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Constraints on surface seawater oxygen isotope change between the Last Glacial Maximum and the Late Holocene

C. Waelbroeck [a, *], T. Kiefer [b], T. Dokken [c], M.-T. Chen [d], H.J. Spero [e], S. Jung [f], M. Weinelt [g], M. Kucera [h], A. Paul [h], on behalf of MARGO Project Members

[a] LSCE/IPSL, Laboratoire CNRS-CEA-UVSQ, 91198 Gif-sur-Yvette, France
[b] PAGES International Project Office, 3012 Bern, Switzerland
[c] Uni Research Climate and Bjerknes Centre for Climate Research, Allegaten 55, 5007 Bergen, Norway
[d] Institute of Applied Geosciences, National Taiwan Ocean University, Keelung 20224, Taiwan
[e] Department Earth and Planetary Sciences, University of California Davis, Davis, CA 95616, USA
[f] Grant Institute, University of Edinburgh, Edinburgh EH9 3JW, UK
[g] Institute for Geosciences, University of Kiel, 24098 Kiel, Germany
[h] MARUM – Center for Marine Environmental Sciences and Department of Geosciences, University Bremen, 28334 Bremen, Germany

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ABSTRACT

Estimates of the change in surface seawater $\delta^{18}O$ ($\delta^{18}O_{sw}$) between the Last Glacial Maximum (LGM) and Late Holocene (LH) are derived from homogenous data sets with rigorous age control, namely MARGO sea surface temperature (SST) estimates and oxygen isotopic ratios ($\delta^{18}O$) of planktonic foraminifers. Propagation of uncertainties associated with each proxy allows the identification of robust patterns of change in $\delta^{18}O_{sw}$. Examination of these patterns on a regional scale highlights which changes in surface currents and hydrological cycle are consistent with both planktonic isotopic data and reconstructed SST. Positive local annual mean LGM-LH $\delta^{18}O_{sw}$ anomalies characterize the glacial tropical Indian Ocean, portions of the western and eastern margins of the North Pacific, the Iberian margin and the tropical North Atlantic, as well as the South African margin. Although reduced precipitation during the LGM with respect to the LH may have contributed to some extent to these local enrichments in surface seawater ^{18}O, the largest positive anomalies appear to be related to changes in ocean circulation. Large local negative annual mean LGM-LH $\delta^{18}O_{sw}$ anomalies are found in the South Pacific and North Atlantic, reflecting the equatorward migration of surface temperature fronts during the LGM with respect to the LH. In the northern North Atlantic, a region characterized by large discrepancies between SST estimates based on different proxies, only SST estimates based on planktonic foraminifer counts yield annual mean LGM-LH $\delta^{18}O_{sw}$ anomalies consistent with a southward shift of the polar front at the LGM relative to the LH.

1. Introduction

Given the large amount of well-dated paleoclimatic data existing for the Last Glacial Maximum (LGM), this time interval is a good target to constrain climate sensitivity and evaluate the capability of models to simulate a climate that is drastically different from the present one (e.g. Braconnot et al. (2012)). Environmental proxy data have been compiled in several projects aimed at reconstructing LGM surface conditions (e.g. Bartlein et al. (2011); MARGO P. M. (2009)). The Multiproxy Approach for the Reconstruction of the Glacial Ocean surface (MARGO) project produced a reassessment of LGM sea surface temperatures (SST) (Kucera et al., 2005a; MARGO P. M., 2009). However, changes in SST are not sufficient to fully describe the changes in surface ocean conditions, as changes in surface water salinity are equally important in determining surface water density, and hence deep-water formation processes and ocean circulation. Although quantitative reconstructions of past sea surface salinity (e.g. Duplessy et al. (1991)) are subject to large uncertainties (Rohling and Bigg, 1998), there is a positive correlation between surface seawater oxygen isotopic ratios ($\delta^{18}O_{sw}$) and salinity that directly results from Rayleigh fractionation processes during evaporation and condensation (Epstein and Mayeda, 1953). Changes in $\delta^{18}O_{sw}$ can thus be interpreted in terms of changes in land-based ice volume, river runoff, local precipitation-evaporation budget, or surface oceanic currents.

