



Supplement of

Variable C / P composition of organic production and its effect on ocean carbon storage in glacial-like model simulations

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S Supplementary material

This document includes supplementary figures and tables, containing data that is described or shown in other forms in the manuscript.

In Fig. S.1, the locations of core sites for observed benthic $\delta^{13}C$ are indicated, and Holocene (HOL) observed benthic $\delta^{13}C$ 5 is compared to the bottom water ocean distribution of $\delta^{13}C$ for $Ctrl_{RED}$. The positions of observation sites are the same as in Peterson et al. (2014).

For comparison with Fig. 3a, we show the surface PO_4 concentration (μM) of the control state with fixed Redfield stoichiometry ($Ctrl_{RED}$) (Fig. S.2).

For comparison with Fig. 5, which shows model ocean $\delta^{13}C$ of model version RED compared to observations, we show 10 the corresponding ocean sections for model version GAM (Fig. S.3).

As an example of sea–ice cover expansion due to the applied glacial–like perturbations, we show the change in sea–ice cover between $Ctrl_{RED}$ and $GLcomb_{RED}$ (Fig. S.4).

Fig. S.5 shows the non–linear relationship between $\overline{P^*}$ and C/P in model version GAM . Note that the complete set of these data are also listed in Table S.1.

15 The supplementary tables S.1 and S.2 list diagnostic variables for climate (Table S.1, model versions RED and GAM , all ensemble members), carbon and nutrients (Table S.2, all model versions, all ensemble members). Table S.3 lists model–data comparison statistics for the $Ctrl$ and $GLcomb$ simulations in each of the model versions RED and GAM , and for the two benthic $\delta^{13}C$ data time slices HOL (0–6 ka) and LGM (19–23 ka).

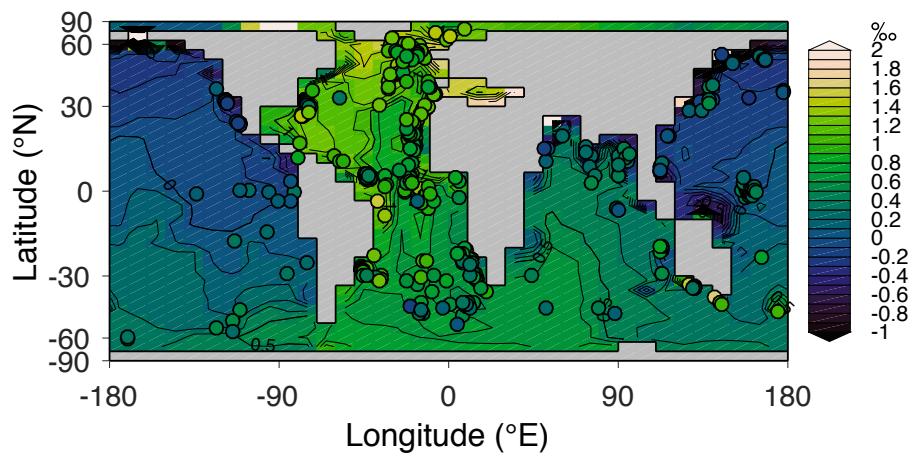


Figure S.1. $Ctrl_{RED}$ bottom water ocean $\delta^{13}\text{C}$ (contours) compared to the Holocene (HOL) time slice of observed benthic $\delta^{13}\text{C}$ (circles) of Peterson et al. (2014).

