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Citation for final published version:

Hollstein, Martina, Mohtadi, Mahyar, Rosenthal, Yair, Moffa Sanchez, Paola, Oppo, Delia, Martínez Méndez, Gema, Steinke, Stephan and Hebbeln, Dierk 2017. Stable oxygen isotopes and Mg/Ca in planktic foraminifera from modern surface sediments of the Western Pacific Warm Pool: Implications for thermocline reconstructions. Paleoceanography 32 (11), pp. 1174-1194. 10.1002/2017PA00312

Publishers page: https://doi.org/10.1002/2017PA003122

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Stable oxygen isotopes and Mg/Ca in planktic foraminifera from modern surface sediments of the Western Pacific Warm Pool: Implications for thermocline reconstructions

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18 Key Points:

- Combined Mg/Ca and stable oxygen isotopes in planktic foraminifera tests from
 accurately dated modern surface sediments
- Seawater oxygen isotope-salinity regressions for surface and subsurface waters in the
 Western Pacific Warm Pool
- Calcification depth estimates and regional multispecies and species-specific Mg/Ca temperature calibrations

26 Abstract

27 Mg/Ca and stable oxygen isotope compositions (δ^{18} O) of planktic foraminifera tests are

- commonly used as proxies to reconstruct past ocean conditions including variations in the
- 29 vertical water column structure. Accurate proxy calibrations require thorough regional studies,
- 30 since parameters such as calcification depth and temperature of planktic foraminifera depend on
- 31 local environmental conditions. Here we present radiocarbon-dated, modern surface sediment
- samples and water column data (temperature, salinity, seawater δ^{18} O) from the Western Pacific
- Warm Pool. Seawater $\delta^{18}O(\delta^{18}O_{SW})$ and salinity are used to calculate individual regressions for western Pacific surface and thermocline waters ($\delta^{18}O_{SW} = 0.37*S-12.4$ and $\delta^{18}O_{SW} = 0.33*S-$
- 11.0). We combine shell δ^{18} O and Mg/Ca with water column data to estimate calcification depths
- of several planktic foraminifera and establish regional Mg/Ca-temperature calibrations.
- 37 *Globigerinoides ruber, Globigerinoides elongatus* and *Globigerinoides sacculifer* reflect mixed
- 38 layer conditions. Pulleniatina obliquiloculata and Neogloboquadrina dutertrei and Globorotalia
- 39 *tumida* preserve upper and lower thermocline conditions, respectively. Our multispecies Mg/Ca-
- 40 temperature calibration (Mg/Ca = $0.26 \exp(0.097 * T)$) matches published regressions. Assuming
- 41 the same temperature sensitivity in all species, we propose species-specific calibrations that can
- 42 be used to reconstruct upper water column temperatures. The Mg/Ca-temperature dependencies
- 43 of *G. ruber*, *G. elongatus* and *G. tumida* are similar to published equations. However, our data
- 44 imply that calcification temperatures of *G. sacculifer*, *P. obliquiloculata* and *N. dutertrei* are
- 45 exceptionally warm in the western tropical Pacific, and thus, underestimated by previously
- published calibrations. Regional Mg/Ca-temperature relations are best described by Mg/Ca = $0.24\exp 0.097*T$ for *G. sacculifer* and by Mg/Ca = $0.21\exp 0.097*T$ for *P. obliquiloculata* and *N.*
- 48 *dutertrei*.
- 49

50 **1. Introduction**

The Western Pacific Warm Pool (WPWP) is a major source of heat and water vapor to the global 51 atmosphere with far-reaching climate impacts [e.g. Gagan et al., 2004]. The area is also thought 52 to play an essential role in the global overturning circulation, because it provides waters to the 53 Pacific equatorial current system and the Indonesian Throughflow, [e.g. Gordon, 1986]. Present 54 climate in the WPWP is mainly controlled by the Austral-Asian monsoon system and large-scale 55 climate phenomena such as the El Niño Southern Oscillation (ENSO). The regional climate is 56 strongly coupled to ocean conditions. Changes in the prevailing climate conditions affect, for 57 example, mixed layer depth and the thermocline structure [e.g. DiNezio et al., 2011; Vecchi et al., 58 2006]. Thus, reconstructing past hydrographic conditions and variations in the vertical structure of 59 the water column allow to draw conclusions on the regional WPWP climate evolution. 60

61

62 There is an ongoing debate how the thermocline depth varied throughout the past. For example,

63 some records indicate a thermocline deepening during the Last Glacial Maximum (LGM) [e.g.

Bolliet et al., 2011], others indicate a thermocline shoaling during the same period [Andreasen and 64 Ravelo, 1997; Beaufort et al., 2001; de Garidel-Thoron et al., 2007; Regoli et al., 2015; Sagawa 65 et al., 2012] and yet others indicate no change compared to the modern ocean [Patrick and Thunell, 66 1997]. Many of these reconstructions are based on the calculation of differences between shell 67 Mg/Ca-derived temperature and/or δ^{18} O of planktic foraminifera calcifying at different depth 68 levels to estimate vertical temperature gradients within the upper water column [e.g. Bolliet et al., 69 2011; de Garidel-Thoron et al., 2007; Regoli et al., 2015]. Previous studies used for example the 70 difference between shell Mg/Ca in G. ruber as surface indicator and P. obliquiloculata or N. 71 dutertrei as thermocline depth indicators [e.g. Bolliet et al., 2011], or the difference between G. 72 ruber sensu stricto and G. ruber sensu lato (here referred to as G. ruber and G. elongatus following 73 Aurahs et al. [2011]) [Regoli et al., 2015]. However, to choose species and interpret such proxy 74 records correctly, it is essential to understand how modern hydrographic conditions are reflected 75 in foraminiferal calcite. 76

77

The choice of species to use depends on regional calcification depths, which are determined by the 78 79 species preferences and local environmental conditions. However, although many paleoclimate reconstructions for the WPWP exist, precise estimates of calcification depths are sparse in this 80 81 area. Published reconstructions rely on plankton tow and sediment trap studies in the central equatorial Pacific, North Pacific or Indian Ocean [Kawahata et al., 2002; Kuroyanagi and 82 83 Kawahata, 2004; Mohtadi et al., 2011; Peeters et al., 2002; Rippert et al., 2016; Watkins et al., 1996]. In addition, precise Mg/Ca-temperature calibrations are a prerequisite to convert Mg/Ca 84 into temperature. For the WPWP there are only two regional Mg/Ca-temperature calibrations [Lea 85 et al., 2000; Sagawa et al., 2012]. Lea et al. [2000] provide a species-specific calibration for G. 86 87 ruber and Sagawa et al. [2012] present a multispecies calibration. Both calibrations are exposed to certain limitations. While the species-specific calibration might be biased by post-depositional 88 effects on the core top planktic foraminifera sample material [Lea et al., 2000], the multispecies 89 equation of Sagawa et al. [2012] bases only on data from a single station. Besides, both calibrations 90 base on late Holocene sediments and therefore, might lack comparability to present hydrography. 91 92 Regional species-specific calibrations for subsurface planktic foraminifera species do not exist for the WPWP. Subsequently, most proxy studies use Mg/Ca-temperature calibrations from other 93 areas [e.g. Bolliet et al., 2011; de Garidel-Thoron et al., 2007; Regoli et al., 2015; Tachikawa et 94

al., 2014]. However, the adequacy of previously published Mg/Ca-temperature calibrations for the
WPWP has not yet been tested.

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Here, we present paired Mg/Ca and δ^{18} O measurements on planktic foraminifera tests from 98 radiocarbon-dated, modern surface sediments in combination with water column data from stations 99 offshore the Philippines and Papua New Guinea (PNG) (Figure 1a and Table 1). Together, these 100 101 areas represent a major part of the WPWP. We estimate species-specific calcification depths and temperatures of various planktic foraminifera species and establish regional Mg/Ca temperature 102 calibrations for the WPWP. In order to estimate calcification depths, we compare shell δ^{18} O with 103 depth profiles of expected equilibrium δ^{18} O of calcite (δ^{18} O_C) at the respective locations. While 104 this is a common approach, an advantage of our study is the availability of concurrently measured 105 salinity and seawater $\delta^{18}O(\delta^{18}O_{SW})$ data, upon which the calculated depth profiles of $\delta^{18}O_C$ are 106 based on. In this framework, we also calculate and provide regional δ^{18} Osw-salinity regressions 107 for surface and subsurface water masses in the WPWP. Finally, we relate Mg/Ca to calcification 108 temperatures to find the most appropriate Mg/Ca calibration for each species and establish a 109 regional multispecies as well as monospecific Mg/Ca-temperature calibrations. We identify the 110 appropriate species to reconstruct past variations in mixed layer depth and thermocline structure 111 112 as well as the appropriate calibrations to convert Mg/Ca into temperature.

113

114 We note that the study is subject to certain limitations. First, it is based on surface sediments. This bears the disadvantages that we do not have direct information about hydrographic parameters at 115 116 periods, when the calcite shells were built. Besides, we cannot fully exclude secondary influences (e.g. dissolution) on our data and, we cannot resolve (intra-)seasonal changes in hydrography. 117 118 Second, our study includes water column data measured during two expeditions. These data provide only snapshots of the WPWP hydrography. Moreover, we did not measure pH or $[CO_3^{2-}]$ 119 and therefore, cannot fully exclude an effect of pH or $[CO_3^{2-}]$ on shell Mg/Ca, although it appears 120 negligible under ambient seawater conditions [Kisakürek et al., 2008; Russell et al., 2004]. Third, 121 since the availability of modern sample material is a prerequisite for calibration studies, our sites 122 are exclusively located in the coastal WPWP, where sedimentation rates are higher than in the 123 open Pacific Ocean. The applicability of our calibrations for the open ocean WPWP needs to be 124 tested in future studies. Finally, especially species-specific calibrations are restricted by the fact, 125

that the temperature range within the study area is rather small. Where necessary, we discuss the limitations of the data in more detail (see section 5). Overall, the strengths of this study outweigh the mentioned limitations. Sediment-based studies have the great advantage that they are performed on the same material used for paleo studies. In relation to this, a great advantage of our study is the availability of (radiocarbon) dated, modern surface sediments. In addition, as mentioned above, our study greatly benefits from concurrent measurements of temperature, salinity and $\delta^{18}O_{SW}$.





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Figure 1. (a) Schematic map of the study area showing the stations, where water column data (stars) and surface sediments (dots) were collected during expeditions SO-228 (blue) and RR-1313

(red). Sites are labelled with station numbers. (b) Mean annual sea surface temperature and (c) sea 137 surface salinity derived from WOA13 [Locarnini et al., 2013; Zweng et al., 2013]. Temperature 138 139 and salinity maps were created with the Ocean data view software [Schlitzer, 2014]. Dashed and solid arrows indicate main surface and (sub)surface currents influencing the study sites. MC -140 Mindanao Current, NEC - North Equatorial Current, NECC - North Equatorial Counter Current, 141 EUC – Equatorial Undercurrent, NGCC – New Guinea Coastal Current, NGCUC – New Guinea 142 Coastal Undercurrent, SEC - South Equatorial Current, SECC - South Equatorial Countercurrent, 143 ITF – Indonesian Throughflow. 144

Table 1. Shell stable oxygen isotopes and Mg/Ca ratios of various planktic foraminifera species in surface sediments from the

