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PAST GLOBAL CHANGES
MAGAZINE

PALEO CONSTRAINTS ON SEA-LEVEL RISE

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PAGES

futurearth

News

PALSEA working group news
This issue of *Past Global Changes Magazine* has been guest edited by leaders of the third phase of the highly successful PALeo constraints on SEA level rise (PALSEA) working group. PALSEA is a PAGES working group and also an international focus group of the Coastal and Marine Processes commission in the International Union for Quaternary Research (INQUA). Although they may have handed over the reins in January this year, the group's Phase 2 leaders have also been very active, with a special issue of *Quaternary Science Reviews*, titled "PALeo constraints on SEA level rise (PALSEA): Ice-sheet and sea-level responses to past climate warming" completed in April 2019. Access all 12 articles here: pastglobalchanges.org/products/special-issues/12491-palsea-special-issue-qsr

PAGES SSC and EXCOM news
The annual SSC Meeting was held in Addis Ababa, Ethiopia, from 25-31 March 2019. The group gathers to discuss finances, current working groups, potential new working groups, workshop support applications, SSC membership, and many other important items which guide the PAGES project. For the first time, a member of PAGES Early-Career Network Steering Committee also joined. Stella Alexandroff presented the network's plans and made a valuable contribution to the proceedings. An ECN representative will be invited to all future SSC Meetings.
Following the meeting, SSC members and local presenters were joined by approximately 100 students at a one-day paleoscience symposium held at Addis Ababa University. Thanks to our SSC member Asfawossen Asrat, from the university's College of Natural Sciences, for organizing this successful symposium.

Working group news
At the end of 2018, several working groups officially came to an end. Aquatic Transitions, Dust Impact on Climate and Environment (DICE), Global Soil and Sediment transfers in the Anthropocene (GloSS) and Pliocene climate variability over glacial-interglacial timescales (PlioVAR) wrapped up their activities. The Warmer Worlds Integrative Activity also finished. Find all former initiatives here: pastglobalchanges.org/ini/wg/former/intro

A new working group, Arctic Cryosphere Change and Coastal Marine Ecosystems (ACME), will be active in the coming months. The aim of this working group is to assess and refine current available marine proxies that can be used to reconstruct cryosphere changes and their ecosystem impacts. All details on how to be involved will soon be available on PAGES' website.

New Science Officer and Finance and Office Manager
PAGES' International Project Office in Bern recently welcomed two new staff members. Sarah Eggleston replaced Lucien von Gunten as Science Officer and Alexandra Gerber replaced Brigitte Schneiter as Finance and Office Manager. Their contact details can be found here: pastglobalchanges.org/about/structure/international-project-office

PAGES at INQUA 2019
Have you seen the extensive list of PAGES sessions at the 20th INQUA Congress to be held from 25-31 July 2019 in Dublin, Ireland? Working groups and SSC members are well represented: pastglobalchanges.org/calendar/upcoming/127-pages/1778-inqua-congress-19

Plus, PAGES' Executive Director Marie-France Loutre will be awarded the INQUA Distinguished Service Medal for her record of sustained and outstanding contributions to the maintenance or development of INQUA's important functions such as organization, operations, outputs, or publicity: pastglobalchanges.org/news/all-news-items/9-latest-news/2217-mfl-inqua-medal-19

PAGES Early-Career Network (ECN)
Since launching in February 2018, the ECN has been busy rallying early-career paleoscientists through a variety of initiatives – webinars, newsletters, regional representation and The Early Pages blog. Read on and join! pastglobalchanges.org/ecn

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

Upcoming issue of *Past Global Changes Magazine*
Our next magazine will be guest edited by members of PAGES' Ocean Circulation and Carbon Cycling (OC3) working group and members of the broader paleoceanographic community. Although preparations are well underway, if you would like to contribute, please contact the IPO: pages@pages.unibe.ch

Calendar

QUIGS workshop: Warm extremes
1-4 July 2019 - Cambridge, UK

PALSEA workshop: Proxy-based paleo sea-level
21-23 July 2019 – Dublin, Ireland

C-SIDE 2nd workshop: Sea-ice database
29-31 August 2019 - Sydney, Australia

LandCover6k workshop: S and SE Asia
11-15 September 2019 – Pondicherry, India

CRIAS 2nd workshop
7-8 October 2019 - Leipzig, Germany

SISAL 4th workshop: SISALv2 database
14-17 October 2019 - Xi'an, Shaanxi, China

pastglobalchanges.org/calendar

Featured products

2k Network
Cody Routson et al. used the 2017 PAGES 2k paleotemperature dataset to show that Arctic warming is associated with drying over the mid-latitudes of the NH. (2019, *Nature* 568)

SISAL
Franziska Lechleitner et al. investigate how representative the spatial and temporal distribution of the available records is for climate in Western Europe and review potential sites and strategies for future studies. (2018, *Quaternary* 1)

VICS
Matthew Toohey et al. use ice-core-derived volcanic stratospheric sulfur injections and NH summer temperature reconstructions to show that, in proportion to their estimated stratospheric sulfur injection, extratropical explosive eruptions since 750 CE have led to stronger hemispheric cooling than tropical eruptions. (2019, *Nat Geosci* 12)

Book volume
A 535-page book volume on possible links between social upheaval, resource utilization, and environmental forces along the Silk Road in China emerged from the PAGES-supported workshop "The Rise and Fall: Environmental Factors in the Socio-Cultural Changes of the Ancient Silk Road Area" (2019, Springer, ISBN 978-3-030-00728-7)

Special issue
The 228-page special issue "Central and Eastern Europe Paleoscience: From Local to Continental Perspective" is an output of the PAGES-supported "Central and Eastern Europe Paleoscience Symposium: From Local to Global" held in May 2016. (2019, *Quat Int* 504)

Cover

The marine terminus of Nigerdlikasik Bræ of the southern Greenland ice sheet near the town of Paamiut. The Greenland ice sheet retreated to within this extent about 10,600 years ago (Carlson et al. 2014). This ice margin retreated about 100 m in the summer of 2009 and will soon become, if it is not already, a land-terminating ice margin (last Google Earth image is from summer 2011; this photo was taken in the summer of 2010).
Photo credit: Dr. Kelsey Winsor, University of Wisconsin-Madison, USA; now at Northern Arizona University, USA.

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A decade of PALSEA: Advances and future aims

Natasha L.M. Barlow[1], G.A. Milne[2] and J.D. Shakun[3]

In 2019, the PAGES and INQUA-CMP (inqua.org/commissions/cmp) working group PALeo constraints on SEA level rise (PALSEA) entered its third phase. Established in 2008 by Mark Siddall and colleagues (Siddall et al. 2009), the second phase of PALSEA (PALSEA2, 2013-2017) was led by Anders Carlson, Andrea Dutton, Antony Long and Glenn Milne. The group continued the successful approach of bringing together observational and modeling scientists focusing on ice-sheet, climate and sea-level change to better define constraints on ice-sheet-driven paleo sea-level rise and apply this knowledge to inform projections of future change. Increased dialogue between these, and broader, communities over the past 10 years of PALSEA have resulted in over 100 peer-reviewed publications tackling societally important questions as to the drivers of ice-sheet and sea-level change. The consequences have been far-reaching, with a key indicator being the significant paleo sea-level and ice-sheet components included in the IPCC AR5 report (Church et al. 2013; Masson-Delmotte et al. 2013), and several members of the PALSEA community currently working as authors of the IPCC AR6 report.

One standout contribution of the PALSEA working group has been the considerable progress made by the observational community to agree on best practice for methods to reconstruct the elevation of former sea levels (Khan et al. p. 10). This has resulted in the production of a standardized sea-level database protocol (Düsterhus et al. 2016; Khan et al. p. 10) and a growing number of high-quality regional and global databases for different time periods (Miller et al. p. 4; Dutton and Barlow, p. 6; Barnett et al. p. 8; Khan et al. p. 10) that provide the foundation for empirical and process-based modeling studies which aim to identify the underlying driving mechanisms across a range of temporal and spatial scales.

Research stimulated by PALSEA has identified processes that complicate estimates of global mean sea level (GMSL), and thus ice volume, from a geographically distributed set of local releative sea level (RSL) reconstructions. This has led to ongoing efforts to improve our understanding and ability to more accurately model processes such as glacial isostatic adjustment (Milne et al. p. 16), mantle dynamic topography (Austermann and Forte, p. 18), sediment flux and associated loading (Ferrier et al. p. 24), and overprinting records of extreme storm or wave events (Engelhart et al. p. 26). As these models improve, so too will estimates of global ice volume during past warm periods, providing a target and stimulus for the data and modeling communities to determine the minimum extent of the Greenland and Antarctic ice sheets and thus the climate drivers of sea-level rise during key intervals of Earth's history (Carlson and Larsen. p. 12; Sime et al. p. 14; de Boer et al. p. 20; Otto-Bliesner et al. p. 22).

Late Holocene RSL research (Barnett et al. p. 8) has shown that an ability to constrain rates of sea-level change can provide important insights into drivers, synchronicity, and feedbacks in the coupled Earth system. However, prior to the radiocarbon dating window (ca. >40 kyr BP), establishing rates of both ice-sheet and sea-level change continues to be a challenge (Miller et al. p. 4; Dutton and Barlow, p. 6). While community efforts to better quantify GMSL have been successful, constraining rates of change during past warm periods remains an elusive target (Fig. 1), but a critical one to more effectively use paleo observations in future projections (Horton et al. p. 28). The spatial aspect of the problem has also been brought to the fore though PALSEA activities. Sea-level change is not globally uniform and so there is now a clear shift towards developing and understanding regional sea-level changes and relating these to GMSL.

The new phase of PALSEA, led by researchers who have benefited from the PALSEA network as early-career scientists (Jacqueline Austermann, Natasha Barlow, Alessio Rovere and Jeremy Shakun), seeks to build on past success and focus efforts on moving towards some of the outstanding goals outlined above. As the contemporary system exhibits accelerated and potentially irreversible changes (e.g. Shepherd et al. 2018), the relevance of the paleo record, which contains information on such responses in the past, becomes even more critical (Horton et al. p. 28). This *Past Global Changes Magazine* brings together contributions that summarize the state-of-the-science following the last decade of investigation and collaboration, as well as provide a stimulus into critical areas of research for PALSEA and the wider community.

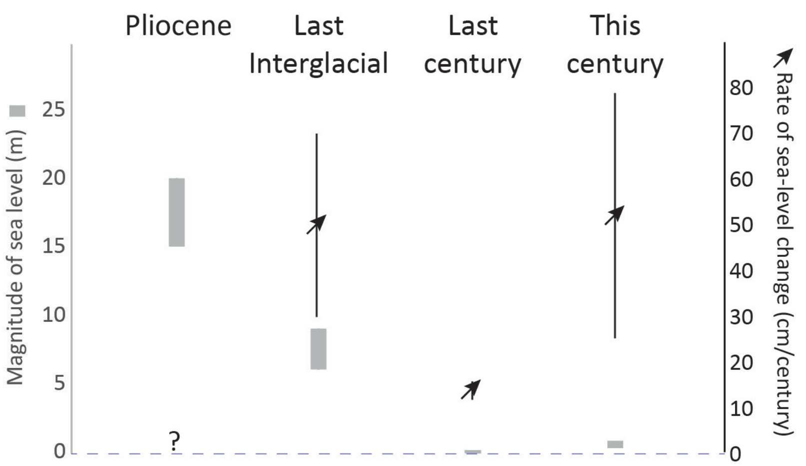

Figure 1: Summary of the magnitude of GMSL highstand during the Pliocene (Miller et al. p. 4), the Last Interglacial (Dutton and Barlow, p. 6; Dutton et al. 2015) relative to present, the last century relative to pre-industrial (1900 CE; Barnett et al. p.8; Kopp et al. 2016) values, and this century relative to the year 2000 (Church et al. 2013). The rate of GMSL change during the Pliocene is not well constrained; LIG estimate based upon the "likely" range of 3-7 m/kyr from Kopp et al. (2013); rate for the last century based upon the year 1900-2000 rate from Kopp et al. (2016); and the rate for this century based upon the average rates of GMSL rise for the 21st century using the projected rise for the period 1986-2005 to 2081-2100 as given in Table 13.5 of Church et al. (2013) using the "likely" ranges for RCPs 2.6 and 8.5 (specifically, the lower bound for RCP 2.6 and upper bound for RCP 8.5).

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Peak sea level during the warm Pliocene: Errors, limitations, and constraints

Kenneth G. Miller[1], M.E. Raymo[2], J.V. Browning[1], Y. Rosenthal[1] and J.D. Wright[1]

Re-evaluation of Pliocene sea levels indicates large errors (up to ±15 m), precluding firm estimates. Sea level appears to have peaked at ~10-20 m above present, consistent with some ice loss from the East Antarctic ice sheet (EAIS) as suggested by models and Antarctic sediments. More accurate estimates of Pliocene peak sea level require improved modeling techniques and proxy evaluation.

The Pliocene recorded a period of global warmth and high sea level that can provide constraints on relationships among global climate, atmospheric CO_2, and sea-level changes (Raymo et al. 2009, 2011; Miller et al. 2012). Global surface temperatures during the most recent period of Pliocene warmth at ca. 3 Ma were 2–3°C warmer than the 20th century (Dowsett et al. 2013). Pliocene atmospheric CO_2 estimates of 400±25 ppmv (e.g. Bartoli et al. 2011) are similar to those observed today.

Published estimates of the peak Pliocene sea level span a wide range, though a peak of 25 m is often cited (e.g. Dowsett et al. 2013). Miller et al. (2012) estimated a peak of 22±10 m by comparing continental margin (Wanganui Basin, New Zealand; VA, USA), atoll (Enewetak), and deep-sea benthic foraminiferal $\delta^{18}O$ ($\delta^{18}O_{benthic}$) and Mg/Ca records. More recent work has shown that much of the variance among continental records can be attributed to regional changes in mantle dynamic topography (MDT) and glacial isostatic adjustment (GIA) (e.g. Raymo et al. 2011) and that estimates derived from continental sections have large errors of ±10 m or larger due to these effects (Rovere et al. 2014). Deep-sea $\delta^{18}O_{benthic}$ and Mg/Ca records potentially provide a means of independently estimating ice volume, and hence global mean sea level (GMSL) variations. For example, Woodard et al. (2014) used $\delta^{18}O_{benthic}$ and Mg/Ca records to provide estimates of the Pliocene peak of 21±10 m. However, Raymo et al. (2018) provided extensive discussion of errors on $\delta^{18}O_{benthic}$-Mg/Ca method, showing that they are potentially quite large (±15 m or larger) due to diagenesis and changing ocean chemistry over millions of years. These are critical areas for future study and advancement.

Measuring sea level relative to the continents

Continental margins contain a record of over a billion years of sea-level change, though the water depth changes observed as transgressions and regressions reflect many processes including GMSL (eustasy), subsidence/uplift (including MDT), and sediment input/loading. "Backstripping" is a method that progressively removes the effects of compaction, loading, and thermal subsidence from water-depth changes, with the residual reflecting the effects of GMSL and non-thermal tectonism (e.g. Kominz et al. 2016), including changes in MDT.

Using the backstripping technique, it is possible to quantify Pliocene differential movement between Virginia (VA) and New Jersey (NJ; Fig. 1). Both records are similar in the Miocene until ~7.5 Myr BP when a hiatus is observed in NJ cores. Backstripping of water depth variations suggests at least ~20 m of differential movement between VA and NJ (Fig. 1). We attribute the difference between VA and NJ to MDT, as suggested by modeling by Rowley et al. (2013). In the absence of other datasets, it would be impossible to tell if VA subsided or if NJ was uplifted (Fig. 1), calling into question the estimates of 17±10 m obtained from the VA records (e.g. Miller et al. 2012).

A new $\delta^{18}O$-Mg/Ca based sea-level record

Previous Pliocene studies used $\delta^{18}O$ as a sea-level proxy and relied on the Lisiecki and Raymo (2005; hereafter LR04) benthic foraminiferal $\delta^{18}O$ stack (Miller et al. 2011) or Atlantic $\delta^{18}O$ and Mg/Ca records overprinted by North Atlantic circulation effects (e.g. Woodard et al. 2014). The LR04 stack incorporates Atlantic and Pacific records though it is weighted toward Atlantic records. LR04 provides a pristine chronology, but like any stack, it shows a reduction in the amplitude of $\delta^{18}O_{benthic}$ signal caused by combining records.

Pacific $\delta^{18}O_{benthic}$ changes reflect variations in deep-water temperature and $\delta^{18}O_{seawater}$; they are less affected by regional circulation and other changes because the Pacific comprises 60% of the global ocean reservoir. Differences in Pacific $\delta^{18}O_{benthic}$ values between the peak Pliocene values and modern values provide a constraint on high sea-level estimates. The relatively minor difference in $\delta^{18}O_{benthic}$ between the modern and Pliocene in the LR04 stack may possibly be attributed to various biases and not accurately scale to the difference in ice volume (Raymo et al. 2018). Still, Pacific $\delta^{18}O_{benthic}$ values can place

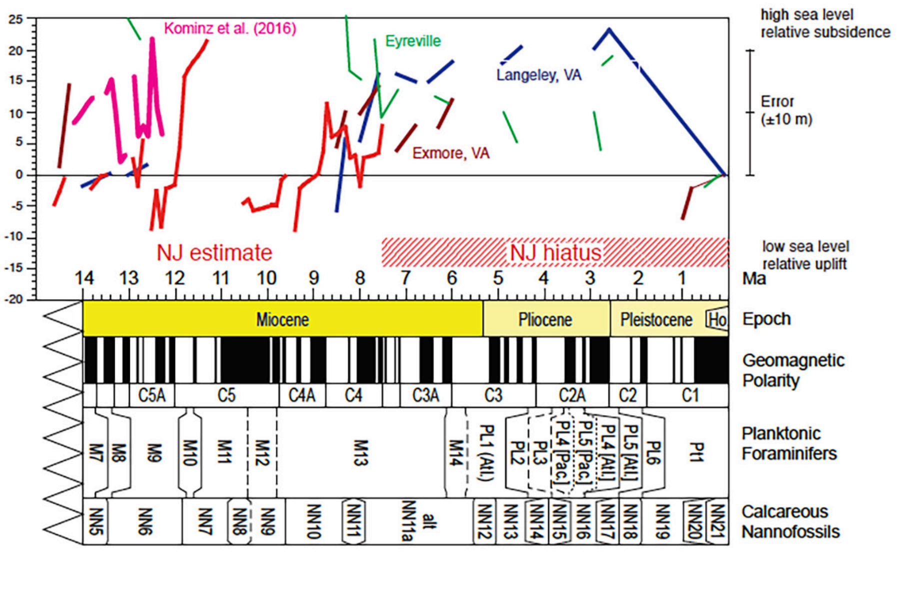

Figure 1: Relative sea level from the US east coast. This figure illustrates differential movement between VA and NJ during the Late Miocene to Pliocene due to MDT as modeled by Rowley et al. (2013). Shown are NJ backstripped estimates (red = Miller et al. 2005; magenta = Kominz et al. 2016), and VA estimates (blue = Langley, purple = Exmore, both after Hayden et al. 2008; green = Exmore after Miller et al. 2012). The marine Miocene section in NJ is replaced by Pliocene upland gravels in outcrop deposited above sea level indicating relative uplift in NJ.

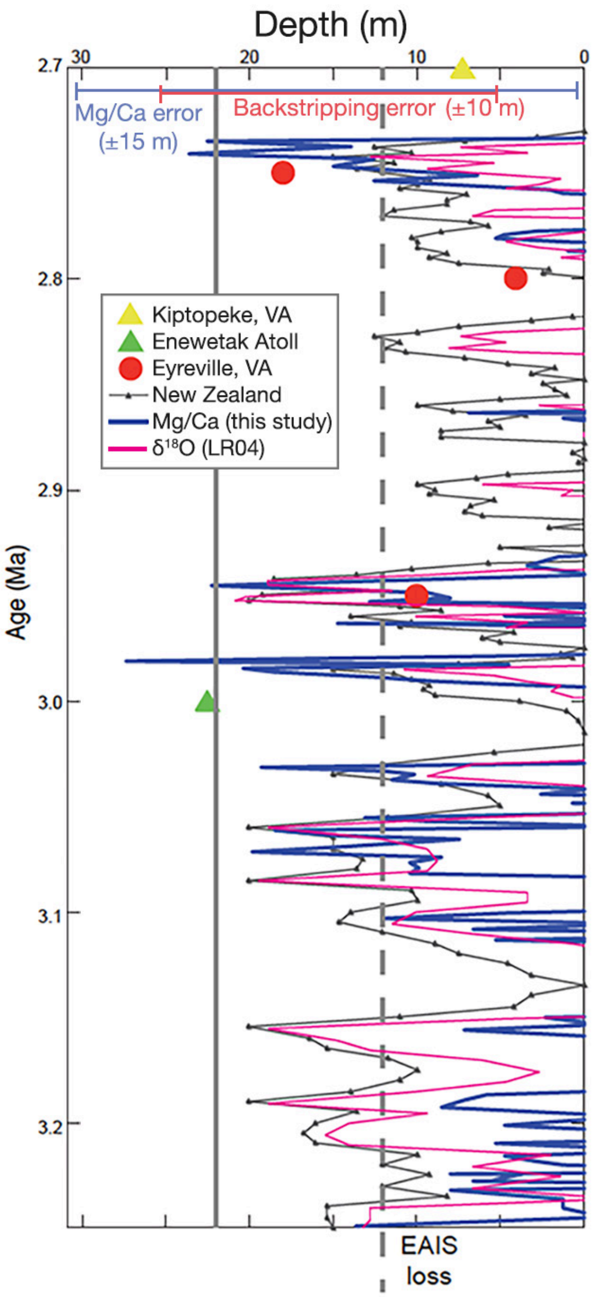

Figure 2: $\delta^{18}O$-Mg/Ca based sea-level estimate updated from Miller et al. (2012). Map shows Exmore (E), Kiptopeke (K) and Langley (L) coreholes and Wanganui Basin (W). Sea levels to the left of the dashed vertical line suggest some melting of the EIAS.

constraints on sea level during the mid-Pliocene warm extremes.

Here, we use the best-resolved Pacific benthic foraminiferal (Uvigerina) record compiled from Pacific Site 846 (3°06'S, 90°49'W, 3307 m water depth; data compiled and astronomically dated by Lisiecki and Raymo 2005; lorraine-lisiecki.com/stack.html). At Site 846, the difference between peak Pliocene $\delta^{18}O_{benthic}$ values and modern is ~0.63‰, similar to the 0.5‰ difference observed at Pacific Site 1208 (3346 m water depth; Woodard et al. 2014), but significantly larger than observed in the LR04 stack (0.3‰). Pacific deep-water temperatures during Pliocene interglacials were warmer than present (~1.5±0.5°C warmer from Mg/Ca; Woodard et al. 2014), suggesting that only 0.13-0.25‰ of the $\delta^{18}O_{benthic}$ signal can be attributed to $\delta^{18}O_{seawater}$ and 10-20 m higher sea levels due to melting of ice sheets. Values less than 10 m can also be excluded by our intuition that sea level in the Pliocene was higher than the last major interglacial (Marine Isotope Stage 5e that has a GMSL 8±2 m above present; Dutton et al. 2015) due to the enhanced Pliocene global warmth.

We use the Site 846 $\delta^{18}O_{benthic}$ record to provide a new sea-level curve following the approach of Cramer et al. (2011), assuming Milankovitch scale (104-105 year) temperature changes comprise ~20% of the $\delta^{18}O_{benthic}$ changes, and the $\delta^{18}O_{seawater}$-sealevel calibration of 0.13‰/10 m (Winnick and Caves 2015). Comparison of the $\delta^{18}O$-Mg/Ca based sea-level estimate with the backstripped estimates from VA, Enewetak, and New Zealand illustrate general agreement and indicate peak values indicative of some loss of the EAIS, but again with large error estimates (Fig. 2). Given the errors in the various analyses (e.g. up to ±15 m; Fig. 2) it could be argued that any agreement in amplitude is entirely serendipitous. Despite the limitations of these methods at present, it is extremely likely (>95% probability) that maximum Pliocene sea levels were higher than modern, and very likely higher (>90% probability) than the last interglacial (8±2m; Dutton et al. 2015) during the peak highstands of the Pliocene warm period.

Summary and future work

Studies of continental margin and deep-sea sediments have increased age resolution and provided improved constraints on the amplitude of sea-level changes. However, our sea-level estimates have large uncertainties (±10 to ±15 m), thus precluding a definitive statement regarding EAIS melt during the Pliocene. For example, the estimate of 22±10 m could allow melting between 0 and 40% of the EAIS (Miller et al. 2012). The Site 846 $\delta^{18}O_{benthic}$ record places constraints likely excluding values above 20 m. Our best estimate of approximately 12-20 m is consistent with melting of the EAIS in the Wilkes and Aurora sub-basins suggested by models (DeConto and Pollard 2003) and sediment tracer data (e.g. Bertram et al. 2018). Future studies would benefit from improved modeling of the effects of MDT, improved understanding of evolution ocean Mg/Ca and diagenesis, and key observations around Antarctica by ocean/ice drilling to pinpoint active and decaying ice sectors through time.

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What do we know about Last Interglacial sea level?

Andrea Dutton[1] and Natasha L.M. Barlow[2]

The Last Interglacial (LIG, Marine Isotope Stage 5e) represents the most recent time period when the polar ice sheets retreated significantly from their present extent, and hence has frequently been cited as a useful, though imperfect, analogue to understand future ice-sheet and sea-level response to a warming climate.

The LIG sea-level highstand that persisted from ~129 to 116 thousand years (kyr) ago has long been acknowledged to be higher than present sea level, though the magnitude of peak sea level and the stability of sea level during the highstand are still actively debated (Dutton et al. 2015a; Austermann et al. 2017; Barlow et al. 2018). While there are important differences between modern, anthropogenically-driven global warming and the orbitally driven warmth of the LIG, there are several relevant and valuable observations to be made. Among these are (1) understanding the sensitivities of the ice sheets in Greenland and Antarctic to warming; (2) identifying the mechanisms contributing to the millennial-scale evolution of climate and sea level during the interglacial; and (3) mapping out the sea-level budget, including the sources, magnitudes, and timing of meltwater contributions. Fundamentally, one of the most critical questions to answer is whether there was a significant contribution from the Antarctic ice sheet to LIG sea level, which is still uncertain.

Magnitude of peak LIG sea level

Sea level varies geographically, due to a combination of processes including glacial isostatic adjustment (GIA) and dynamic topography (Milne et al. this issue; Austermann and Forte, this issue). Therefore, the maximum height of LIG sea level will not be the same at every location or occur at the same time (Dutton and Lambeck 2012). Several research groups have independently assessed peak global mean sea level (GMSL) from a combination of individual observations of relative sea level from globally distributed localities (Kopp et al. 2009; Dutton and Lambeck 2012; Düsterhus et al. 2016) (Fig. 1). Though these estimates vary somewhat from each other, GIA-corrected reconstructions for GMSL appear to converge on values of ~6-9 m above present for the peak of LIG sea-level rise. An important qualification to this interpreted range is the recognition that vertical motion of the earth's surface due to mantle convection (dynamic topography) since the LIG could easily be on the order of a few meters - up or down - depending on the location (Austermann et al. 2017). While this casts additional uncertainty on the provisional ~6-9 m estimate, it is not straightforward to provide either accurate or precise assessments of the magnitude of the dynamic topography signal for specific sites, and hence difficult to determine if and how this estimate of peak sea level should be further modified.

Sources of LIG sea-level rise

There is evidence from both observations and models that the Greenland ice sheet was significantly smaller than present during the LIG. Though the summary of several studies presented by Dutton et al. (2015a) indicated a convergence towards 2 m (± 1.5) of GMSL contribution from Greenland, a subsequent modeling study increased this estimate to 5.1 m (4.1 to 6.2, 95% credible interval; Yau et al. 2016). To some extent, the disagreement between studies in terms of inferred ice-sheet size may be due to the conflicting implications of total gas content in the ice cores versus temperature estimates. Nonetheless, ice-sheet models consistently produce a couple meters or more of sea-level rise coming from Greenland, with peak contributions at ~121-122 kyr before present. In the absence of near-field data for Antarctica, estimates for an Antarctic contribution to LIG GMSL have typically been calculated by subtracting the contributions of other sources (Greenland, thermal expansion, and mountain glaciers) from far-field sea-level estimates. Given the large unknowns that exist in both peak GMSL and the Greenland ice-sheet contribution, this approach does not allow us to definitively determine whether a sector of the Antarctic ice sheet collapsed during the LIG. However, based on sediment provenance from circum-Antarctic cores, or estimates of sufficiently high GMSL early in the LIG (prior to significant retreat in Greenland), some have argued for a smaller Antarctic ice sheet compared to present at some point during the LIG (Dutton et al. 2015b; Wilson et al. 2018). Confidently "fingerprinting" a few meters of GMSL contribution from either Greenland or Antarctica by using the expected patterns in spatial variability of relative sea level due to GIA to identify the timing and sources of meltwater contribution is a provocative idea. However, this approach would require decimeter-scale vertical precision, which is typically well within the uncertainties of geologic sea-level indicators, hence making the fingerprint of individual ice sheets difficult to carry out in practice.

Evolution of the sea-level highstand

The sea-level highstand has been variously reported to have had anywhere from one

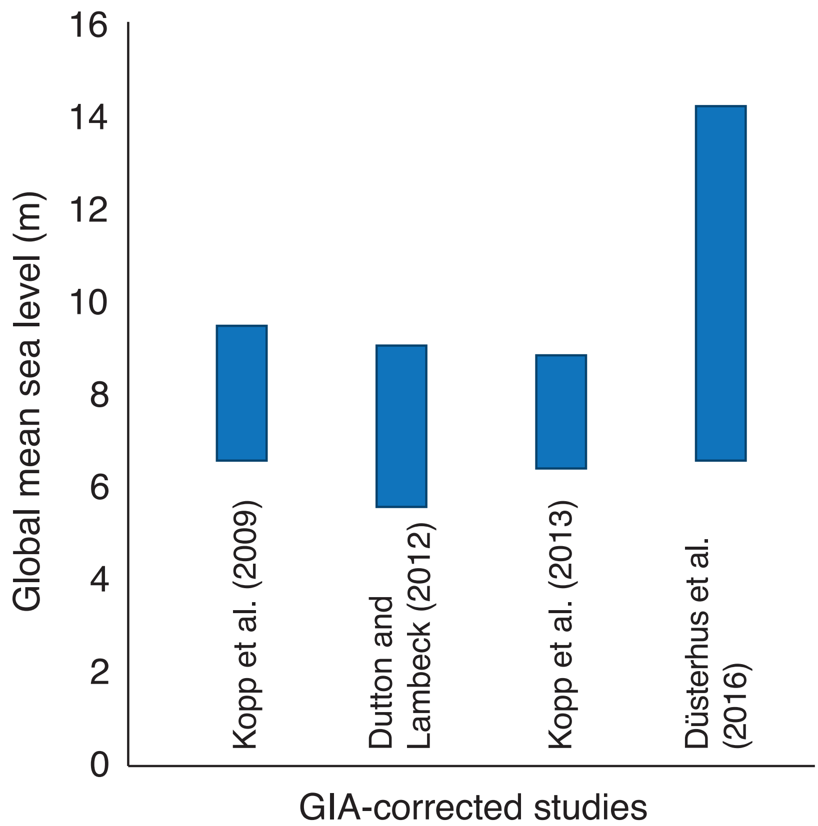

Figure 1: Estimates of global mean sea-level highstand during the Last Interglacial compared to today. All studies correct for glacial isostatic adjustment.

