email pages@pages.unibe.ch and we will update your preferences.

### Upcoming issue of *Past Global Changes Magazine*

Our next magazine on past plant diversity and conservation issues will be guest edited by Rachid Chedaddi and members of the VULPES project (vulpesproject.com). Although preparations are well underway, if you would like to contribute, please contact our Science Officer: sarah.eggleston@pages.unibe.ch

# Calendar

**CVAS workshop: Beyond Palaeoclimate Ping Pong: Improving estimates of past climate variability by consistent data-model comparison**
2-5 June 2020 – Heidelberg, Germany

**Future Earth: Sustainability Research and Innovation 2020 Congress**
14-17 June 2020 – Brisbane, Australia

**PAGES-endorsed: 19th International Swiss Climate Summer School**
23-28 August 2020 – Grindelwald, Switzerland

**ECN workshop: PAGES-INQUA joint ECR workshop: Past Socio-Environmental Systems**
9-13 November 2020 – La Serena, Chile

pastglobalchanges.org/calendar

# Featured products

PAGES involvement, via our working groups and workshops, in the PaCTS project is highlighted in a paper by Deborah Khider et al: pastglobalchanges.org/products/12909

### 2k Network

A PALEOLINK paper in *Climate of the Past* investigates the research potential of historical climatology: pastglobalchanges.org/products/12869

### C-PEAT

Authors analyze testate amoeba-derived hydrological reconstructions from 31 peatlands in Europe to examine changes in peatland surface wetness during the last 2,000 years, in *Nature Geoscience*: pastglobalchanges.org/products/12952

### GPWG2

A *Nature Ecology & Evolution* paper uses the Global Charcoal Database to show climate change had a significant impact on indigenous Amazonian communities before the arrival of Europeans: pastglobalchanges.org/products/12863

### OC3

A *Science Advances* paper from members of PAGES' OC3 working group aims to accurately quantify ocean carbon components to measure $CO_2$ concentrations during glacial periods: pastglobalchanges.org/products/12860

### PEOPLE 3000

Authors integrate archeological and paleoenvironmental records to test the hypothesis that Chilean societies progressively escalated their capacity to shape national biophysical systems: pastglobalchanges.org/products/12857

# Cover

**West Atlantic transect of Holocene dissolved inorganic carbon isotopes.**
Transect calculated based on West Atlantic $\delta^{13}C$ from Holocene core-top $\delta^{13}C$ of benthic foraminiferal tests. Data are from the compilation by Schmittner et al. (2017, Paleoceanography 32: 512-530), shown as white circles. The color scale range is from 0.4 to 1.3 per mil (blue to brown), latitude on the x-axis ranges from about 50°S (left) to 40°N (right), and water depth on the y-axis from 1 to 5 km. Plot courtesy of Frerk Pöppelmeier and Patrick Blaser, Institute of Earth Sciences, Heidelberg University, Germany.

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# Old problems and new challenges in understanding past ocean circulation and carbon-cycle changes

Julia Gottschalk[1], X. Zhang[2] and A. Burke[3]

This *Past Global Changes Magazine* issue celebrates achievements in our understanding of the mechanisms governing changes in ocean circulation and the global carbon cycle in the past, and the complex interplay between them. This issue also emphasizes the current challenges and open questions in the field, to motivate research into improving our understanding of the fundamental links between ocean circulation, carbon cycling, and climate in the past, as well as in assessing the implications for the future.

This year, we mourn the loss of Wallace (Wally) Smith Broecker (1931-2019), professor of Geology at Columbia University. Wally was truly a "conveyor belt" of ideas and remarkable accomplishments in the fields of chemical oceanography and paleoclimatology, and his intellectual legacy has nurtured and will continue to nurture generations to come. His memoir (Broecker 2012) is a highly recommended read, as it also provides an overview of how (paleo-)ocean sciences evolved during his career.

Since the last assessment report of the Intergovernmental Panel on Climate Change (IPCC) in 2013 (Stocker et al. 2013), atmospheric $CO_2$ levels have risen as a result of human activities by a magnitude similar to past millennial $CO_2$ changes (e.g. Bereiter et al. 2015), though at a much faster rate. In this year's Special Report on the Ocean and Cryosphere in a Changing Climate (ipcc.ch/srocc; Pörtner et al. 2019), IPCC has, for the first time, highlighted a recognizable weakening of the Atlantic Meridional Overturning Circulation relative to 1850-1900. These observations emphasize the ongoing dramatic changes in the Earth's climate system today. Studying the fingerprints and records of past climate changes in diverse geological archives provides our best opportunity to document and assess the fundamentals of Earth's climate system under a variety of (extreme) climate boundary conditions.

The advent of stable isotope analyses of calcareous marine fossils (e.g. foraminifera) and ice-core drilling in the 1950s has provided crucial insights into past ocean and climate variability. Nearly 70 years later, the field of paleoceanography is an amalgamation of different techniques applied to study climate variability on various timescales based on many archives. However, overarching questions that motivated Earth scientists decades ago remain of great interest to the paleo-community: What leads to changes in ocean circulation and how has it varied in the past? What drives the variations in greenhouse gas concentrations in the atmosphere?

To address these questions, the Ocean Circulation and Carbon Cycling working group (OC3, pastglobalchanges.org/oc3), which launched in 2014, has worked towards a global synthesis of stable isotope data from foraminifera and their comparison with numerical model simulations (e.g. Muglia et al. 2018). This effort is geared towards assessing deglacial circulation dynamics of different water masses globally and their role in changing ocean carbon storage over time. While a core-top (i.e. Late Holocene) data compilation has been completed and successfully compared against pre-industrial ocean observations (e.g. Schmittner et al. 2017), comprehensive regional and global data products for the last glacial-interglacial transition will be released in the near future.

In addition to using traditional stable-isotope proxies, paleoceanographers, geochemists, and Earth-system modelers distill information from paleodata constraints of past ocean and carbon-cycle dynamics that are derived from a number of proxies, many of which are discussed in this issue. Furthermore, in order to understand climate thresholds and sensitivities, it is important to study a range of climate boundary conditions in the past. Key intervals discussed in this magazine include the last deglaciation, the mid-Pleistocene transition, the Pliocene, and the Paleocene-Eocene Thermal Maximum. However, accurately estimating variations of global geochemical ocean inventories on a variety of timescales, and quantitatively determining the implications for ocean circulation, climate, and the global carbon cycle, remain major challenges. As some authors highlight, community-wide efforts of synthesizing regional data into a global framework and combining different proxy approaches will be important for addressing these challenges, as well as developments of numerical models and model-data assimilation efforts. This issue therefore aims to motivate future scientific research on these crucial aspects in our quest to improve our understanding of mechanisms behind past ocean circulation and global carbon-cycle dynamics.

## AFFILIATIONS

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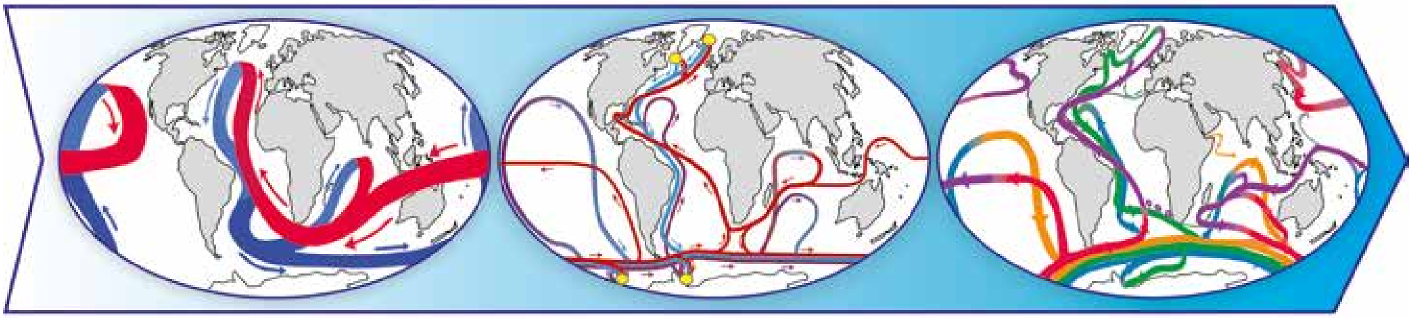

**Figure 1:** Our understanding of processes and feedbacks between different components of the Earth system has remarkably expanded over the last decades, here illustrated by conceptual visualizations of global ocean circulation over time: from the "Great Ocean Conveyor Belt" (left; Broecker 1987), to more complex ocean circulation dynamics (middle) with different deep water formation sites (yellow dots; Rahmstorf 2002) and (right) to an ocean with different water masses that interact and interfere with each other in a complex manner (Talley 2013). Different colors depict different types of water masses (see aforementioned references).

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# Benthic foraminiferal stable carbon isotope constraints on deglacial ocean circulation and carbon-cycle changes

Carlye D. Peterson[1], G. Gebbie[2], L.E. Lisiecki[3], J. Lynch-Stieglitz[4], D. Oppo[5], J. Muglia[6], J. Repschläger[7] and A. Schmittner[8]

**How does deep-ocean circulation influence atmospheric $CO_2$ across deglacial transitions? Although biogeochemical and physical processes complicate interpretation of foraminiferal stable carbon isotope data, these complications can be addressed with expanded data compilations, multiproxy approaches, and model-data assimilation efforts.**

The transition from glacial to interglacial climate involves carbon redistribution between the atmosphere, terrestrial biosphere, and ocean reservoirs. During repeated glaciations of the past ~1 million years (Myr), about 100 ppm of $CO_2$ from the atmosphere was temporarily sequestered in the terrestrial biosphere and ocean. Although terrestrial biosphere carbon storage may have increased or decreased (see Jeltsch-Thömmes et al. 2019 and references therein) between the Last Glacial Maximum (LGM, ~20,000 years (20 kyr) before present) and the preindustrial period, the vast, deep-ocean reservoir most likely controls glacial-interglacial carbon cycling and, hence, atmospheric $CO_2$ variations. On these timescales, ocean circulation and biological productivity influence carbon distribution in the deep ocean and regulate glacial carbon sequestration and deglacial $CO_2$ outgassing. However, the details of these ocean changes and their role in modulating deep-ocean carbon storage remain poorly understood. Compilations of global benthic stable carbon isotopes ($\delta^{13}C$), such as those synthesized by the PAGES Ocean Circulation and Carbon Cycling (OC3, pastglobalchanges.org/oc3) working group, can help decipher these processes.

## Ambiguity in proxy reconstructions

Past changes in ocean circulation and carbon storage have been reconstructed using the spatial distribution of stable carbon isotopes of dissolved inorganic carbon (DIC) inferred from stable carbon isotope records of benthic foraminifera *Cibicides wuellerstorfi* (and related genera) ($\delta^{13}C_{cib}$). These records are influenced by numerous fractionation processes including surface-ocean thermodynamic fractionation, air-sea gas exchange, and biological productivity (see Mackensen and Schmiedl 2019). These processes set the unique $\delta^{13}C$ source properties of modern North Atlantic Deep Water (NADW) and its glacial counterpart. Processes that drive the low $\delta^{13}C$ signature of the deep ocean include diabatic and turbulent mixing of water masses with different carbon isotope signatures during circulation and the degradation of surface-produced organic matter (remineralization) that subsequently sinks into the deep ocean. The low end-member $\delta^{13}C$ signature of modern southern-sourced waters, such as Antarctic Bottom Water (AABW), is achieved through a combination of cold, dense waters forming under sea ice that are isolated from the atmosphere, water-mass mixing (see Talley 2013), and organic-matter remineralization during deep-water formation and transit. Quantifying different fractionation influences is one of the challenges to inferring past changes in deep-ocean circulation and carbon storage from $\delta^{13}C_{cib}$ records.

One way to better constrain influences on $\delta^{13}C_{cib}$ paleorecords is to increase the spatial coverage of high-resolution, well-dated $\delta^{13}C_{cib}$ records. Even in relatively well-sampled regions such as the Atlantic Ocean, we must interpolate and extrapolate $\delta^{13}C_{cib}$ values between core sites to capture spatial variations across ocean basins, which results in large uncertainties. To understand the temporal evolution of $\delta^{13}C_{cib}$, we rely on timeseries of $\delta^{13}C_{cib}$. High-resolution age models reduce the uncertainty in $\delta^{13}C_{cib}$ timeseries, but $\delta^{13}C_{cib}$ records with "high" temporal resolution (better than 3 kyr) are generally restricted to regions with high sedimentation rates and good carbonate preservation (e.g. the Atlantic Ocean). Thus, existing compilations are strongly dominated by regions with more favorable sedimentation regimes. Including low-resolution $\delta^{13}C_{cib}$ records presents a trade-off between temporal and spatial resolution that is likely reasonable for characterizing the LGM and late Holocene time periods (Peterson et al. 2014).

Identifying locations of $CO_2$ degassing can be challenging using $\delta^{13}C_{cib}$ records because the strong air-sea exchange process "erases" the deep-ocean signature. However, independent nutrient proxies can help separate air-sea signals from recently upwelled deep waters (Lynch-Stieglitz et al. 2019). As such, multiproxy records allow us to estimate water-mass $\delta^{13}C$ signatures at the time of their formation (i.e. "preformed" $\delta^{13}C_{DIC}$), as well as their origin and transit (Oppo et al. 2018). Therefore, multiproxy records combined with well-dated, high-resolution $\delta^{13}C_{cib}$ records from numerous locations across the seafloor allow us to reconstruct water-mass properties and explore the ocean circulation and carbon-cycling signals.

Additionally, systematic and regional deviations between late Holocene $\delta^{13}C_{cib}$ and nearby seawater $\delta^{13}C_{DIC}$ estimates are found in more than 1700 $\delta^{13}C_{cib}$ records of varying temporal resolutions (Schmittner et al. 2017). This compilation suggests that the carbonate ion content of seawater has a small (<15%) influence on $\delta^{13}C_{cib}$ records. Although

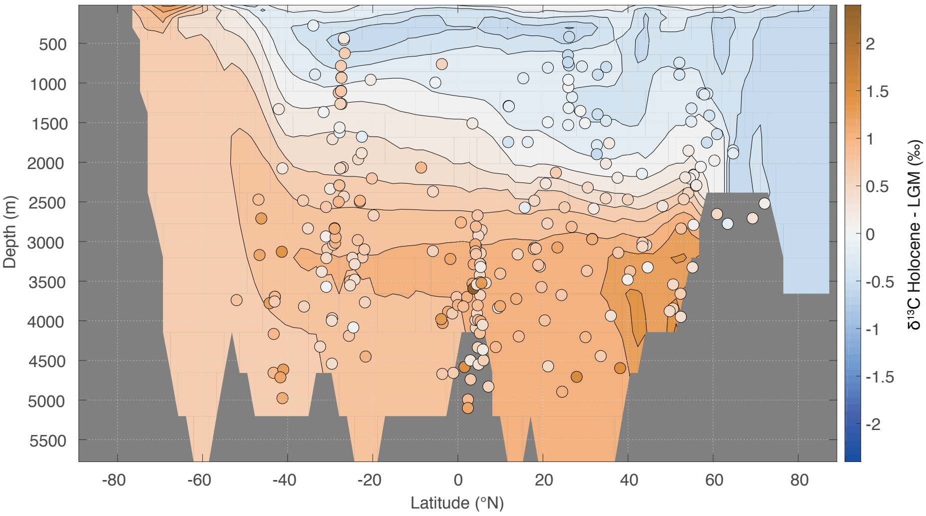

**Figure 1:** Observed $\delta^{13}C_{cib}$ difference between the Holocene and LGM in a zonally averaged cross section through the Atlantic Ocean integrating both the eastern and western basins (circles; $\delta^{13}C_{cib}$ record core sites) that constrain the model simulation of seawater $\delta^{13}C_{DIC}$ (contours) from Muglia et al. (2018).

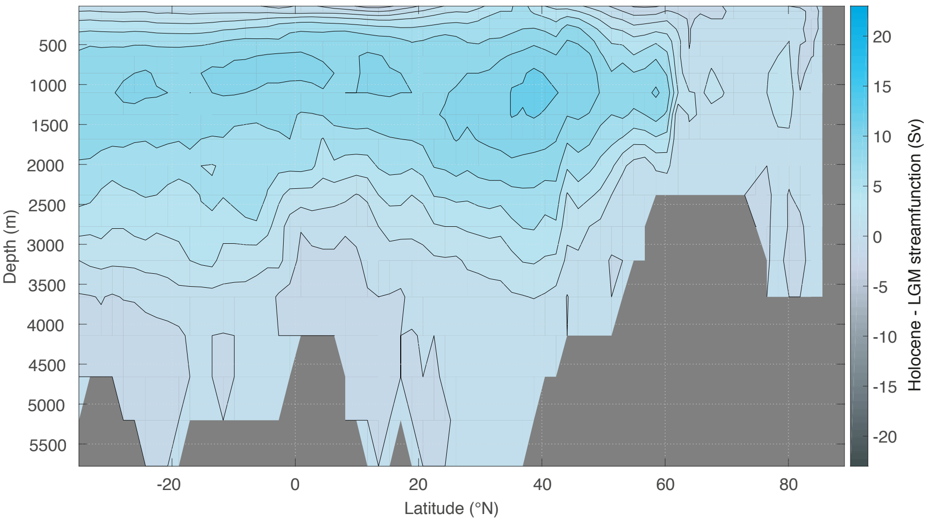

**Figure 2:** Zonally averaged cross section of difference in Atlantic stream function (Sv) between the Holocene and the LGM from the $\delta^{13}C_{cib}$ data-constrained numerical simulations of Muglia et al. (2018). The numerical simulations indicate that a shoaled and weaker AMOC at the LGM results in the closest match with existing datasets of seawater $\delta^{13}C_{DIC}$, i.e. $\delta^{13}C_{cib}$ (Fig. 1).

$\delta^{13}C_{cib}$ and $\delta^{13}C_{DIC}$ lack a perfect one-to-one relationship, previous $\delta^{13}C_{cib}$ interpretations likely hold (Schmittner et al. 2017). The effect of deep-ocean carbonate ion variations on glacial-interglacial $\delta^{13}C_{cib}$ records remains to be evaluated.

## Deglacial ocean circulation changes

Classical interpretations of glacial Atlantic Ocean $\delta^{13}C_{cib}$ records propose a shoaled boundary between northern-sourced NADW and southern-sourced AABW at 2000 m water depth (Curry and Oppo 2005). This interpretation has since been tested with additional $\delta^{13}C_{cib}$ records, with an expanded spatial distribution, and new model-data comparisons (e.g. Hesse et al. 2011). Recently, Oppo et al. (2018) argued that western North Atlantic waters shoaled by about 500 m during the glacial onset, consistent with the prevailing hypotheses that NADW shoaled while AABW expanded (Curry and Oppo 2005). However, it remains challenging to constrain ocean circulation changes in water-mass formation regions principally because the locations of deep-water formation shifted over time. Furthermore, changes in the source properties of water masses could explain changes previously attributed to carbon and nutrient storage change (Repschläger et al. 2015).

Modeling studies constrained by glacial-age $\delta^{13}C_{cib}$ records indicate a shallow and weak Atlantic Meridional Overturning Circulation (AMOC) and enhanced Southern Ocean iron fertilization (Menviel et al. 2016; Muglia et al. 2018), although it remains to be determined how well $\delta^{13}C_{cib}$ spatial variability constrains changes in AMOC strength versus depth. Additionally, model results indicate enhanced glacial Antarctic Intermediate Water (AAIW) formation in the Southern Hemisphere and a more closed circulation between NADW and AAIW (e.g. Ferrari et al. 2014). In the Atlantic Ocean, zonally averaged profiles of the difference between Holocene and LGM model-simulated seawater $\delta^{13}C_{DIC}$ and the $\delta^{13}C_{cib}$ records used to constrain the model indicate a reduced deglacial vertical $\delta^{13}C_{cib}$ gradient coinciding with reduced deep-ocean carbon storage in the same model runs (Fig. 1; Muglia et al. 2018). This is in agreement with results from fewer but higher-resolution deglacial $\delta^{13}C_{cib}$ timeseries (Peterson and Lisiecki 2018). Complementary to this model run that best fits the $\delta^{13}C_{cib}$ records (Fig. 1), the zonally averaged Atlantic stream function (Sverdrup, Sv) difference between the Holocene and LGM time periods indicates a deglacial strengthening of AMOC at intermediate depths (surface to ~1000 m) throughout the Atlantic Ocean (Fig. 2).

Two deglacial depth transects of $\delta^{13}C_{cib}$ records from the Southwest Atlantic and Pacific oceans suggest that the depth of glacial NADW was shallower than the sill depth of the Drake Passage (approximately 2500 m), reducing the contribution of NADW to AABW formation (Sikes et al. 2017). Hence, glacial AABW may have been derived from Pacific Deep Water and Indian Deep Water (Sikes et al. 2017). Expanded abyssal AABW may have resulted from expanded sea ice (Ferrari et al. 2014), reduced basal melting of ice shelves (Miller et al. 2012) or reduced southward meridional water-vapor transport (Muglia et al. 2018). A strong LGM $\delta^{13}C_{cib}$ gradient in the southeastern Atlantic, associated with the lowest $\delta^{13}C_{cib}$ values in the glacial ocean, may indicate a more isolated version of Circumpolar Deep Water (CDW) distinct from the CDW that filled the Pacific and Indian oceans (Ullermann et al. 2016; Williams et al. 2019).

## Conclusion

For more than 50 years, paleoceanographers have sought to characterize the link between deep-ocean circulation and $CO_2$ cycling. To gain a better understanding of these processes, the traditional interpretation of $\delta^{13}C_{cib}$ records should be re-evaluated and updated as we expand our understanding of the climate system and global carbon cycle. Collegial and interdisciplinary collaboration can foster new ideas and insights into the comparison between paleorecords and modeling approaches. By archiving our hard-earned, high-resolution multiproxy paleorecords, densely sampled age models, and model simulations in public databases online, we can improve reconstructions of ocean circulation and carbon-cycle changes based upon more complete paleodata compilations. Certainly, interpretations would benefit from improved age models and additional paleorecords from the Southern, Indian, and Pacific oceans. Together, we can synthesize our work to improve our understanding of carbon-cycle dynamics between global reservoirs and within the ocean, as well as changes in biological, physical, and chemical processes, for the past, present, and future. Community collaboration could help us extract more clues about the deglacial carbon cycle from the data we have already generated.

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# Millennial to centennial changes in deep-ocean ventilation during the last deglaciation

Tianyu Chen[1] and Laura F. Robinson[2]

**The history of ocean ventilation helps to resolve timing and pathways of carbon transfer between the ocean and the atmosphere. Radiocarbon records reveal climate-linked, abrupt changes in the deep-ocean ventilation during the last deglaciation.**

### Radiocarbon as an ocean-ventilation proxy

The transport of surface seawater to depths, known as "ventilation", represents a fundamental aspect of our climate system as it is tightly linked to the dynamics of overturning circulation and the global carbon cycle. Proxy-based reconstruction of past ventilation makes it possible to examine the interaction between the ocean and the atmosphere on long timescales when instrument records are not available. Among various proxies, $^{14}$C is one of the most sensitive for characterizing past deep-ocean ventilation. In the ocean interior, $^{14}$C is exclusively supplied through ventilation of the ocean from surface to deep, and it decays away with a half-life of 5730 years. Today, a large portion of $^{14}$C in the abyssal ocean (Fig. 1) is derived from the formation of North Atlantic Deep Water (NADW), with less than a third from overturning circulation in the Southern Ocean and biological remineralization (Broecker and Peng 1982). Since there is little deep convection in the present North Pacific, it contains the least ventilated waters at ~2 km depth (where the ventilation age is defined as the $^{14}$C age difference between the sample and the contemporaneous atmosphere) resulting from the slow transit of bottom water from the Southern Hemisphere. Along with the $^{14}$C-aging of the deep-water masses, there is a concomitant increase in the dissolved inorganic carbon inventory (~0.14 µmol/kg/year; Fig. 1) associated with the organic carbon respiration and calcite dissolution. As such, $^{14}$C is widely used as a semi-quantitative chronometer of ocean ventilation providing critical constraints on circulation dynamics and carbon storage in the past.

The reconstruction of past deep-water $^{14}$C signatures is not straightforward, as an independent age is required to correct for in-situ $^{14}$C decay in paleoarchives since their formation. Most deep-ocean radiocarbon records have been reconstructed using the fossilized remains of benthic foraminifera extracted from sediment cores (e.g. Skinner et al. 2010). Deep-sea scleractinian corals form a complementary emerging new archive that provides well-constrained, absolute-dated $^{14}$C records of the sub-surface ocean (e.g. Frank et al. 2004; Burke and Robinson 2012; Chen et al. 2015; Hines et al. 2015) since the Last Glacial Maximum (LGM).

### Millennial-scale changes in ventilation

The low atmosphere CO$_2$ concentration during the LGM is thought to be largely caused by coupled oceanic changes in ventilation and the biological pump. Indeed, compiled radiocarbon data suggest an ~700 $^{14}$C-year increase in the average residence time of carbon in the deep ocean (> 1 km) during the LGM compared to the modern ocean, which allows the ocean to store more carbon (Skinner et al. 2017). So how did the deep ocean switch from an isolated, poorly ventilated LGM mode to the opposite in the Holocene? The key lies in the timing and pathways of the dissipation of $^{14}$C-depleted signatures of the deep ocean during the last deglaciation.

During the early deglaciation when the Northern Hemisphere was experiencing a cold stadial (Heinrich Stadial 1, HS1), the atmospheric CO$_2$ concentration was increasing accompanied by a $\Delta^{14}$C decrease (Fig. 2; Reimer et al. 2013), implying mixing from a $^{14}$C-depleted CO$_2$ source. Radiocarbon data from the upper and lower circumpolar deep waters (UCDW and LCDW) highlight converging trends in ventilation ages, indicative of increased Southern Ocean deep convection and air-sea exchange efficiency. This would have brought well-ventilated waters to depths and released $^{14}$C-depleted CO$_2$ to the atmosphere (Anderson et al. 2009; Skinner et al. 2010; Burke and Robinson 2012; Chen et al. 2015).

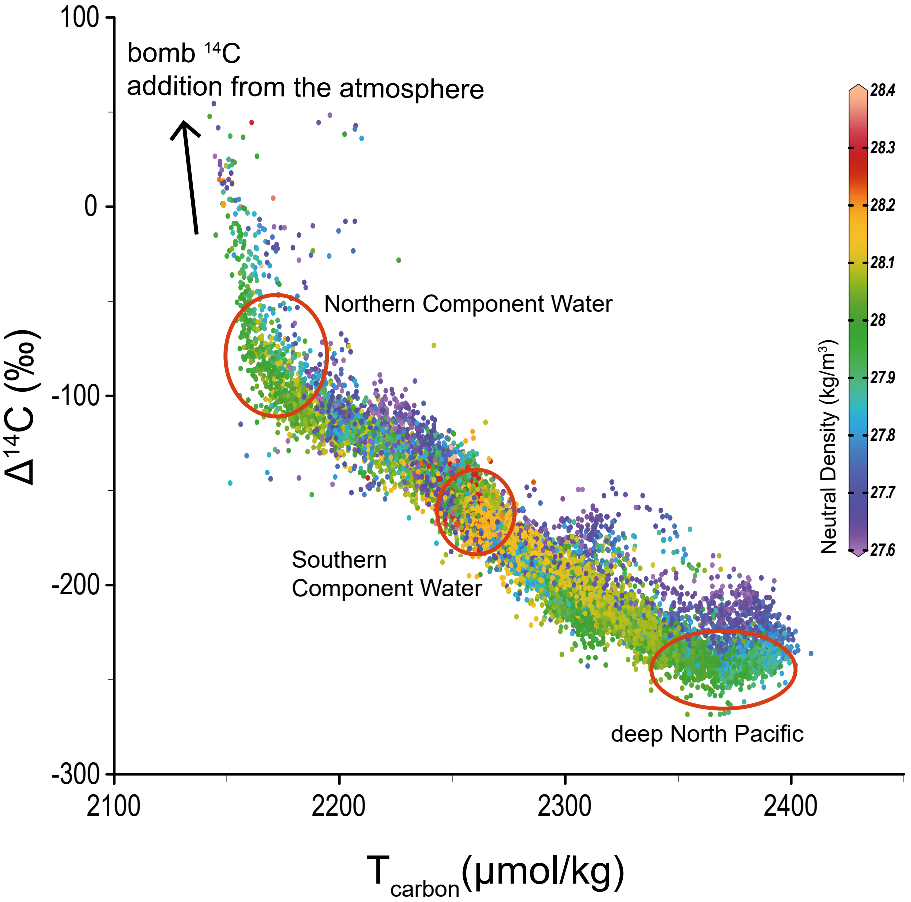

**Figure 1:** Modern distribution of $\Delta^{14}$C and total carbon in deep waters of the global ocean (defined as those with neutral density >27.6 kg/m$^3$). Note that nuclear bomb testing since the 1950s has dramatically increased the level of $^{14}$C in the atmosphere and subsequently deep waters in the North Atlantic. Figure was made with Ocean Data View, and the data are from GLODAP 2019.

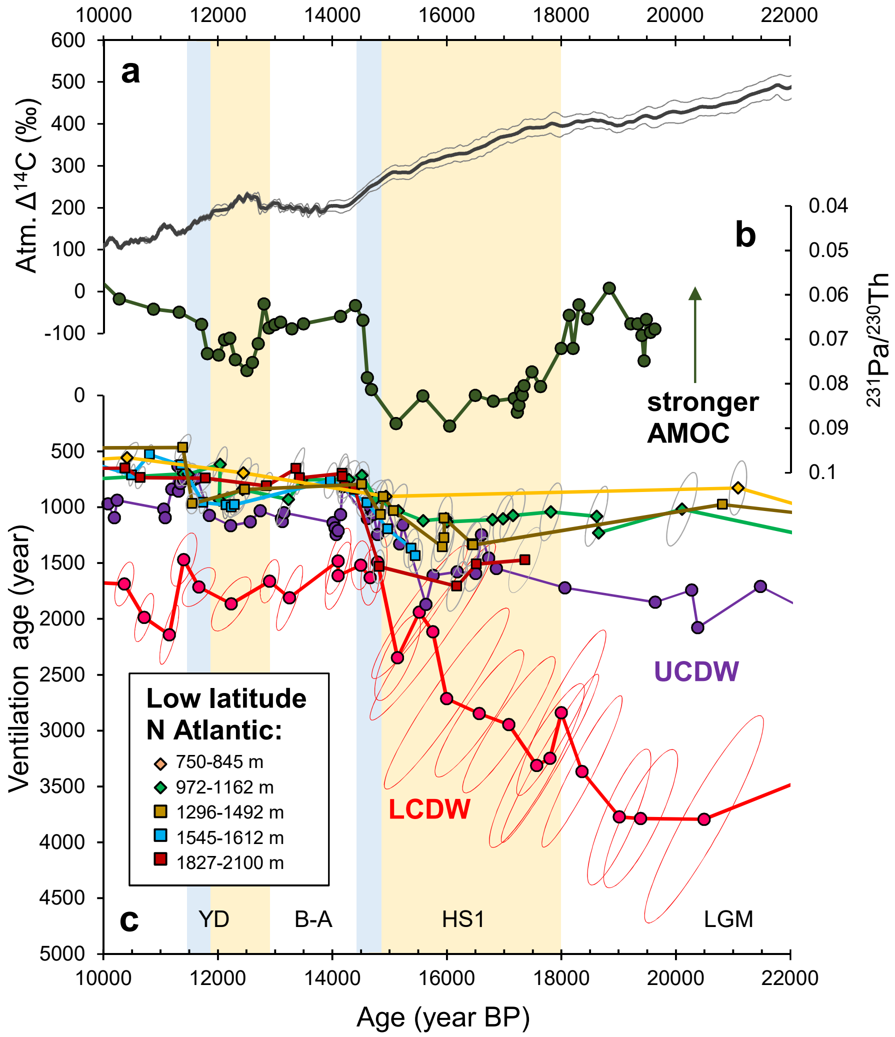

**Figure 2:** Ventilation age evolution of deep waters compared with other climate records. **(A)** Δ$^{14}$C of the atmosphere (IntCal13, Reimer et al. 2013). **(B)** Sedimentary $^{231}$Pa/$^{230}$Th ratios (an AMOC-strength index) from the subtropical North Atlantic (McManus et al. 2004). **(C)** Ventilation age reconstructed from deep-sea corals (UCDW and low latitude Atlantic; Burke and Robinson 2012; Chen et al. 2015) and benthic foraminifera (LCDW; Skinner et al. 2010).

Meanwhile, low-latitude North Atlantic deep waters at ~2 km remained poorly ventilated throughout HS1, some 700-800 years "older" than modern times (Fig. 2). This result is consistent with greatly reduced Atlantic Meridional Overturning Circulation (AMOC) during HS1 (McManus et al. 2004) that reduced the supply of $^{14}$C-enriched waters to the deep North Atlantic. In fact, the deep North Atlantic might have accumulated carbon during HS1 due to reduced ventilation (Menviel et al. 2018). Similar processes probably occurred during the Younger Dryas (YD) albeit with a smaller magnitude. Overall, larger $^{14}$C depth gradients are observed in the low-latitude North Atlantic during cold HS1 and YD compared to the Bølling-Allerød (B-A) warm event (Fig. 2), closely linked with changing production of the well-ventilated North Atlantic deep waters (McManus et al. 2004).

## Centennial abrupt changes in ventilation

A particularly exciting aspect of the data being collected from deep-sea corals is the potential to reveal oceanic changes that occurred on centennial timescales. The transitions from HS1 to the B-A and from the YD to the Holocene are marked by abrupt increases in $^{14}$C of the low-latitude North Atlantic waters (Fig. 2), synchronous with warmings recorded in the Greenland ice cores and rapid increases in atmospheric $CO_2$ concentrations (Chen et al. 2015). The coral $^{14}$C records from the Atlantic and the Southern Oceans also converge during these two transitions. This convergence likely reflects "flushing" events resulting from the abrupt resumption of the AMOC, which released a large amount of respired carbon from the deep ocean to the atmosphere (Chen et al. 2015).