148 Western Pacific Ocean.

Core	Latitude (°N)	Longitude (°E)	Water depth (m)	G. ruber δ ¹⁸ O (‰ VPDB)	G. ruber Mg/Ca (mmol/mol)	G. elongatus δ ¹⁸ O (‰ VPDB)	<i>G. elongatus</i> Mg/Ca (mmol/mol)	<i>G. sacc.</i> δ ¹⁸ Ο (‰ VPDB)	G. sacc. Mg/Ca (mmol/mol)	P. obliq. δ ¹⁸ O (‰ VPDB)	<i>P. obliq.</i> Mg/Ca (mmol/mol)	N. dutertrei δ ¹⁸ O (‰ VPDB)	<i>N. dutertrei</i> Mg/Ca (mmol/mol)	G. tumida (355-425 μm) δ ¹⁸ Ο (‰ VPDB)	G. tumida (355-425 μm) Mg/Ca (mmol/mol)	G. tumida (>425 μm) δ ¹⁸ O (‰ VPDB)	G. tumida (>425 µm) Mg/Ca (mmol/mol)
Philippines																	
RR1313-24 50MC	13.57	123.73	1055	-3.25 -3.15	5.28	-3.24	-	-2.78	3.81	-3.47	3.17	-1.84	-	-	-	-	-
RR1313-25 53MC	12.78	123.48	559	-2.95	5.30	-3.30	-	-	3.95	-	-	-	4.23	-	-	-	-
GeoB 17404-2	7.90	126.54	404	-3.03	5.47	-2.91	-	-2.69	3.95	-	-	-	-	-	-	-	-
GeoB 17410-3	7.87	126.59	771	-3.08	5.44 5.82	-3.79	5.46	-3.16 -2.89 -2.94 -2.55 -2.47	4.04	-	-	-	2.68	-	3.27	-	-
GeoB 17414-2	6.26	125.83	2188	-3.13	4.95	-3.01	-	-2.90	3.55	-2.34	2.69 2.74	-2.31 -2.23 -2.23 -2.12 -2.07	2.62	-	-	-	-
Papua New Guinea																	
GeoB 17419-2	-2.81	144.50	1887	-3.18 -3.14 -3.10 -3.15 -2.90	5.17 5.30	-3.05	5.37	-2.95	3.77	-2.15 -1.80 -1.69 -1.59 -1.57	2.27 2.51	-1.64	2.30	-0.70 -0.64 -0.16	1.79 1.89	-0.94	1.63
RR1313-12 30MC	-3.13	142.76	994	-3.74	5.30	-3.01	-	-3.39	4.26	-2.40	2.91	-	2.59	-	-	-	-
GeoB 17421-2	-3.55	144.20	588	-3.45	4.94	-3.43	5.42	-2.64	3.66	-2.20	2.70	-1.52 -1.42 -1.35 -1.27	1.95	-0.31	2.15	-	-
GeoB 17429-1	-4.10	145.20	1604	-3.02	5.13	-2.81 -2.77 -2.73 -2.59	5.21	-2.62	3.74 3.85	-2.00	2.93	-2.01	2.24 2.39	-0.07	1.41	-0.08	1.72
GeoB 17430-2	-4.22	145.03	1160	-3.38 -3.31 -3.02 -2.98 -2.78	5.19	-2.98	5.14	-2.73	3.89 4.03	-2.15	2.80	-1.75	2.78	-0.01	1.43 1.76	-0.31	1.90
GeoB 17432-3	-5.34	146.20	1388	-3.24	5.30	-2.86	5.14 5.44	-2.62 -2.60 -2.60 -2.47 -1.72	3.58	-2.13	2.63	-2.09	1.54 3.09	-	1.35	0.06	1.56
GeoB 17435-2	-7.27	147.34	1001	-3.29	5.10 5.77	-3.24 -3.02 -2.89 -2.24	5.68	-2.81	3.88	-2.23	2.70 2.71	-2.09	2.26	-0.15	1.68	-0.45 -0.35 -0.08	1.43 1.85

149 **2. Study area**

The WPWP is characterized by exceptionally high ocean temperatures with sea surface 150 temperatures (SST) exceeding 28°C (Figure 1b) [Locarnini et al., 2013]. Sea surface salinity 151 is about 34 psu (Figure 1c) [Zweng et al., 2013]. The average mixed layer depth is about 50-152 153 100 m [Locarnini et al., 2013]. The upper thermocline waters are characterized by higher salinities with maxima of around 34.5–35.0 psu off the Philippines and 35.5 psu off PNG. 154 Salinity maxima correspond to the North and South Pacific Tropical Waters (NPTW and 155 SPTW). The NPTW is formed within the western North Pacific Subtropical Gyre and 156 transported along the Philippines towards the equator by the Mindanao Current (MC) [Fine et 157 al., 1994]. The SPTW originates in the South Pacific Suptropical Gyre [Tsuchiya et al., 1989]. 158 It is transported westwards by the SEC and along the coast of PNG by the New Guinea Coastal 159 Current (NGCC) and Undercurrent (NGCUC) system. Below the NPTW and SPTW waters are 160 161 characterized by lower salinities and are influenced by the Antarctic Intermediate Water (AAIW) originating in the Southern Ocean and/or the North Pacific Intermediate water (NPIW) 162 with stronger predominance of AAIW offshore PNG and of NPIW offshore the Philippines 163 [Fine et al., 1994; Zenk et al., 2005]. 164

165

The seasonal climate variability is mainly controlled by the Austral-Asian monsoon and leads to only minor changes in the WPWP hydrography. Temperature and salinity variations are smaller than 1-2°C and 1 psu [*Locarnini et al.*, 2013; *Zweng et al.*, 2013]. On interannual timescales, El Niño Southern Oscillation (ENSO) affects surface ocean conditions as well as the vertical structure of the water column in the WPWP with drier (wetter) conditions and a shallower (deeper) thermocline during El Niño (La Niña) years.

172

Generally, the northern part of the study area is characterized by oligotrophic surface conditions and a deep chlorophyll maximum (DCM) at the top of the thermocline [*Radenac and Rodier*, 1996]. North of PNG nutrient concentrations and biological productivity are higher than elsewhere in the WPWP [*Radenac et al.*, 2016]. However, the (vertical) distribution of nutrients and chlorophyll is variable on (intra-)seasonal timescales [e.g. *Higgins et al.*, 2006; *Radenac and Rodier*, 1996; *Radenac et al.*, 2016].

179

The (intra-)seasonal distribution of planktic foraminifera is controlled by different factors, such
as temperature, salinity and the availability of light and nutrients. Sediment trap data do not

reveal a clear picture of (intra-)seasonal preferences of planktic foraminifera in the study area
[*Kawahata et al.*, 2002; *Yamasaki et al.*, 2008]. Flux data from the equatorial Pacific showed
large (small) peaks during boreal summer (winter) under El Niño conditions and an increased
shell flux during the first half of the year under La Niña conditions [*Kawahata et al.*, 2002; *Yamasaki et al.*, 2008]. Since no clear (intra-)seasonal pattern is indicated by these data we
assume that planktic foraminifera calcify perennially in the WPWP.

188

189 **3. Materials and methods**

190

3.1. Water column data and $\delta^{18}O_{SW}$ -salinity regressions

For this study, we used profiles of water column data, measured at fifteen stations offshore the 191 Philippines and PNG in May-June 2013 during RV SONNE expedition SO-228 [Mohtadi et 192 al., 2013] and at six stations in August 2013 during RV REVELLE expedition RR-1313 (Figure 193 2) [Rosenthal, unpublished]. Temperature and salinity profiles are based on CTD 194 (Conductivity, Temperature and Depth) data. CTD data were measured using Seabird SBE911 195 (plus) CTD profilers during both expeditions. During CTD casts, water samples for stable 196 isotope analyses were collected from several water depths (supplementary information, Table 197 S1). Sampling was performed with CTD-sampling rosettes equipped with 24 Niskin bottles of 198 10–15 l volume. A part of the collected water was siphoned into 100 ml glass bottles for stable 199 isotope analyses, care was taken to avoid getting bubbles in the samples [Mohtadi et al., 2013; 200 Rosenthal, unpublished]. All SO-228 samples (labelled as GeoB-samples in Table 1) were 201 sealed with wax and stored at 4°C before analysis. $\delta^{18}O_{SW}$ was determined with a Picarro 202 L1102-i CRDS water analyser with vaporization module V1102-i coupled to a CTC/Leaptec 203 PAL auto sampler at the Department of Geography and Earth Sciences, University of Erlangen-204 Nuremberg. Calibration against Vienna Standard Mean Ocean Water (VSMOW) was achieved 205 by calibration to laboratory water standards calibrated against IAEA-standards VSMOW2 and 206 SLAP2 [van Geldern and Barth, 2012]. External reproducibility was 0.05 ‰. For the RR1313 207 samples, δ^{18} Osw measurements were made at Rutgers University, New Jersey on a FISONS 208 209 OPTIMA Mass Spectrometer equipped with a MicroMass Multiprep automatic sample processing system after water sample equilibration with CO₂ using standard methods [Epstein 210 and Mayeda, 1953; Fairbanks, 1982]. All samples were run in duplicate. Precision was 211 212 estimated to be $\pm 0.03 \ \text{\%} (1 \ \sigma)$ as determined by multiple (n = 12) daily analyses of a laboratory standard. Replicates must measure to within 0.068 ‰ to be included in the final data set. 213

Instrument linearity and accuracy was determined by comparison of the laboratory standard to
NBS standard water VSMOW, GISP, and SLAP. Accuracy was estimated to be within 0.03 %
by comparison of measurements of North Atlantic Bottom Water with VSMOW.

217

Generally, $\delta^{18}O_{SW}$ is linearly related to salinity [*Craig and Gordon*, 1965; *Fairbanks et al.*, 218 1992]. However, since both parameters are controlled by a number of factors, intercept and 219 slope of their relation are not the same for all ocean regions. Therefore, regional calibrations 220 are required [LeGrande and Schmidt, 2006]. Because the $\delta^{18}O_{SW}$ -salinity relation is not 221 constant over depth, we generated separate equations for surface and subsurface (SPTW and 222 NPTW) waters. For both, we investigated individual relations for the areas offshore the 223 Philippines and PNG as well as combined, more general, relations representing the entire study 224 area. We do not necessarily consider water samples from all stations and depth intervals. 225 Rather, for each equation we include samples that best characterize the relevant water masses 226 (supplementary information, Figure S1). The SPTW and NPTW regressions include only 227 samples that represent the core of these water masses, the WPWP wide subsurface regression 228 is more general and covers a slightly wider depth range. 229

230



231

Figure 2. (a) Salinity, $\delta^{18}O_{SW}$ and temperature profiles and (b) Temperature-salinity relations at stations offshore the Philippines (red) and Papua New Guinea (black). Water masses are labeled as follows: NPTW – North Pacific Tropical Water, SPTW – South Pacific Tropical Water, NPIW – North Pacific Intermediate Water, AAIW – Antarctic Intermediate Water.

3.2. Sediment samples

Surface sediments were collected with multicorer devices during expedition SO-228 (nine sampling sites) [*Mohtadi et al.*, 2013] and during expedition RR-1313 (three sampling sites) [*Rosenthal et al.*, unpublished]. The upper one or two cm of each multicore were washed over
63 µm sieves and dried.

242

All core sites are situated well above the present lysocline depth of 3300 m where carbonate preservation is expected to be good [see *Berger et al.*, 1982 and references therein]. Presence of aragonitic pteropod shells in most SO-228/GeoB core tops (including the core top from our deepest site) further indicate a good carbonate preservation in our samples.

247

248 3.3. Dating

Age estimates of all GeoB sediment samples are based on accelerator mass spectrometry 249 (AMS) ¹⁴C ages (Table 2). All ¹⁴C ages were measured on monospecific *Globigerinoides* 250 sacculifer or on mixed Globigerinoides ruber, G. elongatus and G. sacculifer samples. The 251 252 measurements were carried out at the Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory, University of California, Irvine (UCI). Fraction modern carbon (F¹⁴C) values 253 above one indicate modern ages for all ¹⁴C dated samples (Table 2). In addition, a few GeoB 254 samples were treated with Rose Bengal and contained stained individuals, indicating that these 255 individuals died only very recently. 256

257

The RR-1313 samples did not contain enough foraminifera for radiocarbon dating. For age 258 control of these samples, we measured the carbon isotopic composition (δ^{13} C) on about 10 259 specimens of G. ruber from the 250-300 µm size fraction from the upper 10 cm of each 260 multicore to check for the Suess effect (Figure S2). The Suess effect describes a rapid decrease 261 in seawater δ^{13} C going along with the depletion in 13 C of atmospheric CO₂, which has been 262 caused by an increase in deforestation and burning of ¹²C rich fossil fuels since the industrial 263 revolution [e.g. Böhm et al., 1996; Friedli et al., 1986]. The δ^{13} C measurements were 264 265 performed at Rutgers University, New Jersey using a Micromass Optima mass spectrometer, coupled to an automatic line for carbonate preparation. The stable isotope values were 266 calibrated against the international Vienna Pee Dee Belemnite (VPDB) standard using an 267 internal standard, which is calibrated against the National Bureau of Standards (NBS) 19 268 standard. The long-term standard deviation for δ^{13} C was 0.06 ‰. Rapid drops in δ^{13} C from our 269 RR-1313 multicores are indicative for Suess effect and hence, modern ages of these surface 270 271 sediments (Figure S2). Thus, all samples used in this study reflect modern hydrographic conditions of the WPWP. 272

273

Table 2. Radiocarbon dating of surface sediments from the Western Pacific Warm Pool. Results are expressed as fraction modern carbon ($F^{14}C$) and conventional ${}^{14}C$ ages.