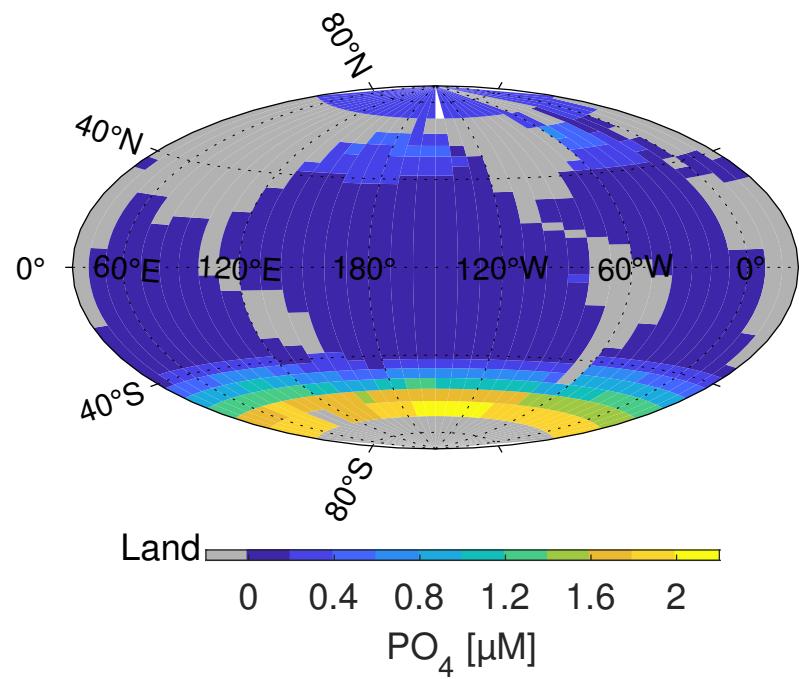


Figure S.2. Surface PO_4 concentration (μM) of the control state with fixed Redfield stoichiometry (Ctrl_{RED}).

