Supplementary material

A. Calculation of the seawater $\delta^{18}O_{sw}$ LGM-LH anomaly

The temperature dependence of the equilibrium oxygen isotopic fractionation of inorganic calcite precipitation can be approximated by the quadratic approximation of the (O'Neil et al., 1969) equation given in (Shackleton, 1974):

$$T = 16.9 - 4.38\,(\delta_c - \delta_w) + 0.1\,(\delta_c - \delta_w)^2 \qquad (1)$$

where T is the calcification temperature expressed in degrees Celsius
δ_c is the calcite $\delta^{18}O_c$ expressed in ‰ V-PDB
δ_w the water $\delta^{18}O_{sw}$ in ‰ V-SMOW (Coplen, 1996).

NB: A correction of 0.27 ‰ is necessary to convert from the V-SMOW scale to the V-PDB scale (Hut, 1987).

Assuming that LGM-LH calcification temperature anomalies can be approximated by MARGO LGM-LH SST anomalies, equation (1) yields:

$$\Delta T = -\,4.38\,(\Delta\delta_c - \Delta\delta_w) + 0.1\,[(\delta_c^{LGM} - \delta_w^{LGM})^2 - 0.1\,(\delta_c^{LH} - \delta_w^{LH})^2] \qquad (2)$$

where $\Delta T = T^{LGM} - T^{LH}$
$\Delta\delta_c = \delta_c^{LGM} - \delta_c^{LH}$
$\Delta\delta_w = \delta_w^{LGM} - \delta_w^{LH}$

Equation (2) can be rewritten as:

$$(\Delta\delta_w)^2 + b\,\Delta\delta_w + c = 0 \qquad (3)$$

where $b = 43.8 + 2\,(\delta_w^{LH} - \delta_c^{LGM})$
$c = -\,10\,(\Delta T + 4.38\,\Delta\delta_c) + (\delta_c^{LGM})^2 - (\delta_c^{LH})^2 - 2\,\delta_w^{LH}\,\Delta\delta_c$

The positive solution of equation (3) is:

$$\Delta\delta_w = \frac{1}{2}\,(-\,b + \sqrt{D}) \qquad (4)$$

where $D = b^2 - 4\,c$

B. Calculation of the uncertainty on $\Delta\delta_w$

Neglecting the covariance between b and D, the variance of $\Delta\delta_w$ can be expressed by:

$$\sigma_\Delta^{\ 2} = \left(\frac{\partial \Delta\delta_w}{\partial b}\right)^2 \sigma_b^{\ 2} + \left(\frac{\partial \Delta\delta_w}{\partial D}\right)^2 \sigma_D^{\ 2} \tag{5}$$

Hence,

$$\sigma_\Delta^{\ 2} = \frac{1}{4}\sigma_b^{\ 2} + \frac{1}{16\ D}\ \sigma_D^{\ 2} \tag{6}$$

where $\sigma_b^{\ 2} = 4\,(\sigma_{\delta_w^{LH}}^{\ 2} + \sigma_{\delta_c^{LGM}}^{\ 2})$

$\sigma_D^{\ 2} = 4\,b^2\,\sigma_b^{\ 2} + 16\,\sigma_c^{\ 2}$

where $\sigma_{\delta_w^{LH}}$ is set to 0.2‰ (Schmidt, 1999)

$\sigma_{\delta_c^{LGM}}$ is the standard deviations on δ_c^{LGM} given in Table S1

$$\sigma_c^{\ 2} = 100\,\sigma_{\Delta T}^{\ 2} + (2\,\delta_c^{LGM} - 2\,\delta_w^{LH} - 43.8)\,\sigma_{\delta_c^{LGM}}^{\ 2} + 4\,\Delta\delta_c^{\ 2}\,\sigma_{\delta_w^{LH}}^{\ 2} + (43.8 - 2\,\delta_c^{LH} + 2\,\delta_w^{LH})\,\sigma_{\delta_c^{LH}}^{\ 2}$$

where $\sigma_{\delta_c^{LH}}$ is the standard deviations on δ_c^{LH} given in Table S1

The errors on δ_c^{LGM}, δ_w^{LH}, ΔT, we use in the present calculation of the uncertainty on $\delta^{18}O_{sw}$ anomalies are also reported in Table S1. The errors on MARGO proxy-specific SST anomalies were taken from (MARGO P. M., 2009) supplementary tables. The errors on MARGO interpolated multiproxy SST anomalies were computed by interpolating the total errors on MARGO SST anomalies at the surrounding grid nodes (MARGO P. M., 2009).

