https://doi.org/10.5194/egusphere-2022-711
Preprint. Discussion started: 22 August 2022

Calcification response of planktic foraminifera to environmental change in the Western Mediterranean Sea during the industrial era

Thibauld M. Béjard[1*], Andrés S. Rigual-Hernández[1], José A. Flores[1], Javier P. Tarruella[1], Xavier Durrieu de Madron[2], Isabel Cacho[3], Neghar Haghipour[4], Timothy Eglinton[4], Francisco J. Sierro[1]

1. Area de Paleontología, Departamento de Geología, Universidad de Salamanca, 37008 Salamanca, Spain
2. Université de Perpignan Via Domitia, CNRS, CEFREM, Perpignan, France
3. GRC Geociències Marines, Departament de Dinàmica de la Terra i de l'Oceà, Facultat de Ciències de la Terra, Universitat de Barcelona, Barcelona, Spain
4. Earth Sciences Department, ETH Zurich, Zurich, 8092, Switzerland

* *Corresponding author:* Area de Paleontología, Departamento de Geología, Universidad de Salamanca, 37008, Salamanca, Spain. *E-mail address*: thibauld.bejard@usal.es.

Abstract

The aim of this work is to investigate the variability of planktic foraminifera calcification in the northwestern Mediterranean Sea on seasonal, interannual and pre-industrial Holocene time scales. This study is based on data from a 12-year-long sediment trap record retrieved in the in the Gulf of Lions and seabed sediment samples from the Gulf of Lions and the promontory of Menorca. Three different planktic foraminifera species were selected based on their different ecology and abundance: *Globigerina bulloides*, *Neogloboquadrina incompta,* and *Globorotalia truncatulinoides*. A total of 273 samples were weighted in both sediment trap and seabed samples. As the traditionally used sieve fractions method is considered unreliable because of the effect of morphometric parameters on the foraminifera weight, we measured area and diameter to constrain the effect of these parameters. The results of our study show substantial different seasonal calcification patterns across species: *G. bulloides* showed a slight calcification increase during the high productivity period, while both *N. incompta* and *G. truncatulinoides* display a higher calcification during the low productivity period. The comparison of these patterns with environmental parameters revealed that Optimum Growth Conditions temperature and carbonate system parameters are the most likely to influence seasonal calcification in the Gulf of Lions. Interannual analysis suggest that both *G. bulloides* and *N. incompta* slightly reduced their calcification between 1994 and

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2005, while *G. truncatulinoides* exhibited a constant and pronounced increase in its calcification that translated in an increase of 20% of its shell weight for the 400-500 μm narrow size class. While our data suggest that carbonate system parameters are the most likely environmental parameter driving foraminifera calcification changes over the years.
Finally, comparison between sediment trap data and seabed sediments allowed us to assess the changes of planktic foraminifera calcification during the late Holocene, including the preindustrial era. Several lines of evidence strongly indicate that selective dissolution did not bias the results in any of our data sets. Our results showed a clear calcification reduction between pre-industrial Holocene and recent data with *G. truncatulinoides* experiencing the largest calcification decrease (32-40%) followed by *N. incompta* (20-27%) and *G. bulloides* (18-24%). Overall, our results provide evidence of clear reduction in planktic foraminifera calcification in the Mediterranean most likely associated with ongoing ocean acidification and consistent with previous observations in other settings of the world's oceans.

Key words: Planktic foraminifera, foraminifera calcification, biogeochemical cycles, Ocean Acidification, Mediterranean Sea.

1. Introduction

Growing population and its linked human activity since the industrial period (about 170 years ago) has caused an unprecedented rise in carbon dioxide, which ecological and economic consequences are considered a major threat (Ipcc, 2022)7/28/22 6:12:00 PM. Atmospheric CO_2 concentrations during the Pleistocene and Holocene ranged from 200 to 280 parts per million (ppm) (Loulergue et al., 2007; Lüthi et al., 2008; Parrenin et al., 2007), but these values have increased dramatically since the onset of the industrial period, exceeding the threshold of 400 ppm in 2015 for the first time for at least the last 800.000 years (Lüthi et al., 2008). Between 25 and 30% of anthropogenic CO_2 has been absorbed by the world's ocean (Sabine et al., 2004). The ocean uptake of atmospheric CO_2 causes a drop in both pH and carbonate ion concentration (Barker et al., 2012), lowering seawater alkalinity; this process is commonly known as Ocean Acidification (OA), and it is expected to affect all areas of the ocean and to have a wide impact on marine life (Hemleben et al., 1989). One of the main questions about recent environmental change is how different ecosystems and regions in global ocean are going to react to the ongoing increase of anthropogenic atmospheric carbon dioxide.
A large body of evidence indicates that ocean acidification has substantial and diverse effects on the distribution and fitness of a wide range of marine organisms

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(Jonkers et al., 2019; Kroeker et al., 2013; Meier et al., 2014; Moy et al., 2009). For example, some fleshy algae and diatom species have been shown to increase their growth and photosynthetic activity at enhanced CO_2 concentrations (Kroeker et al., 2013). In turn, most calcifying organisms such as calcifying algae, corals, pteropods, coccolithophores and foraminifera are negatively affected by this process often showing a reduction in their abundance, calcification and growth rates (Kroeker et al., 2013; Orr et al., 2005).

Planktic foraminifera are a group of marine single-celled protozoans that produce calcareous shells. Their distribution across the water column is conditioned by factors that include, but are not limited to, food availability, temperature, salinity and sunlight (Schiebel and Hemleben, 2005). These organisms are considered to play a key role in marine carbon cycle and carbonate production, accounting for between 32 and 80% of the deep ocean calcite fluxes (Schiebel, 2002). Depending on their ecology and feeding strategies, these organisms can be algal (dinoflagellates) symbiont wearing or not symbiont wearing and be spinose or non-spinose. Planktic foraminifera represent a useful tool for palaeoecological and palaeoceanographic studies, as the abundances of different species and their geochemical signature allow reconstructing sea surface temperatures and water column physical and chemical properties (Lirer et al., 2014; Margaritelli, 2020; Schiebel and Hemleben, 2017).

Previous studies suggest that planktic foraminifera are sensitive to ocean acidification (OA). Laboratory experiments indicate that when carbonate ion concentration decreases, shell weight and calcification decrease too in a variety of species (Bijma et al., 2002; Lombard et al., 2011). Species that host symbionts have been described showing a higher tolerance to dissolution due to the capacity of algal symbionts to alter immediate seawater chemistry (Lombard et al., 2009). Moy et al. (2009) documented a decrease of 30-35% shell weight in the planktic foraminifera *Globigerina bulloides* during the industrial era (defined according to Sabine et al., 2004 from 1800 and therein) in the subantarctic Southern Ocean, most likely induced by anthropogenic-driven ocean acidification. A recent study by Fox et al. (2020) showed that non-spinose (*Neogloboquadrina dutertrei*) foraminifera species exhibit a more pronounced calcification reduction than the spinose (*Globigerinoides ruber*) species in response to increasing CO_2. The main difficulty for studying the impact of OA on foraminifera (and any calcifying organisms) resides in finding long-term continuous records in order to be able to evaluate possible changes in shell calcification (Fox et al., 2020).

The Mediterranean Sea is a semi-enclosed sea with a high saturation state for calcite (Álvarez et al., 2014). Moreover, the Mediterranean is also recognized as a sensitive region increasing atmospheric CO_2 (Ziveri, 2012) due to the fast turnover time of its

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waters (Béthoux et al., 2005) and the fast penetration of anthropogenic CO_2 (Schneider et al., 2010). Sea surface temperatures are predicted to increase by 1.5-2°C by the end of the century, a faster rate than the global average (Lazzari et al., 2014). pH is expected to decrease according to the global average (0.3-0.4 units by 2100) or even exceed the global trend (Hassoun et al., 2015). The Mediterranean Sea is also affected by other stressors (Durrieu de Madron et al., 2011) which impact marine organisms in many ways (Lejeusne et al., 2009). Finally, it is also a region shaped by human development and its associated activities interact with environmental changes (MedECC).

In order to assess the impact of recent environmental change on planktic foraminifera, in this work we present data from Planier sediment trap (data from 1993 to 2006) (Rigual-Hernández et al., 2012) and from seabed sediments from three different sites located in both the Gulf of Lions and the promontory of Menorca. The advantage of sediment traps is that they provide data coming from annual fluxes, avoiding the effects of seasonal abundance and ontogeny and making interannual comparisons more reliable (Jonkers et al., 2019). Three different planktic foraminifera species, each of which characterized by contrastingly different depth habitats and ecologies, were selected for our analysis: *Globigerina bulloides,* a spinose opportunist surface dweller that lies above the thermocline (Schiebel and Hemleben, 2014); *Neogloboquadrina incompta,* a non-spinose temperate surface dweller; and *Globorotalia truncatulinoides,* a non-spinose deep dwelling species which migrates through the water column with a complex life cycle. Our aims for this study are: (i) to compare two widely used foraminifera weighing and size-normalization techniques and provide a baseline of modern foraminifera weight data and calcification in the Western Mediterranean against which future changes in foraminifera calcification can be assessed (ii) document seasonal and interannual trends in the planktic foraminifera calcification of the three planktic foraminifera species, and (iii) evaluate possible changes in shell calcification through the Holocene to the present day by comparing shell weights of the foraminifera collected by the traps with those of the seafloor sediments.