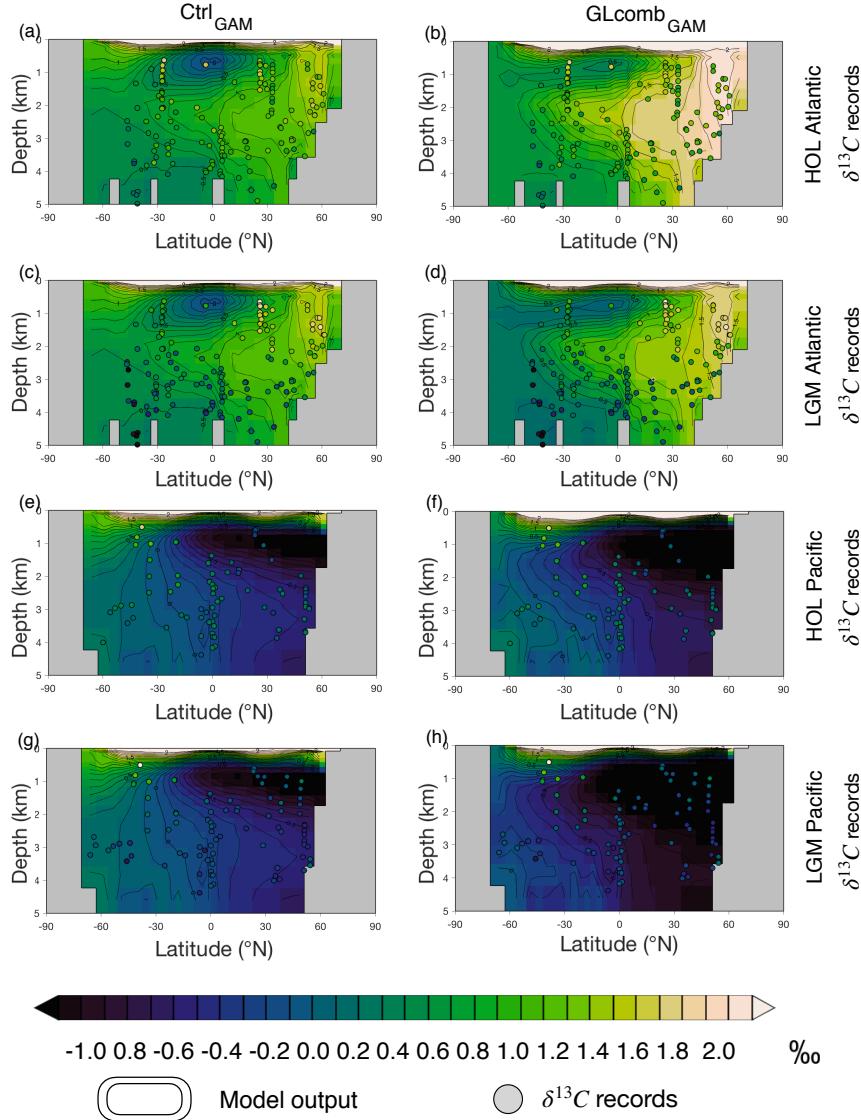


Figure S.3. Model ocean $\delta^{13}\text{C}$ (contours) compared to the two proxy record time slices (HOL and LGM) of benthic $\delta^{13}\text{C}$ (circles) of Peterson et al. (2014). The upper half of the figure shows the Atlantic Ocean (panels a–d), while the lower half shows the Pacific Ocean (panels e–h). The columns represent the model simulations (Ctrl_{RED} or Ctrl_{GAM}), while each row represents one of the proxy record time slices (HOL or LGM). The left hand column shows Ctrl_{GAM} (panels a, c, e, g) and the right hand column shows $GLcomb_{GAM}$ (panels b, d, f, h). The rows show, from top to bottom, a–b) HOL Atlantic, c–d) LGM Atlantic, e–f) HOL Pacific, g–h) LGM Pacific. Note that, before we compare $GLcomb_{RED}$ to LGM observations (panels d and h), a constant of 0.32 ‰ is subtracted from simulated $\delta^{13}\text{C}$, to account for terrestrial release of $\delta^{13}\text{C}$ -depleted terrestrial carbon which is not modelled.

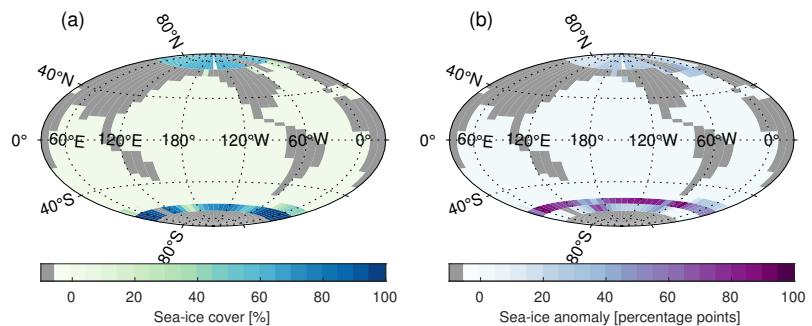


Figure S.4. a) Sea-ice cover (%) of $Ctrl_{RED}$, and b) the sea-ice anomaly $Globcomb_{RED} - Ctrl_{RED}$ (percentage points).

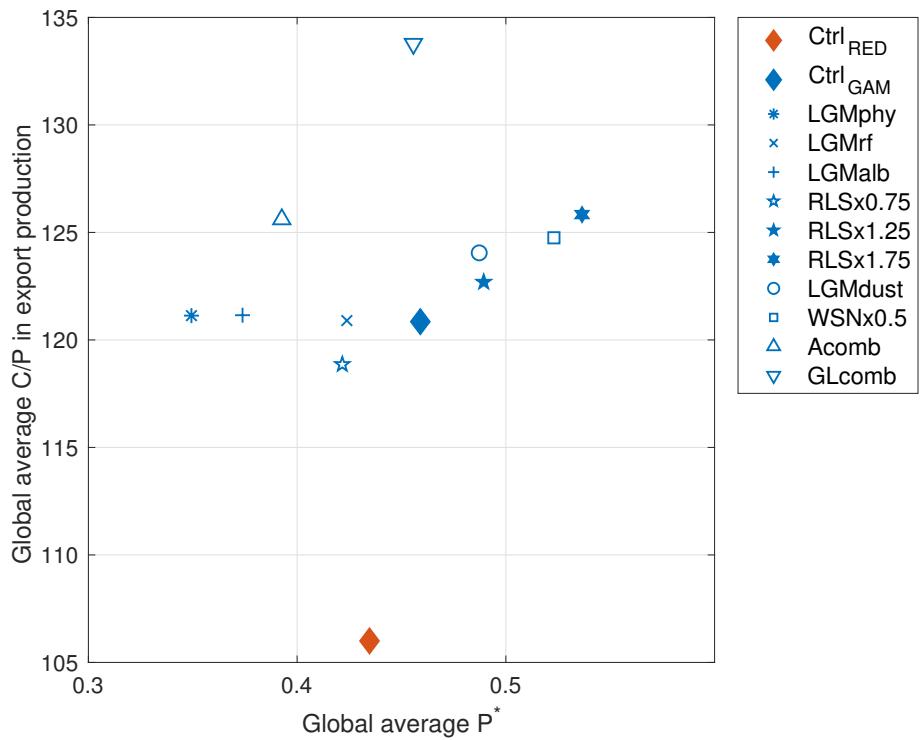


Figure S.5. Global average C/P in export production as a function of \bar{P}^* . Simulations using model versions *RED* and *GAM* are shown in red and blue, respectively. Different symbols indicate the sensitivity experiments, listed in the panel on the right hand side. See also Table S.1.