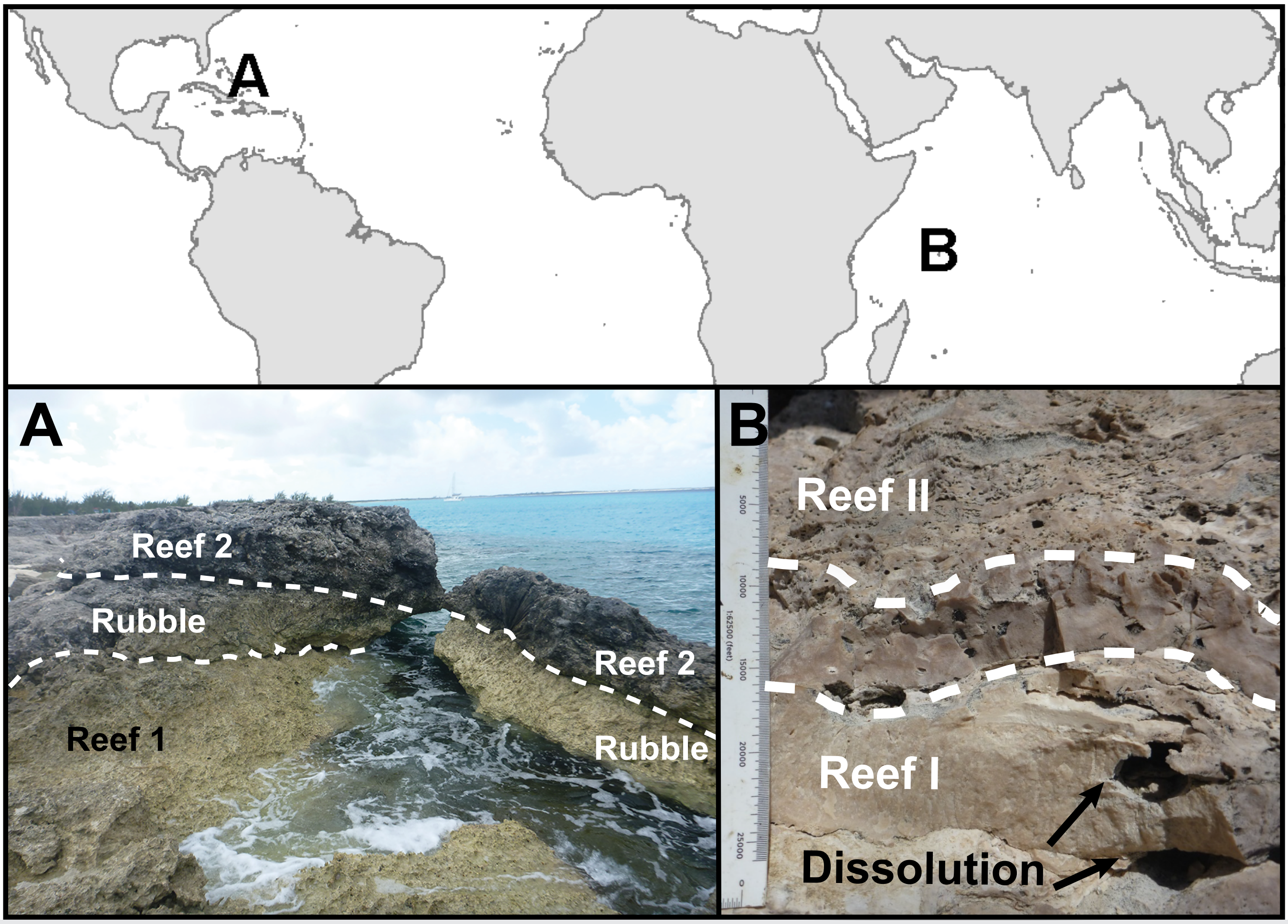

Figure 2: Field evidence from LIG sequences in **(A)** The Bahamas (Skrivanek et al. 2018) and **(B)** Seychelles (Vyverberg et al. 2018) that is consistent with an ephemeral sea-level fall occurring between the development of stratigraphically distinct reef units. Depending on the site, truncated corals in the lower reef, extensive dissolution on the reef surface, or sequence of freshwater and marine cements provide evidence of an ephemeral sea-level fall.

to four peaks, where multiple peaks define millennial-scale fluctuations in sea level. Some reconstructions simply connect age-elevation data points from corals with a line, which ignores potential changes in coral paleowater depths and contextual sedimentary and stratigraphic information from fossil reef outcrops. While the coral age-elevation-taxonomy compilation by Hibbert et al. (2016) drives the point home that paleowater depth ranges of corals can be large, this does not render the entire fossil coral archive useless for addressing the question of whether there were sea-level oscillations during the LIG. Instead, sedimentary evidence for changes in water depth, including intervals of subaerial exposure within the fossil reef or evidence of rapid reef accretion, can be used to more confidently interpret possible meter-scale changes. In fact, several studies have pointed to compelling evidence for abrupt changes in sea level preserved in LIG reef sequences (e.g. Blanchon et al. 2009; Skrivanek et al. 2018). The magnitude of these changes is poorly constrained, however. To confidently confirm these rapid sea-level changes at a global scale, more evidence needs to be amassed from geographically diverse sites with robust chronologies. Some recent studies have argued that a sea-level fall of >4 m, as indicated by Kopp et al. (2009), is not plausible given constraints from phreatic overgrowths in Mallorca caves (Polyak et al. 2018) and other lines of observational and modeling evidence (Barlow et al. 2018). However, these studies do not preclude the possibility of smaller, meter-scale sea-level fluctuation(s) in the low latitude reef sites during the LIG (Fig. 2).

Implications for links between climate, ice sheets, and sea level

There is great interest within the community to move beyond the big-picture view of the correspondence between peak temperatures and peak GMSL during the LIG, for example as depicted in Dutton et al. (2015a). Increasing attention is being drawn to millennial-scale changes in temperature, ice-sheet response, and the accompanying changes in sea level during the LIG to understand the thresholds for ice-sheet collapse, the temporal relation between climate forcing and sea level, and the rates of sea-level change. One of the biggest challenges in linking climate signals to observations of sea-level change is developing accurate, precise, and highly resolved chronologies that can confidently be correlated to other records, for instance, between data from deep-sea cores and U-Th dated archives of sea-level change in coral reefs. Tzedakis et al. (2018) demonstrate that climate in the North Atlantic region was more variable during the LIG than the Holocene, but it is yet to be firmly established how that variability links to concomitant changes in ice volume, meltwater input and sea level.

What is clear, however, is that the more we can extract from the paleo record about the phasing, magnitude, and sources of meltwater input into the oceans, the better we can constrain the models that are used to project future sea-level rise. We envision that interdisciplinary approaches to this question will be essential to unravelling the dynamics of shrinking polar ice sheets in a warming world.

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Late Holocene sea level

Robert L. Barnett[1,2], A.C. Kemp[3] and W.R. Gehrels[4]

Late Holocene proxy-based sea-level reconstructions are key to understanding and identifying drivers of ongoing and future sea-level change. They demonstrate that the rate of 20th century global mean sea-level rise is unprecedented in, at least, the past 3000 years.

Relative sea level (RSL) varies across space (local to global) and through time (minutes to millennia). Proxy-based reconstructions provide insight into the physical processes that govern these spatio-temporal patterns of RSL change, including the distribution of land-based ice melt, glacio-isostatic adjustment (GIA) and ocean-atmosphere dynamics. They can also help to constrain projections of future RSL change under climate change scenarios. Reconstructions of late Holocene (roughly the past 3000 years) RSL changes are of limited use as direct analogues for future changes in which the magnitude of forcing will be greater and faster than climate variability during this period. Analogues for future RSL change are more likely to be found (for example) in the Pliocene (Miller et al. this issue) or the Last Interglacial (Dutton and Barlow, this issue). Nevertheless, the late Holocene is a key period for reconstructing RSL for the following reasons (e.g. Kemp et al. 2015):

- Records are available at abundant sites from polar to tropical regions, offering a uniquely (almost) global spatial coverage;
- Undisturbed geological archives (e.g. coastal sedimentary sequences and coral microatolls) provide near-continuous temporal coverage;
- Reconstructions are supported by chronologies with a high degree of temporal precision (years to decades in some cases);
- Some long-term geological processes can be considered negligible (e.g. dynamic topography) or linear (e.g. GIA) through time, helping in signal separation;
- Proxy-based reconstructions overlap, and can be combined, with instrumental RSL records from tide gauges and satellite altimetry;
- Complementary reconstructions of climate variables (e.g. temperature) allow direct comparison among proxies to gain insight into drivers, synchronicity and feedbacks in coupled systems, especially during periods of known late Holocene climate variability (e.g. Medieval Climate Anomaly, Little Ice Age and 20th century warming)

Sources of late Holocene relative sea-level reconstructions

Late Holocene RSL variability has magnitudes of tens of centimetres and timescales of decades to centuries, (although in tectonically active regions, near-instantaneous and larger-scale RSL jumps can occur from earthquake deformation). Changes on these scales are best reconstructed from intertidal wetlands (salt-marsh and mangrove sediments), coral microatolls, and archaeological remains. Reconstructing RSL relies on establishing a relationship between sea-level proxies and tidal elevation within modern environments, which are then applicable to the geological record as analogues (e.g. Shennan 2015).

Micro-organisms (foraminifera, diatoms, and testate amoebae) and geochemical signatures (for example $\delta^{13}C$ and C/N ratios) in salt marshes and mangroves are found in elevation-dependent vertical niches within the upper intertidal zone (e.g. Barlow et al. 2013). Recognition of their fossil counterparts in dated sediment cores enables RSL to be reconstructed. In many cases, the history of sediment accumulation is established by an age-depth model constrained by radiocarbon dates and recognition of chronological horizons of known age in downcore profiles of elemental abundance, isotopic ratios and/or radioisotope activity. Coral microatolls live slightly below the intertidal zone and grow laterally during times of stable RSL, upward under conditions of RSL rise, and experience die-back (by prolonged exposure to air and direct sunlight) if RSL falls (Meltzner and Woodroffe 2015). Therefore, the architecture of dead coral microatolls records a history of RSL change that can be dated using U/Th, radiocarbon and/or counting of annual bands. Some coastal structures were designed and built to have a specific relation to sea level and can be dated using archaeological and historical context (Morhange and Marriner 2015). For example, submerged Roman fish ponds in the Mediterranean are evidence for RSL rise.

Global mean sea level (GMSL)

Late Holocene RSL reconstructions span the transition from geological to instrumental records and can uniquely estimate when modern rates of sea-level rise began. Tide gauges (after correction for GIA) show evidence of GMSL rise since 1880 CE, which indicates that the onset of modern rise likely predates most instrumental datasets. Proxy reconstructions from widely separated sites (Atlantic coast of North America; Australia;

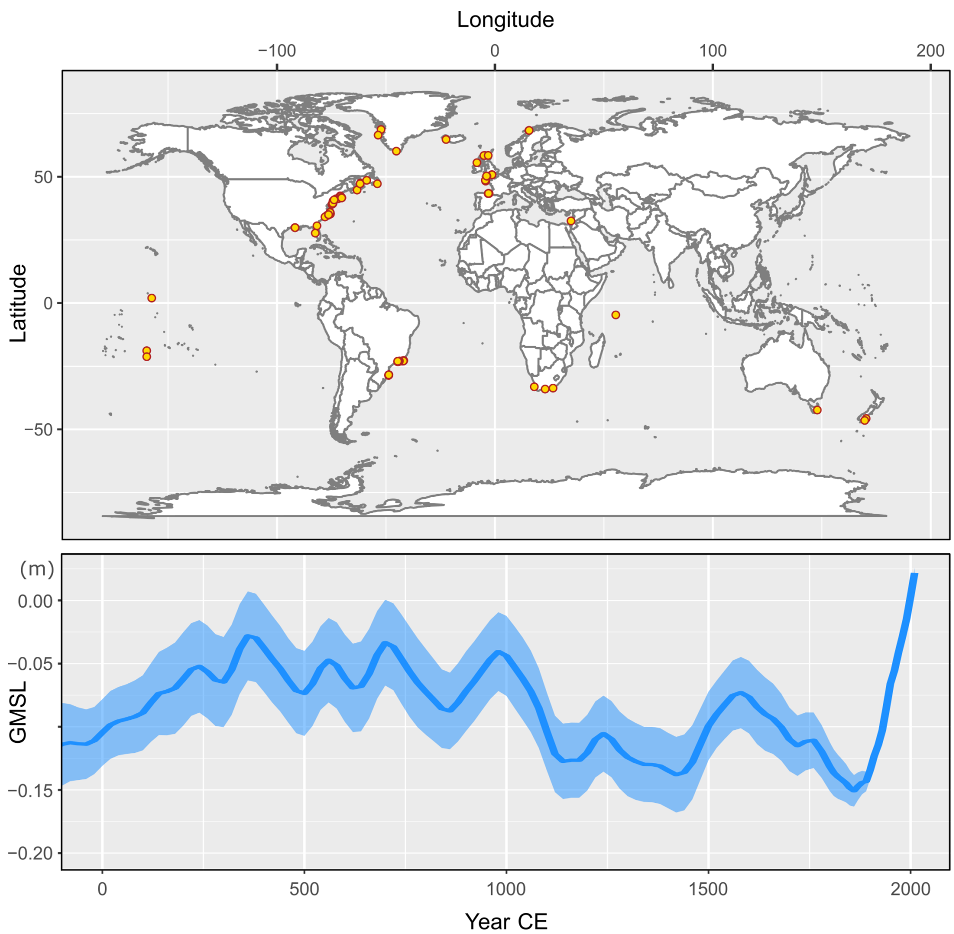

Figure 1: Location of late Holocene relative sea-level reconstructions (top panel) in the database used to develop the Common Era global mean sea-level curve (bottom panel) of Kopp et al. (2016).

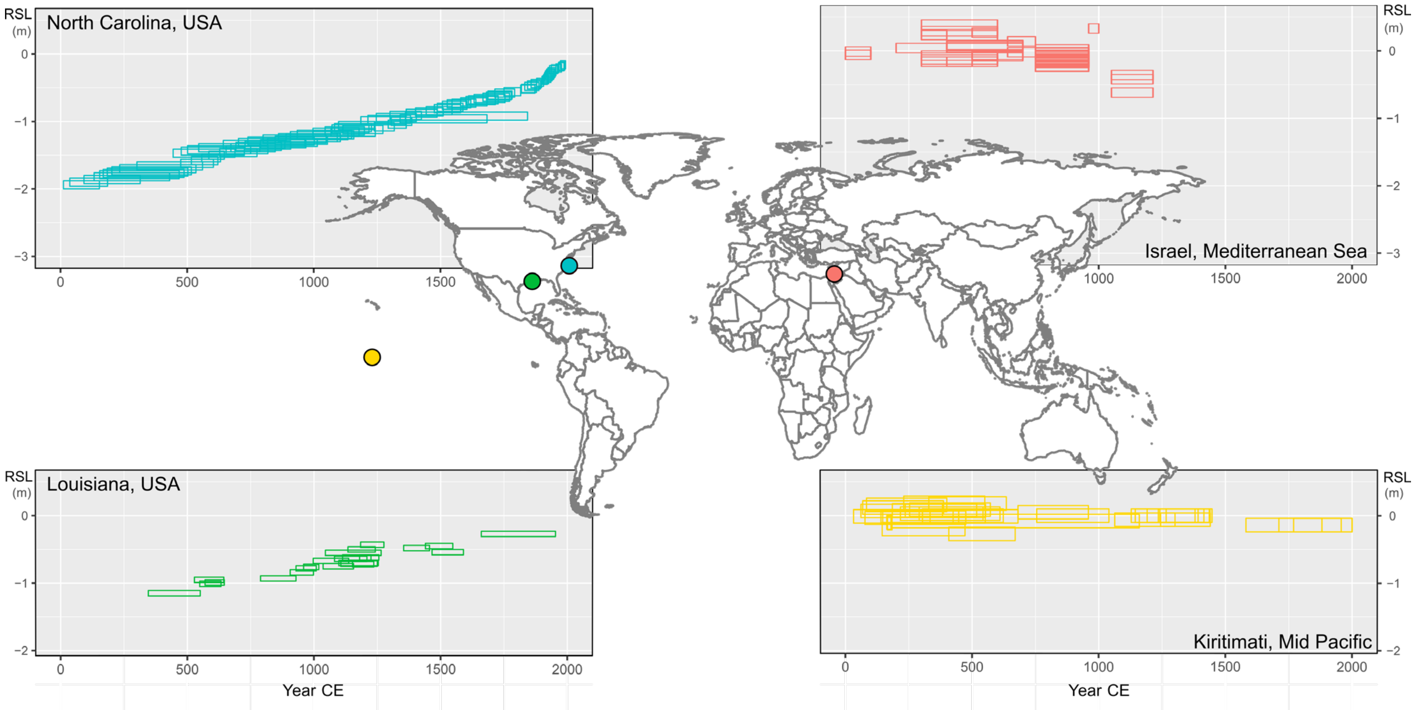

Figure 2: Selected late Holocene RSL reconstructions developed from salt-marsh sediment (North Carolina; Kemp et al. 2017 and Louisiana; González and Törnqvist 2009), coral microatolls (Kiribati; Woodroffe et al. 2012) and archaeological remains (Israel; Sivan et al. 2004).

New Zealand; South Africa) show that RSL rise accelerated during the late 19th or early 20th century. The near-synchronous timing and wide geographic range point to a GMSL change. Kopp et al. (2016) compiled RSL reconstructions and used a spatio-temporal model to estimate late Holocene GMSL (Fig. 1). They concluded, with probability higher than 95%, that the 20th century experienced the fastest rate of rise of any century in the past ~3000 years. Their analysis also revealed a positive GMSL trend (0.1±0.1 mm yr^{-1}) from 0 to 700 CE prior to the Medieval Climatic Anomaly and a negative GMSL trend (-0.2±0.2 mm yr^{-1}) from 1000 to 1400 CE prior to the Little Ice Age.

Calibration of semi-empirical models using the late Holocene GMSL reconstruction of Kopp et al. (2016) and global temperature reconstructions (e.g. PAGES 2k Consortium 2017) is one way in which proxy RSL reconstructions are used to constrain GMSL projections. Temperature projections from Representative Concentration Pathways are used to force the calibrated model and develop GMSL projections. When calibrated only with instrumental data, semi-empirical models often generate higher GMSL projections than process-based models (e.g. Church et al. 2013). However, calibration with late Holocene GMSL and temperature yields similar projections for semi-empirical and process-based models (Kopp et al. 2016). Using these models, Bittermann et al. (2017) explored how GMSL could change under climate scenarios that are compatible with the Paris Agreement.

Regional sea-level changes

Many physical processes that drive late Holocene RSL changes produce distinctive spatial and temporal patterns. Differences and similarities among RSL records can therefore yield insight into the processes that caused late Holocene RSL change. GIA effects include crustal rebound, continental levering, ocean syphoning, and Earth rotational feedbacks from redistribution of mantle and ocean mass (Milne and Mitrovica 1998). Isostatic changes from GIA and sediment- and hydro-(un)loading of the lithosphere cause spatially variable vertical land motion that affects regional RSL signals. RSL changes resulting from Greenland, Antarctic, and glacial meltwater are also spatially variable because of reorganization of the geoid resulting in higher or lower than average RSL rise in the far or near-field respectively (Mitrovica et al. 2001). Late Holocene RSL stability reconstructed from far-field (Indian Ocean) coral microatolls on Kiritimati (Fig. 2) was used to infer minimal ice-ocean mass flux during this period (Woodroffe et al. 2012). Steric (thermal and salinity) changes cause spatially variable sea-surface height changes, although how these signals propagate from the central ocean to the coast remains poorly understood. Ocean and atmosphere circulation modes drive dynamic sea-level variations due to baroclinic gradients causing redistribution of existing ocean mass.

Separation of RSL records into individual driver-related signals remains an active and ongoing challenge. Positive identifications are dependent on a critical spatial density of records so that local-, regional-, and global-scale signals are distinguishable. To date, this density of records only exists in the western North Atlantic Ocean (Fig. 1). Kemp et al. (2018) used a spatio-temporal model to estimate global, regional linear, regional non-linear, and local components of RSL changes with a focus on the western North Atlantic. The analysis resolves GIA effects (the regional linear component) independent from GIA models and identified regional non-linear trends that point to ocean-atmosphere dynamic forcing during the late Holocene. Addressing the spatial distribution bias of RSL records is an important and necessary step towards expanding these spatio-temporal analyses to other regions. A point of emphasis in future work should be replication of RSL reconstructions (within cores, sites and regions) to better differentiate regional RSL signals from possible reconstruction biases and local effects.

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Sea-level databases

Nicole S. Khan[1], F. Hibbert[2] and A. Rovere[3]

The study of past sea levels relies on the availability of standardized sea-level reconstructions, which allow for broad comparison of records from disparate locations to unravel spatial patterns and rates of sea-level change at different timescales. Subsequently, hypotheses about their driving mechanisms can be formulated and tested.

Approach to database compilation

Geological sea-level reconstructions are developed using sea-level proxies, which formed in relation to the past position of sea level and include isotopic, sedimentary, geomorphic, archaeological, and fixed biological indicators, in addition to coral reefs and microatolls, as well as wetland flora and fauna. The past position of sea level over space and time is defined by what are termed sea-level index or limiting points, which are characterized by the following fundamental fields: a) geographic location; b) age of formation, traditionally determined by radiometric methods (e.g. radiocarbon or U-series dating); c) the elevation of the sample with respect to a contemporary tidal datum; and d) the relationship of the proxy to sea level at the time of formation (i.e. the proxy's "indicative meaning", which describes the central tendency (reference water level) and vertical (indicative) range) relative to tidal levels. Although conceptually only four primary fields are necessary to define a sea-level index point, in practice many more fields are required to appropriately archive information related to geological samples (e.g. stratigraphic context, sample collection, laboratory processing), and it is important to distinguish between primary observations and secondary interpretation so that the latter may be updated as science advances (see Hibbert et al. 2016; Hijma et al. 2015).

While this approach was developed through the International Geoscience Programme projects running from the 1970s to present and has been widely applied to Holocene reconstructions (e.g. Shennan and Horton 2002), it has only more recently been adopted for older archives and time periods (e.g. Rovere et al. 2014, 2016). The standardization of sea-level databases of various ages has been one of the main objectives of the PAGES PALeo constraints on SEA level (PALSEA) working group (Düsterhus et al. 2016) and by projects related to it (e.g. the International Union for Quaternary Research (INQUA) Geographic variability of HOLocene relative SEA level (HOLSEA) and MEDiterranean sea-level change and projection for future FLOODing (MEDFLOOD) projects). Here we describe recent progress and advances in database compilation, and highlight remaining challenges and future directions.

Last Glacial Maximum to present

The standardization of sea-level databases spanning time periods from the Last Glacial Maximum (LGM) to present has seen rapid development in recent years. Notable progress has been made through a community effort, unified under the HOLSEA project, to develop a standardized global database of post-LGM sea levels. The first iteration of this database was made available in April 2019 through a special issue entitled "Inception of a Global Atlas of Sea Levels since the Last Glacial Maximum" published in *Quaternary Science Reviews*. Regional contributions in the special issue from Atlantic Canada, the British Isles, the Netherlands, Atlantic Europe, the western Mediterranean, Israel, the Russian Arctic, South Africa, the Malaysian Peninsula, and Southeast Asia, India, Sri Lanka and the Maldives can be combined with recently published regional databases from the Pacific, Gulf, Atlantic, and Caribbean coasts of North America, Atlantic South America, Greenland, Antarctica, northwest Europe, the Barents Sea, the Mediterranean, China, Australia, New Zealand, other low-latitude locations, and high-resolution Common

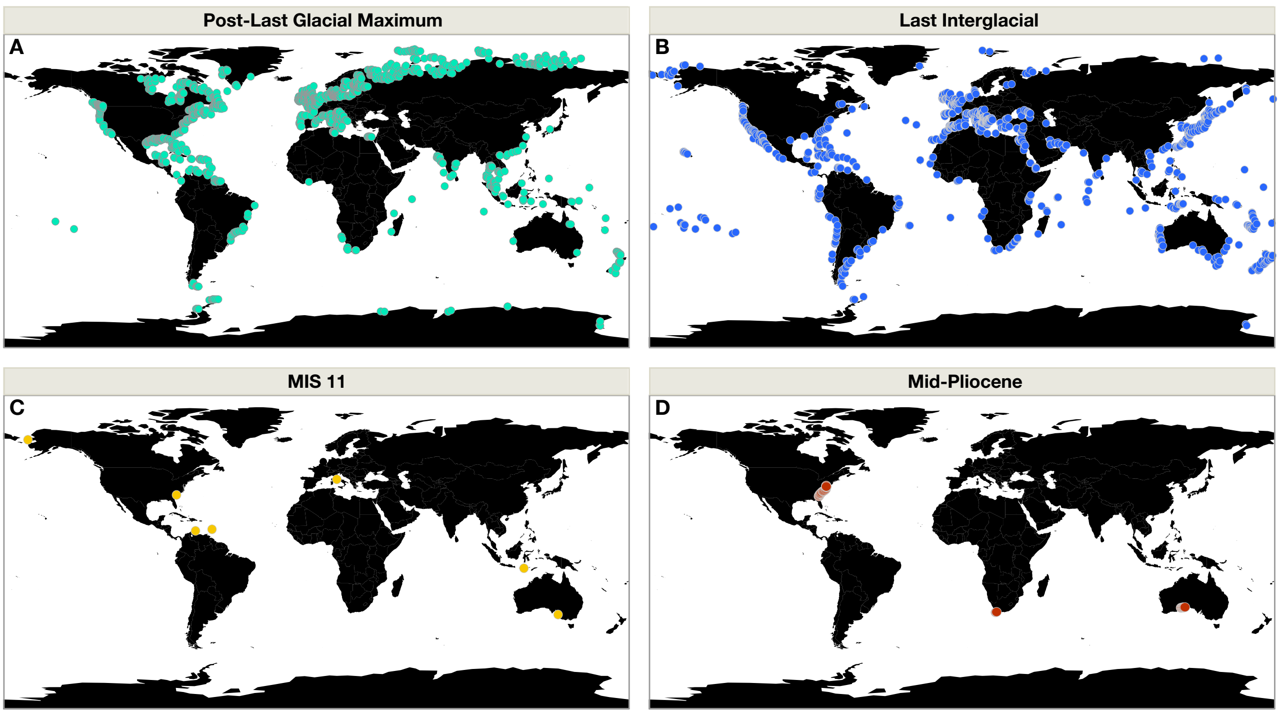

Figure 1: Map showing the spatial distribution of sea-level data from different time periods: **(A)** the Last Glacial Maximum to present from new regional databases, **(B)** the Last Interglacial, **(C)** MIS 11, and **(D)** the Pliocene. References are given in Box 1.

Era reconstructions (Kopp et al. 2016; also Barnett et al. this issue; see Fig 1a). However, updates or further standardization may be required to fully integrate these recently published databases. Key spatial gaps remain in Arctic Canada, Pacific Central America, Pacific South America, and African coastlines, and there is a paucity of data spanning the deglacial period (i.e. older than 8 kyr).

The Last Interglacial

For the Last Interglacial, four primary databases collect Marine Isotope Stage (MIS) 5e sea-level indicators at global scale: 1) Kopp et al. (2009) included data from 42 locations and a variety of archives (isotopic, coral reef, geomorphological) and applied a standardized relationship to sea level at the time of formation (i.e. indicative meaning); 2) Pedoja et al. (2014) included data from 942 sites, however only elevation is reported (and often only mean elevations) without consideration of sample indicative meaning; 3) Dutton and Lambeck (2012) concentrated on coral reef archives from 16 sites (710 data points) and crucially standardized the U-series ages; 4) Hibbert et al. (2016) built on the Dutton and Lambeck dataset (32 locations, ca. 2,500 data points, for the last 700 kyr) adding additional standardization and coral depth distributions derived from modern ecological studies (Fig 1b). While at first glance there appears to be an abundance of Last Interglacial data, not all dated sea-level indicators have a full suite of database fields (for example, species dated, elevation, or reliable age determinations). Screening of the available databases suggests there are ca. 500 Last Interglacial sea-level indicators (excluding isotopic archives) with sufficient documentation to allow further analysis, 319 of which are located at 26 different locations on passive margins (Austermann et al. 2017). Databases from older time periods have often been "standalone" efforts with differing objectives, a major drawback of which is the varying way that archives have been interpreted with respect to past sea levels. One way forward is the approach taken by Rovere et al. (2016), where former sea levels are interpreted in terms of the entire geological or sedimentary facies (with ages derived from samples collected from within that facies), rather than considering each individually dated indicator separately.

Plio-Pleistocene interglacials

Beyond the Last Interglacial, there have been few attempts to compile and standardize sea-level data. Most compilations were completed to support modeling studies that did not focus on the creation of a database per se, and hence standardization is sometimes less rigorous than for Holocene and Last Interglacial proxies. For example, Creveling et al. (2017) report 38 sites dating to MIS 5a and MIS 5c to compare their elevation with glacial isostatic adjustment models. No attempt is made, however, at assessing or standardizing the indicative meaning of each proxy. For older interglacials, Bowen (2010) reported seven sites where MIS 11 shorelines have been preserved (Fig 1c), and Rovere et al. (2015, 2014) estimated the indicative meaning for mid-Pliocene shorelines on the Atlantic coasts of the United States, South Africa, and South Australia (Fig 1d).

Future directions

Progress in improving the standardization of sea-level databases has also been accompanied by advancements in statistical and analytical methods used to infer spatial patterns and rates of RSL change from geological data that have a spatially and temporally sparse distribution and geochronological and elevational uncertainties (e.g. Austermann et al. 2017; Kopp et al. 2009, 2016). Future areas of development include more comprehensive and accurate use of data (e.g. incorporating non-Gaussian data distributions; see Hibbert et al. 2016), integration with physical models and their uncertainties (Milne et al. this issue) using machine learning approaches, and scaling spatio-temporal models to large geological datasets (Ashe et al. 2019).