2. Study area

The Mediterranean is a semi-enclosed sea and it is considered a concentration basin (Bethoux et al., 1999) with a negative hydrological budget: fresh water inputs do not compensate the overall basin evaporation. The surface oceanic waters that enter the Mediterranean through the Strait of Gibraltar and spread towards the eastern basin compensate this negative balance. As described by Millot (1999), the thermo-haline properties of the inflowing Atlantic Waters (AW) are gradually modified in their

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transit towards the Algerian Coast in the form of the Atlantic-Ionian Stream (AIS). The AIS divides into two main branches off the western coast of Sicily: one flows south of Sicily (Béranger et al., 2004) heading towards the Eastern Mediterranean Basin, and the other one enters the Tyrrhenian Sea along the northern coast of Sicily, forming the Tyrrhenian Current (TC) (Figure 1a). The Corsica Channel represents the choke point for water circulation in the Northwestern Mediterranean through which waters of the Tyrrhenian flow into the Ligurian Sea, where the Northern Current (NC) is formed. The NC largely controls the circulation all over the western and northwestern part of the Mediterranean Sea, including the Gulf of Lions and the Balearic Sea (Figure 1a).

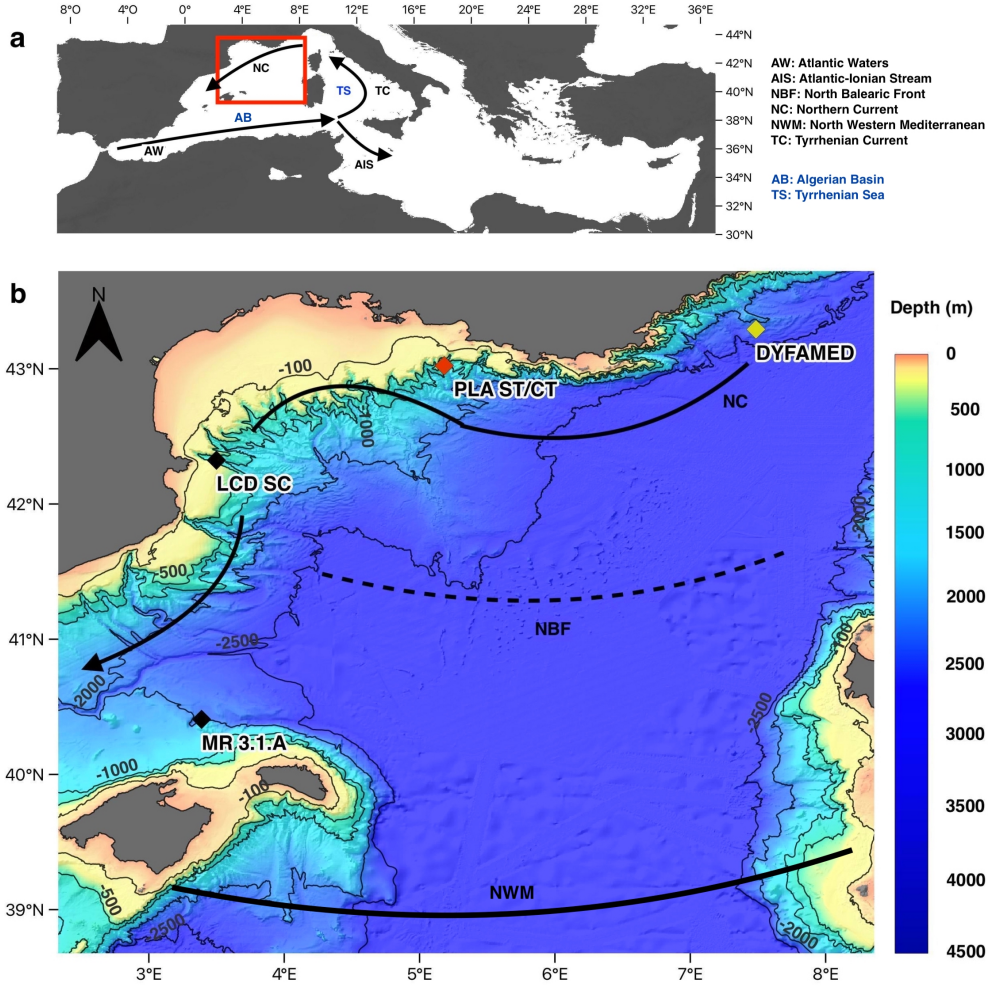

Figure 1. a. Study area location in the Mediterranean Sea and general surface circulation **b.** geographic setting of the Gulf of Lions and location of

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studied sites. Red diamond shows the position of the Planier site sediment trap and core-top (PLA ST/CT). Black diamonds represent the location of the seabed sediments samples analyzed from Lacaze Duthiers canyon (LCD SC) and Menorca promontory (MR 3.1A). Yellow diamond represents the location of the Dynamics of Atmospheric Fluxes in the MEDiterranean Sea (DYFAMED) site, located 200 km upstream Planier station position. Arrows represent the surface circulation (Millot, 1999).

The Gulf of Lions (GoL) is located in the northwestern part of the Mediterranean Sea, and its morphology presents a continental slope with an array of complex submarine canyons (Rigual-Hernández et al., 2012) (Figure 1b). As previously stated, the general circulation is controlled by the counterclockwise NC flowing along the continental slope (Millot, 1991).

Vertical mixing, generated by intense surface cooling and evaporation, occurs in winter in the Gulf of Lions driven by cold, dry northern winds, resulting in dense water on the shelf and offshore (Durrieu de Madron et al., 2005; Houpert et al., 2016; Millot, 1991). This winter mixing recharges surface waters with nutrients. This enrichment with increased solar radiation stimulates primary production in spring. Increasing heat fluxes during spring and summer cause water mass stratification and nutrient depletion, which lasts until late summer, until fall cooling breaks the stratification of the water column and causes a fall bloom (Heussner et al., 2006; Monaco et al., 1999; Rigual-Hernández et al., 2012). River inputs are the main source of suspended particles in the Gulf of Lions, and the Rhone river represents the most important river in the northwestern Mediterranean; however, other sources include Saharan dust deposits and biological production (Heussner et al., 2006; Monaco et al., 1999). Overall, the oceanographic setting of the Gulf of Lions is an exception to the general oligotrophy of the Mediterranean Sea.

3. Material and methods

3.1. Sediment traps, core-tops and sediment cores.

A series of deployments of sediment traps mooring lines in the Gulf of Lions continental margin was initiated in 1993 within the framework of several French and European projects (PNEC, Euromarge-NB, MTP II-MATER, EUROSTRATAFORM) and the monitoring of two sites, Planier and Lacaze-Duthiers stations (Figure 1), continues as a component of the MOOSE project (Mediterranean Ocean Observing System for the Environment). Planier station (43°02'N, 5°18'E) is located at the northeastern end of the Gulf of Lions, in the axis of the Planier Canyon. The sediment trap used for this work was located at around 530 m water depth in a water column

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of ~1000 m. Further details of the mooring design can be found in Heussner et al., 2006. The characterization and quantification of planktic foraminifera fluxes for the period 1993 to 2006 were analyzed by Rigual-Hernández et al., 2012. Here, we used the samples from the latter study for our weight and calcification analysis. This sediment trap is used here as a baseline of the planktic foraminifera dwelling in the modern Mediterranean Sea. Moreover, we analyzed a set of core top and sediment cores collected from several locations of the Northwestern Mediterranean that are considered to represent foraminifera assemblages sedimented during the pre-industrial Holocene era (Table 1).

Table 1: description of the core tops used in this study. Data for PLA CT and LCD SC are available in Heussner et al., (2006), and data concerning MR 3.1.A can be found in Cisneros et al., (2016). Conventional ^{14}C ages and 1-sigma uncertainties have been rounded according to convention.

Site	Location	Water depth (m)	Sediment Samples	Dating method	Species	Sample dated	Radiocarbon age (^{14}C years BP)	1-sigma error (^{14}C years)
Planier (PLA CT)	42.989° N 5.121° E	1095	2	^{14}C	*Globigerina bulloides*	0.5-1 cm	490	60
Lacaze-Duthiers (LCD SC)	42.2656°N 3.54°E	990	7	^{14}C	*Globigerina bulloides*	0.5-1 cm	460	60
Minorca (MR 3.1.A)	40.29°N 3.37° E	2117	40	^{14}C	*Globigerina bulloides*	14-14.5 cm	1980	65

3.2. Sediment core samples processing

A total of 2 sediment samples from Planier core top, 7 from Lacaze-Duthiers sediment core and 40 from Minorca sediment core were weighed (Table 1). Dry bulk sediment samples from all sites was weighed using a Sartorius CP124S balance (precision= 0.1mg).

The samples were then wet-sieved in order to separate the <63μm fraction and dry sieved to separate the bigger fractions (>150 μm and >300 μm). The sediment washing was carried out with potassium phosphate-buffered solution (pH= 7.5) in order to optimize foraminifera preservation. Each fraction was oven dried at a constant temperature (50°C) and then weighed. The >150 μm fraction was used for identification, counting and shell morphometric and weight analyses.

3.3. Foraminifera picking and mass and size estimations

Planktic foraminifera picking focused on three species: *Globigerina bulloides, Neogloboquadrina incompta* and *Globorotalia truncatulinoides.* For the latter species, both coiling morphotypes were selected although the right coiling was substantially less abundant representing less than 3% in our counts, a feature

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consistent with the literature that indicates a low presence of right coiled specimens (Margaritelli et al., 2020; 2022). Different sizes were selected depending on the maximum availability of each species: 250-300, 200-250 and 400-500 μm, for *G. bulloides, N. incompta* and *G. truncatulinoides*, respectively. A total of 273 foraminifera samples were picked for this study, 126 coming from the sediment trap and 147 from the three sediment cores and core tops (Table 2).

