Biogeosciences

Supporting Information for

What controls planktic foraminiferal calcification?

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Text S1. SNW methodology used to produce the new SNW data

SNW measurements were collected from Atlantic core-tops and sediment cores for *G. truncatulinoides, G. ruber* and *O. universa, N. pachyderma, N. incompta* and *G. bulloides.* The former three were analysed from a 300-355 µm sieve size fraction, and the latter three from a 212-250 µm size fraction. Tests were picked if they had low fragmentation, showed no damage or infilling and were from water depths above the lysocline (4000 m).

SNW data was collected through the measurement-based approach (measurement-based weight; MBW; equation 1 in the main text; Barker & Elderfield 2002). Approximately 20-30 individuals were analysed per sample. Samples were weighed using a Mettler Toledo MT5 microbalance (error = ± 0.5 µg) and the mean weight calculated. Size measurements were performed on each individual foraminifera test at 125x magnification using a LEICA MZ12.5 microscope. Individual tests were aligned in the same orientation and the longest axis of the test (Feret's diameter) was determined using ImageJ software. The average maximum length was calculated for each sample and test were size normalised using equation 1 in the main text.

Text S2. Article list for SNW data used in Bayesian models

A) Group-level model

Barker, S. (2002). Planktonic foraminiferal proxies for temperature and pCO_2, Appendix 3. [Doctoral dissertation, University of Cambridge].

Béjard, T.M., Rigual-Hernández, A.S., Flores, J.A., Tarruella, J.P., Durrieu de Madron, X., Cacho, I., Haghipour, N., Hunter, A. and Sierro, F.J., (2023). Calcification response of planktic foraminifera to environmental change in the western Mediterranean Sea during the industrial era. Biogeosciences, 20(7), pp.1505-1528.

Marr, J.P., Baker, J.A., Carter, L., Allan, A.S., Dunbar, G.B. and Bostock, H.C., (2011). Ecological and temperature controls on Mg/Ca ratios of Globigerina bulloides from the southwest Pacific Ocean. Paleoceanography, 26(2).

Pallacks, S., Ziveri, P., Schiebel, R., Vonhof, H., Rae, J.W., Littley, E., Garcia-Orellana, J., Langer, G., Grelaud, M. and Martrat, B., (2023). Anthropogenic acidification of surface waters drives decreased biogenic calcification in the Mediterranean Sea. Communications Earth & Environment, 4(1), p.301.

The current dataset [Pangaea link]

B) Species-level modelling

Barker, S. (2002). Planktonic foraminiferal proxies for temperature and pCO_2, Appendix 3. [Doctoral dissertation, University of Cambridge].

Béjard, T.M., Rigual-Hernández, A.S., Flores, J.A., Tarruella, J.P., Durrieu de Madron, X., Cacho, I., Haghipour, N., Hunter, A. and Sierro, F.J., (2023). Calcification response of planktic foraminifera to environmental change in the western Mediterranean Sea during the industrial era. Biogeosciences, 20(7), pp.1505-1528.

Marr, J.P., Baker, J.A., Carter, L., Allan, A.S., Dunbar, G.B. and Bostock, H.C., (2011). Ecological and temperature controls on Mg/Ca ratios of Globigerina bulloides from the southwest Pacific Ocean. Paleoceanography, 26(2).

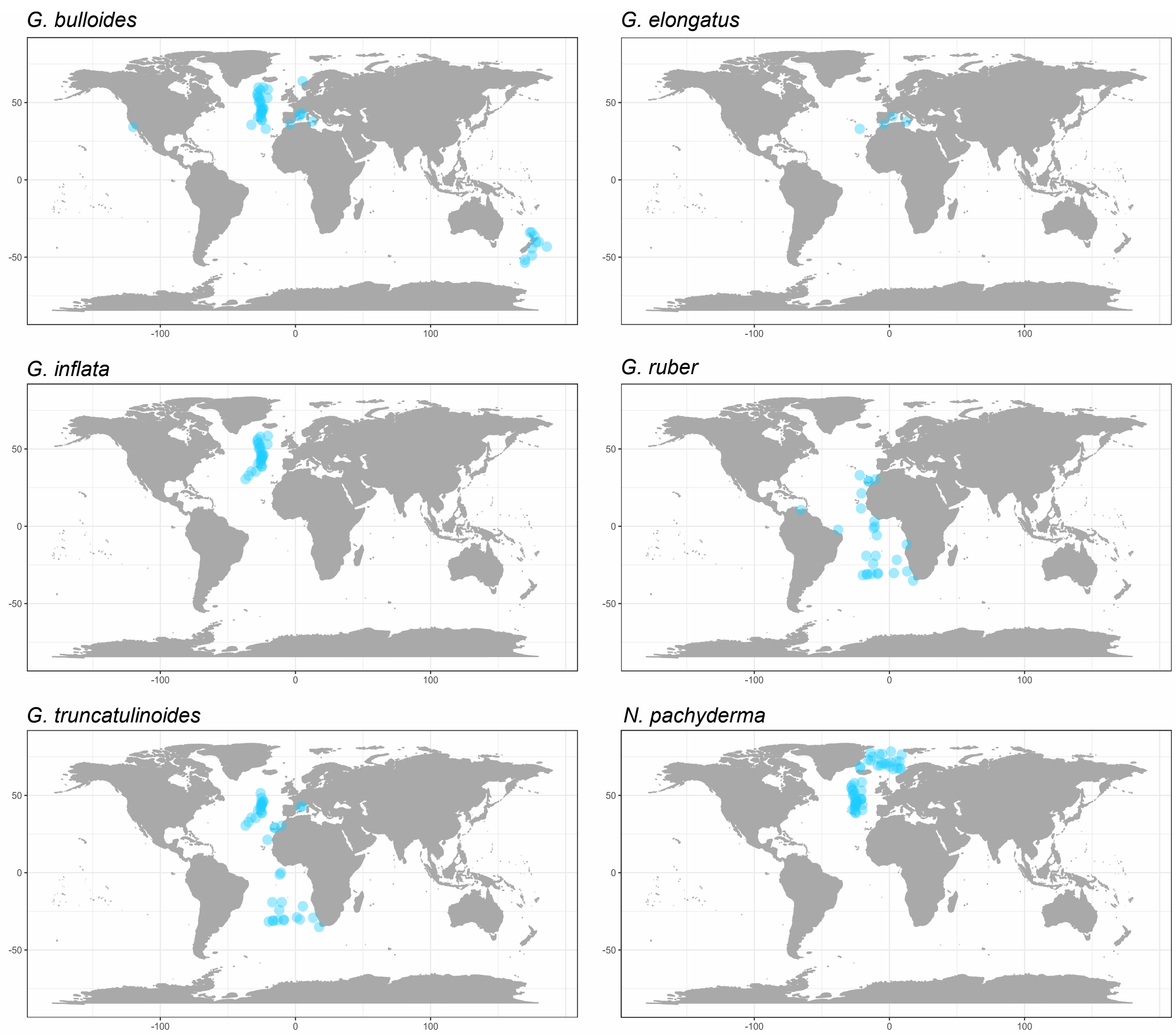
Marshall, B.J., Thunell, R.C., Henehan, M.J., Astor, Y. and Wejnert, K.E., (2013). Planktonic foraminiferal area density as a proxy for carbonate ion concentration: A calibration study using the Cariaco Basin ocean time series. Paleoceanography, 28(2), pp.363-376.