Challenges remain in integrating databases compiled by different research groups over different time periods, and in developing cyberinfrastructure and open access visualization platforms to improve the longevity and accessibility of databases (e.g. Düsterhus et al. 2016). Improved understanding of the mechanisms driving RSL variability will be achieved through the standardization of sea-level databases, which will enhance the comparability and accessibility of information to improve both physical models and statistical reconstructions.

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Last Glacial Maximum to present	
Long et al. (2011)	Greenland
Vacchi et al. (2018a)	Atlantic Canada
Baranskaya et al. (2018)	Russian Arctic
Auriac et al. (2016)	Barents Sea
Lambeck et al. (2010)	Scandinavia
Briggs and Tarasov (2013)	Antarctica
Shennan et al. (2018)	British Isles
Hijma and Cohen (2019) Vink et al. (2007)	northwest Europe
García-Artola et al. (2018)	Atlantic Europe
Vacchi et al. (2014, 2016, 2018b) Shaw et al. (2018) Dean et al. (2019)	Mediterranean
Engelhart and Horton (2012) Hawkes et al. (2016)	US Atlantic
Engelhart et al. (2015) Reynolds and Simms (2015)	US Pacific
Hijma et al. (2015) Love et al. (2016)	Gulf of Mexico
Khan et al. (2017) Milne and Peros (2013)	Circum-Caribbean
Milne et al. (2005)	Atlantic South America
Cooper et al. (2019)	South Africa
Zong (2004)	China
Mann et al. (2019) Tam et al. (2018)	Southeast Asia, India, Sri Lanka, and the Maldives
Clement et al. (2016)	New Zealand
Lewis et al. (2013)	Australia
Hibbert et al. (2016, 2018)	Mid to low latitude locations
Khan et al. (2015)	Global
Last Interglacial	
Kopp et al. (2009)	Global
Pedoja et al. (2011, 2014)	Global
Hibbert et al. (2016)	Global
MIS 11	
Bowen et al. (2010)	see Figure 1
Pliocene	
Rovere et al. (2014, 2015)	see Figure 1

Box 1: Currently available standardized RSL databases. All data are shown in Figure 1. See online version of this article for links to full references (doi.org/10.22498/pages.27.1.10).

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Interglacial ice extents of the Greenland ice sheet

Anders E. Carlson[1] and Nicolaj K. Larsen[2,3]

The Greenland ice sheet has the capacity to raise sea level by ~7.4 m. Current terrestrial and marine data suggest that the ice sheet has usually been smaller than present during interglacial periods, showing a high sensitivity to current regional climate warming.

The Greenland ice sheet is the last surviving ice sheet of what was the order-of-magnitude larger extent of North Hemisphere ice sheets at the last glacial maximum about 21,000 years ago. As such, its responses to ongoing and future global warming represents a major concern regarding its impact on global sea level. In the last decade, the application of ^{10}Be exposure dating along with "threshold" lakes dated by ^{14}C now constrain the timing of when the Greenland ice sheet retreated to a smaller-than-present extent in the Holocene. Likewise, radiogenic isotopic tracers of silt-size particles combined with ice-rafted debris and subglacial bedrock cosmogenic isotopic concentration can provide evidence of how small the Greenland ice sheet may have been in prior interglacial periods. These data can provide important constraints on the sensitivity of the Greenland ice sheet to paleoclimates similar to, or warmer than, present.

The Holocene

The last deglaciation leading into the Holocene is characterized by abrupt climate changes recorded in Greenland ice cores. However, evidence for any response of Greenland ice-sheet margins on land is restricted mainly to the southernmost, westernmost and easternmost edges of Greenland; other terrestrial retreat of the Greenland ice sheet occurred during the Holocene (e.g. Young et al. 2013; Carlson et al. 2014; Larsen et al. 2015, 2018; Winsor et al. 2015; Young and Briner 2015; Sinclair et al. 2016; Reusche et al. 2018). This means that at an extended state on the continental shelf, the Greenland ice sheet appears to have been relatively stable and capable of surviving 10,000 years of deglacial warming before retreating to its current and then smaller-than-present extent.

The application of ^{10}Be exposure dating in a number of fjord transects (Fig. 1) has demonstrated that the deglaciation from the coast to the present ice margin occurred in most places within ~500-1000 yr during the early Holocene (e.g. Winsor et al. 2015; Young and Briner 2015; Sinclair et al. 2016; Larsen et al. 2018). These yield retreat rates of 50-100 m yr^{-1}, which are similar to, or higher than, retreat rates observed at even the most sensitive glaciers today (Winsor et al. 2015). In west and southwest Greenland, the ice-sheet retreat halted during the early Holocene in response to the ~9.3 kyr BP and 8.2 kyr BP cold events (e.g. Young et al. 2013; Winsor et al. 2015). Elsewhere in Greenland, evidence of early Holocene stillstands is lacking – not necessarily because they did not occur, but because late-Holocene advance may have overridden moraines from these stillstands (Carlson et al. 2014; Larsen et al. 2015, 2018; Sinclair et al. 2016; Reusche et al. 2018).

Cosmogenic ages on boulders next to modern ice margins (Fig. 1) and threshold lakes (Fig. 2), and radiocarbon dating on organic remains in historical moraines have been used to constrain periods with smaller-than-present ice extent (e.g. Carlson et al. 2014; Larsen et al. 2015; Young and Briner 2015). These records show that ice had retreated inland of its present extent during the Holocene thermal maximum ~8-5 kyr BP. This minimum ice extent was followed by a late-Holocene advance that culminated during the early 1900s with the formation of pronounced Little Ice Age moraines in most parts of Greenland (Kjeldsen et al. 2015). However, ^{10}Be dating of moraines outside Little Ice Age moraines has shown that the

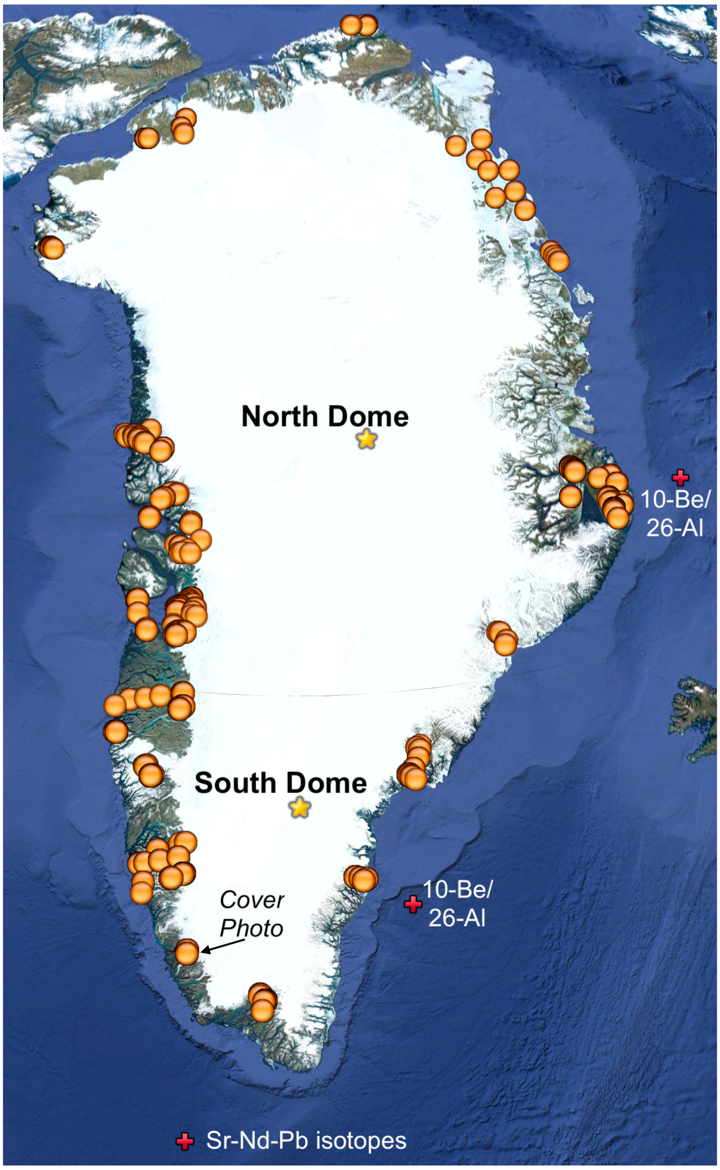

Figure 1: Location of ^{10}Be ages (yellow circles), basal ice and bedrock samples (stars), and marine sediment cores (red crosses) constraining Greenland ice-sheet paleo history. Location of issue cover photo from Nigerdlikasik Bræ denoted by arrow.

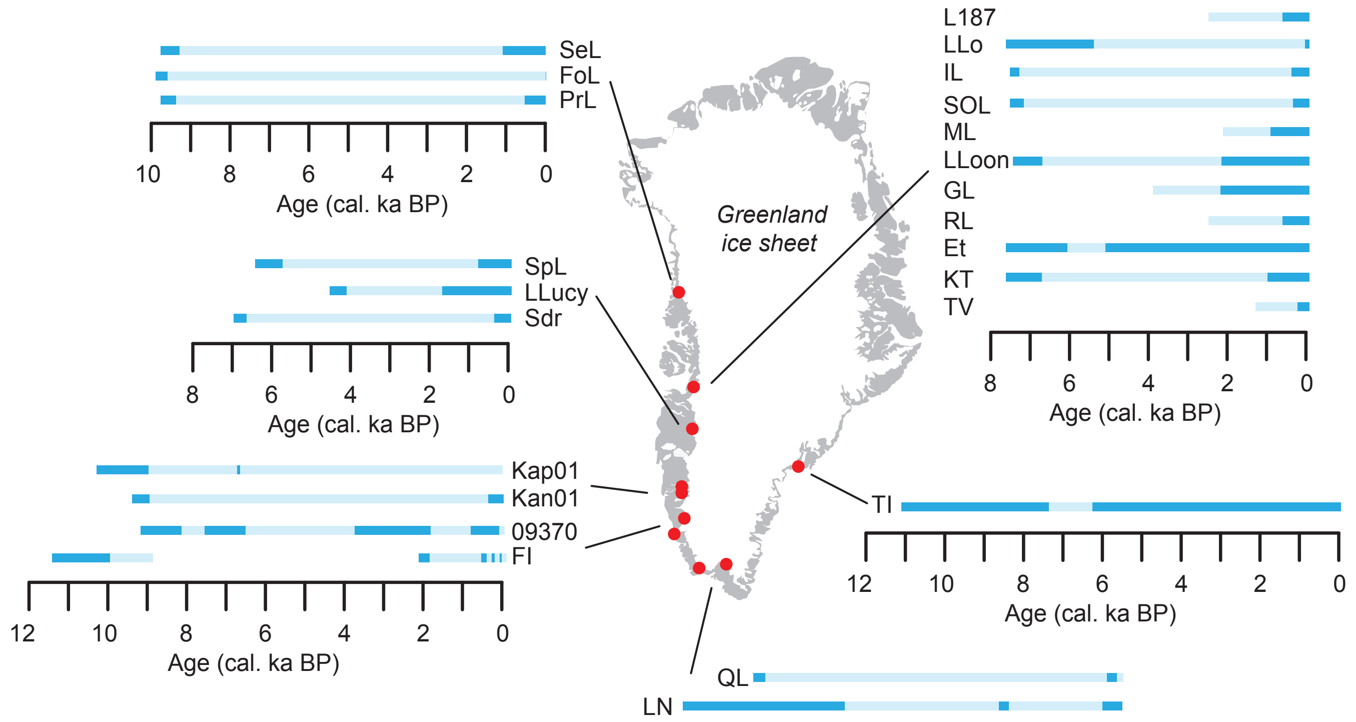

Figure 2: Examples of Holocene constraints on when the Greenland ice sheet was smaller than present based on proglacial threshold lakes (Young and Briner 2015; Larsen et al. 2015 and reference therein). Dark bars indicate that the ice margin is close to the lake and similar to the modern extent; light bars indicate ice-margin retreat out of the lake drainage basin and a smaller-than-present ice extent.

ice extent was larger prior to the Little Ice Age in southernmost (Winsor et al. 2014) and northwestern Greenland (Reusche et al. 2018). These records indicate that for much of the last 10,000 years the Greenland ice sheet was at a more retracted extent than it was in the industrial era.

Prior interglacial periods

The last interglacial period, ~128-116 kyr BP, was an interval generally denoted as warmer than the peak Holocene due to greater precession forcing. Far-field sea-level indicators suggest that global mean sea level was 6-9 m above present, indicating that the global cryosphere was smaller than present. Marine sediment provenance records can constrain ice-sheet location on a given Greenland terrain (Colville et al. 2011). The dating of basal ice by the accumulation of radionuclide gases emitted from the underlying ground provides another means of reconstructing the Greenland ice sheet extent (Yau et al. 2016). The marine provenance records show that the southern Greenland ice dome survived through the last interglacial period (Fig. 1; Colville et al. 2011). The age of basal ice for the southern and northern Greenland domes is much older than the last interglacial (Fig. 1; Yau et al. 2016), in agreement with the marine records. These records suggest that the Greenland ice sheet only contributed less than 2.5 m (~35% of the modern ice-sheet volume; Colville et al. 2011) to the last interglacial sea-level highstand.

Prior to the last interglacial period, marine sediment provenance evidence indicates that the southern Greenland ice sheet nearly completely deglaciated during marine isotope stage 11 ~400 kyr BP (Reyes et al. 2014). This agrees well with the ~400 kyr BP age of basal ice and sediment from the south Greenland ice dome (Fig. 1; Yau et al. 2016). With a basal ice age of ~1000 kyr BP for the north Greenland ice dome (Fig. 1; Yau et al. 2016), these records suggest up to 6 m of sea-level rise coming from the Greenland ice sheet during marine isotope stage 11, accounting for the low end of global mean sea-level estimates for this interglacial period (Reyes et al. 2014).

On a longer timescale, marine and sub-ice cosmogenic records appear to be contradictory. For east Greenland, ice-rafted debris has been continuously deposited over the last three million years. The accumulation of ^{10}Be and ^{26}Al in this ice-rafted debris suggests the general persistence of the north Greenland ice dome in east Greenland over this time period with only short-lived periods of ice retreat and bedrock exposure (Fig. 1; Bierman et al. 2016). This would agree with the basal ice age of north Greenland ice dome of ~1000 kyr BP, suggesting a stable north Greenland ice dome over the latter part of the Quaternary (Yau et al. 2016). Conversely, the accumulation of ^{10}Be and ^{26}Al in the bedrock underlying the north Greenland ice dome could indicate multiple intervals of exposure during the Quaternary (Fig. 1; Schaefer et al. 2016), which would imply a more dynamic ice dome than can be inferred from the marine ^{10}Be and ^{26}Al records (Bierman et al. 2016) and basal ice ages (Yau et al. 2016). However, the eastern mountains of Greenland are one of the last places to deglaciate in Greenland ice-sheet models (e.g. Schaefer et al. 2016), suggesting that the two ^{10}Be and ^{26}Al records may not be in conflict. Nevertheless, it is difficult to rectify the ~1,000 kyr BP age of the north Greenland ice dome basal ice with the accumulation of ^{10}Be and ^{26}Al in the underlying bedrock. The application of a third, shorter-lived cosmogenic isotope from the bedrock, like ^{36}Cl, could help in resolving the potential conflict between these two records.

Summary

The records discussed above demonstrate that the Greenland ice sheet has responded dramatically to past climate warming of only a few degrees Celsius or less above pre-industrial levels – warming levels we have already met or will meet in the next few decades. We can consequently conclude that we have reached, or will shortly reach, a climate state where the modern Greenland ice sheet is no longer stable (Carlson et al. 2014; Reyes et al. 2014).

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On recovering Last Interglacial changes in the Antarctic ice sheet

Louise C. Sime[1], A.E. Carlson[2] and M. Holloway[1,3,4]

The sensitivity of the Antarctic ice sheet to ocean warming is a major source of uncertainty in projecting future sea levels. Antarctic ice from the Last Interglacial sampled in ice cores provides key information to better quantify this sensitivity.

Quantifying the sensitivity of the Antarctic ice sheet (AIS) to increasing ocean temperatures is central to improving projections of global sea-level rise. Capron et al. (2014) compiled strong evidence of a Southern Ocean sea-surface temperature anomaly of up to +3.9 ± 2.8°C 125,000 years ago (125 kyr BP) compared to the present, and sea-level indicators for the Last Interglacial (LIG; around 129 to 116 kyr BP) suggest that this was the last time that global mean sea level (GMSL) was substantially higher than present (Dutton et al. 2015). This strongly suggests that pinning down the response of the AIS during the LIG should give insight into the last time the AIS was substantially smaller than today.

Ice-sheet modeling, alongside other lines of evidence, suggest the potential for massive loss of West Antarctic ice that is grounded below sea level (e.g. DeConto and Pollard 2016). Isotopic analysis of marine sediments and the NEEM Greenland ice core indicate that Greenland likely provided a relatively small ~2 m contribution to maximum LIG sea levels (NEEM Project Members 2013; Colville et al. 2011), so the reconstructed LIG GMSL peak of +6 to 9 m implies that the AIS experienced very significant melt during the LIG (Dutton et al. 2015). However, hunting for more direct evidence of AIS changes during the LIG has thus far proved to be surprisingly difficult, and the ultimate goal of deriving rates of AIS volume change has yet to be achieved.

Terrestrial observations of the extent of the AIS during the LIG are lacking due to subsequent growth of the AIS to its last glacial maximum volume. However, some evidence exists in the marine realm to constrain the LIG AIS. A tephra layer in the ANDRILL sediment core from the Ross Sea shows that at some time in the last 240 kyr, the Ross ice shelf was absent, potentially during the LIG (McKay et al. 2012). According to some ice-modeling studies, if the Ross ice shelf was to completely melt, the West Antarctic ice sheet (WAIS) would also deglaciate (e.g. DeConto and Pollard 2016). A recent study from a marine core off East Antarctica used Neodymium isotopes to show that the portion of the AIS overlying the Wilkes subglacial basin significantly retreated to a smaller-than-present extent during the LIG (Wilson et al. 2018). While similar studies near other sectors of the AIS could provide fruitful information on the LIG extent of the AIS, none of these approaches have, on their own, permitted the definitive establishment of AIS changes during the LIG.

The attractions of ice-core data

Antarctic ice cores are an attractive proposition for reconstructing AIS changes: several ice cores from East Antarctica covering the LIG period have been placed on an improved chronology using new gas and ice stratigraphic links (Bazin et al. 2013). The age uncertainty on this improved chronology is approximately 1500 years during the LIG, which is excellent compared to most other LIG data. Air content measurements from such ice cores have been used to attempt to infer changes in East Antarctic surface elevation over the past 200 kyr (e.g. Martinerie et al. 1994). However, Bradley et al. (2012) demonstrated that existing East Antarctic ice-core sites would experience negligible elevation change in response to a past WAIS collapse, and unknowns in firn modeling make the conversion from air content to atmospheric pressure, needed to infer elevation changes, highly uncertain. However, water isotope ($\delta^{18}O$) data has been measured with a precision generally better than 0.1‰ on these same ice cores. These well-dated and precise measurements (Fig. 1) hold the tantalizing prospect of establishing accurate rates of AIS change during the LIG.

Steig et al. (2015) and Holloway et al. (2016) tackled the question of whether changes in the AIS, particularly ice loss from West Antarctica, would exert a significant control over the $\delta^{18}O$ signal recorded in Antarctic ice cores. Using $\delta^{18}O$-enabled climate modeling, both demonstrated that significant West Antarctic mass loss or gain would cause major changes that should be observable in ice cores from both West and East Antarctica. Key patterns in ice-core $\delta^{18}O$ can be generated by melt from the AIS via resulting influences on atmospheric circulation, sea surface temperatures, and sea-ice extent around Antarctica (Holloway et al. 2017).

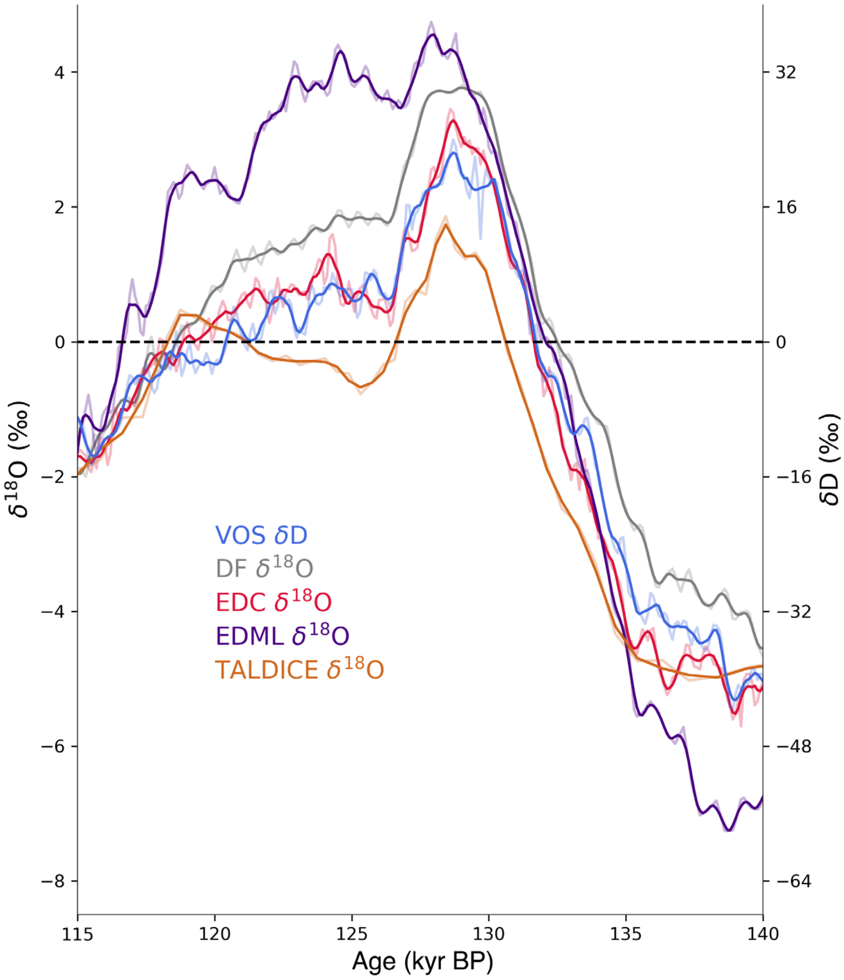

Figure 1: Last interglacial (~129-116 kyr BP) δD and $\delta^{18}O$ anomalies (relative to the most recent 3 kyr BP) from the Vostok (VOS), Dome Fuji (DF), EPICA Dome Concordia (EDC), EPICA Dronning Maud Land (EDML), and Talos Dome (TALDICE) ice-core records. Raw ice-core data (light lines) are shown as well as a smoothed record (dark lines). The locations (filled circles) of these ice cores are shown in Figure 2.

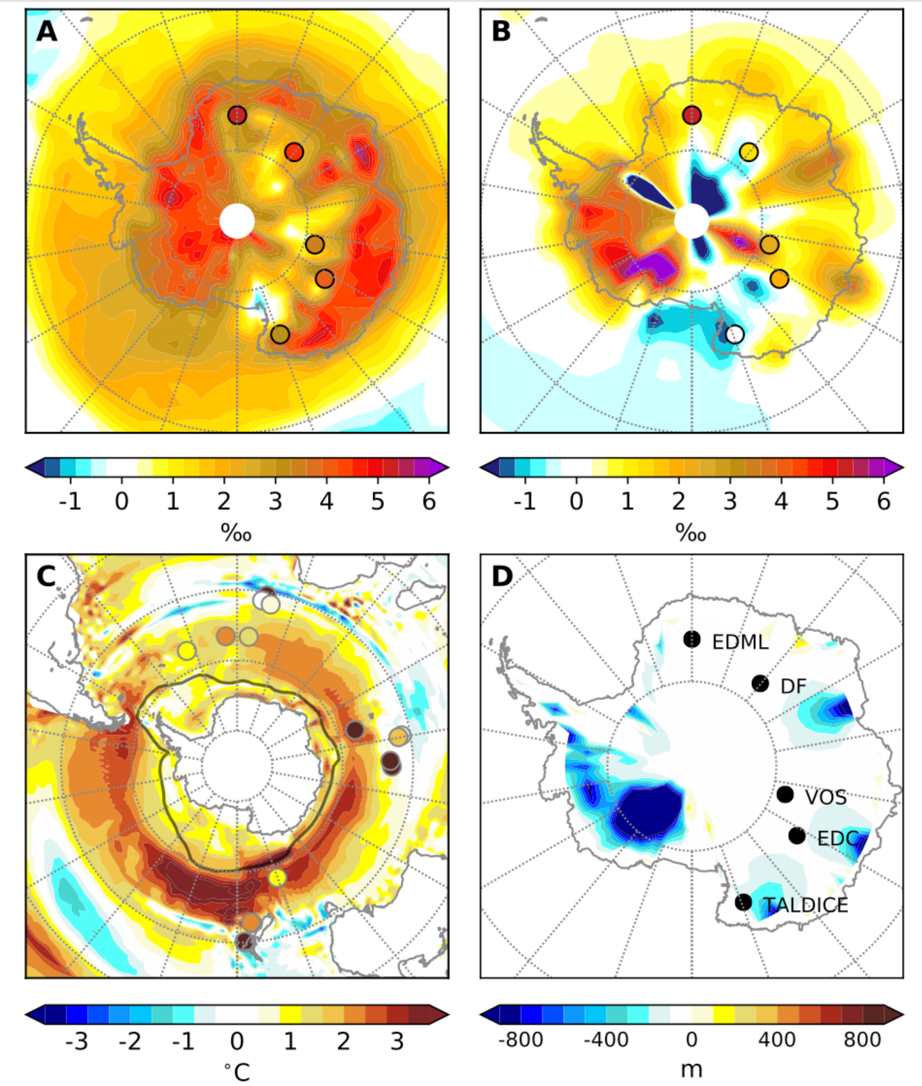

Figure 2: (A) Anomalies in Antarctic δ[18]O from a 128 kyr BP HadCM3 climate model experiment relative to the corresponding pre-industrial experiment. **(B)** As in **(A)** but for a 125 kyr BP experiment including no meltwater forcing and Antarctic ice-sheet topography equivalent to the minimum ice-sheet extent (DeConto and Pollard 2016). **(C)** Simulated summer (JFM) sea surface temperature anomalies (reconstructed anomalies from Capron et al. (2014) are shown as filled circles) and winter sea-ice extent scaled corresponding to **(A)**. **(D)** Antarctic elevation anomalies corresponding to **(B)** and locations of measured ice-core δ[18]O anomalies shown in **(A)**, **(B)**, and Figure 1. See Holloway et al. (2018) for more details.

All of these aspects exert a strong and readily identifiable influence on δ[18]O at the Antarctic ice-core sites (Holloway et al. 2016, 2018).

Constraints from ice-core data thus far

Holloway et al. (2016) investigated whether the distinctive peak in δ[18]O observed in ice cores at ~128 kyr BP (Fig. 1) was due to the loss of West Antarctic ice, but concluded that it was extremely likely that the WAIS was largely still intact at 128 kyr BP. A recent extension of this work (Holloway et al. 2018) using a fully coupled, isotope-enabled climate model demonstrates that the reconstructed penultimate deglacial meltwater event (around 0.2 Sv of meltwater input to the North Atlantic region over around 4 kyr) appears to explain the peak at 128 kyr BP in δ[18]O, via the well-known bipolar seesaw mechanism; these results indicate that meltwater input over ~3600 years can generate the whole ice-core δ[18]O signal at 128 kyr BP (Fig. 2a). The succession of events is thus: (i) Meltwater from Northern Hemisphere ice sheets caused warming of the Southern Ocean; (ii) This in turn melted Antarctic sea ice over a period of around 3-5 kyr BP; and (iii) The loss of sea ice subsequently imprinted itself on the ice cores as a peak in δ[18]O (Holloway et al. 2017). This work also indicates that the climate models used here appear to be capable of accurately capturing key timings and processes during past warm periods.

Of course, the work described above does not address the main aim, which is to uncover AIS change throughout the entire LIG. In particular, determining how the AIS may have responded after the 128 kyr BP ice-core δ[18]O peak (itself a response to the reconstructed Southern Ocean warming and sea-ice retreat; e.g. Fig 2c) is yet to be a focus of ice-core modeling research (e.g. Holloway et al. 2016). The research performed to date does, however, provide key results to build upon:

- It establishes confidence in both climate models and in our understanding of LIG atmosphere and ocean dynamics. It also means that we now know with some confidence that the LIG δ[18]O peak (shown in Fig. 1) was caused primarily by Antarctic sea-ice retreat in response to relatively high Southern Ocean temperatures, themselves generated by meltwater from the penultimate deglaciation.
- It indicates that the AIS was likely resilient to higher-than-present sea surface temperatures and reduced Antarctic sea ice during the early LIG, since the AIS was largely intact at 128 kyr BP. Parts of the AIS could, however, have melted shortly after 128 kyr BP (e.g. Fig. 2b) in direct response to the warming, but this has yet to be established.

Next steps

Focused study on the period following the ice-core δ[18]O peak (~125 kyr BP; Fig. 1) may provide important information on the magnitude and timescales of AIS change in response to a period of reduced sea ice and Southern Ocean warming. An example is illustrated in Figure 2b; ice-core δ[18]O data at 125 kyr BP may be better explained using a reduced AIS configuration relative to present day, suggesting substantial continental ice loss in the 3 kyr period following the reconstructed LIG Antarctic sea-ice minimum.

Based on these recent advances, we suggest that the next steps should include: (i) checking, using δ[18]O-enabled models, how ice cores may respond to other types and magnitudes of AIS changes (e.g. Fig. 2b), (ii) assessing whether our current ice-core data are sufficient to establish AIS changes; and (iii) obtaining new LIG ice-core data as necessary to constrain the models. Once these steps have been taken, we may find ourselves in a position to be able to pin down the most likely timing and contribution of the AIS to GMSL during this past warm interval.

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PAGES

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Advances in glacial isostatic adjustment modeling

Glenn A. Milne[1], D. Al-Attar[2], P.L. Whitehouse[3], O. Crawford[2] and R. Love[4]

We overview two PALSEA-relevant applications of glacial isostatic adjustment modeling and highlight recent advances. These include the consideration of models with lateral Earth structure and the development of methods to determine optimal parameters and model uncertainty.

The primary aim of the PALSEA (PALeo constraints on SEA level rise) working group is to promote and improve the use of constraints from observations and modeling of past sea-level changes and ice-sheet extent to better inform projections of future sea-level change. Glacial isostatic adjustment (GIA) – the deformational, gravitational and rotational response of the Earth to past ice-sheet evolution – plays an important role in reaching this objective in several respects (see Editorial, this issue). Here we review recent advances in two key PALSEA-relevant GIA model applications - estimating global ice volume during past warm periods and the contribution of GIA to future sea-level change - and consider recent developments towards improving uncertainty estimation in GIA model output which is central to these applications.

