Supplementary material of

Atlantic circulation changes across a stadial-interstadial transition

Claire Waelbroeck1, Jerry Tjiputra2, Chuncheng Guo3, Kerim H. Nisancioglu3, Eystein Jansen2,3, Natalia Vazquez Riveiros4, Samuel Toucanne4, Frédérique Eynaud5, Linda Rossignol5, Fabien Dewilde6, Elodie Marches7, Susana Lebreiro8, Silvia Nave9

1LOCEAN/IPSL, Sorbonne Université-CNRS-IRD-MNHN, UMR7159, 75005 Paris, France
2NORCE Norwegian Research Centre, Bjerknes Centre for Climate Research, 5007 Bergen, Norway
3Department of Earth Science, University of Bergen, Bjerknes Centre for Climate Research, 5007 Bergen, Norway
4Geo-Ocean, University of Brest, CNRS, IFREMER, UMR6538, 29280 Plouzané, France
5UMR-CNRS 5805 EPOC - OASU, University of Bordeaux, 50023 Pessac, France
6IUEM, UMS3113, 29280 Plouzané, France
7Service Hydrographique et Océanographique de la Marine, 29228 Brest, France
8Instituto Geológico y Minero de España (IGME)-CSIC, 28003 Madrid, Spain
9LNEG, I.P., UGHGC, 2610-999 Amadora, Portugal

Correspondence to: Claire Waelbroeck (claire.waelbroeck@locean.ipsl.fr)

The supplementary material includes:

- **Supplementary text**

  **Text S1.** New *Cibicides* δ\(^{13}\)C records

  **Text S2.** Dating of the 18 selected cores

- **Supplementary figures**

  **Fig. S1.** NorESM1-F simulated δ\(^{13}\)C-BIO and observed *Cibicides* δ\(^{13}\)C time

  **Fig. S2.** Dating information for cores MD03-2698 and CAR13-05

  **Fig. S3.** Simulated AMOC and δ\(^{13}\)C-BIO evolution versus age in calendar ky BP

  **Fig. S4.** NorESM1-F simulated changes in preformed PO\(_4\) at different water depths

  **Fig. S5.** NorESM1-F simulated changes in PO\(_4\) and Primary Production across the HS4-GI8 transition in the Atlantic euphotic layer

  **Fig. S6.** % change in the simulated δ\(^{13}\)C-BIO change across the HS4-GI8 transition

  **Fig. S7.** Change in the simulated δ\(^{13}\)C-BIO due to remineralization change, versus computed ideal age change

  **Fig. S8.** Change in simulated δ\(^{13}\)C-BIO across the HS4-GI8 transition at the 18 selected sites versus water depth

  **Fig. S9.** NorESM1-F simulated changes in δ\(^{13}\)C-BIO and its partition into \([\Delta\delta^{13}\text{C-BIO}]_{\text{circ+PP}}\) and \([\Delta\delta^{13}\text{C-BIO}]_{\text{rem}}\) at different water depths
- Supplementary tables

Tab. S1. Cibicides δ¹³C records references and dating information

Tab. S2. Observed and computed δ¹³C during HS4, GI8, and corresponding changes across the HS4-GI8 transition

- References

Text S1. New Cibicides δ¹³C records

Cibicides stable isotopes were measured in core CAR2013-PQP-CAR05 (abbreviated as CAR13-05), MD03-2698, MD13-3438, MD16-3511Q, SU90-08 and SU90-44 (Tab. S1), core MD16-3511Q having been collected in the Southern Ocean during the 2016 ACCLIMATE cruise (Waelbroeck and Michel, 2016). Epifaunal benthic foraminifers of the Cibicides genus were hand picked in the > 150 mm size fraction. Cibicides wuellerstorfi samples were picked when possible. However, in some levels of core CAR13-05, MD03-2698, SU90-08 and SU90-44, the only species present was Cibicides kullenbergi. When both species were present, we measured both and did not observe any significant difference in isotopic values between Cibicides wuellerstorfi and Cibicides kullenbergi. Similarly, in a few levels of core MD03-2698, Cibicides sp. was the only species present but we were able to verify that there was no isotopic offset with respect to C. wuellerstorfi. In each of these 6 cores, the measurements made on Cibicides wuellerstorfi, Cibicides kullenbergi, and Cibicides sp. were thus merged.