Pallacks, S., Ziveri, P., Schiebel, R., Vonhof, H., Rae, J.W., Littley, E., Garcia-Orellana, J., Langer, G., Grelaud, M. and Martrat, B., (2023). Anthropogenic acidification of surface waters drives decreased biogenic calcification in the Mediterranean Sea. Communications Earth & Environment, 4(1), p.301.

Qin, B., Li, T., Xiong, Z., Algeo, T.J. and Chang, F., (2017) Deepwater carbonate ion concentrations in the western tropical Pacific since 250 ka: Evidence for oceanic carbon storage and global climate influence. Paleoceanography, 32(4), pp.351-370.

Weinkauf, M.F., Kunze, J.G., Waniek, J.J. and Kučera, M., (2016). Seasonal variation in shell calcification of planktonic foraminifera in the NE Atlantic reveals species-specific response to temperature, productivity, and optimum growth conditions. PLoS One, 11(2), p.e0148363.

The current dataset [Pangaea link]


G. bulloides
G. elongatus
G. inflata
G. ruber
G. truncatulinoides
N. pachyderma
50
0
-50
-100
0
100

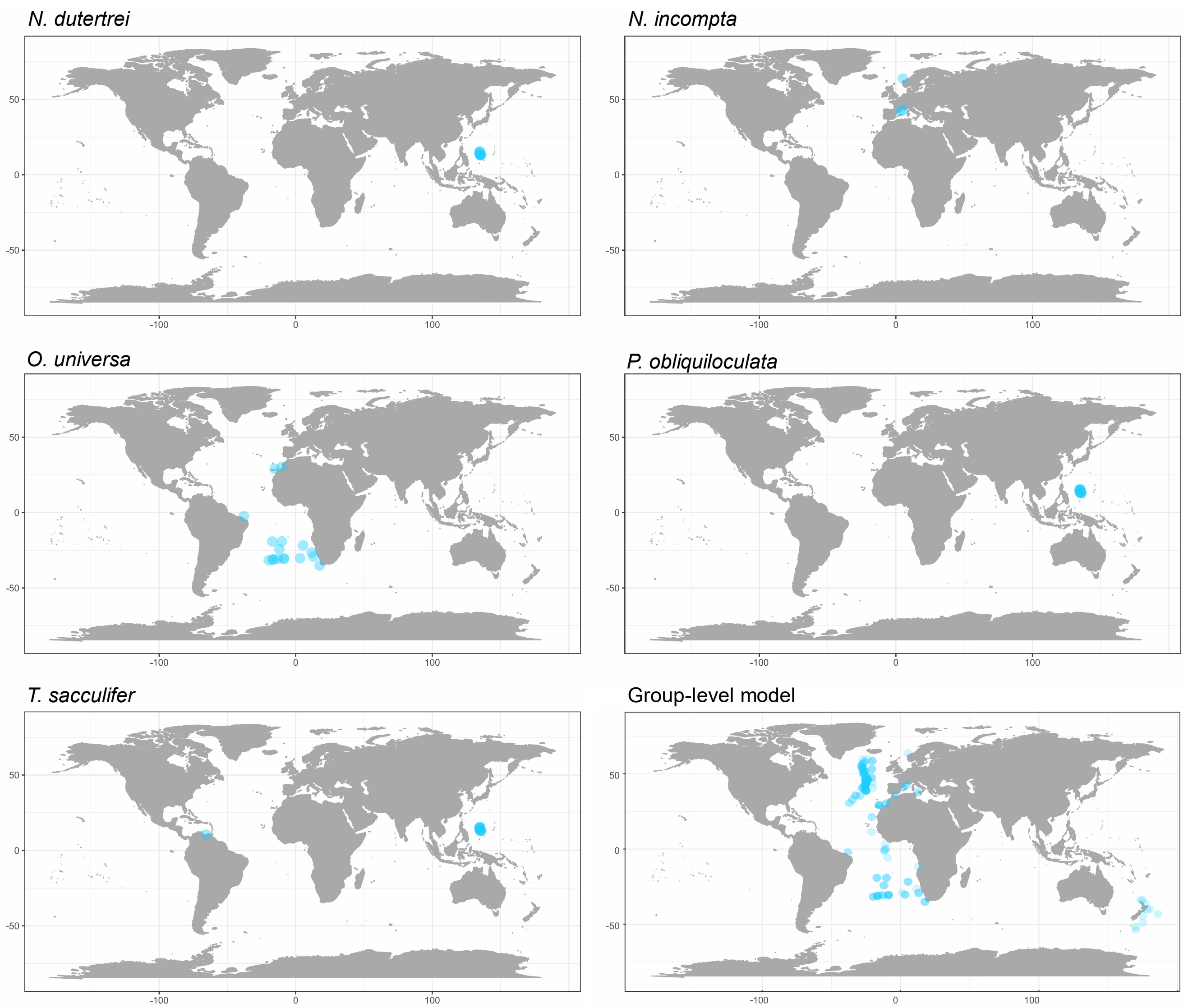


Figure S1. Location of SNW data for individual species, and locations for all SNW data included in the group-level SNW model. Data excludes plankton tow and only include SNW which are measurement based. For the group-level data is from a small size fraction (250-300 and 300-350).