* Corresponding author.

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In addition to a global synthesis of LGM multiproxy SST estimates (MARGO P. M., 2009), the MARGO project also compiled global datasets of planktonic foraminifer oxygen isotopic ratios ($\delta^{18}O_c$) for the Late Holocene (LH) (Waelbroeck et al., 2005) and LGM (this study, supplementary Table S1). MARGO datasets are characterized by a rigorous definition of the LGM and LH chronozones, i.e. 19–23 cal ky BP (ka) and 0–4 ka, accompanied by an assessment of uncertainty (or chronozone quality levels) (Kucera et al., 2005a).

Here we combine MARGO planktonic foraminifer $\delta^{18}O_c$ data and SST estimates to derive regional estimates of the change in surface seawater $\delta^{18}O_{sw}$ between the LGM and LH. The present study thereby provides the first set of LGM-LH seawater $\delta^{18}O_{sw}$ LGM-LH anomalies computed in a systematic way from homogenous data sets with rigorous age control. Furthermore, examination of the estimated LGM-LH $\delta^{18}O_{sw}$ anomalies on a regional scale highlights which changes in surface currents and hydrological cycle are consistent with both planktonic isotopic data and reconstructed SST.

2. Material and methods

We computed LGM-LH $\delta^{18}O_{sw}$ anomalies in 119 sites where both planktonic foraminifer $\delta^{18}O_c$ and SST anomalies are available (Fig. 1). In some cores, planktonic foraminifer $\delta^{18}O_c$ data are available for multiple species, yielding a total of 136 LGM-LH $\delta^{18}O_{sw}$ anomaly estimates. Among those, we only discuss and plot significant $\delta^{18}O_{sw}$ anomalies (i.e. anomalies larger than the corresponding computed propagated 1 sigma error), i.e. 121 $\delta^{18}O_{sw}$ anomaly estimates from 110 sites (Figs. 2–4).

2.1. Planktonic $\delta^{18}O_c$ anomalies

MARGO LGM planktonic $\delta^{18}O_c$ dataset (this study) consists of data from 243 deep-sea cores with thorough age control that has been checked for internal consistency (supplementary Table S1). MARGO LGM planktonic $\delta^{18}O_c$ data were attributed LGM chronozone quality levels of 1–4, as defined in Kucera et al. (2005a), with the LGM interval extended from 21 ka ± 2 ky to 21 ka ± 3 ky in certain cases, in order to maximize geographical coverage. The LH planktonic $\delta^{18}O_c$ data are from the previously published MARGO LH planktonic $\delta^{18}O_c$ dataset (Waelbroeck et al., 2005) to which we added 11 new LH planktonic $\delta^{18}O_c$ data points in key sites (supplementary Table S2). In the present study, we only retain cores with high LGM and LH chronozone quality levels (i.e. levels 1 to 3 for LGM samples, and 1 to 4 for LH samples according to Kucera et al. (2005a) in which both LGM and LH planktonic $\delta^{18}O_c$ data were available from the same planktonic foraminifer species. At each site, we computed LGM-LH calcite $\delta^{18}O_c$ anomalies for all species for which $\delta^{18}O_c$ data were available, i.e. *Globigerinoides sacculifer*, *Globigerinoides ruber* (white), *Globigerina bulloides*, and *Neogloboquadrina pachyderma* (left).

2.2. SST anomalies

Following the approach adopted in (MARGO P. M., 2009), LGM-LH SST anomalies are defined as the difference between LGM SST estimates and World Ocean Atlas SSTs. MARGO proxy-specific LGM SST estimates were derived from two types of proxies: microfossil-based (transfer functions based on planktonic foraminifer, diatom, dinoflagellate cyst and radiolarian abundances) and geochemical (alkenones and planktonic foraminifer Mg/Ca) proxies. The use of a common data set of ambient temperatures at 10 m water depth for the calibration of all proxies (Kucera et al., 2005a) makes MARGO proxy-specific LGM SST estimates easily inter-comparable. At each site, MARGO multiproxy SST estimates were obtained by careful combination of the estimates yielded by different proxies, taking into account the error of the calibration for each proxy, the number of samples per core on which the LGM SST estimate is based, the quality of the age model for each core, and the uncertainty due to the calibration error for each proxy (MARGO P. M., 2009). The final 5° × 5° MARGO LGM multiproxy SST field was obtained by combining multiproxy SST estimates within each grid cell, taking into account the degree of convergence among the SST estimates within each grid cell (MARGO P. M., 2009).