The mean weight of each available sediment trap sample was obtained by weighting between 15 to 45 specimens of *G. bulloides* (mean N= 27), 5 to 25 *N. incompta* (mean N= 15) and 5 to 25 *G. truncatulinoides* (mean N= 13). Concerning the analyses of the core top and sediment core samples, between 15 and 25 *G. bulloides* and *N. incompta* (mean N= 20 for both) and between 9 and 25 *G. truncatulinoides* (mean N= 18) were picked.

Each foraminifera sample was then cleaned by gentle ultrasonication (50 Hz) for 5 to 75 seconds (depending on the species and the degree of visual uncleanliness) in methanol in order to clean the shells. The samples were then left to dry in a temperature-controlled oven at 50°C. One out of three analyzed samples were weighted before and after cleaning in order to assess potential shell mass losses and shell preservation due to ultrasonication. Our results indicate that this method has little impact on shell preservation with around 95% of the total foraminifera conserved in good conditions. Weight loss between non-cleaned samples and cleaned samples are a mean 0.5 to 3 μg depending on the species, mainly due to the presence of clay and non-calcite material in the shells, which justifies this cleaning process.

The weightings were carried in the micropaleontology laboratory of the Geology Department at University of Salamanca using a Sartorius ME5 balance (precision= 0.001 mg). This method allowed us to obtain foraminifera Sieve Based Weight (SBW) by dividing the average shell weight per sample (5-45 tests) by the total number of foraminifera within each sample.

In order to remove the size effect on the weight (Beer et al., 2010) the mean SBW was normalized to the mean diameter and area of the planktic foraminifera to obtain Measurement Based Weights (MBW). Morphometric parameters were measured using a Nikon SMZ18 stereomicroscope equipped with a Nikon DS-Fi3 camera and NISElements software. Foraminifera shells were positioned in order to obtain the maximum area of each individual, in this case, the umbilical side (aperture facing upwards) was measured for the three species.

MBW_{area} and $MBW_{diameter}$ were calculated according to the following formula (Aldridge et al., 2012; Beer et al., 2010), where “parameter” accounts for “area” or “diameter”:

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$$MBWsample = \frac{mean\ SBW_{sample} \times\ mean\ parameter_{size\ fraction}}{mean\ parameter_{sample}}$$

The Area Density (ρA, $\mu g/\mu m^2$) was calculated by dividing the SBW by the mean sample silhouette area (Marshall et al., 2013).
Finally, in order to compare weights patterns from the sediment trap with weights from core tops and sediment cores and overcome the seasonality effect, MBWs were flux-weighted. Mean monthly MBWs values from each species were multiplied by the corresponding mean monthly flux and then divided by the total annual flux.

3.4. Environmental data

Foraminifera fluxes and abundances together with chlorophyll-*a* were obtained from Rigual-Hernández et al., 2012 for the entire time span of the analyzed samples. Both fluxes and abundance come from direct sediment observation from the Planier site, while chlorophyll-*a* data was obtained from SeaWiFS monthly measurements through NASA's Giovanni program on a 0.2 x 0.2° area around the mooring location. Sea Surface Temperature (SST) was recovered from the NOAA database with the same gridding as the data from the NASA's Giovanni program.
Salinity, nutrient concentrations (nitrates and phosphates) and carbonate system parameters data were collected from the DYFAMED database (http://www.obs-vlfr.fr/dyfBase/index.php). DYFAMED site is located around 200-220km (Figure 1b) east of the sediment trap location (43°25´N, 7°52´E), in the Ligurian Sea. From an oceanographic view, its situation is upstream of the NC circulation and can be considered representative of seasonal and interannual variability of biological and water column properties of the open-ocean waters in the northwestern Mediterranean (Heussner et al., 2006; Meier et al., 2014). Alkalinity and total carbon measurements were available for years 1998 to 2000 and mid 2003 to 2005. Missing values comprised in these years were replaced with values obtained from linear regression of the measurements from above and below. The CO2SYS macro has been used to reconstruct the [CO_2], [CO_3^{2-}], [HCO_3^-] and pH values from the measured total alkalinity and dissolved inorganic carbon. The constants used were the CO_2 dissociation constant by Mehrbach et al., 1973 refit by Dickson and Millero, 1987; the KHSO4 by Dickson, 1990; and the seawater scale for pH. In order to have uninterrupted monthly environmental values from the DYFAMED site during available measurements, a resampling every 10 days has been carried out with the QAnalySeries program.
Seasonal correlation analyses were carried out with the Statistica program. A $p<0.05$ was used in order to consider a correlation as significant. The number (N) of correlations depended on data availability and was 10 for *G. bulloides*, 9 for *N.*

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incompta and 12 for *G. truncatulinoides*. On an interannual time scale we acknowledge that our data presents some gaps over the years, and some years in the sediment trap and foraminifera record are not well represented, however, trends provided here give a new insight on interannual calcification trends in the northwestern Mediterranean.

3.5. Radiocarbon dating

Between 50-100 individuals of well-preserved *Globigerina bulloides* shells (>150 μm) were picked for radiocarbon analyses. Radiocarbon ($^{14}C/^{12}C$) was measured as CO_2 with a gas ion source in a Mini Carbon Dating System (MICADAS) at the Laboratory of Ion Beam Physics from ETH Zürich. The employed automated method consists of initial leaching of the outer shell to remove surface material with 100 μl of ultrapure HCl (0.02M) and the subsequent acid digestion of the remaining carbonates with 100 μl of ultrapure H_3PO_4 (85%) (Wacker et al., 2013). Therefore, no cleaning was applied after the picking contrary to the samples used for mass and size measurements. Marble (IAEA-C1) was used for blank correction and results were corrected for isotopic fractionation via $^{13}C/^{12}C$ isotopic ratios.
Both the samples and dates obtained are detailed in Table 1.

4. Results

4.1. Shell morphometric parameters and shell-weight normalization

Table 2 shows the results of the shell area, diameter and SBW, the total foraminifera samples analyzed, the mean number of individuals per sample and the total individuals measured at each of the studied sites.

Table 2. Minimum, mean, maximum and standard deviation values of shell area, diameter and SBW for *Globigerina bulloides, Neogloboquadrina incompta* and *Globorotalia truncatulinoides* at all studied sites. The last 3 columns show the number of samples, the mean number (N) of individuals analyzed per sample and total number of individuals measured for each site.

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PLA Sediment Trap	Area (µm²)				Diameter (µm)				Sieve Based Weight (SBW, µg)				TOTAL	N PER	TOTAL
	Min	Mean	Max	Std.Dev	Min	Mean	Max	Std.Dev	Min	Mean	Max	Std.Dev	SAMPLES	SAMPLE	N
G. bulloides	16978	57353	168492	17261	147.0	267.5	463.2	38.6	3.21	4.43	5.60	0.66	35	27.2	893
N. incompta	26234	42821	135422	8934	182.8	232.4	415.2	22.6	3.17	4.45	5.40	0.59	32	15.0	455
G. truncatulinoides	70712	178952	527622	63572	291.9	468.5	819.6	81.9	10.67	23.11	39.57	7.79	59	13.0	729
PLA Core-Top															
G. bulloides	37163	55395	87894	12302	217.5	264.0	334.5	28.8	5.00	5.22	5.43	0.30	2	17.3	39
N. incompta	27635	36927	49619	5447	187.6	216.3	251.4	15.9	4.46	4.46	4.46	0.00	2	19.7	41
G. truncatulinoides	89778	174748	233229	44313	338.1	467.7	544.9	61.9	34.80	35.40	35.90	0.70	2	14.7	34
MIN Sediment core															
G. bulloides	20895	52132	138424	8722	163.1	256.8	419.8	20.5	4.00	5.07	6.57	0.46	40	19.6	761
N. incompta	24003	35098	57264	4658	174.8	211.0	270.0	13.7	3.45	4.11	5.00	0.34	40	20.3	791
G. truncatulinoides	116686	166318	365851	23262	385.4	459.1	682.5	30.8	28.33	34.99	42.60	3.25	40	14.4	576
LCD Sediment core															
G. bulloides	27624	52472	116605	8793	187.5	257.7	385.3	20.4	4.35	4.73	5.19	0.31	7	20.1	136
N. incompta	28089	37789	51284	4972	189.1	218.9	255.5	14.4	3.68	4.12	4.50	0.26	7	19.8	134
G. truncatulinoides	82534	143138	393754	41620	324.2	423.3	708.1	55.9	25.27	26.68	30.66	1.94	7	15.3	105

Overall, the mean values for both diameter and area correspond to mean narrowed size fraction used during the picking, but morphometric parameters show some variability between the studied sites. Standard deviation of both area and diameter values for the three species are higher in the sediment trap record than in seafloor sediments, with mean values (of all three species) of 82% higher for area and 69% higher for diameter. SBW exhibits the same pattern as both area and diameter standard deviation is a mean 130% higher in the Planier sediment trap. Regarding the variability across the seafloor samples, Planier core-top exhibits a greater area and diameter values (about 40 to 50% increase for the three species) compared to those of the other two sediment cores, probably due to the fewer samples analyzed (Table 2).

The Planier sediment trap results (Table 2) show a higher standard deviation for both area and diameter for the three species, i.e. 76 % and 68% higher for *G. bulloides* compared to the data from core tops, 78% and 54% for *N. incompta* and 81% and 73% for *G. truncatulinoides*.

