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Invited review

Differences between the last two glacial maxima and implications for ice-sheet, $\delta^{18}O$, and sea-level reconstructions

Eelco J. Rohling [a, b, *, 1], Fiona D. Hibbert [a, 1], Felicity H. Williams [a, b, 1], Katharine M. Grant [a], Gianluca Marino [a], Gavin L. Foster [b], Rick Hennekam [c, d], Gert J. de Lange [d], Andrew P. Roberts [a], Jimin Yu [a], Jody M. Webster [e], Yusuke Yokoyama [f, g, h]

[a] Research School of Earth Sciences, The Australian National University, Canberra, ACT 2601, Australia
[b] Ocean and Earth Science, University of Southampton, National Oceanography Centre, Southampton SO14 3ZH, UK
[c] Department of Ocean Systems, Royal Netherlands Institute for Sea Research (NIOZ), Utrecht University, PO Box 59, 1790 AB Den Burg, Texel, The Netherlands
[d] Department of Earth Sciences-Geochemistry, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands
[e] School of Geosciences, The University of Sydney, NSW 2006, Australia
[f] Atmosphere and Ocean Research Institute, The University of Tokyo, 5-1-5 Kashiwanoha, Chiba 277-8564, Japan
[g] Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyoku, Tokyo 113-0033, Japan
[h] Department of Biogeochemistry, Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushimacho, Yokosuka 237-0061, Japan

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A B S T R A C T

Studies of past glacial cycles yield critical information about climate and sea-level (ice-volume) variability, including the sensitivity of climate to radiative change, and impacts of crustal rebound on sea-level reconstructions for past interglacials. Here we identify significant differences between the last and penultimate glacial maxima (LGM and PGM) in terms of global volume and distribution of land ice, despite similar temperatures and radiative forcing. Our analysis challenges conventional views of relationships between global ice volume, sea level, seawater oxygen isotope values, and deep-sea temperature, and supports the potential presence of large floating Arctic ice shelves during the PGM. The existence of different glacial 'modes' calls for focussed research on the complex processes behind ice-age development. We present a glacioisostatic assessment to demonstrate how a different PGM ice-sheet configuration might affect sea-level estimates for the last interglacial. Results suggest that this may alter existing last interglacial sea-level estimates, which often use an LGM-like ice configuration, by several metres (likely upward).

1. Introduction

The volume and spatial distribution of continental ice masses during ice ages over the last 3 million years have been the focus of much research for several reasons. First, temporal changes in the radiative balance of climate are important because ice masses have high albedo and reflect incoming solar radiation (e.g., Hansen et al., 2007, 2008; Köhler et al., 2010, 2015; Rohling et al., 2012; PALAEOSENS project members, 2012; Martínez-Botí et al., 2015; Friedrich et al., 2016). Second, temporal development of ice-age cycles provides critical information about the nature of long-term climate cooling over the past few million years, in response to CO_2 reduction and interactions among ice, land cover, and climate (e.g., Clark et al., 2006; Köhler and Bintanja, 2008; de Boer et al., 2010, 2012; Hansen et al., 2013). Third, variable amplitude of individual ice ages helps to determine the relationship between climate change, astronomical climate forcing cycles, and climate feedbacks on timescales of 10s–100s of kiloyears (e.g., Oglesby, 1990; Imbrie et al., 1993; Raymo et al., 2006; Colleoni et al., 2011, 2016; Ganopolski and Calov, 2011; Carlson and Winsor, 2012; Abe-Ouchi et al., 2013; Hatfield et al., 2016; Liakka et al., 2016). Fourth, the size and spatial distribution of land ice during past glacials determines crustal rebound processes when ice masses

* Corresponding author. Research School of Earth Sciences, The Australian National University, Canberra, ACT 2601, Australia.
E-mail address: eelco.rohling@anu.edu.au (E.J. Rohling).
[1] Joint first authors.

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melt, which in turn affects sea-level reconstructions for subsequent interglacials. The latter are key to investigations of sea-level changes above the present level during warmer-than-present interglacials (e.g., the Last Interglacial, LIG, ~130-118 kyr ago (ka); Hibbert et al., 2016; Hoffman et al., 2017; Hansen et al., 2017), which can reveal ice-sheet disintegration processes of relevance to the future (e.g., Dutton and Lambeck, 2012; Dutton et al., 2015a,b; Yamane et al., 2015; DeConto and Pollard, 2016).

Despite the relevance of these issues, we lack detailed information about ice volumes and their spatial extent during glacial maxima. Based on intervals of maximum global ice volume (lowest sea level), the Last Glacial Maximum (LGM) spanned the ~26.5–19 ka interval (Clark et al., 2009), while the Penultimate Glacial Maximum (PGM) spanned ~155–140 ka, comprising two sea-level minima separated by a minor rise centred on ~145 ka (Grant et al., 2014). In general, we know most about the LGM, and information decreases markedly for older glacial maxima. Even for the PGM, information is so limited that studies often invoke an LGM-like ice volume (e.g., Lambeck and Chappell, 2001; Yokoyama and Esat, 2011). Initial assessment of Red Sea glacial sea-level lowstands seemed to support that view (Rohling et al., 1998), but only constrained the LGM sea-level drop to have been at least as low as that of the PGM, without giving a maximum value. Here we show that subsequent improvements to the Red Sea record firmly indicate a greater sea-level drop during the LGM than during the PGM. Independent evidence from western Mediterranean palaeo-shorelines also suggests that the LGM sea-level drop exceeded the PGM sea-level drop by about 10 m (Rabineau et al., 2006).