At the same time, boron-based pH reconstructions from Southern Ocean deep-sea corals further imply that these strong centennial ventilation events might be associated with delayed sea-ice advances at the beginning of the interstadial, allowing more efficient air-sea exchange (Rae et al. 2018). Multiple causes have to be invoked to account for the carbon release at the end of HS1 and the YD. Atmospheric δ$^{13}$C records, for example, do not show the change expected from release of respired $CO_2$ during the above two intervals, indicating increasing SST and/or increased land biosphere could also have played a role (Bauska et al. 2016). Moreover, the increased supply of nutrients to the surface is expected to stimulate primary productivity, enhancing the loss of alkalinity from surface waters and facilitating carbon release by increased overturning (Bronselaer et al. 2016). These puzzles are being addressed through increasing the resolution of data at these and other important oceanographic locations.

## Concluding remarks

The upwelled $^{14}$C-depleted signatures from the abyssal ocean should eventually dissipate in the upper ocean and the atmosphere. Many uncertainties, unfortunately, still remain regarding intermediate water ventilation, with some $^{14}$C reconstructions closely tracking the evolution of atmospheric $^{14}$C while others showed extreme $^{14}$C depletions. Some studies further suggest that geological carbon addition to the water column could be an important component of the deglacial carbon cycle (e.g. Stott et al. 2019). In addition, consensus has not been reached regarding the magnitude and timing of $^{14}$C variability in the deep Pacific during the last deglaciation. Thus, the timing and pathways of deglacial oceanic carbon release have not yet been fully resolved. A growing understanding of $^{14}$C geochemistry in foraminifera and emerging deep-sea coral studies from the Pacific will provide a fresh look at these issues. Overall, $^{14}$C reconstructions of the deep ocean yield powerful constraints on ocean dynamics and carbon cycle during the last deglaciation.

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# Ice-age storage of respired carbon in the Pacific Ocean

Allison W. Jacobel[1], R.F. Anderson[2], B.A.A. Hoogakker[3] and S.L. Jaccard[4]

**Proxy-based reconstructions of oceanic dissolved oxygen and carbon concentrations have helped to refine our understanding of past ocean-atmosphere carbon partitioning, consistently indicating lower dissolved oxygen in the deep Pacific Ocean during the last ice age. Better quantitative and spatio-temporally resolved estimates of these parameters are critical for closing the carbon budget and elucidating the relative importance of the mechanisms and feedbacks driving past carbon exchange among Earth's carbon reservoirs.**

Over at least the last 800 kyr, glacial-interglacial cycles have been characterized by variations in atmospheric $CO_2$ concentrations of 50-100 ppm (Bereiter et al. 2015 and references therein). The glacial drawdown of atmospheric $CO_2$ is thought to be largely a consequence of changes in southern high-latitude surface-ocean processes including increased $CO_2$ solubility, enhanced water-column stratification, decreased air-sea gas exchange, improved efficiency of the biological pump, and heightened ocean alkalinity (e.g. Sigman et al. 2010). One way to tease apart these mechanisms is to reconstruct relative changes in the carbon storage of the ocean's various water masses, especially those which have biogeochemical signatures strongly influenced by processes occurring in the Southern Ocean that are propogated to other basins. Not only do these reconstructions help provide insight into the relative importance of different air-sea carbon exchange mechanisms, they also help us to balance the global carbon budget by quantifying how much additional carbon was stored in the glacial ocean.

Until recently, consensus on the significance of glacial respired carbon storage in the Pacific Ocean was hampered by conflicting interpretations procured in part from $^{14}C$-derived water-mass ventilation ages, taken to be indicative of carbon accumulation in the abyssal ocean. Numerous caveats to the ventilation age approach have been identified in recent years (e.g. Zhao and Keigwin 2018), suggesting that direct reconstructions of water-mass carbon and oxygen concentrations are a more straightforward way to avoid these interpretive challenges. Indeed, proxy reconstructions focused on dissolved oxygen and respired carbon consistently demonstrate the key role of respired carbon storage in the Pacific Ocean and its role in glacial atmospheric $CO_2$ minima (e.g. Anderson et al. 2019; Hoogakker et al. 2018; Jaccard and Galbraith 2012; Jacobel et al. 2017). With this consensus, subsequent work has turned towards quantifying the total storage, parsing its distribution among the basin's various water masses, and investigating the role of mechanisms driving the observed changes. Important questions remain about whether the relative distributions of carbon and oxygen that characterize the modern ocean (Fig. 1) were maintained during the last ice age despite overall higher carbon storage and lower oxygen availability.

### Dissolved carbon and oxygen in the ocean

One of the early approaches to reconstructing respired carbon in bottom waters utilized the $\delta^{13}C$ of epibenthic foraminifera tests, in which progressive $\delta^{13}C$ depletion along a water-mass trajectory is interpreted as indicative of increased respiration of organic carbon (e.g. Curry and Oppo 2005). Unfortunately, air-sea disequilibrium in water-mass source regions can complicate the interpretation of this signal (Galbraith et al. 2015). Oxygen equilibrates an order of magnitude faster than carbon, and because of the tight stoichiometric relationship between oxygen and respired carbon (imparted by the consumption of oxygen and concomitant release of carbon during microbial respiration), the deviation of dissolved oxygen concentrations from saturation levels is the most direct and quantitative paleoceanographic variable for reconstructing changes in deep-sea carbon storage (Sigman et al. 2010). While the air-sea equilibration of oxygen in water-mass source areas may be incomplete (Ito et al. 2004), any undersaturation at the time of water-mass formation would lead to an underestimation of respiratory $CO_2$ storage (for more detail see Anderson et al. 2019). This results in paleoceanographic estimates that reflect a conservative assessment of changes to respired carbon sequestration through time.

### Proxy toolbox

Although reconstructing dissolved oxygen concentrations is an advantageous way to quantify respired carbon storage, finding simple proxies, especially quantitative ones, has been challenging. Early reconstructions examined sedimentary enrichments in redox-sensitive metals including Cd, Cr, Mn, Mo, Re, and most notably U. One of the

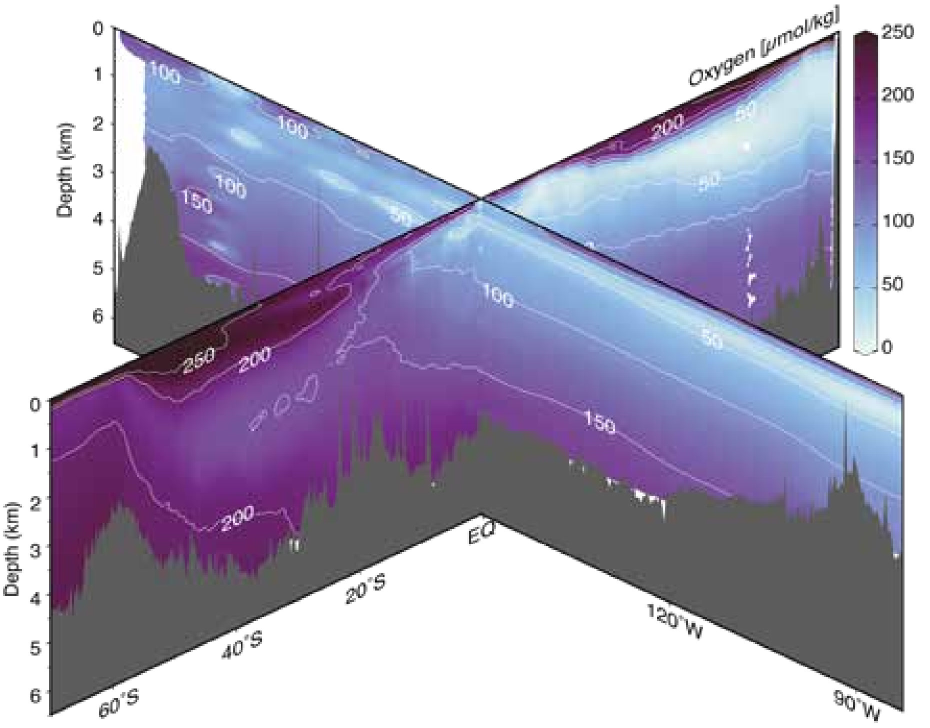

**Figure 1:** Modern distribution of oxygen in the Pacific Ocean. South-to-north transect from 150°W and west-to-east transect along the equator. Data from the PACIFICA dataset (Suzuki et al. 2013). Figure composed using Ocean Data View with in situ data gridded using data-interpolating varational analysis (Schlitzer 2018).

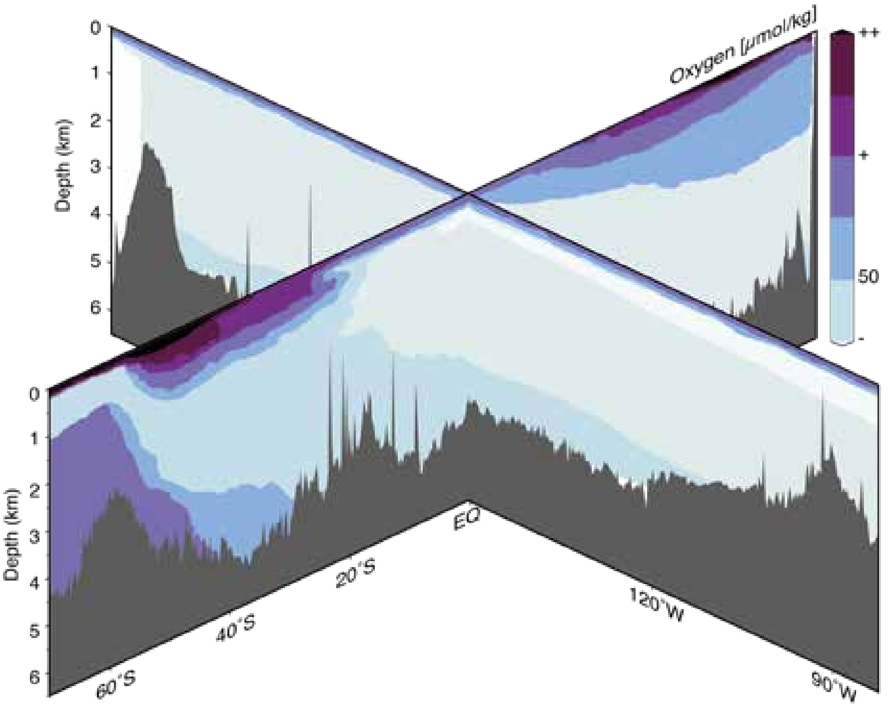

**Figure 2:** Schematic representation of the distribution of oxygen during the Last Glacial Maximum in the Pacific Ocean based qualitatively on model results and paleo reconstructions. Additional spatial and quantitative constraints are needed to refine this conceptual picture.

reasons for the popularization of authigenic U (aU) as a bottom-water oxygen proxy is because it is a product of U/Th series measurements made to quantify mass fluxes to the seafloor using the $^{230}$Th-normalization method. Under reducing (i.e. anoxic) conditions soluble U(VI) is transformed to insoluble U(IV) and is precipitated from porewaters, likely by iron-reducing microbes (McManus et al. 2005). If the co-occurring flux of organic carbon to the sediments can be established (to control for the typically confounding effect of microbial respiration on porewater oxygen concentrations), changes in the sedimentary abundance of aU can be interpreted qualitatively as indicative of changes in bottom-water oxygen availability. Because the post-depositional re-introduction of oxygen can remove aU from sediments, careful attention must be paid to avoid interpreting diagenetic artifacts introduced by down-core diffusion of oxygen and subsequent aU loss (e.g. Jacobel et al. 2017).

Recently, two proxies for quantitatively reconstructing bottom-water oxygen have evolved in parallel. The first is grounded in observations made in the 1980s (McCorkle et al. 1985) suggesting that the carbon isotope gradient in porewaters is, at least in part, related to bottom-water oxygen concentrations. The proxy was recently calibrated by Hoogakker et al. (2015) and empirically relates the carbon isotope gradient ($\Delta\delta^{13}$C) between epifaunal benthic foraminifera and infaunal benthic species to the bottom-water oxygen concentration. The second proxy, most recently detailed by Anderson et al. (2019), makes use of the semi-quantitative relationship between oxygen availability and the remineralization of organic matter (for example the $C_{37}$ alkenone biomarker) by oxic respiration. As with aU, both the $\Delta\delta^{13}$C and biomarker preservation proxies may respond to the rain of labile organic carbon to the site. Thus, reconstructions of bottom-water oxygen content should always be presented alongside, and interpreted in tandem with, a diagenesis-resistant, flux-normalized proxy for organic carbon flux such as biogenic (or excess) barium or opal flux.

## Findings

Numerous records of aU, $\Delta\delta^{13}$C, and $C_{37}$ biomarker preservation have been measured at Pacific Ocean sediment core sites, especially in the equatorial Pacific, where sites provide good coverage of the basin's deep water masses. Where multiple proxies have been measured on co-located samples, general agreement on the sense and timing of bottom-water oxygen changes has been found (Anderson et al. 2019), despite some site-specific data limitations due to changes in the rate of organic carbon fluxes, or post-depositional diagenesis. Importantly, lower oxygen concentrations during the last ice age have been found for all deep equatorial Pacific sites below ~1 km (Anderson et al. 2019), suggesting that the entire deep Pacific below the depth of the modern oxygen minimum zone experienced increased respired carbon storage (see schematic in Fig. 2). Data from the high latitude North and South Pacific Oceans are consistent with findings from the equatorial Pacific (e.g. Jaccard and Galbraith 2012; Jaccard et al. 2009). The latest conservative estimates based on the biomarker preservation proxy (Anderson et al. 2019) suggest that $CO_2$ storage during the last ice age may have been up to ~850 PgC greater than at present. This estimate is based on the assumption that the magnitude of carbon storage in the deep equatorial Pacific during the last ice age is representative of 50% of the ocean's volume – an extrapolation that, while reasonable, reflects the scarcity of quantitative estimates of ocean carbon storage. Although additional data are needed to better constrain the uncertainties associated with this estimate, deep ocean carbon storage of this magnitude is sufficient to close the glacial carbon budget by accounting for both estimates of atmospheric $CO_2$ drawdown and estimates of carbon loss from the terrestrial biosphere.

## Future work

Advances in proxy development and interpretation represent significant progress towards the goal of quantitatively reconstructing respired carbon storage in abyssal Pacific water masses and in those of the other ocean basins during the last ice age and other past climate intervals. As paleoceanographers push these reconstructions to become more robust and spatio-temporally resolved, their ability to provide insight into past changes increases, and their role in validating models of glacial-interglacial change that include biogeochemical cycles (e.g. Khatiwala et al. 2019; Yamamoto et al. 2019) is enhanced. As the global oceans experience increasing impacts from anthropogenic climate forcing, improving biogeochemical models of ocean responses is ever more crucial. Using past variability in climate states as experimental realizations for testing hypotheses about mechanisms of change is critical for improving predictions and targeting preventative and mitigating action.

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# Revealing past ocean circulation with neodymium isotopes

Patrick Blaser[1], M. Frank[2] and T. van de Flierdt[3]

**The dissolved neodymium isotope composition of seawater is widely used to study past changes in provenance and mixing of different water masses in the ocean. We discuss mechanisms controlling signal formation and preservation, proxy strengths, and current challenges.**

The samarium-neodymium (Nd) decay system has been widely used to determine the age of crustal rocks and the provenance of detrital sediments. However, the dissolved radiogenic isotope composition of Nd (expressed as $\varepsilon_{Nd} = [(^{143}Nd/^{144}Nd)/0.512638 - 1] \times 10^4$) in seawater also traces the distribution of major water masses and their mixing. This is the foundation for using Nd isotopes as a tracer for ocean circulation (van de Flierdt et al. 2016).

### Disentangling ocean circulation from carbon storage

For decades, the reconstruction of past ocean circulation relied on the stable isotope composition of the nutrient component carbon (C) in marine calcareous organisms ($^{13}C/^{12}C$ ratio expressed as $\delta^{13}C$; Fig. 1). However, both biological cycling and ocean circulation play major roles in setting the measured $\delta^{13}C$ signature. In contrast, the lithogenic element Nd is not actively involved in marine biological cycling. Recorded in and extracted from oceanic archives, radiogenic Nd isotopes fingerprint where a water mass acquired its Nd isotope signature. Thus, the combination of Nd and C isotopes in oceanic archives allows us to disentangle deep ocean circulation from carbon storage under past climatic conditions and becomes more valuable than the sum of its parts.

For example, Piotrowski et al. (2005) combined Nd, oxygen, and carbon isotopes from a high sedimentation site in the South Atlantic to show that glacial-interglacial transitions first manifested themselves in changes in ice sheets, followed by ocean carbon storage, and finally ocean circulation. Pena and Goldstein (2014) extended the $\varepsilon_{Nd}$ record across the mid Pleistocene and found that Atlantic meridional overturning skipped a beat during interglacial marine isotope stage 23 (approximately 900 kyr BP), increasing carbon sequestration and thereby promoting ice-sheet build-up and setting the stage for the mid-Pleistocene transition. During this period, glacial cycles switched from a 41 kyr periodicity to one of 100 kyr (see also Farmer et al. this issue). For the Last Glacial Maximum, Howe et al. (2016a) compiled Atlantic $\varepsilon_{Nd}$ data suggesting that southern sourced water was less prevalent than inferred from carbon isotopes. This implies that biological cycling must have played a greater role than previously thought. These examples demonstrate the value of seawater derived $\varepsilon_{Nd}$ as a water-mass proxy in the paleoceanographer's toolbox.

### What determines the seawater Nd isotope signal?

Lithogenic in origin, dissolved Nd is introduced into surface waters by erosion and weathering of continental crust. Hence, water masses typically acquire their Nd isotope fingerprint at the interface with continents. Subsequently, convection leads to the export of these characteristic $\varepsilon_{Nd}$ signatures to deep waters (Fig. 1).

The mean residence time of Nd in the deep oceans is on the order of centuries, and is thus similar to the mean ocean overturning time. This similarity of time constants is the decisive factor rendering $\varepsilon_{Nd}$ a suitable tracer for ocean water masses. Hence, $\varepsilon_{Nd}$ behaves largely conservatively away from ocean margins (no significant sources or sinks), with measured signatures primarily reflecting the mixture of distinct water masses transported across ocean basins (Fig. 2a). On regional and local scales, however, geochemical processes can modulate the residence time of Nd dissolved in seawater.

The concentration of dissolved Nd generally increases with water depth, indicating a combined control of advection and vertical transport via adsorption and desorption from particles. This can transfer Nd vertically through the water column and across water-mass boundaries. At the ocean bottom, fluxes of Nd across the sediment-seawater interface have been observed both into and out of bottom waters (Haley et al. 2017). In general, such benthic exchange depends on the reactivity of detrital material releasing Nd in the sediment. Exchange may also be facilitated within benthic nepheloid layers

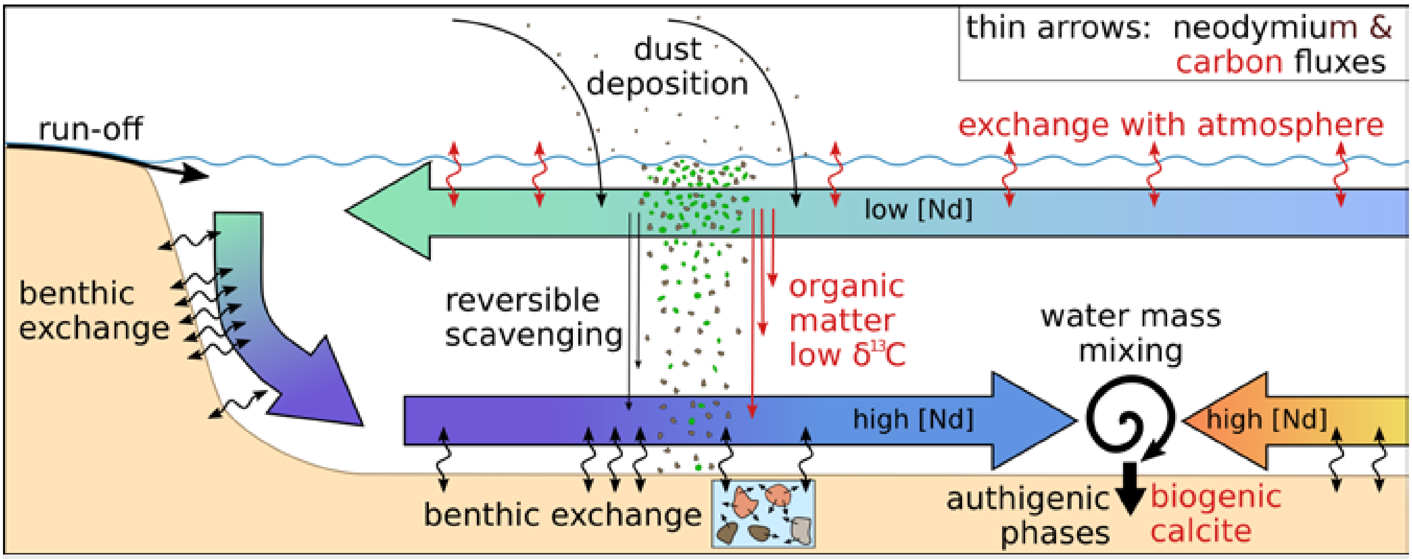

**Figure 1:** Simplified scheme of the most relevant biogeochemical processes influencing Nd and C isotope compositions of water masses; from surface water via deep end-member formation to mixing and archiving. Large arrows represent water masses with colors qualitatively implying different isotope compositions.

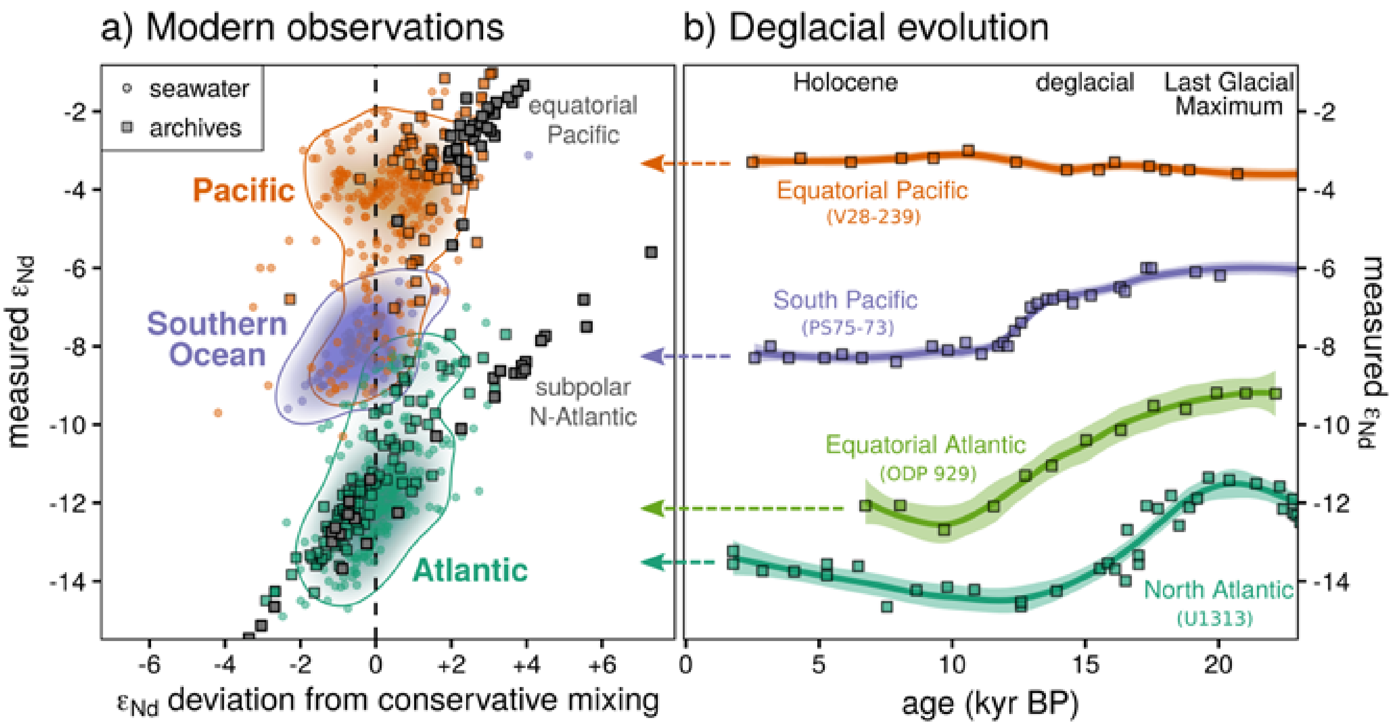

**Figure 2: (A)** Measured $\varepsilon_{Nd}$ of seawater and "young" archives (>1500m depth) vs. their deviation from purely conservative mixing of water-mass end-members (Tachikawa et al. 2017). Pacific $\varepsilon_{Nd}$ values are high due to ubiquitous young volcanic rocks, whereas old terranes around the North Atlantic lead to low $\varepsilon_{Nd}$. The Southern (and Indian) Ocean exhibits intermediate signatures. **(B)** The $\varepsilon_{Nd}$ evolution from four representative deep sites since the Last Glacial Maximum (Basak et al. 2018; Howe et al. 2016b; Hu and Piotrowski 2018; Lippold et al. 2016; Pöppelmeier et al. 2018). Higher glacial $\varepsilon_{Nd}$ in the Atlantic is generally interpreted to indicate the presence of more Pacific-sourced water, but uncertainties in past end-member $\varepsilon_{Nd}$ and Nd concentrations complicate such interpretations.

through the availability of large particle surface areas (van de Flierdt et al. 2016).

Geochemical processes are not necessarily restricted to regions where water masses are formed and their end-member characteristics are defined. Therefore, a non-conservative element is added to the distribution of $\varepsilon_{Nd}$ in seawater. Ultimately, it is the balance of physical water-mass advection (conservative component) and geochemical processes (non-conservative component) that determines the residence time of dissolved Nd in seawater and whether its isotope composition primarily reflects water-mass mixing. In environments in which exchange processes lead to faster replacement of Nd than water-mass transit, $\varepsilon_{Nd}$ may even be applicable as a kinematic proxy, as Du et al. (2018) suggested for the North Pacific.

### What do the archives tell us?

Marine archives record the local Nd isotope signatures of water-mass mixtures. The extraction of unaltered past seawater $\varepsilon_{Nd}$ is challenging but has been achieved from fossil fish debris, deep-sea coral skeletons, and ferromanganese deposits in the form of crusts, nodules, and coatings on bulk sediment particles and inside foraminiferal calcite tests (Fig. 2a).

However, the early diagenetic archiving process is currently not well understood and in some regions all attempts to extract local bottom water $\varepsilon_{Nd}$ from core-top sediments have failed (see gray indicated regions in Fig. 2a). The archiving processes comprise co-precipitation of Nd with iron-manganese oxyhydroxides, diffusion into biogenic apatite, and the precipitation in microbially mediated microenvironments. Hence, for sedimentary $\varepsilon_{Nd}$ signatures, one possible explanation for discrepancies compared to seawater $\varepsilon_{Nd}$ is that a pore-water signal is recorded, which itself can reflect a mixture of bottom water and detrital $\varepsilon_{Nd}$. Pore waters and sedimentary authigenic phases could thus carry additional information about the strength of past benthic exchange (Du et al. 2016).

### Improving Nd isotope-based reconstructions of water masses

Mechanisms and magnitudes of Nd supply to the oceans via particles, reactive sediments, or in dissolved form can vary as a function of climatically controlled parameters such as precipitation or ice and vegetation cover on the continents. Thus, the accuracy of $\varepsilon_{Nd}$ as a paleo water-mass proxy often depends on the knowledge of past end-member characteristics (Fig. 2b; Howe et al. 2016a; Pöppelmeier et al. 2018), the impact of non-conservative processes (Blaser et al. 2019), and the fidelity of the archive and extraction method used (Blaser et al. 2016; Du et al. 2016).

Paleoceanographic reconstructions from settings with little input of reactive detritus and expected large water mass fluxes will be least affected by such uncertainties, and interpretations will ideally be based on $\varepsilon_{Nd}$ gradients between different sites. Better data coverage within and near regions of significant benthic exchange and end-member formation, as well as incorporation of Nd concentrations and $\varepsilon_{Nd}$ in ocean circulation models will be important steps to gain deeper insights into past oceanic Nd cycling and water mass circulation. The combination of several tracers can eliminate uncertainties of individual proxies. At the same time a better understanding of present-day Nd cycling through measurements along ocean sections and dedicated process studies at key locations, currently performed as part of the international GEOTRACES program (geotraces.org), will increase the reliability of interpretations based on Nd isotopes.

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# Pa/Th as a (paleo)circulation tracer: A North Atlantic perspective

Laura F. Robinson[1], G.M. Henderson[2], H.C. Ng[1] and J.F. McManus[3]

**Despite complex geochemical ocean cycling, sedimentary Pa/Th ratios provide a method for reconstructing past Atlantic overturning rates. This review highlights progress and challenges from the combination of modern and paleo studies.**

Measuring rates of processes in the ocean remains a key target in both modern and paleoceanographic studies. Ocean-driven, cross-equatorial heat transport provides a clear physical link between global climate and regional heat distribution, to the extent that constraining the rates of basin-scale meridional overturning circulation is of importance. The decay of radioactive elements (e.g. tritium, radiocarbon) provides a means for quantifying this overturning, given knowledge of isotopic sources and cycling.

In this article we highlight a particular use of radioactive elements within the uranium-series decay chains. The approach relies on the contrasting chemistry of soluble uranium (U) and two daughter elements, thorium (Th) and protactinium (Pa). Specifically, $^{238}$U and $^{235}$U occur in nature in a fixed ratio, and $^{238}$U decays to $^{230}$Th (via $^{234}$U), while $^{235}$U decays to $^{231}$Pa. Since uranium resides in seawater sufficiently long to be very well mixed throughout the ocean, the known concentration and predictable decay rates of each isotope can be used to calculate the production of $^{230}$Th and $^{231}$Pa. These isotopes are therefore produced with a fixed activity ratio of 0.093. Both daughter isotopes are rapidly adsorbed, or "scavenged", onto marine particles, which subsequently accumulate on the seafloor as sediments. Thorium is scavenged more efficiently than Pa by most types of marine particles, leading to contrasting residence times in seawater, allowing for differential lateral transport and measurable shifts in the Pa/Th activity ratio of underlying sediments. These deviations from the production ratio reflect a balance between scavenging and export from the basin via the overturning circulation. Today, the sediments of the North Atlantic have a Pa/Th ratio of ~0.05 because some Pa is being transported southwards and buried in the Southern Ocean (Yu et al. 1996). This export can also be deduced from analyses of seawater Pa and Th concentrations (Deng et al. 2018, as summarized in Fig. 1). In principle, less water advection should result in less export and therefore enhanced burial of Pa, and higher sedimentary Pa/Th ratios in the North Atlantic.

The use of sedimentary Pa/Th ratios to assess past flow was pioneered in 1996 by Yu et al. who compared Holocene and Last Glacial Maximum sediments from across the Atlantic to test whether there was any change in this ratio associated with the cold, glaciated climate. Surprisingly, the results showed very little difference between modern and glacial overturning in the deep ocean. By contrast, Pa/Th analyzed in rapidly accumulating sediments from the Bermuda Rise indicated that there may have been rather large changes in circulation during the deglaciation (McManus et al. 2004). From modestly increased glacial values, suggesting persistent overall overturning, Pa/Th ratios increased markedly to high values close to the production rate during Heinrich Stadial 1, and to elevated values during the Younger Dryas – interpreted as a reduction in overturning strength. Importantly, these changes occurred in association with North Atlantic iceberg discharge events and northern cooling, pointing to a link between freshwater, climate, and reduced Atlantic overturning. The Bermuda Rise Pa/Th record is now widely used as an archetype circulation record for the North Atlantic, providing a modeling target and general reference curve for many paleoclimate studies (e.g. Liu et al. 2009). Similar associations between climate change and changes in sedimentary Pa/Th have been observed throughout the last glacial and deglaciation in the North Atlantic (Gherardi et al. 2005; Böhm et al. 2015; Henry et al. 2016; Lippold et al. 2009; Ng et al. 2018).

## Challenges

The complex geochemical cycling of the uranium-series isotopes adds multiple complications to the use of Pa/Th as a circulation tracer. For example, it has been established that Pa is scavenged more effectively onto opal than it is onto carbonates (e.g. Chase et al. 2002; Luo and Ku 2004). Particle concentration and iron-rich phases are other factors that influence the scavenging efficiency of Pa and Th, so Pa/Th could potentially be affected by changes in productivity, nepheloid layers, or hydrothermal activity (e.g. Bradtmiller et al. 2007; Hayes et al. 2015). Recent paleoclimate studies have assessed both the opal concentration and particle flux rates to investigate their competing influence on sedimentary Pa/Th ratios. For example, Bradtmiller et al. (2014) drew on the approach of Yu et al. (1996) to look at spatial patterns of Atlantic sedimentary Pa/Th in three time-slices, filtering for both opal and particle flux. The average of the North Atlantic data supported the early conclusion of Yu et al. (1996), with no significant difference between modern values and those during the Last Glacial Maximum, although

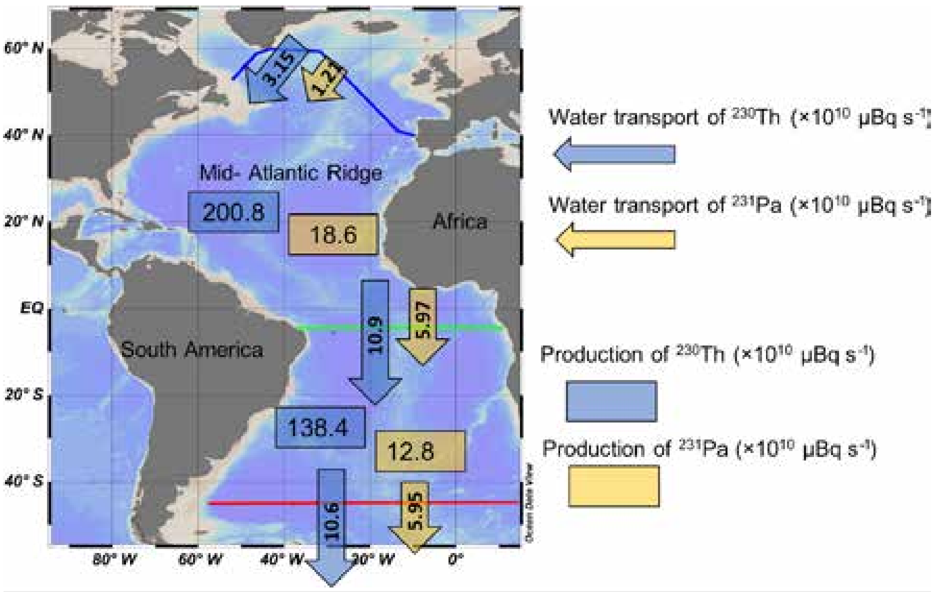

**Figure 1:** This overview figure reproduced from Deng et al. (2018) shows fluxes of $^{230}$Th (blue arrows) and $^{231}$Pa (yellow arrows) at three latitudes in the Atlantic. When compared to the total production of $^{230}$Th (blue boxes) and $^{231}$Pa (yellow boxes) these fluxes indicate that only 4% of the $^{230}$Th, but 26% of the $^{231}$Pa, produced in the North Atlantic are exported southward by ocean circulation in the modern ocean (Deng et al. 2018). It is this relatively larger export of $^{231}$Pa on which the Pa/Th proxy for past circulation relies.