1				/	U	
Core	Lab-ID	Depth (cm)	Species	$F^{14}C$ ± error	¹⁴ C age ± error (years)	Cal. Age
GeoB 17404-2	142715	1-2	G. ruber, G. elongatus,	1.042 ± 0.002	-325 ± 20	>1950 AD
			G. sacculifer G. ruber,			
GeoB 17410-3	158806	1-2	G. elongatus, G. sacculifer	1.064 ± 0.002	-490 ± 20	>1950 AD
GeoR 17414 2	158804	0.1	G. ruber,	1.058 ± 0.002	445 ± 20	N1050 AD
Geob 17414-2	138804	0-1	G. sacculifer	1.058 ± 0.002	-44 <i>3</i> ± 20	>1950 AD
GeoB 17419-2	142718	0-1	G. sacculifer	1.072 ± 0.002	-550 ± 20	>1950 AD
	142719	0-1	G. sacculifer	1.068 ± 0.003	-515 ± 20	>1950 AD
			G. ruber,			
GeoB 17421-2	158805	0-1	G. elongatus, G. sacculifer	1.054 ± 0.002	-420 ± 15	>1950 AD
GeoB 17429-1	142725	0-1	G. sacculifer	1.054 ± 0.002	-415 ± 20	>1950 AD
GeoB 17430-2	142717	0-1	G. elongatus,	1.058 ± 0.002	-445 ± 20	>1950 AD
			G. sacculifer			
GeoB 17432-3	142716	0-1	G. sacculifer	1.049 ± 0.002	-375 ± 20	>1950 AD
GeoB 17435-2	158803	0-1	G. sacculifer	1.066 ± 0.002	-500 ± 20	>1950 AD

3.4. Isotope and trace element analyses

Tests from the foraminiferal species G. ruber, G. elongatus and G. sacculifer (without sac-like 278 final chamber) (all taken from the 250–355 µm size fraction), Neogloboquadrina dutertrei and 279 Pulleniatina obliquiloculata (355–425 µm), and Globorotalia tumida (355–425 µm and >425 280 μ m) were picked under a binocular for δ^{18} O and Mg/Ca analyses. For all species but *G. tumida*. 281 specimens were separately picked for isotope and Mg/Ca analyses. G. tumida specimens were 282 very rare in most of the samples. In order to ensure that fragments of several individuals were 283 used for each measurement, 10 (where available) individuals were picked, crushed, 284 homogenized and then separated for isotope and trace element analyses. 285

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Around 40-120 µg carbonate (around 3–10 specimens) were used for stable isotope analyses. The isotopic composition of all samples was measured at the MARUM-isotope laboratory, University of Bremen, Germany, using a Finnigan MAT 251 mass spectrometer, connected to an automatic line for carbonate preparation (type "Kiel III"). All isotope values were calibrated against the international Vienna Pee Dee Belemnite (VPDB) standard. The internal carbonate standard is a Solnhofen Limestone, which is calibrated to the NBS 19 standard. The analytical standard deviation for δ^{18} O is below ±0.07 ‰. To check the reproducibility of the data we performed up to four (depending on the available material) replicate measurements on 11 samples (Table 1). The results indicate an average standard deviation of 0.22 ‰ for δ^{18} O.

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For Mg/Ca analyses we used 30 (where available) well preserved specimens of G. ruber and 297 G. elongatus, 25 specimens of G. sacculifer, 15 specimens of P. obliquiloculata and N. 298 dutertrei and between 2 and 10 individuals of G. tumida. Although the presence of pteropods 299 indicates negligible effect of carbonate dissolution, all samples were weighed to estimate a 300 301 potential influence of dissolution on the Mg/Ca records. Samples were gently crushed between two glass plates to open the chambers. The full trace metal cleaning procedure followed the 302 protocol described by Barker et al. [2003] with an additional reductive step [Boyle and 303 Keigwin, 1985; Rosenthal et al., 1997; Rosenthal et al., 1999]. Samples were dissolved in 304 0.0065 M HNO₃, centrifuged for 10 min at 10000 rpm and diluted with 0.5 N HNO₃. The final 305 calcium concentration of the samples was on average 3.2 mM. Trace metal ratios were 306 measured at Rutgers University, New Jersey with a Thermo Fisher/Finnigan Element XR 307 sector-field inductively coupled plasma mass spectrometer (ICP-MS). Mg/Ca measurements 308 were performed in low resolution ($\Delta m/m = 300$). Measured ratios were blank corrected. Mass 309 310 drift and matrix effects and the long term precision of the data were controlled with in house standard solutions [Rosenthal et al., 1999]. All Mg/Ca values are given in mmol/mol. Replicate 311 312 measurements on 14 samples revealed an average standard deviation of 0.23 mmol/mol (Table 1). To monitor the cleaning efficacy Al/Ca, Fe/Ca and Mn/Ca were measured alongside Mg/Ca. 313 314 None of these ratios showed a covariance with Mg/Ca (Figure S3). Mg/Ca ratios of individual species do not show a correlation to water depth or shell normalized weights (Figure S4). Thus, 315 316 we exclude any substantial effect of carbonate dissolution on shell Mg/Ca values.

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318 3.5. Estimation of calcification depths and temperatures

In order to estimate species-specific calcification depths we compare shell δ^{18} O of individual species with depth-profiles of δ^{18} O_C, assuming that all species calcified in isotopic equilibrium with seawater. The water depth where shell δ^{18} O matches the expected δ^{18} O_C is considered to reflect the calcification depth of the respective species at the site.

323 Depth-profiles of expected $\delta^{18}O_C$ were calculated from SO-228 and RR-1313 CTD salinity 324 profiles as follows. First, $\delta^{18}O_{SW}$ was calculated from salinity using here established regional 325 (WPWP) $\delta^{18}O_{SW}$ -salinity equations (equations I and II in section 4.1). The average uncertainty

in the calculated $\delta^{18}O_{SW}$ given as the average standard deviation between measured and 326 calculated $\delta^{18}O_{SW}$ is 0.05 ‰. It was necessary to calculate $\delta^{18}O_{SW}$ from CTD salinity instead 327 of using the measured $\delta^{18}O_{SW}$ to obtain continuous profiles. Results were converted from 328 VSMOW to the VPDB scale by subtracting 0.27 ‰ [Hut, 1987]. Then, we applied a set of 329 commonly used δ^{18} O-temperature equations (Table 3) to predict equilibrium δ^{18} O_C using CTD 330 temperature and the previously calculated $\delta^{18}O_{SW}$. Finally, we matched shell $\delta^{18}O$ to the $\delta^{18}O_C$ 331 profiles. Since surface sediments were not always taken at the same positions as CTD, we 332 matched shell δ^{18} O to profile(s) from those station(s), which are nearest to the core sites. To 333 determine uncertainties of the calcification depth of each species and core site we estimated 334 the calcification depths based on shell δ^{18} O with added/subtracted species-specific standard 335 deviations. Depending on the standard deviation and the shape of the profiles, average 336 uncertainties range between ± 10 and 30 m. 337

338 CTD temperatures at depths corresponding to the estimated calcification depths give an 339 estimate of the calcification temperatures for each species and core site. For *G. elongatus*, *P.* 340 *obliquiloculata and N. dutertrei* only a few samples from the Philippines contained enough 341 individuals to perform isotope analyses. For *G. tumida* none of the Philippines' samples 342 contained enough specimens and therefore, depth and temperature estimates for this species 343 are only representative for the area offshore PNG.

Reference	Species	Linear equations T (°C) = $a - b (\delta^{18}O_C - \delta^{18}O_{SW})$			
Reference	Species	a	b		
Bemis et al. [1998]	O. universa (HL)	14.9	-4.8		
Bouvier-Soumacnac and Duplessy [1985]	N. dutertrei	10.5	-6.58		
Farmer et al. [2007]	G. ruber	15.4	-4.78		
	G. sacculifer	16.2	-4.94		
	N. dutertrei	14.6	-5.09		
	P. obliquiloculata	16.8	-5.22		
	G. tumida	13.1	-4.95		
Mulitza et al. [2003]	G. ruber	14.2	-4.44		
	G. sacculifer	14.91	-4.35		
Shackleton [1974]	Uvigerina sp.	16.9	-4.0		
Spero et al. [2003]	G. sacculifer	12.0	-5.67		
		Quadratic equations $T(^{\circ}C) = a - b (\delta^{18}O_C - \delta^{18}O_{SW})^2$ $+ c (\delta^{18}O_C - \delta^{18}O_{SW})^2$			
		а	b c		
Kim and O'Neil [1997]	inorganic	16.1	-4.64 0.09		

345	Table 3. General and s	pecies-specific	δ^{18} O-temperat	ture equations	used in this study

347 **4. Results**

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4.1. Water column data and $\delta^{18}O_{SW}$ -salinity regressions

 δ^{18} Osw = 0.37 (±0.03) * S - 12.4 (±1.0)

The $\delta^{18}O_{sw}$ -salinity relations for the study area during summer 2013 reveal that a $\delta^{18}O_{sw}$ 349 increase of about 0.3 to 0.4 ‰ corresponds to a salinity increase of 1 psu (Figure 3). 350 Regressions for surface waters offshore the Philippines and PNG (considering only samples 351 from the Bismarck and Solomon Seas) are very similar (Figure 3a, blue and red dots, 352 respectively). The regression line for surface waters offshore PNG shows only a slightly steeper 353 slope and consequently, a smaller intercept. Taking all SO-228 and RR-1313 stations across 354 the WPWP into account (Figure 3a, all black and colored dots) the surface $\delta^{18}O_{SW}$ -salinity 355 relation can be described as: 356

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Regression lines describing the $\delta^{18}O_{SW}$ -salinity relations for subsurface waters (NPTW and 360 SPTW) show a shallower slope than for surface waters with slightly higher intercepts (Figure 361 3b). Due to the very small salinity ranges within the NPTW and SPTW it is difficult to assess 362 a robust relationship for each of these water masses. The regressions also greatly depend on 363 the depths and number of stations included in each equation. However, although NPTW and 364 SPTW have different characteristics (see Figure 2), their $\delta^{18}O_{SW}$ -salinity regressions are very 365 similar to each other. Therefore, we also provide one equation for WPWP subsurface waters 366 367 that includes all SO-228 and RR-1313 sample stations (Figure 3b, all black and colored dots).

 $(R^2 = 0.80)$

(I)

$$\delta^{18}O_{SW} = 0.33 (\pm 0.03) * S - 11.0 (\pm 1.1)$$
 (R² = 0.67) (II)



Figure 3. Regional $\delta^{18}O_{SW}$ -salinity relations for (a) surface and (b) subsurface waters in the 372 Western Pacific Warm Pool. Dots indicate individual samples included in the regressions. Red 373 and blue colors indicate subsets of samples included in the regional regressions off Papua New 374 Guinea (PNG) and the Philippines, respectively. Black dots indicate samples from sites that 375 are not included in the regional regressions. Black lines indicate regression lines for the entire 376 study area and colored lines for the subareas. Gray stippled lines show regional δ^{18} Osw–salinity 377 equations published by 1. Fairbanks et al. [1997], 2. Morimoto [2002], 3/5. Leech et al. [2013], 378 4. [LeGrande and Schmidt, 2011]. Bars indicate laboratory standard deviations for oxygen 379 380 isotope measurements.

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4.2. Calcification depth

In general, shell δ^{18} O increases with increasing calcification depth of the species. G. ruber and 383 G. elongatus record the lowest δ^{18} O values and G. tumida records the highest δ^{18} O values. G. 384 sacculifer, P. obliquiloculata and N. dutertrei calcify in between. Shell δ^{18} O and our derived 385 mean calcification depths of the species used are very similar offshore the Philippines and 386 PNG. Therefore, in our discussion we do not distinguish between samples from the Philippines 387 and PNG. Figure 4 and Table 4 give δ^{18} O-derived depths for all species as estimated by 388 applying the δ^{18} O-temperature equation of *Bemis et al.* [1998]. Depth estimates for each species 389 applying different δ^{18} O-temperature equations in comparison are provided in the 390 supplementary information (Figures S4-6). 391



Figure 4. Shell δ^{18} O derived calcification depth estimates for several planktic foraminifera 394 (colored dots) in the Western Pacific Warm Pool. Gray lines indicate depth profiles of predicted 395 δ^{18} Oc calculated from individual CTD casts (see section 3.5 for details). The average 396 calcification depth at each core site is determined by matching shell δ^{18} O to δ^{18} O_C of the 397 profile(s) nearest to the respective core site. Horizontal bars indicate species-specific standard 398 deviations for shell δ^{18} O, vertical bars on black dots show exemplarily average uncertainties in 399 calcification depth derived by projecting shell δ^{18} O with added/subtracted standard deviations 400 on the $\delta^{18}O_C$ profiles. The uncertainty of the $\delta^{18}O_C$ profiles arising from the average standard 401 deviation between measured and calculated $\delta^{18}O_{SW}$ is 0.05 % (not shown). Colored shading 402 indicates calcification depth ranges for the individual species in the study area. The average 403 calcification depth is highlighted by colored horizontal bars. Note the different scaling of the 404 axes in different panels. Individual data points, which are shown outside the range of predicted 405 $\delta^{18}O_{\rm C}$ do not match any profile (see text). 406

Table 4. Calcification depth and temperatures. The calcification depth of each species and core site was estimated by comparing shell408 δ^{18} O to depth profiles of predicted δ^{18} O calcite. Predicted δ^{18} O_c was calculated from CTD salinity applying the δ^{18} O_{sw}-salinity equations409of this study and the δ^{18} O-temperature equation of *Bemis et al.* [1998] using CTD temperature. We assigned a depth of 0 m to samples410that did not match any profile. Calcification temperatures are CTD temperatures at depth corresponding to the estimated calcification411depths.