Robust quantitative assessment of sea-level differences between the last two glacial maxima is especially important because their spatial ice-mass distributions were markedly different (Table 1 summarises previously modelled ice-volume changes, relative to the present). Geological data and numerical modelling strongly suggest that the Eurasian ice sheet (EIS) covered a larger area during the PGM than during the LGM (Svendsen et al., 2004; Colleoni et al., 2011, 2016) (Fig. 1), with most estimates suggesting a PGM EIS volume equivalent to a 33–53 m global sea-level fall (sea-level equivalent, SLE) (Table 1); this is approximately twice the size of the LGM EIS (14–29 m_{SLE}; Table 1 and Clark and Tarasov, 2014). Such contrasting ice-mass distributions between successive glacial maxima highlight significant complexity in the processes that drive glaciation into different ‘modes’ (e.g., Liakka et al., 2016). The difference also has repercussions for glacioisostatic adjustment (GIA) studies of sea-level history during the LIG, which was about 1 °C warmer than the Holocene (Clark and Huybers, 2009; Turney and Jones, 2010; McKay et al., 2011; Hoffman et al., 2017; Hansen et al., 2017), with sea levels that reached 4–10 m higher than today (Rohling et al., 2008; Dutton and Lambeck, 2012; Grant et al., 2012; Stocker et al., 2013; Dutton et al., 2015a, 2015b). Dendy et al. (2017) investigated the sensitivity of the predictions of the last interglacial highstand to uncertainties in the configuration of the major northern hemisphere ice sheets during MIS 6. They focused on the sensitivity of the GIA correction to three major components of sea-level uncertainty during the MIS 6/5 transition: the age model and duration of deglaciation; the number of glacial cycles modelled during the GIA analysis; and the relative distribution of ice volume between the North American and Eurasian ice sheets, assuming that total ice volume for these complexes remained the same at MIS 2 and MIS 6. A key result is that sensitivity to different ice-sheet configurations is in the ~5 m range (relative to the +4 to +10 m observed for LIG sea level). This calls for exploration of further total ice-volume and ice-mass distribution scenarios for the MIS 6/5 transition.

Little evidence exists regarding the PGM North American Ice Sheet complex (NAIS), because the LGM advance obliterated virtually all PGM glaciomorphological evidence (we use EIS and NAIS to refer to all Eurasian and North American ice sheets, respectively, rather than separating all ice masses). For example, even when assuming an LGM-like (~130 m_{SLE}, Clark et al., 2009) or smaller total PGM sea-level drop, with comparable Antarctic ice volume (Table 1) and a 33 to 53 or even 71 m_{SLE} EIS (Table 1), it follows that the NAIS must have been smaller than during the LGM. There is GIA modelling support for a smaller PGM NAIS to account for sea-level observations in Bermuda (Potter and Lambeck, 2003; Wainer et al., 2017), and climate modelling results agree best with global environmental proxy data in scenarios that combine a large EIS with a small NAIS (~30 m_{SLE}) (Colleoni et al., 2016). The lack of glaciomorphological evidence for the PGM NAIS also qualitatively supports a larger NAIS at the LGM than at the PGM.

Here we compile highly resolved data from multiple mutually independent sea-level reconstruction methods to gauge PGM sea level relative to the LGM. All have methodological and glacioisostatic uncertainties, and chronological uncertainties affect comparisons between records. But within individual records from the same method, high coherence is commonly achieved. Hence, confidence is higher for PGM–LGM comparisons within individual records than for relative sea-level comparisons among records. We use our PGM–LGM sea-level compilation in conjunction with a glaciogeomorphological synthesis of the PGM EIS and NAIS extent (Fig. 1, Appendix I; see acknowledgements for data access), as well as information from published ice-sheet modelling studies, to test the small-NAIS hypothesis. We then consider the implications of PGM–LGM differences in ice volume and extent, with respect to: 1) concepts of glacial inception; 2) glacioisostatic corrections to last interglacial sea levels; and 3) global sea-level/ice-volume/$\delta^{18}O$ relationships.

2. PGM–LGM sea-level comparison

We use five primary data sources to quantify PGM *versus* LGM ice volume/sea level (Fig. 2, Table 2). The first two are (near) continuous relative sea-level records derived from surface-water $\delta^{18}O$ residence-time effects in the highly evaporative Red Sea and Mediterranean Sea (Siddall et al., 2003; Rohling et al., 2014). The third source is a (near) continuous time-series of past ice volume/sea level from deep-sea seawater $\delta^{18}O$, hereafter named δ_{sw} (e.g., Martin et al., 2002; Sosdian and Rosenthal, 2009; Elderfield et al., 2012). The fourth source for our assessment of a PGM–LGM sea-level offset concerns fossil coral position data (Z_{cp}) from a comprehensive database that has been harmonised in terms of dating and uplift-correction protocols (Hibbert et al., 2016). The fifth source consists of western Mediterranean palaeo-shorelines (Rabineau et al., 2006). The latter was discussed before, while the other four sources are detailed below.

2.1. Red Sea and Mediterranean records

The marginal-sea method for sea-level reconstruction relies on the fact that water residence time in the highly evaporative, semi-enclosed Red Sea and Mediterranean Sea is a function of sea-level change because of the narrow and shallow straits that connect the basins with the open ocean. In today's Red Sea, the Bab-el-Mandab Strait is only 137 m deep, mean annual evaporation is ~2 m y^{-1}, and the basin has a narrow catchment with no major river systems or other hydrological complications (Siddall et al., 2004). For the Mediterranean, the Strait of Gibraltar is 284 m deep, mean annual evaporation is ~1 m y^{-1}, and large river systems provide considerable hydrological complications. Thus, relative sea-level reconstructions have a higher signal-to-noise ratio at Bab-el-Mandab than at Gibraltar. Accordingly, 1σ precision of individual