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Challenges and research priorities to understand interactions between climate, ice sheets and global mean sea level during past interglacials

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Abstract: Quaternary interglacials provide key observations of the Earth system's responses to orbital and greenhouse gas forcing. They also inform on the capabilities of Earth system models, used for projecting the polar ice-sheet and sea-level responses to a regional warmth comparable to that expected by 2100 C.E. However, a number of uncertainties remain regarding the processes and feedbacks linking climate, ice-sheet and sea-level changes during past warm intervals. Here, we delineate the major research questions that need to be resolved and future research directions that should be taken by the paleoclimate, sea-level and ice-sheet research communities in order to increase confidence in the use of past interglacial climate, ice-sheet and sea-level reconstructions to constrain future predictions. These questions were formulated during a joint workshop held by the PAGES-INQUA PALSEA (PALeo constraints on SEA level rise) and the PAGES-PMIP QUIGS (QUaternary InterGlacialS) Working Groups in September 2018.

Key-words: Interglacials; Paleoclimatology; Polar ice sheets; Sea-level changes; Natural archives; Earth System Modeling.

Introduction

Human-induced global warming has large environmental and societal implications, including the potential for substantial and/or rapid polar ice-mass loss that leads to global sea-level rise. To evaluate the risk of major current and future environmental changes, it is essential to understand climate and cryosphere processes and feedbacks occurring during past periods that were warmer than the pre-industrial. About 50 warm intervals, referred to as interglacials, punctuated the Quaternary (0-2.6 Ma). Each lasted between ~10 to ~30 thousand of years (ka) with the distribution of Northern Hemisphere ice resembling the present, with minimal ice sheets outside of Greenland (PAGES working group on Past Interglacials, 2016). Over the past ~450 ka, ice core records show that interglacial Antarctic surface conditions were similar to, or even warmer than those of the pre-industrial (e.g. Jouzel et al., 2007; Figure 1). Past interglacials are not perfect analogues for future anthropogenic changes, as their warming was caused by different forcing mechanisms. Interglacial polar warming resulted from changes in astronomical forcing and an altered global heat distribution, while future warming is driven by anthropogenic greenhouse gas forcing. Nonetheless, interglacials provide an opportunity to utilize proxy data and Earth system models (ESM) to assess the effects of warmer-than-pre-industrial polar temperatures on critical parts of the Earth system, such as polar ice sheets and sea level.

In this context, the Last Interglacial (LIG, ~129-116 ka) has received particular attention. Being the most recent interglacial prior to the Holocene, the LIG offers a great amount of data, and as the warmest interglacial of the last 800 ka at many locations (PAGES working group on Past Interglacials, 2016), it is especially informative despite some major uncertainties that still prevail. Recent studies estimated that LIG high-latitude surface ocean temperatures were warmer by at least 1℃ and polar surface air temperatures by >3-11℃ relative to pre-industrial temperatures, and that peak warmth did not occur synchronously across the globe (Capron et al., 2017 and references therein). Nevertheless, there are too few continental surface temperature reconstructions and no comprehensive global surface temperature estimate combining ice, marine, and terrestrial paleo-temperature reconstructions.

While commonly reported figures suggest that the LIG was characterized by global mean sea level (GMSL) 6-9 m higher than today (Dutton et al., 2015; Figure 1), there is still considerable uncertainty attached to the amplitude and exact timing of this GMSL peak. LIG sea-level reconstructions from coastal archives are hampered by uncertainties in Glacial Isostatic Adjustment (GIA) related to Earth's internal viscoelastic structure and the size of ice sheets during the preceding glaciation, which both remain poorly constrained. For instance, while benthic δ^{18}O records suggest similar ice volumes between the last two glacial maxima though the spatial distribution of ice might have been different, a recent study proposes that the penultimate glacial maximum ice volume was 21±14m global sea-level equivalent smaller than during the most recent one (Rohling et al., 2017). Additionally, mantle dynamic topography may bias LIG sea level reconstructions, but it remains difficult to reliably quantify this effect (Austermann et al. 2017).

There are also large uncertainties regarding the timing and extent of mass loss from the Greenland and Antarctic ice sheets and their respective contributions to the higher-than-present GMSL throughout the LIG. In particular, the sea-level community still debates the extent of variability in sea level within the LIG, with geomorphological studies inferring global mean sea level to be relatively stable (Barlow et al., 2018) versus models with large high-to-low swings (Kopp et al., 2009); and regional records do not agree on the number or the timing of sea level fluctuations (Vyverberg et al., 2018 and references therein).

It would be valuable to assemble similar datasets for older interglacials to assess the relationship between polar climate and ice sheets/sea level, and thus evaluate how consistent this relationship has been. However, for these intervals, both climate and sea-level data are more limited.