Com	<i>G. ruber</i> (250-355 μm)		<i>G. elongatus</i> (250-355 μm)		<i>G. sacculifer</i> (250-355 μm)		P. obliquiloculata (355-425 μm)		<i>N. dutertrei</i> (355-425 μm)		<i>G. tumida</i> (355-425 μm)		<i>G. tumida</i> (>425 μm)	
Core	Depth (m)	Temp. (°C)	Depth (m)	Temp. (°C)	Depth (m)	Temp. (°C)	Depth (m)	Temp. (°C)	Depth (m)	Temp. (°C)	Depth (m)	Temp. (°C)	Depth (m)	Temp. (°C)
Philippines														
RR1313-24 50MC	7	29.8	0	29.6	85	28.4	0	29.8	140	24.3	-	-	-	-
RR1313-25 53MC	77	28.3	0	28.8	-	-	-	-	-	-	-	-	-	-
GeoB 17404-2	47	28.9	57	28.5	83	27.8	-	-	-	-	-	-	-	-
GeoB 17410-3	22	29.3	0	29.9	70	28.2	-	-	-	-	-	-	-	-
GeoB 17414-2	25	29.2	37	28.7	45	28.2	88	25.8	94	25.3	-	-	-	-
Papua New Guinea														
GeoB 17419-2	32	29.7	40	29.8	60	29.6	147	24.6	150	24.2	200	18.8	175	20.9
RR1313-12 30MC	0	29.7	-	-	0	29.7	114	27.5	-	-	-	-	-	-
GeoB 17421-2	0	29.7	0	29.7	77	28.3	117	26.7	157	23.1	240	17.7	-	-
GeoB 17429-1	60	29.0	67	28.6	72	27.9	125	25.8	123	25.8	248	16.4	250	15.9
GeoB 17430-2	42	29.2	63	28.7	68	28.5	108	26.3	153	24.7	252	15.8	230	17.6
GeoB 17432-3	0	29.4	66	28.6	75	27.5	103	26.2	107	26.0	-	-	263	15.6
GeoB 17435-2	0	28.9	40	28.9	45	26.7	90	26.9	97	26.2	258	16.6	238	17.7

4.2.1. Mixed layer species: G. ruber, G. elongatus and G. sacculifer

Average shell δ^{18} O values are very similar for G. ruber and G. elongatus (-3.19 and -3.11 ‰, 416 Table 1). This implies very similar calcification depths for both species in the WPWP. 417 Depending on the selected δ^{18} O-temperature equation, shell δ^{18} O derived mean calcification 418 depths range from 0 to 45–105 m (Figures 4 and S4). Applying the δ^{18} O-temperature equations 419 of Bemis et al. [1998] and Shackleton [1974] the estimated depth range is within the upper 80 420 m of the water column for both, G. ruber and G. elongatus. By applying the equations of Kim 421 and O'Neil [1997] and Farmer et al. [2007] calcification depths shoal to 0-45 m and 0-65 m, 422 respectively, while the application of the species-specific equation of *Mulitza et al.* [2003] 423 result in a slightly deeper depth range (0–105 m) (Figure S5a). 424

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Shell δ^{18} O of *G. sacculifer* varies around -2.73 ‰ (excluding RR1313-12 30MC) (Table 1). 426 Applying different δ^{18} O-temperature equations, the mean calcification depth varies between 45 427 and 95 m. It ranges from 45 to 85 m using the equation of Bemis et al. [1998] (Figure 4c) and 428 from 55 to 95 m applying the δ^{18} O-temperature equations of *Shackleton* [1974] and *Spero et* 429 al. [2003]. The equations of Farmer et al. [2007] and Kim and O'Neil [1997] lead to slightly 430 shallower calcification depths (0-70 m) and the equation of Mulitza et al. [2003] to deeper 431 calcification depths (70-110 m) (Figure S5b). Note that sample RR1313-12 30MC shows an 432 extremely low δ^{18} O value (-3.39 ‰), which does not match any profile. 433

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4.2.2. Upper thermocline species: P. obliquiloculata and N. dutertrei

Shell δ^{18} O of *P. obliquiloculata* varies around -2.15 % (excluding RR1313-24 50MC) (Table 436 1). For the majority of the samples this indicates a calcification depth between 90 and 125 m 437 when applying the δ^{18} O-temperature equation of *Bemis et al.* [1998] (Figure 4d). Applying the 438 equations of Shackleton [1974] or Bouvier-Soumagnac and Duplessy [1985] leads to very 439 similar calcification depths (85–120 and 90–130 m), the equations of *Kim and O'Neil* [1997] 440 and Farmer et al. [2007] leads to slightly shallower calcification depths (70-105 and 40-75 m) 441 (Figure S6a). Our foraminifera tests from site GeoB 17419-2 record exceptionally high δ^{18} O 442 values resulting in, compared to the other core sites, relatively deeper (20-40 m) calcification 443 depths. With a δ^{18} O value of -3.47 ‰ (Table 1), sample RR1313-24 50MC does not match any 444 $\delta^{18}O_C$ profile. 445

The *N. dutertrei* average shell δ^{18} O of -1.88 ‰ is slightly higher than that of *P. obliquiloculata*. By using the equations of *Bemis et al.* [1998], *Shackleton* [1974] or *Farmer et al.* [2007] shell derived calcification depths vary between around 90 and 160 m (Figures 4e and S5b). The application of the δ^{18} O-temperature equation from *Kim and O'Neil* [1997] or *Bouvier-Soumagnac and Duplessy* [1985] result in slightly shallower or deeper depth ranges (80–150 or 95–155 m) (Figure S6b).

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4.2.3. Lower thermocline species: G. tumida

Average shell δ^{18} O of G. tumida is -0.15 % for the 355–425 µm size fraction and -0.14 % for 455 the >425 µm size fraction (excluding GeoB 17419-2) (Table 1). Shell δ^{18} O of individual 456 samples differ by maximal 0.3 ‰. Hence, under the restriction of the small set of samples, our 457 data indicate, that there is no major size effect on the calcification depths of G. tumida. Based 458 on the equation of Bemis et al. [1998] the calcification depth of G. tumida at most sites is 459 between 230 and 265 m water depth (Figure 4f). The application of the equations from 460 Shackleton [1974] and Kim and O'Neil [1997] results in slightly shallower calcification depths, 461 ranging between 195 and 235 m. Based on the species-specific equation of *Farmer et al.* [2007] 462 the estimated calcification depths are slightly deeper, ranging between 255 and 310 m (Figure 463 S7). Exceptionally low δ^{18} O in G. tumida shells from GeoB 17419-2 indicates up to 70 m 464 shallower calcification depth at this site, independent of the size fraction used. 465

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4.3. Shell Mg/Ca

Mg/Ca ratios recorded in the Philippines and PNG samples are very similar. G. ruber and G. 468 elongatus record highest Mg/Ca, averaging 5.26 and 5.37 mmol/mol, respectively. Shell 469 Mg/Ca in G. sacculifer varies around 3.85 mmol/mol. N. dutertrei and P. obliquiloculata show 470 similar shell Mg/Ca varying around 2.60 and 2.66 mmol/mol, respectively. G. tumida shows 471 472 lowest Mg/Ca ratios around 1.88 mmol/mol (355–425 µm) and 1.69 mmol/mol (>425 µm). Hence, average Mg/Ca of the different species confirms the results obtained from oxygen 473 474 isotope ratios with calcification depths being shallowest for G. ruber, G. elongatus and G. sacculifer, intermediate for P. obliquiloculata and N. dutertrei and deepest for G. tumida. 475 Mg/Ca ratios of P. obliquiloculata in RR1313-24 50MC, N. dutertrei in RR1313-53MC, and 476 G. tumida in GeoB 17410-3 are exceptionally high (3.17 mmol/mol, 4.23 mmol/mol, and 3.27 477 478 mmol/mol) (Table 1). The high Mg/Ca value of P. obliquiloculata in RR1313-24 50MC goes

along with exceptionally low δ^{18} O and could therefore indicate an extremely shallow calcification depth at this site. Due to the limited number of specimens of *N. dutertrei* in RR1313-25 53MC and *G. tumida* in GeoB 17410-3, we could not measure the oxygen isotope composition in these samples.

483

484 **5. Discussion**

485

5.1. Water column data and $\delta^{18}O_{SW}$ -salinity regressions

Generally, our surface and subsurface $\delta^{18}O_{sw}$ -salinity regressions are within the range of 486 published WPWP regressions [Fairbanks et al., 1997; Leech et al., 2013; LeGrande and 487 Schmidt, 2011; Morimoto, 2002]. However, slope and/or intercept differ from previous 488 regression lines. Especially the regressions of Fairbanks et al. [1997], LeGrande and Schmidt 489 [2011] and the surface regression of *Leech et al.* [2011] show shallower slopes (around 0.3) 490 and accordingly, larger intercepts (between -10.47 and -9.14) than our regressions. The 491 regression of *Morimoto et al.* [2002] is almost identical to our PNG surface equation ($\delta^{18}O_{SW}$) 492 = 0.42*S-14.3). Since δ^{18} Osw-salinity relations depend on local environmental conditions, 493 deviations are most probably due to different sampling sites, water depths and periods. 494

495

For the first time, we generated equations for individual water masses (surface waters, NPTW 496 and SPTW). Our results reveal that for both, WPWP wide and regional regressions, the ratio 497 between $\delta^{18}O_{SW}$ and salinity is higher in surface than in subsurface waters. Therefore, it appears 498 reasonable to use different $\delta^{18}O_{SW}$ -salinity regressions for surface and subsurface water masses. 499 The regression coefficients of our regression lines (Figure 3) indicate that the application of a 500 501 more general, WPWP wide regression for combined NPTW and SPTW is more robust than individual regressions for the NPTW and SPTW. This is due to the very small salinity range 502 503 within the NPTW offshore the Philippines and the SPTW offshore PNG.

- 504
- 505

5.2. Calcification depths and temperatures

Accurate calcification depth estimates are indispensable to deduce precise calcification temperatures for each species. The accuracy of the depth estimates depends on the precision of the δ^{18} Osw-salinity equation applied, the choice of the δ^{18} O-temperature equation, the availability of local water column data, the seasonal and interannual variations in local 510 hydrography and possible shell disequilibrium effects [see *Regenberg et al.*, 2009; *Steph et al.*,

- 511 2009].
- 512

A comparison between predicted $\delta^{18}O_C$ calculated using discrete $\delta^{18}O_{SW}$ measured in water samples and predicted $\delta^{18}O_C$ using $\delta^{18}O_{SW}$ calculated from CTD salinity shows that the calculated values reproduce measured $\delta^{18}O$ precisely (Figure S8). The average deviation between calculated and measured $\delta^{18}O_{SW}$ is ± 0.07 ‰, the maximal deviation is ± 0.35 ‰ and only 6 out of 98 samples yielded $\delta^{18}O_{SW}$ differences larger than 0.20 ‰ (see Table S2). The comparison provides reliability to the accuracy of the $\delta^{18}O_{SW}$ -salinity equations for our sampling period and sites.