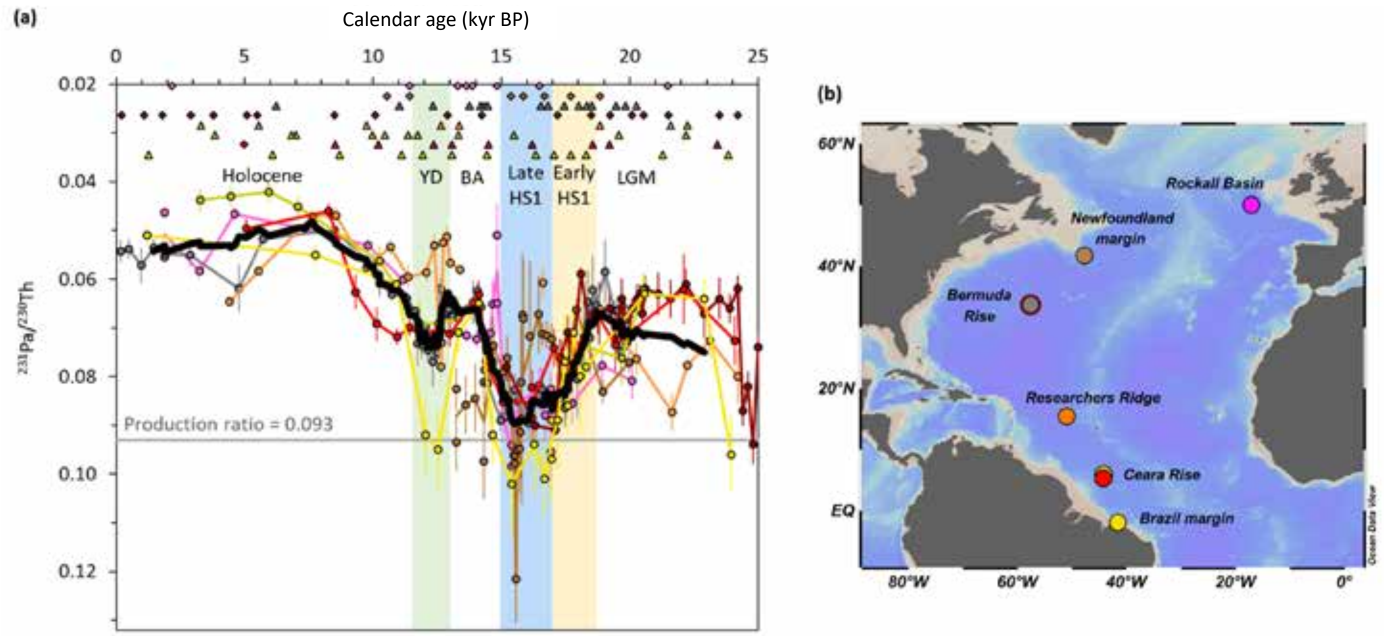

**Figure 2:** Past changes in AMOC rate over the last 25,000 years. **(A)** Compilation of selected Atlantic sedimentary $^{231}$Pa/$^{230}$Th records (Ng et al. 2018). Bold black line is the composite $^{231}$Pa/$^{230}$Th record that reflects the average basin-scale changes in circulation rate (Ng et al. 2018); colors correspond to sites identified in **(B)** site map. Error bars represent two standard errors of the mean. Triangle and diamond symbols respectively signify $^{14}$C and non-$^{14}$C chronological tie-points. Annotations of key climate events: LGM: Last Glacial Maximum; HS1: Heinrich Stadial 1; BA: Bølling-Allerød; YD: Younger Dryas (Ng et al. 2018).

spatial and depth differences were apparent. By contrast, the Pa/Th ratio was higher for Heinrich Stadial 1 sediments, consistent with a slowdown in the overall meridional overturning circulation during that time of cold conditions in the North Atlantic.

### Modern observations

Important to the principle of using Pa/Th as a tracer for circulation is the deduction that the scavenging of both isotopes is reversible. Both isotopes generally increase in concentration with depth in the ocean, in both dissolved and particulate phases. Bacon and Anderson (1982) explained this behavior with a simple one-dimensional reversible scavenging model. Over the following decades, analysis of additional seawater profiles led to development of more complicated scavenging models with an "advection" component allowing for a quantification of timescales for Atlantic overturning rates ranging from decades to centuries (Moran et al. 2001). A dramatic increase in the number of seawater analyses, modeling studies, and understanding of Pa/Th in the ocean comes from the ongoing international GEOTRACES program (Schlitzer et al. 2018). Although this greater spatial coverage has enabled broadscale estimates of the export of Pa and Th from the Atlantic (e.g. Fig 1; Deng et al. 2018), the expected pattern of a Pa/Th evolution towards higher values as waters travel along the advective pathways of the Atlantic is not apparent in seawater data. These data suggest that there are aspects of the marine chemistry of Pa and Th that are not yet fully understood, and will require further investigation into their sources, sinks, and cycling. Without this understanding, it is challenging to interpret Pa/Th data from a single location. It remains the case, though, that with sufficient cores to characterize the sedimentary ratio of Pa/Th at a basin scale, the net export of Pa can provide powerful information about advection from the basin.

A remaining difficulty in this respect, however, is to robustly interpret sediment data at times when water-mass proxies (e.g. $\delta^{13}$C, Cd/Ca) indicate that there was deep-water flow both into and out of the North Atlantic.

Assessing the basin-scale behavior of Pa/Th in such situations is an important target of ongoing modeling efforts. Early efforts to simulate the behavior of Pa/Th in the Atlantic confirmed its potential sensitivity to changes in overturning circulation rates, including on millennial timescales (Marchal et al. 2000). A subsequent study utilized an inverse method to place constraints on the departures from the observed modern circulation constrained by relatively limited sedimentary data (Burke et al. 2011). More recently, the direct incorporation of Pa and Th in ocean circulation models (e.g. Missiaen et al. 2019) heralds new possibilities for insights derived from comparisons of simulations with both water-column and sedimentary data.

### Where are we now?

Despite challenges, there is a clear place for the use of sedimentary Pa/Th in the reconstruction of past circulation rates. By using multiple cores, and by assessing the potential complicating factors from variable scavenging rates, Pa/Th can act as a powerful proxy. Indeed, a recent synthesis of Atlantic deglacial sedimentary cores, filtered for particle and opal flux, yields a coherent pattern over the last 25,000 years (Fig. 2; Ng et al. 2018). In particular, cores from the deep high-latitude North and the West Atlantic all yield broadly similar results as the original high-resolution Bermuda Rise records, emphasizing a strong case for a broad overturning control on the sedimentary Pa/Th ratio, with links to past millennial climate events.

With closer integration of GEOTRACES seawater and core-top sediment data with modeling there is scope to move from general statements on overall overturning rates to a more nuanced interpretation. While quantifying overturning rates may remain challenging, drawing on the strength of these intriguing isotopes has the potential to continue to reveal new information on how and why the oceans have changed in the past.

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# Boron in $CaCO_3$ as a record of past seawater carbonate chemistry

Michael J. Henehan and Hana Jurikova

**Boron incorporated in marine biogenic carbonates records the pH of seawater during precipitation. From reconstructing atmospheric $CO_2$ beyond ice-core records to deciphering the ocean's role in storing and releasing carbon, boron is proving to be a vital tool in paleoclimate research.**

Around a third of anthropogenic $CO_2$ released to date has been taken up by the ocean. Its future capacity to sequester carbon, however, given potentially dynamic biogeochemical feedbacks, is unclear. Studies of the geological past provide numerous examples of how the ocean regulates and moderates atmospheric $CO_2$ levels. To learn from these, however, we need effective recorders of the ocean's carbonate system. Boron (B)-based proxies – namely B/Ca ratios and the boron isotope ($\delta^{11}B$)-pH proxy applied to marine carbonate archives are among the most promising tools for reconstructing past ocean carbonate chemistry and atmospheric $CO_2$. Here we briefly summarize some of the progress, problems, and prospects in the field.

### Chemical basis of boron (B) proxies

In short, B-based proxies rely on the predictable pH-dependent speciation of dissolved B in seawater, between borate ion ($B(OH)_4^-$, prevalent at higher pH) and boric acid ($B(OH)_3$, prevalent at lower pH), as shown in Figure 1. The B/Ca proxy works on the assumption that the more of the charged borate ion there is in solution (due to higher pH and lower $CO_2$), the more B will be incorporated into the skeletal $CaCO_3$ of marine calcifiers. The $\delta^{11}B$-pH proxy instead leverages the constant isotope fractionation associated with borate ion and boric acid speciation. This fractionation results in a predictable relationship between the $\delta^{11}B$ of borate (the species incorporated into biogenic $CaCO_3$) and pH. This foundation in aqueous chemistry has contributed to the considerable success of B-based proxies to date.

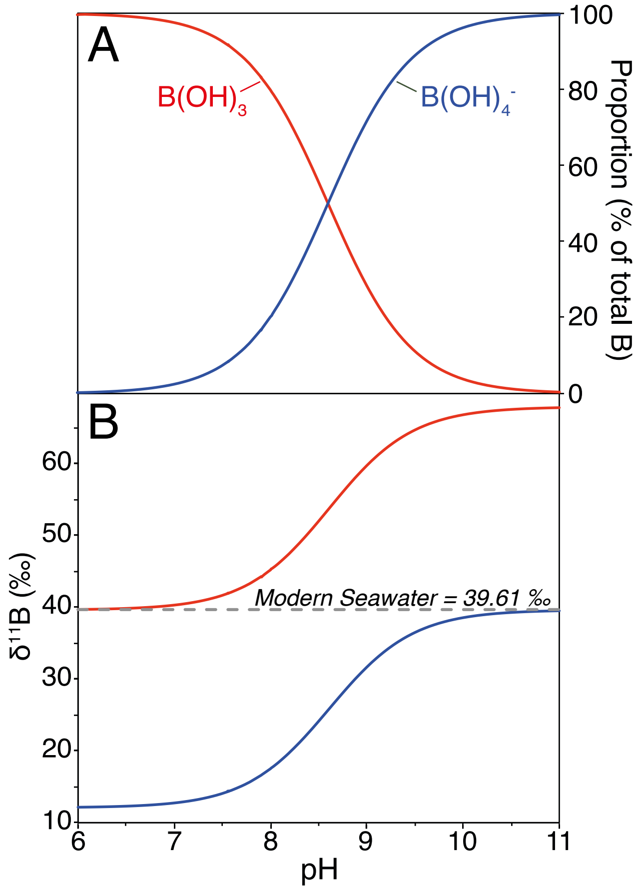

**Figure 1: (A)** The relative abundance of boric acid (in red) and borate ion (blue) changes with pH. **(B)** A fixed isotope fractionation of ~27‰ (independent of pH) between the two means that the isotopic composition ($\delta^{11}B$) of both species changes predictably with pH. Since borate is incorporated into carbonate, carbonate $\delta^{11}B$ reflects the pH of the solution in which it grew.

### The B/Ca proxy

The B/Ca proxy is attractive in that the analytical method is simpler, and it requires less sample material than the $\delta^{11}B$-pH proxy. However, the outlook for this proxy is, at present, mixed. In planktic foraminifera, a host of environmental controls are now known to influence how much of the borate present in solution at any given pH is ultimately incorporated into calcite. These include salinity, ambient phosphorous concentration, light levels, and calcification rate (e.g. Allen and Hönisch 2012; Babila et al. 2014; Henehan et al. 2015; Salmon et al. 2016). Clearly, this complicates the use of B/Ca in planktic foraminifera as a straightforward pH proxy. Indeed, high-profile early applications of the proxy to reconstruct surface-ocean pH and hence atmospheric $CO_2$ (Tripati et al. 2009) have since been shown to have been driven by secondary parameters involved in calculation, rather than the measured B/Ca data itself (Allen and Hönisch 2012). On the other hand, in deep-sea benthic foraminifera strong empirical relationships are observed between B/Ca and bottom-water carbonate saturation ($\Delta[CO_3^{2-}]$; Yu and Elderfield 2007). This has been valuable in tracking the migration of $CO_2$-rich deep-water bodies, and for the most part these reconstructions have been consistent with independent observations (e.g. $^{14}C$, $\delta^{13}C$, deep-sea coral $\delta^{11}B$). Collinearity between salinity, phosphorous, and $\Delta[CO_3^{2-}]$ within benthic foraminiferal B/Ca calibration datasets (Henehan 2013), however, means some of the non-carbonate system controls seen in planktic foraminifera could still play a role.

On a more positive note, for all of its documented competing controls, in many geological records B/Ca does appear to behave like a pH proxy. For instance, at the Paleocene-Eocene Thermal Maximum, B/Ca declines in tandem with excursions in $\delta^{11}B$ (Penman et al. 2014), suggesting that in some settings planktic foraminiferal B/Ca ratios can be at least qualitatively informative. It is thus premature at this point to discount the proxy entirely.

### The boron isotope-pH proxy

Using boron isotopes circumvents many issues associated with B/Ca, allowing for quantitative reconstruction of pH and $CO_2$. For example, diagenetic recrystallisation of fossil $CaCO_3$ may result in loss of B (thus changing B/Ca), but the isotopic composition of the remaining B is unaffected (Edgar et al. 2015). Furthermore, factors like temperature and salinity have no competing effects on $\delta^{11}B$ outside of their well-understood quantifiable effect on aqueous B speciation (e.g. Henehan et al. 2016). Most importantly, the dominant control of seawater pH on $\delta^{11}B$ has been repeatedly demonstrated. For example, pH reconstructed from the $\delta^{11}B$ of core-top deep-sea benthic foraminifera closely matches the pH of the water in which they grew (Rae et al. 2011), indicating the sole incorporation of borate into foraminifera and supporting the chemical foundation of the proxy.

For other calcifiers, although the control of pH on $\delta^{11}B$ is clear, skeletal carbonate rarely records the $\delta^{11}B$ of ambient seawater borate ($\delta^{11}B_{borate}$) exactly. Instead, their $\delta^{11}B$ reflects a combination of $\delta^{11}B_{borate}$ and a superimposed (typically species-specific) physiologically induced offset, termed a "vital effect". In the case of corals, this vital effect reflects the pH to which the calcifying fluid has been raised, which in turn varies with bulk seawater pH (Venn et al. 2013). In brachiopods and bivalves the situation is perhaps more complex, but their $\delta^{11}B$ demonstrably varies with ambient pH (e.g. Jurikova et al. 2019).

In planktic foraminifera – our primary archive of surface-water pH and atmospheric $CO_2$ – vital effects are also ubiquitous (unlike in deep-sea benthic foraminifera). Although we know foraminifera also raise the pH of their internal calcifying fluid (Bentov et al. 2009), thus far the most compelling explanation for species-specific deviations from $\delta^{11}B_{borate}$ is microenvironment alteration (e.g. Henehan et al. 2016). This framework recognizes that planktic foraminifera don't "see" ambient seawater, but rather a layer of seawater immediately surrounding their shell that is too small for turbulent mixing. It predicts, and indeed explains why, symbiont-bearing foraminifera living in the euphotic zone record higher-than-ambient pH and $\delta^{11}B_{borate}$: because their photosynthetic symbionts take up $CO_2$ from their microenvironment. Conversely, species living below the euphotic zone, or those that don't host symbionts, are surrounded by seawater that is richer in respired $CO_2$, and hence lower in pH. This also explains the lack of vital effects in deep-sea benthic foraminifera, as their slow metabolic rates mean diffusion can keep pace with release of respired $CO_2$.

Although foraminiferal $\delta^{11}B$ clearly varies with pH and $CO_2$ regardless of vital effects (see e.g. data from Chalk et al. 2017 plotted in Fig. 2a), individual species differ significantly in their $\delta^{11}B$-pH (or more commonly $\delta^{11}B_{calcite}$-$\delta^{11}B_{borate}$) calibrations. If a species' calibration is known, pH and $CO_2$ values can be calculated from oligotrophic ocean regions with an accuracy and precision rivaled only by ice cores (Fig. 2b; in purple). However, without a calibration, for example with extinct species, quantifying absolute pH is more challenging. For example, if one erroneously applied a calibration derived for *Orbulina universa* to these same *Globigerinoides ruber* data from Chalk et al. (2017; Fig. 2c, in orange), reconstructed $CO_2$ would be inaccurate. Thankfully, efforts to model and constrain vital effects in extinct species are ongoing (e.g. within the SWEET consortium; deepmip.org/sweet); these will reduce this source of uncertainty in deep-time reconstructions.

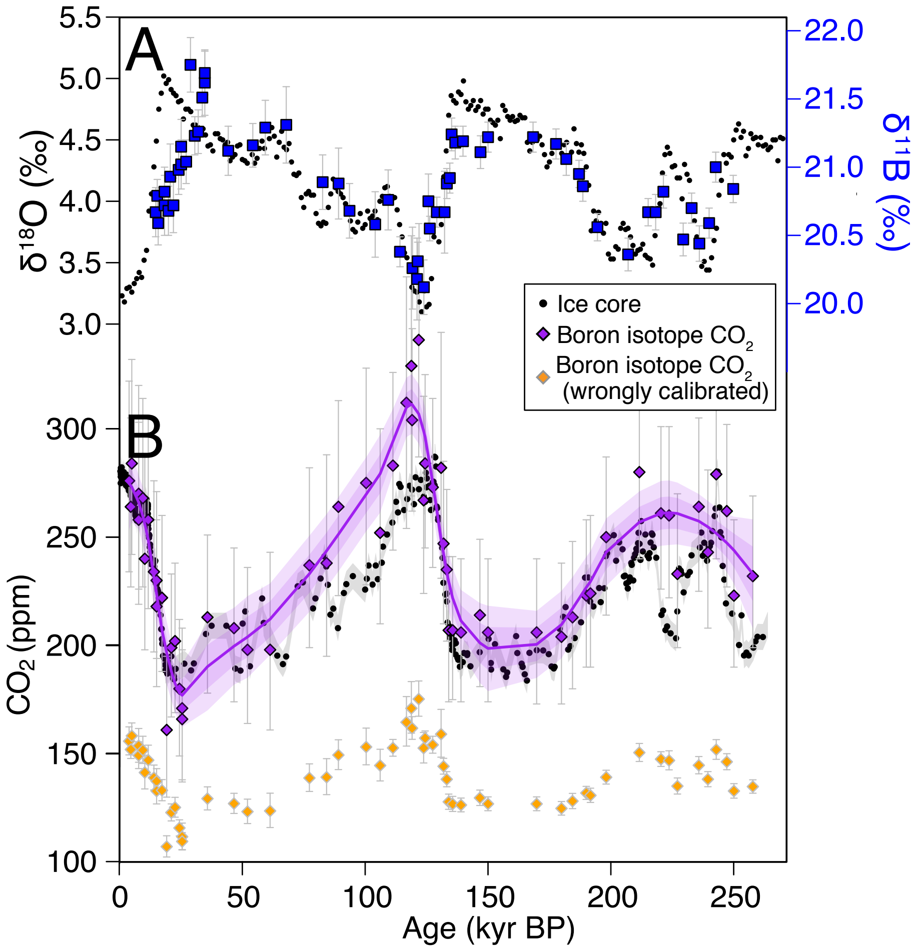

**Figure 2: (A)** Foraminiferal (*Globigerinoides ruber*) $\delta^{11}B$ values from Chalk et al. (2017; in blue) covary strikingly well with glacial-interglacial cycles as expressed in benthic foraminiferal $\delta^{18}O$ from Lisiecki and Raymo (2005), which in turn reflects global ice volume and deep-sea temperatures. **(B)** When correctly calibrated for the species' experimentally quantified vital effect, the resulting reconstructed $CO_2$ (violet) is in good agreement with the ice-core composite record from Lüthi et al. (2008; black). **(C)** However, applying an inappropriate calibration (such as could arise when dealing with extinct species) can lead to spurious $CO_2$ estimates (orange). Here this is illustrated by applying the *Orbulina universa* calibration of Henehan et al. (2016) to the same *G. ruber* data.

Beyond reconstructing atmospheric $CO_2$ (by measuring $\delta^{11}B$ in planktic foraminifera from regions where the atmosphere and surface ocean $CO_2$ are in equilibrium), the $\delta^{11}B$-pH proxy can also be used to detect transient regional changes in air-sea $CO_2$ disequilibrium. This has elucidated the role of changing ocean carbon storage in driving glacial-interglacial $CO_2$ change, with $CO_2$ release from the deep ocean to the atmosphere now known to have played a major role in pushing the Earth out of the last ice age (e.g. Martínez-Botí et al. 2015; Rae et al. 2018). There is considerable potential for such approaches to be applied in deeper time, for instance to investigate changes in ocean carbon storage during hyperthermal events. Ongoing analytical advances and shrinking sample size requirements mean these sorts of applications are coming into reach, potentially overhauling our understanding of how the ocean has influenced atmospheric $CO_2$ through geological history.

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# The deglacial rise in atmospheric $CO_2$: A (not so) simple balance equation

Katrin J. Meissner[1,2] and Laurie Menviel[1]

**Climate models are not able to simulate the full extent of atmospheric $CO_2$ rise during the deglaciation. Involved processes are complex and non-linear; improvement could be achieved with better representations of transient ocean circulation changes and more complex parametrizations of ecosystems.**

Our planet experienced dramatic changes over the past 20,000 years (kyr), transitioning from full glacial conditions to the current interglacial, the Holocene. During this deglaciation, large Northern Hemispheric ice sheets disintegrated, leading to a global sea-level rise of ~134 m (Lambeck et al. 2014). Changes in biogeochemical cycles on land and in the ocean caused a net release of greenhouse gases into the atmosphere, resulting in a rise of ~90 parts per million (ppm) in $CO_2$, ~300 parts per billion (ppb) in $CH_4$ and ~60 ppb in $N_2O$ (Köhler et al. 2017). Marine and terrestrial ecosystems reorganized spatially to adapt to the temperature and precipitation changes that resulted from all of these processes.

These changes did not occur in a continuous or predictable way. The last glacial termination was, on the contrary, quite complex; it was characterized by millennial-scale variability and interhemispheric asynchronies. Like an old flickering fluorescent bulb when switched on, different regions warmed, and cooled again, at different times during the transition. As can be seen in Figure 1, the rise in greenhouse gas concentrations also showed a stepwise behavior, with periods of rapid changes, including $CO_2$ rises of ~13 ppm within 100-200 years (Marcott et al. 2014), and other periods of stagnation or even reversal.

## A rather simple math question

While part of the glacial terrestrial carbon on exposed continental shelves was lost due to flooding (182-266 petagram carbon (PgC); Montenegro et al. 2006), $CO_2$ fertilization, generally warmer and wetter conditions, and the newly available land under retrieving ice sheets were conducive to an overall increase in terrestrial carbon during the deglaciation. Recent estimates of net reservoir changes based on global mean ocean $\delta^{13}C$ suggest a 300 to 460 PgC increase across the last deglaciation (Menviel et al. 2017), or even higher (~850 PgC; Jeltsch-Thömmes et al. 2019).

To account for the increase in atmospheric $CO_2$, the ocean must therefore have released a total of ~500 to 1050 PgC across the deglaciation, of which ~190 PgC led to the observed increase in atmospheric $CO_2$ and 300 to 850 PgC were fixed on land. How did the ocean pull this off?

There is plenty of carbon in the ocean. The modern ocean is estimated to contain ~38,000 PgC (Ciais et al. 2013), making the glacial-interglacial change a mere 1-3% of reservoir change. This rather small change – from an oceanic point of view – had large effects on the climate system. It was likely caused by a combination of the physical, biological, and chemical processes detailed below (Fig. 2). However, no state-of-the-art climate model has been able to simulate the full amplitude of change so far and the sequence of events is still poorly constrained. We have not (yet) been able to solve our rather simple math problem.

## Physical and chemical processes

Given that $CO_2$ is more soluble in cold than warm water, some of the marine carbon release can be explained by ocean warming during the deglaciation (~+25 ppm; Kohfeld and Ridgwell 2009; Ciais et al. 2013). Melting ice sheets add freshwater to the ocean, decreasing salinity, which would have partly counteracted the temperature solubility effect (~-6 ppm; Kohfeld and Ridgwell 2009). This process also decreases ocean alkalinity and DIC concentrations. Such a decrease in alkalinity decreases the solubility of $CO_2$; however, decreasing alkalinity and DIC at a 1:1 ratio leads to an increase in solubility (~-7 ppm; Kohfeld and Ridgwell 2009). Changes in pressure due to rising sea levels and a decrease in deep-ocean alkalinity would have led to changes in the accumulation/dissolution rates of calcium carbonate in marine sediments, which is a negative feedback, and has a tendency to restore carbonate ion concentrations, and therefore alkalinity. Furthermore, the effect of weathering on land would have led to a small drawdown of atmospheric $CO_2$, mitigated by changes in the carbonate compensation depth.

## Biological processes

Some of the surface's dissolved inorganic carbon (DIC) is removed by photosynthesis and transformed into organic carbon. A small percentage of this organic carbon is exported into deeper layers and remineralized into DIC. The strength of this "soft tissue pump" depends on the net primary productivity, which is a function of temperature, nutrient and light availability, competition between species, and the Redfield ratios of the species in question. Nutrient availability depends on ocean circulation and on external fluxes of micronutrients, such as aeolian iron or silica fertilization from dust. For example, the net effect of decreasing dust deposition during the deglaciation has been estimated to have contributed ~+19 ppm to the $CO_2$ rise (Lambert et al. 2015). The strength of the "soft tissue pump" also depends on the remineralization depth of organic carbon. This is a function of the particles' sinking speed and the remineralization rates in the deep ocean. A shoaling of the remineralization depth could have led to a +20 to +30 ppm increase in $CO_2$ (Kwon et al. 2009; Matsumoto 2007; Menviel et al. 2012), but large uncertainties remain.

Calcifying organisms form $CaCO_3$ shells or skeletons in addition to their soft tissue. The calcification process removes alkalinity from surface waters and increases alkalinity at depth upon dissolution. A decrease in surface alkalinity reduces the ability of surface waters to dissolve carbon; this pump has therefore been termed the "carbonate counter pump". Any changes in the competition between calcifying and non-calcifying organisms during the deglaciation, for example due to changes in silicic acid or iron availability, would have changed the strength of the combined biological pump (Matsumoto

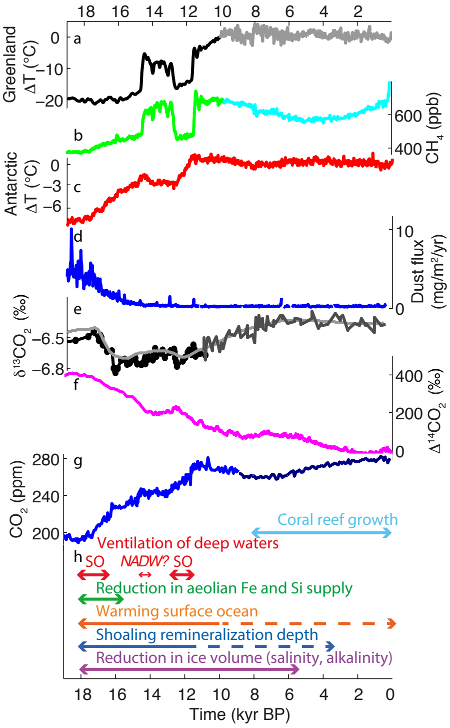

**Figure 1:** Timeseries of **(A)** Greenland surface air temperature anomalies, **(B)** atmospheric $CH_4$ concentrations, **(C)** Antarctic surface-air-temperature anomalies, **(D)** dust flux, **(E)** $\delta^{13}CO_2$, **(F)** $\Delta^{14}CO_2$, **(G)** $CO_2$, **(H)** estimated time span of processes discussed in text; SO stands for ventilation of Southern Ocean, NADW for deepening of North Atlantic Deep Water. References are given in the online version of this article (doi.org/10.22498/pages.27.2.60).

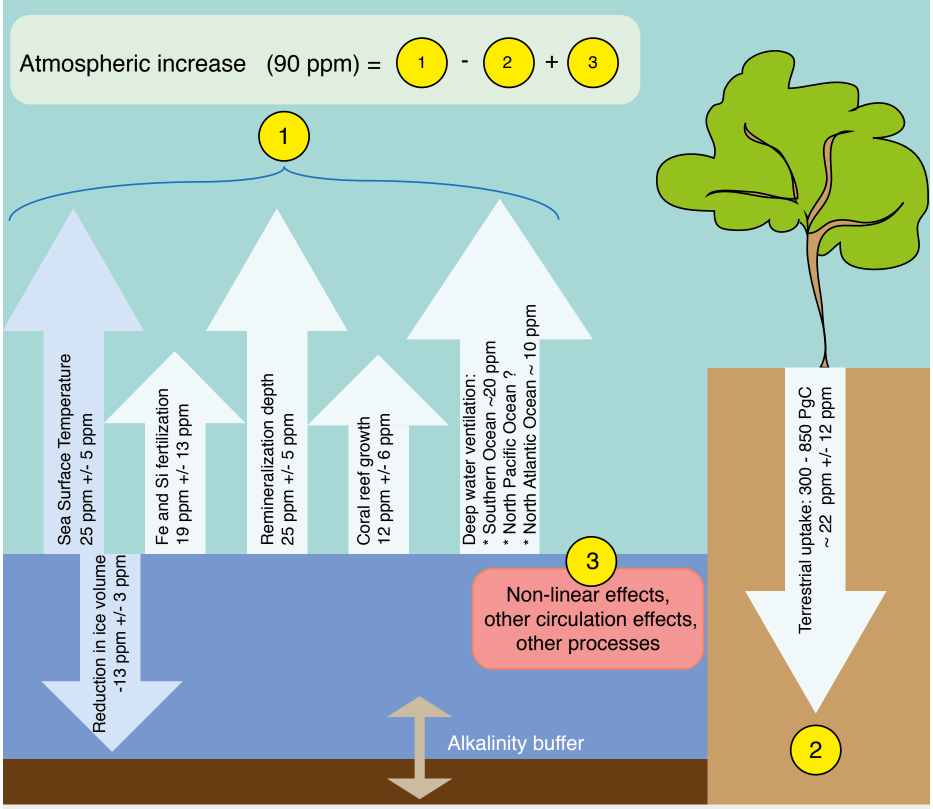

**Figure 2:** Best estimates of processes contributing to atmospheric $CO_2$ changes during the deglaciation. Dark arrows indicate high level of scientific understanding, light arrows indicate medium to low level of scientific understanding. Estimates are discussed in the text or in references in the online version of this article (doi.org/10.22498/pages.27.2.60).

et al. 2002). In addition, a protective calcite shell changes the sinking speed of particles and thus the remineralization depth. The flooding of continental shelves increased the habitat of calcifying coral reefs, decreasing alkalinity and contributing to the Holocene atmospheric $CO_2$ increase (~+12 ppm; Kohfeld and Ridgwell 2009).

### Tying it all together: Ocean circulation

Ocean circulation connects all of the processes mentioned above in a complex way. It transports nutrients to the surface for biological carbon fixation. It also determines the residence time of deep water masses and therefore the total accumulation of remineralized carbon in the deep ocean. While much emphasis has been put on understanding North Atlantic circulation changes (e.g. Ritz et al. 2013; Huiskamp and Meissner 2012), it has recently become clear that the Southern Ocean, where most of surface/deep-water exchange takes place, is likely a more important player. Changes in Southern Ocean circulation can be prompted by changes in winds, sea-ice cover, and meridional density gradients, all of which took place during the deglaciation (Menviel et al. 2018). Finally, the Pacific Ocean is not only the largest ocean basin, it is also characterized by very sluggish circulation and therefore a much higher DIC content than any other ocean basin. Any small increase in ventilation in this basin has the potential to dramatically increase atmospheric $CO_2$ concentrations (Menviel et al. 2014; Rae et al. 2014).

### What are the models missing?

Although there has been considerable progress in carbon cycle modeling over the past 20 years, we still do not understand, nor are able to accurately simulate, all of the observed changes during the last deglaciation.

The main culprit is likely an insufficient representation and understanding of changes in ocean circulation. As discussed above, deep water masses are supersaturated in old carbon, holding 100 times more carbon than needed to explain the glacial-interglacial changes. Small circulation changes can result in considerable follow-on effects on ocean-air carbon fluxes.

So far, only models of intermediate complexity have been able to study the sequence of events leading to changes in glacial-interglacial atmospheric $CO_2$. The spatial grids of these models are coarse and do not resolve small-scale processes in the ocean that are potentially important. While they capture the main changes in water masses well enough, they are overall too diffusive. Models that are better skilled in representing physical circulation changes, such as eddy-resolving models, cannot be integrated long enough to even get today's deep ocean circulation into equilibrium, let alone today's marine carbon cycle. Simulating a full transient deglaciation with such models is still far beyond the horizon with today's available computer power. However, these models can be used to test single processes under idealized and fixed boundary conditions.