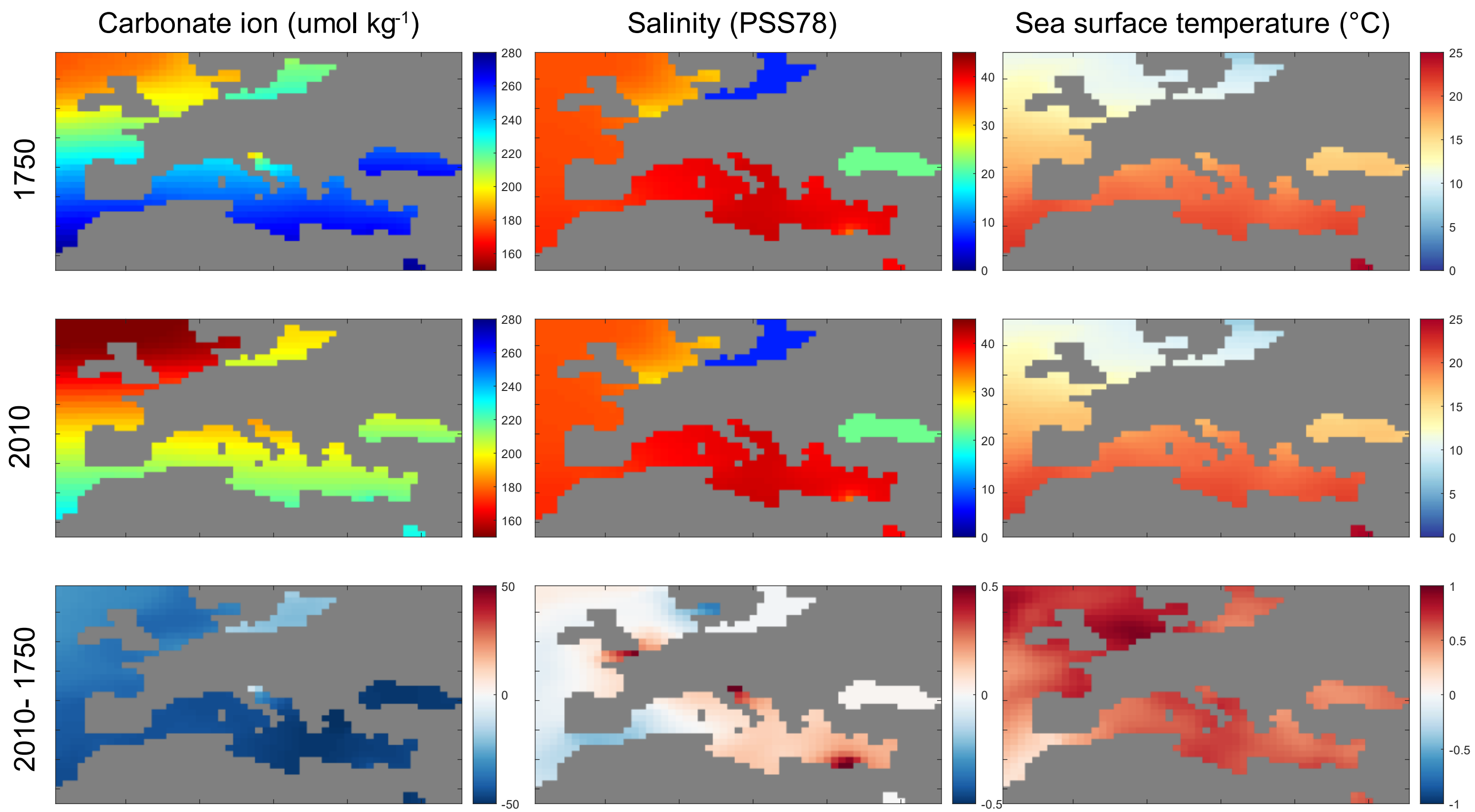


Figure S2. Mediterranean carbonate ion concentration, sea surface salinity and sea surface temperature outputs for the preindustrial (1750; preindustrial values were assumed the same as in 1850, which is average of 1850:1854) and modern (2010; average of 2005-2014), and the difference between these two time periods. Outputs are from CESM2 in the CMIP6 suite and are corrected for model drift and to GLODAP observational data, following the methods in Jiang et al. (2023). These model outputs have been manipulated to calculate decadal averages and units converted using density functions found in table S1 and the International Thermodynamic Equation of Seawater - 2010 (TEOS-10; McDougall & Barker, 2011). Carbonate ion concentration is calculated from dissolved inorganic carbon (DIC) and alkalinity using CO2SYS (van Heuven et al., 2011).