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For the following analyses we use calcification depth estimates based on the δ^{18} O-temperature 521 equation that was generated by Bemis et al. [1998] in a culture experiment for O. universa. 522 Although it has been obtained on a single species not used in our study, this equation is 523 commonly used for other planktic foraminiferal species [e.g. Mohtadi et al., 2014; Spero et al., 524 2003; Thunell et al., 1999] and its application gives realistic results for all species used here. 525 The equations of Shackleton [1974], Bouvier-Soumagnac and Duplessy [1985], and Spero et 526 527 al. [2003] lead to similar calcification depths. The quadratic equation of *Kim and O'Neil* [1997] results in marginally shallower depths for surface and similar depths for subsurface dwellers. 528 529 The application of the equations of Farmer et al. [2007] result in slightly shallower calcification depths. The equations of *Farmer et al.* [2007] are based on sample material from 530 531 much greater water depths (mostly 3000-4000 m) where carbonate is affected by dissolution [*Hertzberg and Schmidt*, 2013] which would increase δ^{18} O in foraminiferal tests. 532 Consequently, the application of these equations would underestimate calcification depths. The 533 equations proposed by Mulitza et al. [2003] result in deeper calcification depths. These 534 equations are based on plankton tow studies and might overestimate calcification depths due 535 to lower δ^{18} O in shells of living foraminifera [see *Regenberg et al.*, 2009 and references 536 therein]. 537

538

Based on the assumption that planktic foraminifera calcify perennially in the WPWP we assume that our δ^{18} O data represent mean annual conditions. However, we note that data from individual samples might be biased and reflect other than normal conditions (e.g. a single season or El Niño/La Niña conditions). We are well aware that our hydrographic data show a snapshot and therefore, do not necessarily represent mean annual hydrography. However,

seasonal temperature and salinity variations are very small in our study area and mostly 544 restricted to the mixed layer (see section 2). Interannual variations in ocean hydrography are 545 mainly caused by ENSO variability. Our water column data were collected during a normal 546 year and are thus, not biased to El Niño or La Niña conditions. Considering the paucity of 547 continuous subsurface temperature, salinity and especially $\delta^{18}O_{SW}$ data from the WPWP, our 548 work provides the first simultaneous measurements on these parameters at different water 549 depths at stations in close proximity to our core sites and thus, the hitherto most suitable 550 hydrographic estimates for the determination of calcification depths and temperatures. 551

552

Nonetheless, we also compared shell $\delta^{18}O$ with depth-profiles of $\delta^{18}O_C$ calculated by using 553 mean annual temperature and salinity data from the World Ocean Atlas 13 (WOA13) 554 [Locarnini et al., 2013; Zweng et al., 2013]. Shell δ^{18} O of most G. ruber and G. elongatus 555 samples do not match the WOA13 $\delta^{18}O_C$ profiles. WOA13 derived calcification depths of G. 556 sacculifer extent over a larger depth range than SO-228 and RR-1313 CTD (from here on 557 referred to as CTD) calcification depths. WOA13 depth estimates of P. obliquiloculata, N. 558 *dutertrei* and *G. tumida* differ only slightly from CTD derived depth estimates (maximal 35 m) 559 with a tendency to shallower depths. Overall, for our study, the application of CTD data gives 560 561 more realistic results than the application of WOA13 data.

562

Previous studies have shown that many species do not calcify in isotopic equilibrium with 563 seawater [see Ravelo and Hillaire-Marcel, 2007 and references therein]. Potential reasons are 564 the photosynthetic activity of symbionts, incorporation of low $\delta^{18}O$ metabolic CO₂, species-565 specific calcification rates, the addition of gametogenic calcite, and possibly carbonate ion 566 concentrations of the ambient seawater [see Ravelo and Hillaire-Marcel, 2007 and references 567 therein]. Disequilibrium effects depend on local conditions and the sample material used. For 568 most species used in our study, negative disequilibrium effects ranging between 0.0 and 1.0 % 569 are presumed [see Lončarić et al., 2006; Niebler et al., 1999 and references therein]. No vital 570 effects are reported for G. tumida. Correcting for negative disequilibrium effects would 571 increase shell δ^{18} O, and subsequently result in deeper calcification depths and colder 572 calcification temperatures [see discussion in Regenberg et al., 2009]. However, the large 573 variety of factors that could possibly influence shell δ^{18} O makes it difficult to correct δ^{18} O for 574 disequilibrium effects precisely. In addition, most published δ^{18} O-temperature equations do not 575 take into account biological disequilibrium effects on δ^{18} O. Therefore, we did not correct δ^{18} O 576 values for disequilibrium effects. 577

Overall, our results show that G. ruber and G. elongatus calcify within the mixed layer (0-80 579 m) and G. sacculifer calcifies at the bottom of the mixed layer (45–85 m). P. obliquiloculata 580 and *N. dutertrei* calcify within the upper thermocline, whereby our δ^{18} O values indicate that *N*. 581 dutertrei calcifies within a larger depth range (90-160 m) than P. obliquiloculata does (90-125 582 m). G. tumida seems to calcify well below P. obliquiloculata and N. dutertrei within the lower 583 thermocline at depth between 230 and 265 m. In relation to water masses, this means that G. 584 ruber, G. elongatus and G. sacculifer calcify in surface waters. P. obliquiloculata, and N. 585 586 dutertrei calcify predominantly within the NPTW offshore the Philippines and within the SPTW offshore PNG. G. tumida calcifies within the transition between NPTW/SPTW and 587 NPIW or AAIW. Our depth estimates generally agree with results from sediment traps and 588 plankton tows in the central equatorial Pacific, North Pacific and Indian Oceans [Kuroyanagi 589 and Kawahata, 2004; Mohtadi et al., 2009; Peeters et al., 2002; Rippert et al., 2016; Watkins 590 et al., 1996]. However, our data show a tendency to somewhat deeper absolute calcification 591 depths and wider depth ranges for most species, probably owing to a generally thick mixed 592 layer and deep thermocline in the WPWP. Recent results from the eastern WPWP indicate even 593 deeper habitat depths of planktic foraminifera [Rippert et al., 2016]. Such differences in 594 595 absolute calcification depths are likely related to the specific regional hydrographic conditions in each study area. For G. ruber and G. elongatus, our data imply very similar calcification 596 597 depths. This is in sharp contrast to studies from the South China Sea and North Pacific Ocean that suggest a deeper habitat depth for G. elongatus [Kawahata, 2005; Steinke et al., 2005; 598 599 Wang, 2000] but in agreement with studies from the eastern Indian Ocean and the Caribbean Sea, which suggest the same habitat depth for both species [Mohtadi et al., 2009; Thirumalai 600 601 et al., 2014].

602

5.3. Mg/Ca versus calcification temperatures

A large number of studies revealed that Mg/Ca in planktic foraminiferal tests show an exponential relationship with ocean temperatures [e.g. *Anand et al.*, 2003; *Cléroux et al.*, 2008; *Dekens et al.*, 2002; *Elderfield and Ganssen*, 2000; *McConnell and Thunell*, 2005; *Mohtadi et al.*, 2009; *Mohtadi et al.*, 2011; *Nürnberg et al.*, 1996; *Regenberg et al.*, 2009]. Some culture and core top studies also described a positive salinity effect on shell Mg/Ca of planktic foraminifera [*Arbuszewski et al.*, 2010; *Ferguson et al.*, 2008; *Kısakürek et al.*, 2008; *Mathien-Blard and Bassinot*, 2009; *Nürnberg et al.*, 1996]. However, studies suggesting a significant

salinity influence have been criticized due to substantial dissolution effects, seasonality 611 [Arbuszewski et al., 2010] or diagenetic alteration [Ferguson et al., 2008] on the sample 612 material [Hertzberg and Schmidt, 2013; Hönisch et al., 2013]. However, in our study area the 613 salinity range is rather small (between 33.9 and 35.6 psu). Variations between stations at water 614 depths that correspond to the calcification depth of individual foraminifera species at the 615 corresponding core sites are below 1.2 psu. There is no significant correlation between Mg/Ca 616 and salinity (R-values range between 0.00 and 0.35 for individual species). Besides, shell 617 Mg/Ca in samples from offshore the Philippines and PNG are very similar, although these areas 618 are influenced by water masses characterized by different salinities (Figure 2). Therefore, we 619 argue that shell Mg/Ca in our samples is not biased by salinity. Some studies also indicate a 620 negative effect of pH or [CO₃²⁻] on Mg/Ca [Evans et al., 2016; Kisakürek et al., 2008; Lea et 621 al., 1999; Russell et al., 2004; Spero et al., 2015]. To date, it is not clear whether pH or [CO₃²⁻ 622] exert a dominant control on Mg/Ca [Allen et al., 2016; Evans et al., 2016]. Moreover, the 623 effect is neither constant over temperature [Spero et al., 2015], nor the same for different 624 planktic foraminifera species [e.g. Allen et al., 2016] and some studies provide confidence that 625 the effect is negligible for ambient seawater conditions [Kisakürek et al., 2008; Russell et al., 626 2004]. Since pH or $[CO_3^{2-}]$ were not measured during both SO-228 and RR-1313 expeditions, 627 we cannot estimate the range of these parameters over the study area. We do not apply any 628 corrections for possible effects of carbonate chemistry on shell Mg/Ca, while we cannot fully 629 630 exclude such effect on our samples. More extensive culture and/or sediment trap studies are required to quantify the effect pH or $[CO_3^{2-}]$ on Mg/Ca of the various planktic foraminifera 631 632 species.

633

Mg/Ca to temperature calibrations are usually expressed as $Mg/Ca = B \exp (A*Temperature)$. 634 We combined data of all species and compared shell Mg/Ca to CTD temperature at δ^{18} O-635 derived calcification depths in a multispecies approach (Figure 5). A depth of 0 m was assigned 636 to samples, where shell δ^{18} O did not match the δ^{18} O_C. Mg/Ca and temperature show a clear 637 exponential relationship (Figure 5). Previous studies suggest that this relationship is best 638 described by a reduced major axis (or geometric mean) regression (RMA) of the natural Log 639 of (Mg/Ca) against calcification temperature [Anand et al., 2003; Rosenthal and Lohmann, 640 2002]. An advantage of the RMA is that it accounts for both, uncertainties in Mg/Ca and 641 calcification temperatures. Especially in field studies, calcification temperatures inherit an 642 intrinsic scatter that arises from a range of different factors including uncertainties in the depth 643 estimates or seasonality for example. 644

645 Using the RMA approach, the multispecies Mg/Ca-temperature relation is described by the646 following equation:

647

648

$$Mg/Ca = 0.26 (\pm 0.04) \exp 0.097 *T (\pm 0.006)$$
(III)

649

The calculation followed *Isobe et al.* [1990]. The uncertainties of the slope and intercept are given as standard deviations assuming that the intrinsic scatter of the data dominates any errors of the measurement process.

653

For comparison, we also calibrated shell Mg/Ca against WOA13 mean annual temperatures. Despite the differences in estimated calcification depths, WOA13 derived calcification temperatures are very similar to CTD derived calcification temperatures. The reason is that temperatures of the WOA13 climatology are generally lower than our CTD temperatures at the same depth levels. Due to the similarity of the calcification temperatures, the WOA13 derived regression is within the error range of the regression based on CTD derived calcification temperatures. (A = 0.101, B = 0.24).

661

662 Our multispecies Mg/Ca-temperature relation is in good agreement with previously published multispecies and species-specific temperature calibrations (Figure 5 and Table 5). However, 663 comparing our calibration to published ones, it has to be noted that our calibration is based on 664 samples that were treated by reductive cleaning, whereas most published calibrations are based 665 on samples cleaned without a reductive step. Previous studies indicate that the reductive 666 cleaning leads to a decrease in Mg/Ca [e.g. Barker et al., 2003; Xu et al., 2010]. To estimate 667 the effects on the Mg/Ca-temperature relations, we applied a correction assuming that the 668 Mg/Ca relations were reduced by about 10 % in all samples [e.g. Barker et al., 2003; Martin 669 and Lea, 2002; Rosenthal et al., 2004]. We note that some studies suggest different values for 670 individual species [e.g. Xu et al., 2010], but since exact rates of Mg/Ca loss are unknown for 671 most species, we presume a constant rate of 10 % for all species. The resulting regression line 672 shows the same slope as the original calibration (0.097), and an only slightly modified intercept 673 (0.24). Thus, the modified calibration is within the error range of the original one. 674

675

A multispecies equation does not seem accurate enough to describe the Mg/Ca-temperature relation of individual species in the WPWP. For example, all the *G. ruber* and *G. elongatus* samples fall above, and all the *P. obliquiloculata* and *N. dutertrei* samples fall below the 679 regression line. That means, calcification temperatures of G. ruber and G. elongatus are overestimated, and those of P. obliquiloculata and N. dutertrei are underestimated by the 680 multispecies regression. For that reason, species-specific regression lines are additionally 681 required to reconstruct calcification temperatures for individual species precisely. Since the 682 temperature range between the sites in our study area is very narrow, it is difficult to determine 683 the temperature sensitivity for individual species unequivocally. Hence, we calculated regional 684 species-specific regressions by assuming the same temperature sensitivity, A = 0.097, as it was 685 calculated by the multispecies approach, for all species (Figure 5). The resulting regression 686 687 lines for G. ruber and G. elongatus are very similar to the multispecies and species-specific regression published by Anand et al. [2003] or Dekens et al. [2002], respectively (Mg/Ca = 688 0.39 exp 0.09*T). For the temperature range relevant for this study the regression lines of G. 689 tumida fall next to the multispecies regression lines of Anand et al. [2003] and Sagawa et al. 690 [2012]. However, especially slope and intercept of the Sagawa et al. [2012] regression differ 691 from those of our species-specific regression (Table 5) and it is important to note that the slope 692 affects the amplitude of temperature variations in paleorecords. The regression lines of G. 693 sacculifer, P. obliguiloculata and N. dutertrei deviate from previously published correlations 694 (Figure 5). Calcification temperatures of these species are exceptionally warm in the western 695 696 tropical Pacific Ocean despite deeper calcification depths and thus, G. sacculifer, P. obliquiloculata and N. dutertrei require regional, species-specific Mg/Ca-temperature 697 698 calibrations. Assuming the temperature sensitivity calculated by the multispecies approach (A = 0.097) our data indicate an intercept of B = 0.24 for G. sacculifer and an intercept of B =699 700 0.21 for both *P. obliquiloculata* and *N. dutertrei* (Figure 5).