Another culprit is most certainly the representation of ecosystems in our climate models. These model components are still in their infancy. They are highly simplified, representing the whole complexity of marine life with a few functional types for plankton based on simple equations for population dynamics. Carbon uptake, the sinking speed of particles, and remineralization rates are underconstrained and therefore overtuned (Duteil et al. 2012). It is questionable whether these models' ecosystem sensitivities can be trusted under boundary conditions that are significantly different from present-day conditions.

Finally, none of our state-of-the-art climate models include the whole complexity of sediment feedbacks, which played a non-negligible role during the deglaciation.

### How do we solve this?

The proxy community is providing an increasingly coherent picture of deglacial changes. For example, recent high-resolution atmospheric $CO_2$ and isotope records from Antarctic ice cores have highlighted the millennial variability and timing of the deglacial atmospheric $CO_2$ increase and potential source reservoirs (Fig. 1). At the same time, the modeling community is simulating the deglaciation, or parts of it, with models of increasing complexity and higher resolution. The ultimate goal in the not-so-distant future is a transient deglacial modeling framework based on high-resolution models including high-complexity ecosystem models and sediment feedbacks to refine the sequence of the events and processes involved in the deglacial atmospheric $CO_2$ increase.

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# Data constraints on ocean-carbon cycle feedbacks at the mid-Pleistocene transition

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**The mid-Pleistocene transition marks the final turn of the Earth system towards repeated major ice ages after ~900,000 years ago. Recent advances in paleoceanographic research provide insight into how ocean processes facilitated the climate changes at that time.**

Approximately 900,000 years ago (900 kyr BP), ice ages switched from occurring every 41 kyr to every 100 kyr, lengthening in duration, and strengthening in terms of cooling and ice volume. This "mid-Pleistocene transition" (MPT) occurred without notable changes in Earth's orbit around the sun (i.e. incoming solar radiation). Lacking a defined external trigger, the MPT must represent a fundamental reorganization of Earth's internal climate system, including its greenhouse gas composition, ocean circulation, seawater chemistry, and/or development of more favorable conditions for ice-sheet growth. Recent advances in paleoceanography have made significant progress towards identifying when, how, and why the different components of Earth's climate system changed across the MPT. Here we summarize the biogeochemical insights gleaned from ocean sediments that directly reflect on the global carbon cycle (Fig. 1).

The global climate state of the mid-Pleistocene can be inferred from the benthic foraminiferal oxygen isotope stack of Lisiecki and Raymo (2005) (Fig. 2a), which integrates deep-ocean temperatures and global ice volume. This record shows the MPT as the transition from 41-kyr glacial cycles prior to 1250 kyr BP to dominant 100-kyr glacial cycles by 700 kyr BP (Fig. 2, light blue shading). Within this interval, an anomalously weak interglacial stands out at 900 kyr BP (the "900 ka event"), at the midpoint of what is considered the first 100-kyr glacial cycle (Fig. 2, dark blue shading; Clark et al. 2006).

Proposed explanations for the MPT often invoke declining atmospheric carbon dioxide ($CO_2$) as a fundamental tool to change the climate response to orbital forcing (Clark et al. 2006). Available $CO_2$ reconstructions during this time period are of low temporal resolution but suggest that glacial $CO_2$ decreased by 20-40 ppm sometime between ca. 1000 and ca. 800 kyr BP (Fig. 2b). The ocean most likely caused this $CO_2$ decline via enhanced biological $CO_2$ uptake and/or reduced release of sequestered $CO_2$ back to the atmosphere. General Pleistocene model simulations (Chalk et al. 2017; Hain et al. 2010) highlight three pathways for glacial ocean $CO_2$ sequestration: weaker deep-ocean circulation, increased ocean biological productivity through iron fertilization, and reduced $CO_2$ exchange between deep waters and the ocean surface (broadly termed "stratification"). The common premise behind these pathways is that the missing atmospheric $CO_2$ was trapped in the deep ocean.

## Records of ocean circulation

Earlier attempts to reconstruct deep-ocean circulation across the MPT relied on benthic foraminiferal carbon isotope ratios ($\delta^{13}C$). However, regional biology, air-sea gas exchange, and the size of the terrestrial biosphere also impact deep-ocean $\delta^{13}C$, hindering quantitative circulation reconstructions (Lynch-Stieglitz and Marchitto 2014). In contrast, neodymium isotopes ($\varepsilon_{Nd}$) provide a potentially quantitative approach to separate deep-ocean waters of different geographical origins (Blaser et al. this issue). Distinct $\varepsilon_{Nd}$ values for North Atlantic-sourced and Pacific-sourced deep waters are set by weathering of older and younger continental material into each basin, respectively. In the modern ocean, Nd isotopes behave "quasi-conservatively"; that is, they reflect water-mass mixing, and are not substantially fractionated by biological or physical processes. Moreover, North Atlantic and Pacific end-member $\varepsilon_{Nd}$ values have remained approximately constant over the Pleistocene (Pena and Goldstein 2014).

Across the MPT, ocean circulation has been reconstructed from $\varepsilon_{Nd}$ at three South Atlantic locations (Fig. 1; Farmer et al. 2019; Pena and Goldstein 2014). All three records show a dramatic $\varepsilon_{Nd}$ increase following the ca. 950 kyr BP interglacial, indicating reduced North Atlantic deep-water formation and a relatively greater contribution of Pacific-sourced deep water. The elevated $\varepsilon_{Nd}$ values lasted for ca. 100 kyr, right through the ca. 910 kyr BP interglacial (Fig. 2c; Pena and Goldstein 2014). This also marked a transition in glacial deep Atlantic circulation, with weaker circulation (higher $\varepsilon_{Nd}$) evident in all studied glacials after 950 kyr BP compared to glacials before 950 kyr BP. Intriguingly, this North Atlantic circulation weakening broadly overlaps with the "900 ka event" and the likely period of glacial $CO_2$ decline (Fig. 2a-c).

## Ocean impacts on atmospheric $CO_2$

Proxy constraints on ocean-carbon chemistry reveal how weakened ocean circulation may have impacted $CO_2$. Using the elemental ratios B/Ca and Cd/Ca in benthic foraminifera, Lear et al. (2016), Sosdian et al. (2018), and Farmer et al. (2019) observed that glacial deep waters became significantly more "corrosive" (lower carbonate ion concentration)

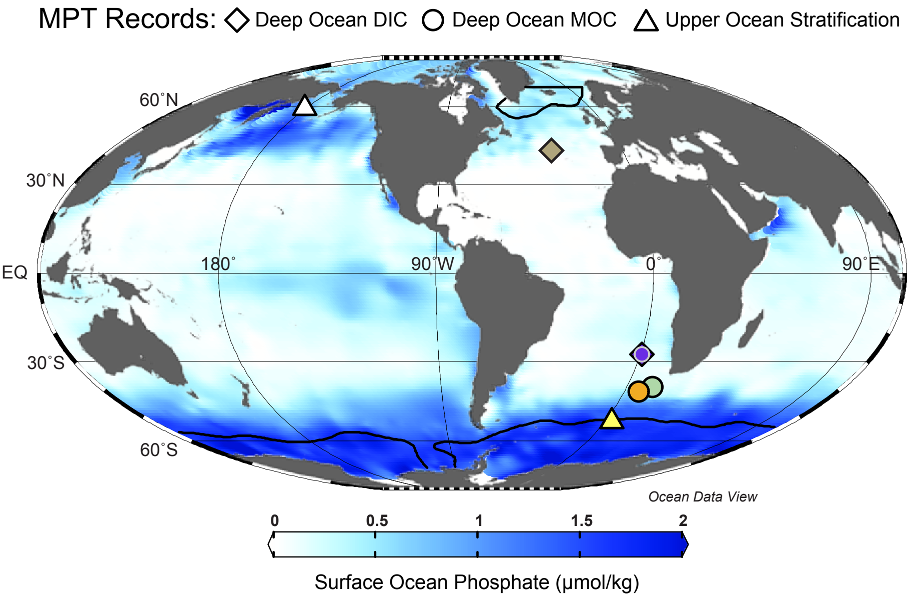

**Figure 1:** World map of surface-ocean phosphate concentrations (from GLODAP v2; Lauvset et al. 2016) and core sites of MPT ocean circulation and carbon-cycle reconstructions. A limiting nutrient for ocean productivity, phosphate occurs at high concentrations in areas of the surface ocean where biological consumption of carbon is inefficient, thus limiting ocean uptake of atmospheric $CO_2$. Regions with sufficiently dense surface water to form deep waters (black contour) directly link surface ocean nutrient consumption with deep-ocean circulation and carbon storage. Broadly, enhanced nutrient consumption in these regions lowers atmospheric $CO_2$. Symbols and colors of core locations match data series shown in Figure 2.

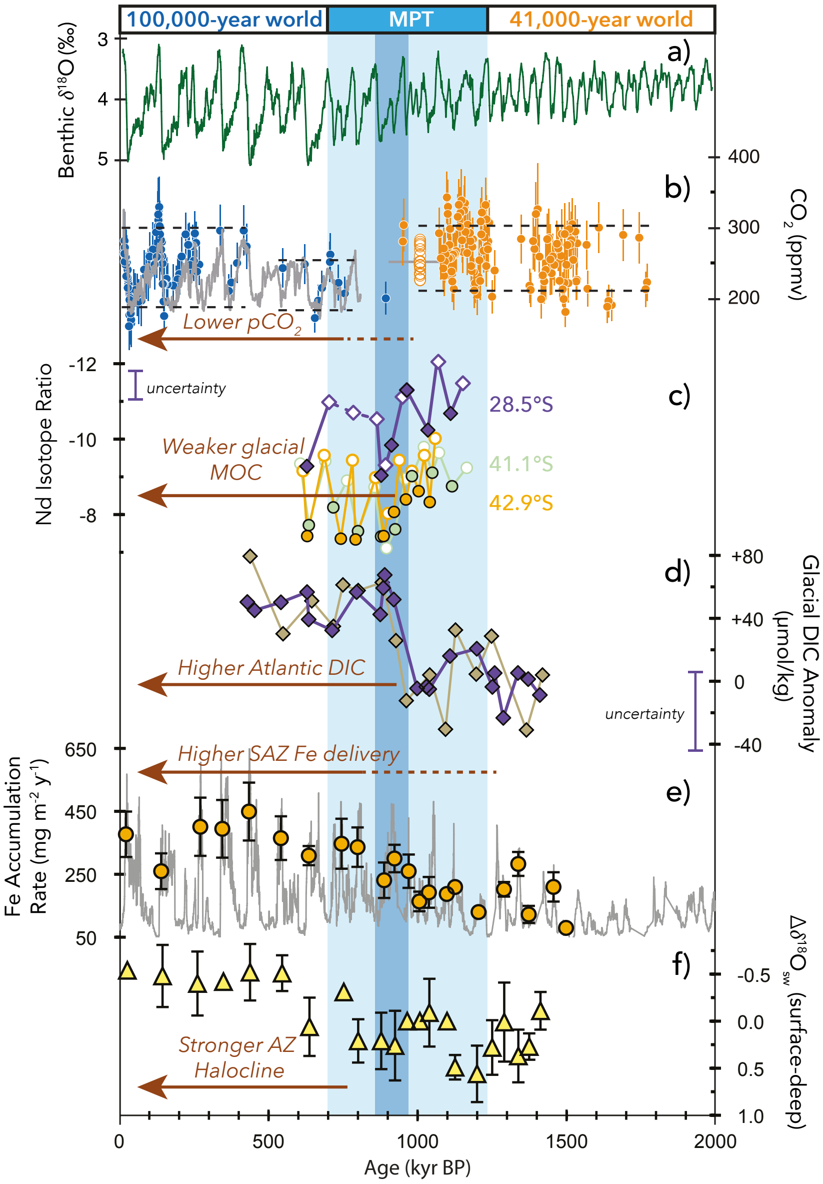

**Figure 2:** Paleoclimatology of the MPT. Brown arrows denote onset and duration of principal changes. Light blue vertical bar denotes MPT interval; dark blue bar denotes interval of the first 100-kyr glacial cycle within the MPT. **(A)** Benthic oxygen isotope stack (Lisiecki and Raymo 2005); **(B)** atmospheric $CO_2$ compilation (grey line: Bereiter et al. 2015 compilation; open circles: Higgins et al. 2015; blue and orange filled circles: Dyez et al. 2018 compilation); **(C)** glacial (filled) and interglacial (open circles) deep Atlantic circulation from $\varepsilon_{Nd}$ (purple: Farmer et al. 2019; light orange/green: Pena and Goldstein 2014); **(D)** glacial deep Atlantic dissolved inorganic carbon content calculated from benthic foraminifer B/Ca (purple: Farmer et al. 2019; olive: Lear et al. 2016 and Sosdian et al. 2018); **(E)** Subantarctic Zone (SAZ) iron flux (line) and binned glacial maxima averages (circles) (Martínez-García et al. 2011); **(F)** density gradient between Antarctic Zone (AZ) surface and deep waters (Hasenfratz et al. 2019).

and nutrient-enriched after 950 kyr BP throughout the Atlantic Ocean. Translated to total dissolved carbon, these observations support a ~50 µmol/kg increase during glacials after 950 kyr BP (Fig. 2d), equivalent to a 50 billion ton increase in carbon inventory throughout the deep Atlantic (Farmer et al. 2019). Pairing this information with $\varepsilon_{Nd}$, Farmer et al. (2019) demonstrated that this deep-ocean carbon accumulation coincided with weakened deep Atlantic Ocean circulation (Fig. 2c-d), suggesting that weaker circulation facilitated accumulation of carbon and other nutrients in the deep Atlantic.

The implications of deep Atlantic carbon storage on $CO_2$ are difficult to quantify because no simple equivalence exists between carbon concentration in the deep Atlantic Ocean and atmospheric $CO_2$. In model simulations, the magnitude of $CO_2$ reduction from weaker Atlantic circulation depends upon nutrient consumption in the surface Southern Ocean (Hain et al. 2010); with higher nutrient consumption, $CO_2$ sequestration is strengthened. Martínez-Garcia et al. (2011) reconstructed iron flux to the Subantarctic Southern Ocean, finding that peak glacial iron input increased around the beginning of the MPT (ca. 1250 kyr BP), with integrated glacial iron input increasing more gradually over the MPT (Fig. 2e). If this flux represents bioavailable iron, then increasing Subantarctic iron fertilization across the MPT would have increased ocean $CO_2$ sequestration (Fig. 2e; Chalk et al. 2017; Martínez-García et al. 2011). Addressing the hypothesis of increased stratification, Hasenfratz et al. (2019) reconstructed the glacial density contrast between surface and deep waters in the Antarctic Zone of the Southern Ocean, finding an increased density gradient around 700 kyr BP indicating a stronger halocline and longer surface-ocean residence time (Fig. 2f). This implies that a water-column density barrier to $CO_2$ outgassing in the Southern Ocean strengthened by the end of the MPT.

In summary, three key oceanic pathways for atmospheric $CO_2$ drawdown – deep Atlantic Ocean circulation, Subantarctic iron fertilization, and Southern Ocean stratification – all shifted towards favoring a stronger ocean $CO_2$ sink and reduced atmospheric $CO_2$ across the MPT. Yet all three pathways differ in their timing, and these scenarios are not necessarily exhaustive. For example, Kender et al. (2018) argue for enhanced stratification in the Bering Sea after 950 kyr BP (Fig. 1, white triangle), which may have also amplified oceanic $CO_2$ drawdown.

Thus, evaluating the relative and cumulative $CO_2$ impact of these pathways is an important focus for future MPT research. At the same time, sparse records of key ocean-$CO_2$ pathways across the MPT must be expanded – particularly from the Pacific, which is the largest carbon reservoir in the modern ocean (Fig. 1). High-resolution atmospheric $CO_2$ reconstructions are also needed to constrain the precise timing of MPT $CO_2$ change, especially around 900 kyr BP, and to evaluate the relative importance of different oceanic processes (Fig. 2b). By expanding these proxy applications and integrating available evidence, paleoclimatologists will progress towards a mechanistic understanding of the controls on this crucial window of Earth's climate evolution, encompassing the rise of hominids and the background climate that mankind is altering today.

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# Modeling perspectives on the mid-Pleistocene transition

Matteo Willeit and Andrey Ganopolski

**Model simulations reveal the importance of atmospheric $CO_2$ and glacial erosion for Quaternary climate dynamics, in particular for the transition from glacial cycles with a periodicity of 40,000-year to 100,000-year cycles at around 1 million years ago.**

The Quaternary is the most recent geological period, covering the past ~2.6 million years. It is characterized by the presence of glacial-interglacial cycles associated with the cyclic growth and decay of continental ice sheets in the Northern Hemisphere. Climate variations during the Quaternary are best seen in oxygen isotopes measured in deep-sea sediment cores, which represent variations in global ice volume and ocean temperature (Lisiecki and Raymo 2005). These data show clearly that there has been a general trend towards larger ice sheets and cooler temperatures over the last 3 million years, accompanied by an increase in the amplitude of glacial-interglacial variations and a transition from mostly symmetrical cycles with a periodicity of 40,000 years (40 kyr) to strongly asymmetric 100-kyr cycles at around 1 million years ago (Fig. 1a). The ultimate causes of these transitions in glacial cycle dynamics still remain debated.

The role of atmospheric $CO_2$ changes in shaping Quaternary climate dynamics is not yet fully understood, largely because of the poor observational constraints on atmospheric $CO_2$ concentrations for the time prior to 800 kyr before present (BP), beyond the period covered by high-quality ice-core data. Proxy-based reconstructions suggest that, over the past ~2 million years, $CO_2$ did not significantly deviate from the range of concentrations measured in ice cores, but that it was substantially higher during the late Pliocene (e.g. Hönisch et al. 2009; Martínez-Botí et al. 2015). A long-term cooling trend associated with a decrease in atmospheric $CO_2$ concentration has been invoked as a possible mechanism to explain the glaciation of Greenland and more generally the Northern Hemisphere at around 3 million years ago (Lunt et al. 2008; Willeit et al. 2015).

It has also been suggested that Northern Hemisphere continents were all covered by thick terrestrial sediments before the Quaternary, an expected outcome of the tens of millions of years that the bedrock was exposed to weathering before the initiation of glacial cycles. The observed present-day sediment distribution, which is characterized by exposed bedrock over large parts of northern North America and Eurasia, is a result of glacial erosion by Quaternary ice sheets. It has been proposed that gradual removal of the sediment layer by glacial erosion could have changed the ice sheets' response to orbital forcing (Clark and Pollard 1998).

## Modeling natural climate variability of the past 3 million years

We have used the simplified Earth system model CLIMBER-2 to elucidate the drivers behind the transitions in glacial cycles of the Quaternary (Willeit et al. 2019). Besides the ocean and atmosphere, the model includes a dynamic vegetation module, interactive ice sheets for the Northern Hemisphere, and a fully coupled global carbon cycle, allowing us to interactively simulate atmospheric $CO_2$ (Ganopolski and Brovkin 2017). The model was driven only by changes in the

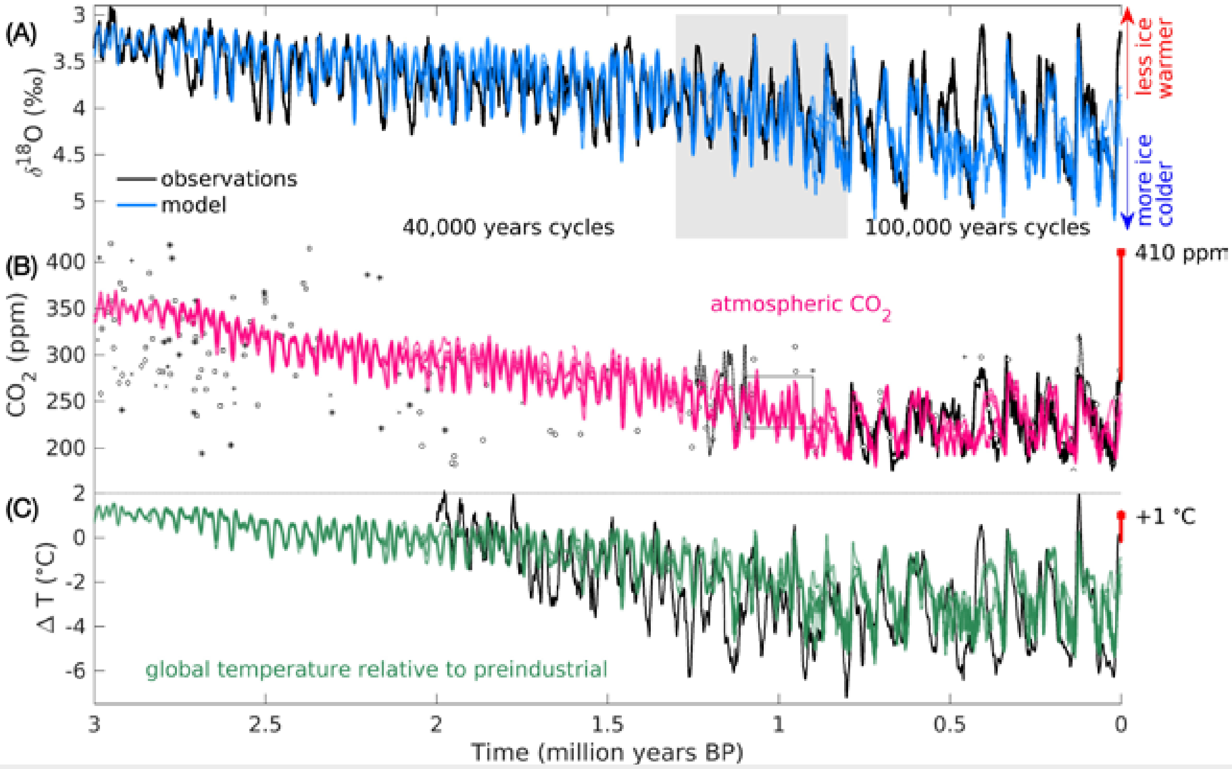

**Figure 1: (A)** Comparison of modeled and observed (Lisiecki and Raymo 2005) stable oxygen isotopes in deep sediment cores over the last 3 million years. The grey shaded area indicates the period characterized by the transition from glacial cycles with a period of 40 kyr to cycles with a period of 100 kyr. Modeled benthic $\delta^{18}O$ is estimated from the modeled sea level, $z_{SL}$, and deep ocean temperature, Td, as follows: $\delta^{18}O = 4.0 - 0.22\,Td - 0.01\,z_{SL}$. **(B)** Modeled atmospheric $CO_2$ concentration compared with ice-core data (solid black line; Bereiter et al. 2015) and various proxy reconstructions (symbols and dotted line, circles: Hönisch et al. 2009; squares: Martínez-Botí et al. 2015; *: Bartoli et al. 2011; + and ×: Seki et al. 2010; diamonds: Badger et al. 2013; black box: Higgins et al. 2015; dotted lines: Chalk et al. 2017). The red line represents the observed $CO_2$ increase since the beginning of the industrial revolution and the red square indicates the observed value at the end of 2018. **(C)** Modeled global temperature relative to preindustrial compared with reconstructions (Snyder 2016). The red line and square indicate the temperature increase of ~1°C since preindustrial.

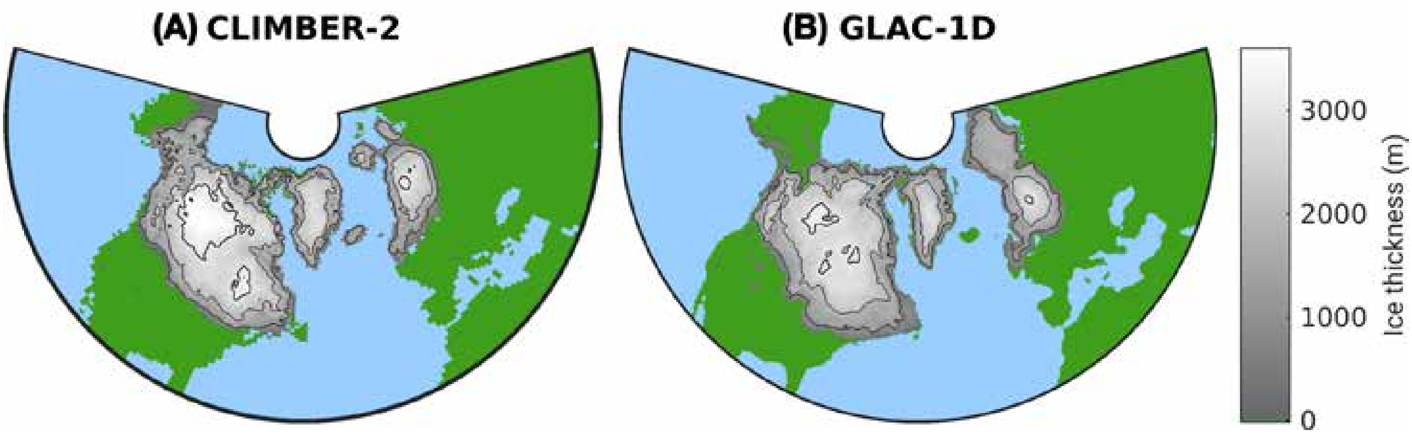

**Figure 2:** Comparison of the ice-sheet extent and thickness at the Last Glacial Maximum (21 kyr BP) from **(A)** the CLIMBER-2 model (Willeit et al. 2019) with **(B)** the model-based reconstruction of Tarasov et al. (2012).

orbital configuration and different scenarios for slowly varying boundary conditions, including $CO_2$ outgassing from volcanoes as a geologic source of $CO_2$, and changes in sediment distribution over the continents. Antarctica is prescribed at its present state in the model, but its effect on sea level is accounted for, to a first approximation, by assuming an additional 10% contribution from Antarctica on top of sea-level variations from simulated changes in Northern Hemisphere ice volume.

When the model is driven by orbital variations and optimal sediment distribution and volcanic outgassing scenarios, it reproduces the evolution of many reconstructed characteristics of Quaternary glacial cycles. It simulates most of the details of the observed oxygen isotope $\delta^{18}O$ curve (Fig. 1a), including long-term trends and glacial-interglacial variability. The relative contribution of deep-sea temperature and sea-level variations to $\delta^{18}O$ variability changes substantially through time, with temperature variations more important during the early Quaternary, and sea-level variations dominating the signal during the late Quaternary. The model also captures the secular cooling trend of approximately -1°C/million years in sea surface temperatures. The intensification of Northern Hemisphere glaciation after ~2.7 million years ago is marked by a rather abrupt increase in global ice-volume variations and an increase in iceberg flux from the Laurentide ice sheet into the North Atlantic, in good agreement with a proxy for ice-rafted debris. Interglacial atmospheric $CO_2$ concentrations decrease from values of ~350 parts per million (ppm) during the late Pliocene to values between 260 and 290 ppm, typical of the past 800,000 years, at ~1 million years ago (Fig. 1b). The amplitude of glacial-interglacial $CO_2$ variations increases from ~50 ppm at the beginning of the Quaternary to ~80 to 90 ppm during the 100-kyr cycles of the past million years.

### Initiation of NH glaciation and transition from 40- to 100-kyr cycles

Our results imply a strong sensitivity of the Earth system to relatively small variations in atmospheric $CO_2$. A gradual decrease of $CO_2$ to values below ~350 ppm led to the start of continental ice-sheet growth over Greenland and more generally over the Northern Hemisphere at the end of the Pliocene and beginning of the Pleistocene, around 2.7 million years ago. Subsequently, the waxing and waning of the ice sheets acted to gradually remove the thick layer of unconsolidated terrestrial sediments that had been formed previously over continents by the undisturbed action of weathering over millions of years. The erosion of this sediment layer – it was essentially bulldozed away by moving glaciers – affected the evolution of glacial cycles in several ways. First, ice sheets sitting on soft sediments are generally more mobile and thinner than ice sheets grounded on hard bedrock, because ice slides more easily over sediments compared to bedrock. This makes ice sheets more vulnerable to increasing summer insolation and thus facilitates their retreat. Additionally, glacial sediment transport to the ice-sheet margins generates substantial amounts of dust that, once deposited on the ice-sheet surface, increases melting of the ice sheets by lowering surface albedo. Model results show that the gradual increase in the area of exposed bedrock over time led to more stable ice sheets, which were less responsive to orbital forcing and ultimately paved the way for the transition to 100-kyr cycles at around 1 million years ago.

### Putting the results into present-day and future perspectives

Our simulations further suggest that global temperature never exceeded the preindustrial value by more than 2°C during the Quaternary (Fig. 1c). Ice-sheet evolution is very sensitive to temperature, and the initiation of Northern Hemisphere glaciation at around 3 million years ago would not have been possible in the model if global temperature were to have been higher than 2°C relative to preindustrial during the early Quaternary. Since the model has been shown to accurately reproduce the sea-level variations over the last 400 kyr and also the spatial ice-sheet distribution at the last glacial maximum (Fig. 2), we are confident that the sensitivity of ice sheets to climate is well represented in the model.

Likewise, our results indicate that the measured $CO_2$ concentration of ~410 ppm at the end of 2018 is unprecedented over the past 3 million years. The climate sensitivity of the model is around 3°C global warming for a doubling of $CO_2$ concentration. This falls in the middle of the current best estimates of climate sensitivity, which range between 1.5 and 4.5°C. It is theoretically possible that the real climate sensitivity is lower than 3°C, in which case the modeled $CO_2$ concentration needed to fit the oxygen isotope record during the early Quaternary would be higher than in the present model simulations, but it would still be unlikely to exceed the present-day value.

In the context of future climate change, our results imply that a failure to significantly reduce $CO_2$ emissions to comply with the Paris Agreement target of limiting global warming well below 2°C will not only bring Earth's climate away from Holocene-like conditions, but also push it beyond climatic conditions experienced during the entire current geological Period, the Quaternary.

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# Long eccentricity cycles in oceanic carbon reservoir

Pinxian Wang and Jun Tian

**The 400-kyr eccentricity cycles dominate marine $\delta^{13}C$ records until 1.6 Myr BP, coeval with the final formation of an abyssal carbon reservoir in the Southern Ocean. Eccentricity-driven global monsoon cycles are hypothetically responsible for this 400-kyr rhythm, which could have been further influenced by oceanographic processes related to polar ice-sheet growth.**

According to Milankovitch theory, Earth's eccentricity has periods of 100 and 400 thousand years (kyr). Therefore, a long eccentricity cycle (400 kyr) should be embedded in paleoclimate records. The absence of such a signal puzzled the paleoclimate community 30 years ago and was considered a fundamental problem in paleoclimate research ("the 400-kyr problem"). Recently, an increasing number of proxy records have revealed the existence of these 400-kyr cycles, at least in many records from the Cenozoic and Mesozoic (e.g. Giorgioni et al. 2012; Kocken et al. 2019). The remarkable 400-kyr eccentricity signal in deep-sea records now is referred to as the "heartbeat" of the ocean system (Pälike et al. 2006), and is used for astronomical calibration of the Cenozoic, Mesozoic, and beyond.

### Complexity of the 400-kyr $\delta^{13}C$ signal

Because of the long residence time of carbon in the oceanic reservoir greater than 100 kyr, the long eccentricity cycle is best documented in the deep-sea $\delta^{13}C$ records, with maximum values ($\delta^{13}C_{max}$) occurring at eccentricity minima. This $\delta^{13}C$ oscillation reflects periodic changes in the sources and sinks of oceanic and atmospheric carbon, likely driven by the global monsoon. However, the mechanism remains unclear (Wang et al. 2017). The "rain-ratio hypothesis", for example, ascribed these $\delta^{13}C$ cycles to the ratio of organic versus inorganic carbon deposition in the deep ocean, which is dominated by the ratio of diatoms to coccoliths (Archer et al. 2000). However, this was challenged by the discovery of the "ballast mineral" effect, as silicate and carbonate biominerals can affect deep-water flux of organic carbon (Armstrong et al. 2001). By contrast, the dissolved organic carbon (DOC) hypothesis (Wang et al. 2014) attributes the $\delta^{13}C$ changes to the ratio between particulate and dissolved organic carbon (POC/DOC) in the ocean, which in turn depends on the monsoon-controlled nutrient supply. This DOC hypothesis was based on the recently identified microbial carbon pump (MCP) in the ocean (Jiao et al. 2010) and supported by numerical modeling (Ma et al. 2014).

The hypothesis discussed above does not account for the signal observed in $\delta^{13}C$ records from the Quaternary. As displayed in Figure 1, the 400-kyr signal is clear in all $\delta^{13}C$ timeseries from various oceans during the Pliocene, and a total of 13 $\delta^{13}C_{max}$ events corresponding to long eccentricity minima have been identified (Wang et al. 2010). For the Quaternary, however, the rhythmic beat of $\delta^{13}C_{max}$ at long eccentricity minima ended at 1.6 million years before present (Myr BP), and the following $\delta^{13}C_{max}$ events were out of phase with the minimum eccentricity signal; the records rather show a 500-kyr cycle over the last million years (Fig. 1). It remains unclear why the long eccentricity cycles disappeared in the Quaternary.

### Polar glaciation, Southern Ocean, and the 400-kyr cycles

As shown by spectral analysis, the 400-kyr eccentricity signal in $\delta^{13}C$ records became obscured after 1.6 Myr BP at all open-ocean sites but not in the Mediterranean Sea, which has been largely isolated from the global ocean since the late Miocene (Fig. 1e). Accordingly, the disappearance of the 400-kyr cyclicity around 1.6 Myr BP might be attributed to the restructuring of the global ocean, which disturbed responses of the oceanic carbon reservoir to the long eccentricity cycle. This in particular refers to formation of an abyssal carbon reservoir in the Southern Ocean (SO), which began 1.6 Myr BP. Stratification of the polar water column started to drive vertical thermal stratification between deep and intermediate waters in the SO around 2.7 Myr BP, isolating its abyss from the intermediate ocean and finally generating the largest carbon reservoir in the global ocean since 1.6 Myr BP (Hodell and Venz-Curtis 2006).