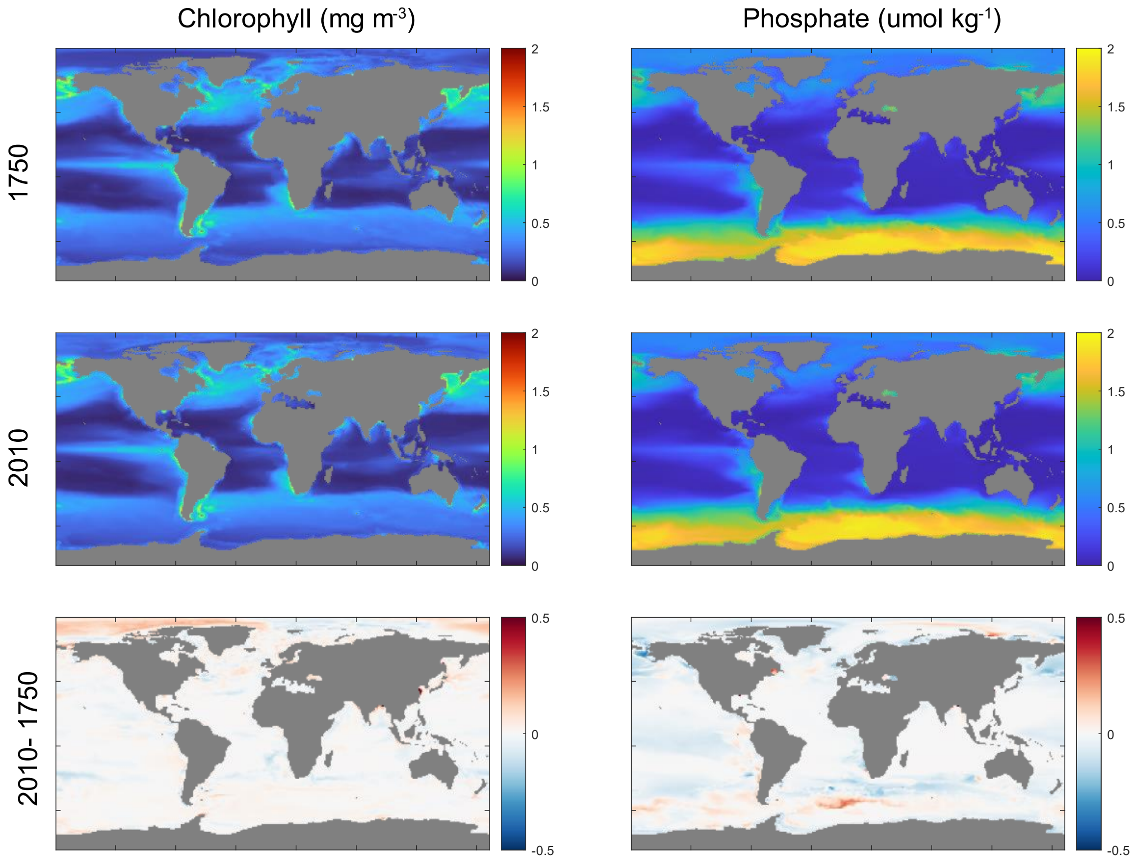


Figure S3. Chlorophyll and phosphate model outputs for the preindustrial (1750; preindustrial values were assumed the same as in 1850, which is average of 1850:1854) and modern (2010; average of 2005-2014), and difference between these time periods. Outputs are the median of CESM2, MRI ESM2, GDFL CM4, MIROC, and GFDL ESM4 from the CMIP6 suite. These data were not corrected for model drift, or to observational data as the observational data coverage is insufficient and DIVA gridding produces spurious results. Note that these model outputs have been manipulated to calculate decadal averages and units converted using density functions found in table S1 and the International Thermodynamic Equation of Seawater – 2010 (TEOS-10; McDougall & Barker, 2011).

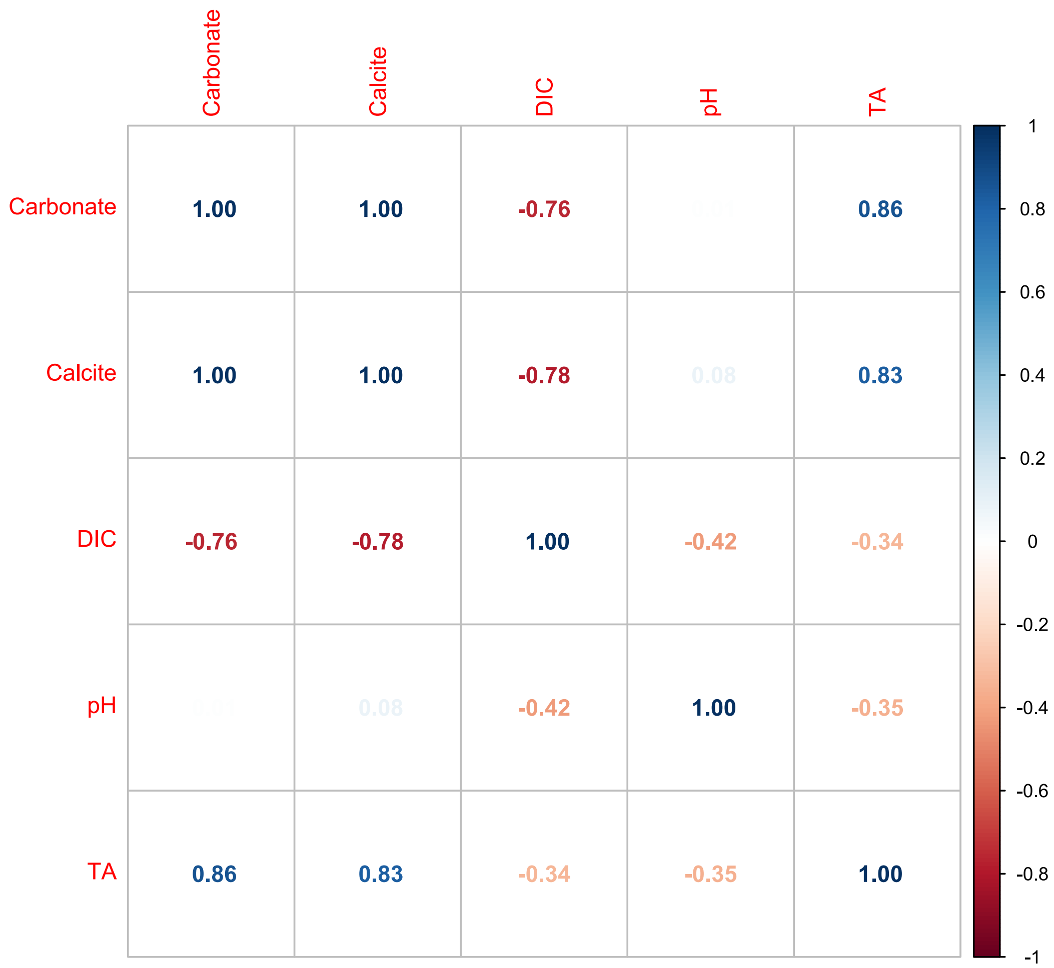


Figure S4. Spearman's output showing the high degree of correlation ($\rho > 0.7$) in the carbonate system, hence why only carbonate ion concentration was selected to represent the carbonate system.