Because of the lack of precision of the initial individuals picking, carried out with a micrometer installed in the microscope, the selection is not totally accurate. Due to this issue, one third of the of the total measured foraminifera (i.e. 1645 of 4694) were out of the desired size fraction, of which 12% were bigger (580/4694) and 23% were smaller (1065/4694). Nonetheless, only 0.02% were more than 20% out of the selected size range (64/4694 more than 20% bigger and 29/4694 more than 20% smaller). Mean size difference for the foraminifera out of the size fraction is around 7%. Results vary according to the site and the species. 50% of the individuals from

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the Planier sediment trap (1046/2077) and 26% of the individuals coming from the core tops (692/2617) were out of range. *G. bulloides* showed a 45.5% (53.2% in the sediment trap and 39.3% in the core-tops samples) of individuals out of selected size fraction, while this value is 21.5% (22.2% in sediment trap, 21.1% in sediment cores) for *N. incompta* and 35% for *G. truncatulinoides* (53.4% in sediment trap, 16.7% in sediment cores).

Even though a narrow size class was selected for each species (See section 3.3), a clear correlation between area and SBW was found in our data set (Figure 3).

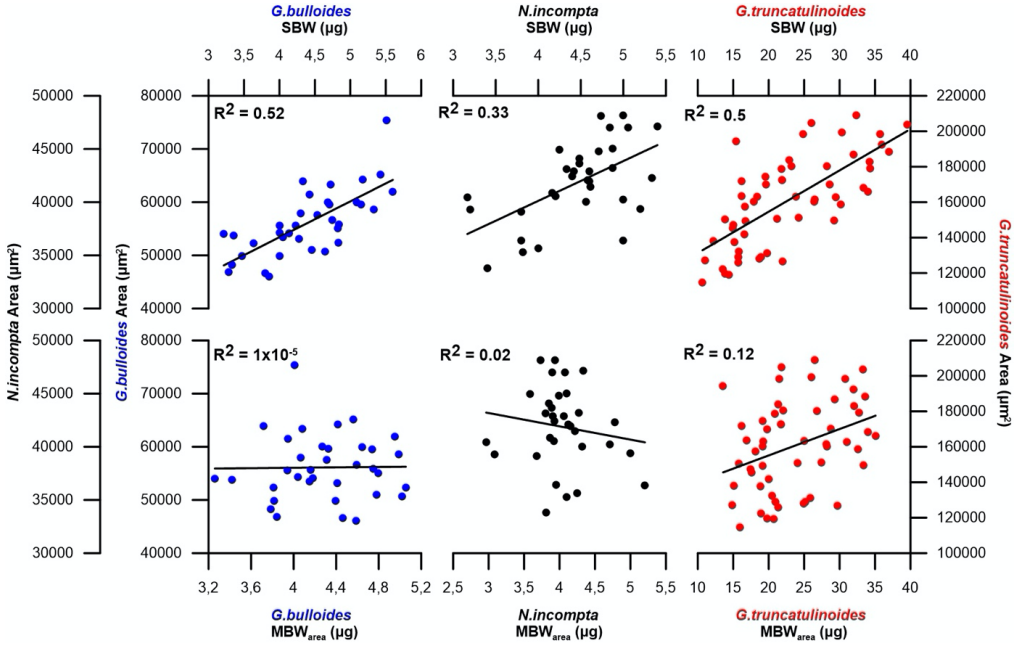

Figure 2. SBW in μg and MBW_{area} in μg against the mean test area in μm^2 for foraminifera samples in the Planier sediment trap. Dark blue dots correspond to *G. bulloides*, black dots *to N. incompta* and red dots to *G. truncatulinoides*.

In Figure 2, we show the values for the Planier sediment trap record for both SBW and MBW_{area} for all three species considered in this study, and their correlation with the measured area. In particular, SBW shows a positive correlation with area: $0.33<r^2<0.53$. This indicates that the SBW is dependent on the size of the specimens within the selected size range. Thus, to isolate the component of variation in foraminifera shell thickness that represents a change in calcification and does not occur as a direct result of changes in shell size, normalization of the shell weight was performed following the formula detailed in section 3.3. (Beer et al., 2010). After

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normalization MBW_{area} shows no correlations with area: $1x10^{-5}<r^2<0.12$ (Figure 2). Note that the weight variations in our dataset are quite considerable, especially for *G. truncatulinoides*, probably due to the wider size fraction. Diameter does show correlation with SBW: $0.33<r^2<0.5$; and shows a non-negligible correlation with MBW_{diam}: $0.2<r^2<033$. Our data demonstrates that SBW correlates more strongly with MBW_{diam} than with MBW_{area} for the 3 species: 0.9>0.48 for *G. bulloides*, 0.89>0.52 for *N. incompta* and 0.97>0.81 for *G. truncatulinoides*. These values are consistent with previous studies (Beer et al., 2010).

Differences between SBW and both MBW_{area} and MBW_{diam} vary depending on the species: SBW is slightly heavier for *G. bulloides*, heavier for *N. incompta* and lighter for *G. truncatulinoides*. The mean standard deviation for all 3 species is around 8%: 7.8% for *G. bulloides*, 6.4% for *N. incompta* and 13% for *G. truncatulinoides*. We take these values as the error adjustment for SBW in the different size fractions (250-300 μm, 200-250 μm and 400-500 μm respectively). It is difficult to compare these results with other studies as size fractions and species are often different, but this error estimates are in the same order of magnitude as some other MBW published in core-tops records and sediment traps (de Moel et al., 2009; Moy et al., 2009).

These findings highlight the fact that the use of sieve fractions does not provide enough control on the influence of morphometric parameters in test weight. Morphometric variations described in table 1 indicate that the typically used sieve fractions may be unreliable due to the number of individuals out of the desired fractions. The correlations between SBW and shell area are consistent with previous studies (Aldridge et al., 2012; Beer et al., 2010) and underscore the importance of isolating the component of variation in foraminifera shell thickness that represents a change in calcification and does not occur as a direct result of change in shell size. Thus, the shell weight was size-normalized after Beer et al., 2010 by isolating the influence of isometric scaling on wall thickness and calcification density.

Area and diameter show a perfect correlation ($r^2= 1$) for all 3 species, highlighting a relationship between the different MBWs. Moreover, both MBW_{area} (Figure 2) and MBW_{diam}, in either the sediment trap data and core-top data, do not correlate with area and diameter ($1x10^{-5} < r^2< 0.33$ and $0.001 < r^2< 0.2$ respectively) indicating that size does not have an influence on these values. This suggests that our size-normalization procedure adequately removes the size influence and therefore, our MBW data represents a robust parameter reflecting test wall thickness and calcification intensity not influenced by test size. Therefore, MBWs can be considered as a reliable calcification intensity proxy.

Based on all the above, from this point we'll focus our discussion on the MBW_{area} and ρA (area density) to discuss the foraminifera shell weight variability on seasonal, interannual and pre-industrial Holocene time scales.

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4.2. Seasonnal variations of foraminifera calcification in the NW Mediterranean

Mean annual MBW_{area} and ρA values were calculated for the three species to illustrate the seasonal variability of these parameters (Figure 3). Monthly data corresponds to the average result of all the data corresponding to each month between the twelve-year time series (1993-2006) at both sites.

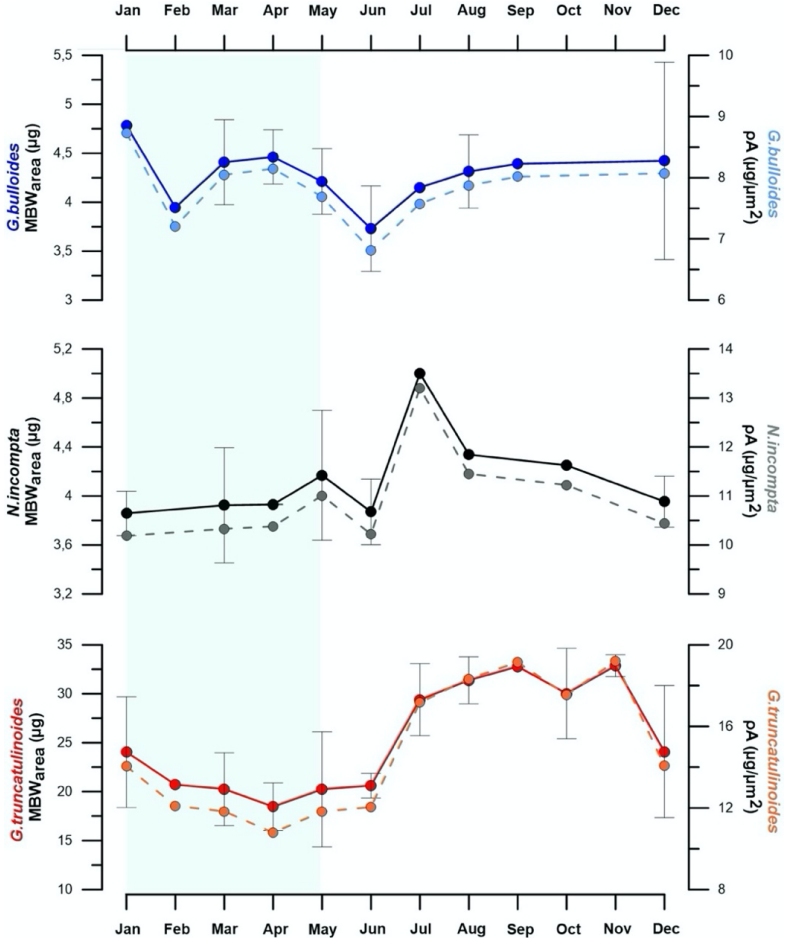

Figure 3. Mean MBW_{area} and ρA ($x10^{-5}$) composite year values for *G. bulloides* (dark and light blue lines), *N. incompta* (black and grey lines) and *G. truncatulinoides* (red and orange lines) in the Planier sediment trap across a composite year. Light green back represents the high productivity period in the study zone (Rigual-Hernández et al., 2012).