Estimating global ice volume during past warm periods

A core aim of PALSEA is to estimate the peak in global mean sea level (GMSL), from which global ice volume can be inferred, during past warm periods when GMSL was greater than at present. There are three periods in relatively recent Earth history for which observations indicate that GMSL was above the present value: the Mid-Pliocene warm period (~3 Myr BP), Marine Isotope Stage 11 (~420-370 kyr BP), and Marine Isotope Stage 5e (~129-116 kyr BP; the Last Interglacial). Estimating GMSL from a sparse distribution of local relative sea level (RSL) indicators is non-trivial due to under-sampling and the fact that local sea level can depart significantly from the global mean value. GIA is one of a number of processes (e.g. dynamic topography and sediment loading; see contributions on these topics in this issue) that should be considered when estimating GMSL from RSL records. A small number of studies have demonstrated that the GIA "overprint" can significantly bias estimates of GMSL for each of the three warm periods mentioned above (e.g. Raymo et al. 2011; Raymo and Mitrovica 2012; Kopp et al. 2009; Dutton and Lambeck 2012; Dendy et al. 2017). Specifically, they show that the GIA contribution to RSL can range from order 1-10 m depending on the data location and the choice of model inputs (parameters).

Regarding model inputs, the ice-loading history and Earth viscosity structure are the most important. There is considerable uncertainty in both of these, so it is necessary to perform model-sensitivity analyses to map out which parametric uncertainty dominates at the specific data locations. The analysis of Dendy et al. (2017) is the most thorough in this respect. In addition to uncertainty in model parameters, limitations in the model itself, due to, for example, missing processes or simplifications in the geometry, can lead to considerable error or bias in the output (formally known as model structural error). A recent advancement in this area is the development of coupled models that account for feedbacks between GIA-related processes and ice dynamics (see Whitehouse 2018). One limitation in all of the GIA studies noted above is the use of spherically symmetric Earth models in which parameters vary only with depth. GIA models that include a 3D Earth structure have been applied in some studies that consider post-Last Glacial Maximum sea levels or geodetic observations (Whitehouse 2018) and the impact has been shown to be non-negligible. However, the computational expense of these models currently prohibits their use for earlier times such as those mentioned above due to the longer time integrations required.

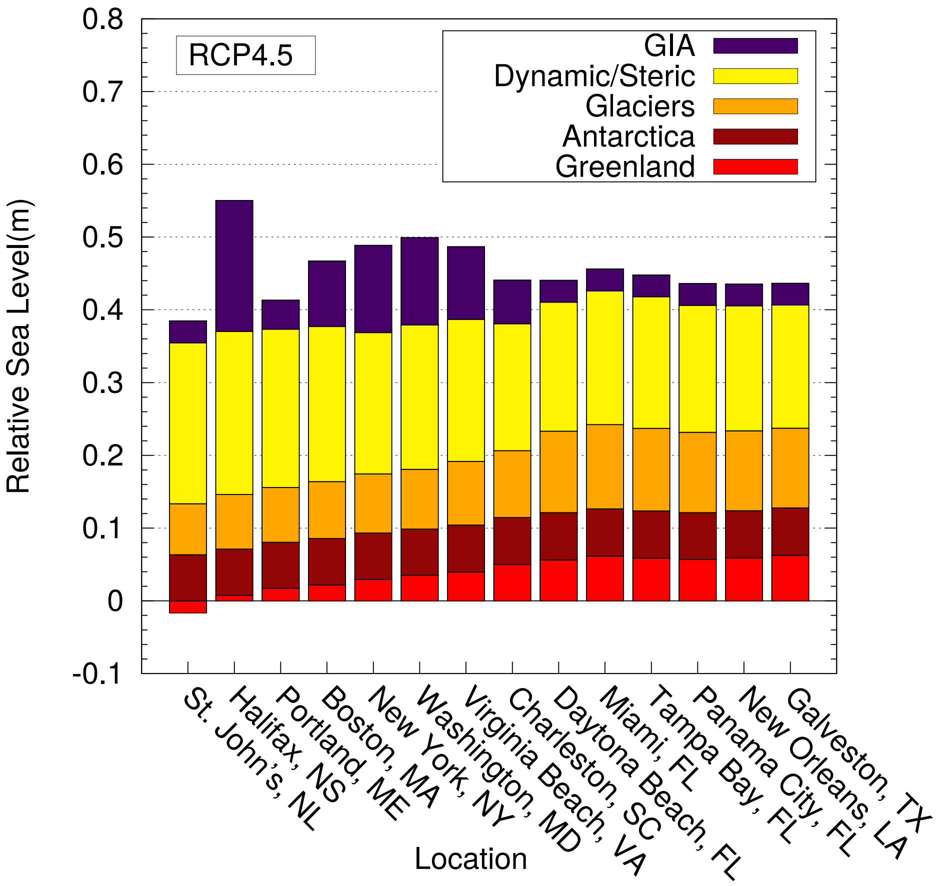

Figure 1: Regional sea-level projections for 2085–2100 relative to 2006–2015 for the intermediate representative concentration pathway (RCP) 4.5. The future contribution from melting of land ice is determined from the respective sea-level fingerprints of the Antarctic and Greenland ice sheets as well as the global distribution of glaciers and ice caps. The contribution from ocean circulation (dynamic) and steric changes is also shown. Figure adapted from Love et al. (2016).

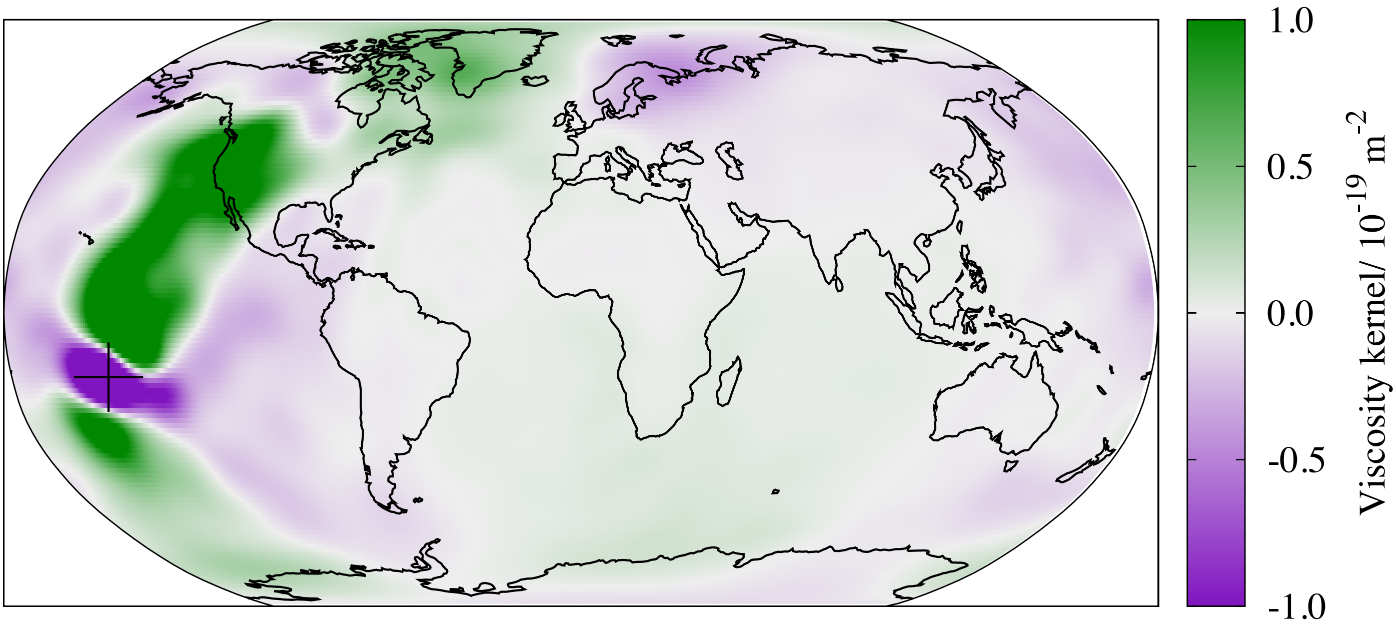

Figure 2: The sensitivity of modeled sea level in Tahiti (as marked by the cross) 9000 years ago to perturbing the background mantle viscosity structure at a depth of 1756 km. The background viscosity structure is scaled from a tomographic model of seismic shear wave-speed variations using a simple empirical relation. Results for other depths and times, when combined, define sensitivity kernels that can be used to invert RSL data from Tahiti for an optimal 3D viscosity model with uncertainty estimates (Crawford et al. 2018).

The contribution of GIA to future sea-level change

The construction of comprehensive regional RSL projections, which requires the compilation and summation of contributions from different processes, has only been attempted relatively recently (e.g. Slangen et al. 2014). In regions that were recently deglaciated, GIA will be a significant contributor to future RSL change. The GIA component has been either explicitly included using process model output (Slangen et al. 2014) or estimated from tide-gauge records as part of a linear trend that could also include other secular processes (for example, tectonics; Kopp et al. 2014). In the former case, one issue has been the lack of accurate uncertainty estimates on GIA model output.

Recent studies (Love et al. 2016; Yousefi et al. 2018) have sought to address this issue by using a large suite of model runs sampling a broad range of Earth and ice-model parameters as well as a state-of-the-art regional RSL database to estimate model uncertainty. The PALSEA-led effort to produce regional RSL databases using standard protocols (Khan et al. this issue) has greatly enhanced the quality and availability of these databases, facilitating improved GIA model development. The studies of Love et al. (2016) and Yousefi et al. (2018) demonstrate the relative importance of GIA for future sea-level change along the Atlantic and Pacific coasts of North America (e.g. Fig. 1) and, perhaps more importantly, that uncertainty in defining the GIA contribution is large and that spherically symmetric Earth models are not able to accurately reproduce observations of recent RSL change in these regions.

Towards improved GIA models

Two key aspects of GIA model development relevant to the applications outlined above include the use of Earth models that can accommodate lateral Earth structure as well as methods to estimate model parameters and the uncertainty associated with each. Past studies have used large ensemble forward modeling and statistical methods to estimate uncertainty in the ice (e.g. Tarasov et al. 2012) and spherically symmetric Earth models (e.g. Caron et al. 2017). Given the interdependence of these model inputs, future analyses should aim to jointly infer ice- and Earth-model parameters and their uncertainty. Estimating parametric uncertainty is more challenging with 3D Earth models given the much larger parameter space and the uncertainty in constraining lateral viscosity structure (Whitehouse 2018).

A step towards overcoming the latter issue is the determination of sensitivity kernels for GIA observables. These kernels quantify the linearized dependence of observations on underlying parameters, and can be used in both inversions and uncertainty quantification (Fig. 2). Early studies estimated such kernels using finite-difference approximations (e.g. Zhong et al. 2003), but here the computational cost scales with the number of model parameters, and so rapidly becomes infeasible. A better approach is through the use of the adjoint method, which produces exact kernels at the cost of just two forward simulations (Al-Attar & Tromp 2014). Using this approach, the inversions for ice history and 3D Earth structure from GIA observables is a realistic goal, with promising synthetic tests having been performed recently (Crawford et al. 2018; Fig. 2).

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The importance of dynamic topography for understanding past sea-level changes

Jacqueline Austermann[1] and Alessandro M. Forte[2]

Mantle flow pushes Earth's surface up or drags it down, causing kilometer-scale topographic anomalies. As this so-called "dynamic topography" evolves, it can influence local sea level and the sensitivity of ice sheets to climate change.

Local sea-level reconstructions have been the foundation for understanding past ice-sheet behavior, especially records spanning the last deglaciation and past interglacial periods. Linking the evolution of local sea level to global mean sea level, which is also related to ice-volume changes, requires a correction for any uplift or subsidence of the field site that has occurred since the sea-level record was formed. Such vertical movements can occur due to tectonic crustal deformation, glacial isostatic adjustment (GIA; e.g. Milne et al. this issue), erosion, or sediment loading (e.g. Ferrier et al. this issue).

Another process that shapes Earth's surface is dynamic topography, which is the topography generated by vertical forces arising from buoyancy-induced flow within the Earth's mantle (Fig. 1). While this process was first recognized decades ago, the full extent to which dynamic topography affects sea-level records over the Plio-Pleistocene and interacts with the Earth climate system as a whole (e.g. ice sheets and oceans) has only recently been explored.

Definition of mantle dynamic topography

Today's surface topography is shaped by crustal isostasy, in which, for example, crustal roots support mountain belts, and dynamic topography, which is driven by stresses in the sub-crustal mantle that are caused by (shallow) isostatic and (deeper) flow-driven contributions (Forte et al. 1993). Both of these components evolve with time as lateral density variations in the sub-crustal mantle convect and cool the rocky mantle. This leads to spatio-temporal changes in dynamic topography that contribute to the evolution of Earth's surface.

While convection extends from the lithosphere to the core-mantle boundary, sensitivity studies reveal that density heterogeneity in the shallow mantle (e.g. the lithosphere and asthenosphere) contributes most to the overall topographic signal (Forte et al. 2015). The definition of dynamic topography used here includes the topographic signature of the lithosphere (e.g. cooling and subsidence of the oceanic lithosphere), as it constitutes the upper thermal-boundary layer of Earth's convective interior. However, it is important to note that a lithospheric signal is sometimes removed from models or observations in order to investigate sub-lithospheric or deep-mantle drivers of surface topography.

Present-day dynamic topography

Estimates of present-day dynamic topography can be obtained by removing the crustal isostatic effect from the observed topography, which requires knowledge of the crustal thickness and density, as well as overlying sediment, water, and ice loads. Global estimates of dynamic topography reveal large-scale undulations with magnitudes that exceed 2 km (Forte et al. 2015). Within the oceans, a detailed assessment has shown that the sub-lithospheric contribution to dynamic topography has a magnitude that ranges from approx. -1.5 km (Australia-Antarctic discordance) to 2 km (around Iceland) and can have steep lateral gradients (e.g. 1 km of dynamic topography change over a lateral distance of 1000 km along the West African Margin; Hoggard et al. 2016).

These observations of dynamic topography can be used to improve numerical models of mantle convection and understand the dynamics of the Earth's interior. Models of present-day mantle convection require an input density field of the Earth's interior (estimated from seismic tomography), a rheological constitutive equation that describes the relationship between deformation and stress, and boundary conditions, which govern the tangential stresses at the surface and core-mantle boundary. Assuming conservation of mass and momentum, one can determine the instantaneous velocity and dynamic stress fields (Forte et al. 2015). The resulting dynamic topography is calculated by balancing radial stresses at the Earth's surface (Fig. 1). Current mantle convection models provide satisfactory fits to the present-day observations of dynamic topography and gravity anomalies (Simmons et al. 2010); however, debate over the largest and small-scale features still exists (Hoggard et al. 2016).

Changes of dynamic topography

To understand the role of dynamic topography in sea-level reconstructions, we are interested in the temporal evolution of dynamic topography, rather than its absolute

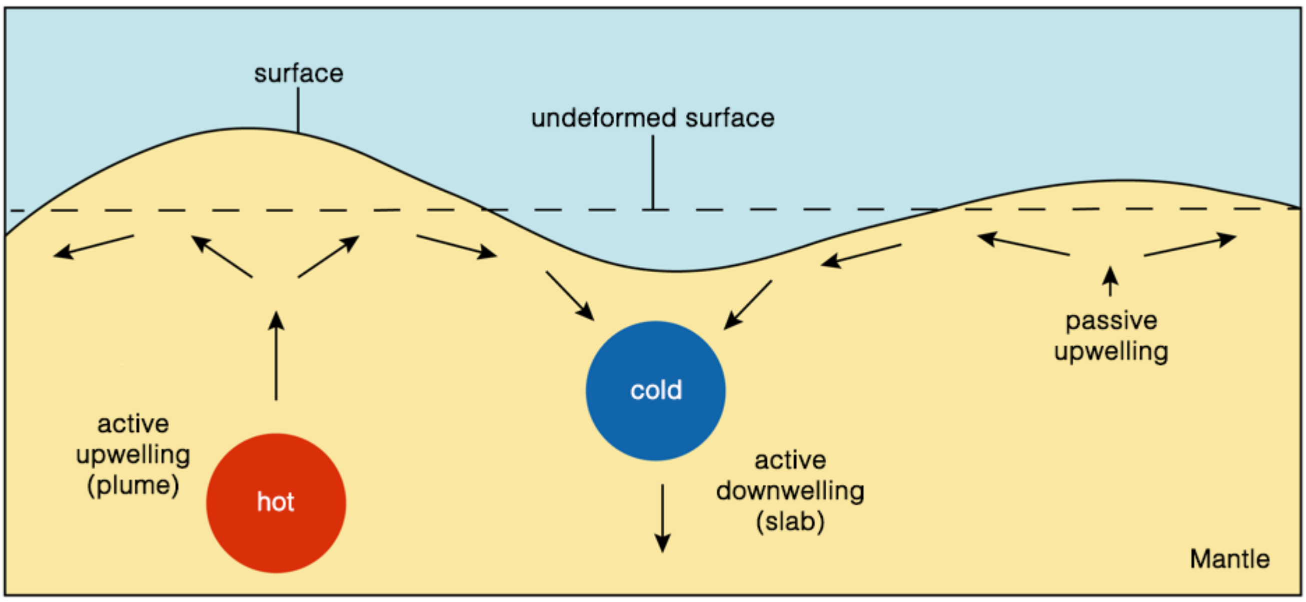

Figure 1: Illustration of how flow in the mantle can generate dynamic surface topography (modified from R. Moucha, personal communication).

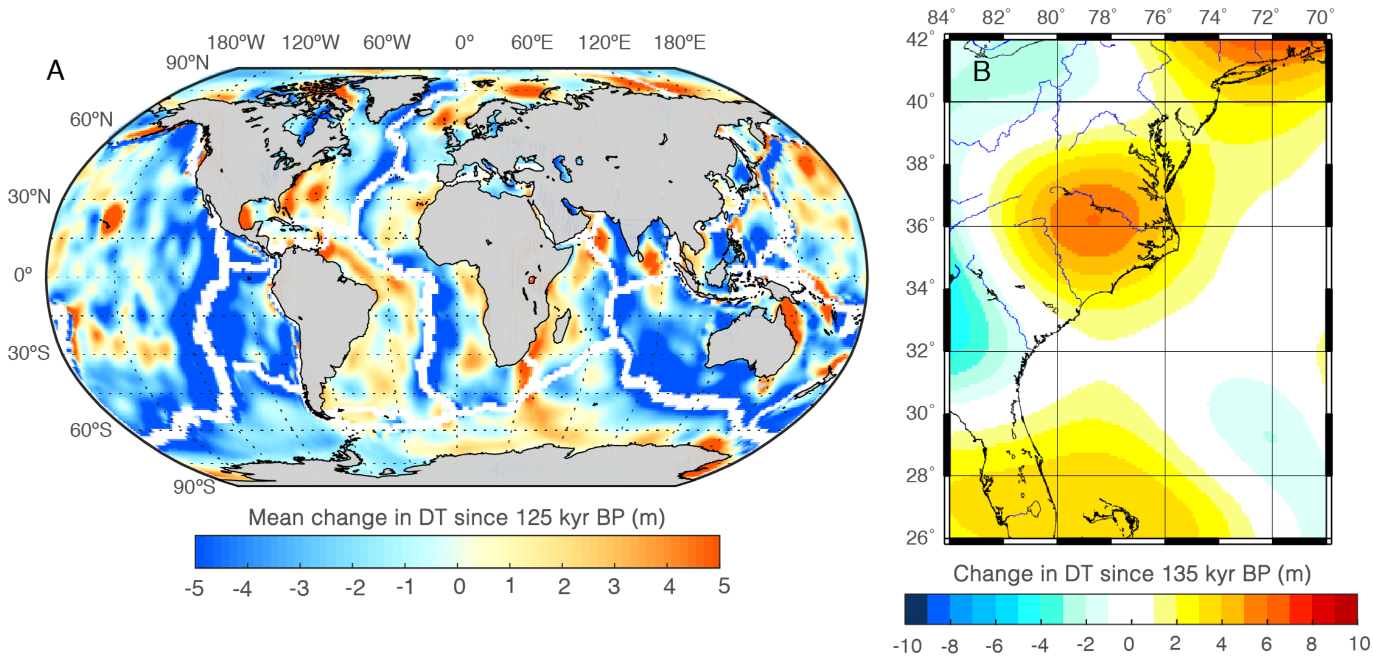

Figure 2: Model results of dynamic topography (DT) change since the last interglacial period from **(A)** the mean of 12 different models (Austermann et al. 2017) and **(B)** one preferred model scenario for the US east coast (Dutton and Forte 2016) based on mantle convection reconstructions by Glišović and Forte (2016).

(present-day) value. Importantly, present-day amplitudes do not provide information on the change of dynamic topography through time. For example, locations that are dynamically supported today are equally likely to be uplifting or subsiding.

Changes in dynamic topography can be deduced from a variety of geological and geomorphological data. For example, a careful analysis of stratigraphy from onshore and offshore Australia indicates changes in dynamic topography (subsidence) of up to 75 m/Myr on the Northwest Shelf (Czarnota et al. 2013). Paleo shorelines from the US east coast, Australia, and South Africa indicate rates of uplift of up to 20 m/Myr (Rovere et al. 2014). Model-derived estimates of the rate of change in dynamic topography can vary from a few meters per million years (Flament et al. 2013) up to over 100 m per million years (Rowley et al. 2013; Austermann et al. 2017) depending on the model input parameters, particularly the viscosity structure, magnitude of density perturbations, and whether density variations in the asthenosphere and lithosphere are considered.

The contribution of dynamic topography to past sea-level and ice-sheet changes

Initial indications that dynamic topography can cause local sea-level changes stems from observations and modeling work on continental flooding histories over the Phanerozoic (Bond 1979; Gurnis 1993). It is now recognized that local paleo sea-level reconstructions, whether from continental flooding, backstripping at passive margins, or stratigraphy in sedimentary basins, are not equal to global mean sea-level change, due to regionally varying changes in dynamic topography (Moucha et al. 2008). This limitation also applies to the more recent past of the Plio-Pleistocene.

Mapping of Pliocene shorelines shows significant variations in their elevations relative to one another and along the shoreline feature (Rovere et al. 2014). The most prominent example is the Orangeburg Scarp along the US east coast, which exhibits a change in elevation of up to 40 m after correcting for glacial isostatic adjustment. Rowley et al. (2013) have shown that this relative deformation can be explained by changes in dynamic topography. However, uncertainties in input parameters for numerical models of dynamic topography, as well as an incomplete understanding of the contribution of competing deformation processes, such as sediment loading, still hinder a quantification of global mean sea level and, hence, ice-sheet stability during this time period. This work prompted a re-examination of sea-level records from earlier interglacials. Model predictions indicate that dynamic topography can contribute up to several meters of deformation to local sea-level records dating to the last interglacial period (Fig. 2). This modeling is corroborated by a significant correlation between the predicted deformation and the observed elevations of sea-level indicators from the last interglacial (Austermann et al. 2017). Estimates of excess global mean sea level during this time period are 6-9 m (Dutton et al. 2015), which does not account for dynamic topography. If key sites have been affected by changes in dynamic topography, this 6-9 m estimate could be incorrect by a few meters. Improving estimates of global mean sea level and ice-sheet stability during past interglacials therefore hinges on a better understanding of dynamic topography.

Mantle flow underneath ice sheets can also directly affect ice-sheet evolution. For example, dynamic topography changes along the grounding line of the Antarctic Wilkes Basin potentially made this sector more susceptible to retreat in the Pliocene epoch (Austermann et al. 2015).

Mantle flow directly affects sea-level records, ice-sheet behavior, and ocean dynamics, which has led to intriguing new links between the solid Earth and the climate system. This nascent connection provides promising avenues to potentially answer some open questions in paleoclimate research, as well as the opportunity to expand observational constraints on the structure and dynamics of Earth's deep interior.

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Paleo ice-sheet modeling to constrain past sea level

Bas de Boer[1], F. Colleoni[2], N.R. Golledge[3] and R.M. DeConto[4]

Numerical ice-sheet models are a key tool to estimate the contribution of ice sheets to past sea-level change. Here, we highlight a few developments and applications of ice-sheet models that allow ice-sheet contributions to past sea-level changes to be estimated.

Past warm intervals such as the mid-Piacenzian Warm Period (mPWP: 3.264-3.025 million years ago) or the Last Interglacial (LIG: 129-116 thousand years (kyr) ago) have been widely studied to constrain past sea-level changes (e.g. Sutter et al. 2016; de Boer et al. 2017). Also, those intervals are studied for process understanding of the Earth system as an analogue for future warming (e.g. DeConto and Pollard 2016). Geological evidence indicates that global mean sea level during the mPWP and LIG were likely to be up to 20 m or more (Miller et al. 2012) and 6-9 m (Dutton et al. 2015) relative to the present, respectively. This reflects the cumulative (a)synchronous contribution of the Greenland and Antarctic ice sheet (GrIS and AIS). Numerical ice-sheet models are the only means to determine their individual contribution to past sea-level changes.

Ice sheets in the climate system

Over the past decades, critical aspects of ice-sheet models related to the interactions with the ocean, the atmosphere, basal hydrology, and the solid Earth, have been substantially improved. The mass budget of the ice sheets is largely affected by processes that act at the interface between these different systems (Fig. 1). Of the present mass budget of the GrIS, surface melting accounts for 60% of the mass loss (van den Broeke et al. 2016). During the mPWP (besides increased greenhouse gases) and the LIG, higher summer insolation (Fig. 1c,d) can increase mass loss significantly and induce ice-sheet retreat (e.g. Robinson and Goelzer 2014; de Boer et al. 2017).

The ocean plays a key role in AIS changes (e.g. Sutter et al. 2016; Golledge et al. 2017), largely due to the fact that large sectors of the bed lie well below sea level. Punctuated intrusion of relatively warm and saline ocean water – Circumpolar Deep Water (CDW) – underneath the ice shelves (Fig. 1b) enhances ice-shelf basal melting and thinning, leading to a significant contribution to the mass loss of ice shelves. Under warm climatic conditions, climate models show that intrusion of CDW is fostered by a southward shift and strengthening of the westerly winds, which leads to a more vigorous Antarctic Circumpolar Current (ACC), and increases sub ice-shelf melting (see also Fig. 4 in Colleoni et al. 2018).

Development of paleo ice-sheet models

The basic principles that enable the use of 3D ice-sheet models for long-term paleoclimate applications involve the adoption of approximate flow equations (i.e. the shallow ice and shallow shelf approximations). This allows for relatively fast calculations (e.g. 100 kyr in a few hours), on coarse grids of 20-40 km, of continental-scale ice sheets. Complex atmospheric or oceanic interactions would require coupling (a)synchronously with a climate model, but are still computationally too expensive. Therefore, in stand-alone ice-sheet models, atmospheric and oceanic variations are crudely parameterized, and long-term transient evolution in surface air temperatures and precipitation usually follows reconstructions of ice-core or benthic oxygen isotope records (e.g. Huybrechts 2002; de Boer et al. 2017).

To determine the surface mass balance, long-term paleo ice-sheet simulations rely on simple parametrizations of snow accumulation and surface melting. Melt can be computed using the Positive Degree Day method (PDD), which uses only temperature (e.g. Huybrechts 2002), or alternatively accounting for insolation forcing on surface melt through the Insolation Temperature Melt (ITM) model (e.g. Robinson and Goelzer 2014). PDD and ITM are computationally inexpensive parameterizations and capture

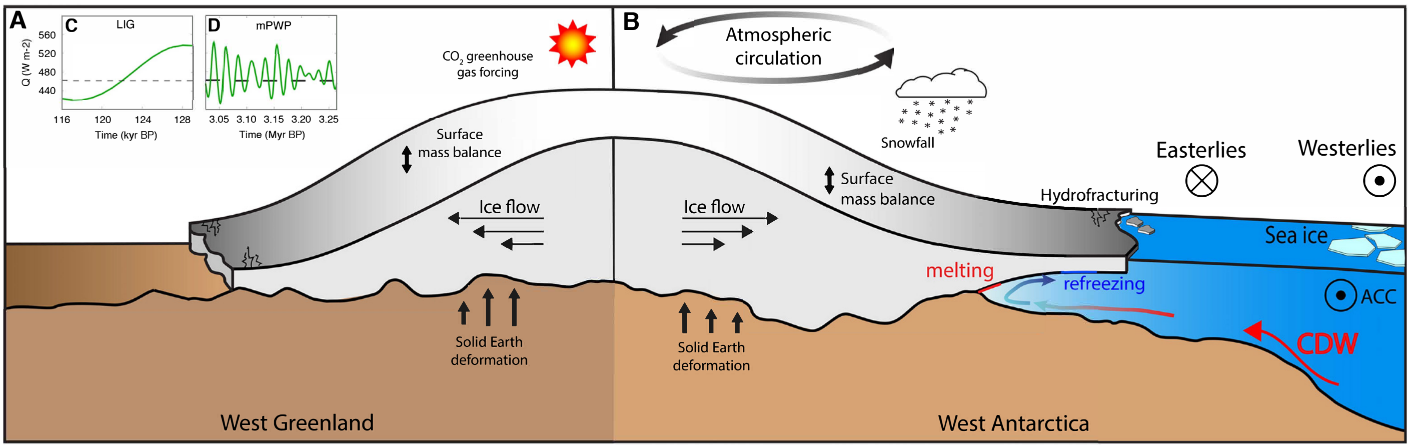

Figure 1: Schematic representation of an ice sheet that **(A)** terminates on land. Heavy crevassing at the edges, insolation, snowfall, and temperature control the mass balance. **(B)** Schematic of an ice sheet that terminates at the ocean. Melting at the grounding line is induced due to intrusion of CDW in the cavities underneath the ice shelves. Hydrofracturing and sub-shelf melting dominate the mass balance of ice shelves that buttress the ice sheet. Inset shows insolation at June 65°N (Laskar et al. 2004) during **(C)** the LIG (129-116 kyr ago) and **(D)** the mPWP (3.264-3.025 Myr ago). The horizontal dashed line shows present insolation at 462.29 W m^{-2}.