In September 2018, the PAGES-INQUA PALSEA (PALeo constraints on SEA level rise) and the PAGES-PMIP QUIGS (QUaternary InterGlacialS) Working Groups held a joint workshop gathering key expertise from the sea-level, ice-sheet and climate paleocommunities, in order to formulate a series of priority research questions to motivate further research and cross-cutting initiatives. Here, we report those key questions that may provide future research foci for communities working on paleo climate, sea level and ice sheets.

Priority research questions

To use past interglacial climate, ice-sheet and sea-level records to support our predictions of future sea-level changes with greater confidence, eight research areas require further investigation:

1. Sea level and temperature. How did interglacial sea-level highstands relate to regional (e.g., high latitudes, tropics) and global temperatures? This can be subdivided into the following questions:

- How did global and regional climates evolve during past interglacials?
- When and how high were sea level highstands during past interglacials?
- How does the timing of peak temperature and sea level compare within an interglacial?

2. Variability in sea level and climate. Were there centennial- to millennial-scale oscillations in GMSL or in climate during interglacials? This question is crucial for estimating the maximum rates of sea-level changes when the configuration of the ice sheets most closely resembled that of today (e.g., during the LIG and Marine Isotope Stage 11; Figure 1).

3. Contribution of ice sheets. What determined the size of polar ice sheets in different interglacial climates? Furthermore, what were the relative contributions and when were peak contributions of the different ice sheets to GMSL rise during interglacials?

4. Ice-sheet resilience. Can large polar ice sheets persist under a large multi-millennial-scale warming and how long must warmth persist to lead to their disappearance? For example, a decade ago the Greenland ice sheet was considered to be largely deglaciated during the LIG. However, more recent data and reconstructions suggest that this ice sheet largely persisted through the LIG despite a regional warming of at least 4°C (e.g., Colville et al., 2011; NEEM community members, 2013). Collectively, results from Greenland point to important unanswered questions for the LIG. Meanwhile, similar research on other ice sheets and during older interglacials is necessary too.

5. Glacial maxima. What was the size and extent of each ice sheet during past glacial maxima? Was the partitioning of ice between ice sheets consistent between glacial periods? These are crucial boundary conditions needed to correct interglacial sea-level indicators for GIA effects.

6. Interglacial oceanic circulation. How did oceanic circulation evolve during interglacials, and how did this affect polar climate and the Antarctic and Greenland ice sheets? Also, could significant freshwater contributions from a Southern Hemisphere source have impacted oceanic circulation and regional climate anomalies?

7. Holocene versus older interglacials. How can we use the Holocene, for which paleodata are most abundant, to learn about older interglacials?

8. Interglacial relevance to the future. Which ice-sheet processes relevant to future changes can be meaningfully constrained by interglacial reconstructions, and which are fundamentally different from processes in past interglacials?

To provide answers to these research questions, several technical research issues should first be addressed. There is still a strong need for highly-resolved climate and sea-level records for the LIG, and even more so for prior interglacials. It is also necessary to improve absolute and relative chronologies for paleoclimatic and sea-level records, along with methodological developments to synchronize records from different types of archives and fully integrate tracers and age uncertainties. Uncertainties remain on the rate of sea-level rise prior to and during the LIG. Further, sea-level modeling requires a better understanding of Earth's internal viscoelastic structure and dynamics. Paleoclimate records provide insight into the spatio-temporal structure and amplitude of interglacial climate change to inform ESM simulations. However, a better assessment of the respective influence of the controlling factors and the seasonality of proxy records is required to improve the interpretation of temperature reconstructions. Plans should be implemented to fill geographical gaps, such as better spatial coverage of paleodata in the Southern and Pacific Oceans and on continents, especially in the high latitudes. There is an urgent need to find direct (near-field) evidence to detect and quantify ice-mass loss in Antarctica, which is crucial to constrain the degree to which it may have contributed to LIG, and other interglacial, GMSL. For Greenland, important inconsistencies exist between ice-sheet model results, climate proxy reconstructions and geological evidence for ice sheet size (Colville et al., 2011; NEEM community members, 2013; Yau et al., 2016). Uncertainties in Greenland leave it unclear how much contribution from Antarctica would be required to explain LIG far-field sea level estimates; and furthermore, maximum contributions from the ice sheets may have been out of phase with each other (Dutton et al., 2015). Finally, further coordinated ESM efforts should simulate the transient evolution of interglacials, and explicitly include climate proxies (e.g., oxygen and carbon isotopes), climate-ice-sheet interactions and dynamic vegetation. These modeling exercises should be extended beyond the LIG when comprehensive datasets become available, to provide improved quantitative understanding of warmth, sea level, ice sheets, and their interactions through multiple interglacials.