The mean MBW_{area} and ρA for the three species in the Planier sediment trap are 4.29 µg (± 0.45 µg) and 7.81 (± 0.91), respectively, for *G. bulloides*, 4.04 (± 0.4 µg)

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μg and 10.67 (± 1.21) for *N. incompta* and 23.25 (± 6.2 μg) μg and 13.57 (± 3.6) for *G. truncatulinoides*.

The temporal variations in shell calcification exhibit a clear seasonal pattern for the three species. The composite year shows that all the three species exhibit a clear but different seasonal pattern (Figure 3).

In the case of *G. bulloides*, maximum annual calcification values are reached during winter (January; 4.78 μg), and minimum during summer (June; 3.72 μg). The observed 1 μg difference in calcification between maximum and minimum values corresponds to a 24.5% change in the mean MBW_{area} value. Mean seasonal standard deviation is ± 0.47 μg, with the lowest value in April, ± 0.27 μg; and the highest value in December, ± 1 μg.

Neogloboquadrina incompta shows a maximum in calcification in mid-summer (July; 5 μg) and two minima in mid-winter (January; 3.85 μg) and early summer (June; 3.87 μg). Thus, the annual seasonal amplitude is 1.15 μg which translates into a 28% seasonal MBW_{area} variability. Standard deviation is ± 0.28 μg, with the highest value in May, ± 0.53 μg; and the lowest one in April with no deviation.

Finally, *G. truncatulinoides* displays a seasonal maximum MBW_{area} value in late summer- autumn (November; 32.85 μg) and minima in spring (April; 18.45 μg). Seasonal MBW_{area} difference is 14.3 μg: a 60% variability. Mean typical seasonal deviation is ± 3.7 μg, with December and November showing the highest and lowest variability respectively: ± 1.1 and ± 6.7 μg.

4.3. Interannual MBW_{area} trend

Trends throughout the record are represented in Fig 4. In order to obtain representative data for each year, maximize data availability of each species and avoid the impact of non-representative months on the interannual trends, only MBWs from the productive period (January to May) of each year analyzed were included. The same strategy was applied for the environmental data, with the exception of the carbonate system parameters.

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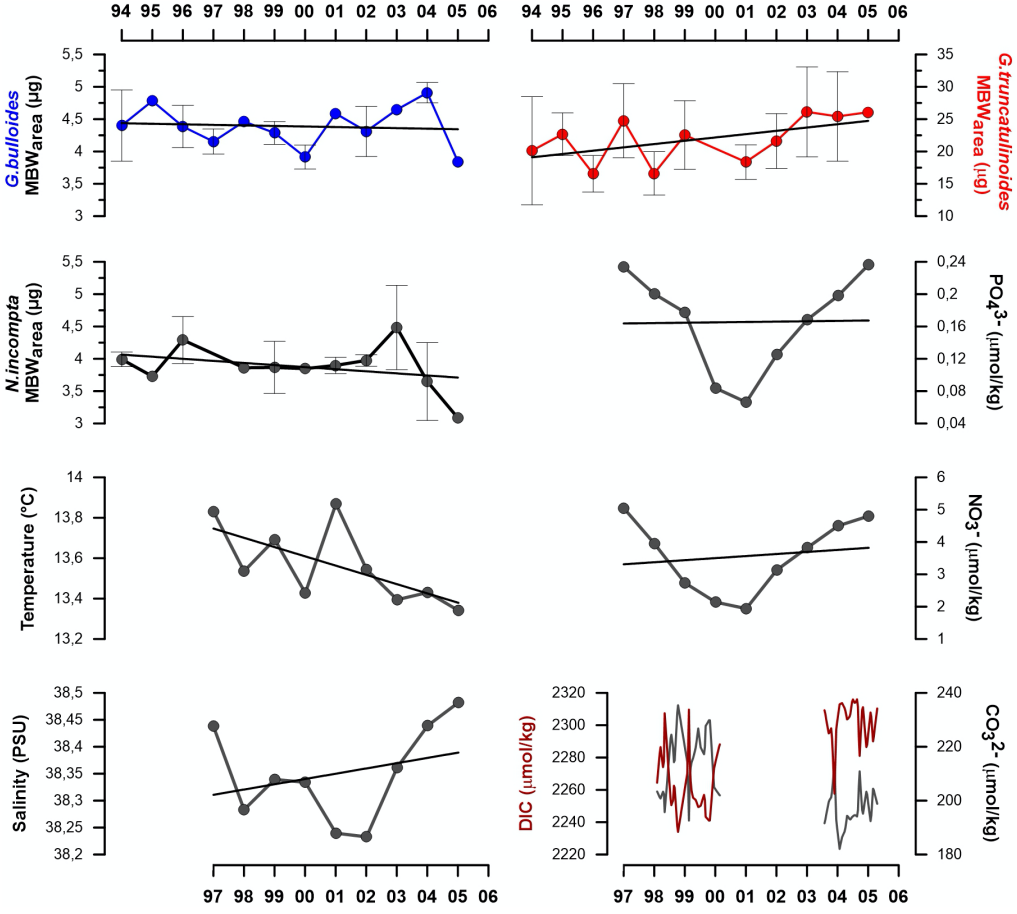

Figure 4. Inter-annual variations in the *G. bulloides*, *N. incompta* and *G. truncatulinoides* MBW_{area} and the environmental data from the DYFAMED site (available since 1997). Except for the carbonate system parameters, trends represent mean values from the high productivity period of each year (see study area). DIC represents Dissolved Inorganic Carbon. Black lines represent the trends from the MBW_{area} and resampled data.

Planktic foraminifera calcification variability across the twelve-year record varied depending on the species (Figure 4). *G. bulloides* MBW_{area} showed a slight but constant decrease over the studied interval. Minimum values were reached during years 2000 and 2005 (3.9 and 3.85 µg respectively). On the other hand, *N. incompta* MBW_{area} showed little to none interannual variability, excepting a calcification reduction the last two years (3.1 µg). Finally, *G. truncatulinoides* MBW_{area} showed a different pattern, with a constant and steep calcification increase throughout the

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record, with minimum calcification values observed in 1996 (16.5 μg) and maximum in 2003 (26.1 μg).

Temperature (SST) displayed a constant decrease over the years, from 13.8 to 13.4 °C, while salinity showed a slight increase, mainly since 2002. From late 2000 until late 2002, nutrient concentrations were exceptionally low (Figure 4). This feature has already been described in the Gulf of Lions (Meier et al., 2014). However, data from the carbonate system showed variations across the years. Between the 2 periods for which direct on-situ measurements were available, 1998 to 2000 and 2003 to 2005 (Figure 4) CO_3^{2-} dropped by 10-15 μmol/kg, DIC increased by 40 to 60 μmol/kg, leading to a pH decrease of 0.02 to 0.025. Meier et al., 2014, linked this pH decrease to recent years coccoliths weight reductions in the Gulf of Lion.

4.4. Sediment trap, core tops and sediment cores MBW patterns

Foraminifera weights analyzed in core tops and sediment cores from the NW part of the Mediterranean allowed a further insight on the reduced foraminifera calcification during the Holocene (Figure 6).

Flux weighted MBWs (see section 3.3) from Planier sediment trap for the three planktic species were 4.1 μg for *G. bulloides*, 3.3 μg for *N. incompta* and 22.3 μg for *G. truncatulinoides* (Figure 6). Data from Planier core-top showed higher mean MBW_{area} values: 5.3 μg, 4.65 μg and 35.4 μg. ^{14}C dating in this core-top revealed a date of 489 years (± 59 years). Overall, in the last 489 years, *G. bulloides* weight has been reduced by 1.2 μg, *N. incompta* by 1.3 μg and *G. truncatulinoides* by 12-13 μg. Located west of Planier site, Lacaze Duthiers sediment core mean MBWs were: 4.99 μg for *G. bulloides*, 4.14 μg for *N. incompta*, and 32.9 μg for *G. truncatulinoides*. ^{14}C dating was carried out on the core-top sample of this sediment core that displayed a date of 460 years (± 59 years). Corresponding MBWs from this sample for *G. bulloides*, *N. incompta* and *G. truncatulinoides* respectively were: 4.7 μg, 4.2 μg and 34 μg. Overall, compared to the data from the sediment trap, this corresponds to a 0.6 μg weight loss for *G. bulloides*, 0.9 μg for *N. incompta* and 12.2 μg for *G. truncatulinoides* in 460 years.

Located in the Gulf of Minorca, northwest of Planier site, Minorca sediment core mean MBWs were: 5.4 μg for *G. bulloides*, 4.5 μg for *N. incompta* and 36.3 μg for *G. truncatulinoides* (Figure 6). ^{14}C dating on this core top was carried out on an intermediate depth (see section 3.4) due to the lack of availability of enough specimens in the core-top and displayed a date of 1979 years (± 63 years). Corresponding MBWs for this sample were 4.9 μg, 4.4 μg, 35.1 μg for the three species. Therefore, weight reduction was: 0.8 μg for *G. bulloides*, 1.1 μg for *N. incompta* and finally, 12.8 μg for *G. truncatulinoides.*

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5. Discussion

5.1. Seasonal controls on planktic foraminifera shell calcification in the NW Mediterranean

As described in section 4.2., the seasonal variability of MBW_{area} displays important differences across the three species analyzed. The different seasonal pattern in MBW_{area} is reflected by the lack of correlation between the seasonal pattern of MBW_{area} of the different species, i.e., r= -0.23 (p>0.05) between *G. bulloides* and *N. incompta* and r= 0.16 (p>0.05) between *G. bulloides* and *G. truncatulinoides*. Only the seasonality of *N. incompta* MBW_{area} and *G. truncatulinoides* MBW_{area} share some similarities, as reflected in the significant and positive correlation (r= 0.66; p<0.05). In order to examine the main controls on foraminifera seasonal calcification in the Gulf of Lions, here we compare the seasonal variability of planktic foraminifera calcification with foraminifera fluxes previously estimated for the Planier sediment trap (Rigual-Hernández et al., 2012), satellite data for the studied site and a suite of environmental parameters measured at the DYFAMED site (see section 3.4).