702

Figure 5. Shell Mg/Ca versus calcification temperature for different planktic foraminifera species. Black bars indicate species-specific standard deviations of Mg/Ca. Black and colored dashed lines indicate regional multispecies and species-specific regressions calculated with a RMA regression (this study). Gray solid lines show published multispecies (large graph) and species-specific (small graphs) regression lines. Numbers denote published calibrations (see also table 5). Note that a, b and c refer to different calibrations in the same publication.

- 10)
- 710
- 711 **Table 5.** Multispecies and species-specific Mg/Ca temperature in comparison to previously

Reference	Species	Exponential relation Mg/Ca = B exp (A*Temperature)			
		A	В		
Anand et al. [2003] (1a)	multispecies	0.09	0.38		
<i>Sagawa et al.</i> [2011] (2)	multispecies	0.077	0.455		
Elderfield and Ganssen [2000] (3)	multispecies	0.1	0.352		
This study	multispecies	0.097	0.26		
Anand et al. [2003] (1b)	G. ruber	0.09	0.44		
McConnell and Thunell [2005] (4)	G. ruber	0.068	0.69		

published relations. Calibration numbers introduced in figure 5 are given in gray.

<i>Lea et al.</i> [2000] (5)	G. ruber	0.089	0.3
Dekens et al [2002] (6a)	G. ruber	0.09	0.38
This study	G. ruber	0.097	0.31
This study	G. elongatus	0.097	0.32
<i>Dekens et al.</i> [2002] (6b)	G. sacculifer	0.09	0.37
<i>Nürnberg et al.</i> [1996] (7)	G. sacculifer	0.089	0.39
<i>Nürnberg et al.</i> [2000] (8)	G. sacculifer	0.076	0.49
This study	G. sacculifer	0.097	0.24
Anand et al. [2003] (1c)	P. obliquiloculata	0.09	0.328
<i>Cléroux et al.</i> [2008] (9b)	P. obliquiloculata	0.039	1.02
This study	P. obliquiloculata	0.097	0.21
<i>Dekens et al.</i> [2002] (6c)	N. dutertrei	0.08	0.6
This study	N. dutertrei	0.097	0.21
<i>Cléroux et al.</i> [2008] (9a)	Deep dwelling species	0.052	0.78
Rickaby and Halloran [2005] (10)	G. tumida	0.09	0.53
<i>Regenberg et al.</i> [2009] (11)	G. tumida	0.041	1.23
<i>Mohtadi et al.</i> [2011] (12)	G. tumida	0.068	0.41
This study	G. tumida (355-425 µm)	0.097	0.33
This study	<i>G. tumida</i> (>425 μm)	0.097	0.31

A comparison of Mg/Ca-temperatures and calcification temperatures gives a measure of the uncertainty inherent in the Mg/Ca-temperature calibrations [*Anand et al.*, 2003]. We compared Mg/Ca-temperatures calculated by the application of species-specific calibrations to δ^{18} Oderived calcification temperatures (Figure 6). The average standard error between Mg/Ca and δ^{18} O-derived calcification temperatures is 0.5°C. The consistency of Mg/Ca and δ^{18} O-derived calcification temperatures validates our previous steps and assumptions, and gives further evidence, that Mg/Ca and δ^{18} O data are not influenced by secondary effects.



722 Figure 6. Consistency of temperature estimates. (a) Mg/Ca- versus δ^{18} O-derived calcification 723 temperatures. Mg/Ca-temperatures are based on species-specific regressions; δ^{18} O-724 temperatures were calculated with the equation of *Bemis et al.* [1998]. The black solid line 725 shows the correlation between Mg/Ca- and δ^{18} O-temperatures. For comparison, the 1:1 726 relationship is shown (stippled line). (b) Comparison of Mg/Ca-temperatures (filled symbols) 727 and δ^{18} O-temperatures (open symbols). Note that (a) includes only samples with paired δ^{18} O 728 and Mg/Ca measurements, whereas (b) includes all samples where δ^{18} O or Mg/Ca 729 measurements are available. Samples where only δ^{18} O or Mg/Ca measurements are available 730 are marked with stars. Sample numbers are related to cores as defined in Table S3. 731

733

5.4. Application of our Mg/Ca-temperature regression

734 Our species-specific equations were applied to convert Mg/Ca into temperature (Figure 7). While our regional Mg/Ca to temperature relations were established on the basis of only 735 samples for which we have δ^{18} O measurements and thereby direct estimates of foraminiferal 736 calcification depths at the respective core site, we applied the equations to all samples where 737 we measured Mg/Ca ratios (see. Table 1). Temperatures obtained from G. ruber and G. 738 elongatus match mixed layer temperatures. Mg/Ca temperatures of G. sacculifer correspond to 739 temperatures from the mixed layer bottom and uppermost thermocline. Mg/Ca temperatures 740 calculated from *P. obliquiloculata* and *N. dutertrei* reflect upper and those calculated from *G*. 741 742 tumida lower thermocline conditions. P. obliquiloculata and N. dutertrei are most suitable to

- track changes in NPTW and SPTW since they calcify at water depths corresponding to the core
- 744 of these water masses.
- 745



746 Figure 7. (a) Mg/Ca temperatures calculated by applying the newly established species-747 specific calibrations projected on CTD temperature profiles (grey lines). Horizontal bars denote 748 temperature errors, calculated following the method described in Mohtadi et al. [2014]. 749 Colored vertical bars indicate calcification depth ranges resulting from the application of our 750 species-specific Mg/Ca-temperature calibrations. (b) For comparison, we show shell δ^{18} O-751 derived calcification depth estimates for all species in combination. Gray lines indicate depth 752 profiles of predicted δ^{18} Oc calculated from CTD casts. Samples where only Mg/Ca or δ^{18} O 753 measurements are available are marked with stars. 754

756 6. Conclusions

We presented novel, paired Mg/Ca and δ^{18} O measurements on multispecies planktic foraminifera tests from accurately dated modern surface sediments in combination with water column data (CTD and δ^{18} O_{SW}) from the WPWP. Based on CTD salinity and δ^{18} O_{SW} we establish new δ^{18} O_{SW}-salinity regressions for surface (mixed layer) and subsurface (thermocline) waters (NPTW and SPTW) in the WPWP. Our data imply that it is reasonable to apply different δ^{18} O_{SW}-salinity regressions for surface and thermocline water masses. Due to very similar regression lines for the Philippines and PNG areas, individual regressions for sub(surface) waters from both areas can be combined into more robust equations representing the entire study area. These equations are $\delta^{18}O_{SW} = 0.37*S-12.4$ for surface and $\delta^{18}O_{SW} = 0.33*S-11.0$ for thermocline waters.

767

Shell δ^{18} O-derived estimates reveal that the calcification depths of planktic foraminifera 768 offshore the Philippines and offshore PNG are very similar. Our estimates match results from 769 other areas, and reveal that, also in the WPWP, G. ruber and G. elongatus reflect mixed layer 770 conditions (0-80 m), G. sacculifer reflects bottom of mixed layer and uppermost thermocline 771 conditions (45-85 m). P. obliquiloculata and N. dutertrei preserve upper (90-160 m) and G. 772 tumida lower thermocline conditions (230-265 m). Hence, our data imply that these species are 773 the best choice to reconstruct thermocline conditions in the WPWP. N. dutertrei inhabits a 774 slightly larger depth range than P. obliquiloculata in the WPWP. Therefore, P. obliquiloculata 775 might be more suitable to reconstruct the upper thermocline. Previous thermocline 776 reconstructions that are based on other species need to be reconsidered in face of the new 777 results. For example, shell δ^{18} O does not indicate different habitat depths for G. ruber and G. 778 *elongatus*. Hence, for the WPWP, the data do not support the use of G. ruber – G. elongatus 779 records to reconstruct variations in the vertical structure of the upper water column. 780

781

Our newly established regional multispecies Mg/Ca-temperature regression is within the range 782 of published multispecies and species-specific Mg/Ca-temperature calibrations (Mg/Ca = 0.26783 exp 0.097*T as calculated using reduced major axis regression). However, the Mg/Ca 784 temperature relation of most individual species is more accurately described by species-specific 785 calibrations. We find that the regional regressions for G. ruber, G. elongatus and G. tumida are 786 787 similar to the species-specific or multispecies equations published by Dekens et al. [2002] and Anand et al. [2003]. Calcification temperatures of G. sacculifer, P. obliquiloculata and N. 788 dutertrei are exceptionally warm in the western tropical Pacific and thus, require regional, 789 species-specific calibrations. The application of previously published calibrations would 790 underestimate the calcification temperatures of these species. Using a reduced major axis 791 regression we calculate the species-specific calibration Mg/Ca = $0.24 \exp 0.097$ *T for G. 792 sacculifer and Mg/Ca = 0.21 exp 0.097*T for P. obliquiloculata and N. dutertrei. Nevertheless, 793 further studies are needed to confirm the applicability of these calibrations for the open Pacific 794 Ocean and for paleo-reconstructions. 795

797 Acknowledgments

- 798 We would like to thank the captains, crews, and the scientific shipboard parties of expeditions
- ⁷⁹⁹ SO–228 and RR–1313. We thank Henning Kuhnert, Birgit Meyer-Schack and Ryan Bu for
- technical assistance. John Southon (UC Irvine) is acknowledged for performing radiocarbon
- 801 measurements. GeoB sample material was stored, curated and supplied by the GeoB Core
- 802 Repository at the MARUM Center for Marine Environmental Sciences, University of
- 803 Bremen, Germany. RR samples were provided by the Rutgers Core Repository. We thank two
- anonymous reviewers for their constructive comments, which helped to improve the quality of
- 805 our manuscript. The work is funded by the DFG-Research Center / Cluster of Excellence "The
- 806 Ocean in the Earth System", the BMBF project 03G0228A (EISPAC) and by the NSF project
- 807 OCE1131371. The data reported in this paper will be made available on Pangaea
- 808 (www.pangaea.de) and WDS (www.icsu-wds.org).
- 809

810 **References**

- Allen, K. A., B. Hönisch, S. M. Eggins, L. L. Haynes, Y. Rosenthal, and J. Yu (2016), Trace element proxies for
- 812 surface ocean conditions: A synthesis of culture calibrations with planktic foraminifera, *Geochimica et*
- 813 Cosmochimica Acta, 193, 197-221, doi:10.1016/j.gca.2016.08.015.
- Anand, P., H. Elderfield, and M. H. Conte (2003), Calibration of Mg/Ca thermometry in planktonic foraminifera
- from a sediment trap time series, *Paleoceanography*, *18*(2), 1050, doi:10.1029/2002PA000846.
- 816 Andreasen, D. J., and A. C. Ravelo (1997), Tropical Pacific Ocean thermocline depth reconstructions for the
- 817 Last Glacial Maximum, *Paleoceanography*, *12*(3), 395-413, doi:10.1029/97PA00822.
- 818 Arbuszewski, J., P. deMenocal, A. Kaplan, and E. C. Farmer (2010), On the fidelity of shell-derived
- δ^{18} Oseawater estimates, *Earth and Planetary Science Letters*, 300(3-4), 185-196,
- doi:10.1016/j.epsl.2010.10.035.
- 821 Aurahs, R., Y. Treis, K. Darling, and M. Kucera (2011), A revised taxonomic and phylogenetic concept for the
- 822 planktonic foraminifer species Globigerinoides ruber based on molecular and morphometric evidence, *Marine*
- 823 *Micropaleontology*, 79(1-2), 1-14, doi:10.1016/j.marmicro.2010.12.001.
- 824 Barker, S., M. Greaves, and H. Elderfield (2003), A study of cleaning procedures used for foraminiferal Mg/Ca
- paleothermometry, *Geochem Geophy Geosy*, 4(9), 8407, doi:10.1029/2003GC000559.
- 826 Beaufort, L., T. de Garidel-Thoron, A. C. Mix, and N. G. Pisias (2001), ENSO-like forcing on oceanic primary
- 827 production during the Late Pleistocene, *Science*, *293*(5539), 2440-2444, doi:10.1126/science.293.5539.2440.
- Bemis, B. E., H. J. Spero, J. Bijma, and D. W. Lea (1998), Reevaluation of the oxygen isotopic composition of
- 829 planktonic foraminifera: Experimental results and revised paleotemperature equations, *Paleoceanography*,
- 830 *13*(2), 150-160, doi:10.1029/98pa00070.
- 831 Berger, W. H., M. C. Bonneau, and F. L. Parker (1982), Foraminifera on the deep-sea floor: lysocline and 832 dissolution rate, *Oceanologica Acta*, *5*, 249-258.
- 833 Böhm, F., M. M. Joachimski, H. Lehnert, G. Morgenroth, W. Kretschmer, J. Vacelet, and W.-C. Dullo (1996),
- 834 Carbon isotope records from extant Caribbean and South Pacific sponges: Evolution of δ^{13} C in surface water
- Bolliet, T., A. Holbourn, W. Kuhnt, C. Laj, C. Kissel, L. Beaufort, M. Kienast, N. Andersen, and D. Garbe-
- Schonberg (2011), Mindanao Dome variability over the last 160 kyr: Episodic glacial cooling of the West
- Pacific Warm Pool, *Paleoceanography*, 26(1), PA1208, doi:10.1029/2010pa001966.
- Bouvier-Soumagnac, Y., and J. C. Duplessy (1985), Carbon and oxygen isotopic composition of planktonic
- foraminifera from laboratory culture, plankton tows and Recent sediment: implications for the reconstruction of
- paleoclimatic conditions and of the global carbon cycle, *Journal of Foraminiferal Research*, 15, 302-320.