In the present study, we use MARGO LGM-LH SST proxy-specific anomalies when available. In addition, we interpolated MARGO

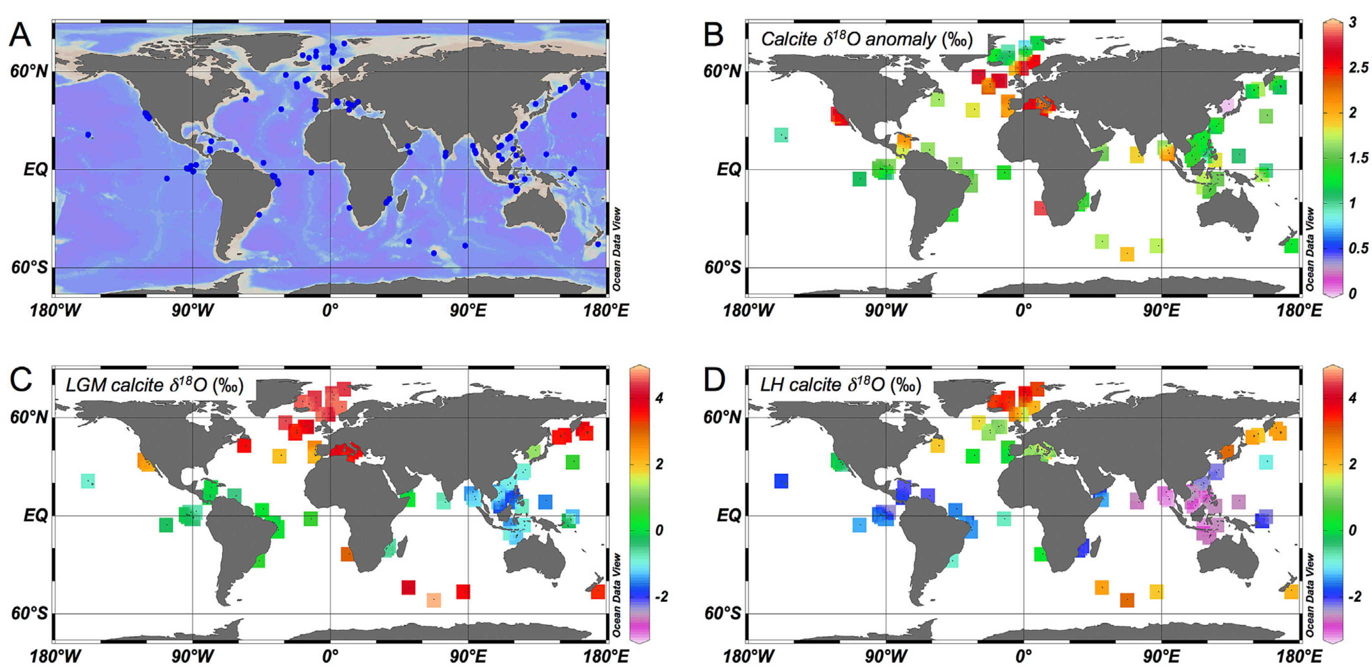

Fig. 1. **A**. Locations of the cores meeting our selection criteria (see methods in main text). **B**. LGM-LH planktonic foraminifer calcite $\delta^{18}O_c$ anomaly. **C**. LGM planktonic foraminifer $\delta^{18}O_c$ (this study). **D**. LH planktonic foraminifer $\delta^{18}O_c$ (Waelbroeck et al., 2005).