Table 3. Correlation matrix of seasonal test weights and the environmental parameters from Planier (sediment trap and satellite data) and DYFAMED site (see section 3.4). Significant correlations (p<0.05) are set in bold.

Parameters			Planier site data								DYFAMED site data					
			G. bull.	*N. inc.*	*G. truncat.*	*G. bull.*	*N. inc.*	*G. truncat.*	Chl-a	SST	Salinity	$[NO_3]$	$[PO_4]$	pH	$[CO_3]$	$[CO_2]$
				MBW_{area}			Fluxes									
Planier site data	MBW_{area}	*G. bull.*		-0.232	0.167	0.012	0.027	0.152	0.318	-0.320	-0.163	0.292	0.330	0.096	-0.189	0.243
		N. inc.	-0.232		**0.667**	-0.582	-0.407	-0.405	-0.484	**0.688**	0.368	-0.272	-0.235	-0.350	0.474	-0.280
		G. truncat.	0.167	**0.667**		**-0.905**	-0.725	**-0.666**	**-0.585**	**0.672**	-0.299	-0.258	-0.512	-0.113	**0.732**	-0.541
	Fluxes	*G. bull.*	0.012	**-0.582**	**-0.905**		**0.911**	**0.861**	**0.773**	**-0.755**	0.264	0.338	0.526	0.213	**-0.748**	0.548
		N. inc.	0.027	-0.407	**-0.725**	**0.911**		**0.953**	**0.817**	**-0.621**	0.364	0.329	0.391	0.103	**-0.700**	**0.596**
		G. truncat.	0.152	-0.405	**-0.666**	**0.861**	0.953		**0.739**	**-0.707**	0.446	**0.586**	**0.590**	-0.012	**-0.801**	**0.714**
		Chl-a	0.318	-0.484	**-0.585**	**0.773**	0.817	**0.739**		**-0.702**	-0.004	0.190	0.277	0.501	-0.428	0.255
		SST	-0.320	**0.688**	**0.672**	**-0.755**	-0.621	**-0.707**	**-0.702**		0.047	**-0.688**	**-0.696**	-0.416	**0.649**	-0.410
		Salinity	-0.163	0.368	-0.299	0.264	0.364	0.446	-0.004	0.047		0.305	0.420	**-0.714**	**-0.604**	**0.733**
DYFAMED site data		$[NO_3]$	0.292	-0.272	-0.258	0.338	0.329	**0.586**	0.190	**-0.688**	0.305		**0.876**	-0.183	**-0.682**	**0.620**
		$[PO_4]$	0.330	-0.235	-0.512	0.526	0.391	**0.590**	0.277	**-0.696**	0.420	**0.876**		-0.162	**-0.834**	**0.709**
		pH	0.096	-0.350	-0.113	0.213	0.103	-0.012	0.501	-0.416	**-0.714**	-0.183	-0.162		0.338	**-0.596**
		$[CO_3]$	-0.189	0.474	**0.732**	**-0.748**	**-0.700**	**-0.801**	-0.428	**0.649**	**-0.604**	**-0.682**	**-0.834**	0.338		**-0.939**
		$[CO_2]$	0.243	-0.280	-0.541	0.548	**0.596**	**0.714**	0.255	-0.410	**0.733**	**0.620**	**0.709**	**-0.596**	**-0.939**	

Among all the environmental parameters, de Villiers (2004) suggested that shell calcification, and therefore MBWs, is primarily controlled by the Optimum Growth Conditions (OGC) that can be defined as the most suitable environmental conditions for the development of a given planktic foraminifera species. Based on the latter

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study, it could be expected that favorable environmental conditions for foraminifera growth would lead to both greater shell fluxes and enhanced shell calcification. Our correlation analysis shows different relationships between foraminifera abundance (as inferred from foraminifera shell fluxes) and shell weight. In particular, *G. bulloides* MBW_{area} shows no correlation with its fluxes (Table 3), while both *N. incompta* and *G. truncatulinoides* exhibit a negative correlation between MBW_{area} and their species fluxes although only significant for the latter species ($r= -0.4$, $p>0.05$ and -0.66, $p<0.05$ respectively). Interestingly, *G. truncatulinoides* calcification correlates negatively and significantly with all three species fluxes, a pattern opposite to what the OGC theory predicts (de Villiers, 2004), i.e., optimum ecological niche is associated with enhanced calcification. Thus, a possible explanation reconciling our observations with the OGC theory may be that *G. truncatulinoides* tend to prioritize energy allocation toward growth and reproduction at the price of a reduced calcification.

An alternative proxy for OGC that may be considered is chlorophyll-*a* concentration. Chlorophyll is considered an indicator of the algal biomass concentration, which is known to represent a large part of some foraminifera species diet, specially for *G. bulloides* (Schiebel and Hemleben, 2017). Our data shows a positive but not significant correlation between chlorophyll concentration and *G. bulloides* MBW ($r= 0.32$, $p>0.05$), suggesting a negligible influence of phytoplankton concentration on *G. bulloides* calcification. A stronger trend would be expected under the OGC theory as algae are a vital part of its diet (Hemleben et al., 1989). We speculate that *G. bulloides* may feed only on certain groups of phytoplankton which changes in seasonal abundance in the photic zone do not necessarily follow the seasonal pattern of total chlorophyll concentration (Marty et al., 2002). In the case of *N. incompta* and *G. truncatulinoides*, correlations between MBW_{area} and chlorophyll-*a* are negative and stronger although only significant for the latter species ($r= -0.58$, $p<0.05$). This observation indicates that optimum calcification conditions for *G. truncatulinoides* are reached at times of minimum annual algal biomass concentration in the photic zone. It is possible that, due to its deeper habitat (Schiebel and Hemleben, 2017), *G. truncatulinoides* feeds on phytoplankton dwelling in subsurface levels of the water column. In fact, a deep chlorophyll maximum is known to develop during large part of the year in the Northwestern Mediterranean (Estrada et al., 1993) but its presence is not detected by satellites. This interpretation is in agreement with earlier work by Pujol and Vergnaud Grazzini (1995) who found peak abundances of this species during the summer below the thermocline.

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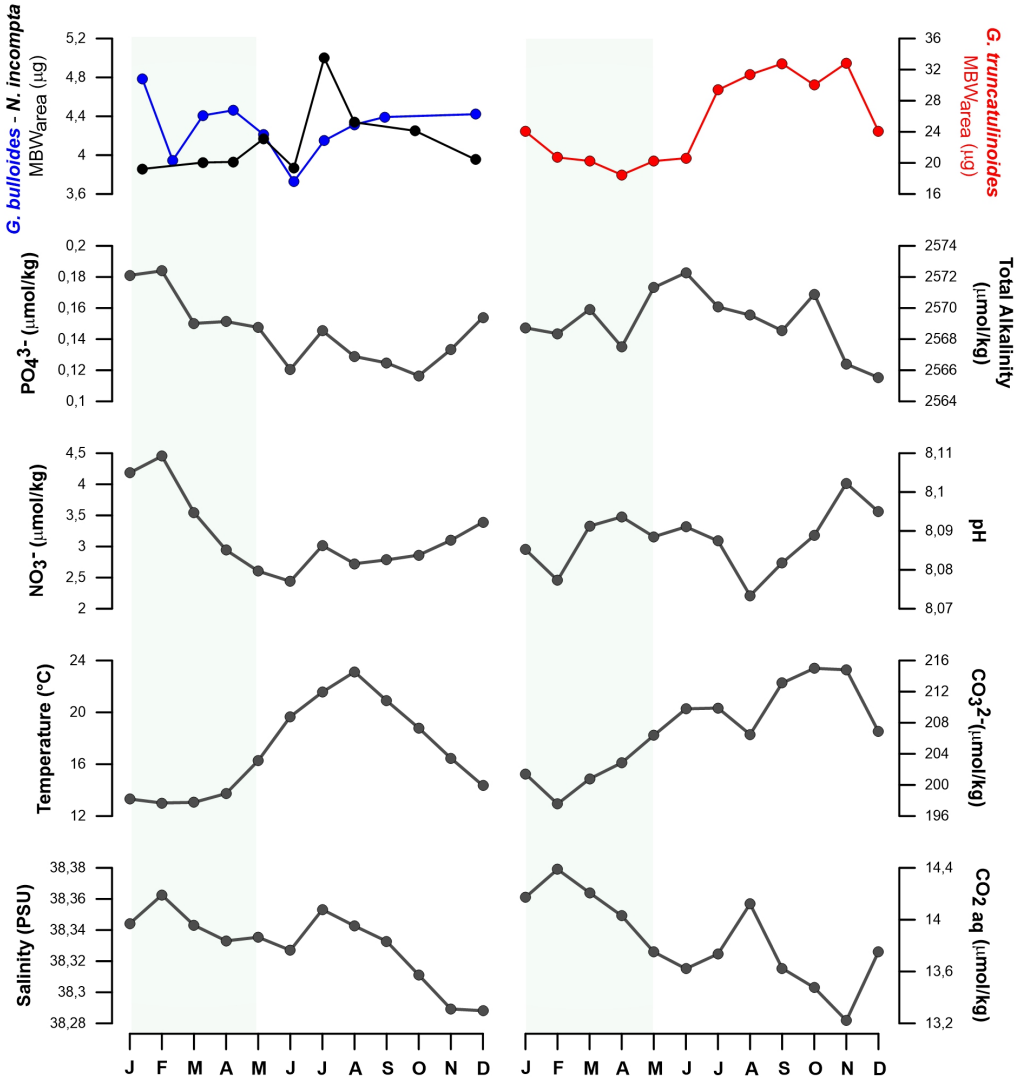

Figure 5. *Globigerina bulloides*, *Neogloboquadrina incompta* and *Globorotalia truncatulinoides* seasonal MBW_{area} variations compared with resampled seasonal signal of environmental parameters from the DYFAMED site across a composite year.