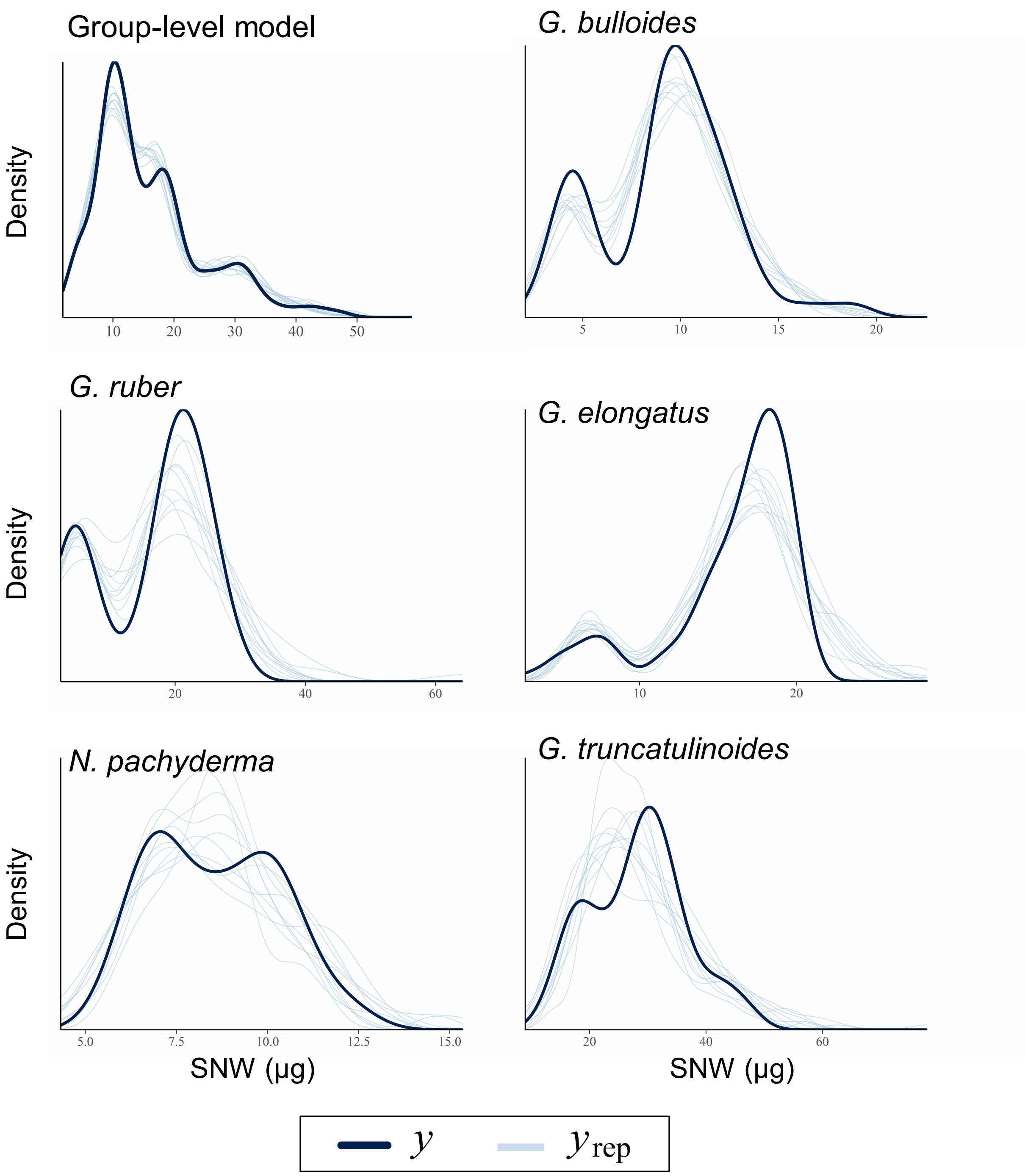


Figure S5. Kernel density estimate of the observed dataset "y", with density estimates for 100 simulated datasets "y_{rep}" drawn from the posterior predictive distribution showing goodness of fit of SNW for the species-level models, plotted using the pp_check function from the brms package. The closer that "y_{rep}" is to "y" means the better the model was able to reproduce the original data distribution. All models have a reasonable fit.