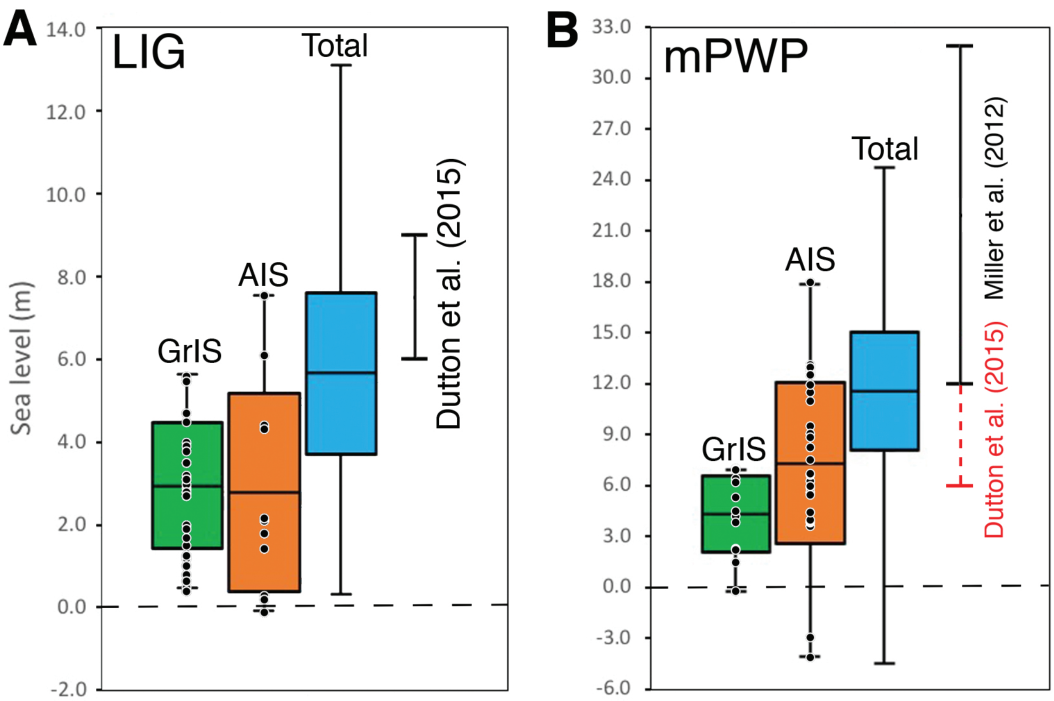

Figure 2: Overview of published sea-level contributions (in meters) from the GrIS (green) and AIS (orange). **(A)** The LIG compared with the range from Dutton et al. (2015) and **(B)** the mPWP compared with the range from Dutton et al. (2015) in red, and Miller et al. (2012) in black. Simulations are shown by the black dots in **(A)** and **(B)**; sources are listed in the online supplementary material. From each source we used either one value or the mean value of an ensemble, including the range. Boxes indicate the total mean, with one standard deviation. The maximum and minimum modeled ice sheet within the total ensemble are indicated by the whiskers (in black). Totals (blue) are calculated by summing the mean, minimum and maximum and averaging the standard deviations from the GrIS and AIS.

the glacial-interglacial behavior of continental-scaled ice sheets, but differences can be large relative to full energy balance models (e.g. Plach et al. 2018).

Similarly, for the ice-shelf-ocean interface, long-term ice-sheet simulations rely on local heat-balance parameterizations using a vertically uniform oceanic temperature, or a spatially varying field based on present-day observations (e.g. DeConto and Pollard 2016). More complex schemes are being developed, such as plume-melt models (Lazeroms et al. 2018), which account for the interaction with the local geometry and the spatially varying oceanic temperatures, or ocean box models, directly coupled to ice-sheet models, which simulate the overturning circulation in ice-shelf cavities (Reese et al. 2018). Accordingly, model developments are critical to improve calculation of GrIS and AIS contribution to past and future sea-level variations.

Modeling past sea level from the GrIS and AIS

Over recent decades, numerous studies have estimated the contribution to past sea level from the GrIS and AIS (Fig. 2). Different approaches have been used, using either a single surface-air temperature anomaly or steady state climate forcing, transient or equilibrium simulations, or fully coupled to a (lower resolution) climate model (see for example overviews in Dutton et al. 2015; Dolan et al. 2018; Plach et al. 2018). The broad range of simulated individual contributions from the GrIS and AIS clearly illustrate the uncertainties related to the use of different ice-sheet and climate models to estimate past sea-level changes (as also shown in Dolan et al. 2018).

The total mean sea-level change estimated from ice-sheet models is on the low end compared to the geological evidence for both the LIG and the mPWP (blue boxes in Fig. 2a,b). A higher contribution from the LIG AIS could stem from interactions with the ocean (e.g. Sutter et al. 2016), although two-way interaction with the climate cannot be ignored. The driving processes leading to increased ice-cliff calving are not yet fully understood but could account for a significant retreat of the LIG and mPWP AIS (DeConto and Pollard 2016), whereas gaps in knowledge of the subglacial topography leads to greater uncertainties for AIS contribution to mPWP sea level (Gasson et al. 2015). Surface melt of the GrIS can be significantly enhanced relative to the present due to increased summer insolation (Fig. 1c,d) during the mPWP and LIG (Robinson and Goelzer 2014; de Boer et al. 2017).

Outlook

Precisely quantifying the impact of processes, such as calving and ice-cliff failure, on the GrIS or AIS and the impact of the interaction between ocean warming and sub-glacial topography on ice-sheet retreat remains challenging (DeConto and Pollard 2016). Nonetheless, more precisely located and time-varying geological data will allow for a much more detailed study of coupled paleo ice-sheet climate simulations. This might reduce model-data discrepancies and lead to a consensus of past sea-level contributions from the GrIS and AIS in the coming years, thus providing stronger constraints to future sea-level projections.

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Arctic warming and the Greenland ice sheet during the Last Interglacial

Bette L. Otto-Bliesner[1], M. Lofverstrom[2], P. Bakker[3] and R. Feng[4]

The Last Interglacial is a recent warm interval with sea level higher than today. Climate modeling groups are simulating this time interval. Here, we illustrate feedbacks from vegetation changes and retreat of the Greenland ice sheet on regional responses to orbital forcing.

The Last Interglacial (LIG, 129 to 116 kyr BP; thousands of years before present, where present is defined as 1950 CE) is recognized as an important time interval for testing our knowledge of interactions between climate and ice sheets in warm climate states that led to deglaciation of the Greenland and potentially western Antarctic ice sheets. The LIG was already recognized as an important time period of relevance for the future in the First Assessment Report of the Intergovernmental Panel on Climate Change (IPCC; Folland et al. 1990). It gained more prominence since the Fourth and Fifth Assessment reports (IPCC AR4 and AR5) with new reconstructions highlighting that global mean sea level was ~6-9 m higher than present for several thousand years (Dutton et al. 2015). Questions remain regarding the contribution of the Greenland ice sheet to this highstand, as well as when and by how much temperatures peaked in the Northern Hemisphere high latitudes.

PMIP4-CMIP6 Last Interglacial simulations

Positive boreal summer insolation anomalies (with respect to present), associated with the orbital configuration of eccentricity, perihelion, and obliquity (Berger and Loutre 1991), occurred in the Northern Hemisphere from about 135 to 122 kyr BP, with maximum anomalies from 130 to 124 kyr BP. Anomalies were greater than 50 W/m^2 for July at 65°N from 128 to 124 kyr BP. Correspondingly, negative austral summer insolation anomalies were present in the Southern Hemisphere. Antarctic ice-core records reveal that the greenhouse gas concentrations were relatively constant from 128 to 121 kyr BP; the atmospheric CO_2 concentration was stable at pre-industrial values (about 280 ppmv) between 128 and 120 kyr BP (Schneider et al. 2013), while atmospheric CH_4 concentrations peaked around 720 ppbv at ~128.5 kyr BP and then declined slowly (Loulergue et al. 2008).

The suite of Paleoclimate Modelling Intercomparison Project (PMIP4) simulations in the Coupled Model Intercomparison Project (CMIP6) include a Tier 1 experiment for 127 kyr BP (*lig127k*; Otto-Bliesner et al. 2017). It is designed to address and compare the climate responses to orbital forcings stronger than the mid-Holocene experiment for 6 kyr BP (Fig. 1). The CMIP6 *lig127k* experiment will provide a basis to investigate the linkages between ice sheets and climate change in collaboration with the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6; Nowicki et al. 2016).

The CMIP6 *lig127k* experiment is a time-slice (or equilibrium) experiment for 127 kyr BP. To provide a large ensemble of simulations from many international modeling groups, the boundary conditions are set to allow easy implementation in the same models used for the future scenarios of CMIP6. That is, the orbital parameters and greenhouse gas concentrations are set to represent 127 kyr BP, while the ice sheets (i.e. Greenland and Antarctica) and global land-ocean distribution are the same as in the pre-industrial control run (*piControl*). Although aerosols and vegetation may be interactive in some CMIP6 models, those without these capabilities are asked to use the same boundary conditions as in their *piControl* simulation.

Vegetation feedbacks

Vegetation during the LIG responded to the latitudinal and seasonal insolation changes associated with the orbital forcing. Pollen and macro-fossil evidence show that boreal forests extended farther north than today and, except in Alaska and central Canada, extended to the Arctic coast (CAPE 2006; LIGA 1991). Given the impact of increased forest cover on albedo and evapotranspiration, these vegetation changes, not included in the CMIP6 *lig127k* experiment unless models realistically simulate them interactively, could have had significant impacts on the surface energy budget in the Arctic, amplifying high-latitude warming (Swann et al. 2011).

To quantify the strength of this climate-vegetation feedback for explaining the inferred Arctic and Greenland warmth during the LIG, PMIP4-CMIP6 also includes a 127 kyr BP Tier 2 experiment where the vegetation cover at Northern Hemisphere high latitudes is changed from tundra to boreal forest. Simulations with the pre-release versions of the Community Earth System Model (CESM) v. 2.0 coupled to the Community Ice Sheet Model (CISM) v. 2.0 indicate that Arctic vegetation responses to the direct orbital warming are important for simulating high-latitude warming and sea-ice extent, and retreat of the Greenland ice sheet and its contribution to the LIG sea-level highstand.

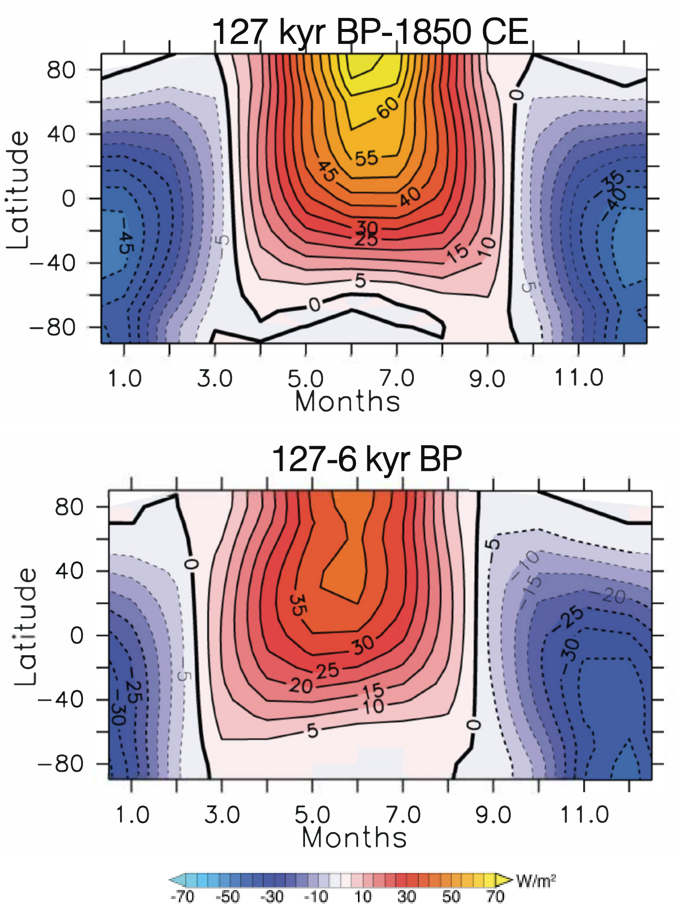

Figure 1: Latitude-month insolation anomalies for 127 kyr BP minus 1850 CE and 127 minus 6 kyr BP.

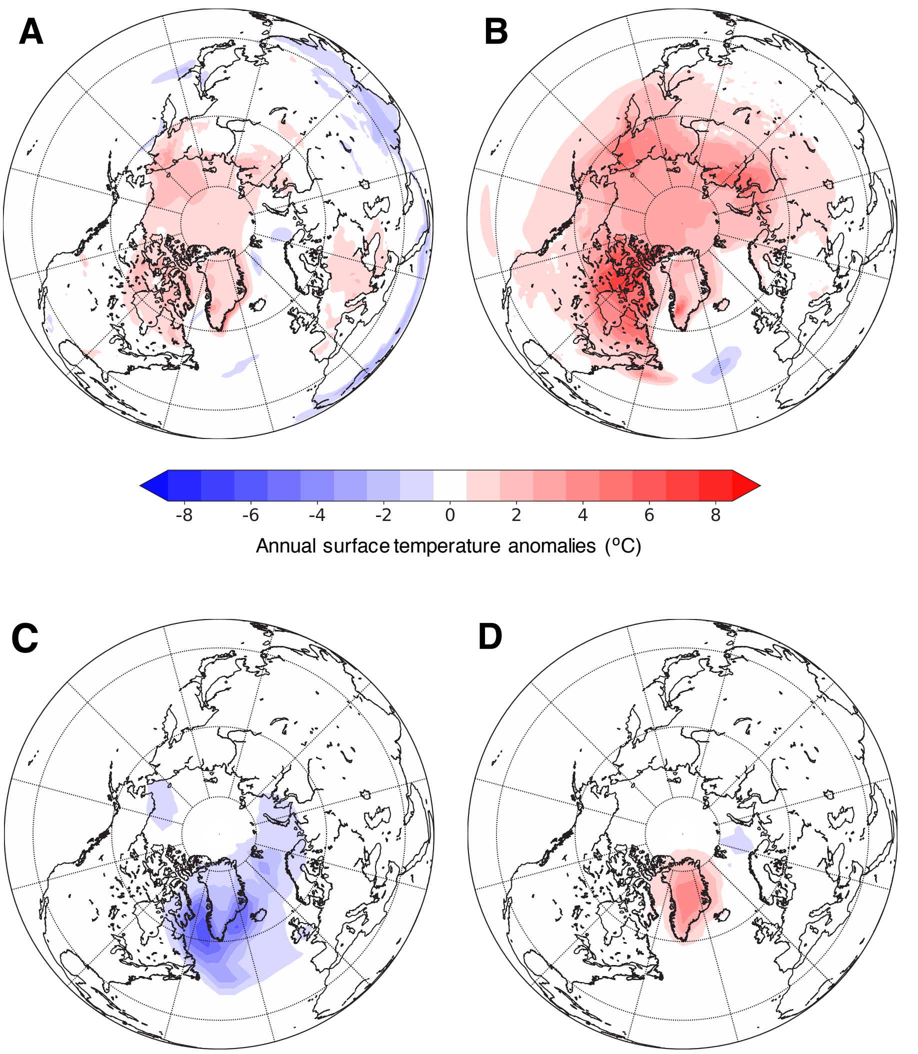

Figure 2: Annual surface temperature anomalies (°C) as simulated by climate models for the Last Interglacial. **(A)** *LIG* (orbital and GHG forcing) minus *PI* (preindustrial control); **(B)** *LIGveg* (*LIG* plus high-latitude tundra replaced by boreal forest) minus *LIG*; **(C)** *LIGmwf* (*LIG* plus Greenland meltwater to North Atlantic) minus *LIG*; and **(D)** *LIGgris* (*LIG* plus albedo and topography changes for retreat of Greenland ice sheet) minus *LIG*. **(A)** and **(B)** are from 127 kyr time-slice simulations with CESM-CISM, **(C)** and **(D)** are from 130 kyr BP time-slice simulations with LOVECLIM.

With orbital and GHG forcing only in a 127 kyr BP CESM-CISM simulation (Fig. 2a), the Arctic and Greenland are warmer than pre-industrial annually, but only modestly, by ~1-2°C over northern North America and northern Eurasia, and ~2°C in western Greenland. The memory of the cryosphere and positive feedbacks from changes in surface and cloud albedo amplify the warmer boreal summer temperatures and reduce sea-ice extent through the boreal winter months. The ice sheet over Greenland retreats minimally in western Greenland, retaining most of the modern ice-sheet area. The overall Greenland surface-mass balance remains positive with Greenland contributing only about 0.5 m of equivalent global sea-level change over 3000 years. The global, annual surface temperature change is ~0°C, similar to the results of LIG simulations assessed in the IPCC AR5 (Masson-Delmotte et al. 2013).

With the prescribed high-latitude vegetation change of the 127 kyr BP Tier 2 experiment, the simulated annual warming increases in the Arctic, particularly over northern Siberia and northeast Canada, where the feedback between vegetation and surface warming is responsible for an additional warming of ~4-8°C (Fig. 2b). Annual surface temperature change compared to the pre-industrial control run in the northwest of Greenland is greater than 4°C and in the southwest greater than 7°C. After 3000 years of 127 kyr BP forcing and feedbacks, the Greenland ice sheet has retreated significantly along its west periphery, with a total ice-sheet area of ~85% of modern and contributing ~2 m sea level equivalent to the LIG highstand.

Effects of the retreating Greenland ice sheet

Other slow feedbacks are also important for explaining regional Arctic and Greenland changes. As the Greenland ice sheet retreats under warmer summer temperatures, meltwater is discharged into the North Atlantic Ocean. This freshwater has the potential to slow down the Atlantic Meridional Overturning Circulation (AMOC) and cool the North Atlantic and surrounding continental regions, depending on the rate and amount of meltwater discharged. Thus, meltwater resulting from the retreat of the Greenland ice sheet can provide a negative feedback to the orbital warming. Simulations for 130 kyr BP with the LOVECLIM model (Bakker et al. 2012) indicate a reduction of the deep convection and cooling of ~4-6°C in the Labrador Sea when a constant runoff flux of 0.05 Sv, equivalent to 2.3 m of Greenland melt, is added for 500 years to ocean grid cells surrounding Greenland (Fig. 2c). Warmer July surface temperatures as compared to pre-industrial still persist over the Nordic Seas and Europe. Lowering the Greenland ice sheet, on the other hand, results in a local warming over Greenland of up to 4°C (Fig. 2d).

Future outlook

Uncertainties in the boundary conditions for the LIG suggest that the PMIP4-CMIP6 *lig127k* simulation, designed to maximize the multi-model ensemble size, may not capture important feedbacks for explaining the observed Arctic warmth and for assessing the contribution of the Greenland ice sheet to the LIG sea-level highstand. Future Earth system models will need to include next-generation dynamic global vegetation models with considerations of climate, soil, and vegetation competition; a Greenland ice-sheet model with predictive ice-ocean interactions; and eventually solid Earth models, in order to simulate both fast and slow feedbacks of the entire Earth system on the transient evolution of the Greenland ice sheet during the Last Interglacial. Equally important will be new LIG reconstructions detailing the range and composition of vegetation at high latitudes, volume and flow pattern of the Greenland ice sheet, volume and extent of sea ice, and state of the ocean circulation.

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The importance of sediment in sea-level change

Ken L. Ferrier[1], W. van der Wal[2], G.A. Ruetenik[1] and P. Stocchi[3]

The movement of sediment across Earth's surface affects sea level by deforming the solid Earth, modifying the gravity field, and displacing and absorbing water. Recent studies show that accounting for sediment redistribution is important for interpreting and predicting sea-level change.

Since the 19th century, it has been recognized that spatially variable sea-level changes result from changes in surface loading, which perturb Earth's gravity field and the elevation of the crust (Jamieson 1865; Woodward 1888). Several decades ago, this connection was formalized in a gravitationally self-consistent theory of sea-level change (Farrell and Clark 1976), which, for the first time, accounted for both solid Earth deformation and the gravitational attraction of water toward itself, thus capturing the perturbations in both the sea floor and the sea surface that accompany ice melt. This theory has since been extended to account for several processes that were not included in Farrell and Clark's classic study, including shoreline migration (Johnston 1993), Earth rotation (Milne and Mitrovica 1996), sediment redistribution (Dalca et al. 2013), and dynamic topography (Austermann and Mitrovica 2015).

To date, most applications of this theory have focused on sea-level responses to the growth and retreat of ice sheets, which produce the largest changes in surface loads over glacial-interglacial timescales. The retreat of the Laurentide ice sheet, for example, produced a rate of mass unloading ~10^2-10^3 times higher than that due to erosion in Earth's most rapidly eroding mountain ranges.

Recent work has shown that sediment erosion and deposition, like ice growth and melt, produce significant changes in Earth's crustal elevation, gravity field, and rotation axis, all of which induce changes in sea level. In this paper, we review the ways in which sediment redistribution affects sea level and demonstrate how this can improve our understanding of past sea-level change.

Processes and observations of sediment redistribution

Sea-level responses to changes in surface loading are described by the sea-level equation (Eq. 1), which describes the change in sea level from one time to another, ΔSL (Fig. 1; Dalca et al. 2013).

$$\Delta SL = \Delta G - \Delta H - \Delta I - \Delta R \qquad (1)$$

Here ΔH and ΔI are changes in the thicknesses of sediment and grounded ice, respectively, and are the drivers of sea-level change. ΔG and ΔR are changes in the elevations of the sea-surface gravitational equipotential and crust, respectively, and are responses to ΔH and ΔI that depend on Earth's viscoelastic structure. Solid Earth responses to sediment redistribution over long timescales (>10^5 years) are often determined solely from the elastic flexure of the lithosphere, while responses over shorter timescales depend on the transient viscoelastic behavior of the mantle. Gravitational responses, by contrast, are essentially instantaneous, and continue evolving during sediment redistribution.

Quantifying ΔH requires establishing the rates and patterns of sediment erosion and deposition through time and space. At the largest scale, this includes erosion by fluvial, glacial, and hillslope processes, and deposition in subaerial floodplains, marine deltas, and fans. Integrated over the globe, these fluxes of sediment are large. Rivers currently carry ~18 ± 9 billion tons/year of sediment to the ocean (Willenbring et al. 2013), which is an order of magnitude smaller than ice-sheet mass change globally, but which can dominate changes in loading locally.

Because rates of erosion and deposition vary strongly in space, it is necessary to turn to empirical measurements to obtain realistic estimates of ΔH. Erosion rates are

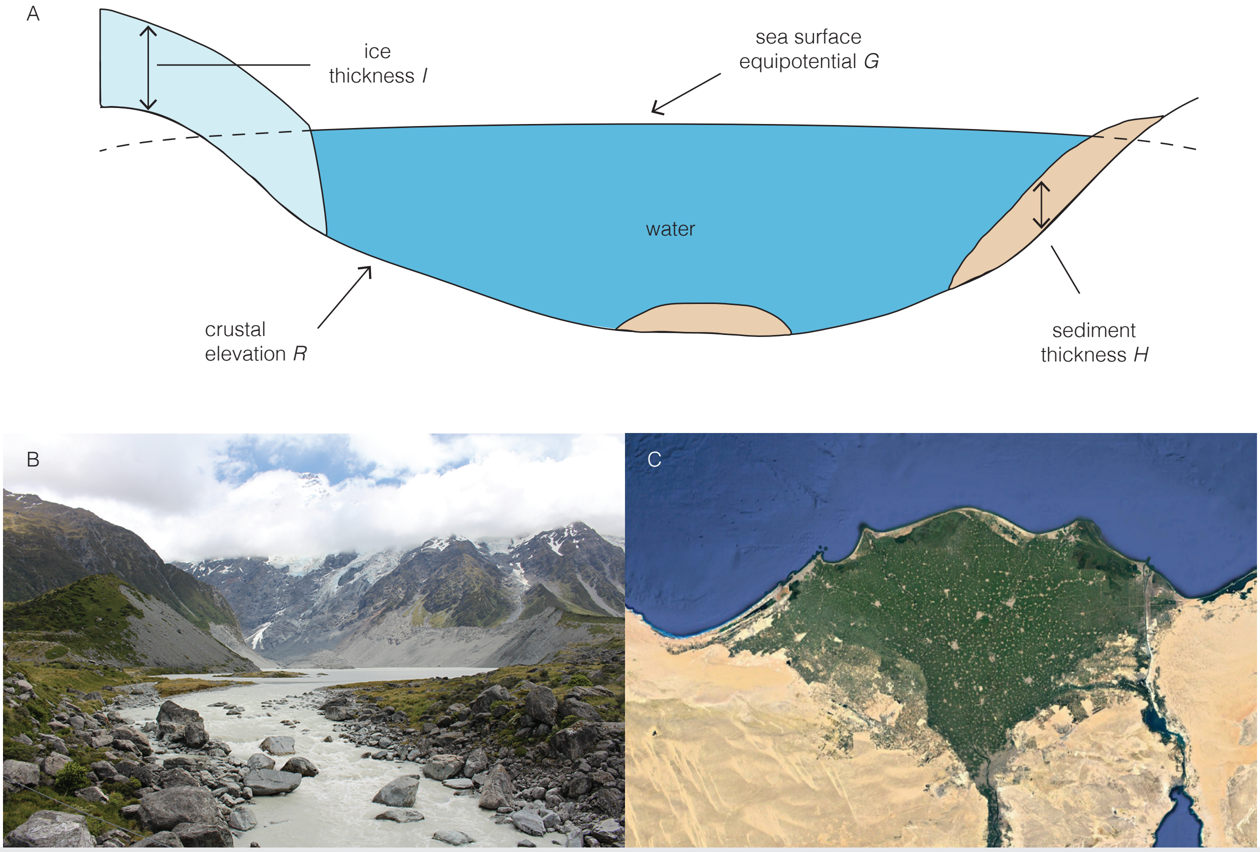

Figure 1: (A) Components in the sea-level equation (Eq. 1). The largest influences of sediment on sea-level change are in places with rapid erosion, such as rapidly uplifting mountains, e.g. **(B)** the New Zealand Southern Alps, or rapid deposition, e.g. **(C)** the Nile Delta (Google Earth 2019).

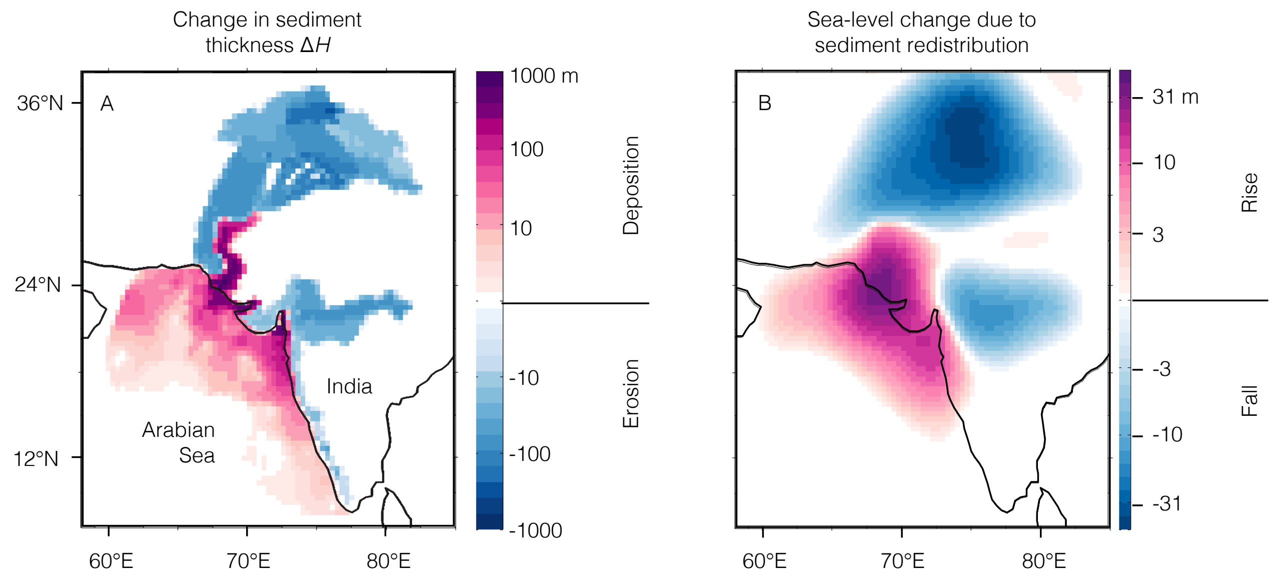

Figure 2: (A) Cumulative changes in sediment thickness over a 122-kyr simulation dominated by rapid erosion in the western Himalaya and rapid deposition on the Indus delta and plain. **(B)** Modeled changes in sea-level (ΔG - ΔR) due to sediment redistribution are as large as ~30 m, far exceeding published estimates of eustatic sea-level change over this period. This highlights the importance of accounting for the effects of sediment redistribution when using paleo sea-level markers to infer past sea-level change. Modified from Ferrier et al. (2015).

routinely inferred from fluvial sediment and solute fluxes, which provide rates averaged over annual to decadal timescales, and from cosmogenic nuclide concentrations in fluvial sediment, which yield rates averaged over ~10^3-10^5 years. Deposition rates are traditionally inferred from the age and thickness of sediment cores, which typically yield rates over ~10^2-10^5 years. Recently, new approaches have been developed to infer sediment deposition rates through remotely sensed perturbations in the gravity field (Mouyen et al. 2018). Although no single method can yield a continuous record of the history of erosion and deposition, the combination of methods provides useful constraints on the history of sediment redistribution over a range of timescales.

Effects of sediment redistribution and compaction on sea level and ocean water volume

Figure 2 illustrates responses to sediment redistribution in a simulation of sea-level change driven by erosion in the Indus River basin and deposition in the Arabian Sea and the Indus plain (Ferrier et al. 2015). This produces a cumulative change in sediment thickness (ΔH) as large as hundreds of meters over the 122-kyr simulation (Fig. 2a) and a sediment flux from the Indus River of ~400 million tons/year, one of the largest fluvial sediment fluxes on Earth. This results in sea-level changes >30 m near the center of the Indus delta (Fig. 2b), implying that a hypothetical paleoshoreline that formed there during the Last Interglacial would now be submerged by tens of meters.

The gravitationally self-consistent sea-level theory was recently extended (Ferrier et al. 2017) to account for two sedimentary effects that had long been recognized but not yet accounted for in the theory: the effects of sediment compaction on sediment thickness, and the effects of sedimentary water storage on global ocean water volume. Ferrier et al. (2018) applied this theory to a global sediment budget constrained by modern fluvial sediment fluxes, and showed that sedimentary water storage is capable of modifying the global volume of ocean water by the equivalent of ~2 ± 1 m in global mean sea level since the Last Interglacial, a significant fraction of the inferred 6-9 m drop in global mean sea level over this time (Kopp et al. 2009).

These sedimentary effects have important implications for interpreting past sea-level records. First, they imply that paleoshoreline elevations need to be corrected for the deforming effects of sediment, especially near locations of rapid deposition and erosion and over long time periods. Second, paleoshoreline-based inferences of past global ice volume need to properly account for changes in the volume of water stored in sediment.