C. Supplementary tables and figures

Table S1. MARGO LGM planktonic oxygen isotopic data. This table lists all MARGO LGM planktonic oxygen isotopic data, complete references. Raw data from unpublished records (noted as "this study" in the publication column) are provided in the joint text file "Raw_data.txt".

Table S2. Seawater $\delta^{18}O_{sw}$ anomaly estimates. This table comprises detailed information on seawater $\delta^{18}O_{sw}$ anomaly estimates for each ocean, complete references. Raw data from unpublished records (noted as "this study" in the reference columns) are provided in the joint text file.

Figure S1. Zoom on the North Indian and Indo-Pacific regions. Annual mean SST anomalies (left panels) and corresponding residual $\delta^{18}O_{sw}$ anomalies (right panels) are interpolated using the DIVA (Data-Interpolating Variational Analysis) tool provided by the ODV (Ocean Data View) software (Schlitzer, 2007). **A1.** Multiproxy annual mean SST anomaly interpolated from MARGO multiproxy gridded field (MARGO P. M., 2009). **A2.** Residual $\delta^{18}O_{sw}$ anomaly derived from SST anomalies shown in A1 and planktonic foraminifer $\delta^{18}O_c$

anomalies. **B1.** and **B2.** Same as in A but for annual mean SST anomalies reconstructed using planktonic foraminifer abundances.

Figure S2. Atlantic Ocean annual mean SST anomalies (left panels) and corresponding residual $\delta^{18}O_{sw}$ anomalies (right panels). **A1.** Multiproxy annual mean SST anomaly interpolated from MARGO multiproxy gridded field (MARGO P. M., 2009). **A2.** Residual $\delta^{18}O_{sw}$ anomaly derived from SST anomalies shown in A1 and planktonic foraminifer $\delta^{18}O_c$ anomalies. **B1.** and **B2.** Same as in A but for annual mean SST anomalies reconstructed using planktonic foraminifer abundances. **C1.** and **C2.** Same as in A but for annual mean SST anomalies derived from planktonic foraminifer Mg/Ca south of 50°N and from dinoflagellate cyst abundances north of 50°N. **D1.** and **D2.** Same as in A but for annual mean SST anomalies derived from alkenone $U^{K'}{}_{37}$.

Figure S3. Zoom on the North Atlantic and Mediterranean regions. Annual mean SST anomalies reconstructed using planktonic foraminifer abundances (left panel) and corresponding residual $\delta^{18}O_{sw}$ anomalies (right panel) are interpolated using the DIVA (Data-Interpolating Variational Analysis) tool provided by the ODV (Ocean Data View) software (Schlitzer, 2007).

References

Coplen, T.B., 1996. Editorial: more uncertainty than necessary. Paleoceanography 11(4), 369-370.

MARGO Project Members (C. Waelbroeck, A. Paul, M. Kucera, A. Rosell-Melé, M. Weinelt, R. Schneider, A.C. Mix), 2009. Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum. Nature Geoscience 2, 127-132.

O'Neil, J.R., R.N. Clayton, T.K. Mayeda, 1969. Oxygen isotope fractionation in divalent metal carbonates. J. chem. Phys. 51, 5547-5558.

Schlitzer, R., 2007. Ocean Data View. http://odv.awi.de/.

Schmidt, G.A., 1999. Error analysis of paleosalinity calculations. Paleoceanography 14(3), 422-429.

