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Sensitivity of Last Interglacial sea-level high stands to ice sheet configuration during Marine Isotope Stage 6

S. Dendy [a, b, *], J. Austermann [b, c], J.R. Creveling [d], J.X. Mitrovica [b]

[a] Lamont-Doherty Earth Observatory, Columbia University, United States
[b] Department of Earth and Planetary Sciences, Harvard University, United States
[c] Department of Earth Sciences, University of Cambridge, United Kingdom
[d] College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, United States

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ABSTRACT

Estimates of peak global mean sea level (GMSL) during the Last Interglacial (LIG, ~129-116 ka) based on geological sea level high-stand markers require a correction for the contaminating influence of glacial isostatic adjustment (GIA). This correction is obtained by calculating the viscoelastic response of the Earth to changes in the ice and ocean load prior to and following the LIG. While ice retreat over the last deglaciation is relatively well constrained, changes in ice cover prior to the LIG are more uncertain. We investigate the sensitivity of numerical predictions of GIA during the LIG to variations in the geometry of pre-LIG ice cover and the timing of the deglaciation into the LIG, with a particular focus on Marine Isotope Stage (MIS) 6 (~190-130 ka). We demonstrate that reconstructing the pre-LIG ice history by replicating the last glacial cycle back in time, rather than using ice volume approximations based on oxygen isotope records, can introduce errors in LIG high-stand predictions of ~5 m at sites on the peripheral bulge of major ice complexes, and up to ~2 m at far-field sites. We also demonstrate that predictions of LIG sea level are more sensitive to the geographic distribution of ice cover during MIS 6 than previously recognized. Adopting simulations which vary the relative size of Late Pleistocene ice cover over North America and Eurasia can yield a change in predicted high-stand elevations of ~5 m in both the near and far field of northern hemisphere ice sheets. This far-field sensitivity arises, in part, from the reorientation of Earth's rotation axis during MIS 6, which in turn drives sea-level changes with a distinct geographic signature. In future work we will apply the insights gained here to re-evaluate the observed geographic variability in geological high-stand markers of LIG age and estimates of GMSL based upon them.

1. Introduction

Global mean temperatures during the Last Interglacial (LIG), or Marine Isotope Stage (MIS) 5e, which extended from ~129-116 ka (Dutton and Lambeck, 2012), are reconstructed to have been on average ~1–2 °C warmer than the present (Otto-Bliesner et al., 2013; Turney and Jones, 2010), making it a valuable testing ground for investigating ice sheet stability in a moderately warmer world (Dutton et al., 2015a). Geologic records of past sea-level high stands provide an important constraint on LIG ice sheet melt. For example, Kopp et al. (2009) analyzed a variety of records, including sedimentary and biological facies, coral reef terraces, erosional surfaces, and marine oxygen isotope records, within a Bayesian statistical framework, and concluded that it was extremely likely (>95% probability) that LIG peak global mean sea level (GMSL) exceeded 6.6 m, and was unlikely (33% probability) to have exceeded 9.4 m. Dutton and Lambeck (2012) focused on two sites, the Seychelles and Western Australia, where they argued that fossil corals in these tectonically stable areas provide particularly robust constraints on local sea level. These authors concluded that GMSL during the LIG peaked 5.5–9 m above present with an additional uncertainty of ±1.5 m introduced by the ice and Earth model parameters. A reanalysis of the data from the Seychelles, that also accounted for the geographic variability in sea level associated with polar ice sheet collapse, reduced the upper bound estimate to 7.6 ± 1.7 m (Dutton et al., 2015b; Hay et al., 2014). While these

* Corresponding author. School of Earth, Society and Environment, University of Illinois, Urbana-Champaign, United States.
E-mail address: sdendy2@illini.edu (S. Dendy).

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bounds on peak GMSL are relatively consistent, inferences of the timing of major polar ice sheet melt during the LIG vary substantially, with debate over an early, late or double peak in LIG GMSL (Dutton et al., 2015b; O'Leary et al., 2013; Kopp et al., 2009, 2013).

Reconstructions of GMSL during the LIG must account for the geographically variable signal of glacial isostatic adjustment (GIA). The above studies corrected for GIA by using numerical simulations that incorporate the deformational, gravitational and rotational impacts on sea level driven by the ice age surface mass (ice plus ocean) loading. GIA simulations require, on input, models for both the space–time geometry of the ice cover across at least the last two glacial cycles (i.e., MIS 7 to present) and the viscoelastic structure of the Earth.

This study focuses on the sensitivity of these GIA predictions to the timing and geometry of ice cover prior to the LIG, with a focus on the ice history during Marine Isotope Stage 6 (MIS 6; 190-130 ka). We examine this interval because it encompasses the major expansion and decay of northern hemisphere ice volume leading into and out of the penultimate glacial maximum (PGM). Geological records of the areal extent of MIS 6 ice are limited, largely due to erosion during subsequent glacial advances. However, available reconstructions based on glacial terminations, ice-rafted debris, seismic records, microfossils and sediment core $\delta^{18}O$ measurements, as well as climate modeling, suggest that the Eurasian Ice Sheet was larger during the PGM than the LGM (Svendsen, 2004; Lambeck et al., 2006; Colleoni et al., 2016). Given that total ice volumes during the penultimate and last glacial maximums were comparable (e.g., Waelbroeck et al., 2002), a larger Eurasian ice cover implies a smaller Laurentide Ice Sheet (Colleoni et al., 2016). GIA modeling that incorporates more extensive Eurasian ice cover during the PGM has been performed (Lambeck et al., 2006). However, a more systematic study of the sensitivity of LIG high stand predictions to variations in the relative size of the North American and Eurasian ice cover, and the physics underlying this sensitivity, is warranted. Such an investigation is the principal focus of this study.