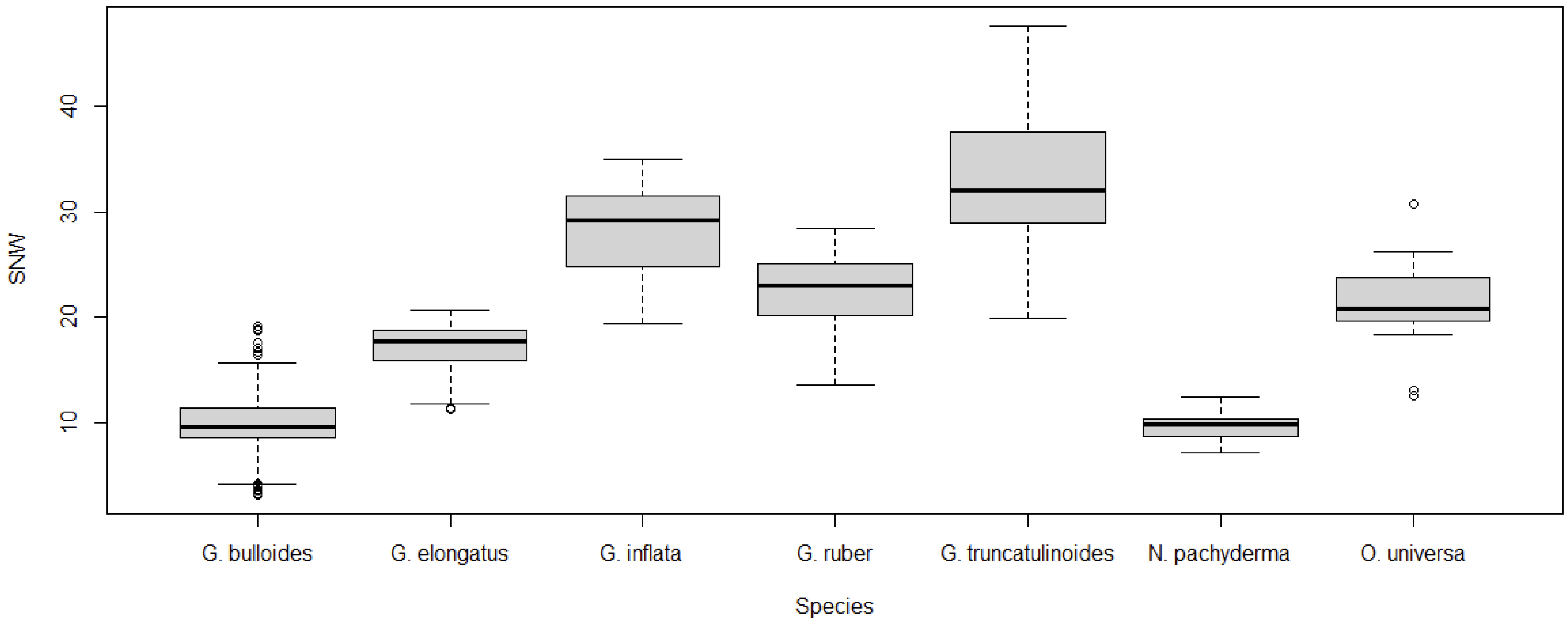
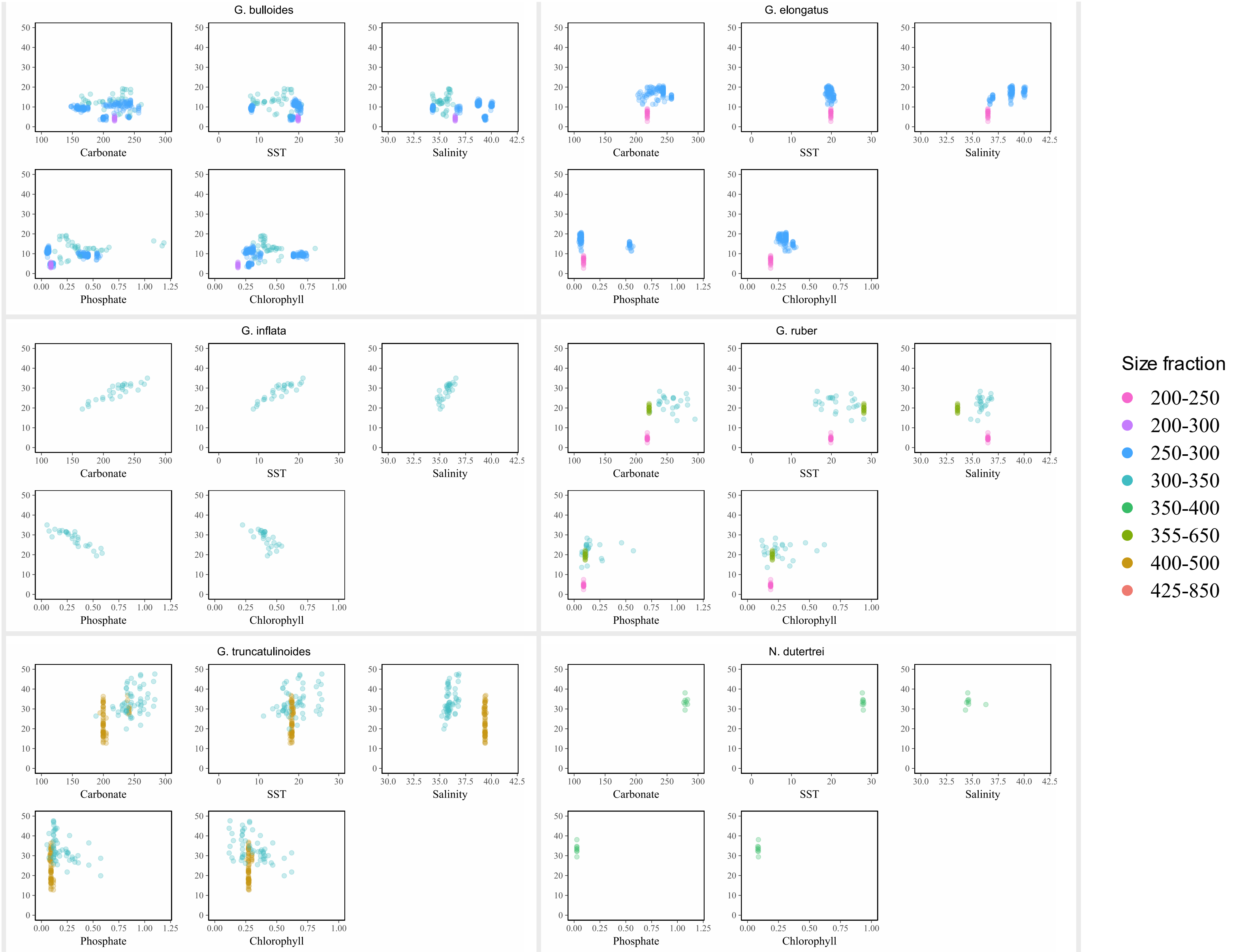


Figure S6. Size-normalised weight (SNW) of foraminiferal species. The boxplots show the range of variance in SNW between species is unequal ("heteroscedastic). We account for this heteroscedasticity in group-level model by adding a shape term which allows the variance between each species to vary.