- 842 Boyle, E. A., and L. D. Keigwin (1985), Comparison of Atlantic and Pacific paleochemical records for the last
- 215,000 years: changes in deep ocean circulation and chemical inventories, *Earth and Planetary Science Letters*, 76, 135-150.
- 845 Cléroux, C., E. Cortijo, P. Anand, L. Labeyrie, F. Bassinot, N. Caillon, and J.-C. Duplessy (2008), Mg/Ca and
- 846 Sr/Ca ratios in planktonic foraminifera: Proxies for upper water column temperature reconstruction,
- 847 *Paleoceanography*, 23(3), PA3214, doi:10.1029/2007pa001505.
- 848 Craig, H., and L. I. Gordon (1965), Deuterium and oxygen-18 variations in the ocean and the marine
- atmosphere, in *Stable isotope in oceanographic studies and paleotemperatures*, edited by E. Tongiorgi, pp. 9-
- 130, Spoleto, Pisa (Consiglio Nazionale delle Ricerche, Laboratorio di Geologia Nucleare).
- de Garidel-Thoron, T., Y. Rosenthal, L. Beaufort, E. Bard, C. Sonzogni, and A. C. Mix (2007), A multiproxy
- assessment of the western equatorial Pacific hydrography during the last 30 kyr, *Paleoceanography*, 22,
 PA3204, doi:3210.1029/2006PA001269.
- 254 Dekens, P. S., D. W. Lea, D. K. Pak, and H. J. Spero (2002), Core top calibration of Mg/Ca in tropical
- foraminifera: Refining paleotemperature estimation, *Geochemistry, Geophysics, Geosystems*, 3(4), 1022,
 doi:10.1029/2001GC000200.
- DiNezio, P. N., A. Clement, G. A. Vecchi, B. Soden, A. J. Broccoli, B. L. Otto-Bliesner, and P. Braconnot
- (2011), The response of the Walker circulation to Last Glacial Maximum forcing: Implications for detection in
 proxies, *Paleoceanography*, 26(3), PA3217, doi:10.1029/2010PA002083.
- Elderfield, H., and G. Ganssen (2000), Past temperature and δ^{18} O of surface ocean waters inferred from
- 861 foraminiferal Mg/Ca ratios, *Nature*, 405(6785), 442-445, doi:10.1038/35013033.
- Epstein, S., and T. Mayeda (1953), Variation of O¹⁸ content of waters from natural sources, *Geochimica et Cosmochimica Acta*, *4*, 213-224.
- 864 Evans, D., B. S. Wade, M. Henehan, J. Erez, and W. Müller (2016), Revisiting carbonate chemistry controls on
- 865 planktic foraminifera Mg / Ca: implications for sea surface temperature and hydrology shifts over the
- Paleocene–Eocene Thermal Maximum and Eocene–Oligocene transition, *Climate of the Past*, *12*(4), 819-835,
 doi:10.5194/cp-12-819-2016.
- 868 Fairbanks, R. G. (1982), The origin of Continental Shelf and Slope Water in the New York Bight of Maine:
- Evidence from $H_2^{18}O/H_2^{16}O$ Ratio Measurements, *Journal of Geophysical Research*, 87(C8), 5796-5808.
- Fairbanks, R. G., C. D. Charles, and J. D. Wright (1992), Origin of global meltwater pulses, in *Radiocarbon after four decades*, edited by R. E. Taylor, pp. 473-500, Springer Verlag.
- Fairbanks, R. G., M. N. Evans, J. L. Rubenstone, R. A. Mortlock, K. Broad, M. D. Moore, and C. D. Charles
- (1997), Evaluating climate indices and their geochemical proxies measured in corals, *Coral Reefs*, 16, 93-100.
- Farmer, E. C., A. Kaplan, P. B. de Menocal, and J. Lynch-Stieglitz (2007), Corroborating ecological depth
- preferences of planktonic foraminifera in the tropical Atlantic with the stable oxygen isotope ratios of core top
- 876 specimens, *Paleoceanography*, 22(3), doi:10.1029/2006PA001361.
- 877 Ferguson, J. E., G. M. Henderson, M. Kucera, and R. E. M. Rickaby (2008), Systematic change of foraminiferal
- 878 Mg/Ca ratios across a strong salinity gradient, *Earth and Planetary Science Letters*, 265(1-2), 153-166,
- 879 doi:10.1016/j.epsl.2007.10.011.
- 880 Fine, R. A., R. Lukas, F. M. Bingham, M. J. Warner, and R. H. Gammon (1994), The western equatorial Pacific
- a water mass crossroads, *Journal of Geophysical Research*, 99(C12), 25063-25080, doi:10.1029/94jc02277.
- Friedli, H., H. Lötscher, H. Oeschger, U. Siegenthaler, and B. Stauffer (1986), Ice core record of the ${}^{13}C/{}^{12}C$ ratio of atmospheric CO₂ in the past two centuries, *Nature*, *324*, 237-238.
- 884 Gagan, M. K., E. J. Hendy, S. G. Haberle, and W. S. Hantoro (2004), Post-glacial evolution of the Indo-Pacific
- Warm Pool and El Niño-Southern oscillation, *Quaternary International*, *118-119*, 127-143, doi:10.1016/s1040-6182(03)00134-4.
- Gordon, A. L. (1986), Interocean exchange of thermocline water, *Journal of Geophysical Research*, *91*(C4),
 5037, doi:10.1029/JC091iC04p05037.
- 889 Hertzberg, J. E., and M. W. Schmidt (2013), Refining *Globigerinoides ruber* Mg/Ca paleothermometry in the
- Atlantic Ocean, Earth and Planetary Science Letters, 383, 123-133, doi:10.1016/j.epsl.2013.09.044.
- 891 Higgins, H. W., D. J. Mackey, and L. Clementson (2006), Phytoplankton distribution in the Bismarck Sea north
- 692 of Papua New Guinea: The effect of the Sepik River outflow, *Deep-Sea Research Part I: Oceanographic*
- 893 *Research Papers*, *53*(11), 1845-1863, doi:10.1016/j.dsr.2006.09.001.
- Hönisch, B., K. A. Allen, D. W. Lea, H. J. Spero, S. M. Eggins, J. Arbuszewski, P. deMenocal, Y. Rosenthal, A.
- D. Russell, and H. Elderfield (2013), The influence of salinity on Mg/Ca in planktic foraminifers Evidence
- from cultures, core-top sediments and complementary δ^{18} O, *Geochimica et Cosmochimica Acta*, 121, 196-213,
- doi:10.1016/j.gca.2013.07.028.
- 898 Hut, G. (1987), Consultants group meeting on stable isotopic reference samples for geochemical and
- 899 hydrological investigations, edited, p. 42, International Atomic Energy Agency, Vienna.
- 900 Isobe, T., E. D. Feigelson, M. G. Akritas, and G. J. Babu (1990), Linear Regression in Astronomy I., The
- 901 Astrophysical Journal, 364, 104-113.

- Kawahata, H. (2005), Stable isotopic composition of two morphotypes of Globigerinoides ruber (white) in the subtropical gyre in the North Pacific, *Paleontological Research*, *9*(1), 27-35.
- 904 Kawahata, H., A. Nishimura, and M. K. Gagan (2002), Seasonal change in foraminiferal production in the
- 905 western equatorial Pacific warm pool: evidence from sediment trap experiments, Deep-Sea Research Part II:
- 906 *Topical Studies in Oceanography*, 49(13-14), 2783-2800, doi:10.1016/S0967-0645(02)00058-9.
- 807 Kim, S.-T., and J. R. O'Neil (1997), Equilibrium and nonequilibrium oxygen isotope effects in synthetic
- 908 carbonates, *Geochim Cosmochim Ac*, *61*(16), 3461-3475, 10.1016/s0016-7037(97)00169-5.
- 909 Kısakürek, B., A. Eisenhauer, F. Böhm, D. Garbe-Schönberg, and J. Erez (2008), Controls on shell Mg/Ca and
- 910 Sr/Ca in cultured planktonic foraminiferan, *Globigerinoides ruber* (white), *Earth and Planetary Science Letters*, 911 272(2,4), 260, 260, doi:10.1016/j.arel.2008.06.026
- 911 273(3-4), 260-269, doi:10.1016/j.epsl.2008.06.026.
- 912 Kuroyanagi, A., and H. Kawahata (2004), Vertical distribution of living planktonic foraminifera in the seas
- 913 around Japan, *Marine Micropaleontology*, 53(1-2), 173-196, DOI 10.1016/j.marmicro.2004.06.001.
- Lea, D. W., T. A. Mashiotta, and H. J. Spero (1999), Controls on magnesium and strontium uptake in planktonic
- 915 foraminifera determined by live culturing, *Geochimica Et Cosmochimica Acta*, 63(16), 2369-2379,
- 916 doi:10.1016/S0016-7037(99)00197-0.
- Lea, D. W., D. K. Pak, and H. J. Spero (2000), Climate impact of late quaternary equatorial pacific sea surface
 temperature variations, *Science*, 289(5485), 1719-1724.
- 919 Leech, P. J., J. Lynch-Stieglitz, and R. Zhang (2013), Western Pacific thermocline structure and the Pacific
- 920 marine Intertropical Convergence Zone during the Last Glacial Maximum, *Earth and Planetary Science Letters*,
- 921 *363*, 133-143, doi:10.1016/j.epsl.2012.12.026.
- 922 LeGrande, A. N., and G. A. Schmidt (2006), Global gridded data set of the oxygen isotopic composition in
- seawater, *Geophysical Research Letters*, 33(12), doi:10.1029/2006gl026011.
- 924 LeGrande, A. N., and G. A. Schmidt (2011), Water isotopologues as a quantitative paleosalinity proxy,
- 925 *Paleoceanography*, 26(3), doi:10.1029/2010pa002043.
- Locarnini, R. A., et al. (2013), *World Ocean Atlas 2013, Volume 1: Temperature.*, U.S. Government Printing
 Office, Washington, D.C.
- Dentec, Washington, D.C.
 Lončarić, N., F. J. C. Peeters, D. Kroon, and G.-J. A. Brummer (2006), Oxygen isotope ecology of recent
- 929 planktic foraminifera at the central Walvis Ridge (SE Atlantic), *Paleoceanography*, 21(3),
- 930 doi:10.1029/2005pa001207.
- Martin, P. A., and D. W. Lea (2002), A simple evaluation of cleaning procedures on fossil benthic foraminiferal
 Mg/Ca, *Geochem Geophy Geosy*, 3(10), 1-8, doi:10.1029/2001gc000280.
- 933 Mathien-Blard, E., and F. Bassinot (2009), Salinity bias on the foraminifera Mg/Ca thermometry: Correction
- 934 procedure and implications for past ocean hydrographic reconstructions, *Geochemistry, Geophysics*,
- 935 *Geosystems*, 10(12), doi:10.1029/2008gc002353.
- 936 McConnell, M. C., and R. C. Thunell (2005), Calibration of the planktonic foraminiferal Mg/Ca
- paleothermometer: Sediment trap results from the Guaymas Basin, Gulf of California, *Paleoceanography*,
 20(2), doi:10.1029/2004pa001077.
- 939 Mohtadi, M., S. Steinke, J. Groeneveld, H. G. Fink, T. Rixen, D. Hebbeln, B. Donner, and B. Herunadi (2009),
- 940 Low-latitude control on seasonal and interannual changes in planktonic foraminiferal flux and shell
- geochemistry off south Java: A sediment trap study, *Paleoceanography*, 24(1), PA1201,
- 942 doi:10.1029/2008pa001636.
- 943 Mohtadi, M., D. W. Oppo, A. Luckge, R. DePol-Holz, S. Steinke, J. Groeneveld, N. Hemme, and D. Hebbeln
- 944 (2011), Reconstructing the thermal structure of the upper ocean: Insights from planktic foraminifera shell
- chemistry and alkenones in modern sediments of the tropical eastern Indian Ocean, *Paleoceanography*, 26(3),
 PA3219, doi:10.1029/2011pa002132.
- 947 Mohtadi, M., M. Prange, D. W. Oppo, R. De Pol-Holz, U. Merkel, X. Zhang, S. Steinke, and A. Luckge (2014),
- North Atlantic forcing of tropical Indian Ocean climate, *Nature*, *509*(7498), 76-80, doi:10.1038/nature13196.
- 949 Mohtadi, M., et al. (2013), Report and preliminary results of RV SONNE cruise SO-228, Kaohsiung-
- 950 Townsville, 04.05.2013- 23.06.2013, EISPAC-WESTWIND-SIODP. Berichte aus dem MARUM und dem
- 951 Fachbereich Geowissenschaften der Universität Bremen, 295, 110 pp. urn:nbn:de:gbv:46-00103343-13.
- 952 Morimoto, M. (2002), Salinity records for the 1997–98 El Niño from Western Pacific corals, *Geophysical*
- 953 Research Letters, 29(11), doi:10.1029/2001gl013521.
- 954 Mulitza, S., D. Boltovskoy, B. Donner, H. Meggers, A. Paul, and G. Wefer (2003), Temperature:δ¹⁸O
- relationships of planktonic foraminifera collected from surface waters, *Palaeogeography, Palaeoclimatology, Palaeoecology, 202*(1-2), 143-152, doi:10.1016/s0031-0182(03)00633-3.
- 957 Niebler, H.-S., H.-W. Hubberten, and G. Gersonde (1999), Oxygen isotope values of planktic foraminifera: a
- 958 tool for the reconstruction of surface water stratification, in *Use of Proxies in Paleoceanography: Examples*
- *from the South Atlantic*, edited by G. Fischer and G. Wefer, pp. 165-189, Springer-Verlag, Berlin, Heidelberg.
- 960 Nürnberg, D., J. Bijma, and C. Hemleben (1996), Assessing the reliability of magnesium in foraminiferal calcite
- as a proxy for water mass temperatures, *Geochimica et Cosmochimica Acta*, 60(5), 803-814.