Since then, the ocean circulation has been divided into an actively circulating upper branch and a sluggish abyssal branch in the SO. As the restructuring of the ocean was accompanied by the growth of polar ice sheets, it is plausible that global glaciation modulates responses of oceanic carbon cycles to the orbital forcing. This is supported by empirical evidence showing that the long eccentricity signal in the marine $\delta^{13}C$ records starts to vanish at 1.6 Myr BP (Wang et al. 2014). It is possible that mechanisms of polar ice-sheet growth disturbing the long-term carbon cyclicity show parallels to some climate events in the Miocene. For

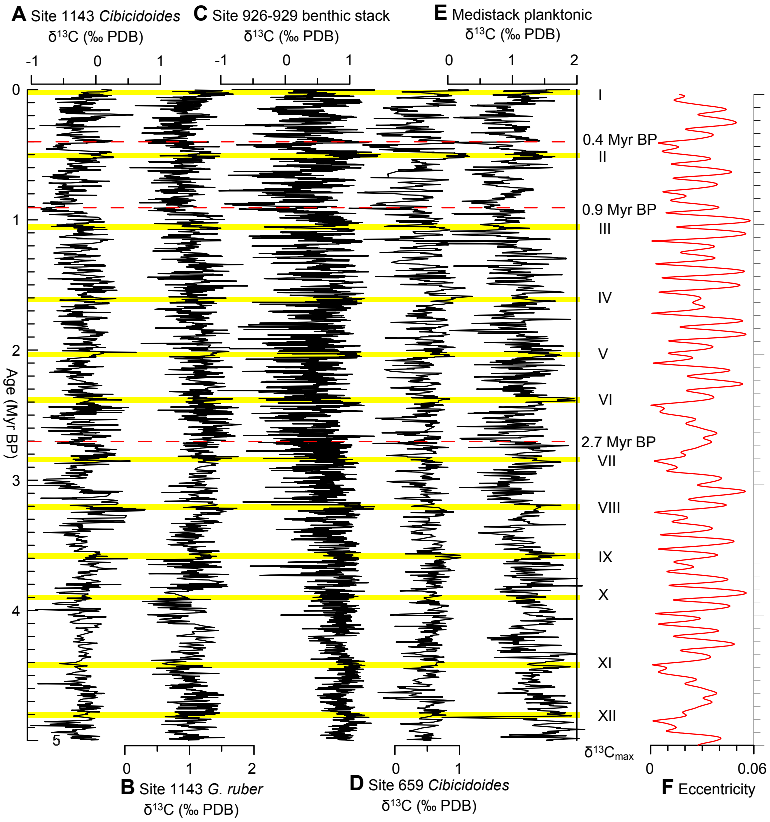

**Figure 1:** Carbon isotopic records from various oceans over the past 5 Myr **(A)**, **(B)** ODP Site 1143, South China Sea; **(C)**, **(D)** Atlantic; **(E)** Mediterranean stack; **(F)** Eccentricity. Yellow bars indicate the $\delta^{13}C_{max}$ events (modified from Wang et al. 2014).

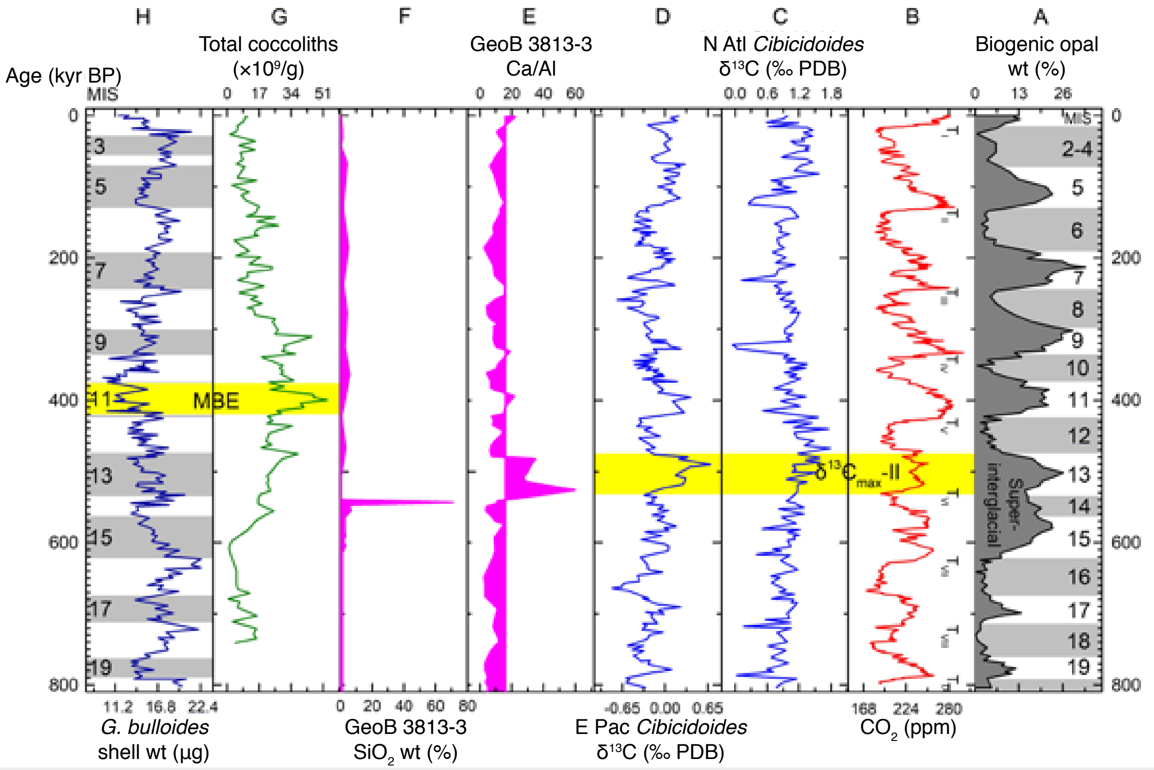

**Figure 2:** Connection between the $\delta^{13}$Cmax-II and Mid-Brunhes events. **(A)** Biogenic opal wt % in Core PS28-254, off W. Antarctic (Hillenbrand et al. 2009); **(B)** Ice-core $CO_2$ (ppm) at EPICA Dome C (Lüthi et al. 2008); **(C)**, **(D)** Benthic $\delta^{13}C$ at ODP 982 and ODP 849 (Barker et al. 2001); **(E)**, **(F)** Ca/Al ratio and biogenic opal in Core GeoB 3813-3, S. Atlantic, respectively (Gengele and Schimitder 2001); **(G)** Total coccoliths from ODP 1082, SO; **(H)** *Globigerina bulloides* shell weight as dissolution index from ODP 982, N. Atlantic (Barker et al. 2006)

example, the eccentricity-forced $\delta^{13}C$ signal was temporarily obscured around 13.9 Myr BP, presumably as a consequence of the amplification of the Antarctic ice sheet (Holbourn et al. 2007; Tian et al. 2014).

Clearly, the oceanic $\delta^{13}C$ oscillation on a $10^5$-year timescale is controlled by both astronomical and oceanographic factors. Astronomically, the oceanic carbon reservoir responds to changes in the POC/DOC ratio, which result from changes in the monsoon-driven nutrient supply. Oceanographically, the abyssal carbon reservoir in the SO might modulate the DOC distribution in the ocean by high-latitude processes associated with ice-sheet growth and decay. As a result, the oceanic $\delta^{13}C$ signal is dominated by a regular 400-kyr beat when the low-latitude processes prevail, such as in the ice-free Hot-House world (Miller et al. 1991). In the Ice-House world, on the other hand, the 400-kyr rhythm in the $\delta^{13}C$ sequence can be obscured by processes associated with ice-sheet development. This may provide an explanation for the observed disappearance of 400-kyr $\delta^{13}C$ cycles in the Quaternary after 1.6 Myr BP.

## 400-kyr $\delta^{13}C$ cycles and Quaternary climate transitions

Changes in the long-term cyclicity of the oceanic carbon reservoir may have serious climatic consequences. Two such changes occurred during the last million-year period, namely the mid-Pleistocene transition (MPT) centered at 0.9 Myr BP and the mid-Brunhes event (MBE) around 0.4 Myr BP. Importantly, both were preceded by $\delta^{13}C_{max}$ events: the MPT by $\delta^{13}C_{max}$-III (~1.0 Myr BP), and the MBE by $\delta^{13}C_{max}$-II (~0.5 Myr BP) (Fig. 1; Wang et al. 2004). This indicates that changes in the oceanic carbon reservoir might be strong enough to cause such a major climatic shift during glacial periods. If so, the next step is to determine the potential driving mechanisms and the role of the Southern Ocean.

Figure 2 illustrates how $\delta^{13}C_{max}$-II could have led to the MBE via processes in the SO. The event $\delta^{13}C_{max}$-II occurred during the younger part of the "super-interglacial" spanning from marine isotope stage (MIS) 15 to 13 (621-478 kyr BP; Fig. 2a-d), associated with a possible collapse of the West Antarctic Ice Sheet (Hillenbrand et al. 2009). The abnormally prolonged stratification in the SO during this period led to a large increase in the abyssal reservoir of Si and other nutrients. Meanwhile, the northward leakage of its Si-rich water to the low-latitude ocean caused a series of biogeochemical events including basin-scale sub-surface diatom blooms in the Southern Atlantic and the accumulation of the vast laminated diatom mat deposits (Fig. 2f). This was followed by coccolithophore blooms when Si was exhausted (Fig. 2e; Gingele and Schmieder 2001). In parallel, the small-sized coccolithophore assemblages began to dominate the global ocean during MIS 15, peaking in MIS 11 and leading to the deep-water carbon dissolution that characterized the mid MBE (Fig. 2g-h; Barker et al. 2006). Therefore, $\delta^{13}C_{max}$-II was connected to the MBE by a sequence of events, and probably a similar connection also exists between the $\delta^{13}C_{max}$-III and the MPT (Wang et al. 2014).

Since the Earth is currently in a new $\delta^{13}C_{max}$, it is crucial to understand the nature of $\delta^{13}C_{max}$ events and their impacts on the global climate and ocean. This is particularly important for the debates on the next glacial inception (e.g. Berger and Loutre 2002; Müller and Pross 2007). We thus suggest that climate models with a carbon cycle should be used to test hypotheses regarding the dynamics of the carbon cycle in the past on long timescales, which will be crucial for us to improve our long-term future projections.

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# The influence of circulation change on sedimentary records of the Paleocene-Eocene Thermal Maximum

Donald E. Penman[1] and Sandra Kirtland Turner[2]

**The Paleocene-Eocene Thermal Maximum (PETM, 56 Myr BP) was a rapid greenhouse-gas-driven global warming event highlighted for comparison to anthropogenic climate change. Proxies and modeling indicate that changing patterns of global overturning circulation overprinted paleoceanographic records of this event.**

In 1991, Kennett and Stott published a groundbreaking record of the carbon and oxygen isotope composition of foraminifera from Southern Ocean deep-sea sediments spanning the Paleocene-Eocene boundary. They observed striking negative excursions in both isotopic systems, unlike any rapid shifts known from the paleoceanographic record, coincident with the largest benthic extinction of the Cenozoic. The oxygen isotopes indicated a sudden warming of both surface and deep Antarctic waters, while the carbon isotope excursions (CIE) suggested a collapse in vertical $\delta^{13}C$ gradients. Those authors concluded that changes in the global overturning circulation must be the cause of these unusual paleoceanographic observations and the extinction – but a proliferation of coeval sedimentary records in the decades since has transformed this interpretation.

## From local findings to global observations

The CIE and warming first recognized in the Southern Ocean have now been observed globally from both the marine and terrestrial realms (Fig. 1; see e.g. McInerney and Wing 2011 for a compilation), in organic and inorganic carbon, and coincide with evidence for global ocean acidification (Babila et al. 2018; Zachos et al. 2005), large reorganizations of the hydrologic cycle (Wing et al. 2005; Zachos et al. 2003), and biotic turnover both on land and in the sea (Speijer et al. 2012). The modern interpretation holds that this event (now known as the Paleocene-Eocene Thermal Maximum or PETM) was driven by the geologically rapid (within thousands of years) addition of a large mass (thousands of gigatons) of isotopically light carbon into the atmosphere and ocean. Without the global coverage provided by more recent observations, Kennett and Stott did not know what triggered their proposed change in circulation, but in a sense their interpretation still holds: marine records of the PETM reflect not only global carbon cycle processes, but also the regional effects imparted by the changes in ocean circulation that we still think occurred during the PETM.

## Basinal asymmetry in pelagic PETM sedimentary records

Comparison of PETM deep-sea records reveals several regional differences in lithology and geochemistry that illustrate the profound influence of changing ocean circulation during the event. $CaCO_3$ dissolution is a hallmark of pelagic PETM records, characterized by a temporary decline or absence of the calcareous microfossils that typically constitute pelagic sediments, resulting in a conspicuous clay layer. This dissolution is an expected consequence of $CO_2$ addition to seawater, which lowers pH and carbonate saturation state (Ω) in tandem. Paleoceanographers often quantify the extent of dissolution by reconstructing the shoaling of the carbonate compensation depth (CCD), the "snowline" of the ocean below which carbonates are absent from sediments. However, there are significant regional differences in the extent of PETM $CaCO_3$ dissolution (or the existence and thickness of clay layers). In the South Atlantic, PETM clay layers identified from a depth transect of ocean drilling sites indicate that the CCD shoaled by greater than 2 km and suggest the dissolution of $CaCO_3$ over huge regions of the seafloor (Zachos et al. 2005). In contrast, a similar depth transect in the subtropical North Pacific shows comparatively limited $CaCO_3$ dissolution, constraining the CCD shoaling in that basin to less than 0.5 km (Colosimo et al. 2005; Zeebe and Zachos 2007). Much of this basinal asymmetry can be explained by a reorganization of deep-sea circulation. Deep water becomes more corrosive to $CaCO_3$ (lower Ω) with age due to the accumulation of respired organic carbon, such that the modern CCD in the deep North Pacific (filled with the ocean's oldest seawater) is ~1 km deeper than in the North Atlantic (which, as a region of deep-water formation, contains the youngest deep water). Using a sediment model forced with records of varying $CaCO_3$ weight percentages (wt. %) at different globally distributed pelagic sites, Zeebe and Zachos (2007) determined that $CaCO_3$ undersaturation at the peak of the PETM was more severe in the Atlantic than in the Pacific – the opposite of the modern pattern. Those authors concluded that deep-water circulation patterns must have been reversed (relative to the modern configuration) during the acidification phase of the PETM. This idea was expanded upon by the

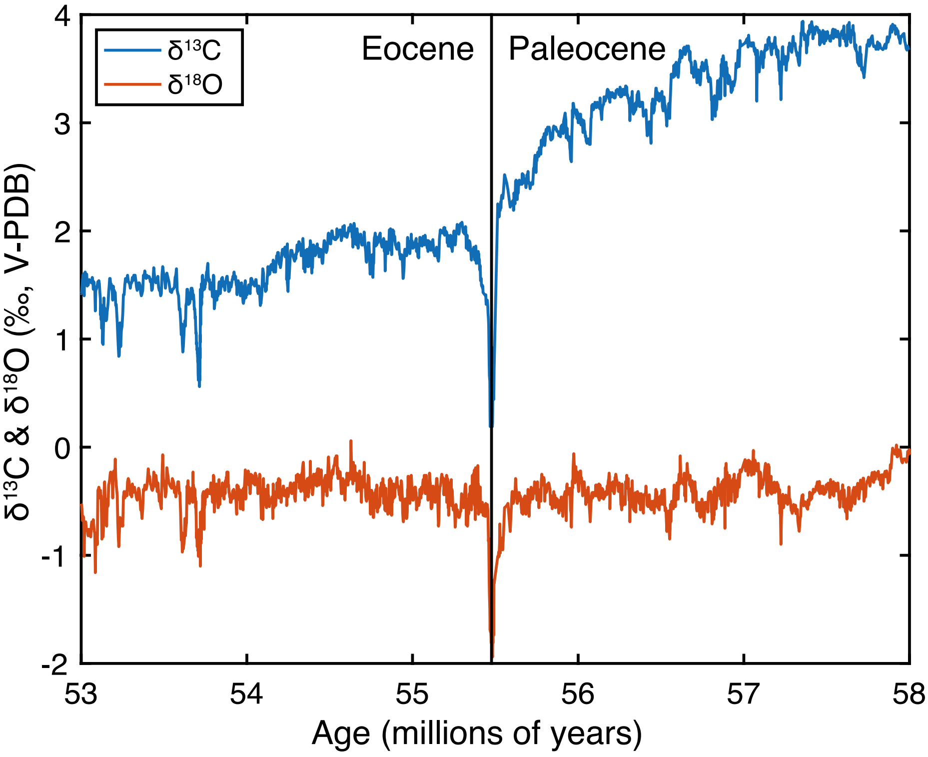

**Figure 1:** Bulk-sediment carbon and oxygen isotope stratigraphy of Site 1262 from the late Paleocene through the early Eocene (Zachos et al. 2010). The large negative excursions in both isotope systems at the Paleocene-Eocene boundary represents the PETM.

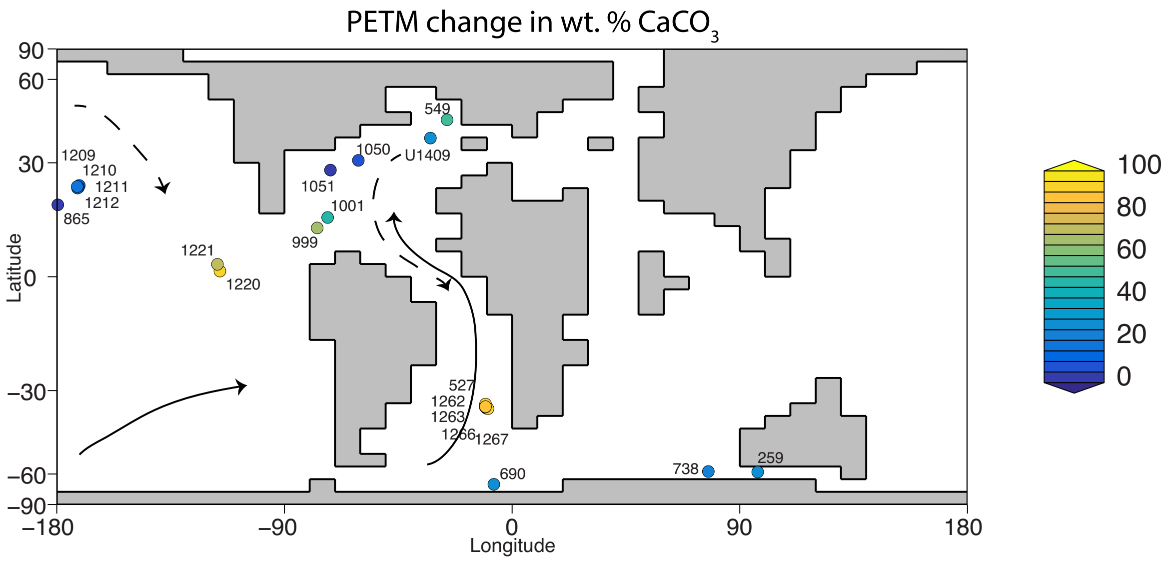

**Figure 2:** Change in pelagic sedimentary wt. % $CaCO_3$ over the PETM (colored circles) plotted on the cGENIE model Paleocene land mask (Panchuk et al. 2008). Data were compiled from Zeebe and Zachos (2007) and Panchuk et al. (2008), but see references therein for original records. Arrows show inferred circulation for pre-event (solid lines) and PETM (dashed lines) based on changing $\delta^{13}C$ gradients and basinal asymmetry in $CaCO_3$ dissolution.

PETM carbon-cycle simulation of Zeebe et al. (2009), who implemented a transient shift in the locus of deep-water formation from the Southern Ocean to the North Pacific.

## Disparate benthic CIE magnitudes

Another hallmark of the PETM that is susceptible to overprinting by changing ocean circulation is the size of the benthic foraminiferal CIE, which varies significantly from site to site (McInerney and Wing 2011; Nunes and Norris 2006). In theory, the benthic CIE due to a rapid carbon release should simply reflect the mass and $\delta^{13}C$ of the carbon input, and be relatively homogenous throughout the deep sea, given that typically low pelagic sedimentation rates are unlikely to resolve differences on timescales shorter than ocean mixing (1-2 kyr). The $\delta^{13}C$ of dissolved carbon in deep seawater decreases as it ages due to the accumulation of isotopically light respired organic carbon. In the modern ocean, this leads to a 1‰ $\delta^{13}C$ difference between young North Atlantic deep water and old North Pacific deep water. Deep-water circulation is hence a powerful lever on regional benthic $\delta^{13}C$ – an abrupt reversal of the modern deep-water aging gradient would force Pacific benthic $\delta^{13}C$ 1‰ heavier and Atlantic $\delta^{13}C$ 1‰ lighter in the long term. An abrupt reorganization of deep-water circulation patterns at the PETM onset could similarly help explain the range of deep-ocean benthic foraminiferal CIE sizes observed globally, which span 0.5‰ to 3.5‰ (McInerney and Wing 2011). Nunes and Norris (2006) produced a global compilation of deep-ocean benthic CIE records and argued that the generally smaller CIE magnitude in the Northern Hemisphere compared to the Southern Hemisphere resulted from a switch in the locus of deep-water formation from the Southern Ocean to the North Atlantic. Additional complications remain, including truncation of the base of the event due to carbonate dissolution at some sites (leading to an apparently smaller CIE) and the role of bioturbation (mixing by benthic organisms) but changing ocean circulation patterns are clearly a factor in the disparate magnitude of benthic CIEs.

## Additional geochemical indicators

While deep-sea records of $CaCO_3$ wt. % and $\delta^{13}C$ are most common, there is evidence for ocean circulation impacting other PETM geochemical records as well. Proxies for deep-ocean oxygen (Pälike et al. 2014) and patterns of silica burial (Penman et al. 2019) indicate asymmetry between the Atlantic and Pacific basins during the PETM. Neodymium isotopes, a quasi-conservative tracer of ocean circulation, may even more directly indicate changes in deep-ocean ventilation associated with shifting patterns of overturning circulation (Abbott et al. 2016; Blaser et al. this issue).

## Mechanisms for PETM circulation change from ocean-physics models

Sedimentological evidence suggests that a change in deep-ocean circulation was likely during the PETM, and physical models provide possible causal mechanisms. Using a model of ocean physics forced offline by an atmospheric general circulation model, Bice and Marotzke (2002) explored the role that the hydrologic cycle might have played in linking global warming to changes in ocean circulation at the PETM. With warming, the hydrologic cycle intensifies, transporting more water vapor from low to high latitudes. This increases the poleward latent heat flux and redistributes evaporation and precipitation globally, changing patterns of sea-surface salinity. Both of these (heat and freshwater transport) change the density gradients of surface seawater, which makes surface waters in different regions of the ocean more or less susceptible to sink and form deep water. Bice and Marotzke's experiments favored a switch from Southern to Northern Hemisphere deep-water formation during peak PETM forcing, broadly consistent with the hypotheses proposed by Zeebe et al. (2009) and Nunes and Norris (2006), but the exact locus and flux of northern deep-water formation is sensitive to uncertain paleogeography and is still debated. Numerical modeling of an instantaneous warming event simulated with the UVic Earth system model of intermediate complexity by Alexander et al. (2015) provides a consistent and more detailed scenario in which corrosive North Atlantic bottom water spills into the South Atlantic with the onset of North Atlantic deep-water formation over the several thousand years following instantaneous $CO_2$ release.

Together, modeling and geochemical study of the PETM demonstrate that it is crucial to consider changes in the global overturning circulation, and not just global carbon cycle processes, in the interpretation of sedimentary records of ancient climate perturbations.

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# Arctic Cryosphere Change and Coastal Marine Ecosystems working group

Maija Heikkilä[1], A. Pieńkowski[2], S. Ribeiro[3] and K. Weckström[1]

The Arctic cryosphere is transforming rapidly in response to recent climate change. Accelerated melt of glaciers, ice caps and the Greenland ice sheet, increased glacial runoff, diminishing sea-ice extent and volume, coastal erosion, and permafrost thaw all have profound impacts on Arctic coastal environments (Fig. 1). The fjords and other nearshore areas form a productive zone that is vital to both Arctic biodiversity and the subsistence of local communities. Increased inputs of freshwater and sediments from land, together with diminishing sea-ice cover, will have a critical effect on future biogeochemical cycling, primary production, and key ecosystem services in the coastal zone.

Recent studies show that the impacts of land-derived freshwater on coastal circulation and contributions of dissolved and particulate matter are heavily dependent on the marine system, and have a non-linear impact on primary productivity (Hopwood et al. 2018). For example, marine-terminating glaciers induce nearshore nutrient upwelling and hence primary production, while fjords fed by land-terminating glaciers are low-production zones often characterized by a light-limiting layer of suspended matter (Meire et al. 2017). Furthermore, the coastal zone interacts dynamically with the open ocean. Land-derived meltwater can affect primary production far away from the coastal zone (Arrigo et al. 2017), while waters transported by large-scale current systems have an influence on the hydrography of some coastal systems (Sejr et al. 2017).

A major challenge facing arctic marine scientists today is the paucity of reference ecological data from which to interpret recent and future changes. Many proxy methods have been proposed based on microfossil, biogeochemical, and to some extent molecular records of sympagic, planktic, and benthic organisms to reconstruct past marine ecosystem changes. In particular, deciphering past sea-ice concentrations (de Vernal et al. 2013), sea-surface temperatures (e.g. Caissie et al. 2010), and changes in ocean circulation (Rahmstorf 2002) have attracted attention, as they are tightly linked to global paleoclimate changes. However, the multi-faceted nature of coastal ecosystems necessitates consideration of regional- and local-scale influence of cryosphere changes, and their fingerprints in biological and biogeochemical proxy records. Clearly, there is a need for closer cooperation between different proxy specialists and for critical assessment of the current analytical, numerical, and ecological knowledge.

The ACME working group was launched in July 2019, with the aim to assess and refine available marine proxies that can be used to reconstruct past cryosphere changes and their ecosystem impacts in the Arctic coastal zone. A particular focus is placed on the techniques and the quality of data, on the training of early-career scientists, and on the establishment of new community-driven protocols.

ACME is envisioned to run over two three-year phases. The main product goal of Phase 1 (2019-2022) is a database that contains a spatial network of currently available sites and proxies commonly used for reconstructing sea ice, primary production, meltwater runoff and terrestrial inputs in Arctic coastal and fjord environments. Each database entry will follow the criteria defined by the ACME community in the early stages of Phase 1. This will ensure that quality assessment of database entries will be easy for the end users. Furthermore, ACME seeks to facilitate community integration by promoting knowledge transfer and collaboration among proxy specialists, and knowledge integration of the paleo and monitoring communities. Importantly, ACME fosters critical, methodological understanding and data handling skills of the next generation of paleoceanographers and paleoenvironmental researchers.

From 17 October to 15 November 2019, ACME conducted a survey to collect community perspectives on the current state and future directions of Arctic coastal paleoceanography. The results of the survey will provide a basis for outlining priority research questions and community directions, and give an overview of spatial, methodological, and ecological knowledge gaps identified by the community.

The ACME community will meet during the first workshop to plan the database structure and proxy-specific data entry criteria at the EGU General Assembly from 3-8 May 2020 in Vienna, Austria. For more information about this working group, see the ACME website (pastglobalchanges.org/acme), sign up for the ACME mailing list (listserv.unibe.ch/mailman/listinfo/acme.pages), and follow ACME on Twitter (@AcmePages).

**Figure 1:** Cryosphere changes both on sea and on land have a profound influence on coastal marine ecosystems in the Arctic.

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# Cycles of Sea-Ice Dynamics in the Earth System working group

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Sea ice is a critical component of the climate system (Fig. 1), influencing heat and gas exchange between the atmosphere and polar oceans. Given the high albedo of sea ice relative to that of open water, seasonal variability in sea-ice extent impacts reflectivity of the Earth's surface. Changes in the Antarctic sea-ice seasonal cycle also affect Southern Ocean water mass buoyancy, thereby modulating Southern Ocean upper and lower overturning cells and global ocean circulation. Through its interactions with the glacial ice margin, sea ice affects, and is affected by, ice sheets and ice shelves. Finally, sea-ice decay impacts ocean primary productivity through its roles in seeding phytoplankton and driving upper-ocean stratification and nutrient distribution (e.g. Armand et al. 2017). At present, average Antarctic sea-ice extent ranges between summer minima of ~3 million km$^2$ to winter maxima of ~18 million km$^2$ (Cavalieri and Parkinson 2008). Changes in sea-ice extent over longer time periods have been studied since the late 1970s. Community-based research efforts have focused on understanding different sea-ice proxies (e.g. the PAGES Sea Ice Proxies working group: pastglobalchanges.org/science/wg/former/sea-ice-proxies), and on reconstructing Antarctic sea-ice extent for specific time periods, such as the Last Glacial Maximum through the project MARGO (Multiproxy Approach for the Reconstruction of the Glacial Ocean Surface; pastglobalchanges.org/science/wg/former/margo; Gersonde et al. 2005).

The C-SIDE working group (pastglobalchanges.org/c-side) was established to extend Southern Ocean sea-ice reconstructions back further in time, with a focus on the past 130,000 years. This longer timescale allows us to evaluate the role of sea ice on major climate transitions including the glacial inception, when carbon was sequestered in the ocean, and deglaciation, when ocean carbon reserves were released into the atmosphere. This time frame also encompasses the penultimate interglacial when Antarctica was ~2°C warmer than today – a useful "process" analogue for future warming scenarios. The main difference between C-SIDE and previous large-scale projects (MARGO) is that C-SIDE aims to document sea-ice dynamics along with understanding processes and interactions between Antarctic sea ice and global climate on different timescales. In addition, C-SIDE aims to include these data in Earth system modeling efforts, including the Paleoclimate Modelling Intercomparison Project (pmip3.lsce.ipsl.fr).

Our first C-SIDE workshop was held from 24-26 October 2018 in Vancouver, Canada (Patterson et al. 2019; pastglobalchanges.org/products/pages-magazine/12816). Major accomplishments included developing a format for compiling proxy datasets from both marine-sediment and ice-core records, establishing an initial inventory of 170 sites with potential information on sea-ice changes, and assigning data-mining efforts to be completed before the next workshop. These tasks are critical as we seek to provide denser spatial coverage and higher temporal resolution of sea-ice variability through time.

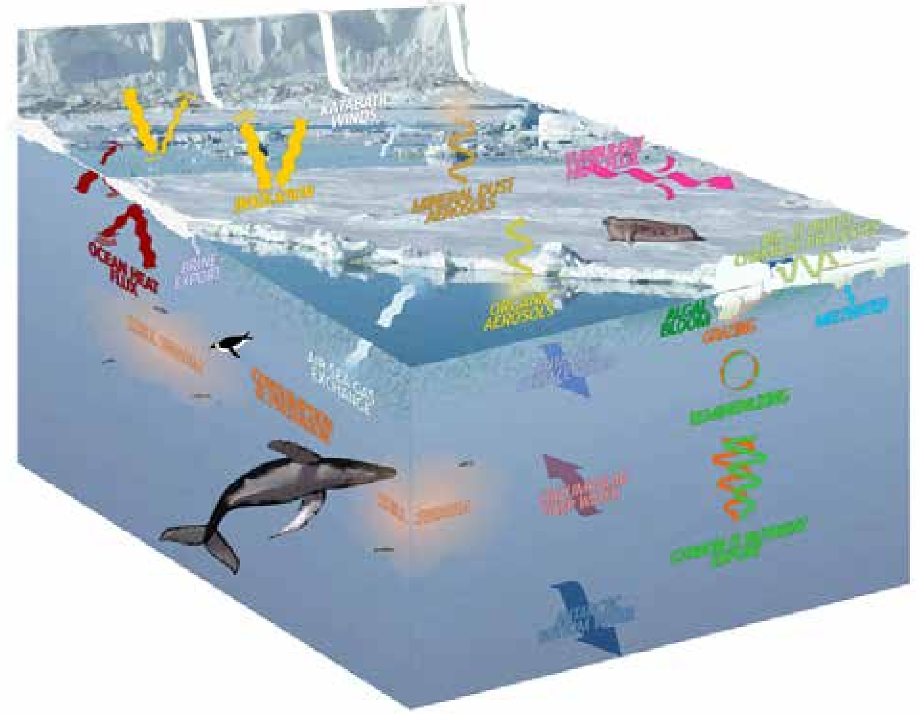

**Figure 1:** Principal feedbacks and interactions between Antarctic sea ice and the ocean, biosphere, atmosphere, and cryosphere (reproduced from Patterson et al. 2019).

Our second workshop, "Sea-ice database and model-data framework" (pastglobalchanges.org/calendar/2019/127-pages/1944), was held 29-31 August 2019 in Sydney, Australia, immediately prior to the 13th International Conference on Paleoceanography (pastglobalchanges.org/calendar/2019/127-pages/1722). The primary goal was to complete our inventory of paleo records, with details about the temporal extent of each published, unpublished, and future targeted record, as well as the data type used to reconstruct sea ice. These include, but are not limited to, diatom assemblages, organic biomarkers such as highly branched isoprenoids, isotopic evidence, and geochemical data from ice cores. Our database will be completed by entering sea-ice records that allow for examination of full time series as well as spatial patterns associated with specific time intervals, including the Holocene, the last 40 kyr, MIS 5, and the last 130 kyr. Ultimately, our plan is to target regional transects, extending from ice sheets to the equatorward extent of sea ice. We recognize that, at this time, only a limited number of datasets extend back 130,000 years, with even fewer that span latitudinal transects. However, identification of the data gaps is critical for the establishment of new priorities for future field-based data collection.