G. bulloides
G. elongatus
G. inflata
G. ruber
G. truncatulinoides
N. dutertrei
Carbonate
SST
Salinity
Phosphate
Chlorophyll
Size fraction
200-250
200-300
250-300
300-350
350-400
355-650
400-500
425-850

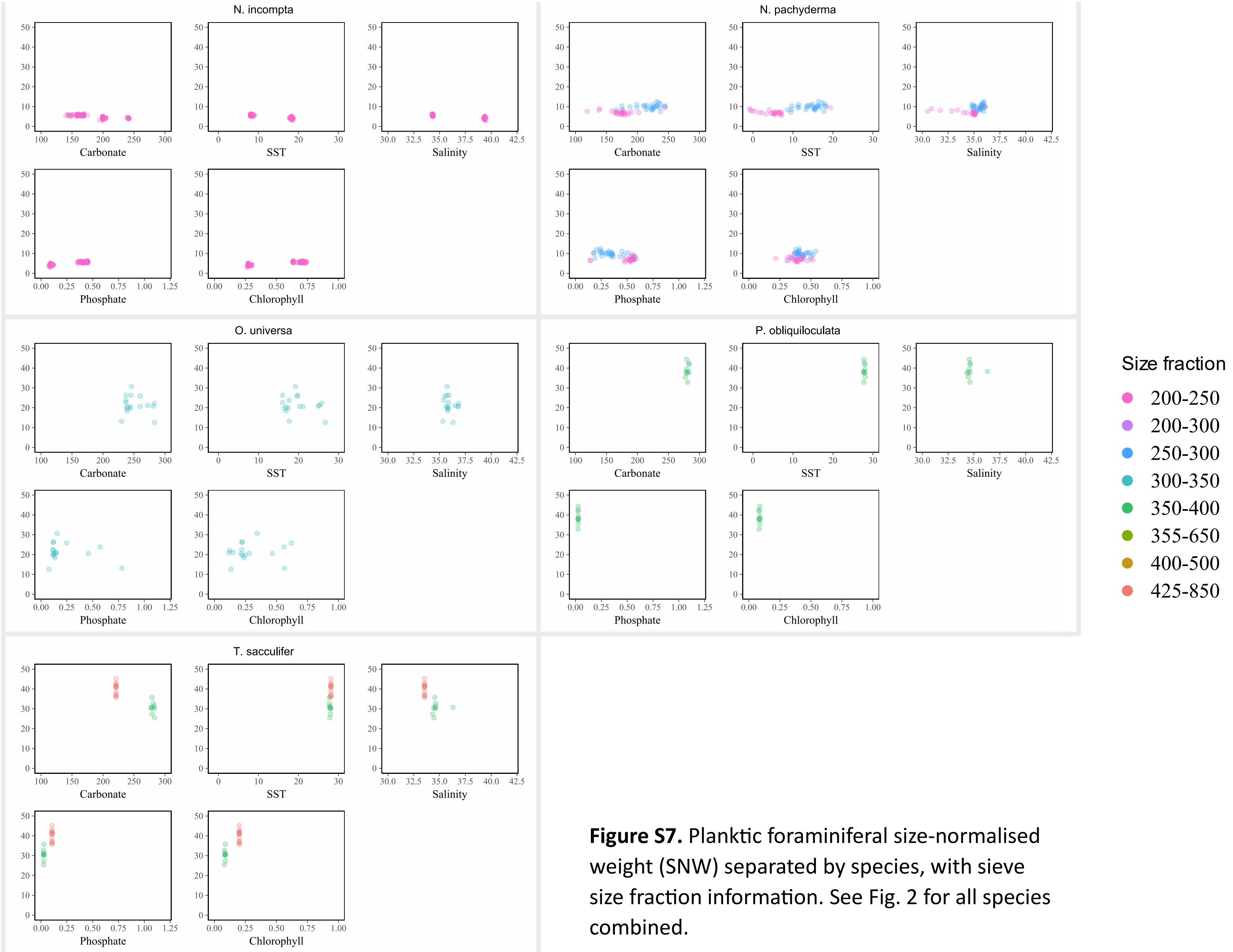


Figure S7. Planktic foraminiferal size-normalised weight (SNW) separated by species, with sieve size fraction information. See Fig. 2 for all species combined.

Table S1. Breakdown of CMIP6 models used to extract environmental data. All models include a "historical" simulation with forcing terms following their historical records (1850–2010), and a "piControl" with steady preindustrial forcing. "pi" is short for preindustrial control or PiControl. TEOS is short for the International Thermodynamic Equation of Seawater (TEOS-10). We only used data which was regridded (.gr) and not natural gridded (.gn). A tick mark [✓] indicates which model is used. n/a is where data is not available on the ESGF (Earth System Grid Federation).
[1] The Jiang model output uses the median values from all models listed in the table, which has been processed as per the methods in Jiang et al (2023).
[2] The Jiang model output was for the open-ocean, therefore did not contain data for the Mediterranean. The biogeochemistry output for the CEMS2 model was the closest match to the median biogeochemistry of the 14 model ensemble, hence CESM2 was used to extract carbonate system, temperature and salinity data for the Mediterranean.