Conclusions

Over the past five years, a number of studies have applied the gravitationally self-consistent sea-level theory to show that sediment redistribution can be a major driver of sea-level change. These studies have shown that sea-level responses are especially large in river systems with large sediment loads (Ferrier et al. 2015; Kuchar et al. 2018), and that sediment redistribution by other processes (e.g. subglacial erosion; van der Wal and IJpelaar 2017) can induce sea-level responses as well.

Several challenges remain. The history of sediment redistribution is poorly known in many locations due to limited measurements of paleo erosion rates, deposition rates, porosity, and density, especially for periods further in the past. In addition, lateral variations in mantle viscosity and lithospheric effective elastic thickness can strongly modulate sea-level changes, but exploring these effects is challenging due to uncertainties in Earth's rheological structure and the computational expense of modeling sea-level responses on a laterally varying Earth. Such challenges motivate continued efforts to constrain the Earth's sediment redistribution history and its three-dimensional structure, and to include erosion and deposition in coupled Earth system models that link climate forcings to sediment redistribution, glaciation, and sea-level change. Improved constraints on sediment redistribution, for example, may be useful in aiding interpretations of Gravity Recovery and Climate Experiment (GRACE) satellite data. Together, these studies highlight the rich behavior of sea-level responses to sediment redistribution, and reveal opportunities for improving our understanding of past and future sea-level change.

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Storms and extreme events: Insights from the historical and paleo record

Simon E. Engelhart[1], J.E. Pilarczyk[2] and A. Rovere[3]

Past land-falling coastal storms have left geological imprints. Studying them can help gauge the intensity/frequency of extreme storm events beyond the instrumental and historical record and provide insights on the severity of storms under warmer climates.

The potential for increased impacts from coastal storms is among the most concerning aspects related to future climate warming. Increasing impacts from these events can be broadly related to two factors. Firstly, it is expected that as relative sea level (RSL) continues to rise through 2300, significant regions, including major metropolitan areas, will be exposed to inundation without requiring any increase in the strength of storms (e.g. Garner et al. 2017). Secondly, increased intensity and frequency of the most extreme events is possible. Together, these two causative factors indicate that coastal flooding is likely to double by 2050 due to the combined effect of RSL rise and storm surge (Vitousek et al. 2017). The study of land-falling coastal storms under future climate scenarios accelerated in the aftermath of Hurricane Sandy (2012) and has been under the spotlight again after Typhoon Haiyan (2013), Hurricanes Harvey, Irma and Maria (2017), and Hurricanes Florence and Michael and Typhoon Mangkhut (2018).

Our understanding of how storms are related to climate is limited by the short instrumental and historical record. A solution to this is to develop and apply proxies for past storms that can improve our ability to provide insights into future storms under a warmer climate (e.g. linkage between proxy sea surface temperature records and hurricane frequency/intensity). Here we describe the characterization of storms in the paleo record including those from historical, Holocene, Late Pleistocene, and Last Interglacial periods, and identify some of the main questions that still need to be answered.

Historical storms

Recent land-falling storms provide opportunities to characterize the sedimentary and geomorphic signatures of events of known intensity and impact. The deposits left behind by instrumentally recorded events (e.g. Hurricane Irma, Fig. 1a) serve as important modern analogues for interpreting older historical and paleo events for which available information is limited (Brandon et al. 2014). Lessons learned in the wake of Typhoon Haiyan's unusual bore-like (deep, high-velocity flow and short inundation duration in contrast to the more commonly reported gradual rise and prolonged inundation) storm surge provide important insight into the limitations of distinguishing storm impacts from those associated with tsunamis (Soria et al. 2017), whereas insight gained from studies of sediments deposited by Hurricanes Camille and Katrina showed that similarly intense storms have impacted coastlines of the Gulf of Mexico multiple times over centennial timescales (Bregy et al. 2018).

Emerging research uses modern and historical storm analogues to validate techniques that can be used to enhance the reconstruction of long-term records that capture the variability in recurrence and intensity of storms over centennial to millennial timescales. Sediment grain size is used to infer the flow depth of water over the coastal barrier during past storms (Woodruff et al. 2008), and foraminifera are being used to determine sediment provenance and distance of transport by storm surges (Kosciuch et al. 2018). In the absence of real-time tide-gauge data, these techniques are the only means to reconstruct the flow depth and inland extent of the storm surges that predate the instrumental record, providing information concerning variability in storm intensity under different climates than today's.

Late Pleistocene and Holocene storms

Traditionally, the reconstruction of land-falling storms beyond the historical record has focused on the identification of anomalous high-energy sediments within low-energy sedimentary environments such as coastal lakes, sinkholes, and fresh/salt marshes (Fig. 1) or erosive features within salt marshes. These methods have successfully produced centennial- to millennial-scale records of storm impact on coastlines, although there are complications such as barrier height changes over time; the changing sensitivity

Figure 1: (A) Hurricane Irma (2017) sediments deposited on top of beach sand on the island of Anegada, British Virgin Islands. The deposit represents an important modern analogue for interpreting a series of paleo-storm and tsunami deposits preserved within coastal ponds on the island. **(B)** Overwash deposits (sands and silts) from historical storms (photograph and X-ray view) recorded within saltmarsh peat at Succotash Marsh, Rhode Island, USA. Cores were taken in close proximity to those in Donnelly et al. (2001).

Figure 2: "Cow and Bull," two large boulders deposited during the LIG on a steep cliff in the island of Eleuthera, The Bahamas. Researchers are debating whether these boulders were deposited by LIG "superstorms" (Hearty 1997), storms similar to modern ones (Rovere et al. 2017), or tsunamis (see discussion in Engel et al. 2015). Others interpret these landforms as karst remnants (Mylroie 2018).

of coastal sites to inundation as RSL and coastline position changes through time; and the preservation potential of the storm deposited sediments. Some of these concerns can be addressed by more recent work using deep-sea sediment cores that contain storm-triggered turbidites as a potential record (e.g. Toomey et al. 2017). Submerged records, including those from blue holes and the deep sea, have the additional advantage of comprising comparatively long records that can stretch into the late Pleistocene (e.g. Toomey et al. 2017) compared to many of the marsh- and coastal lagoon-based approaches that are typically limited to the late Holocene (last 4000 years; e.g. Donnelly et al. 2001). The impacts of storms have also been studied in high-energy environments using boulder deposits (e.g. Cox et al. 2018), but the reconstruction of long-term records is complicated by difficulties in dating deposits and separating individual events from large-scale boulder fields.

Deeper in the past

Boulder and wave runup deposits are the primary parameters used to reconstruct extreme storms on longer timescales (e.g. during past interglacials) that can be used as process analogues for the warmer world predicted for 2100 and beyond. One such candidate for the study of paleo extreme storms is the Last Interglacial, (LIG, ca. 125 kyr BP). Hansen et al. (2016) used numerical simulations and paleo storm proxy data to propose that a future warmer climate could be characterized by "superstorms" (intensities not measured in historical times). They posit that similar "superstorms" may have happened in the western Atlantic during the LIG thanks to geological evidence reported from The Bahamas (Hearty 1997). This evidence consists of very large boulders deposited during the LIG on the island of Eleuthera (Fig. 2) and LIG chevron ridges/runup deposits reported in The Bahamas and Bermuda. The interpretation of these landforms as being indicative of stronger storms during the LIG remains controversial (Engel et al. 2015). Nevertheless, Hansen et al. (2016) revived the study of geological storm proxies in past warmer climates, which had been neglected since the late 90s. Since the publication of Hansen et al. (2016), several papers (including comments and replies arguing about the interpretation of the geological proxies) were published on LIG "superstorms" (Mylroie 2018 and comments and replies therein). The main conclusion that can be drawn from these papers is that more research is needed on extreme storms at these timescales. New-generation hydrodynamic models can help unravel the energy of different coastal storms and hence their ability to generate particular landforms (see Rovere et al. 2017 for an example on LIG boulders).

Future research directions

Although still underutilized on a global scale, long-term geologic reconstructions of past storms are necessary to capture important information concerning the variability in storm frequency and magnitude – information requested by coastal managers as well as insurance companies. Future research directions include expanding the proxy toolkit to extract crucial information from deposits left by land-falling storms such as high-impact events that have a smaller surge but intense rainfall. Further, there is a need to expand Late Pleistocene and Holocene records beyond the Atlantic and Gulf coasts of North America, identify other LIG storm proxies beyond the frequently cited Western Atlantic boulder records, and reduce the subjectivity in the geological interpretation of the intensity of LIG extreme storms. Information derived from geological evidence can be used to constrain and validate inundation models, enhancing our ability to assess the hazard and associated risk for many of the world's coastlines.

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Geological records of past sea-level changes as constraints for future projections

Benjamin P. Horton[1,2,3], R.E. Kopp[3,4], A. Dutton[5] and T.A. Shaw[1]

Geological records of sea level have varied in response to a wide range of boundary conditions and climate forcings, and these geological records can serve as a valuable guide to projecting the dynamics of ice-sheet retreat and sea-level rise into the future. However, using geological records in this manner requires a robust understanding of regional variability and rigorous quantification of uncertainty.

Sea-level projections depend upon an accurate understanding of the relationship between climate forcing and the spatio-temporal evolution of sea level, as well as its different driving mechanisms. Yet this understanding is limited by the timescale of the instrumental data; most available records contain data only from the 20th and 21st centuries (Horton et al. 2018). Complementing instrumental data, geological records can provide valuable archives of the sea-level response to past climate variability, including during periods of higher global mean temperatures (Dutton et al. 2015), and can help improve estimates of the relationship between future temperature and sea-level change (Kopp et al. 2016). However, current ties between geological sea-level records and future projections are often vague and tentative; improved interconnections between the two sub-disciplines are thus a key to progress (Horton et al. 2018).

Sea-level-rise projections and geological records of past sea-level change share two fundamental challenges. First, regional sea-level changes vary substantially from global mean sea level (GMSL) change (Khan et al. 2015). Understanding regional variability is critical to both interpreting geological records and generating projections for effective coastal risk management. Second, uncertainty, which is pervasive in reconstructions of geological changes and both physical and statistical modeling approaches used to project future changes, requires careful assessment and quantification.

Here, we highlight two case studies – semi-empirical models of GMSL rise and estimates of the Antarctic contribution to sea level – to illustrate the way in which geological records can improve future projections, and conversely how the need for improved future projections can guide the development of geological sea-level research questions.

Common Era

Semi-empirical models use a statistical relationship between past global mean temperature and past GMSL to estimate the response of future sea levels to projected temperatures. Many semi-empirical models link instrumental records of sea level and temperature with multiple mathematical terms (Vermeer and Rahmstorf 2009). For example, the fast-response term is conceptually linked to heat storage in the ocean mixed layer and the slow-response is conceptually linked to the deep ocean and ice sheets. As of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2013, semi-empirical models were almost universally calibrated only to the instrumental record and yielded projections higher than the bottom-up, process-based projections preferred by the IPCC. For example, Schaeffer et al. (2012) provided a median semi-empirical projection of 21st century GMSL rise under a moderate-emissions pathway (Representative Concentration Pathway (RCP) 4.5) that was 90 cm, compared to the IPCC's median projection of 53 cm (Church et al. 2013).

The instrumental semi-empirical approach is, however, potentially biased by the short time span of instrumental records, which often post-date the onset of accelerated sea-level rise (Kemp et al. 2011), as well as the presence of substantial decadal and multi-decadal sea-level variability that is unrelated to global temperature changes (Horton et al. 2018). One solution to this problem is the use of longer geological records of sea level (Kemp et al. 2011).

Although temperature and sea-level variability over the Common Era (the last 2000 years) are not analogous to future changes, empirical relationships between high-resolution sea-level records can be paired with temperature reconstructions showing periods of both warming and cooling to examine the dynamic response of sea level to climate forcing on multi-decadal to multi-centennial timescales (Kemp et al. 2011). Common Era proxy records using salt-marsh sediment sequences permit the reconstruction of near-continuous time series of decimeter-scale sea-level changes over this period. Although Glacial Isostatic Adjustment (GIA) is the dominant cause of regional variability (Fig. 1a), it is approximately linear over the Common Era (Engelhart et al. 2009). Simple linear detrending of long-term local trends can thus circumvent uncertainties induced by parameterizations of GIA models, which are needed to correct earlier reconstructions (Dutton et al. 2015). Furthermore, detrending highlights allows for close examination of decadal to centennial variability in GMSL. However, such detrending masked any small changes in GMSL driven by multimillennial-scale processes other than GIA, and prevents an assessment of whether current GMSL is higher than its peak Common Era level.

Kopp et al. (2016) calibrated a semi-empirical model to a new statistical reconstruction of GMSL and existing global-mean temperature reconstructions. The resulting model indicated that without 20th century global warming, GMSL would have risen by less than 60% of the observed increase from 1900 to 2000 CE and might even have fallen. This estimate is in reasonable agreement with estimates of the human contribution to 20th century sea-level rise based on process models (Slangen et al. 2016). Subsequently, the projections from the semi-empirical model were substantially lower than those calibrated only to instrumental records and, indeed, reconciled the differences between semi-empirical models and the IPCC's preferred process-based projections. For RCP 4.5, the Kopp et al. (2016) median projection of 21st century GMSL rise was 51 cm, which is essentially indistinguishable from that of the IPCC. Their 66% probability interval of 39-69 cm was in good agreement with the IPCC's "likely" range, 36-71 cm (Fig. 1b).

While the agreement between semi-empirical projections and the IPCC's 2013 projections could be viewed as increasing confidence in both, this may be instilling false hope. By construction, the semi-empirical model assumes that the processes driving changes in GMSL over the Common Era are the same as those that will be important in the 21st century, yet the rapid ongoing changes in polar ice sheets suggests that they may not be. Perhaps the agreement is indicating instead that the process models that informed the 2013 IPCC assessment are implicitly exhibiting the same historical

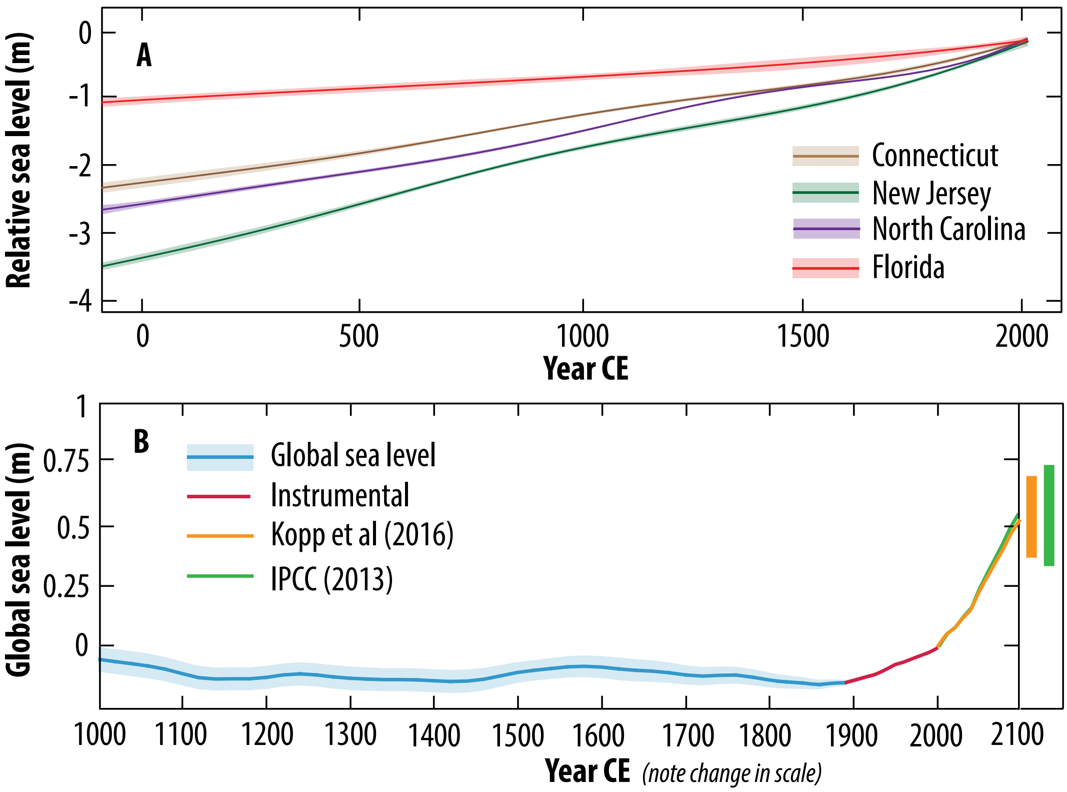

Figure 1: (A) Common Era relative sea-level change on the U.S. Atlantic coast (Kemp et al. 2015 and references therein). **(B)** Global sea level for the past millennia and 21st century semi-empirical model projections for RCP 4.5 (Kopp et al. 2016). Orange and green bars show the 5th-95th percentile of RCP 4.5 for semi-empirical (Kopp et al. 2016) and process-based (Church et al. 2013) models, respectively.

biases that are explicit in the semi-empirical model.

Last Interglacial (LIG) and Mid-Pliocene Warm Period (MPWP)

Geological records from the LIG (~128,000-116,000 years ago) and MPWP (~3.2-3.0 million years ago) provide alternative sources of constraints on GMSL change in periods with higher temperatures (Dutton et al. 2015). In particular, these past warm climate intervals can shed light on the dynamics of potential rapid destabilization of sectors of the Antarctic ice sheet that remain poorly constrained in current ice-sheet models. Indeed, after the uncertainty in future greenhouse gas emissions, the possible instability of marine-based sectors of the Antarctic ice sheet is the largest driver of uncertainty in future sea-level-rise projections (Kopp et al. 2017). While no particular past warm interval is a perfect analogue of the present climate forcing, many offer insight into thresholds, time lags between forcing and response, and potential rates of ice-sheet retreat (Dutton et al. 2015).

For the LIG, current estimates of peak GMSL rise indicate that it is extremely likely that it exceeded 6 m (Kopp et al. 2009). Yet while it is generally accepted that sea level during both the LIG and the Pliocene were higher than present, precisely quantifying the magnitude of GMSL rise has proven challenging (Horton et al. 2018). Chronological and vertical uncertainties, and potentially significant contributions from GIA and mantle dynamic topography (Austermann et al. 2017), hinder accurate interpretations of geological data, especially for the Pliocene. Moreover, rates of sea-level change for the LIG and MPWP range from highly uncertain to completely unconstrained depending on the time period (Dutton et al. 2015).

DeConto and Pollard (2016) used both LIG and MPWP constraints to calibrate their continental-scale model of the Antarctic ice sheet. In their model, LIG behavior is correlated with sea-level contributions under low-emissions scenarios in the short term (i.e. until 2100 CE), while MPWP behavior is more indicative of behavior under high-emissions scenarios, especially in the long term (i.e. centuries into the future). However, due in part to the large uncertainties that still exist in LIG and MPWP sea-level reconstructions, there is still ample room for re-interpretation of the geological records, and, consequently, the constraints they provide to future projections of sea-level rise.

These types of exercises, where geological sea-level records are employed to constrain the physical parameterization of the ice-sheet models, help to clarify some important targets for the geological sea-level community. To improve future projections, a key target is to better quantify the magnitude of peak GMSL, which in turn heavily relies upon improving the solid Earth models employed in modeling GIA and dynamic topography. A second key target is establishing both the timing of meltwater input from both Greenland and Antarctica, and constraining the climatic contexts associated with these events.

Ultimately, the fundamental observation from the LIG and MPWP that can be carried over to the present day is that ice sheets (and sea level) have the potential to respond rapidly and non-linearly to warming temperatures. This knowledge should empower us to act now and prepare for a waterier future as global mean temperatures and sea levels continue to rise.

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Climate variability in Antarctica and the Southern Hemisphere over the past 2000 years

Elizabeth R. Thomas

Cambridge, UK, 3-4 September 2018

CLIVASH2k is a PAGES 2k Network project investigating Climate Variability in Antarctica and the Southern Hemisphere over the past 2000 years. Founded as part of the third phase of the PAGES 2k Network, it expands upon the efforts of the former regional groups which aimed to spatially reconstruct important state variables for the climate system. The focus of CLIVASH2k is understanding the drivers of climate variability, and incorporating climate reconstructions from Antarctica, the sub-Antarctic and the wider Southern Hemisphere to explore the regional to hemispheric teleconnections and associated modes of variability.

Forty researchers from more than 20 nations attended the two-day workshop hosted at the British Antarctic Survey. The workshop focused on three main scientific questions:

1) What is our current understanding of sea-ice variability?
2) What are the best proxies or regions for capturing changes in westerly winds?
3) How can paleoclimate data inform predictions of future climate change?

1) Sea ice plays a key role in modulating Antarctic climate, and the best archives of past sea ice arise from marine sediments and ice cores. New marine sea-ice proxies, such as highly branched isoprenoid biomarkers and the increased temporal resolution, are providing unprecedented records of sea-ice dynamics over the past 2000 years. Advanced analytical capabilities are also producing new ice-core proxies, such as organic compounds, sea salts and halogen species. The expanding network of marine records and coastal ice cores, including ice cores from the sub-Antarctic islands, is greatly improving our spatial coverage, especially in regions such as the Antarctic Peninsula and coastal Adelie Land. There is now a realistic potential to combine marine and ice-core proxies in these regions to produce multi-proxy reconstructions. However, the spatial coverage in most other regions is still too poor to produce a comprehensive sea-ice reconstruction for the past 2000 years.

2) Circumpolar westerly winds are a major driver of climate variability. The observed variability in Antarctic surface-mass balance during the 20th century (Fig. 1; Medley and Thomas 2019) is attributed to changes in westerly winds and the Southern Annular Mode (SAM). New paleoclimate reconstructions of the SAM and past westerly wind strength were presented, including Antarctica ice-core and terrestrial records (peat and moss banks), and lake sediments from the sub-Antarctic islands and South America. However, there is little consensus on what each of the proxies is telling us about westerly winds, with apparent differences in the interpretation of increased strength versus a shift in the location of the wind belt. The group agreed that defining the proxies from all archives would be beneficial and that we need to utilize the observational records and climate models to provide clarity in our interpretations.

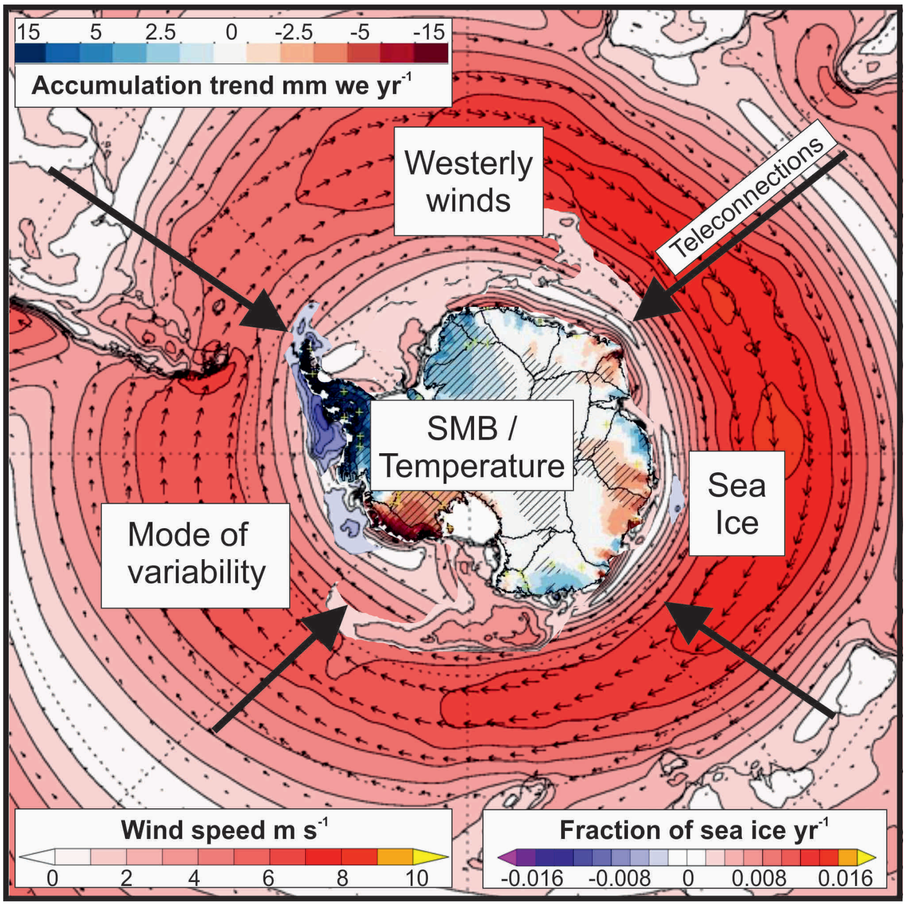

Figure 1: Drivers of climate variability in Antarctica and the Southern Hemisphere. The trend in Antarctic snowfall (Medley and Thomas 2019), the trend in Antarctic sea ice and the zonal wind anomalies from ERA-interim (1979-2010).

3) An important aspect of CLIVASH2k is engaging with climate modelers to ensure that paleoclimate data can improve predictions of future climate change. Our workshop, supported by the SCAR scientific research program "Antarctica Climate Change in the 21st Century (AntClim21)" (scar.org/srp/antclim21), brought together climate modelers and paleoclimate specialists. We learned that many climate models struggle to capture the observed changes in key climate parameters, particularly sea ice. Paleoclimate data offers one solution to constrain the models, providing realistic boundary conditions; however, incorporating paleoclimate data is complex and difficult. Advances in data assimilation show promise, but a number of issues remain. The group identified the following recommendations for the paleoclimate community. The modelers require: 1) quantitative rather than qualitative data, 2) gridded data with good spatial coverage, 3) accurate error estimates, 4) a robust description of what the proxies mean, and 5) accurate dating.

The CLIVASH2K working group will hold its next meeting at INQUA in July 2019.

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Understanding past changes in sea ice in the Southern Ocean

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1st C-SIDE workshop, Vancouver, Canada, 24-26 October 2018

C-SIDE (pastglobalchanges.org/ini/wg/c-side/intro) aims to reconstruct changes in Antarctic sea-ice extent in the Southern Ocean over the past 130,000 years and to understand the impact of sea ice on processes such as productivity, nutrient cycling, ocean circulation, carbon cycle, and air-sea gas exchange.

At this inaugural workshop, 32 participants (including three who joined remotely) from 11 countries brought together a broad spectrum of complementary expertise from proxy-based sea-ice reconstructions to Earth system modeling. The two-day program (pastglobalchanges.org/ini/wg/c-side/meetings/127-pages/1812-c-side-wshop-oct-18) featured presentations, speed talks, break-out groups and plenary discussions. A particular highlight was a well-attended evening public presentation at the SFU Harbour Centre followed by a public Q&A session.

Workshop participants presented the current understanding of paleo proxies used to reconstruct Antarctic sea-ice conditions, including fossil diatom assemblages, highly-branched isoprenoid biomarkers, and ice-core chemical constituents. All these proxies have great potential as indicators of past sea-ice changes but each has its limitations. Participants considered how various proxy information could be combined to provide complementary evidence of sea-ice changes and described ongoing needs for ground-truthing, culture experiments and process-based modeling to improve our understanding of what each proxy represents.

Presentations on past Antarctic sea-ice changes demonstrated a need for improved temporal resolution and spatial coverage of sea-ice records. However, participants also identified a substantial amount of exciting, ongoing work that will partly help fill these data gaps. One critical target is the ability to reconstruct summer sea-ice extent and to constrain the seasonal cycle of sea ice because it directly impacts deep-water formation, primary production, and air-sea gas exchange. Workshop participants suggested that ongoing and published work be integrated to develop a series of Southern Ocean transects that cross oceanographic fronts and include both ice and sediment cores.

Complementary presentations described improvements in model representation of present-day sea ice and the difficulty in capturing spatial heterogeneity of sea-ice extent around Antarctica. At the same time, Earth system model transient simulations can provide a dynamic framework for identifying how physical circulation (e.g. Southern Hemisphere westerly winds and deep-water formation) as well as biogeochemical processes (e.g. nutrient and carbon cycling) both in and beyond the Southern Ocean are linked to Antarctic sea-ice changes.

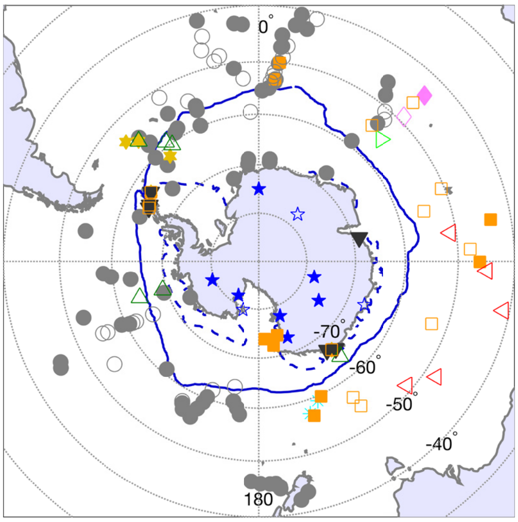

Figure 1: Locations of 160 sites identified by C-SIDE workshop participants with published (closed) and unpublished (open) proxy data that can be used for reconstructing sea-ice characteristics over the past 130,000 years. Sites are identified by H. Bostock & K. Kohfeld (cyan asterisks), M. Chadwick (dark green triangles), O. Esper (grey circles), P. Ghadi (green sideways triangle); J. Mueller (gold stars), A. Nair & X. Crosta (pink diamonds), M. Patterson & A. Leventer (red sideways triangles), X. Crosta (orange squares), X. Crosta & J. Mueller (black inverted triangles), and R. Rhodes (blue stars). Dark blue solid and dashed lines represent the 1981-2010 median sea-ice extent in September and February, respectively (taken from National Snow and Ice Data Center, nsidc.org/data/seaice_index/archives/)

The last full glacial-interglacial cycle is a key interval of focus because: (a) it offers the chance to explore how Antarctic sea ice responded during periods of warmer temperatures than today; and (b) it includes major climate transitions from both warm-to-cold and cold-to-warm climate states, which may shed light on the pace of sea-ice/climate responses, as well as on the potential reversibility of these responses.

Researchers involved in developing proxies agreed upon a framework with which to share and consolidate available datasets that will ultimately be used to produce consistent reconstructions. Likewise, modelers decided how to synthesize sea-ice and sea-surface temperature simulations from the paleoclimate modeling projects PMIP3 and PMIP4 (when these become available in 2019). Collating complementary datasets that can be used to quantify the interaction of sea ice with the wider climate system was recognized as an important objective. A presentation and Q&A session with developers of the Linked Paleo Data (lipd.net) facility sparked interest and discussion around issues of data sharing.