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# Understanding long-term human-climate-ecosystem interactions for sustainability

Jacob Freeman[1,2], E. Robinson[1], C. Latorre[3] and M. Cannon[1]

The prehistory of human-environment interactions is a source of knowledge critical for meeting the challenges of a globalizing planet confronting population growth and climate change. The PEOPLE 3000 working group (pastglobalchanges.org/people3000) combines archaeological and paleoecological case studies with mathematical modeling to investigate how co-evolving human societies and ecosystems can successfully cope with the interrelated forces of globalization, population growth, and climate change, and why, in some cases, societies fail to cope with these interrelated forces and reorganize accordingly.

PEOPLE 3000 has two interrelated objectives. First, we seek to describe and explain basic patterns of human population ecology by building large radiocarbon datasets and integrating these datasets with paleoenvironmental datasets and formal, mathematical models. Second, we seek to evaluate concepts from contemporary policy documents from the long-term perspective offered by the integrated analysis of formal models, radiocarbon, and paleoenvironmental datasets.

For example, Freeman and colleagues synthesized and used large datasets of archaeological radiocarbon to document that the energy output of human societies over the last 10,000 years displays synchrony – the simultaneous fluctuation of human populations (Freeman et al. 2018). Synchrony is a well-documented process in the population ecology of non-human animals, but this was the first time it was described among human populations. This work describes a basic population ecology process – synchrony – that may be used to inform sustainability research. Preliminary evidence suggests that human synchrony results from globalization rather than simultaneous responses to climate. Similarly, Robinson et al. (2019) integrate radiocarbon records with downscaled, transient paleoclimate models to examine how the distribution of population in the Western USA and climatic zones coevolved over time. They find strong evidence of climate-zone filling and the "packing" of people into climate zones over time, which may have contributed to late Holocene population collapses.

Finally, in one of our ongoing projects, PEOPLE 3000 is evaluating the policy concept of "climate-smart agriculture". Climate-smart agriculture mitigates ecological degradation, enhances productivity, and maintains the robustness of production to climate change (Lipper et al. 2014). Yet, the relationships between these "triple win" processes are not well understood over the long term. In fact, these tenets conflict with a large body of theory. Models from resilience theory suggest that increasing productivity necessarily means giving up robustness (Carpenter et al. 2015). Large datasets of archaeological radiocarbon allow us to study the fundamental process of population stability to evaluate whether prehistoric societies undergoing population growth and climate change achieved simultaneous increases in the productivity and the robustness of agriculture or traded these off. Our results suggest partial support for the core tenet of climate-smart agriculture that societies can simultaneously increase productivity and robustness (Fig. 1).

Over the next year, PEOPLE 3000 seeks to expand our coverage to develop biogeographic analyses of human energy dynamics and continue to evaluate policy concepts using the long-term perspective provided by paleorecords. Specifically, we will:

- Develop records of paleoclimate and, more importantly, ecosystem change to integrate with a cutting-edge, global dataset of archaeological radiocarbon.
- Expand our current global archaeological radiocarbon datasets, add additional proxies for population and economy size, and publish the expanded dataset.
- Publish papers that use the long-term perspective offered by the integration of formal models and paleodata to evaluate basic concepts from the sustainability literature.
- Collaborate with the LandCover6k working group by developing population growth rates for different regions of the world that will provide baselines for anthropogenic land-use models.
- Build community outreach through our museum partners and exhibits based on the results of PEOPLE 3000 research.

PEOPLE 3000 is an exciting and open network committed to pushing the boundaries of research in human population ecology to provide a firmer foundation for understanding the concept of sustainability. Join our mailing list to receive updates! listserv.unibe.ch/mailman/listinfo/people3000.pages

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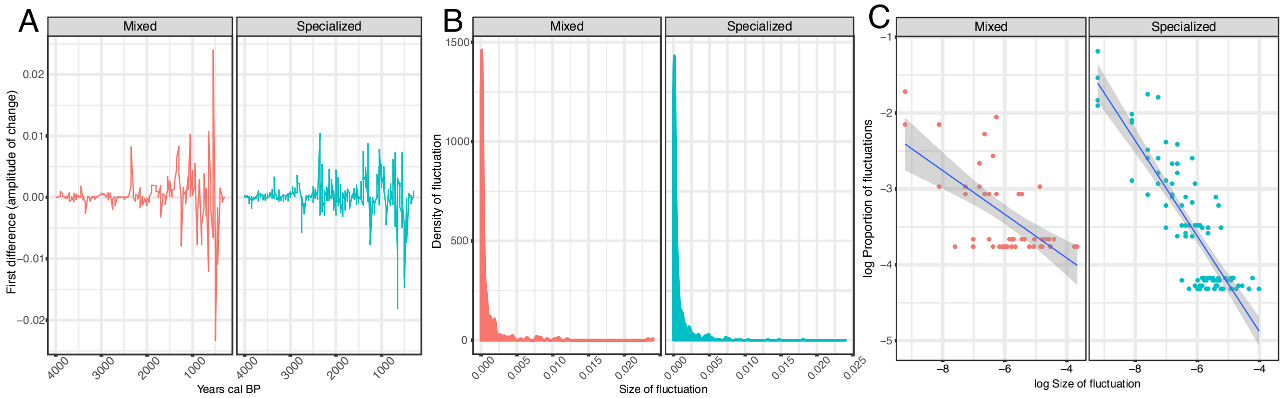

**Figure 1: (A)** The first difference of summed probability distributions of radiocarbon from mixed forager-farmer and specialized farming societies in North and South America over the last 4000 years cal BP. **(B)** Density plots of the size of first difference (amplitude of change) and the density of such changes among mixed forager-farmer and specialized farming systems. Note, most changes are small, but a few changes are large. **(C)** Power functions fit by regressing the log of the size of fluctuation on the log of the proportion (density) of fluctuations. Mixed forager-farmers have a shallower slope indicating more sensitivity to disturbance (more moderate-sized amplitudes of change). Specialized systems have a steeper slope indicating less sensitivity to disturbance.

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# Climate Reconstruction and Impacts from the Archives of Societies working group

Chantal Camenisch[1], M. Bauch[2], H. Huhtamaa[3], Q. Pei[4] and S. White[5]

Historical climatology is the interdisciplinary field that explores past climates and the human dimension using written records, human artifacts, and early instrumental measurements, collectively termed "the archives of societies". These sources range from chronicles, diaries, and newspapers to flood markers on historic buildings and pre-standard thermometer and barometer readings (Brázdil et al. 2005; Fig. 1).

Research in historical climatology may both complement and extend research in paleoclimatology (Brönnimann et al. 2018). Similar to high-resolution natural archives, the archives of societies may contain proxies for one or more climate parameters dating back as far as several millennia, depending on the region and approach. Archives of society have the advantage of possibly containing seasonal or even monthly information and are not restricted to a particular period (e.g. the growing season). This factor may permit full-year reconstructions utilizing a single approach. In addition, written historical records may provide detailed meteorological descriptions and narratives enabling investigations of historical climate as well as weather impacts and adaptations.

Nevertheless, using the archives of societies poses significant challenges. Their information is neither as continuous nor homogenous as that provided by natural proxies, and their quantity and quality vary by region and tend to diminish further back in time. Historical climatology requires careful interpretation to overcome problems of subjectivity and errors of recording and transmission. Historical climatologists in different regions of the world have independently developed methods to address these problems but have not yet coordinated global best practices in source interpretation or production of data, nor has the field established clear language and standards for the attribution of past societal change to climatic variability and change.

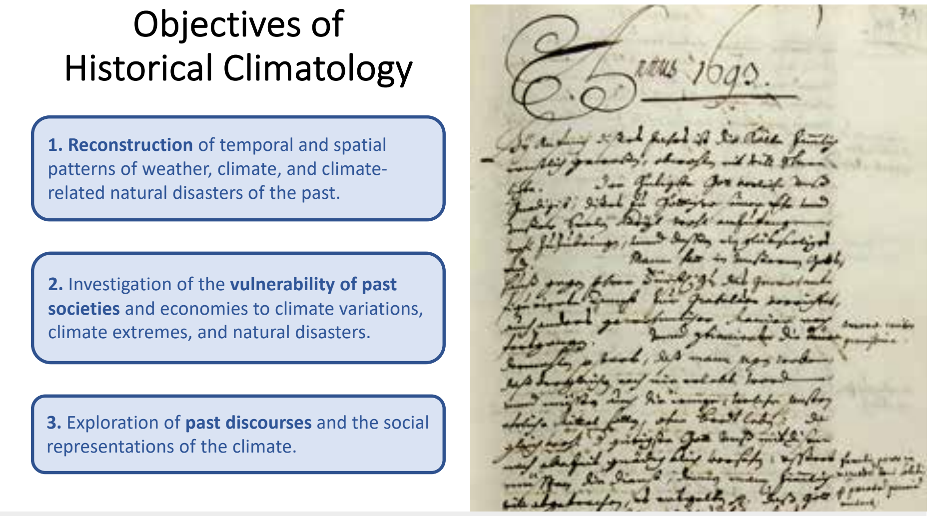
## Scientific goals

The recently established PAGES working group Climate Reconstruction and Impacts from the Archives of Societies (CRIAS, pastglobalchanges.org/crias) aims to improve methods in historical climatology and to coordinate global best practices in source interpretation and production of data, especially for use by paleoclimatologists and modelers. To this end, three main goals have been defined:

*1) Sharing methods among historical climatologists working in different regions to exchange best practices and ensure the compatibility of results*

In East Asia and Europe, in particular, research in the field of historical climatology already has a long tradition. One goal of CRIAS is to intensify discussions regarding standards of source criticism and reconstruction methods among scholars from these two regions and to extend this discussion to other continents. This process has begun with a comprehensive worldwide review of methods for creating climate indices.

*2) Working with paleoclimatologists and modelers to determine whether and how data drawn from the archives of societies may inform their research (and vice versa)*



Objectives of Historical Climatology

**1. Reconstruction** of temporal and spatial patterns of weather, climate, and climate-related natural disasters of the past.

2. Investigation of the **vulnerability of past societies** and economies to climate variations, climate extremes, and natural disasters.

3. Exploration of **past discourses** and the social representations of the climate.

**Figure 1:** Objectives of Historical Climatology (Brázdil et al. 2005) and examples of archives of society: page from a weather diary from a monk in Einsiedeln, Switzerland, written at the end of the 17th century. Credit: Diarium P. Josef Dietrich, Bd. 8 (1692-1694) (KAE, A.HB.8, S. 71) klosterarchiv.ch/e-archiv_archivalien.php

A closer collaboration between historical climatologists and paleoclimatologists seems very promising. To enable such a discussion, it is necessary to explore ways to solve problems derived from inhomogeneous records in the archives of society, the loss of low-frequency variability, and the treatment of uncertainties in reconstructions based on the methods of historical climatology.

*3) Communicating standards of climatic causation used in historical research, especially for the benefit of natural and social scientists whose work has historical human dimensions*

As with other interdisciplinary fields, historical climatology must deal with diverging disciplinary concepts, standards, and language used to address causality. This challenge arises particularly in the attribution of past societal changes to climatic variability or change. In order to avoid confusion among scholars in different disciplines as well as overly deterministic statements, CRIAS aims to promote more rigorous standards and language in historical climate impact and adaptation research.

## Working group activities

In October 2018, a first workshop on "Methods and Interdisciplinary Communication in Historical Climatology" was organized in Bern, Switzerland (Camenisch et al. 2019). A second workshop was held in October 2019 in Leipzig, Germany, on "Integrating Documentary Evidence into Climate Reconstruction and Impact Studies" (dantean.hypotheses.org/crias), and a third workshop is scheduled in the second half of 2020 in Hong Kong. As a result of these activities, several papers and special issues are in preparation.

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# Mapping past land use in Europe for climate modeling

Rosie R. Bishop[1] and Marc Vander Linden[2]

Hemmenhofen, Germany, 28-30 January 2019

The PAGES LandCover6k (pastglobalchanges.org/landcover6k) Europe group workshop, hosted by Dr. Elena Marinova at the Research Center for Wetland Archaeology in Hemmenhofen, Germany, was attended by an interdisciplinary group of European researchers, which included archaeobotanists, zooarchaeologists, landscape archaeologists, and environmental scientists.

The workshop built on discussions from two earlier LandCover6k Europe group workshops in 2018 (both in Barcelona, Spain) and research that had been undertaken by the group over the past year.

The workshop focused on several key themes:

- Evaluating the project methodologies for mapping land use.
- Evaluating initial regional European land-use maps for the period 4250-3750 cal BCE (6000 BP).
- Refining definitions of land use for global mapping and the categories for the accompanying database of sites.
- Data ownership and plans for future publications from the project.

Day one involved a series of presentations from different participants. The workshop began with a welcome address from Dr. Renate Ebersbach, the director of the research center. Following this, the European group coordinators, Dr. Nicki Whitehouse (University of Plymouth, UK), Prof. Marco Madella (UPF, Barcelona, Spain) and Dr. Ferran Antolin (University of Basel, Switzerland), updated the group on progress since the previous meeting and introduced the agenda for the workshop.

Dr. Oliver Boles (University of Pennsylvania, USA) presented the definitions of land use that will be used for mapping, and there was discussion regarding the standardized categories to be used for the database of site information that will accompany the maps. It is necessary to develop standardized definitions of different types of land use (e.g. hunter-gathering, pastoralism) to enable global comparisons to be made (Morrison et al. 2018).

This discussion was followed by a series of papers reviewing methodological issues for modeling past land use. Dr. Marc Vander Linden (University of Cambridge, UK) updated the group on the site mapping that had been undertaken since the previous meeting and explained the decision to use kernel densities to map European land use. Prof. Sandy Harrison (University of Reading, UK) then outlined the types of information needed as input for climate models and how archaeologists can provide relevant data or improve existing estimates based on expert knowledge. Key information modelers require include: the dates of first agriculture and percentage of agricultural land, estimates of population growth, how much biomass was removed (percentage of different crops and domestic animals, as well as mass density in kg/m$^2$ of wood and nuts harvested), and the mix of C3 versus C4 crop plants grown. Finally, Dr. Tilman Baum (University of Basel, Switzerland) discussed a modeling land-use case study in the Alpine Foreland using agent-based simulations.

In the second part of the meeting, the preliminary land-use maps generated at a previous meeting in May 2018 (Whitehouse et al. 2018) were evaluated by regional sub-groups (Northwest Europe, Northern Europe, Southeast Europe, Southwest Europe; Fig. 1) to establish data gaps and errors. The initial maps were constructed using expert knowledge, together with a European database of radiocarbon dates collated by Dr. Marc Vander Linden and subsequent data collections by the group.

Day two focused on refining the standardized categories that will be used in the database of sites to accompany the maps, and discussing the plans for papers that will be produced from the project.

## Future research

The project team is currently working to fill in gaps in datasets. The aim is to produce initial land-use maps using basic top-level classifications of land use (e.g. hunter-gathering/agriculture) to allow climate modelers to test whether human impacts on land cover in prehistory were large enough to influence climate change. The datasets will be increasingly refined and used to produce more detailed maps that will incorporate information on different hunting and gathering, farming, and fuel-procurement strategies. It is hoped that the final output of the project will prove useful for both the modeling and archaeological communities.

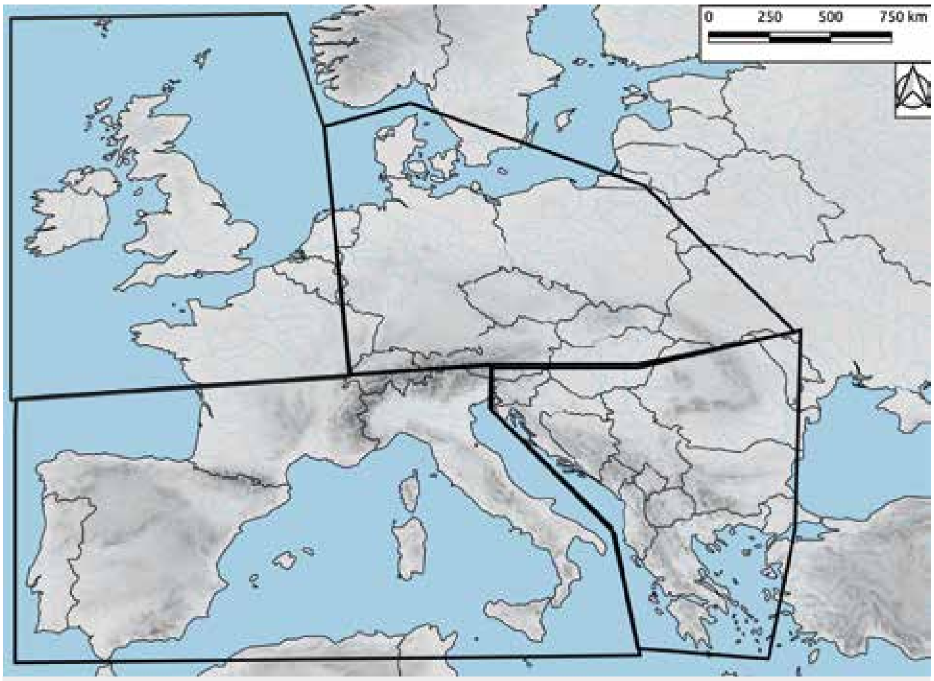

**Figure 1:** Distribution of the regional sub-groups (Northwest Europe, Northern Europe, Southeast Europe, Southwest Europe).

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# Holocene land cover and land use in South and Southeast Asia for climate modeling

Anupama Krishnamurthy[1], M.-J. Gaillard[2], S. Prasad[1] and K.D. Morrison[3]

**Pondicherry, India, 11-14 September 2019**

This four-day workshop of the working group LandCover6k (pastglobalchanges.org/landcover6k) hosted at the French Institute of Pondicherry emphasized hands-on training in pollen-vegetation modeling methods and fieldwork protocols for pollen-based land-cover reconstructions (LC) and archaeology-based land-use mapping (LU). The training was provided by LandCover6k members to a group of mainly ECRs and also senior palynologists, ecologists, archaeologists, and historians working in South and Southeast Asia (45 participants).

The first day included presentations on:

- LandCover6k, its activities, and the state-of-the-art methods for achieving pollen-based LC reconstructions using the Regional Estimates of VEgetation Abundance from Large Sites (REVEALS) model (Sugita 2007).
- Archaeology-based LU mapping, including per-capita land-use estimates and other quantitative information, e.g. regarding domestic animals and crops (Morrison et al. 2018).
- Establishing standard chronologies for pollen records with an introduction to chronology using radiocarbon dating and Bayesian age-depth modeling (Blaauw and Christen 2013).

The group discussions and 20 poster presentations facilitated exchanges on regional initiatives for achieving the goals of LandCover6k as well as an overview of a possible regional-scale data synthesis starting with homogenizing the attributions of pollen types and plant taxa of this region, including their ecological significance. Finally, Y. Subbarayalu gave a special lecture entitled "An independent LU data synthesis: Historical atlas of South India and its GIS database."

The second day, mainly in the field, introduced standard protocols for distance-weighted vegetation data (Bunting et al. 2013; Fig 1) necessary to estimate Relative Pollen Productivities (RPPs, a key input in REVEALS) using the Extended R-Value (ERV) model, followed by discussions on the various regional challenges. A positive conclusion was the broad feasibility in tropical landscapes, given the new results from Southeast India (which will be published within the framework of Navya Reghu's PhD thesis) and Cameroon (Gaillard et al. 2019).

The remaining two days consisted of parallel sessions focused on LC and LU to achieve the overarching goals of the work packages WP-LC6 and WP-LU6 (pastglobalchanges.org/science/wg/landcover6k/scientific-goals), respectively.

The LC session included running ERV, REVEALS, and BACON age-depth models. The LU session focused on the application of the hierarchical scheme of global land-use classes used in LandCover6k and the effective use of Google Earth for LU mapping. The LU group capitalized on the participants' expertise by continuing work on correcting and completing paper maps produced during the regional LandCover6k initiative started a few months ago in Delhi under HoLa, an International Focus Group of INQUA HABCOM (inqua.org/commissions/habcom/ifg). This allowed for the near completion of a basic land-use map for South Asia at 12 kyr BP, 6 kyr BP, 4 kyr BP, and CE 1500 for publication. The plenary discussion sessions on the relevance of regional paleo and historical databases had a special focus on NEOTOMA (Williams et al. 2018), including a brief demonstration of the database. A special lecture by Shanti Pappu and Kumar Akhilesh provided perspectives on the changing archaeological landscape of South India through the Quaternary with public outreach insights.

During the final plenary, workshop participants discussed the available Holocene pollen data, including modern pollen-vegetation datasets from different ecological zones (WP-LC6) and the pressing need for a regional historical database (WP-LU6). It was decided to move forward with WP-LC6 in two ways in at least four distinct ecological zones where sufficient data and ongoing studies are available (Central Indian forests, Western Himalayas and Kashmir, Coastal Mangroves, Sri Lanka):

- Initiate fieldwork using the standard protocol for collection of pollen-vegetation data demonstrated during the workshop to obtain new estimates of RPPs for major plant taxa of the region.
- Use the numerous existing modern pollen samples to validate available RPPs from other regions, such as China and Europe (Li et al. 2018; Mazier et al. 2012), for common plant taxa in e.g. the Western Himalayas and Kashmir, and test newly obtained RPPs from Southern India in the Central Indian forests.

It is feasible to extend these LC and LU goals in Cambodia, Vietnam, and Indonesia in the next year or two. In terms of databases, using available ones like NEOTOMA seemed most practical; however, the addition of a regional web portal would be useful. This workshop (pastglobalchanges.org/calendar/2019/127-pages/1830) allowed the LU group (WP-LU6) to propose a roadmap for a regional historical database: to begin setting it up at the University of Pennsylvania where it is technically feasible to do so immediately and to eventually move it to a host institution in South/Southeast Asia.

**Figure 1:** Participants recording distance-weighted vegetation data as per protocol in tropical peninsular India.

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# 4th Summer School on Speleothem Science (S4)

Brittany Marie Ward[1], T. Pollard[2], E. Corrick[2] and O.A. Dumitru[3]

**Cluj-Napoca, Romania, 11-17 August 2019**

Speleothem science is a rapidly growing discipline in the field of paleoclimatology. The application of speleothem-based research includes diverse topics such as the reconstruction of sea-level rise (Dumitru et al. 2019), assessment of monsoon dynamics (Dykoski et al. 2005), exploration of human-climate relationships (Pickering et al. 2019), calibration of the radiocarbon timescale (Noronha et al. 2014), precisely dating of the timing of global abrupt climate changes (Moseley et al. 2014), and many more. The necessity of a student-focused training school on this topic was acknowledged in 2011 by a group of PhD students, who went on to hold the inaugural Summer School on Speleothem Science (S4) in Heidelberg, Germany, in 2013. At its core, S4 has remained a student-led initiative and was subsequently held in Oxford, UK (2015) and Burgos, Spain (2017).

The fourth iteration of S4 was hosted at the Babeș-Bolyai University in Cluj-Napoca, Romania, from 11-17 August 2019 (speleothemschool.com). The school was the largest S4 yet, with 63 early-career participants from 24 countries, as well as 19 invited lecturers, in attendance. The four-day academic program consisted of lectures, workshops, a career development panel, and two poster sessions, in which participants presented their current research. The academic component of the school covered fundamental aspects of speleothem science in a lecture format, generated valuable discussion between participants and experts during question periods, and aimed to create a welcoming atmosphere to integrate early-career speleothem researchers into the field of speleothem science. The lecture program covered fundamental topics in speleothem science, such as speleothem formation and stable isotope analysis, but also included discussion of frontier research topics, such as characterization of cave-system hydrology using advanced geophysical imaging methods, exploration caving being undertaken in Northeast Greenland, and new speleothem drip-rate proxies based on the dissociation kinetics of trace metal-organic ligand complexes. The workshop program also introduced participants to a selection of software packages relevant to the field, including COPRA (depth-age modeling software), PHREEQC (geochemical modeling), and CaveCalc (cave drip water and speleothem chemistry modeling), as well as a hands-on session on uncertainties in timeseries analysis.

The academic program was followed by a two-day field trip to the Apuseni Mountains of Transylvania. Participants were guided by Babeș-Bolyai University and Emil Racoviță Institute of Speleology researchers to Transylvania's impressive karst landscape, visiting the world-renowned Meziad Cave, Bears' Cave (Fig. 1), and the impressive Scărișoara Ice Cave. Participants were able to gain an appreciation of speleothem formation environments, see examples of cave monitoring stations, practice interpreting stalactite patterns on the cave roof, and see firsthand a 15 m-thick cave glacier that has yielded a 10,000-year-old paleoclimate record. Participants came together for a traditional Romanian dinner during the field trip in the Hotel Perla Apusenilor and were treated to a performance of Romanian folk music with alphorns.

The 2019 Organizing Committee aims to provide lasting resources to S4 2019 participants and other speleothem researchers by sharing the S4 2019 Course Notes, which are now available via the S4 ResearchGate profile (researchgate.net/project/Summer-School-on-Speleothem-Science). Further, the S4 aims to establish a strong social media presence on both Twitter and Instagram. These platforms can be used to advertize upcoming workshops in the broader field of speleothem science, highlight new research and generate discussion within the community, spread the word of PhD, postdoctoral, and faculty positions, and share stories from the lab and the field. Follow S4 at @SumSchSpelSci on Twitter and @s4_speleothem on Instagram.

The S4 provides a unique opportunity for international networking in a casual and inclusive setting, fostering relationships between early-career researchers, and bringing together the future of Speleothem Science. We look forward to passing the torch to the S4 2021 Organizing Committee.

**Figure 1:** S4 2019 participants touring the immaculately decorated Bears' Cave of Chișcău, Romania, where Emil Racoviță Institute of Speleology researchers are undertaking cave sediment and paleontological research.

## ACKNOWLEDGEMENTS

We thank the Babeș-Bolyai University, PAGES, the International Association of Sedimentology (IAS) and the European Geoscience Union (EGU) for their financial and logistical support that made this event possible.

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# Peatland ecosystem services during the Anthropocene and beyond

Angela V. Gallego-Sala[1], J. Loisel[2] and M. Garneau[3]

University of Exeter, UK, 1-4 May 2019

Members of the C-PEAT working group (pastglobalchanges.org/c-peat) met at Exeter University for the first meeting of Phase II of the working group. The aim of the workshop (pastglobalchanges.org/calendar/2019/127-pages/1937) was to discuss the more recent (post-industrial) role of peatlands in the carbon cycle and the ecosystem services (ES) they have provided and will continue to provide in the future.

In our planning meeting in Texas last year, the C-PEAT scientific committee highlighted the need to predict peatland responses to anthropogenic disturbances, so integrating human impacts on ecosystem functioning was integral to this workshop. The discussion was divided into two topics/days: 1) carbon cycling in peatlands since the Industrial Revolution and 2) other ES provided during this period. Workshop participants included not only the habitual peat paleo community but, in addition, we invited peatland flux scientists, peat modelers, peatland stakeholders and ES experts, including several tropical peatland experts. Bringing different expertise into the same room allowed for interesting presentations, group discussions and brainstorming exercises (Fig. 1).

**Carbon cycling in peatlands**

Under this heading the community worked towards bringing together ongoing efforts to gather regional, national and global databases of the recent carbon accumulation records in peatlands. The brainstorming work focused on many topics including: 1) developing a better analysis of this part of the record to tease out allogenic versus autogenic drivers of carbon accumulation, 2) locating the carbon accumulation hotspots on a global scale, and developing a peatland health index based on existing peat carbon data syntheses, 3) identifying the changes in radiative forcing of peatlands driven by recent changes using regions with high data density (Canada and Fennoscandia), and 4) exploring the economic impacts of the carbon sink loss brought about by anthropogenic impacts. The meeting produced many ideas for future work and direction of research within the community, including the preparation of at least two community manuscripts that will present key results from the aforementioned research objectives.

**Other peatland ecosystem services provision**

We discussed current and future peatland ES, including ongoing restoration efforts and loss of ES in different areas around the globe. In particular, we discussed what the paleo record may tell us about the changes in ES since the Industrial Revolution and how it may inform predictions of future trajectories of ES. Besides carbon regulation, workshop participants identified a suite of ES and their relative importance across different regions of the world. For example, while Andean peatlands are most significant for water provision and regulation, those from the Indonesian lowlands matter most in terms of their food provisioning, biodiversity hotspot and climate change mitigation capacity (Law et al. 2015). We also explored how the C-PEAT paleo peat community may inform management of these important ecosystems and planned two outcomes that represent our first steps in working more closely with practitioners and other stakeholders: 1) policy briefing note – the community will produce a note for policymakers highlighting the main drivers of carbon accumulation of peatlands to help them make better decisions to improve ecosystem management; 2) Marie Skłodowska-Curie Innovative Training Network – the community will apply for a EU-funded training network in January 2021 using contacts with stakeholders to strengthen the application.

**Figure 1:** Discussion session after brainstorming during the C-PEAT workshop in Devon.

**Next steps**

One of the next steps for C-PEAT is to better integrate tropical and extra-tropical peatlands in the databases, an attempt already started in one of the latest community papers (Gallego-Sala et al. 2018). To achieve this, our next meeting will be held in May 2020 in Bangkok, Thailand, with a focus on tropical peatlands.

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# Human paleobiogeography and the synchrony of social-ecological systems on Earth

Erick Robinson[1], J.B. Finley[1], J. Freeman[1], M. Cannon[1] and C. Latorre[2]

**3rd PEOPLE 3000 workshop, Vernal, UT, USA, 20-24 May 2019**

The PEOPLE 3000 working group (P3k WG; pastglobalchanges.org/people3000) focuses on integrating archaeological and paleoecological case studies with mathematical modeling. We seek to understand how co-evolving human societies and ecosystems successfully cope with the interrelated forces of population growth, increasing social complexity and climate change, and why some societies subsequently collapse/reorganize. Here we report on the most recent workshop held at Utah State University Vernal (pastglobalchanges.org/calendar/2019/127-pages/1909). This workshop challenged participants to consider how integrated paleodata can be used to inform contemporary policy on "climate-smart food systems". We posed the following question to participants: did societies across the world throughout prehistory achieve "triple-wins" of increasing economic productivity while reducing anthropogenic impacts on the environment that threaten to decrease the resiliency of societies to environmental change?

This workshop aimed to broaden the geographic scope of the WG and incorporate more early-career researchers (ECRs). We accomplished this goal. ECR attendees specialized in the archaeological and paleoenvironmental data of Central America, Europe, Southwest Asia, Central Asia, and Northern Africa attended the meeting. This enabled us to expand our archaeological radiocarbon dataset to ca. 130,000 dates (Fig. 1). We had a computer scientist attend the meeting in order to facilitate the integrated development of this radiocarbon dataset and overcome the various metadata obstacles to comparative global-scale analyses. This dataset is now the largest archaeological radiocarbon dataset in the world, and overcoming the various metadata obstacles presents unprecedented opportunities for the study of human population ecology. A new collaboration with the LandCover6k project was furthered by the attendance of one of their group leaders at this workshop. Synergies are bound to emerge between these PAGES WGs from the use of the archaeological radiocarbon database as a resource for establishing population growth rates for different regions of the world that in turn can be used to provide baselines for anthropogenic land-use models.

First steps were taken at this workshop to overcome the central challenge of integrating archaeological, paleoclimate, and paleoenvironmental data. This challenge is largely caused by gaps in the spatial and temporal coverage of these different records, and the impacts these gaps have on data resolution and our ability to identify correlations and possible causal processes. In order to overcome these challenges, the P3k WG has developed a new method for modeling human paleodemography according to transient paleoclimate model simulations, rather than modern nation-state boundaries (Robinson et al. 2019). We turned to PaleoView (Fordham et al. 2017) to extract continuous climate model simulation data for every region from which we have significant amounts of archaeological radiocarbon data. We then acquired multi-proxy paleoenvironmental data for each of these regions in order to start comparing PaleoView to multiple proxy records from different regions. Comparative studies of PaleoView and regional paleoenvironmental records will enable us to identify relevant key ecological parameters for "tipping points" in human social-ecological systems.

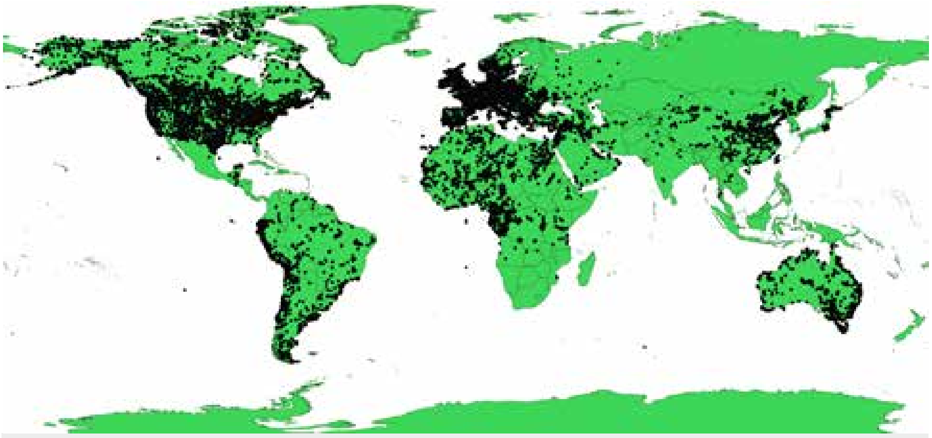

**Figure 1:** Locations of all archaeological radiocarbon dates in the PEOPLE 3000 database.

The workshop included several public outreach engagements including tours of local archaeological and rodent midden (paleoecological) sites at Dinosaur National Park, a guided tour of the McConkie Ranch rock art panels, and an open house held at the Uintah County Museum. During the open house, scholars from the P3k WG invited members of the public for an evening of conversation about climate-smart food systems. Conversations focused on insights made possible through the interdisciplinary work of archaeologists and paleoecologists from around the world. Together, workshop participants and community members explored strategies, successes, and failures from local contexts and shared perspectives for developing climate-smart food systems for our futures.

P3k WG participants gave in-depth interviews on their research, workshop experience, and collaboration. These interviews will be made available to the public through online podcasts, videos, and Utah Public Radio segments to be aired in early 2020.