Concluding remarks

Investigation of the community-identified research priorities described here will lead to an improved understanding of climate and ice-sheet (and subsequently sea-level) responses to astronomical and greenhouse gas forcing, and thereby the Earth system response to global surface conditions similar to or warmer than the pre-industrial climate. Improved data will be useful benchmarks to inform on model capabilities used for climate, ice-sheet and sea-level projections in capturing millennial-scale patterns and amplitudes of the responses in warm(er) worlds. Addressing these outstanding questions requires organized interdisciplinary collaborations between scientists working on climate, ice sheets, sea level and the solid Earth. Hence, cross-cutting activities such as the 2018 PALSEA-QUIGS workshop are necessary and should be repeated to facilitate knowledge exchange between the different disciplines.

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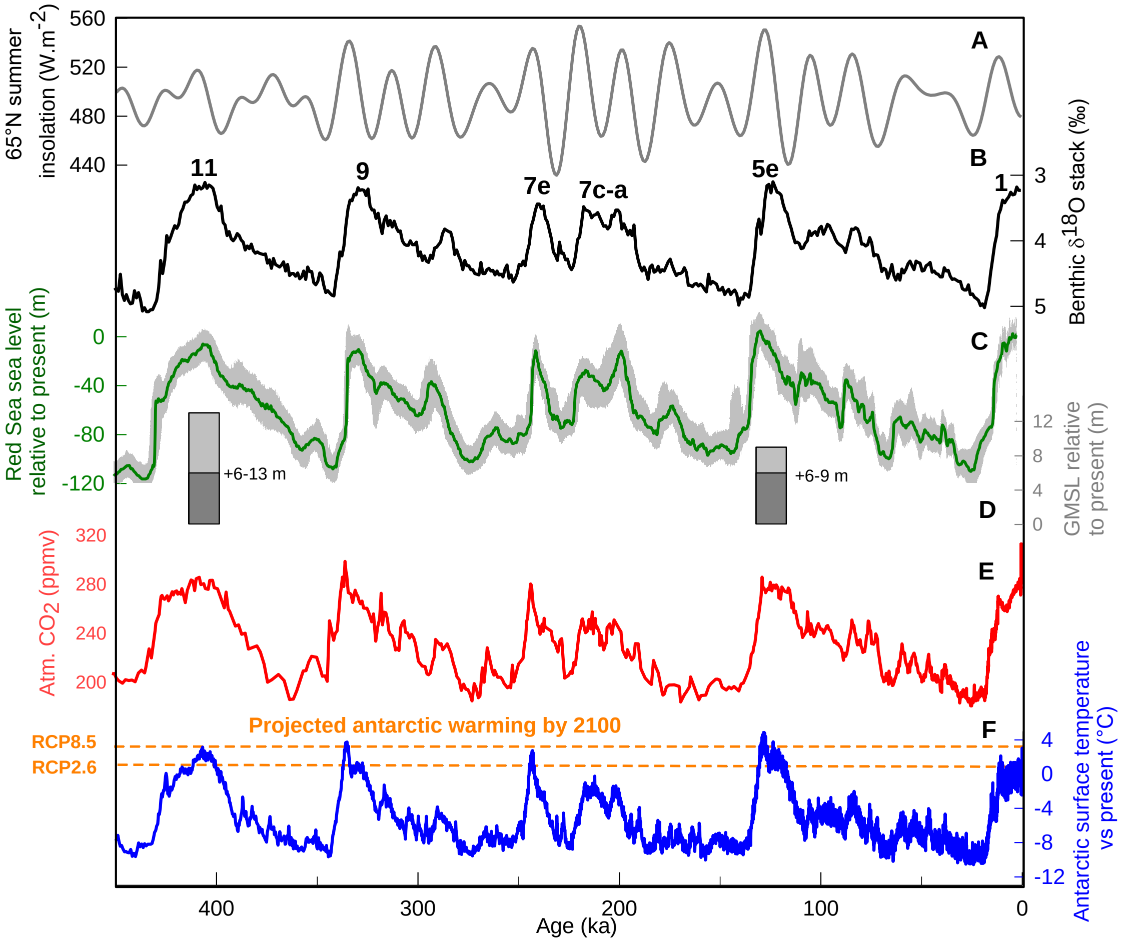
Figure 1. Key paleoclimatic records over the past 450 ka.

(A) Northern Hemisphere 21 June insolation, grey. (B) Benthic foraminifera $\delta^{18}O$ composite, black (Lisiecki and Raymo, 2005), numbers designate the Marine Isotope Stages (MIS) corresponding to interglacial intervals. (C) Red Sea sea-level curve relative to present, green, and 95% probability interval, light grey (Grant et al. 2014). (D) Global mean sea level (GMSL) estimates relative to present for MIS 11 and the LIG (referred to MIS 5e), light grey shading indicates the uncertainty of GMSL maximum (Dutton et al., 2015). (E) Atmospheric CO_2 concentrations, red (Bereiter et al., 2015) and (F) Antarctic surface temperature relative to present, blue (Jouzel et al., 2007) from the EPICA Dome C ice core. The projected Antarctic warming by 2100 based on the Representative Concentration Pathways (RCP) 8.5 and RCP 2.6 scenarios is indicated with orange dashed lines.



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