- 962 Nürnberg, D., A. Müller, and R. R. Schneider (2000), Paleo-sea surface temperature calculations in the
- 963 equatorial east Atlantic from Mg/Ca ratios in planktic foraminifera: A comparison to sea surface temperature
- 964 estimates from Uk37, oxygen isotopes, and foraminiferal transfer function, Paleoceanography, 15(1), 124-134, 965 10.1029/1999PA000370.
- 966 Patrick, A., and R. C. Thunell (1997), Tropical Pacific sea surface temperatures and upper water column thermal
- 967 structure during the Last Glacial Maximum, Paleoceanography, 12(5), 649-657, doi:10.1029/97pa01553.
- 968 Peeters, F. J. C., G.-J. A. Brummer, and G. Ganssen (2002), The effect of upwelling on the distribution and
- 969 stable isotope composition of Globigerina bulloides and Globigerinoides ruber (planktic foraminifera) in
- 970 modern surface waters of the NW Arabian Sea, Global and Planetary Change, 34(3-4), 269-291,
- 971 doi:10.1016/S0921-8181(02)00120-0.
- Radenac, M.-H., and M. Rodier (1996), Nitrate and chlorophyll distributions in relation to thermohaline and 972
- 973 current structures in the western tropical Pacific during 1985-1989, Deep Sea Research Part II: Topical Studies 974 in Oceanography, 4-6, 725-752.
- 975 Radenac, M. H., F. Leger, M. Messie, P. Dutrieux, C. Menkes, and G. Eldin (2016), Wind-driven changes of
- 976 surface current, temperature, and chlorophyll observed by satellites north of New Guinea, J Geophys Res-977 Oceans, 121(4), 2231-2252, 10.1002/2015JC011438.
- 978 Ravelo, A. C., and C. Hillaire-Marcel (2007), Chapter Eighteen The Use of Oxygen and Carbon Isotopes of 979
- Foraminifera in Paleoceanography, 1, 735-764, doi:10.1016/s1572-5480(07)01023-8.
- 980 Regenberg, M., S. Steph, D. Nürnberg, R. Tiedemann, and D. Garbe-Schönberg (2009), Calibrating Mg/Ca
- 981 ratios of multiple planktonic foraminiferal species with δ^{18} O-calcification temperatures: Paleothermometry for
- 982 the upper water column, Earth and Planetary Science Letters, 278(3-4), 324-336,
- 983 doi:10.1016/j.epsl.2008.12.019.
- 984 Regoli, F., T. de Garidel-Thoron, K. Tachikawa, Z. Jian, L. Ye, A. W. Droxler, G. Lenoir, M. Crucifix, N.
- 985 Barbarin, and L. Beaufort (2015), Progressive shoaling of the equatorial Pacific thermocline over the last eight glacial periods, Paleoceanography, 30(5), 439-455, doi:10.1002/2014pa002696. 986
- 987 Rickaby, R. E. M., and P. Halloran (2005), Cool La Niña During the Warmth of the Pliocene?, Science,
- 988 307(5717), 1948-1952, doi:10.1126/science.1104666.
- 989 Rippert, N., D. Nürnberg, J. Raddatz, E. Maier, E. Hathorne, J. Bijma, and R. Tiedemann (2016), Constraining
- 990 foraminiferal calcification depths in the western Pacific warm pool, Marine Micropaleontology, 128, 14-27, 991 doi:10.1016/j.marmicro.2016.08.004.
- 992 Rosenthal, Y., and G. P. Lohmann (2002), Accurate estimation of sea surface temperatures using dissolution-
- 993 corrected calibrations for Mg/Ca paleothermometry, Paleoceanography, 17(3), 16-11-16-16, 1044, 994 10.1029/2001pa000749.
- 995 Rosenthal, Y., E. A. Boyle, and N. Slowey (1997), Temperature control on the incorporation of magnesium,
- 996 strontium, fluorine, and cadmium into benthic foraminiferal shells from Little Bahama Bank: Prospects for
- 997 thermocline paleoceanography, Geochimica Et Cosmochimica Acta, 61(17), 3633-3643, doi:10.1016/S0016-998 7037(97)00181-6.
- 999 Rosenthal, Y., M. P. Field, and R. M. Sherrell (1999), Precise determination of element/calcium ratios in
- 1000 calcareous samples using sector field inductively coupled plasma mass spectrometry, Analytical Chemistry, 1001 71(15), 3248-3253, doi:10.1021/AC981410x.
- 1002 Rosenthal, Y., et al. (2004), Interlaboratory comparison study of Mg/Ca and Sr/Ca measurements in planktonic
- 1003 for aminifera for paleoceanographic research, Geochem Geophy Geosy, 5, doi:10.1029/2003GC000650.
- 1004 Russell, A. D., B. Hönisch, H. J. Spero, and D. W. Lea (2004), Effects of seawater carbonate ion concentration
- 1005 and temperature on shell U, Mg, and Sr in cultured planktonic foraminifera, Geochimica et Cosmochimica Acta, 1006 68(21), 4347-4361, 10.1016/j.gca.2004.03.013.
- 1007 Sagawa, T., Y. Yokoyama, M. Ikehara, and M. Kuwae (2012), Shoaling of the western equatorial Pacific
- 1008 thermocline during the last glacial maximum inferred from multispecies temperature reconstruction of
- 1009 planktonic foraminifera, Palaeogeography, Palaeoclimatology, Palaeoecology, 346-347, 120-129,
- 1010 doi:10.1016/j.palaeo.2012.06.002.
- 1011 Schlitzer, R. (2014), Ocean Data View, odv.awi.de, edited.
- 1012 Shackleton, N. (1974), Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera
- 1013 genus Uvigerina: Isotopic changes in the ocean during the last glacial, in Les méthodes quantitatives d'étude des
- 1014 variations du climat au cours du Pléistocène, edited by L. Labeyrie, pp. 203-209, CNRS, Paris.
- 1015 Spero, H. J., K. M. Mielke, E. M. Kalve, D. W. Lea, and D. K. Pak (2003), Multispecies approach to
- 1016 reconstructing eastern equatorial Pacific thermocline hydrography during the past 360 kyr, *Paleoceanography*,
- 1017 18(1), doi:10.1029/2002PA000814.
- 1018 Spero, H. J., S. M. Eggins, A. D. Russell, L. Vetter, M. R. Kilburn, and B. Hönisch (2015), Timing and
- 1019 mechanism for intratest Mg/Ca variability in a living planktic foraminifer, Earth and Planetary Science Letters,
- 409, 32-42, 10.1016/j.epsl.2014.10.030. 1020

- 1021 Steinke, S., H.-Y. Chiu, P.-S. Yu, C.-C. Shen, L. Löwemark, H.-S. Mii, and M.-T. Chen (2005), Mg/Ca ratios of
- 1022 two *Globigerinoides ruber* (white) morphotypes: Implications for reconstructing past tropical/subtropical
- 1023 surface water conditions, *Geochemistry, Geophysics, Geosystems*, 6(11), doi:10.1029/2005gc000926.
- 1024 Steph, S., M. Regenberg, R. Tiedemann, S. Mulitza, and D. Nürnberg (2009), Stable isotopes of planktonic
- 1025 for a from tropical Atlantic/Caribbean core-tops: Implications for reconstructing upper ocean
- 1026 stratification, *Marine Micropaleontology*, 71(1-2), 1-19, doi:10.1016/j.marmicro.2008.12.004.
- 1027 Tachikawa, K., A. Timmermann, L. Vidal, C. Sonzogni, and O. E. Timm (2014), CO₂ radiative forcing and
- 1028 Intertropical Convergence Zone influences on western Pacific warm pool climate over the past 400 ka,
- 1029 *Quaternary Science Reviews*, 86(0), 24-34, doi:10.1016/j.quascirev.2013.12.018.
- 1030 Thirumalai, K., J. N. Richey, T. M. Quinn, and R. Z. Poore (2014), Globigerinoides ruber morphotypes in the
- 1031 Gulf of Mexico: a test of null hypothesis, *Scientific reports*, *4*, 6018, doi:10.1038/srep06018.
- Thunell, R., E. Tappa, C. Pride, and E. Kincaid (1999), Sea-surface temperature anomalies associated with the
 1997/1998 El Niño recorded in the oxygen isotope composition of planktonic foraminifera, *Geology*, 27(9), 843846.
- 1035 Tsuchiya, M., R. Lukas, and R. Fine (1989), Source Waters of the Pacific Equatorial Undercurrent, *Progress in* 1036 *Oceanography*, 23, 46.
- 1037 van Geldern, R., and J. A. C. Barth (2012), Optimization of instrument setup and post-run corrections for
- 1038 oxygen and hydrogen stable isotope measurements of water by isotope ratio infrared spectroscopy (IRIS),
- 1039 *Limnology and Oceanography: Methods*, *10*(12), 1024-1036, doi:10.4319/lom.2012.10.1024.
- 1040 Vecchi, G. A., B. J. Soden, A. T. Wittenberg, I. M. Held, A. Leetmaa, and M. J. Harrison (2006), Weakening of
- 1041 tropical Pacific atmospheric circulation due to anthropogenic forcing, *Nature*, *441*(7089), 73-76,
- 1042 doi:10.1038/nature04744.
- 1043 Wang, L. J. (2000), Isotopic signals in two morphotypes of *Globigerinoides ruber* (white) from the South China
- Sea: implications for monsoon climate change during the last glacial cycle, *Palaeogeogr Palaeocl*, *161*(3-4), 381-394, doi:10.1016/S0031-0182(00)00094-8.
- 1046 Watkins, J. M., A. C. Mix, and J. Wilson (1996), Living planktic foraminifera: Tracers of circulation and
- productivity regimes in the central equatorial Pacific, *Deep Sea Research Part II: Topical Studies in Oceanography*, 43(4-6), 26.
- 1049 Xu, J. A., W. Kuhnt, A. Holbourn, M. Regenberg, and N. Andersen (2010), Indo-Pacific Warm Pool variability
- 1050 during the Holocene and Last Glacial Maximum, Paleoceanography, 25(4), PA4230,
- 1051 doi:10.1029/2010PA001934.
- 1052 Yamasaki, M., A. Sasaki, M. Oda, and H. Domitsu (2008), Western equatorial Pacific planktic foraminiferal
- 1053 fluxes and assemblages during a La Niña year (1999), Marine Micropaleontology, 66(3-4), 304-319,
- 1054 doi:10.1016/j.marmicro.2007.10.006.
- 1055 Zenk, W., G. Siedler, A. Ishida, J. Holfort, Y. Kashino, Y. Kuroda, T. Miyama, and T. J. Müller (2005),
- Pathways and variability of the Antarctic Intermediate Water in the western equatorial Pacific Ocean, *Progress in Oceanography*, 67, 245-281, doi:10.1016/j.pocean.2005.05.003.
- 1058 Zweng, M. M., et al. (2013), World Ocean Atlas 2013, Volume 2: Salinity, Washington, D.C.
- 1059