In addition, marine oxygen isotope records suggest that the deglaciation leading into the LIG was faster than the post-LGM deglaciation (Marino et al., 2015; Shakun et al., 2015; Waelbroeck et al., 2002). The age model for these records is based on orbital tuning and globally averaged sedimentation rates (Imbrie et al., 1984; Lisiecki and Raymo, 2005). A relatively fast MIS 6 deglaciation, compared to the post-LGM deglaciation, is also supported by uranium/thorium dating of fossil corals from Tahiti that indicate a sea-level low stand of −70 m at 133 ka (Thomas et al., 2009). The sensitivity of GIA predictions to the rate of deglaciation into the LIG is therefore also explored here.

2. Methods

The sea-level calculations described here are based on a gravitationally self-consistent theory that incorporates time varying shorelines and the feedback of load-induced perturbations to Earth's rotation into sea level (Kendall et al., 2005). We adopt a form of the theory that assumes a spherically symmetric, self-gravitating, Maxwell viscoelastic Earth model. The elastic and density components of the model are given by the seismic model PREM (Dziewonski and Anderson, 1981) and the viscosity structure is characterized by three parameters: an infinite viscosity (elastic) lithosphere of prescribed thickness, *LT*, and constant upper and lower mantle viscosities which we denote by ν_{um} and ν_{lm}, respectively. We define a reference Earth model with values $LT = 95$ km, $\nu_{um} = 0.5 \times 10^{21}$ Pa s and $\nu_{lm} = 5 \times 10^{21}$ Pa s, but consider the sensitivity of the results to variations in these three parameters.

Our reference ice history, I_{REF}, is characterized by four glacial cycles (Fig. 1A; red line). To construct the most recent cycle, we first adopt the ICE-6G global ice reconstruction from the Last Glacial Maximum (LGM) to the present day (Argus et al., 2014; Peltier et al., 2015). Between the end of the LIG and the LGM, we adopt an ice history that follows the GMSL curve inferred by Waelbroeck et al. (2002), which is derived from benthic $\delta^{18}O$ records and relative sea level (RSL) data. During this interval, we prescribe an ice geometry that matches the post-LGM geometry with the same GMSL value; in this regard, I_{REF} exclusively adopts an ICE-6G geometry with dominant northern hemisphere ice cover over North America (and Greenland) during glacial maxima. During the LIG, which we assume extended from 129-116 ka (Dutton and Lambeck, 2012), we adopt a GMSL and ice geometry equal to the present day. We emphasize that the numerical GIA predictions below do not include any excess ice melting during the LIG relative to present-day. We use this approach because our goal is to isolate the sensitivity of predicted sea-level high stands during the LIG to variations in the deformational, rotational and gravitational effects of GIA, rather than any differences in GMSL during the LIG relative to the present. The 13 kyr duration is chosen for illustrative purposes, and we note that there is considerable debate associated with the timing and duration of the LIG (Govin, 2015). We discuss the impact on the predictions of assuming a shorter LIG in the Discussion section.

Finally, we construct three glacial cycles prior to the LIG by replicating the modeled LIG to present cycle (as described above) and stringing these together to span ~480 to 0 ka. The GMSL curve associated with this reference ice history is shown in Fig. 1A (red line). We note that, in constructing this reference ice history, we do not intend to imply that the glacial maximum during MIS 2 (the LGM), MIS 6 (the PGM), MIS 8, and MIS 10 all had comparable ice volumes (see, for instance, Waelbroeck et al., 2002); rather, we provide a preliminary calculation that assumes similar magnitude cycles in order to serve as a reference case. We examine the effect of glacial cycles with variable amplitude glacial maxima in the sensitivity analysis described below.

3. Sensitivity tests and discussion

3.1. GIA-induced high-stand timing and elevation

Fig. 2 shows the numerical prediction of RSL at the beginning (129 ka) and near the end (119 ka) of the modeled LIG computed using the reference Earth and ice (I_{REF}) models discussed above. One should interpret these figures as representing the predicted height of a sea-level marker of either age relative to present sea level, and in this regard we only plot contours in regions where RSL is above zero (i.e., where the ancient sea-level marker is predicted to be exposed at present day). The physics underlying these plots has been discussed in numerous GIA studies (e.g., Mitrovica and Milne, 2002; Dutton and Lambeck, 2012; Lambeck et al., 2012; Raymo and Mitrovica, 2012).

In the far field of the Late Pleistocene ice sheets, sea level falls during an interglacial because of the combined effects of equatorial ocean syphoning across low latitudes and, at locations close to shorelines, the tilting upward of the crust by continental levering (Mitrovica and Milne, 2002). As a result, at far-field sites, the predicted high stand due to GIA occurs at the start of the interglacial when one assumes no excess melting during the LIG (as we do in Fig. 2), and the high-stand elevation in this case reflects the difference in isostatic disequilibrium at the start of the LIG versus the present-day (Raymo and Mitrovica, 2012; Dutton and Lambeck, 2012). The modeled LIG far-field high stands are predicted to lie up to ~3 m above present sea level in Fig. 2A.

In contrast to such sites, in near-field regions characterized by peripheral bulge subsidence, or at some locations where