Access the poster highlighting these outreach events at pastglobalchanges.org/products/pages-outreach/12884

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# European Association of Archaeologists 25 years: Beyond paradigms

Sophie Hüglin[1], A. Alterauge[2] and A. Hafner[2]

**Bern, Switzerland, 4-7 September 2019**

The European Association of Archaeologists (EAA; e-a-a.org/eaa2019) met in Bern to hold its 25th Annual Meeting under the motto "Beyond paradigms" (Criado-Boado and Hüglin 2019). EAA currently has more than 2500 members from more than 50 countries of which more than 1800 took part in this year's conference. The six themes of the conference reached from "Global Change and Archaeology" to "Digital Archaeology, Science and Multidisciplinarity". Each of the themes not only received the attention of several sessions, but was also addressed by a keynote lecture. Due to the high number of sessions (166) and presentations – this year over 1500 – there were more than 30 parallel sessions. Thanks to the local hosts, Albert Hafner and Amelie Alterauge, and to the EAA Secretariat from Prague, the meeting ran exceptionally smoothly.

The theme "Archaeology of Mountainous Landscapes" was specifically connected with Switzerland and the Alps. Linked to this theme, the current president of Swiss Archaeology, Thomas Reitmaier, led a four-day "Grand Tour to the Archaeology of Mountainous Landscapes". Like all other excursions it was expertly organized by ArchaeoConcept and all tours were fully booked. The keynote lecture dedicated to the theme, delivered by Francesco Carrer, was entitled "Aiming High: The rise of mountain archaeology and its role in today's changing world". Another thematic focus in Bern was archaeoastronomy through the cooperation with SEAC (European Society for Astronomy in Culture), which organized a keynote, three sessions, and a round table. Finally, all keynote presentations and talks from more than 50 sessions will be available online on EAA's YouTube channel.

Linked to this Annual Meeting, PAGES, represented by its executive director Marie-France Loutre, acted as a co-organizer of the scientific program. PAGES hosted a flyer table in the exhibition tent "Archaeology in Switzerland" where the institutions that supported the local organizers in strategic, financial or practical ways had the opportunity to exhibit their work. In total, six institutions provided information and publications for the public. The exhibition tent was an addition to the European Archaeology Fair (EAF). At more than 25 stands, a range of publishers presented their new publications, and several other organizations and companies demonstrated the latest technologies in archaeological research. PAGES members Ariane Burke and Basil Davis convened session #317 "Celebrating 25 Years of Collaboration: How archaeology and the Earth sciences are coming together to solve real-world problems".

It should be mentioned that the EAA aims to be more than a platform for academic research and networking, but also wants to encourage archaeologists to engage in society and take social responsibility. Therefore, at each meeting an EAA Task Force works on a formal statement that addresses pressing issues. In 2019, at the Annual Members Business Meeting, the EAA adopted the "Bern Statement: Archaeology and the Future of Democracy" (e-a-a.org/BernStatement). The statement emphasizes that: "Archaeologists within EAA will not accept any form of a political use of history for propaganda purposes, especially where archaeological issues are taken out of the context of their standard academic discourses (including scholarly debates) and used for the purposes of divisive nationalistic, anti-democratic, exclusionary or chauvinistic argument". The statement was very well received by partner organizations including Europa Nostra (europanostra.org) and is currently being translated into many European languages. National archaeological organizations are also disseminating the statement by publishing it in their journals.

The EAA will have its next Annual Meeting between 26-30 August 2020 in Budapest, Hungary, under the motto "Networking" (e-a-a.org/EAA2020/Home.aspx). The call for papers will open 18 December 2019 and close 13 February 2020. The EAA encourages all archaeologists to contribute to and participate in the conference and to follow the EAA to Kiel, Germany, in 2021 and Belfast, Northern Ireland, in 2022.

**Figure 1:** The entertaining opening ceremony in the French Church featured a dialogue between Colin Renfrew (left) and Kristian Kristiansen (middle) on the founding of EAA 25 years ago, and a keynote by Caroline Heitz (right), representing the generation that will shape EAA in the 25 years to come (Photos: Katka Kleinova and Sophie Hüglin).

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# Climatic and hydrological extremes: Linking the instrumental period of the last decades with the more distant past

Stephan Dietrich[1], B. Wilhelm[2], H. Goosse[3] and B.L. Valero-Garcés[4]

### PAGES Extremes Integrative Activity workshop, Koblenz, Germany, 18-20 February 2019

Weather and climate extreme events in a changing climate are able to cause major losses; however, their assessment by scientists remains challenging. As summarized in the IPCC Assessment Report 5 (AR5), this is due to their extreme nature, encompassing weather and climate timescales as well as compound events (such as droughts and tropical cyclones). Thus, both observations and proxy analysis (for paleo timeseries) of extremes are limited.

According to the chapter outlines (wg1.ipcc.ch/AR6/outline.html) of the Working Group I contribution to the AR6 there is a need for enhanced process understanding about, inter alia, the mechanisms, drivers, and feedbacks leading to extremes as well as an assessment of potential surprises including case studies across timescales. In addition, the World Climate Research Programme focuses on the Grand Challenge on Weather and Climate Extremes (wcrp-climate.org/grand-challenges/grand-challenges-overview) from both (i) a service perspective, asking what the frequency and magnitudes of various impact-causing extremes are in the near and long-term future and (ii) a science perspective, looking for causes and mechanisms of variability and change in extremes in order to improve the prediction of change.

The aim of the workshop (pastglobalchanges.org/calendar/2019/127-pages/1827) was to produce a synthesis presenting analyses on long timescales in a way that is suitable for non-specialists. In addition, we aimed to reinforce the coordination between existing research lines on climatological and hydrological extreme events of the past including the instrumental era. Being informed about the accuracy of the available data and the robustness of their interpretation is particularly important for scientists outside of the field. Furthermore, this workshop was designed to provide a platform for scientists working on the more recent period to explain their needs and how their techniques could be applied to longer-term changes.

To address these issues, we organized a workshop in the scenic town of Koblenz, Germany, as a follow-up to a splinter meeting at the European Geosciences Union General Assembly in Vienna in April 2018. The workshop was organized and co-sponsored by the International Centre for Water Resources and Global Change (a UNESCO Category 2 Water Centre) and hosted by the Federal Institute of Hydrology in Koblenz, Germany. We brought together 20 scientists from eight different countries (including one who joined remotely) with a mixture of early-career and established scientists working in the following fields: global and regional climate modeling, event attribution, proxy reconstruction based on different archives, and statistical techniques. Nearly all scientists had a focus on floods, low flows or droughts. The workshop participants did not expect a synthesis to cover all of these fields, but rather only for what the group defined as hydrological worst-case events (paleo high-magnitude hydro-meteorological hazards).

**Figure 1:** The workshop coincided with the record-breaking 2018 drought, which strongly influenced Central Europe, here in the form of historic lows in water levels. In addition to the strong environmental effects, the continuing drought had an increasing impact on river navigation. This example underlines the importance of extending the observational timeseries into the more distant past. This is necessary for a better understanding of the frequency and size distribution of worst-case extremes and their potential forcing in the area of global change. Photo by Sebastian Kofalk (Federal Institute of Hydrology), 2018, from the village of Osterspai with a view of Boppard Hamm, Germany.

The workshop consisted of two sections: first, a series of keynotes for setting the scene and oral presentations from participants presenting their work and fields of interest. Second, a series of parallel breakout groups about (i) worst-case (flooding and drought) events, (ii) the physical mechanisms and (iii) requirements of paleo- and observational data. The participants discussed some prominent examples like the Magdalena flood in 1342, which caused significant hazards in Central Europe (see also contemporary example in Fig. 1), or examples where water managers were already using tree-ring data to assess the impact and extent of droughts.

The participants agreed to publish an opinion paper on the occurrence of these extreme events, the underlying climate dynamics, and the impacts on the landscape and humans as a follow-up to the workshop. An additional focus will be on best-practice examples about the data requirements (quality and discoverability of data) and perspectives for the value of paleodata to increase knowledge about current and future extreme events. This opinion paper will give us the opportunity to reach a wide range of users. With this opinion paper, we are particularly interested in targeting users who are not aware of the relevant information provided by paleoscientists and who do not read the specialized literature on this subject. Similarly, new findings from the modern community should also stimulate the discussion within the paleo community.

Find out more about the PAGES Extremes Integrative Activity here: pastglobalchanges.org/science/int-act/extremes

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# Understanding volcanic impacts through time

Celine Vidal[1], M. Toohey[2], M. Sigl[3], K. Anchukaitis[4], F. Ludlow[5] and A. LeGrande[6]

4th VICS workshop, Cambridge, UK, 13-16 April 2019

The Volcanic Impacts on Climate and Society (VICS; pastglobalchanges.org/vics) working group initiated Phase 2 this year. The aim of Phase 2 is to extend the scope of VICS to major eruptions throughout the Holocene and beyond by exploring evidence of volcanic forcing, testing model experiments, and placing an increased emphasis on archaeological evidence of societal impacts and responses to complement the focus on written records from Phase 1. This year, the meeting – the largest to date – gathered 70 delegates with expertise in history, archaeology, dendrochronology, ice cores, climate modeling, tephrochronology, and volcanology.

**Eruptions of the Common Era**

The integration of historical records continues to improve our understanding of the physical processes that occurred during past volcanic eruptions and their links with societal hardships, such as the 1783 Laki (Iceland) or 1257 Samalas (Indonesia) eruptions. The exegesis of historical records can help establish links between severe volcanically induced climate deterioration and major societal stressors such as famines and/or epidemics, which may in some cases promote large-scale societal reorganizations (e.g. Manning et al. 2017). Presenters demonstrated a growing recognition that the repeated occurrence of volcanic climatic "shocks", increasingly clear in paleoclimatic records, now provides historians and archaeologists with an important diagnostic tool to chart the evolution of societal vulnerabilities to sudden environmental change.

Presenters highlighted advances in satellite observations of volcanic aerosol, detection of volcanic signals in ice cores, and the use of idealized and comprehensive aerosol models. While uncertainties in aerosol reconstructions will always be present, current efforts are helping to constrain volcanic forcing estimates. For example, analysis of the isotopic composition of ice-core sulfate can be linked to injection height, which has a large impact on the reconstructed radiative forcing (Burke et al. 2019). Advances in dendrochronological records were presented, including work investigating the sources of differences between hemispheric reconstructions, and work looking at the impact of volcanic eruptions on large-scale temperature gradients and their potential impacts. A perspective from the Southern Hemisphere argued that large eruptions in the instrumental era have consistently led to cold temperatures in South Africa.

New evidence was presented on the search for the eruptions responsible for the frequently studied sulfate peaks in ice cores in 536 and 540 CE and major cooling suggested by tree rings in the mid-sixth century, marking the onset of what has been termed the Late Antique Little Ice Age (Büntgen et al. 2016). This cold period coincides with major societal reorganizations in Eurasia and Central America (Fig. 1). Source candidates such as Ilopango volcano (El Salvador) and El Chichón (Mexico) were suggested (Nooren et al. 2017), with new age estimates leading to different conclusions. This highlights the challenge and importance of accurate dating when identifying eruptions and their potential impacts.

**Pre-Common Era eruptions**

Beyond the Common Era, tree rings show some strong volcanic cooling events throughout the Holocene (e.g. in the fourth and seventh millennia BCE, Nicolussi et al. 2009). Climate modeling suggests that the seventh millennium BCE Mt. Mazama eruption (USA) would have triggered strong cooling in the Northern Hemisphere (Krüger et al. 2018).

Further in the past, archaeological studies are key to understanding the impact of large events, such as the Laacher See eruption (Germany) 13,000 years ago, which had profound effects on the way of life of local contemporaneous Final Paleolithic foragers (Riede 2017). Tephrochronological studies in Eastern Africa are helping to constrain the impact of explosive volcanism on our hominid ancestors in the Pleistocene. In the Ethiopian rift valley, a dozen major eruptions between 360,000 and 100,000 years ago drastically remodeled landscapes and ecosystems, and potentially isolated populations in regions of the rift (Vidal et al. unpublished data).

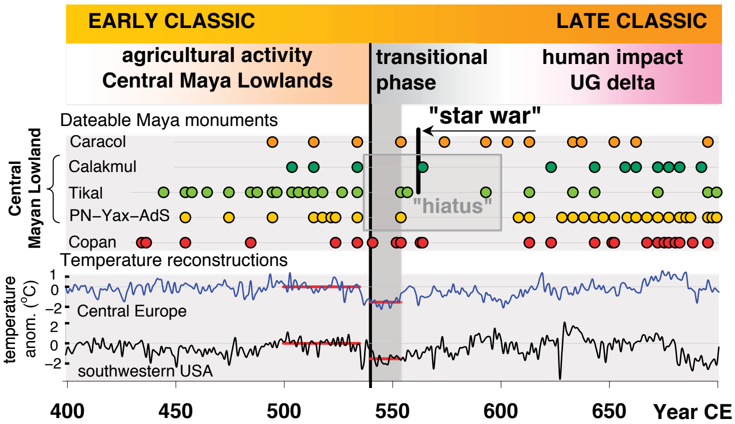

**Figure 1:** Late Antique Little Ice Age and transformations in the Mayan culture and Northern Hemispheric summer cooling (modified from Nooren et al. 2017 and references therein). Key: PN: Piedras Negras; Yax: Yaxchilan; Ad S: Altar de Sacrificios.

**Outlook**

Interdisciplinary groups defined during the second VICS workshop (Zaragoza, Spain, May 2017) are currently working on case studies of eruptions of the Common Era and the first two centuries BCE. It is planned that the outcome of these study groups will take the form of a special issue in *Climate of the Past* to be published in 2020. Another future focus for VICS will be the investigation of the impact of volcanic halogen on the ozone layer and possible records and proxies of ozone depletion, a process that has recently attracted high interest (e.g. McConnell et al. 2017).

The interdisciplinary nature of research on volcanic impacts is a great strength, but can also pose a challenge for those new to the topic. The VICS community identified the potential value of a "best practices" document, including recommendations for each area of expertise, which would aim to give background on the most important methods, data sets, and assumptions that underpin VICS' research efforts.

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# How hot was the Holocene?

Basil A.S. Davis

**Climate-12k workshop, Sainte Croix, Switzerland, 10-13 June 2019**

Our ability to understand the natural variability of the Earth's climate before modern anthropogenic greenhouse warming relies on establishing a public network of reliable proxy-temperature records from across the terrestrial and oceanic regions of the world. The PAGES 2k Network (pastglobalchanges.org/2k) has been successful in extending our knowledge of the Earth's temperature variability back 2000 years, and Climate-12k was established in December 2018 to further extend it back to 12,000 years before present.

This time period includes the early-mid Holocene thermal optimum, when unequivocal evidence exists of higher-than-present temperatures, at least at higher latitudes in the Northern Hemisphere. However, the global picture of Holocene temperature change remains poorly understood, based either on very sparse data networks that manage to cover the entire Holocene, or "snap-shots" that have greater numbers of sites but only for a single time-slice, such as the mid Holocene (6000 BP).

The Climate-12k project began with an appeal for published quantitative Holocene temperature reconstructions and other temperature-sensitive multiproxy records in early 2019 that culminated in a PAGES-endorsed workshop in Switzerland in June (pastglobalchanges.org/calendar/2019/127-pages/1911), organized by Basil Davis (University of Lausanne), Oliver Heiri, (University of Basel), Sam Jaccard (University of Bern) and Darrell Kaufman (Northern Arizona University).

Pre-workshop activities involved compiling data from different sources and formats into a single standardized dataset. This included data from public archives and publication data supplements, as well as previously privately held data from research groups and individual scientists. By the time of the workshop, the Climate-12k project had compiled records from over 600 sites (Fig. 1) that conformed to the project selection criteria. This focused data collection efforts on records that are at least 4000 years long, with a minimum 400-year median sampling interval and 3000-year dating interval.

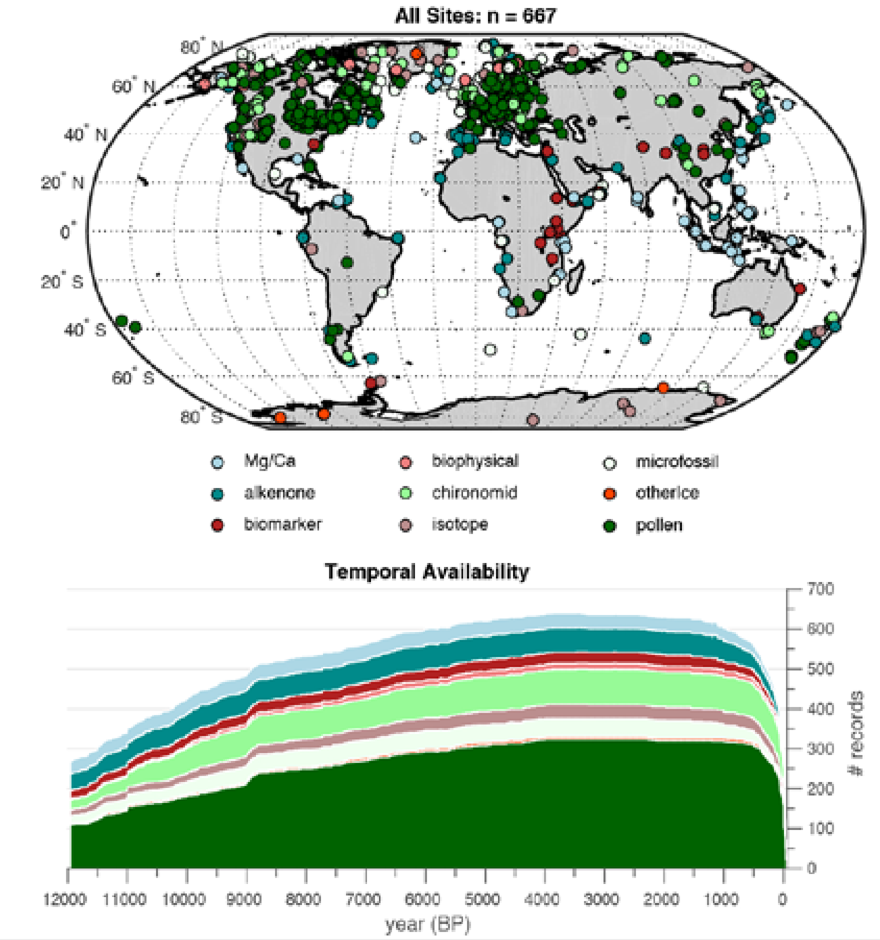

**Figure 1:** The global distribution of Holocene temperature records in the Climate-12k database (v.0.26)

The number of applications to attend the workshop greatly exceeded the 30 places that were available, which had to represent the world's main geographical regions and proxies, together with expertise in databases and data analysis as well as climate modeling.

The workshop format involved a small number of invited talks to provide background, but was mostly based around group discussions and break-out teams. These were designed to review the collected data, refine the selection criteria, agree on essential metadata, learn about the Linked Paleo Data (LiPD; lipd.net) database format, as well as discuss analysis and publication.

A key motivation behind the Climate-12k project has been to provide a new analysis of global and regional Holocene temperature trends in time for inclusion in the next IPCC report (AR6). A database publication and an analysis paper are both planned for submission before the end of the year, which is the deadline for consideration for the Working Group 1 report.

Looking further ahead to next year, it was also proposed at the workshop that a second workshop should be organized to both continue expansion of the temperature dataset, and to expand the project to include Holocene hydroclimate records. In the meantime, workshop participants were enthusiastic about a potential application to establish Climate-12k as an official PAGES working group.

## ACKNOWLEDGEMENTS

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# Past climate changes and human adaptation

International Meeting on PALEOCLIMATE: CHANGES AND ADAPTATION
June 18-19 | 2019 | Coimbra-Portugal

Rui Pena dos Reis[1], M.H. Henriques[1], L. Oosterbeek[2], E.I. Alves[3], P. Rosina[2], G.G. Garcia[1] and P. João[4]

## International Meeting on Paleoclimate, Coimbra, Portugal, 18-19 June 2019

Climate is the planetary response of the atmospheric circulation to changes in its composition, the solar system configuration, Earth's rotation, and the distribution of the oceans and continents. As a result, it is continuously evolving, expressed at a global scale by subsiding and uplifting convection cells. These changes have long been recognized and documented in geologic objects of all ages. There are climate signals in many rocks, different geologic features, fossil fragments and imprints, prehistoric remains, and historical reports that can be analyzed and interpreted in order to learn more about past climate changes. Lessons from the past support the view that change is the rule, not the exception, as evidenced by strongly contrasting and chaotic extremes, defined by the whole ensemble of extra-planetary, external, and internal geodynamic controls.

Science-based knowledge is crucial to address current challenges, and this played a major role in the organization of the PAGES-endorsed International Meeting on Paleoclimate: Change and Adaptation (pastglobalchanges.org/calendar/2019/127-pages/1920). This event was organized by two research and development centers at the University of Coimbra (the Geosciences Center and the Center for Earth and Space Research) within the framework of two UNESCO Chairs (Geoparks, Sustainable Regional Development and Healthy Lifestyles, and Humanities and Cultural Integrated Landscape Management; en.unesco.org/unitwin-unesco-chairs-programme).

The conference was attended by 133 participants from 19 nations, including 64 researchers and 69 students. A total of 69 papers were presented and published in a special online volume (uc.pt/fctuc/ID/Geo/DOWNLOAD_DOCUMENTS/AREADOMENIU8). The meeting also included a fieldtrip to the Aspiring Estrela Geopark, where the landscapes formed during the Last Glacial Maximum are particularly well exposed (Fig. 1).

The organizers and participants took an observational approach in the presentations and open discussion on paleoclimatic signals designed to improve our look at the present and to ground future perspectives. The discussion focused primarily on three different topics, including paleoclimates in the solar system: external forcing; climate record in geological time: lessons to learn; and climate events and human adaptations throughout the Quaternary.

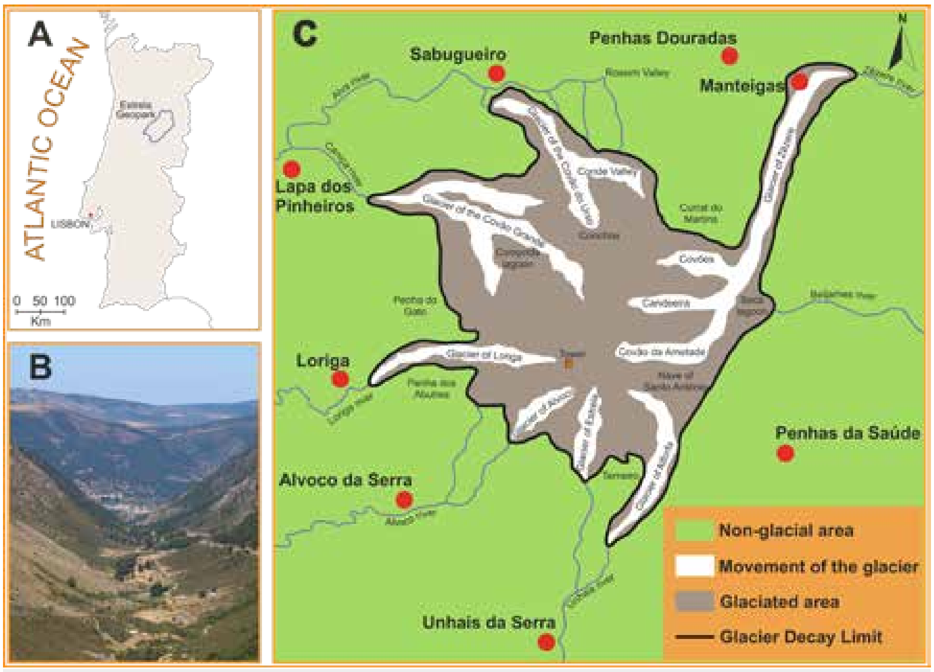

**Figure 1: (A)** Location map of the Aspiring Estrela Geopark (Portugal); **(B)** Zêzere glacial valley (Photo Credit: Aspiring Estrela Geopark); **(C)** Schematic paleogeographic model of glacier surface of the Estrela plateau ice-field during the last maximum of the glaciation of the Serra da Estrela.

Polar climate and prehistorical climate signals, as well as planetary climate science, were the subjects of four complementary keynote presentations: climatic catastrophes in the solar system by David Grinspoon, animal extinctions and climate change in the Quaternary period by François Djindjian, the record of Holocene environmental changes in polar and mountain ice cores by Jefferson Simões, and early Holocene paleohydrological and sedimentary indices from the alluvial archives of the Middle Moulouya (the Ait Blal sequence, Morocco) by Larbi Boudad.

Contributions on the Quaternary gave evidence supporting the importance of focusing on adaptive strategies of humans in the past allowing them to overcome often fast climatic oscillations. This enabled early humans both to cope with extreme dry and cold conditions in several moments throughout the Pleistocene as well as to design innovative strategies, including advances in farming techniques, as a response to the 8.2 kyr event. A special session on rock art and climate change, which involved key clusters from Portugal, Spain, and France, enabled assessment of both the prehistoric art motives as indirect evidence of climate changes (through the depiction of diverse zoocenosis) and the impact of these on the conservation of the art itself. These discussions, which also engaged the UNESCO Chair on Humanities and Cultural Integrated Landscape Management, demonstrated that while human impact on the climate was negligible, humans' adaptive capacity had important impacts on the biosphere dating back to the dawn of food production.

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# Warm extremes: Marine Isotope Stage 5e and its relevance for the future

Eleonora Regattieri[1], P. Scussolini[2], W.-L. Chan[3] and S. Sherriff-Tadano[3]

**QUIGS-PMIP workshop, Cambridge, UK, 1-4 July 2019**

The QUIGS working group (pastglobalchanges.org/quigs) aims to understand climate and environmental changes during quaternary interglacials, by integrating paleoclimatic records and climate model simulations.

This workshop (pastglobalchanges.org/calendar/2019/127-pages/1910) kicked off QUIGS' second phase (2019-2021), where improved datasets and new model experiments are being used to address research questions and knowledge gaps identified during QUIGS' first phase (2015-2017). The meeting focused mainly on the Last Interglacial (LIG, known in the marine record as Marine Isotope Stage (MIS) 5e) and its relevance for understanding Earth-system responses to ongoing and future climate change, although other past warm periods were also considered.

A total of 40 delegates from 12 countries participated. The first day was dedicated to discussing the latest results of the new PMIP4 climate simulations. Experiments on the LIG and mid Holocene (MH) based on the Tier 1 PMIP4 protocol are complete, ongoing, or planned for most models, and include transient simulations and experiments with different ice sheets, vegetation, and freshwater fluxes. Results will be analyzed by adopting the fixed-angular celestial calendar, essential to studying seasonality across geological timescales. Latest modeling results for the LIG consistently show summer warming at Northern Hemisphere high latitudes, marked strengthening of boreal monsoons, and weakening of austral monsoons. Several modeling studies also pointed out the importance of vegetation feedback on the amplitude of Northern Hemisphere warming. Results in the Southern Hemisphere are not as consistent: e.g. the Southern Ocean warms up or cools down depending on the model, hinting at different mechanisms at work.

From the second day, the spotlight expanded to proxy-based climate reconstructions and proxy-model comparison. A series of invited talks reviewed the current knowledge of LIG climate. Improved reconstructions of global LIG surface temperature anomalies (relative to the pre-industrial) from marine, ice-core, and continental records were presented (Fig. 1), highlighting that seasonal biases of many records still have to be addressed, and giving recommendations for the comparison to simulations of the 127 kyr BP snapshot. The latest progress in high-resolution greenhouse gas reconstructions from EPICA Dome C were presented, reporting, e.g. more stable $CO_2$ concentrations during the LIG than previously thought. Regarding LIG sea level, the latest estimates of its peak height and temporal evolution were presented, and the main sources of uncertainty were systematically identified. Challenges still to be addressed by the wider community include improved constraints on MIS 6 ice sheets, through both paleorecords and modeling, and a proper understanding of the magnitude of LIG melting from Greenland and Antarctica.

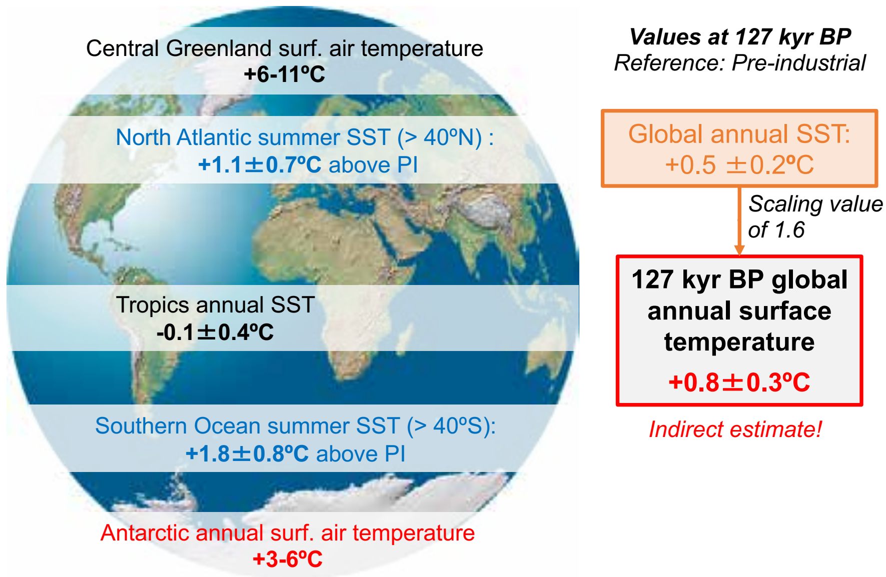

**Figure 1:** Summary of LIG surface temperature anomalies from marine sediment and ice-core records (courtesy of E. Capron; estimates deduced from datasets using approaches presented by Capron et al. 2017, Hoffman et al. 2017, and Fischer et al. 2018).

Another slot of invited talks summarized the latest advances in LIG and MH modeling. The LIG precipitation from the new PMIP4 runs compares favorably to new proxy-based global synthesis. Some modeling groups focus on monsoon regions and on high boreal latitudes.

The meeting also saw a series of selected proxy talks and posters considering different types of globally distributed archives and proxies. Topics ranged from estimates of mean ocean temperature, polar sea-ice extent, and regional sea-level variations, to syntheses of micropaleontological and pollen records.

Discussions in plenum and in working groups identified the main challenges still to be addressed by both communities and suggested possible ways forward. These issues related to (i) chronological mismatching and seasonal biases in climate reconstructions; (ii) uncertainties in the MIS 6 ice-sheet extent and distribution, essential to an accurate modeling of LIG climate and sea level; (iii) uncertainties in vegetation evolution during the LIG interval, also important for numerical simulations; and (iv) uncertainties in sea ice, important for understanding the dynamics of Arctic amplification.

A short-term key goal was established for the QUIGS community to strive to publish relevant LIG science in time to contribute to the forthcoming 6th Assessment Report of the IPCC (AR6). In the longer term, focus will be placed on unraveling specific mechanisms, such as interactions between ice sheets, ocean, climate, and vegetation, and on comparing simulations of the LIG to those of the MH, and PMIP4 to PMIP3 and other CMIP simulations.

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# Big data: Challenges and solutions of archiving over 130,000 years of sea-level change

Patrick T. Boyden[1] and Sophie Williams[2]

**Dublin, Ireland, 21-23 July 2019**

The PALSEA (PALeo constraints on SEA level rise; pastglobalchanges.org/palsea) working group convened recently at Trinity College, Dublin. This meeting (pastglobalchanges.org/calendar/2019/127-pages/1821) was the first in the new phase (2019-2021) of the PAGES-INQUA project focusing on using ecological and chronological data to refine proxy-based reconstructions of sea level in light of recent developments in the discipline (e.g. Barlow et al. 2018; Shennan et al. 2018; Capron et al. 2019). The end goal of this work is to produce standardized sea-level databases. The meeting particularly focused on two large databases: HOLSEA (focusing from the Last Glacial Maximum (LGM) to present) and WARMCOASTS (focusing on the Last Interglacial; Fig. 1).

The HOLSEA project (Geographic variability of HOLocene SEA level; holsea.org) is concerned with determining the geographic variability of sea-level change in the last ~20,000 years. The project, led by Nicole Khan at the University of Hong Kong and funded by INQUA, seeks to better quantify how global sea level has changed since the LGM, and identify the driving trends of spatial variability in relative sea level over this time period. While the HOLSEA project has several aims, the specific goals of the breakout group were to discuss the data archiving process and to address any comments on the sea-level data template used within the HOLSEA database introduced by Khan et al. (2019).

User interaction with the database was discussed, with emphasis on challenges faced when entering poorly resolved sites. Well-resolved sites primarily use sedimentary indicators and are easy to enter. Poorly resolved sites, however, are located in the high latitudes, where geomorphic indicators are used and environmental variables are difficult to obtain. Other issues included accessibility to data, conflicting data interpretation, and problems with old data using outdated radiocarbon calibration curves.

The second half of the discussion focused on using the database to address challenges across interdisciplinary boundaries. Finally, the group discussed future uses of the database in addressing spatial variability of sea level, fingerprinting sources of ice melt, reconstructing paleo-shoreline changes, and integrating the database into glacial isostatic adjustment (GIA) models.

WARMCOASTS (Sea level and extreme waves in the Last Interglacial) is led by Alessio Rovere and funded by an ERC starting grant. The project focuses on the reconstruction of sea level and analysis of extreme waves during the Last Interglacial (LIG), approximately 125 kyr BP. Drawing on work by the HOLSEA group, the overarching goal of WARMCOASTS consists of advancing our current understanding of LIG sea-level changes and reducing uncertainties related to field evidence. The first phase of the project has begun with the development of a global, open-access database: the World Atlas of Last Interglacial Shorelines (WALIS). This provides a standardized template for scientists from around the world to make their published datasets available for other scientists to utilize. More information can be found on the WARMCOASTS website (warmcoasts.eu).

During the WARMCOASTS breakout session, the database development team introduced the data management user interface. Participants discussed questions regarding the logistics of programing and managing the database. The current development team is small in number but enthusiastic about wider collaboration. A central theme of the session was a debate regarding whether to include only raw data or also to provide a non-quantifiable description of the corresponding data point. It was agreed that while raw data itself should be the main focus of the database, a short description of geological context would prove to be invaluable for those using the data in the future.