Table S.1. Carbon and nutrient variables in control states (*Ctrl*) and ensemble members (Table 1) of model versions *RED* and *GAM*. The columns list global ocean values for C/P ratio in the export flux of organic matter (dimensionless quantity), total content of DIC (DIC_{cont} , PgC), average concentration of DIC (\overline{DIC}_{tot} , $\mu mol kg^{-1}$), average concentration of remineralised DIC (\overline{DIC}_{rem} , $\mu mol kg^{-1}$), average concentration of remineralised acidic carbon (\overline{AC}_{rem} , $\mu mol kg^{-1}$), average concentration of PO_4 (\overline{P}_{tot} , $\mu mol kg^{-1}$), average concentration of remineralised PO_4 (\overline{P}_{rem} , $\mu mol kg^{-1}$) and average of the nutrient utilisation efficiency (\overline{P}^*). The modern ocean observed C/P is given as determined by Anderson and Sarmiento (1994) and the global ocean carbon inventory (DIC_{cont}) is estimated to 38,700 PgC (Stocker, 2014). Observed modern day \overline{P}_{tot} was computed as a simple whole ocean average based on WOA18 (Garcia et al., 2018). The observational estimate for \overline{P}^* is given by Ito and Follows (2005).

Experiment acronym	C/P ratio	DIC_{cont} (PgC)	\overline{DIC}_{tot} ($\mu mol kg^{-1}$)	\overline{DIC}_{rem} ($\mu mol kg^{-1}$)	\overline{AC}_{rem} ($\mu mol kg^{-1}$)	\overline{P}_{tot} ($\mu mol kg^{-1}$)	\overline{P}_{rem} ($\mu mol kg^{-1}$)	Global \overline{P}^*
Observ.	117 ± 14	$\sim 38,700$	-	-	-	2.12	-	0.36
<i>Ctrl_{RED}</i>	106.00	35,882	2,234.0	146.16	106.64	2.1520	0.9354	0.435
<i>Ctrl_{GAM}</i>	120.85	36,134	2,249.7	172.28	124.17	2.1518	0.9877	0.459
<i>LGMrf_{RED}</i>	106.0	35,910	2,235.7	136.32	99.982	2.1520	0.8783	0.408
<i>LGMrf_{GAM}</i>	120.90	36,162	2,251.4	160.56	116.22	2.1518	0.9120	0.424
<i>LGMalb_{RED}</i>	106.00	35,937	2,237.4	121.72	89.678	2.1522	0.7875	0.366
<i>LGMalb_{GAM}</i>	121.15	36,192	2,253.3	143.32	104.12	2.1520	0.8045	0.374
<i>LGMphy_{RED}</i>	106.00	35,953	2,238.4	113.33	83.791	2.1524	0.7358	0.342
<i>LGMphy_{GAM}</i>	121.13	36,206	2,254.2	134.11	97.749	2.1521	0.7519	0.349
<i>WNS × 0.5_{RED}</i>	106.00	35,911	2,235.8	170.91	125.16	2.1524	1.0983	0.510
<i>WNS × 0.5_{GAM}</i>	124.75	36,170	2,251.9	201.96	145.91	2.1523	1.1257	0.523
<i>RLS × 0.75_{RED}</i>	106.00	35,843	2,231.5	141.81	96.857	2.1508	0.8525	0.396
<i>RLS × 0.75_{GAM}</i>	118.86	36,084	2,246.5	164.24	111.20	2.1505	0.9068	0.422
<i>RLS × 1.25_{RED}</i>	106.00	35,914	2,235.9	149.20	114.68	2.1526	1.0069	0.468
<i>RLS × 1.25_{GAM}</i>	122.69	36,175	2,252.2	177.94	134.76	2.1525	1.0534	0.455
<i>RLS × 1.75_{RED}</i>	106.00	35,956	2,238.6	156.51	128.25	2.1536	1.1250	0.522
<i>RLS × 1.75_{GAM}</i>	125.83	36,230	2,255.7	189.51	152.39	2.1535	1.1553	0.537

Table S.1. Continued.