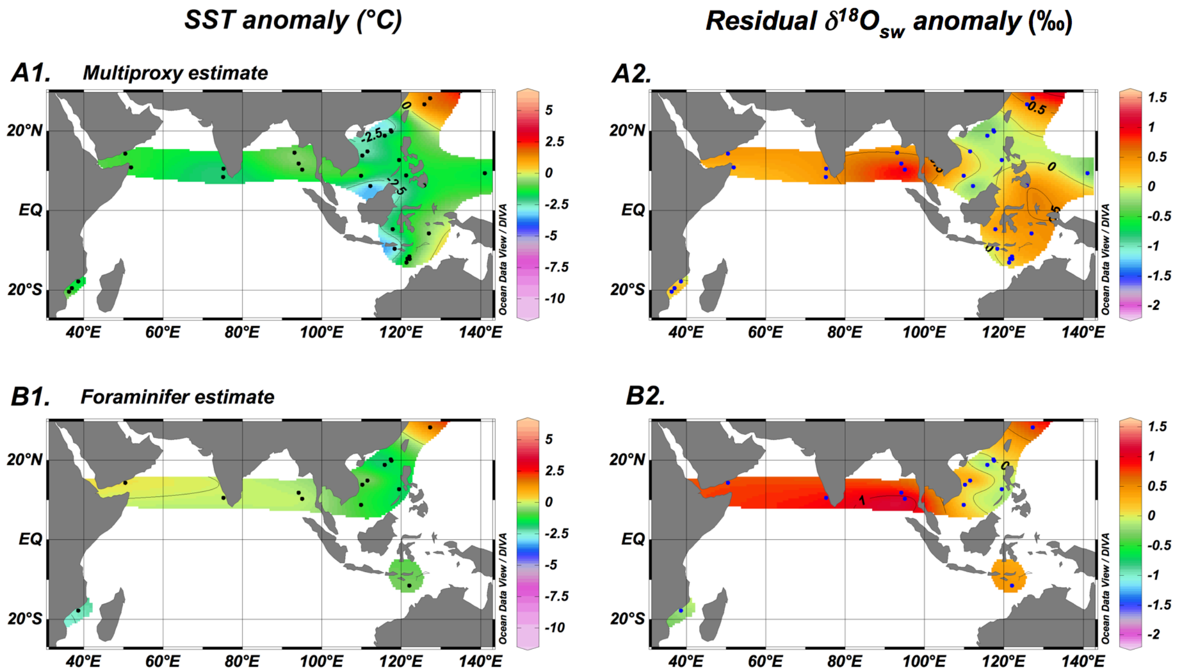
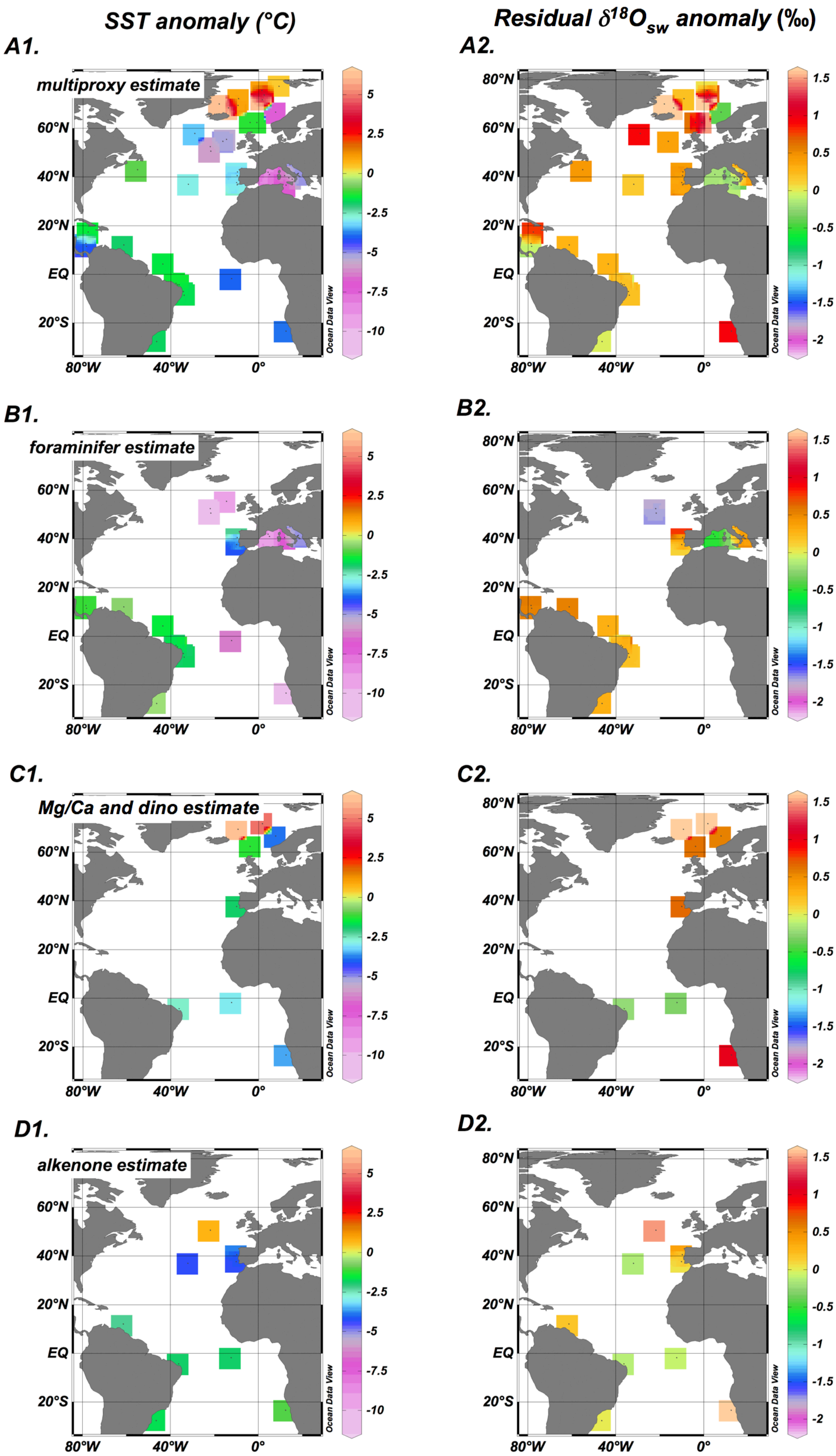
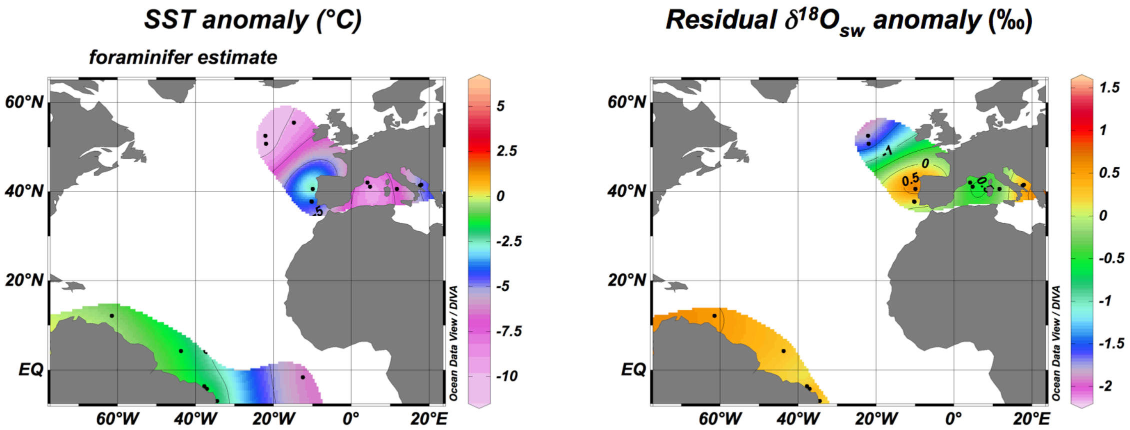

SST anomaly (°C)
Residual δ18Osw anomaly (‰)
A1. Multiproxy estimate
A2.
B1. Foraminifer estimate
B2.
20°N
EQ
20°S
40°E
60°E
80°E
100°E
120°E
140°E
5
2.5
0
-2.5
-5
-7.5
-10
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Ocean Data View / DIVA

Fig. S1



SST anomaly (°C)
Residual $\delta^{18}O_{sw}$ anomaly (‰)
A1.
multiproxy estimate
A2.
B1.
foraminifer estimate
B2.
C1.
Mg/Ca and dino estimate
C2.
D1.
alkenone estimate
D2.
80°N
60°N
40°N
20°N
EQ
20°S
80°W
40°W
0°
5
2.5
0
-2.5
-5
-7.5
-10
1.5
1
0.5
0
-0.5
-1
-1.5
-2
Ocean Data View

Fig. S2



SST anomaly (°C)
foraminifer estimate
60°N
40°N
20°N
EQ
60°W
40°W
20°W
0°
20°E
5
2.5
0
-2.5
-5
-7.5
-10
Ocean Data View / DIVA
Residual $\delta^{18}O_{sw}$ anomaly (‰)
-1
0
0.5
1.5
1
-0.5
-1.5
-2

Fig. S3