The samples were cleaned in a methanol ultrasonic bath during a few seconds. In the case of core SU90-08 which had been already studied at LSCE, the samples were further roasted under vacuum at 380 °C for 45 min prior to isotopic analyses (Duplessy, 1978) for the sake of consistency with previous measurements made on that core.

Cibicides ¹³C/¹²C ratios (δ¹³C, expressed in ‰ versus VPDB) were measured at LSCE on an Isoprime100 mass-spectrometer on samples of 1 to 5 specimens. VPDB (Vienna PDB) is defined with respect to NBS19 calcite standard (δ¹⁸O = 2.20‰ and δ¹³C = +1.95‰) (Coplen, 1988). The mean external reproducibility (1σ) of carbonate standards is ± 0.05 ‰ for δ¹⁸O and ± 0.03 ‰ for δ¹³C; measured NBS18 δ¹⁸O is -23.27 ± 0.10 ‰VPDB and δ¹³C is -5.01 ± 0.03 ‰VPDB.

Text S2. Dating of the 18 selected cores

The age models of the set of 92 cores published in (Waelbroeck et al., 2019) have been updated using IntCal20. The updated age models are available on the Seanoe data repository (https://www.seanoe.org/data/00484/59554/). 6 of the 18 cores selected in the present study are not included in the set of previously published age models because they are dated by a combination of direct chronological markers and alignment to one of the 92 previously dated core taken as a reference (Tab. S1).

- Core CAR13-05 is dated by a combination of radiocarbon dates, tie points defined by alignment of its % Neogloboquadrina pachyderma, a proxy of sea surface temperature (SST), to the NGRIP air temperature proxy record on the GICC05 age scale, and alignment of its IRD signal at the onset of HS4 HS3 and HS2 with the IRD signal of well-dated neighboring core SU92-03 taken as reference.
- Core KNR191-CDH19 is dated by alignment of its CaCO$_3$ XRF-signal to the %CaCO$_3$ signal of well-dated core KNR31-GPC5 that was collected at the same site.

- The upper 7 m of core MD01-2444 are dated by alignment of its *Globigerina bulloides* $\delta^{18}$O signal with that of well-dated neighboring core MD99-2334K. Below 7 m (i.e. for ages older than ~27 ka), core MD01-2444 is directly dated by alignment of its foraminiferal SST and *G. bulloides* $\delta^{18}$O signals to the NGRIP temperature signal on the GICC05 age scale.

- Core SU90-44 is mainly dated by alignment of its *N. pachyderma* $\delta^{18}$O and % *N. pachyderma* signals with the corresponding signals of well-dated neighboring core DSDP609. In addition to this alignment to core DSDP609, 1 alignment tie point is defined by direct alignment of core SU90-44 % *N. pachyderma* signal to the NGRIP temperature on the GICC05 age scale.

- IODP core U1308 is mainly dated by alignment of its reflectance signal to that of core DSDP609, collected at the same site. Two additional tie points were defined by alignment of its Ca/Sr signal to DSDP609 IRD record.

- Core MD13-3438 was collected at the same site as core MD95-2002. It is dated by alignment of its Ti/Ca XRF signal to that of core MD95-2002 down to 14 m. Planktonic foraminifera census counts were produced on core MD13-3438 between 13.3 and 16.2 m. Therefore, core MD13-3438 could be dated by direct alignment of its % *N. pachyderma* and Ti/Ca XRF signals to NGRIP temperature and Ca++ signals respectively between 14 and 16.2 m. Finally, core MD13-3438 was dated by direct alignment of its Ti/Ca XRF signal to the NGRIP Ca++ signal below 16.2 m.

The dating files of these 6 additional cores are provided in the same format as that of the 92 age models published in (Waelbroeck et al., 2019) and can be downloaded from the Seanoe data repository at xxx.

Finally, 4 previously published age models were improved with respect to their 2019 version. All updated age models are available on the Seanoe data repository (https://www.seanoe.org/data/00484/59554/), together with a readme file shortly describing the changes made. For the sake of completeness, here is a description of the changes made to the age models of the 4 cores involved in the present study.

- In core NA87-22, the tie points defined by alignment of its % *N. pachyderma* signal to NGRIP were revised before 34 ka in order to avoid unreasonably large surface reservoir ages.