Experiment acronym	C/P ratio	DIC_{cont} (PgC)	$\overline{DIC_{tot}}$ ($\mu mol kg^{-1}$)	$\overline{DIC_{rem}}$ ($\mu mol kg^{-1}$)	$\overline{AC_{rem}}$ ($\mu mol kg^{-1}$)	$\overline{P_{tot}}$ ($\mu mol kg^{-1}$)	$\overline{P_{rem}}$ ($\mu mol kg^{-1}$)	Global $\overline{P^*}$
$LGMdust_{RED}$	106.00	35,916	2,236.1	113.33	113.02	2.1515	0.9931	0.462
$LGMdust_{GAM}$	124.05	36,179	2,252.4	134.11	134.75	2.1512	1.0482	0.487
$Acomb_{RED}$	106.00	36,002	2,241.5	122.01	94.115	2.1528	0.8259	0.384
$Acomb_{GAM}$	125.61	36,270	2,258.2	150.58	113.85	2.1525	0.8452	0.393
$GLcomb_{RED}$	106.00	36,021	2,242.7	146.62	111.86	2.1537	0.9808	0.455
$GLcomb_{GAM}$	133.77	36,307	2,260.5	186.19	138.32	2.1534	0.9813	0.456

Table S.2. Climatic variables for all control states ($Ctrl$) and ensemble members (Table 1). The variables are atmospheric CO_2 (pCO_2^{atm} , ppm), global averages of temperature in the ocean (T_{avg}^{oce} , $^{\circ}\text{C}$) and in the atmosphere (T_{avg}^{atm} , $^{\circ}\text{C}$), transport in the Atlantic meridional overturning circulation (AMOC, Sv) and sea ice cover (%). The observational estimate for $\overline{T_{oce}}$ has been calculated using the World Ocean Atlas 2018 (Locarnini et al., 2018). Average modern day AMOC strength is estimated by McCarthy et al. (2015) from the RAPID-MOCHA array at 26° N. Modern day sea ice cover is given as an interval due to seasonal variability (Comiso, 2008). No observational estimate for $\overline{T_{atm}}$ is given, since modern atmospheric observations are strongly influenced by rising pCO_2^{atm} (Stocker, 2014).

Experiment acronym	pCO_2^{atm} (ppm)	T_{oce} ($^{\circ}\text{C}$)	$\overline{T_{atm}}$ ($^{\circ}\text{C}$)	AMOC (Sv)	Sea ice (%)
Observ.	278	3.49	N/A	17.2 ± 0.9	3 to 6
$Ctrl_{RED}$	278.0	3.56	12.38	14.25	5.41
$Ctrl_{GAM}$	278.0	3.57	12.38	14.27	5.42
$Ctrl_{121}$	278.0	3.59	12.37	14.25	5.42
$LGMrf_{RED}$	265.2	2.89	10.46	14.99	7.38
$LGMrf_{GAM}$	265.5	2.90	10.46	14.97	7.35
$LGMalb_{RED}$	252.8	1.97	8.18	13.82	9.30
$LGMalb_{GAM}$	251.6	1.97	8.16	13.82	9.38
$LGMphy_{RED}$	245.4	1.45	6.83	13.67	10.6
$LGMphy_{GAM}$	244.9	1.45	6.84	13.66	10.6
$WNS \times 0.5_{RED}$	265.1	3.98	12.12	12.66	5.68
$WNS \times 0.5_{GAM}$	261.7	3.99	12.05	12.72	5.74
$WNS \times 0.5_{121}$	263.5	3.97	12.09	12.66	5.69
$RLS \times 0.75_{RED}$	295.8	3.64	12.66	14.13	5.21
$RLS \times 0.75_{GAM}$	301.4	3.68	12.75	14.09	5.08
$RLS \times 0.75_{121}$	298.7	3.65	12.71	14.13	5.14
$RLS \times 1.25_{RED}$	264.0	3.50	12.13	14.44	5.68
$RLS \times 1.25_{GAM}$	262.3	3.49	12.09	14.46	5.74
$RLS \times 1.25_{121}$	259.8	3.49	12.05	14.46	5.78
$RLS \times 1.75_{RED}$	244.7	3.38	11.77	14.55	6.06
$RLS \times 1.75_{GAM}$	234.7	3.33	11.57	14.56	6.27
$RLS \times 1.75_{121}$	240.6	3.36	11.69	14.59	6.14

Table S.2. Continued.