Model	Variant	pi start point	Density factor (kg/m3)	Carbonate system, salinity & temperature	Phosphate	Chlorophyll	Net primary productivity
Jiang Model output[1]	-	-	-	✓[2]	-	-	
ACCESSESM1-5	r1i1p1f1	161	1024.5	-	.gn	.gn	.gn
CESM2	r11i1p1f1	601	TEOS	-	✓	✓	✓
CMCC-ESM2	r1i1p1f1	1850	TEOS	-	.gn	.gn	.gn
CNRM-ESM-2	r1i1p1f2	1850	TEOS	-	.gn	.gn	.gn
GFDL-CM4	r1i1p1f1	151	1035	-	✓	✓	✓
GFDL-ESM4	r1i1p1f1	101	1035	-	✓	✓	✓
IPSL- CM6ALR	r1i1p1f1	1910	1028	-	.gn	.gn	.gn
MIROC-ES2L	r1i1p1f2	1850	TEOS	-	✓	✓	✓
MPI-ESM1-2- LR	r1i1p1f1	1850	1025	-	.gn	.gn	.gn
MRI-ESM2-0	r1i2p1f1	1850	1024.5	-	✓	✓	✓
CanESM5	r1i1p1f1	5201	1025	-	n/a	.gn	.gn
NorESM2-LM	r1i1p1f1	1600	TEOS	-	n/a	n/a	n/a
UKESM1-0-LL	r1i1p1f2	2250	TEOS	-	n/a	n/a	.gn
EC-Earth3-CC	r1i1p1f1	1850	TEOS	-	n/a	n/a	n/a

Table S2. Extended version of table 2. Compilation of previous studies assessing the relationship between planktonic foraminiferal size-normalized weight (SNW) and the environment. + = positive correlation, − = negative correlation, ~ = no response, a = Not specifically tested, only implied, b = Variable measured at the sea surface, c = Variable measured at 100m depth, d = Variable measured at 200m depth, e = Depth not explicitly stated. This table summarizes information from measurement based SNW (i.e. silhouette area [ρA], or diameter normalised) studies only and omits those which only normalised to size by sieving (i.e. sieve-based weights; SBW) or use plankton tow data. [1] Barker & Elderfield (2002); [2] Béjard et al. (2023); [3] Marr et al. (2011); [4] Marshall et al. (2013); [5] Osborne et al. (2016); [6] Pallacks et al. (2023); [7] Weinkauf et al. (2016).

Species	Data type	SNW measurement type	Symbiont	Spinose	Carbonate ion	pH	CO2	Temperature	Productivity	Phosphate	Nitrate	Salinity	Optimum conditions
symbiont-barren, spinose													
G. bulloides[6]	Core	MBW, diameter	Non-Symbiont	Spinose	+ b		− b	− b					
G. bulloides[1]	Coretop	MBW, diameter	Non-Symbiont	Spinose	+ *b			~ ab					
G. bulloides[3]	Coretop	MBW, diameter	Non-Symbiont	Spinose				− e					
G. bulloides[5]	Trap/Core	MBW, ρA	Non-Symbiont	Spinose	+ e			~ e		~ e			
G. bulloides[2]	Trap	MBW, diameter	Non-Symbiont	Spinose	~ e	~ e	~ e	~ b	~ e	~ e	~ e	~ e	~
G. bulloides[7]	Trap	MBW, ρA	Non-Symbiont	Spinose	~ *e			~ b	~ b				−
symbiont-obligate, spinose													
G. elongatus[6]	Core	MBW, diameter	Symbiont	Spinose	+ b		− b	− b					
G. elongatus[7]	Trap	MBW, ρA	Symbiont	Spinose	~ e			+ b	− b				+

G. ruber[7]	Trap	MBW, ρA	Symbiont	Spinose	~ *e			+ b	– b				~
G. ruber[4]	Trap	MBW, ρA	Symbiont	Spinose	+ e			+ e					
G. sacculifer[4]	Trap	MBW, ρA	Symbiont	Spinose	+ e			+ e					
symbiont-barren, non-spinose													
G. inflata[1]	Coretop	MBW, diameter	Non-Symbiont	Non-Spinose	+ *ab			~ ab					
G. trunc[1]	Coretop	MBW, diameter	Non-Symbiont	Non-Spinose	+ *ab			~ ab					
G. trunc[2]	Trap	MBW, diameter	Non-Symbiont	Non-Spinose	+ e	~ e	~ e	+ b	– e	~ e	~ e	~ e	–
N. incompta[2]	Trap	MBW, diameter	Non-Symbiont	Non-Spinose	~e	~ e	~ e	+ b	~ e	~ e	~ e	~ e	~
N. pachyderma[1]	Coretop	MBW, diameter	Non-Symbiont	Non-Spinose	+ *ab			~ ab					

Table S3. Effect size and 95% credible interval [lower, upper] for the association between SNW and the environment, from group-level (i.e. across species) and species-level Bayesian modelling. If the credible interval crosses zero, there is a <95% probability that there is an effect. Colour indicates a positive or negative result. Note that the modelled dataset is slightly different between the group-level model and the species-level models. The group-level model dataset includes species which were omitted from species-level models due to their low sample size, and the size fraction ranges are more restricted for the group-level model due to a bias against larger size fractions in cooler environments (see methods).

Model	Carbonate	Phosphate	Salinity	NPP
Group-level	0.05 [0.02, 0.07]	−0.09 [−0.11, −0.07]	−0.03 [−0.06, 0.01]	0.01 [−0.01, 0.03]
G. bulloides	0.04 [−0.02, 0.09]	0.03 [−0.01, 0.08]	0.02 [−0.03,0.07]	0.12 [0.05, 0.19]
G. ruber	0.35 [0.14, 0.56]	0.04 [−0.13, 0.22]	−1.06 [−1.24, −0.88]	−0.04 [−0.11, 0.02]
G. elongatus	0.19 [0.12, 0.26]	0.27 [0.22, 0.32]	0.47 [0.41, 0.54]	0.33 [0.27, 0.40]
N. pachyderma	0.23 [0.14, 0.31]	0.05 [−0.05, 0.15]	−0.30 [−0.44, −0.16]	0.09 [0.02, 0.17]
G. truncatulinoides	0.03 [−0.11, 0.16]	−0.13 [−0.26, −0.01]	0.06 [−0.11, 0.26]	−0.00 [−0.05, 0.05]