- In core SU90-08, the largest of the two successive increases in the foraminiferal SST signal was chosen to define the tie point at end of HS4 through the alignment of the SST signal to the NGRIP temperature signal.

- In core MD99-2331, the tie points defined by alignment of its % *N. pachyderma* signal to NGRIP were revised around 25 ka in order to avoid unreasonably large surface reservoir ages.

- In MD03-2698, the tie points defined by alignment of its *G. bulloides* $\delta^{18}$O signal to NGRIP were revised to account for the increased temporal resolution of the newly generated *G. bulloides* $\delta^{18}$O record.
**Fig. S1.** NorESM1-F simulated $\delta^{13}$C-BIO and observed *Cibicides* $\delta^{13}$C time series over the 36-41 ka time interval at the 18 selected sites. Full coordinates of the sites are given in Tab. 1. The grey band corresponds to the Heinrich stadial 4 chronozone. The dotted vertical line indicates the beginning of the freshwater flux input (see Fig. S3).
Fig. S2. Dating information for cores MD03-2698 and CAR13-05 over 32-45 ka. (a) Location of the 2 cores. (b) MD03-2698 *G. bulloides* δ¹⁸O record (ACCLIMATE data), a proxy for SST on the Iberian margin. (c) CAR13-05 % *N. pachyderma* (ACCLIMATE data), a proxy for SST. (d) *Cibicides* δ¹³C records of both cores. (e) Sediment accumulation rates of both cores. Diamonds and squares above the X-axis in panels b-d denote radiocarbon dates and alignment pointers, respectively (Waelbroeck et al., 2019). Plots made with the PARIS software (Lougheed et al., 2022).
Fig. S3. Simulated AMOC and δ¹³C-BIO evolution versus age in calendar ky BP. **Upper panel**: simulated maximum North Atlantic meridional stream function at 26.5°N. The dotted vertical lines indicate the beginning and end of the 800 y long freshwater flux hosing experiment. Model years have been shifted so that the midslope of the stadial-interstadial transition takes place at end of Heinrich stadial 4 (i.e. at 38.17 ka). **Lower panel**: simulated δ¹³C-BIO at two core sites, as represented in Fig. S1. The grey band highlights the portion of the represented time interval belonging to HS4.
Fig. S4. NorESM1-F simulated changes in preformed PO$_4$ at 2500, 3500 and 4500 m depth in the Atlantic Ocean across the HS4-GI8 transition. Pre- and post-transition values correspond to 100 y averages over model year Y 5700-5800 of the “fw-on” run, and Y 5950-6050 of the “fw-off” run, respectively.
Fig. S5. NorESM1-F simulated changes in PO$_4$ and Primary Production across the HS4-GI8 transition in the Atlantic euphotic layer. (a)-(c) Simulated PO$_4$ in the upper 100 m. (d)-(f) Simulated PP in the euphotic layer (upper 112.5 m). Pre- and post-transition values correspond to 100 y averages over model year Y 5700-5800 of the “fw-on” run, and Y 5950-6050 of the “fw-off” run, respectively.
**Fig. S6.** % change in the simulated $\delta^{13}$C-BIO change across the HS4-GI8 transition due to ocean circulation and surface PP changes in the 11 sites located above 4200 m which exhibit significant GI8-HS4 $\delta^{13}$C-BIO changes.

**Fig. S7.** Change in the simulated $\delta^{13}$C-BIO due to remineralization change, versus computed ideal age change across the HS4-GI8 transition at each core site. Symbols as in Fig. S1.
**Fig. S8.** Change in simulated $\delta^{13}$C-BIO across the HS4-GI8 transition at the 18 selected sites versus water depth.
Fig. S9. NorESM1-F simulated changes in δ¹³C-BIO and its partition into \([\Delta \delta^{13}C\text{-BIO}]_{\text{circ}+\text{PP}}\) and \([\Delta \delta^{13}C\text{-BIO}]_{\text{rem}}\) at 2500, 3500 and 4500 m depth in the Atlantic Ocean across the HS4-GI8 transition.
Table S1. Cibicides δ¹³C records references and dating information