Something to consider when using chlorophyll as an OGC proxy is that it can be confounded with the nutrient concentrations. Previous studies have described that, in those settings where foraminifera abundance covaries with nutrient concentrations, then nutrients are probably a better OGC proxy than chlorophyll concentrations (Schiebel et al., 2001). In turn, the correlation of nutrients (nitrates and phosphates) with fluxes were positive for all three species, although only

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significative ($p<0.05$) for *G. truncatulinoides* abundance ($r= 0.58$ and 0.59 for nitrates and phosphates respectively).

It is important to note that nitrate and phosphate concentration variations were closely linked to each other ($r= 0.876$, $p<0.05$) (Table 3), making it difficult to determine if the resulting effect on foraminifera calcification is due to the effect of a single driver or to the combination of both. High phosphate concentrations are generally considered an inhibitor for foraminifera calcification (Zeppenfeld, 2019). Evidences show that calcite formation is inhibited by PO_4^{3-} due to its adsorption on the calcite surface, impeding its precipitation by blocking the crystal growth. Aldridge et al., 2012 showed a negative effect of phosphate concentration on *G. bulloides* and this feature has been shown in other calcareous organisms such as coccolithophores (Paasche and Brubank, 1994) and calcifying algae (Demes et al., 2009), resulting in a higher growth and calcification under controlled PO_4^{3-}. On the other hand, no studies show a reduced calcification in marine organisms under high NO_3^- values. Our work shows that nutrient concentrations (both nitrates and phosphates) do not correlate significantly with any of the three species MBW studied. NO_3^- correlations were not significant for all three species, while PO_4^{3-} correlations were also very weak, with the exception of the one with *G. truncatulinoides* MBW_{area} ($r= -0.512$, $p= 0.07$) (Table 3). Although the p-value of this correlation is slightly higher than what we use as threshold for significance (i.e., 0.05), the negative correlation between *G. truncatulinoides* MBW_{area} and phosphate could be considered almost significant. Thus, our data suggest that enhanced $[PO_4^{3-}]$ levels could act as an inhibitor for *G. truncatulinoides* calcification in our study region.

Previous studies have suggested that salinity may have an influence on foraminifera calcification. Zarkogiannis et al., (2022) found that salinity may control calcification of certain foraminifera species in the central Atlantic region. However, our data suggest that the role of salinity on calcification in our study region is unlikely since its seasonal amplitude is tiny (0.1 PSU; Figure 6). This idea is supported by the lack of correlation between salinity and MBW_{area} for the three species studied (Table 3).

Temperature (Sea Surface Temperature) has been described as a major factor that controls the size (Schmidt et al., 2004) and porosity (Burke et al., 2018) of planktic foraminifera, therefore it could represent a major control factor on shell calcification in the NW Mediterranean. In particular, calcification could be positively linked to temperature through different mechanisms: (i) warmer temperatures have been shown to increase enzymatic activity and therefore enhanced growth and calcification rates (Spero et al., 1991); (ii) Lombard et al., (2011) stated that higher temperatures could also increase feeding and ingestion rates, but it remains unclear if this could result in a calcification rate increase. Our data revealed that SST correlates negatively, but without significance with *G. bulloides* calcification, while

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correlations between SST and *N. incompta* and *G. truncatulinoides* were both positive and significant (r= 0.69 and 0.67 respectively, p<0.05). These trends could be expected considering the relationship between temperature and nutrient concentrations (r= -0.69 and -0.70 for NO_3^- and PO_4^{3-} respectively) and the correlations between the three species MBW_{area} and nutrients concentrations (Figure 5). Finally, in addition to having an impact on the size and calcification of the planktic foraminifera, temperature is well known as a major control of the carbonate system, due to the increased solubility of atmospheric CO_2 at lower temperatures, and therefore it could have an indirect effect on foraminifera calcification by affecting the carbonate system.

Data for the carbonate system were only available for years 1998 to 2000 and 2003 to 2005 and, therefore gaps comprised in these years were filled with estimates using the CO2sys macro (see Methods). The relationship between CO_3^{2-} and MBW has been described in previous studies (Barker and Elderfield, 2002; Marshall et al., 2013) and the bulk of evidence indicates that foraminifera MBWs to be positively linked with CO_3^{2-} concentrations (Aldridge et al., 2012; Osborne et al., 2016). However, it appeared that planktic foraminifera response to CO_3^{2-} was not uniform and varied across species (Beer et al., 2010; Lombard et al., 2010). The trends between carbonate system parameters and MBWs were similar to those observed when comparing MBWs with temperature, highlighting the covariations between these two parameters (Figure 5). Our data showed that CO_3^{2-} concentrations were not significantly correlated with *G. bulloides* MBW_{area} nor with *N. incompta*. Only *G. truncatulinoides* MBW_{area} displayed a clear significant correlation with CO_3^{2-} concentration (r= 0.73, p<0.05), implying that carbonate availability may represent a key control on *G. truncatulinoides* in the Northwestern Mediterranean. On the other hand, CO_2 concentrations, excepting a negative and almost significant relationship with *G. truncatulinoides* MBW_{area} (r= -0.54, p= 0.06), showed no correlation with the other 2 species MBWs. None of the remaining carbonate system parameters (pH, alkalinity and calcite saturation), exhibited a significant seasonal correlation with the MBWs.

In summary, OGC, SST and CO_3^{2-} are the most likely parameters that control the seasonal changes in the planktic foraminifera species studied here. The combined effect of these parameters seems to control foraminifera calcification in the Gulf of Lions; however, it should be considered that covariation between these parameters is strong, and therefore it is difficult to isolate the effect of a single parameter. Our results are in agreement with earlier studies that stated that OGC (de Villiers, 2004), temperatures and CO_3^{2-} (de Villiers, 2004; Marshall et al., 2013; Osborne et al., 2016) concentrations are the main factors that impact calcification in planktic foraminifera.

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5.2. Interannual trends in planktic foraminifera calcification

As stated previously, the Mediterranean Sea is a sensitive zone to atmospheric CO_2 accumulation (Ziveri, 2012) and is experiencing ongoing ocean acidification. On an interannual time scale, different studies (Beer et al., 2010; Osborne et al., 2016) have shown that sea surface warming and carbonate system parameters are the most likely parameters to control calcification on key calcifying phytoplankton species such as the coccolithophore *Emiliania huxleyi* organisms (Meier et al., 2014). However, datasets from sediment traps that cover a wide span of years and in which foraminifera weights have been analyzed are rare (Kiss et al., 2021), therefore it is difficult to place our results in a more global context. Our analysis suggests that the trends observed in the carbonate system (Figure 5), i.e., the DIC rise and $[CO_3^{2-}]$ decrease may be responsible for the slight calcification reduction in both *G. bulloides* and *N. incompta*, particularly in recent years. During the second time span carbonate parameters were available (2003 to 2005), both of these species started experiencing a calcification reduction (Figure 5). *G. bulloides* displayed a relative maximum MBW_{area} in 2004, corresponding to a relative maximum in $[CO_3^{2-}]$ and relative minimum in DIC. While in 2005, calcification started to decrease, according to the opposite pattern in $[CO_3^{2-}]$ and $[CO_2]$. *N. incompta* started a decreasing calcification pattern from 2003 to 2005, matching the carbonate system parameters trends in recent years. Our data showed that pH decreased from a mean 8.12 for the 1998-2000 years to a mean 8.08 for the 2003-2005 years. This pH decrease, combined with the carbonate system parameters seem to affect *G. bulloides* and *N. incompta* calcification patterns in recent years, however, the degree to which each species react to a change in these parameters differs.

Notably, the trend in *G. truncatulinoides* is opposed to the previous two species and shows a steady and steep increase throughout our record. Over the analyzed time span, its MBW increased around 20% (equivalent to an increase of ~5 μg). If this calcification increase continues on current trends, then the average MBW of *G. truncatulinoides* will double by 2024. Analysis of present *G. truncatulinoides* populations is urgently needed to assess if the observed trend held true during the last two decades. It is important to note that while *G. truncatulinoides* exhibits an intimate correlation with $[CO_3^{2-}]$ on a seasonal scale, no clear correlation was found with the interannual changes of $[CO_3^{2-}]$ (Figure 5). In fact, our analysis suggests that the most likely environmental parameter exerting an influence on the calcification of this species is nitrate concentration (Figure 5). A similar enhancement in shell calcification has been described in the Balearic Sea for *G. truncatulinoides* in high-resolution sediment cores (Pallacks et al., 2020), but also in *Globorotalia inflata*. Taken together, our observations and the study mentioned above, suggest that deep

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dwellers are unaffected by recent ocean acidification and changes in the carbonate system and that the recent change in one or several environmental drivers may be stimulating the calcification of these species.