A primary objective of the workshop is to produce a review paper that synthesizes the current knowledge of past Antarctic sea-ice changes and their impact on the climate system. The next C-SIDE workshop is planned for 29-31 August 2019, just prior to the International Conference on Paleoceanography in Sydney, Australia. It will focus on synthesizing and reconciling the various sea-ice proxies and model simulations across the entire glacial cycle. We thank PAGES and Simon Fraser University, Canada, for financial support.

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Impacts of sea-level rise from past to present: iSLR18

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PAGES EARLY-CAREER NETWORK

Utrecht, The Netherlands, 26-29 August 2018

The iSLR18 conference for early-career researchers (ECRs) was designed to initiate cross-disciplinary engagement for the next generation of sea-level researchers from around the world. The meeting welcomed 68 ECR scientists from 24 different countries to Utrecht, the Netherlands, in August 2018. The range of expertise reflected a broad range of disciplines, which allowed participants to build new partnerships and discuss cross-disciplinary approaches towards addressing some of the key outstanding questions in sea-level science.

The meeting was constructed around four presentation sessions, a full-day excursion to the Holland coastal plain and Rhine River delta, and an evening public engagement event. The four main talks during the public engagement event highlighted the status of current sea-level research of the past, present and future (Fig. 1). The event ended with a lively discussion on possible sustainable solutions for the impact of future sea-level rise on the Dutch coastal delta system. Presentation session topics provided scientific foci for the meeting, which were enhanced through keynote and invited ECR speakers for each.

The session on **Past Sea-Level Changes** introduced the value of geological and sedimentary archives for developing high-resolution and precise sea-level data for periods preceding instrumental data collection. These geological records are now being used to investigate if Arctic or Antarctic ice sources were responsible for the unprecedented rates of sea-level rise during the 20th century. Moreover, these data are used for exploring the roles of different mechanisms in driving sea-level variability during the Holocene across regional to global scales.

Moving towards **Recent and Future Sea-Level Changes**, the second session covered a wide range of topics that are important for sea-level change, looking back to the 20th century and ahead to the 23rd century. A thought-provoking talk showed that accounting for glaciers that have disappeared might help to close the 20th century sea-level budget. Other talks focused on important processes that make local sea-level change and variability very different from the global mean – for example, the Indian summer monsoon and coastal erosion in Brazil. The closing talk gave an outlook for the future in considering coastal flood hazard in New York City following the impact of Hurricane Sandy in 2012.

The importance of **Mitigation, Adaptation and Coastal Impacts** in view of future sea-level changes were addressed in the third session. Several presentations showed that both future sea-level extremes and degradation of coastal zones need to be considered when developing mitigation and adaptation strategies. Most importantly, it is crucial to inform and educate people living near the coast to implement such strategies. The talks revealed that regardless of the global nature of future extreme sea levels, a local focus is essential for mitigating and adapting coastal impacts.

Finally, the **Submerged Landscapes** session showed how Holocene relative sea-level rise drowned past landscapes and affected human settlements. Examples from Africa, Europe, North America, and the Middle East discussed how populated continental shelves were submerged. The presentations could be divided into submerged landscapes offshore covered by seawater, or onshore buried by thick sediment sequences. The session had a strong focus on data retrieval to reconstruct the timing of drowning and rates of relative sea-level rise. Scuba diving in Sweden, deep coring in the Mississippi Delta, and geotechnical and geophysical investigation in the North Sea exemplified this multidisciplinary session.

Following the success of iSLR18, the question raised was: *"What's next?"* The synergies created by PAGES and INQUA in Utrecht have set the scene for similar ECR conferences in the future. ECR meetings could fill the years between PAGES and INQUA congresses and could be dedicated to multi-disciplinary research areas that would benefit from synthesizing theories, knowledge, and data. Topics could focus on paleo-informed research for developing the resilience of human-environment systems, in conjunction with the PAGES PALSEA, LandCover6k, PAGES 2k Network, Global Paleofire, EcoRe3 and PEOPLE 3000 working groups and INQUA CMP and PALCOM Commissions.

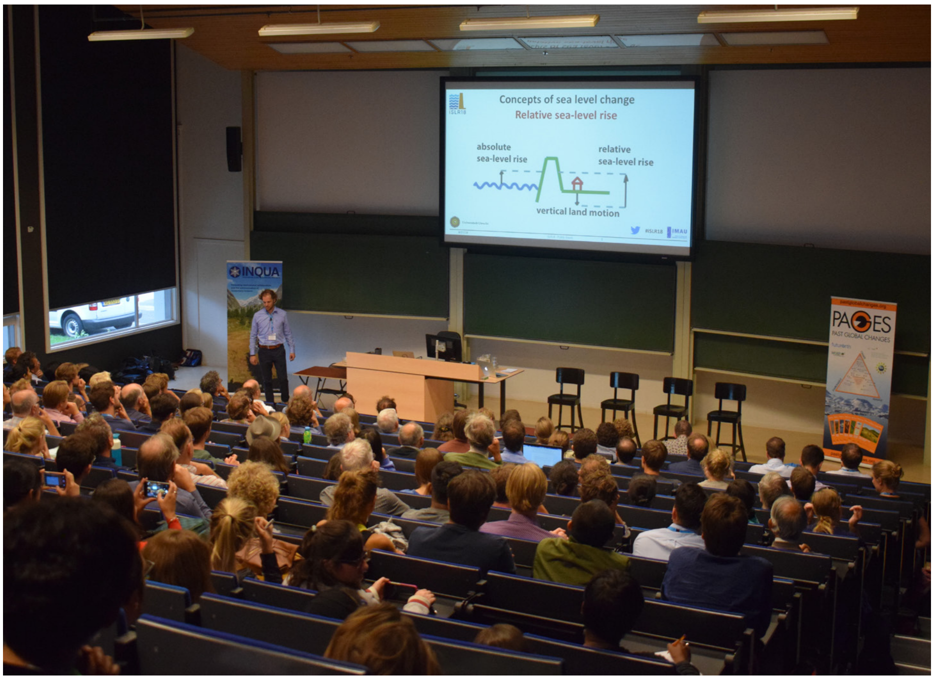

Figure 1: iSLR18 organizer Bas de Boer presenting the concept of relative sea-level change to a lay audience on Monday evening's public outreach event.

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Climate, ice sheets and sea level during past interglacial periods

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PALSEA-QUIGS joint workshop, Galloway, NJ, USA, 24-27 September 2018

The goal of the first joint workshop held by the PALeo constraints on SEA level rise working group (PALSEA, pastglobalchanges.org/ini/wg/palsea/intro) and PAGES-PMIP Working Group on Quaternary Interglacials (QUIGS, pastglobalchanges.org/ini/wg/quigs/intro) was to identify the state of our understanding on the interplay between climate, polar ice sheets and sea level during past interglacials.

The four-day meeting included three oral sessions with 26 talks, a poster session, an outreach event, a field excursion (Fig. 1), and two discussion sessions.

The first oral session focused on studies of climate, ice sheets, and sea level during the Last Interglacial (LIG). Converging evidence from marine, ice-core and terrestrial records indicate that high-latitude surface ocean temperatures were warmer by at least 1°C relative to pre-industrial and surface air temperatures by >3-11°C (see Fischer et al. 2018 for a recent review). Recent developments in Earth system modeling, in the framework of PMIP4 (Otto-Bliesner et al. 2017), suggest vegetation and sea-ice feedbacks are key to reproducing LIG surface air warmth at the amplitude observed in paleoclimate records. Large uncertainties remain regarding the timing and extent of mass loss from the Greenland and Antarctic ice sheets and their total respective contributions to the higher-than-present global sea level throughout the LIG.

Figure 1: PALSEA-QUIGS scientists coring a salt marsh on the New Jersey coast. Data from salt marshes yield high-resolution records of Holocene sea-level change. Image credit: Robert Kopp.

The second oral session focused on climate, ice sheets, and sea level during even older interglacials, particularly Marine Isotope Stages (MIS) 11, 13 and 31. Recent work has indicated there are differences in the spatiotemporal expression and amplitude of climatic changes across interglacials. Challenges identified during the workshop include aligning proxy records chronologically, as well as an overall lack of well-dated sea-level benchmarks for these older interglacial periods.

The third oral session centered on Holocene sea level. Compared to earlier interglacials, the Holocene has the advantage that well-dated archives of sea level are available in higher spatiotemporal resolution. This wealth of information allows for better constraints on processes that are also relevant to understanding sea level during older interglacials, such as glacial isostatic adjustment (GIA).

The meeting concluded with discussions dedicated to the identification of the most pressing areas where more research is needed. The key research questions identified include:

- How do interglacial sea-level highstands relate to interglacial temperatures in the high-latitudes, tropics, and globally?
- What determines the size of polar ice sheets in different interglacial climatic contexts?

Discussions primarily focused on the LIG, and emphasized a need for well-dated and highly-resolved climate and sea-level records for this time interval, as well as prior interglacials. Highlighted uncertainties included the rate of sea-level rise at the onset of the LIG, and the net amplitude of LIG global sea-level rise given potential hemispheric phasing of polar-ice-sheet growth and retreat. It was noted that constraining the ice-sheet configuration during the preceding glacial maxima has important implications for interglacial relative sea-level indicators because of the GIA effects.

The group also discussed the importance of using paleoclimate records to better characterize the structure (spatial and temporal) and amplitude of interglacial climate change in order to evaluate Earth system model simulations. This requires better spatial coverage of paleodata, particularly in the Southern and Pacific Oceans. Finally, emphasis was placed on the need to find direct evidence for significant ice-mass loss both in Greenland and in Antarctica, which is crucial to constrain their respective contributions to LIG global sea level.

These key research questions will be summarized in an upcoming opinion paper for the broader paleo sea-level and paleoclimate communities, to encourage future work on the topics. The PALSEA and QUIGS working groups will continue to pursue collaboration through future joint initiatives (e.g. joint sessions at international meetings).

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Abrupt changes, thresholds, and tipping points in Earth's history and future implications

Ed Brook[1] and Victor Brovkin[2]

AIMES-PAGES joint workshop, Hamburg, Germany, 14-16 November 2018

There is increasing realization and concern that human modification of the Earth system runs the risk of inducing abrupt transitions in climate, ocean circulation, the cryosphere, ecosystems, and society (Turney et al. 2016). Our ability to predict when and where such transitions, so-called "tipping points", might happen is limited. While abrupt climate change has long been identified in ice-core records (Johnsen et al. 1992) and other archives, skillfully modeling abrupt change has largely been limited to simple models (Valdes 2011). Recently, a multi-model assessment revealed abrupt events in state-of-the-art models, suggesting the possibility of predicting the likelihood of such events (Drijfhout et al. 2015).

Advancing our understanding of the full range of possible abrupt climate, environmental, and societal changes through the continued assessment and collection of paleo data and improved multi-model experiments will help us to assess future risks. However, how to best use the paleo records in this regard is not well established. The AIMES-PAGES workshop on abrupt changes, thresholds, and tipping points in the Earth system was organized around this question. Both PAGES and AIMES (Analysis, Integration and Modelling of the Earth System; aimesproject.org) are Future Earth Global Research Projects. Within PAGES, the topic of "Thresholds, tipping points and multiple equilibria in the Earth system" is an established integrative activity. Within AIMES, the assessment of tipping points is identified as one of the four major AIMES projects. The workshop was an outgrowth of a splinter group meeting at the 2018 EGU General Assembly, organized by PAGES, that explored community interest in this topic.

Workshop attendees were drawn from a diversity of subdisciplines in paleoenviromental modeling, data collection, and social-environmental systems. Following a series of introductory talks from the perspective of different components of the Earth system (terrestrial and marine environments, the cryosphere, the atmosphere, and human-social systems), breakout groups spent a full day in focused discussion organized around the physical climate system, ecosystems, biogeochemical cycles, and social systems. The primary task of the groups was to evaluate the potential for significant progress in using paleoclimate data to predict future tipping points and abrupt change.

All of the breakout groups reported that significant work is needed to fully take advantage of the paleo record for evaluating the potential for crossing critical thresholds in the near future. Topics emphasized include cryospheric change and its cascading impacts (including sea-level change and permafrost thaw), hydroclimate instabilities (including changes in fire, wetlands, and rainfall), oceanic changes (including hypoxia and rapid changes in ocean circulation), and the interaction of human societies with these changes. Early detection of abrupt transitions is another area of considerable interest that requires further attention.

The groups agreed that it is vital to include the paleo perspective in evaluating future tipping points and related changes, given model uncertainties and the short timescale of direct observations. A synthesis paper describing the future challenges and opportunities in this area is in preparation, and planning for follow-up research and workshops is underway.

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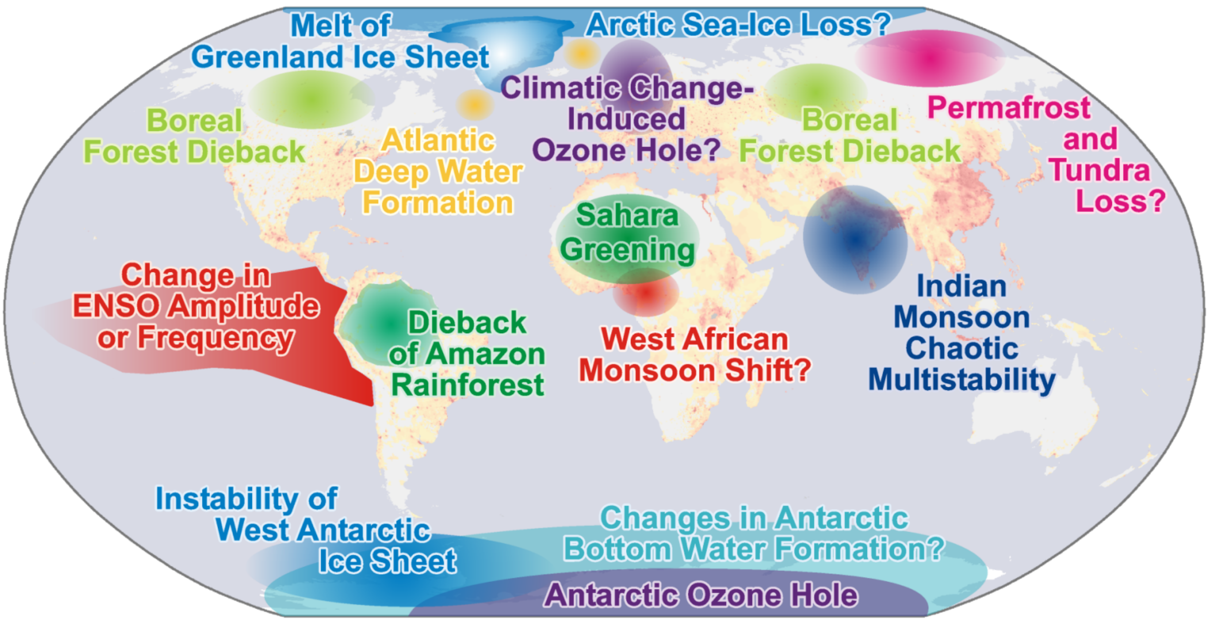

Figure 1: Climate system elements that may be susceptible to tipping point behavior, with background shading showing population density. Modified from Lenton et al. (2008); copyright 2008 National Academy of Sciences.

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Trace element and isotope proxies in paleoceanography: Starting a new synergic effort around marine geochemical proxies

Kazuyo Tachikawa[1], R. Anderson[2], L. Vidal[1] and C. Jeandel[3]

GEOTRACES-PAGES joint workshop, Aix-Marseille, France, 3-5 December 2018

Reconstruction of past ocean states relies on the use of "proxies" (indicators or tracers), since it is impossible to directly measure variables such as water temperature, biological production and ocean circulation. In order to clarify the ocean's response to natural and anthropogenic forcings, it is essential to improve our knowledge of proxy behavior and the associated uncertainty. This task will be most efficiently achieved by the synergy between marine geochemists and paleoceanographers, as well as proxy and climate modelers. The first joint workshop of GEOTRACES-PAGES (geotracespages.sciencesconf.org) was such an occasion to identify open questions and scientific gaps of proxies used in paleoceanography. We focused mainly on trace elements and their isotopes (Fig. 1) that are targets of the GEOTRACES program (geotraces.org). These proxies are preserved in biogenic phases and/or bulk sediments and can be used to compare with simulated distribution to quantify physical and biogeochemical processes (Fig. 1). Sixty-four researchers and students from 11 countries from four continents gathered for this objective. The workshop consisted of a series of keynote talks and discussions around working groups with the following subjects: biological productivity, oceanic circulation, particle flux and sedimentation rate, and physical and/or biogeochemical modeling.

The keynote talks pointed out some recent findings, including the importance of recycled iron for biological productivity on seasonal-to-ice-age timescales (Rafter et al. 2017), and complex biomineralization processes of silicifiers and their impact on the silicon isotopic ratio (Hendry et al. 2018). Multi-tracer analysis of the same water sample is one of the strongest strategies of the GEOTRACES program, and multi-proxy reconstruction provides the most reliable results. However, different proxies sometimes tell us distinct stories. Since each proxy has its own advantage and potential bias, decoupling them can provide additional information. One of the most interesting examples of this decoupling is deep water circulation in the Atlantic Ocean during the last glacial maximum (LGM, 23-18 kyr BP). Three of the most frequently used geochemical proxies in paleoceanography do not tell a single, simple story: benthic foraminiferal carbon isotopic ratios ($^{13}C/^{12}C$ or $\delta^{13}C$) suggest weaker and shallower glacial North Atlantic deep water circulation with a dominant contribution of the southern source water (Lynch-Stieglitz et al. 2007), whereas the neodymium isotopic composition ($^{143}Nd/^{144}Nd$ or ε_{Nd}) recorded in authigenic oxides of planktonic foraminiferal calcites indicates a significant proportion of northern component waters in the North Atlantic over the LGM (Howe et al. 2016). The particle-reactive radionuclide ratio $^{231}Pa/^{230}Th$ suggests persistent southward transport of ^{231}Pa during the LGM (Bradtmiller et al. 2014). Reconciliation of these proxy reconstructions will be achieved by improved spatial coverage of tracer data in the modern ocean and proxy-enabled model experiments (Menviel et al. 2017; Muglia et al. 2018) with well-constrained parameters (e.g. particle concentration and partition coefficients according to the chemical composition of the particle), which can be obtained by process studies of the modern ocean, for example, from GEOTRACES.

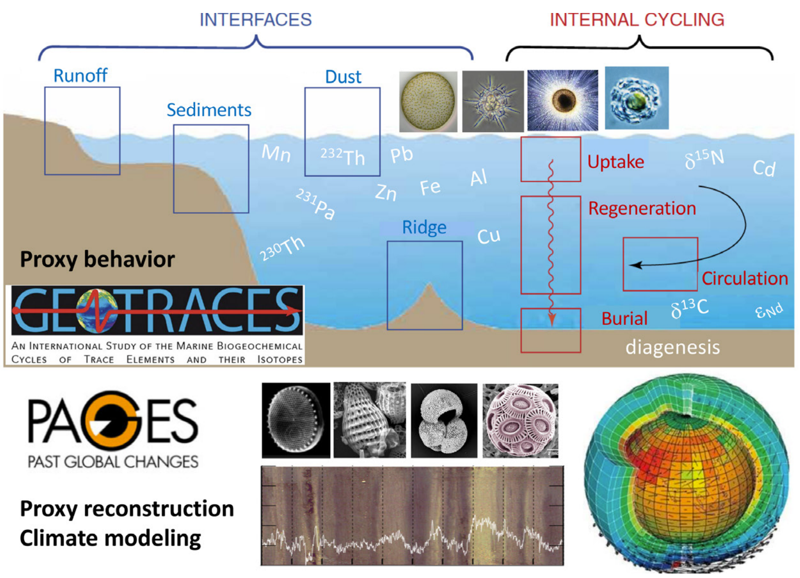

Figure 1: A schematic diagram presenting possible areas of interaction between the GEOTRACES and PAGES communities: targeted geochemical proxies, factors affecting their distribution, and paleoceanographic approaches associated with the proxies.

The workshop identified the necessity to reinforce the study of the water-sediment interface and early diagenetic processes. Benthic fluxes from the water-sediment interface may affect proxy distribution in the water column, and early diagenesis could modify the signature acquired in the upper-water column. More systematic and coordinated sampling of surface sediments and pore waters with samples collected in the overlying water column would help to scrutinize proxy behavior across this interface and promote core-top calibration.

The workshop was a great occasion to trigger coordinated actions that will be further developed in coming years. We identified products such as a compilation database of core-top samples suitable for proxy development and calibration, sensitivity tests and model-data comparisons, a synthesis paper on trace elements and isotope proxies used in paleoceanography and particle flux, intercalibration of methods used to analyze core-top sediments, and an outreach piece on paleo productivity.

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Past plant diversity changes and mountain tree species conservation

Rachid Cheddadi[1], N. Mhammdi[2] and F. Sarmiento[3]

Rabat, Morocco, 1-5 October 2018

Cuenca, Ecuador, 10-15 March 2019

Two recent PAGES-endorsed conferences on "Past plant diversity changes and mountain tree species conservation" provided a great opportunity for scientists from different disciplines to discuss the issue of how the knowledge of plant diversity and ecosystem responses to past climate changes may help in managing species' persistence under ongoing global climate change. They were held under the umbrella of the ongoing project VULnerability of Populations under Extreme Scenarios (VULPES, vulpesproject.com, 2016-2020). The choice of locations was driven by the fact that both Morocco and Ecuador are hotspots of biodiversity with impressive numbers of endemic species, many of which are threatened with extinction. Both conferences were sponsored and introduced by the local authorities, which stated loudly and clearly the importance of organizing such meetings in their countries, where biodiversity is a national cause. In Ecuador, the protection of wildlife is now included in the constitution, and plants are protected by law.

Scholars have clearly shown that under current global climate change, many plant species should either adapt locally to persist in situ or migrate, if at all possible; otherwise, their modern range will be impacted to the extent of potential extinction. The geographical distribution of many mountain tree species is becoming more fragmented, often with a trend toward a reduction of the established areas. These tree species are considered by the IUCN Red List (iucnredlist.org) as endangered or threatened with extinction. The VULPES project focuses on a small number of these vulnerable mountain tree species (case studies) in Africa, China, and South America using a multi-disciplinary, multi-scale, and multi-species approach. Sessions at the two conferences were designed to fit this approach and to allow for, on the one hand, presentations of project results by the partners to a wider community, and, on the other hand, input by members of this wider community through the presentation of their own results and open discussion.

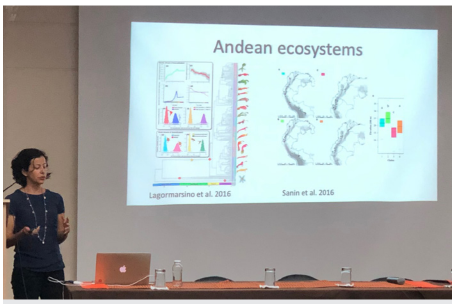

Figure 1: Selene Báez discusses the effects of current global environmental change on Neotropical montane forests (Cuenca 10-14 March, 2019). Photo credit: Elena Sarmiento

In Rabat (vulpesproject.wixsite.com/biodiv2018), there were five sessions, each of which was introduced by an invited keynote speaker. Here we examined the relationship between past environmental changes and their impacts on plant species' diversity. The five sessions dealt with climate models and past climate variability (keynote Michel Crucifix, University of Louvain, Belgium), the species refugia during climatically unsuitable time periods (keynote Keith Bennett, University of St Andrews, UK), species migration and impacts on their genetic diversity (keynote Arndt Hampe, University of Bordeaux, France), modeling the species range (keynote Signe Normand, Aarhus University, Denmark) and, finally, the lessons we can draw from the past to help conserve plant species (keynote Steve Jackson, University of Arizona, USA). The conference was small (about 50 attendees) with brilliant presentations, which led to very interesting and in-depth discussions. In addition to the scientific attendees, Moroccan stakeholders were also present and clearly showed their interest in being involved in the process. The head of the Scientific Institute of Rabat, Dr. M. Fekhaoui, organized a tour of the local museum where hundreds of endemic plant and animal species from Morocco have been inventoried. The conference was followed by a two-day excursion to one of the largest and best preserved Atlas cedar forests, in the Ifrane National Park. The Atlas cedar is an endemic species to North Africa and considered to be endangered by the IUCN Red List. Twenty-five participants joined the excursion, which allowed for additional interesting discussions on many topics related to species conservation.

In Cuenca (vulpes-ecuador2019.com), in order to increase the discussion time among the 70 attendees, there was one "opening" and one "closing" keynote each day. The first day was introduced by Paul Valdes (University of Bristol, UK) on modeling past climates and the contribution of models to comprehending the mountain climate system. The closing keynote was David Neill (Universidad Estatal Amazónica, Puyo, Ecuador) with an open discussion on the endemic plant species from the sandstone summits (*Andean tepuis*) of the Cordillera del Cóndor in Peru and Ecuador. The second day was dedicated to plants' genetic diversity and long-term refugia. The introductory keynote was given by Mark Bush (Florida Institute of Technology, USA) on the microrefugia concept and how they may contribute to the future persistence of species in situ. Pierre Taberlet (University of Grenoble, France) provided the closing keynote on genetics and conservation biology within the context of Quaternary refugia. During the third day, three excellent choices of excursions were organized: (1) Ingapinca Inca archaeological site; (2) El Cajas National Park into the páramo, glacial lakes, and Andean (Polylepis) forests; and 3) El Collay community-protected forests and socioecological production landscape in the Azuay highlands. The last day of the conference was dedicated to practical scenarios for mountain forest conservation, with an introductory keynote by Veerle Vanacker (University of Louvain, Belgium) on landscape dynamics in tropical Andean ecosystems in response to natural and anthropogenic disturbances. Selene Báez (National Polytechnic School, Quito, Ecuador; Fig. 1) provided the last keynote of the conference on the effects of current global environmental change on Neotropical montane forests. This conference was marked by the participation of a large number of university students from Quito, Loja, and Cuenca, who took part actively through very interesting posters.

The discussions that took place at both conferences highlighted several interesting points: firstly, the size of the meeting (between 50 and 70 participants) was key to enabling extended presentations as well as in-depth discussions. Secondly, the multi-disciplinary sessions with a joint focus on how we may contribute to better conservation of the biodiversity were highly appreciated by all participants, stakeholders, and students. These two conferences were concrete opportunities to exchange new ideas and learn new approaches, techniques, and concepts. One of the main conclusions is that the problem of preserving biodiversity cannot be tackled by one single discipline, concept, or approach. We need to combine our knowledge and work together through not only multi-disciplinary projects but also small multi-disciplinary meetings, where enough time is dedicated to in-depth discussions and direct exchanges with stakeholders and students.

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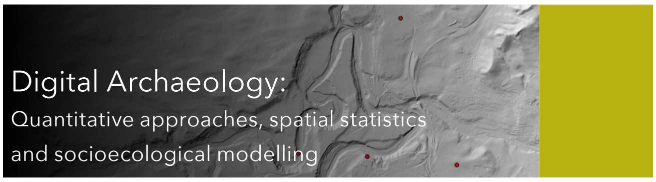

Archaeology that counts: International colloquium on digital archaeology

Martin Hinz[1,2], J. Laabs[1,2] and M.E. Castiello[1]

Bern, Switzerland, 4-6 February 2019

Quantitative methods are transforming how archaeology approaches the investigation of the human past. The emerging possibilities of data integration and computational modeling enable interdisciplinary research on a new level. In large part due to the current challenges imposed by climate change, there is a growing awareness of the importance of past environmental conditions on human history. Archaeology possesses an unmatched record of societal responses to such changes, which can only be utilized by integrated research and quantitative analysis.

In order to facilitate the exchange of knowledge from recent research in this field, the Institute of Archaeological Sciences and the Oeschger Centre for Climate Change Research at the University of Bern, Switzerland, organized the first International Colloquium on Digital Archaeology in Bern. For two days, 60 participants from different disciplines, many of whom were young academics, exchanged information on the status and potential of digital archaeology and socioecological modeling as an integral part of responsible and relevant research approaches. The diverse and valuable contributions were complemented by the keynote speakers' inspiring talks.

Oliver Nakoinz (University of Kiel, Germany) started by situating digital and quantitative archaeology both thematically and historically. He pointed out that only integrative research that realistically reflects both societal and environmental influences on human development enables us to make meaningful statements about the past. The main part of the lecture therefore established quantitative archaeology not only as an integral part of archaeology itself, but rather as a natural link between the scientific approach aimed at structural analysis and the traditional approach of the humanities aimed at negotiating historical meaning and developing narratives.

Many of the following contributions dealt with quantitative approaches in spatial and non-spatial archaeological case studies as well as data-mining and new techniques of supervised and unsupervised pattern recognition in archaeological and ecological data. Juan Barceló's (Universitat Autònoma de Barcelona, Spain) keynote closed the first day and opened a rich final discussion with his pointed and provocative lecture. He reflected on the challenges and opportunities of big data and machine learning for a subject like archaeology and made his position clear that scientific archaeology can only be quantitative. This did not go unchallenged, and an active debate arose, which only ended because of the conference program's time restraints.

The following day was opened by Mikhail Kanevski (University of Lausanne, Switzerland), who, from the perspective of computer science, showed the unexplored potential of artificial intelligence. He spoke about machine learning in the field of geospatial data and demonstrated that this tool is one of the most promising for the investigation of complex environmental phenomena. Especially when considering the multilayered human influence, it is of utmost importance to separate effective factors from noise for specific research questions. His contribution was an enormous enrichment for the methodological scope of the colloquium.

The conference ended with a lecture from Michael Barton (Arizona State University, USA). He stated that the time of purely reconstructive archaeology is over, because reconstructing the past has turned out to be impossible. Rather, it is necessary to use the long-term perspective and the far-reaching data of archaeology for questions regarding the interaction between humans and the environment and to enable robust testing of assumptions about human dependency and decision making with regard to environmental change through explicit, quantitative and computer-supported models. This can position the discipline as an important driver in current discussions.

The colloquium and the discussions showed that archaeology is on the brink of fundamental changes in handling and analyzing big data and complex systems. This will not only impact the discipline itself but will influence the interdisciplinary work in which archaeology is involved. Digital and quantitative archaeology is an important interface between the natural sciences and the humanities for the investigation of long-term human-environment interactions in the past and their added value for today's discourses. This perspective is already advocated by the PAGES LandCover6k and PEOPLE 3000 working groups.

We, therefore, were happy that PAGES endorsed the colloquium and offered us the opportunity to demonstrate why conferences and workshops connected to digitization and quantitative approaches in the field of archaeology are important for the future collaboration between (paleo-)environmental/climate and (pre-)historic sciences.