Experiment acronym	pCO_2^{atm} (ppm)	T_{avg}^{oce} (°C)	T_{avg}^{atm} (°C)	AMOC (Sv)	Sea ice (%)
$LGMdust_{RED}$	262.2	3.48	12.09	14.44	5.80
$LGMdust_{GAM}$	256.9	3.48	11.99	14.47	5.87
$LGMdust_{121}$	259.5	3.48	12.05	14.47	5.78
$Acomb_{RED}$	222.5	1.45	6.83	13.67	10.6
$Acomb_{GAM}$	214.9	1.45	6.84	13.66	10.6
$Acomb_{121}$	217.3	1.44	6.84	13.59	10.6
$GLcomb_{RED}$	214.9	1.94	6.86	12.05	10.2
$GLcomb_{GAM}$	198.2	1.91	6.85	12.09	10.3
$GLcomb_{121}$	206.2	1.93	6.86	12.02	10.3

Table S.3. Model–data comparison statistics for the *Ctrl* and *GLcomb* simulations in each of the model versions *RED* and *GAM*, and for the two benthic $\delta^{13}\text{C}$ data time slices HOL (0–6 ka) and LGM (19–23 ka). Correlations are computed between benthic observations and model water mass $\delta^{13}\text{C}$ in the grid cell corresponding to the observation depth. Standard deviations (STD) are the normalized values (STD_{model}/STD_{data}), which are scaled by the number of observations.

Model – data	Global corr.	Global STD	Atlantic corr.	Atlantic STD	Indo–Pacific corr.	Indo–Pacific STD
<i>Ctrl_{RED}</i> – HOL	0.78	1.23	0.50	0.83	0.39	0.81
<i>Ctrl_{GAM}</i> – HOL	0.76	1.38	0.45	0.94	0.36	0.95
<i>GLcomb_{RED}</i> – HOL	0.76	1.82	0.46	1.22	0.34	1.10
<i>GLcomb_{GAM}</i> – HOL	0.76	2.11	0.44	1.46	0.33	1.31
<i>Ctrl_{RED}</i> – LGM	0.58	0.96	0.64	0.43	0.06	0.83
<i>Ctrl_{GAM}</i> – LGM	0.55	1.08	0.58	0.48	0.01	0.96
<i>GLcomb_{RED}</i> – LGM	0.58	1.40	0.61	0.62	0.06	1.07
<i>GLcomb_{GAM}</i> – LGM	0.57	1.62	0.60	0.74	0.02	1.28

References

- Anderson, L. A. and Sarmiento, J. L.: Redfield ratios of remineralization determined by nutrient data analysis, *Global biogeochemical cycles*, 8, 65–80, 1994.
- Comiso, J. C.: Variability and trends of the global sea ice cover, in: *Sea ice: an introduction to its physics, chemistry, biology and geology*, 5 edited by Thomas, D. N. and Dieckmann, G. S., John Wiley & Sons, 2008.
- Garcia, H. E., Weathers, K., Paver, C. R., Smolyar, I., Boyer, T. P., Locarnini, R. A., Zweng, M. M., Mishonov, A. V., Baranova, O., Seidov, D., and Reagan, J. R.: *World Ocean Atlas 2018, Volume 4: Dissolved Inorganic Nutrients (phosphate, nitrate, silicate)*, Tech. Rep. 84, NOAA Atlas NESDIS, 35 pp., 2018.
- Ito, T. and Follows, M. J.: Preformed phosphate, soft tissue pump and atmospheric CO₂, *Journal of Marine Research*, 63, 813–839, 2005.
- Locarnini, R. A., Mishonov, A. V., Baranova, O. K., Boyer, T. P., Zweng, M. M., Garcia, H. E., Reagan, J. R., Seidov, D., Weathers, K., 10 Paver, C. R., and Smolyar, I.: *World Ocean Atlas 2018, Volume 1: Temperature*, Tech. Rep. 81, NOAA Atlas NESDIS, 52 pp., 2018.
- McCarthy, G., Smeed, D., Johns, W. E., Frajka-Williams, E., Moat, B., Rayner, D., Baringer, M., Meinen, C., Collins, J., and Bryden, H.: Measuring the Atlantic meridional overturning circulation at 26 N, *Progress in Oceanography*, 130, 91–111, 2015.
- Peterson, C. D., Lisiecki, L. E., and Stern, J. V.: Deglacial whole-ocean $\delta^{13}\text{C}$ change estimated from 480 benthic foraminiferal records, 15 *Paleoceanography*, 29, 549–563, 2014.
- Stocker, T.: *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2014.