This was the first of three foreseen PALSEA meetings during this phase, and was successful in leading to more cohesion within the sea-level science community, particularly as we utilize more "big data" approaches in the discipline. The next workshop in 2020 is planned to be held at Columbia University and will focus on the recent advancements in GIA and ice-sheet models and their contribution to our understanding of paleo shorelines.

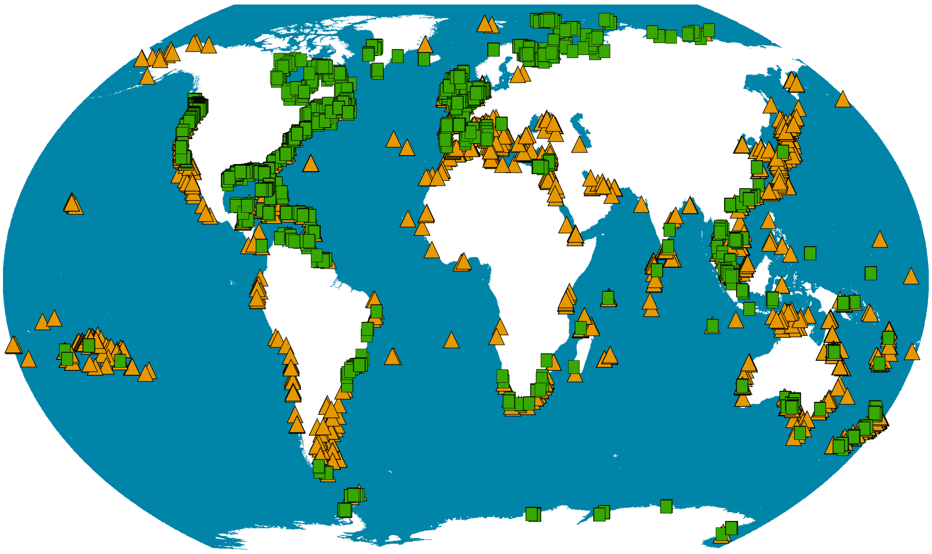

**Figure 1:** Overview of current paleo sea-level data within the HOLSEA (green squares) and WARMCOAST (orange triangles) databases. Initial work on the WARMCOAST database has been to combine data from previously published datasets as a foundation (Kopp et al. 2009; Pedoja et al. 2011; Hibbert et al. 2016).

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# Understanding glacial-interglacial changes in Southern Ocean sea ice

Matthew Chadwick[1,2], J. Jones[3], K.-A. Lawler[4], J. Prebble[5], K.E. Kohfeld[3] and X. Crosta[6]

### 2nd C-SIDE workshop, Sydney, Australia, 29 August–1 September 2019

The Cycles of Sea-Ice Dynamics in the Earth System working group (C-SIDE; pastglobalchanges.org/c-side) conducted its second three-day workshop which brought together 35 participants from 24 institutions in 12 countries. Following the success of the first workshop (doi.org/10.22498/pages.27.1.31), the C-SIDE working group used the second workshop to achieve three main objectives: (1) refine and further develop a Southern Ocean sea-ice database; (2) compile proxy records that best complement the sea-ice records; and (3) identify model simulations for comparisons with sea-ice data. To achieve these goals, the workshop attendees spent two days in three breakout groups dedicated to these objectives, with a final day to work on the planned workshop publications.

The first breakout group worked to refine the existing inventory of Southern Ocean sea-ice records for the last 130 kyr (initiated during Workshop 1 and coordinated by J. Jones and K. Kohfeld). The focus was now on refining the data categories and using the database to identify useful records for interrogating sea-ice changes across the full glacial cycle.

The second breakout group focused on identifying and compiling complementary proxy records in the Southern Ocean that would help to establish links between sea ice and circulation, productivity, and nutrient cycling. Sea-surface temperature proxies, stable isotopes ($\delta^{18}O$ and $\delta^{13}C$), ventilation proxies ($\varepsilon_{Nd}$, radiocarbon, bottom-water oxygenation), opal fluxes, nitrogen and silica isotopes, and IRD were all identified as the most useful complementary datasets. Sea-surface temperature proxies, stable isotopes, and opal fluxes are particularly promising due to the relative wealth of existing records.

The final breakout group aimed to identify model simulations that would be most helpful for comparisons with the sea-ice data. Participants identified the Last Glacial Maximum and the Last Interglacial as key intervals to be targeted because of upcoming simulations that are (or will be) part of the paleoclimate modeling projects PMIP3 and PMIP4.

Breakout discussions centred around making sure that data input followed a mutually understood, standard procedure. In particular, the group worked to clarify which data collection was ongoing, published, and unpublished. Ultimately, this allowed researchers to map regions and time periods that required better data coverage, higher resolution, and quality control. The collective work of participants resulted in a database that shows the wealth of both published and unpublished sea-ice records (Fig. 1), but an overall scarcity of records that cover the full glacial cycle and a dearth of sea-ice reconstructions for MIS 3 and 4 (Fig. 1). However, 10 sea-ice records that cover the entire 130 kyr were identified to produce a first interbasin comparison of sea-ice changes.

On the final day, attendees gathered to work on a publication strategy. A special issue of *Climate of the Past* was suggested for 2020, with a minimum of six papers outlined by the attendees and an invitation to the broader community to participate. The proposed publications included: (1) an overarching review paper outlining our understanding of sea-ice changes over the last glacial cycle; (2) a new sea-ice compilation examining sea-ice extent and duration in the three Southern Ocean sectors; (3) an LGM data-model comparison using PMIP3 simulations; (4) data-model comparisons for the Last Interglacial time period (127 kyr BP); (5) analyses of sea ice and complementary records; and (6) a paper comparing new carbon cycling and circulation modeling with sea-ice data. Appropriate authors for each of the papers were selected and timelines were constructed to create realistic publication outcomes.

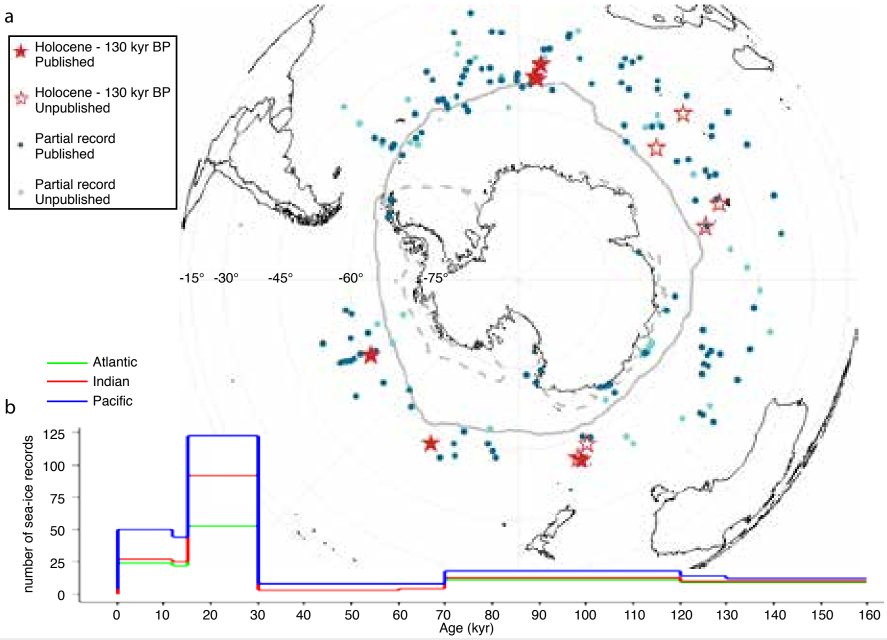

**Figure 1: (A)** Locations of sediment cores with published (filled stars, darker dots) and unpublished (open stars, lighter dots) Southern Ocean sea-ice records. Stars indicate cores covering the last 130 kyr. The 1981-2010 monthly median sea-ice extent is shown for February (dashed line) and September (solid line) (Fetterer et al. 2017). **(B)** Cumulative number of published sea-ice records vs time from the Atlantic (green), Indian (red), and Pacific (blue) sectors of the Southern Ocean.

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# Under the Southern Cross: 13th International Conference on Paleoceanography

Georgina Falster[1], L. Armbrecht[2] and L. Missiaen[3]

### Sydney, Australia, 2-6 September 2019

Paleoclimate records contain valuable information on long-term climate variability, providing important insights into possible future climate. Producing such records requires collaboration between researchers from many disciplines, including oceanography, climatology, physics, biology, chemistry, and geochronology. Every three years, researchers from these disciplines gather for the International Conference on Paleoceanography (ICP), to share new findings, present methodological advances, and discuss current challenges.

The 13th ICP (icp13.com.au) was held in September 2019 in Sydney, Australia, at the University of New South Wales, and was the first ICP to be held in the Southern Hemisphere. Over 430 delegates – including 140 students – from 31 different countries were warmly welcomed by the Bedegal People, the traditional custodians of this part of Australian country. Twenty-eight students and early-career researchers were awarded travel grants, including six grants awarded by PAGES.

The meeting followed the established ICP format of a small number of invited plenary speakers complemented by dedicated poster sessions. Presentations were grouped according to six main themes, covering new developments in proxies and models, the relationship of paleoclimate with biology and evolution, the carbon cycle, and ocean circulation, with a particular focus on Southern Ocean processes. The 30 plenary talks at ICP13 covered a broad range of topics, including the potential of new and established proxies, using novel numerical methods for improved paleoceanographic reconstructions, the importance of ice-ocean interactions and deep-time studies, and the challenge of bringing together information from proxy data and numerical simulations.

The breadth of paleoceanographic research being undertaken by the community was also reflected in the poster sessions, where approximately 400 posters covered spatial and temporal scales of investigation ranging from local to global, and from days to millions of years, respectively (Fig. 1). These poster sessions provided fertile ground for discussion of new research, which is a key tenet of the ICP.

Plenary talks and posters were supported by four perspective lectures and four special talks. The perspective presentations covered broader aspects of paleoceanography including atmospheric $CO_2$ variability on different timescales, new strategies for modeling complex marine ecosystems, the influence of climate on early human migration patterns, and the degree to which variability in climate proxy data accurately reflects variability in past climates. The special talks included a tribute to the pioneering work of the late Wally Broecker, a demystification of publishing in *Nature*, and highlights from two ongoing programs: the Australian and New Zealand International Ocean Discovery Program Consortium (ANZIC, iodp.org.au) and the global ocean trace elements program (GEOTRACES, geotraces.org). Throughout the conference, the outstanding quality of research being undertaken by early-career researchers was highlighted by plenary speakers frequently citing ECR contributions to the work being presented. Ten graduate students also earned awards for outstanding poster presentations.

The ICP traditionally encourages social interactions and development of new collaborations, and ICP13 was no exception. Wednesday's conference dinner was held aboard the "Starship Sydney", cruising the picturesque Sydney Harbour. Delegates enjoyed spectacular sunset views of the iconic Opera House and Harbour Bridge – a perfect backdrop for networking. The (in)famous "Paleomusicology" concert featured performances as diverse as the scientific presentations at ICP13, with styles ranging across classical, country, and comedy.

Official pre- and post-conference workshops included meetings of several PAGES working groups (C-SIDE, PAGES Early-Career Network, and CoralHydro2k), as well as the CROCCA2S post-cruise meeting, ICEPRO collaboration meeting, a DeepMIP meeting, and an IODP pre-proposal meeting, along with many unofficial side meetings during which delegates reinforced or built new collaborations within the paleoceanography community. Throughout the week, delegates actively promoted paleoceanography science using the #ICP13 tag on social media.

Many thanks to the ICP13 organizing committee and sponsors for such an inspiring meeting. Now it's time to look forward to the next ICP, which will be held in Bergen, Norway, from 28 August to 2 September 2022 – don't forget your umbrella! More information at info.icp14@iub.no.

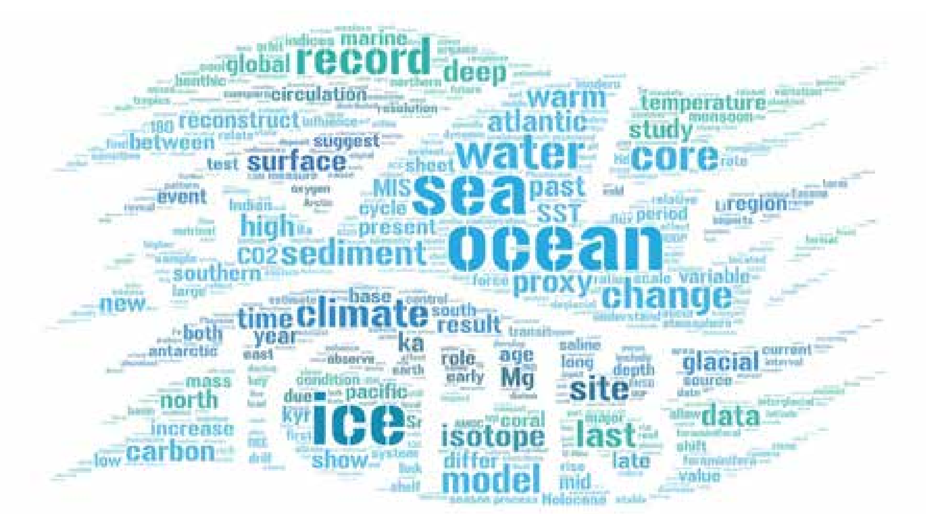

**Figure 1:** Word cloud created from all abstracts submitted to ICP13. The size of each word reflects the number of times it appears in the abstract book.

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# Toward community resources for paleoclimate data assimilation, reanalysis, and proxy system modeling

DAPS workshop participants*

2nd DAPS workshop, College Park, MD, USA, 29-31 May 2019

Friends and members of the Data Assimilation, Reanalysis and Proxy System Modeling (DAPS; pastglobalchanges.org/daps) working group came together for a brief meeting to discuss activities and progress since our first meeting in Louvaine-la-Neuve, Belgium, in May 2017.

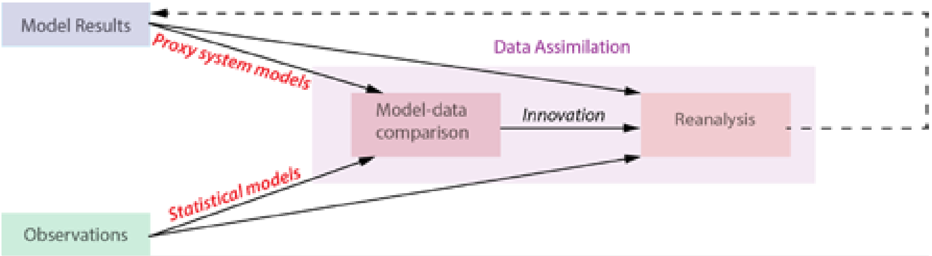

**Figure 1:** Schematic representation of the procedure leading to a reanalysis (i.e. a reconstruction of the state of a system) using data assimilation (modified from Goosse 2016). Reproduced from the PAGES/DAPS website (pastglobalchanges.org/daps).

## Data assimilation for paleoenvironmental reconstruction: methods intercomparison

Operational systems for weather to seasonal forecasting are now modular and open platforms, allowing for automated quality control, rejection of nonconforming observations, assessment of stochastic parameterizations, uniform multivariate skill assessment, and assessment of novel approaches such as use of future forecasts (see schematic Fig. 1). By comparison with the methods used in the DAPS Data Assimilation Intercomparison Project (DAIP), we identified similarities and differences between operational online data assimilation (DA) for weather and seasonal forecasting, and offline assimilation, optimal interpolation and linear regression/transfer function approaches to paleoclimatic reconstruction (Hakim et al. 2016; Franke et al. 2017). A key question, even for offline or time-independent formulations, is whether and how to incorporate information at local versus remote scales in space. Can we trust the remote information, and at what level of filtering? Conversely, do we trust the local information? The answers likely depend on multiple approaches to skill estimation and validation of the results, at the process, data and parameter levels. Under some conditions, temporally aware data assimilation might improve results – processes for which timescales of variation are much longer than the timescales resolved by observations. For the present generation of paleo DA, this condition has not yet been met, but might be in the future, for analysis of variations associated with the intermediate and deep ocean, deep soil moisture, vegetation, and the cryosphere. These long timescales are at the heart of what might be gained from the exercise: identifying processes consistent with the observational evidence given uncertainties in all elements.

## Proxy system modeling: spatial and structural considerations

We reviewed results from two Data Model Intercomparison projects (DMIP) across sensors, archives, and model complexity. Applying a bivariate linear model across marine carbonate archives identifies discrepancies between simulated and observed variance, which may be due to complex and variable growth responses. Limited validated information was retrieved from complex and nonlinear proxy system models producing tree-ring width simulations, and arose from modeling observations as bivariate indicators of both temperature and moisture variation, and under slowly changing mean climate states. However, conclusions might be sensitive to limitation by observational target and uncertainty, parameter estimation, timescale, and evaluation metrics. For more complex processes and targets, more complex models might outperform simpler ones, but require additional inputs and parameters to be specified. At present, bivariate linear regression-based PSMs may be a good point of reference and null hypothesis on PSM complexity sufficient for use in paleo reanalysis products (Zhu et al. 2019a). Advances in unified platforms for proxy system modeling and evaluation, and for exploiting digitized paleodata and metadata via the Linked Paleo Data (LiPD; lipd.net) format (Dee et al. 2015; Zhu et al. 2019b) will enable more comprehensive studies and advances in the use of PSMs in paleoclimatic data assimilation exercises.

## Products and next steps

An overarching theme that emerged from our discussions, fueled by nearly intravenous espresso and homemade food, was that a common, open platform for development and assessment of approaches to paleoenvironmental data assimilation, reanalysis and proxy system modeling is sorely needed. As a result of a concentrated working session, such a community platform is being constructed (daps-pages.github.io) as a basis for ongoing work, and papers synthesizing DAIP, DMIP and challenges/outlook are developing. However, DAPS was founded as a three-year project, and will sunset in 2019 – unless new leadership proposes a second phase! If you are interested in picking up on the themes and initiatives described here, please contact the group leaders (pastglobalchanges.org/science/wg/daps/people) for more information and suggestions for doing so.

### ACKNOWLEDGEMENTS

M.N. Evans would like to thank the organizers of the PAGES2k-PMIP3 Workshop, Madrid, 2013, which produced such a vigorous and productive discussion of the questions arising from comparing paleodata and climate simulations; and which inspired our personalized DAPS nametags. Funding for ECR travel and accommodation was provided by PAGES; and for an outreach event (science.umd.edu/events/scienceontap-2019-05.html), meeting space and refreshments by the University of Maryland, College Park, College of Mathematical and Natural Sciences, Earth System Science Interdisciplinary Center, Geology and Atmospheric and Oceanic Sciences Departments, and Reena Gupta.

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# Climatic modes of variability over the Holocene: Model-data synergies to improve future projections

Armand Hernández[1], B. Martrat[2], L. Comas-Bru[3], C. Martin-Puertas[4], P. Moffa-Sánchez[5], E. Moreno-Chamarro[6], P. Ortega[6] and D. Swingedouw[7]

### Barcelona, Spain, 25-27 September 2019

The spatial structure of climate variability follows recurrent patterns, often referred to as modes of climate variability. The modes are suitable tools for understanding regional climate patterns on different spatio-temporal scales, which are in turn closely related to energy production, food security, and key ecosystem services like oceanic and terrestrial $CO_2$ uptake and water availability (e.g. Jerez et al. 2013; Bastos et al. 2016; Zubiate et al. 2017). It is thus essential to improve our understanding of the evolution of climate modes of variability and their interactions at a global scale during the current interglacial period (i.e. the Holocene, covering the past 11,700 years). This is crucial to: (i) understand the potential variability of these modes and estimate their response to external forcing at the wide range of temporal scales, and (ii) evaluate the ability of different climate models to reproduce them robustly, given that identifying the most reliable simulations narrows down uncertainty in future near-term fluctuations in climate and associated hazards.

For three days, 25 participants – including seven early-career researchers – from 11 countries of four continents shared their expertise in the research field of modes of variability during the first joint workshop of CLIMOVAR (CLImatic MOdes of VARiability) and IBCC-lo2k (IBerian Climate Change paleoarchive – synthesis and stewardship of land-ocean data, taking the past 2000 years as a reference). CLIMOVAR, emphasizing the atmospheric/oceanic dimension of the climate modes, aligns well with the IBCC-lo2k initiative, which synthesizes and preserves the climate measurements of the past, integrating land and ocean data of the Iberian region. In this sense, the meeting provided a unique opportunity to explore synergies between paleoclimatologists using natural proxy archives, paleoclimate modelers, and statisticians, in order to better evaluate prevailing atmospheric and oceanic circulation modes on interannual-to-centennial timescales.

The CLIMOVAR/IBCC-lo2k team discussed five main topics of broad interest to the community: (i) describing climate modes of variability during the Holocene; (ii) bridging the gaps between models and climate proxy records; (iii) deciphering the role of external forcing on climate modes of variability; (iv) evaluating the impacts of climate modes of variability; and (v) assessing potential synergies with existing PAGES working groups. All topical sessions included short talks for participants to present their work and subsequent exciting discussions. Moreover, two keynote talks, discussion panels, and an outreach event (Fig. 1) completed the large variety of individual contributions.

The workshop allowed us to highlight that modes of variability are different from mean-state changes, so that it is necessary to first define a mean state for a given period before correctly defining variability modes. The general consensus was to apply for a new PAGES working group with the following specific goals: (i) focus on the Holocene time windows also covered by modeling initiatives like the Paleoclimate Modelling Intercomparison Project (PMIP4); (ii) use pseudo-proxies from models to test whether it is possible to reliably reconstruct modes of variability during the selected Holocene time windows with the available proxy data and produce the actual reconstructions that are validated by the models; (iii) screen existing databases to find high-quality records necessary to reconstruct variability modes using state-of-the-art statistical approaches, including machine learning methods; (iv) evaluate the capacity of climate models to simulate changes in climatic modes of variability in response to variations in external forcing; (v) strengthen links with current working groups; and (vi) expand the group to include researchers from a variety of communities (e.g. wide regional representation, experts in each mode and key period) related to the study of modes of variability. We also agreed that the edition of a special issue based on modes of climate variability would be one of the main outputs of the working group.

The workshop also included an outreach activity at CosmoCaixa (Barcelona Science Museum) to engage secondary school students in climate change (Fig. 1). A video, entitled "Climate Change: the FAQs" (youtube.com/watch?v=I-2wR9zx7Rg), was officially released during this event. The video was created by some of the co-organizers of the workshop with the aim of answering the most common questions about climate change posed by young students. A total of 180 attendees had the opportunity to watch the video and ask additional questions during a round-table discussion with a Catalonian government representative, two science communicators, a climate-change activist, and two climatologists, all of whom work on different aspects of climate change.

**Figure 1:** Armand Hernández, leader of the workshop organizing team, presents the video "Climate Change: the FAQs" to the outreach event audience (comprised primarily of secondary school students) at the end of the CLIMOVAR meeting. Photo credit: Jordi Cortés.

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# Paleoscience symposium: Paleoclimates and paleoenvironments

Asfawossen Asrat

**Addis Ababa, Ethiopia, 28 March 2019**

PAGES' 2019 Scientific Steering Committee (SSC; pastglobalchanges.org/about/structure/scientific-steering-committee) and Executive Committee meetings were held from 25-27 March 2019 in Addis Ababa, Ethiopia, hosted by the School of Earth Sciences of Addis Ababa University. Following the meetings, a one-day symposium on paleoclimates and paleoenvironments was held at the College of Natural and Computational Sciences of Addis Ababa University. Finally, SSC members participated in a two-day field excursion to the Main Ethiopian Rift from 29-30 March 2019.

The symposium (pastglobalchanges.org/calendar/2019/127-pages/1930) was co-organized and hosted by the African Center of Excellence for Water Management (ACEWM) and well attended by ~100 participants including PAGES SSC members, staff members of the College, early-career researchers, and postgraduate students of ACEWM (from Ethiopia, Malawi, Rwanda, Tanzania and Uganda). The symposium featured 11 talks followed by very interactive discussions.

To start the symposium, ACEWM Director Feleke Zewge introduced the center, which is an initiative of the Government of Ethiopia and the World Bank Group. It was established to address the water challenges in Africa with a focus on eastern and southern African countries, with a particular focus on training a critical mass of Africans through short-term training and MSc/PhD degree programs as a means to address national and regional water development needs using a holistic, integrative and transformative approach.

The subsequent three talks introduced Future Earth (Hannah Moersberger), PAGES (Marie-France Loutre) and the PAGES Early-Career Network (Stella Alexandroff; Fig. 1). These talks, besides highlighting the major features and objectives of the respective networks, emphasized the need for African researchers to be actively involved in the associated initiatives and activities, and indicated some possible avenues for such involvement. These talks prompted an extended discussion on the challenges African researchers, and particularly early-career researchers, face in their endeavors to network and collaborate with research initiatives and groups in other parts of the world.

The ensuing presentations by SSC members focused on paleoclimatic and paleoenvironmental studies from various parts of the world. These included an overview of recent products and progress of the PAGES 2k Network focusing on Africa2k (Mike Evans), reliability of future climate model predictions with particular emphasis on the challenges of modeling the hydrological cycle in North Africa (Paul Valdes), past perspectives on tipping elements in the Atlantic Ocean and South America (Cristiano Chiessi), and the use of paleoecology in exploring ecosystem resilience at biome boundaries in southern Africa (Lindsey Gillson). The afternoon session featured some examples of paleoclimatic and paleoenvironmental research in Ethiopia, particularly on speleothem paleoclimatology (Asfawossen Asrat) and paleoecology and tree-ring paleoclimatology (Zewdu Eshetu), as well as the impacts of climate change on the future of coffee farming in Ethiopia (Sebsebe Demissew).

The presentations piqued the interest of many of the postgraduate students who raised several interesting and challenging questions, making the sessions truly interactive. The sessions, as well as the coffee breaks, helped postgraduate students and early-career researchers to freely interact with SSC members. The symposium successfully achieved its objectives of providing targeted information about Future Earth, PAGES and the PAGES Early-Career Network and aroused the interest of many young African researchers who plan to champion the causes of these networks and initiatives. At the same time, the symposium helped these young Africans interact, discuss and network with prominent paleoscientists from various parts of the world, and explore possible avenues of collaboration.

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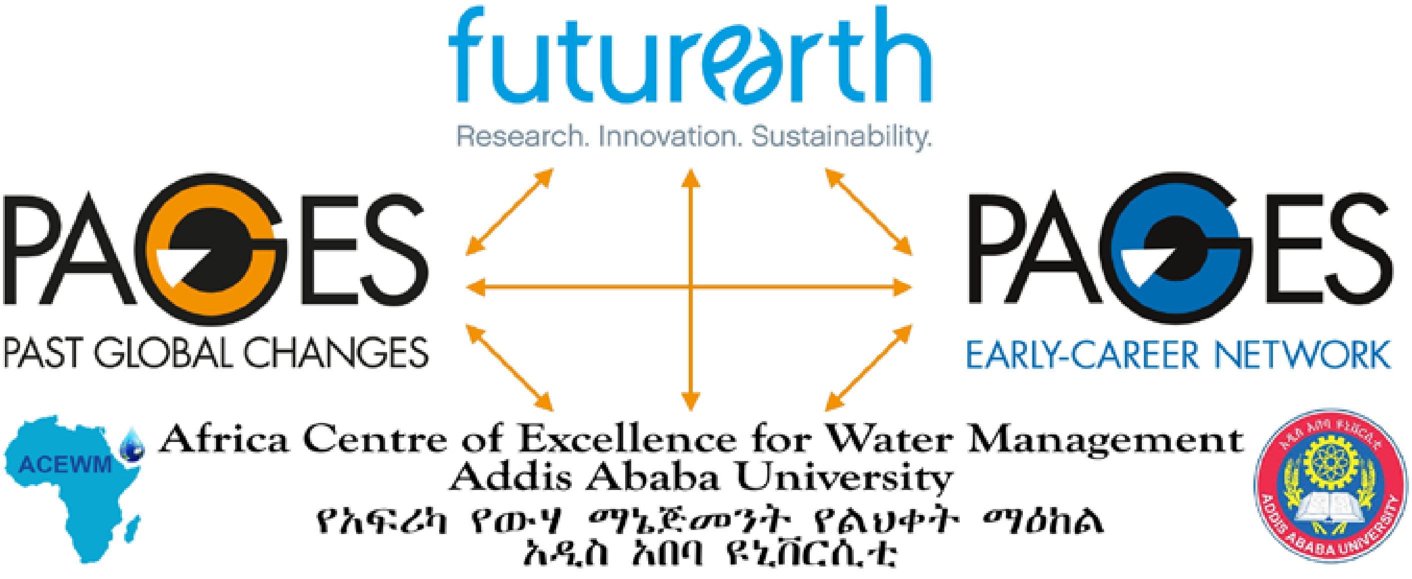

**Figure 1:** Symposium speakers included representatives of Future Earth, The PAGES Early-Career Network, the Africa Centre of Excellence for Water Management, Addis Ababa University and PAGES SSC members.

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# Demystifying the grant writing process for early-career paleoscientists

Phoebe Tsz-Wai Chan[1] and Víctor Merino-Campos[2]

**1st PAGES Early-Career Network workshop, Prague, Czech Republic, 26-29 May 2019**

For the first time in its (young) history, the PAGES Early-Career Network (ECN; pastglobalchanges.org/ecn) organized a workshop for early-career researchers (ECRs) who are or will be looking for funding in science in the near future. The main goals of this workshop, titled "Funding starts here" (pastglobalchanges.org/calendar/2019/127-pages/1908), were to:

- introduce ECRs to the different funding agencies and opportunities available in Europe and the United States
- provide a framework for understanding the grant-writing process – from writing to submission and review – based on strategies and advice given by invited speakers (see Fig. 1)

The workshop was centered around five invited speakers who have either had experience as an applicant and/or served on the evaluation panel of different funding agencies (e.g. the European Research Council (ERC), Horizon 2020, Marie Skłodowska-Curie actions and the US National Science Foundation (NSF)).

Grant writing is central to launching, advancing, and maintaining careers in academia. However, the grant-writing process is long and arduous, often taking several attempts before success is achieved. As Chung et al. (2008) pointed out, fewer and fewer proposals are being funded even though more applications are being submitted each year. This means that there is increased pressure to excel at writing grant proposals. Therefore, having the opportunity to receive advice from experienced professionals can greatly improve our chances of achieving our research goals.

The workshop kicked off with an ice-breaker dinner at a local restaurant offering traditional Czech cuisine, where we had the opportunity to meet and mingle with fellow ECRs. The next morning, we were welcomed by the PAGES ECN organizing committee, followed by an introduction to the main components of a research grant proposal by the first invited speaker, Petr Kuneš. Petr explained what should be considered when writing the different parts of a proposal, along with some practical tips for grant writing. Special emphasis was placed on having ambitious yet concrete and achievable goals. The next speaker, Jonas Bunikis, offered tips and advice for applying to the ERC and highlighted best practices as well as common mistakes in the application process. Later, Alessio Rovere shared an inspirational story about his ERC starting-grant success and provided a very real look at what it takes to be successful in writing ERC starting grants.

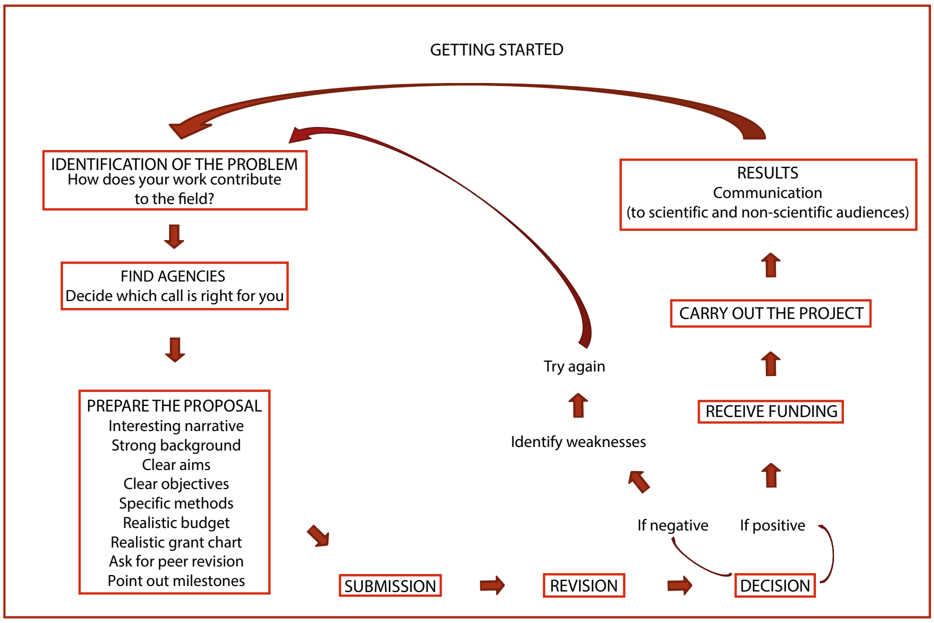

**Figure 1:** Funding cycle summarizing the steps of the grant-writing process based on the main learnings from the workshop. Advice is pointed out at different stages of the cycle.

On the second day, Jana Čejková introduced opportunities and eligibility requirements within the Horizon 2020 and Marie Skłodowska-Curie actions programs, while Maria Uhle described the structure of the US NSF funding system, with a particular focus on the opportunities available to ECRs in the paleosciences. During the workshop, participants also had the opportunity to work together and apply their newfound knowledge in the development of a three-year research project of their own design. On the last day, participants presented their group's research ideas, following the previously outlined components of a research proposal, which was then assessed with feedback from peers and the expert panelists.

The PAGES ECN "Funding starts here" grant-writing workshop provided valuable information for PhD students and researchers in the early stages of their careers. It introduced them to opportunities available in Europe and North America, answered vital questions about the grant-writing and evaluation processes, and gave participants hands-on experience in developing a research proposal. The meeting resulted in a special interdisciplinary and cultural exchange, where young researchers from different nationalities came together to learn and share knowledge and experiences. We are thankful to have been a part of this experience!

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