The colloquium's abstract booklet can be accessed at: doi.org/10.5281/zenodo.2628304

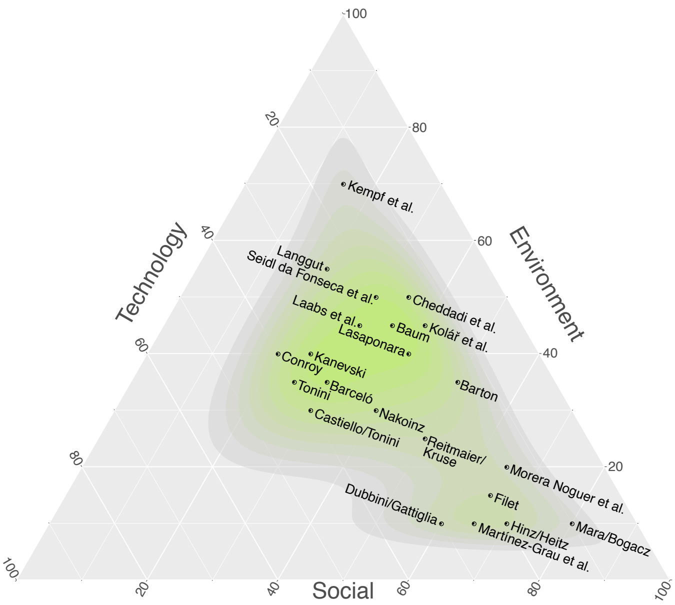

Figure 1: Processes studied and presentations from this workshop situated on a triangular diagram of past environment, society, and technology.

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Co-designed paleo experiments on land-cover and land-use change impacts

Sandy P. Harrison[1], M.-J. Gaillard[2] and B.D. Stocker[3]

Sitges, Spain, 24-28 September 2018

Members of the PAGES LandCover6k working group (LandCover6k), the Paleoclimate Modeling Intercomparison Project (PMIP), and representatives of the carbon-cycle modeling community and PAGES' PEOPLE 3000 working group met in Sitges, Spain, to co-design paleo simulations to evaluate the impact of land-use and anthropogenic land-cover change on climate and the carbon cycle over the Holocene.

The impact of anthropogenic land-cover change due to land use (LULC) on biogeochemical cycles and climate is still uncertain. Climate-model simulations indicate that LULC impacts on temperature and precipitation are large, both in and beyond the regions where these changes occur (Smith et al. 2016). However, the LULC changes used to drive these simulations are unrealistic (Gaillard et al. 2010). Furthermore, the currently available LULC scenarios (HYDE: Klein Goldewijk et al. 2017; KK10: Kaplan et al. 2011) are inconsistent with the constraints imposed by carbon budgeting (Stocker et al. 2017). Creating more realistic LULC scenarios, using paleovegetation reconstructions and archaeological data, is the central goal of LandCover6k.

The group has made considerable progress towards LULC reconstructions for key regions and times (Morrison et al. 2018). It is now time to test and use these reconstructions. Discussions at the Sitges workshop focused on how to incorporate LandCover6k information into LULC scenarios, to design biogeochemical model simulations to test the reliability of these reconstructions, and to design Earth system model simulations to provide a realistic assessment of the impact of LULC changes on climate and the carbon cycle over the Holocene.

The first day of the workshop focused on overview presentations of the various initiatives relevant to this goal and the research interests of different communities (for presentations see the LandCover6k homepage: pastglobalchanges.org/ini/wg/landcover6k/intro). Discussions around the presentations ensured there was common understanding of the terminology and clarified the data needs of each community. Subsequent breakout group discussions addressed co-operative activities from several different perspectives. Key issues were (a) how information from the LandCover6k project could be used to improve the HYDE and KK10 scenarios or (b) as input to and/or validation of climate model simulations, (c) how HYDE and KK10 scenarios could be used as input for climate model and/or carbon-cycle simulations, and (d) whether existing products fulfilled the minimum and/or desirable requirements for climate and carbon-cycle modeling experiments.

Positive outcomes of the workshop were (a) agreement on data collection priorities to maximize the usefulness of LandCover6k products in the short, medium and long term, and (b) the design of protocols for model simulations to test LULC impacts on climate and biogeochemical cycle (Fig. 1). Some data syntheses need to be fast-tracked to test whether available information has discernable impacts on LULC scenarios, including new estimates of population growth/decline through time from archaeological ^{14}C dates (Crombé and Robinson 2014), maps of the initial date of the introduction of agriculture from archaeological studies and related land conversion inferred from pollen-based vegetation maps, and information about the type of crops and grazing animals.

Short-term (six-month) goals encompass products needed as input to model simulations designed for inclusion in the next IPCC report. The intermediate (12-month) goals are LandCover6k products that contribute directly to this report (e.g. comparisons between pollen-based LULC reconstructions based on different methodologies, evaluation of the HYDE and KK10 LULC scenarios using the pollen-based reconstructions), while the longer-term goals include LandCover6k products that will be ready by the end of the second phase of LandCover6k. A more complete description of the experimental protocols will be published as a joint-authored paper, to help enable modeling groups to run the LandCover6k-PMIP co-designed simulations.

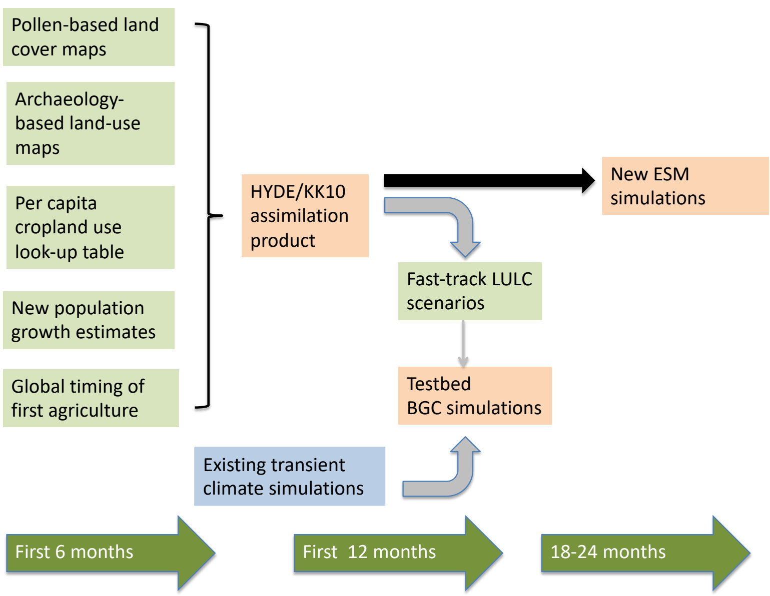

Figure 1: Schematic showing how LandCover6k fast-track products will feed into the production of new land use-land cover (LULC) scenarios. Offline simulations with biogeochemical models will provide a validation of the realism and impact of the LandCover6k products. The ultimate goal is to produce new LULC scenarios as forcing for Earth system model simulations.

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Global soils and sediment transfers in the Anthropocene: Database meeting

Thomas Hoffmann[1] and Veerle Vanacker[2]

3rd GloSS workshop, Koblenz, Germany, 18-20 October 2018

The PAGES Global Soil and Sediment transfers in the Anthropocene (GloSS) working group aims to build a comprehensive global database on soil and sediment transfers in the Anthropocene, to identify hotspots of soil erosion and sediment deposition in response to human impacts, and locate data-poor regions as strategic foci for future work (Fig. 1).

The third workshop of the GloSS working group was hosted by the Federal Institute of Hydrology (Koblenz) and supported by the UNESCO-IHP International Center for Water Resources and Global Change (ICWRGC). The workshop aimed to synthesize the results from the regional task forces, discuss progress on the GloSS database and identify ways to motivate the GloSS members and the broader scientific community working with human impacts on soils and sediments to contribute to the compilation of the GloSS database. A total of 19 participants from different disciplines (geomorphology, geology, soil science, ecology, (paleo)limnology, and hydrology) and 10 countries from four continents contributed to the workshop.

The first day was dedicated to reports by the regional taskforce leaders that highlighted the progress of the regional working groups in terms of data compilation. The keynotes were given by Rajiv Sinha and Sohini Bhattacharjee (Indian Institute of Technology, Kanpur, India), Juan Restrepo (EAFIT, University of Medellin, Colombia), Duncan Cook (Australian Catholic University, Melbourne), Allan James (University of South Carolina, USA), Dongfeng Li (National University of Singapore), Aleksey Sidorchuk (Moscow State University, Russia), and Gert Verstreaten (Leuven University, Belgium). Stephan Dietrich (ICWRGC, Germany) gave a presentation of the global GEMStat water quality database (gemstat.org), which is hosted at the ICWRGC in Koblenz, and Jean Phillipe Jenny (INRA Thonon, France) presented results from a European database on lake sediments.

All keynotes presented a wealth of studies and data that provide the backbone for the GloSS database. However, it was noted by the keynote speakers that the focus of the GloSS working group on the full sediment pathway including hillslope and river systems (channels and floodplains), as well as lakes and deltas, is a major challenge (obstacle) to the compilation of the database. In contrast to other databases that have been compiled by the PAGES community, GloSS deals with various sedimentological archives and proxies over various temporal and spatial scales, with varying sensitivity to human disturbances. It was further noted that colleagues from the scientific community hesitate to contribute their data to the GloSS community if the benefit is not fully clarified.

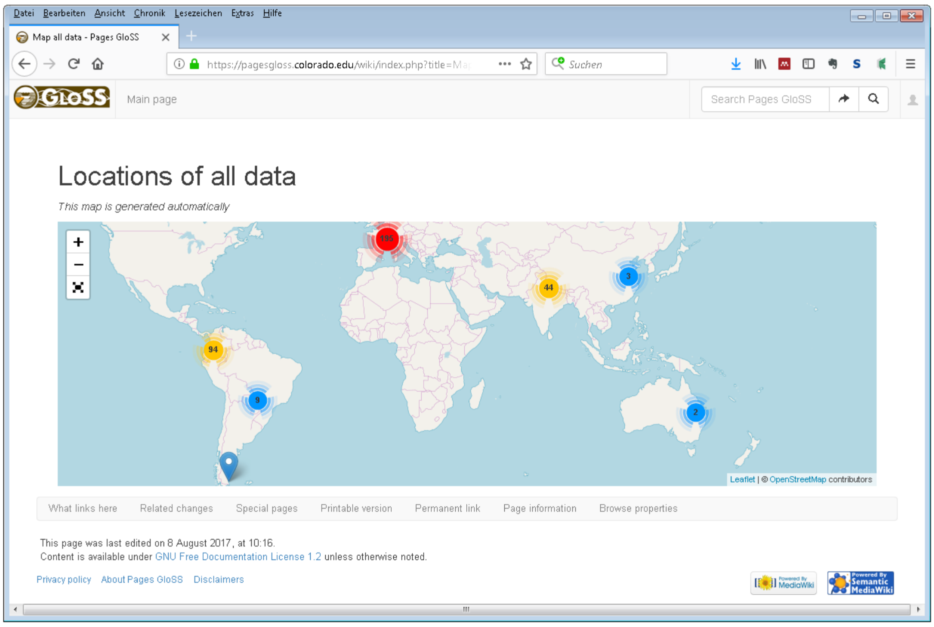

Figure 1: Screenshot of the GloSS wiki. The colored points indicate the number of datasets entered in the wiki as of 20 March 2019. The wiki is an open platform to enter data on past and present soil and sediment transfer. For more information see: pagesgloss.colorado.edu/wiki.

During the second day, participants discussed the major shortcomings of the GloSS database and developed a strategy to increase the number of contributions from the scientific community to the GloSS working group. First, the strategy includes a statement on the publication policy of the GloSS working group, indicating that all publications derived from the GloSS working group results and the GloSS database should be published by the key authors and the GloSS consortium. Each scientist who provides information and data that support the population of the database will be a part of the GloSS consortium. Second, the strategy includes the compilation of a special issue in the journal *Anthropocene*. The special issue will include a mixture of i) regional synthesis papers that highlight the specific histories of human disturbance on soils and sediments on various continents, ii) large-scale/global compilations, and iii) parameter-specific databases that are of relevance for the GloSS community. The special issue will be completed by a paper on the conceptual framework of the GloSS database with a focus on the global synthesis.

The third day was dedicated to a city field trip along the Rhine River in Koblenz. Participants learned about the long-term history of soil erosion and sediment transport in the Rhine basin and the present-day sediment issues related to the management of the waterways in Germany. One focus was on the sediment-monitoring activities of the Federal Institute of Hydrology and the Water and Shipping Authority in Germany and the sediment budget analysis of the Rhine, which highlights the functioning of the heavily exploited Rhine waterway in the Anthropocene.

This group officially ended as a PAGES working group in 2018, but it is still active. Find it here: pastglobalchanges.org/ini/wg/former/gloss/intro.

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Analyses of the SISAL database: Regional patterns in isotope signatures

Yassine Ait Brahim[1], N. Kaushal[2] and L. Comas-Bru[3]

3rd SISAL workshop, Agadir, Morocco, 8-12 October 2018

PAGES' SISAL (Speleothem Isotope Synthesis and Analysis) working group was set up to create a database of speleothem $\delta^{18}O$ and $\delta^{13}C$ records and to synthesize these records for targeting climate questions such as investigating long-term drivers of the global monsoon and for data-model comparisons (Comas-Bru et al. 2017). The first version of the database (SISAL_v1; Atsawawaranunt et al. 2018a; Fig. 1), with 371 speleothem records and 10 composites from 174 cave systems, has been made available online with an accompanying paper describing its structure (Atsawawaranunt et al. 2018b).

Building on this foundation, the 3rd SISAL workshop was held from 8-12 October 2018 at Ibn Zohr University in Agadir, Morocco. Twenty-four participants, including 12 early-career researchers, came to Agadir from 14 countries. The SISAL members gave presentations about their SISAL-related activities on the first day. The discussions involved: (i) the current status of the database; (ii) an update by the age modeling group, which aims to provide a common denominator for age-uncertainty envelopes through the construction of a set of new age-depth models termed "SISAL chronologies" employing a range of commonly used techniques – a critical addition to the next version of the database (SISAL_v2); (iii) progress and feedback on the regional review papers that are part of a special issue in the journal *Quaternary* (mdpi.com/journal/quaternary/special_issues/speleothem_records_climate); and (iv) preliminary work on the first scientific SISAL paper and three additional papers using the SISAL database.

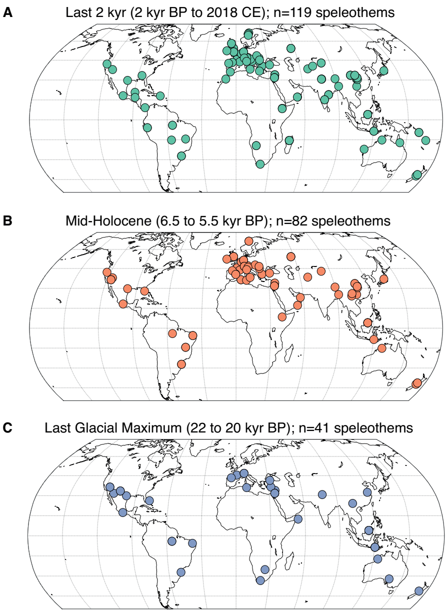

Figure 1: Speleothem records in SISAL_v1 (Atsawawaranunt et al. 2018a,b) for the key periods relevant to the studies that the workshop focused on: **(A)** the last two millennia, **(B)** the mid-Holocene, and **(C)** the Last Glacial Maximum. In each, "kyr BP" refers to thousands of years before present, where present is 1950 CE.

On the following three days, the analyses and discussions were centered around the first scientific SISAL paper ("Evaluating model outputs using integrated global speleothem records of climate change since the last glacial") and the three additional papers currently in progress: "Hydrological records of the evolution of regional monsoons during the Holocene and the Last Interglacial", "The Holocene from the speleothems' view: Global trends and teleconnections", and "The MCA/LIA as reflected by speleothems". Participants separated into small groups to work on these analyses with daily feedback from the larger group. By the end of the workshop there were paper outlines with clearly defined timelines, preliminary analyses, and further steps to be taken. Data gaps of key climate events from different regions necessary to make these papers robust were identified and have been prioritized. In accordance with the co-authorship agreement created to encourage inclusivity, all researchers are welcome to contribute intellectually to these papers.

Two talks were given by participants at the workshop. On Day 1, Mike Rogerson presented an idea of drip water synthesis. On Day 3, Colin Prentice gave an invited talk titled "Stable carbon isotope ratios in plants and the atmosphere, from inter-annual variability to glacial-interglacial cycles", reflecting on the idea of interpreting global patterns in speleothem $\delta^{13}C$ records from the SISAL database.

During the workshop, it was decided that SISAL_v2, which will incorporate records identified as missing during the workshop and the SISAL chronologies, will be released in late 2019. In the closing session, participants discussed locations for the next workshop to be held in October 2019, a SISAL session and poster presentations at EGU 2019, potential collaborations with other PAGES working groups, funding sources, and the perspectives of SISAL's future (e.g. the extension of the SISAL database with the addition of more records and/or, for example, trace element and drip water measurements). Finally, informal SISAL meetings at the INQUA 2019 and EGU 2019 conferences were scheduled.

The last day of the workshop was spent exploring the Wintimdouine cave (30.68°N, -9.34°W, 1400 m.a.s.l) and its associated geology. Located 70 km northeast of Agadir city, the Wintimdouine cave (i.e. "the spring of lakes" in the Moroccan Berber language) is developed within the karst system of Tasroukht in the Western High Atlas Mountains. It includes the longest known underground river in Africa with 19 km explored so far. Participants had the chance to enter the cave and examined various beautiful forms of speleothems.

Those researchers with data to add to the database are encouraged to contact the regional coordinator for the geographic area of their stalagmite record. The deadline for submission for the second version of the database is 30 June 2019. For more information about SISAL and how to get involved, go to pastglobalchanges.org/ini/wg/sisal

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A joint effort to bring together global, regional modeling and proxy communities

Juan José Gómez-Navarro[1], P. Ludwig[2], N. Zeiher[3], S. Talento[4], U. Parveen[5] and S. Wagner[6]

2nd PALEOLINK workshop, Murcia, Spain, 6-8 February 2019

Past climate changes and variations are assessed with proxy reconstructions based on various archives and climate modeling approaches. However, combining both proxy and modeling approaches still includes profound temporal- and spatial-scale gaps. Empirical climate reconstructions are most skillful on a local-to-regional scale covering time periods up to millennia and more, albeit they exhibit a coarse temporal resolution. In contrast, results from comprehensive General Circulation Models (GCM) or Earth system models, which have high temporal resolution, are only representative on regional- to large-scale spatial scales. Thus, innovative and integrated efforts are necessary to bridge the gap between the scales and to bring data and models to a common basis for comparison of past climatic and environmental changes. Therefore, Regional Climate Models (RCM) may be helpful to overcome this spatial and temporal mismatch, but are currently seldom used in the paleo perspective (Fig. 1).

To address these issues, leaders of the PAGES 2k Network project PALEOLINK organized a workshop in the scenic town of Murcia, as a follow up to the PALEOLINK kick-off meeting at the European Geosciences Union (EGU) General Assembly in Vienna in April 2018. The workshop brought together 22 scientists from different countries – most of them early-career scientists working in the fields of global and regional climate modeling, as well as proxy reconstruction based on different archives and statistical techniques.

The workshop consisted of two sections: a series of oral talks with participants presenting their work and fields of interest, followed by sufficient time for questions, and a series of breakout groups running in parallel.

During the first section, talks were organized around four main topics, ranging from climate reconstructions, using (regional) climate and forward modeling, to model-data integration. In the second section, several breakout groups were created to address specific open issues and future directions applicable to the entire working group. These groups were not previously defined, but were proposed in situ based on the previous discussions, with the aim to condense ideas stemming and emerging from the preceding talks.

In the first round, four topics were addressed including i) statistical reconstruction methods of hydroclimate variables, ii) identification of variables/regions where the added value in regional paleoclimatic model simulations is most noticeable, iii) regional oceanographic models, and iv) regional glacial and interglacial concepts and models. In the second round, workshop participants were encouraged to change groups, thereby sharing their experiences and expertise in order to co-develop strategies and synergetic structures between the different groups. The workshop concluded with summarizing the main results and defining strategies for workshop products related to scientific papers and research initiatives led by enthusiastic group leaders, and coordinating the goals and tasks within the various groups.

An open follow-up meeting took place in a splinter meeting at EGU 2019, where attendants and interested new colleagues in the field of paleoclimatic and paleoenvironmental research had the opportunity to be involved in post-workshop activities. In the future, we plan to aim for additional meetings in the form of online webinars and in-person meetings at larger conferences. In particular, the PALEOLINK leaders are co-conveners of a session at the 20th INQUA congress in July 2019 in Dublin. The group is completely open to input and active participation from the paleoclimatic and paleoenvironmental community interested in addressing issues in the context of the link between the different paleoclimatic spatial and temporal scales.

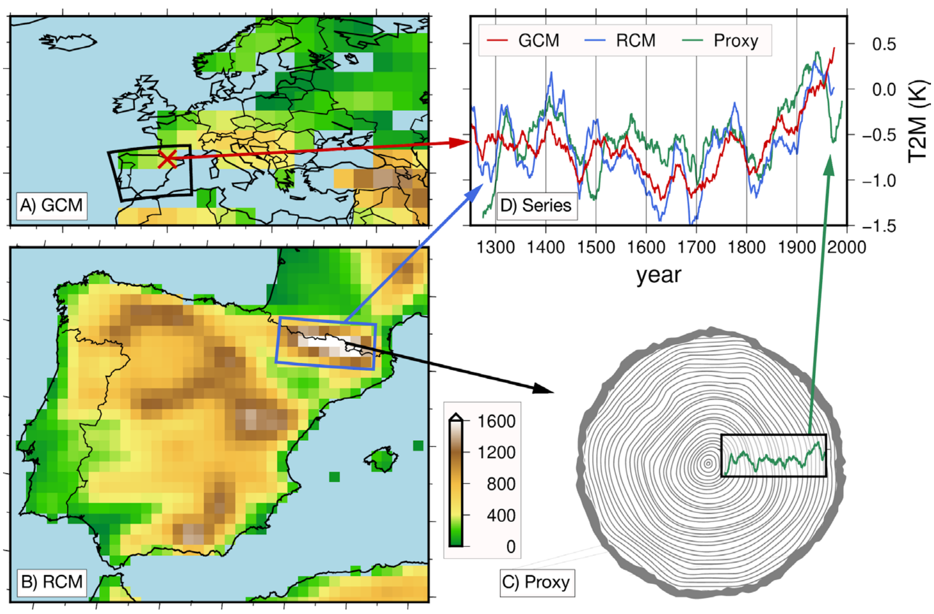

Figure 1: Schematic of GCM/RCM-proxy data comparison for temperature in the Pyrenees: **(A)** part of the GCM model domain (orography shaded). Black box marks RCM domain, red cross marks grid point for time series data in **(D)**; **(B)** RCM model domain (orography shaded). Blue box marks area averaged over the Pyrenees for RCM data in **(D)**, black arrow illustrates location of **(C)** tree rings used as proxy. **(D)** Synopsis of GCM, RCM, and proxy data time series. Figure taken from Ludwig et al. (2018) with permission.

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Methods and interdisciplinary communication in historical climatology

Chantal Camenisch[1], S. White[2], M. Bauch[3], Q. Pei[4] and C. Rohr[1]

1st CRIAS workshop, Bern, Switzerland, 1-2 October 2018

The recently founded PAGES working group Climate Reconstruction and Impacts from the Archives of Societies (CRIAS) held its first workshop on methods and interdisciplinary communication from 1-2 October 2018 in Bern, Switzerland. CRIAS focuses on the methods of historical climatology, a discipline which deals with three different fields:

1. The reconstruction of climate and weather on the basis of archives of society that contain man-made sources such as chronicles, account books or even pictures (Fig. 1 is an example of an illumination in a Bernese medieval chronicle).
2. The impacts of climate and weather on past societies.
3. The history of climate science and perceptions.

After the opening remarks from steering committee member Sam White, the program began with a panel on the state of the field in Historical Climatology, with a focus on Central Europe and China. The presenters Andrea Kiss, Rudolf Brázdil, Xiuqi Fang and Jie Fei gave insight into their research based on the archives of society on drought in medieval Hungary, on the Central European temperature and precipitation series, the unique Chinese historical records, which go back for more than 2000 years, and on the water-level changes of Lake Nansi during the Qing dynasty. This panel gave participants the possibility to compare the rich historiographic tradition of China with that of parts of Europe, which will be one of the goals of this working group in the next years.

The focus of the second panel was on the narrative sources used in Historical Climatology. Qing Pei gave a comprehensive introduction into weather-sensitive Chinese sources, their context of origin, and their content. Chantal Camenisch and Lukas Heinzmann presented results from their recent research, which includes climate impacts on society in Rouen, France, from 1315 to 1715, and weather conditions and climate impacts recorded in an extended and detailed diary written by a monk in the Einsiedeln, Switzerland, monastery during the Late Maunder Minimum.

The third panel was dedicated to phenological observations in documentary sources and the production of climate indices. Because the source density in Europe in the early 14th century is considerably less dense compared to later centuries, Martin Bauch and Thomas Labbé proposed new ways of using climate indices for the reconstruction of this climatological key period. Melanie Salvisberg presented an index-based flood reconstruction of the Gürbe river, Switzerland, and flood impacts in the Gürbe valley. Based on the harvest length reported in manorial accounts (account rolls or books in the feudal system), Kathleen Pribyl reconstructed summer precipitation in East Anglia. The last paper of this panel, presented by Christian Pfister and Thomas Labbé, was dedicated to the longest available homogenized grape harvest series from Beaune, France, (1354-2018) and the temperature reconstruction based on that evidence.

New frontiers in Historical Climatology was the topic of the last panel of the workshop. These new frontiers were found in Southern India, where Gemma Ives reconstructed monsoons from 1730 to 1920. Marie-Michèle Ouellet-Bernier presented a sea-ice-cover reconstruction from Nunatsiavut in Labrador which was based on the reports of Moravian missionaries from 1750 to 1950. Dagomar Degroot's presentation focused on the rich information of Dutch ship logbooks. Finally, David Nash talked about precipitation series from South Africa.

Dominik Collet, Rüdiger Glaser, Michael Kahle, Heli Huhtamaa, and Chaochao Gao lead a roundtable focusing on the importance of interdisciplinary collaboration and ways to combine data from the archives of society and data from those of nature. The last part of the workshop comprised discussions in three break-out groups on "preserving, classifying and disseminating data", "climate history as global history", and "comparing Chinese and Central European historical climatology". The aim of the workshop was to determine the future outline of the working group in a broader frame and to bring together Historical Climatologists from different continents. Both aims were achieved in Bern, thanks in part to the financial and administrative support from the Oeschger Centre of Climate Change Research and PAGES.

Figure 1: Avalanche killing Bernese and Fribourgese mercenaries at the Gotthard massive in 1478. Bern, Burgerbibliothek, Mss.h.h.I.3, p. 917 – Diebold Schilling, Amtliche Berner Chronik, Bd. 3 (e-codices.ch/de/list/one/bbb/Mss-hh-I0003)

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Bruno Messerli (1931-2019)

PAGES Co-Director 1996-2001

Ray Bradley[1], M. Grosjean[2], T.F. Stocker[3] and H. Wanner[2]

After a long illness, Bruno Messerli passed away during a clear winter night in February 2019, surrounded by his wife Béatrice and his whole family. Bruno was an outstanding scientist, colleague and friend, full of enthusiasm, ideas and congeniality, and always ready to take the lead. We will miss him dearly.

After studying geography, geology and history and completing his doctoral thesis on the geomorphology of the Sierra Nevada in Andalusia, Spain, Bruno began his career with an impressive habilitation thesis on the Pleistocene glaciation of mountain ranges around the Mediterranean. This was the start of Bruno's broad and fruitful fieldwork in high-altitude mountains – in Africa (the Tassili, Tibesti, Aïr and Hoggar mountains in the Sahara, Semien mountains and Mount Kenya in East Africa), the arid Andes of South America and the Himalayas. For decades, his scientific work was driven by the question of whether or not the highest mountains in the most arid zones of the world were glaciated during the Last Glacial Maximum, or if the lack of moisture prevented widespread glaciation, despite extremely low temperatures. He investigated how glaciation in the mountains related to paleolakes and water resources in the nearby lowlands.

Bruno was a real mountaineer who loved the mountains and their people. Bruno's brilliant research work is characterized by his broad view of climate dynamics and climate history, with all its ecological consequences. In the spirit of his early mentor Carl Troll, he was able to outline an impressive picture of the long-term dynamics of the mountain climate system and its influence on geomorphological processes and natural resources, such as water, soil and vegetation. His contributions to studies of mountain hazards and highland-lowland interaction were seminal for many of his young colleagues. Together with his friend Hans Oeschger, Bruno was fascinated by new research methods such as radiocarbon dating, which he readily utilized to advance his research.

With his relentless enthusiasm, Bruno was a continuous generator of ideas and new projects. Parallel to his efforts in high-mountain research he initialized two research programs on regional and urban climate in the region and city of Bern, Switzerland, and supported research on Little Ice Age fluctuations in the Alps. He never hesitated to fight for mountain protection and development, always recalling the significance of the mountain landscape as a key resource for people living in it. He was proud to be one of the initiators and "fathers" of the Mountain Agenda in the 1992 Rio Declaration on Environment and Development (Chapter 13 in Agenda 21: "Managing Fragile Ecosystems: Sustainable Mountain Development", un-documents.net/a21-13.htm). He was a co-founder of the International Centre for Integrated Mountain Development (ICIMOD) in Nepal and of the Mountain Research Initiative, based in Switzerland. Bruno also enjoyed a long collaboration with the Food and Agriculture Organization of the United Nations, which acts as a task manager of the Mountain Agenda. His contribution to mountain research has thus had a broad and long-lasting impact.

Bruno was also an active and talented academic leader. He was professor of physical and regional geography at the University of Bern from 1969 to 1996 and acted as director of the Institute of Geography from 1978 to 1983. From 1986 to 1987 he served as Rector of the University of Bern. Bruno was very happy when the Institute of Geography formed a new division focusing on sustainability in mountain areas of the world, now the Centre for Development and Environment. He also acted as President of the International Geographical Union from 1996 to 2000. Just three years after Hans Oeschger founded PAGES, Bruno joined the team, acting as co-director from 1996 to 2001. He was excited by the spirit of the PAGES team, in part because mountain climate research, historical climatology and the reconstruction of past climate based on natural archives and documentary data were some of his passions.

It is no surprise that Bruno received many prizes and honors, including honorary doctorates from the University of Innsbruck, Austria, and Free University of Berlin, Germany, the Prix Vautrin Lud, and he even shared the prestigious Marcel Benoist Prize with Hans Oeschger and Werner Stumm.

The international science community mourns an inspiring leader and scientist, a true giant of mountain research, but above all we have lost a dear friend. We all express our deep condolences to Bruno's family, and especially to his wife Béatrice, who was his active and charming partner, accompanying him on many trips around the world, both as a supporter and as a scientific advisor.

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