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth, m</th>
<th>Latitude, decimals</th>
<th>Longitude, decimals</th>
<th>Cibicides δ¹³C references</th>
<th>Dating</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU/90-24</td>
<td>2085</td>
<td>62.07</td>
<td>-37.03</td>
<td>[Elliott et al., 2002]</td>
<td>[Waelbroeck et al., 2019]</td>
</tr>
<tr>
<td>NA87-22</td>
<td>2161</td>
<td>55.50</td>
<td>-14.70</td>
<td>[Vidal et al., 1997]</td>
<td>[Waelbroeck et al., 2019] improved</td>
</tr>
<tr>
<td>SU/90-44</td>
<td>4255</td>
<td>50.10</td>
<td>-17.91</td>
<td>ACCLIMATE data</td>
<td>this study</td>
</tr>
<tr>
<td>U1308</td>
<td>3883</td>
<td>49.88</td>
<td>-24.23</td>
<td>[Jodrell and Channell, 2016]</td>
<td>this study</td>
</tr>
<tr>
<td>MD13-3438</td>
<td>2180</td>
<td>47.45</td>
<td>-8.45</td>
<td>ACCLIMATE data</td>
<td>this study</td>
</tr>
<tr>
<td>CA13-05</td>
<td>4870</td>
<td>45.00</td>
<td>-17.91</td>
<td>ACCLIMATE data</td>
<td>this study</td>
</tr>
<tr>
<td>SU/90-08</td>
<td>3080</td>
<td>43.05</td>
<td>-30.04</td>
<td>[Waelbroeck et al., 2019] improved</td>
<td>this study</td>
</tr>
<tr>
<td>MD99-2331</td>
<td>2120</td>
<td>42.15</td>
<td>-9.68</td>
<td>LSCF unpublished data</td>
<td>[Waelbroeck et al., 2019] improved</td>
</tr>
<tr>
<td>CH69-K09</td>
<td>4100</td>
<td>41.76</td>
<td>-47.35</td>
<td>[Labyere et al., 1999]</td>
<td>[Waelbroeck et al., 2019]</td>
</tr>
<tr>
<td>MD95-2040</td>
<td>2465</td>
<td>40.58</td>
<td>-9.86</td>
<td>[Voelker and de Abreu, 2011]</td>
<td>[Waelbroeck et al., 2019]</td>
</tr>
<tr>
<td>MD03-2698</td>
<td>4602</td>
<td>38.24</td>
<td>-10.39</td>
<td>ACCLIMATE data</td>
<td>[Waelbroeck et al., 2019] improved</td>
</tr>
<tr>
<td>MD95-2042</td>
<td>3146</td>
<td>37.80</td>
<td>-10.17</td>
<td>[Stackleton et al., 2000]</td>
<td>[Waelbroeck et al., 2019]</td>
</tr>
<tr>
<td>MD01-2444</td>
<td>2460</td>
<td>37.55</td>
<td>-10.13</td>
<td>[Skinner et al., 2007]</td>
<td>this study</td>
</tr>
<tr>
<td>KN191-CDH19</td>
<td>4541</td>
<td>33.69</td>
<td>-57.58</td>
<td>[Henry et al., 2016]</td>
<td>[Waelbroeck et al., 2019]</td>
</tr>
<tr>
<td>GeoB3910</td>
<td>2344</td>
<td>-4.24</td>
<td>-36.35</td>
<td>[Buckel et al., 2015]</td>
<td>[Waelbroeck et al., 2019]</td>
</tr>
<tr>
<td>MD16-3511Q</td>
<td>4435</td>
<td>-35.36</td>
<td>29.24</td>
<td>ACCLIMATE data</td>
<td>[Waelbroeck et al., 2019]</td>
</tr>
<tr>
<td>TN05-721</td>
<td>4981</td>
<td>-41.10</td>
<td>7.80</td>
<td>[Ninnemann et al., 1999; Barker and Diz, 2014]</td>
<td>[Waelbroeck et al., 2019]</td>
</tr>
<tr>
<td>MD07-3076Q</td>
<td>3770</td>
<td>-44.15</td>
<td>-14.22</td>
<td>[Gottschalk et al., 2016]</td>
<td>[Waelbroeck et al., 2019]</td>
</tr>
</tbody>
</table>

References
Barker, S., and Diz, P.: Timing of the descent into the last Ice Age determined by the bipolar seesaw, Paleoceanography, 29, 489-507, 2014.