Here, we theorize that the interannual patterns presented in Figure 5 mainly reflect the seasonal changes in the regional oceanographic setting. As described previously (see study area), the Gulf of Lions is influenced by a strong seasonality. The recent SST decrease could be linked to an enhancement in water mixing, as cold and deep salty water reach up to the surface. This mechanism would be less intense during years 2000 to 2002, corresponding to a SST increase along with a salinity decrease and absolute minimums in nutrients concentrations (Figure 5), as water stratificates, these are consumed by primary production. Finally, in recent years, water mixing seems to be reactivated, as SST keeps decreasing and nutrients concentrations increase again. This mechanism also affects the carbonate system parameters, as water mixing brings to surface deeper DIC enriched waters to the surface, coupled with a [CO_3^{2-}] reduction. Our data shows that alkalinity patterns display similar tendencies to DIC, however, until the second time span covered by carbonate system data, alkalinity variations are proportionally higher than DIC variations (see Supplementary material), suggesting a water mixing phenomenon. On the other hand, DIC variations turn to be higher than alkalinity variations from 2003 to 2005, suggesting an additional effect of carbon inputs on the carbonate system not reflected in the alkalinity data.

5.3. Holocene core-top data comparison

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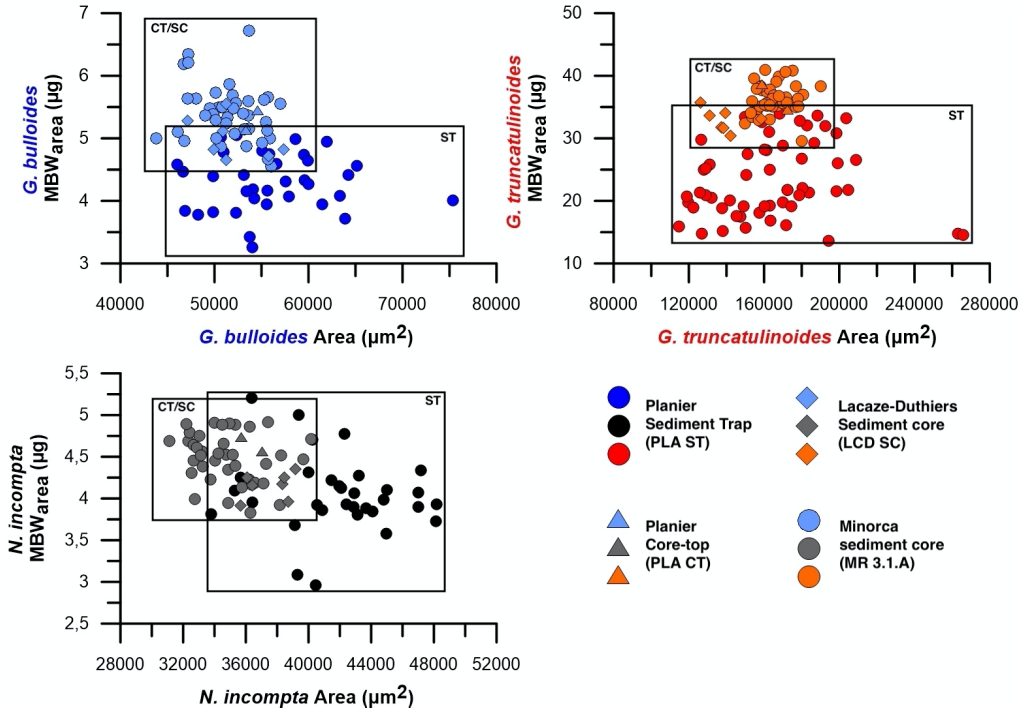

Figure 6. MBW_{area} in µg and area in µm² comparison in the sediment trap (PLA ST), Planier core-top (PLA CT), and both Lacaze-Duthiers (LCD SC) and Minorca sediment core (MR 3.1.A). Darker colors represent data from the sediment trap, while lighter colors represent data from the different seabed sediments.

The comparison of the well-preserved assemblages of planktic foraminifera in the Holocene-aged surface sediments with those collected by a long-sediment trap record offers a unique opportunity to assess the impact of recent environmental change on the calcification of calcareous zooplankton in the Mediterranean Sea. However, when comparing data from sediment traps and seabed sediments, the possible role of calcite dissolution must be taken into account.

Calcite dissolution in the water column and/or on the sea floor could be invoked as a source of variability between the sediment trap and surface sediment data sets (e.g., Dittert et al., 1999). Therefore, in order to obtain meaningful interpretations from our data sets it is important to assess the possible role of dissolution in the preservation of planktic foraminifera shells. Several lines of evidence suggest, however, that calcite preservation does not represent an important source of bias in our study area. Firstly, the Mediterranean Sea is supersaturated with respect to calcite (Millero et al., 1979) and the location of all the analyzed samples is much shallower than the location of the calcite saturation horizon (Álvarez et al., 2014),

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758 therefore, calcite dissolution seems unlikely (Schneider et al., 2007). Secondly,
759 several sediment trap studies have documented that calcareous plankton
760 experience negligible dissolution in their transit from the surface ocean to the sea
761 floor (Beaufort et al., 2007; Moy et al., 2009; Rigual-Hernández et al., 2020). Thirdly,
762 if partial dissolution was to take place here, MBWs from the seabed sediments and
763 core tops would be lighter than the ones from the sediment traps, which is not the
764 case (Figure 6). Fourthly, SEM observations of all 3 species in samples from the
765 sediment traps showed no sign of dissolution and foraminifera were well preserved
766 (see Supplementary material). All these arguments suggest that calcite dissolution
767 does not represent an important control in the weight of the planktic foraminifer shells
768 in the analyzed samples.
769 Overall, the lower shell weights of the foraminifera collected by the traps strongly
770 suggest that the three planktic foraminifera species have experienced a reduction in
771 their calcification since the industrial era and/or late Holocene. While the shell weight
772 of each species measured in the sediments show some variability across seabed
773 sediments (Figure 6), our data suggest an overall reduction of 18-24% for *G.*
774 *bulloides*, 20-27% for *N. incompta*, and 32-40% for *G. truncatulinoides.* It is important
775 to note that the range of shell weight variability across core-tops and sediment cores
776 (4.5-6.7 μg and 0.37 μg typical deviation for *G. bulloides*, 3.8-4.9 μg and 0.23 μg
777 typical deviation for *N.incompta*, and 29.5-40.9 μg and 2.6 μg typical deviation for *G.*
778 *truncatulinoides*) is substantially lower than the difference with the sediment trap
779 data (3-5 μg and 0.5 μg typical deviation for *G. bulloides*, 2.9-5.2 μg and 0.5 μg
780 typical deviation for *N. incompta* and 12-35 μg and 6 μg typical deviation for *G.*
781 *truncatulinoides*), implying that the shell weight of modern foraminifera populations
782 for the three species is lower than anywhere in the NW Mediterranean in the pre-
783 industrial times. The source of the variability across core tops and sediment cores is
784 most likely caused by the different age of the samples, ranging from 1979 years at
785 Minorca mid-depth (see section 3.1.) sample to 460 years at Planier core-top sample
786 and the different environments associated to the location of each core top.
787 Something to consider when comparing recent sediment trap data with pre-industrial
788 Holocene data is the life cycle of the species. As all the species analyzed presented
789 some reduction in shell calcification, the degree to which the different specimens
790 responded varied. The greatest weight reductions were observed for *G.*
791 *truncatulinoides* populations, while *G. bulloides* populations exhibited the lowest
792 weight loss.
793 Previous work stated that those species hosting photosynthetic algal symbionts
794 exhibit a higher tolerance to environmental changes that may affect their calcification
795 (Lombard et al., 2009). This is due to the fact that these symbionts can modify the
796 sea water chemistry that is close range to the shell, allowing a calcification

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enhancement. Since none of the species studied here are symbiont bearing species, they are among the most vulnerable foraminifera species to any sea water chemistry change. Moy et al., (2009) work in the Southern Ocean, showed a 30-35% calcification reduction for *G. bulloides* during the industrial era. Our study shows that such a similar reduction in *G. bulloides* MBW_{area} (i.e., a mean 20% taking into account the 3 sites studied) has also taken placed in the Mediterranean Sea. Even though the species studied were different in Fox et al., (2020), and that shell thickness was analyzed, that work showed a massive shell reduction for *N. dutertrei* (around 75%) and a smaller reduction for *G. ruber* (around 20%). *N. incompta* weight reduction in this study is around 25%, despite that life cycles are different between these species, our results come in the same line. Data for *G. truncatulinoides* calcification comparison between pre-industrial Holocene and post-industrial Holocene is scarce. One of the few available studies is the one of Pallacks et al., (2020) in the western Mediterranean sea using pre-industrial data and recent foraminifera weight data obtained from high resolution core-tops. Size-normalized weights showed that all the species calcification decreased since the onset of the industrial revolution, an observation that is supported by our data (Figure 6). *G. truncatulinoides* showed a 24% weight reduction, which is a lower reduction than what is shown in our study (around 35% MBW_{area} decrease), but shows a similar trend. Taken together, all these observations suggest that a decrease in major planktic foraminifera calcification is not a regional feature but a global scale process. Therefore, it is likely that global changes in the ocean, such as ocean acidification, could be the main responsible for such a change.

6. Conclusions

The variability in shell calcification of three planktic foraminifera species (*Globigerina bulloides*, *Neogloboquadrina incompta* and *Globorotalia truncatulinoides*) was studied in the northwestern Mediterranean Sea at different time scales using sediment trap and seabed samples. The analysis of 273 samples and more than 4000 individuals revealed that:

i. The Sieve Based Weight (SBW) method is not a reliable tool as calcification indicator due to the influence of morphometric parameters on foraminifera weight. The Measured Based Weight (MBW) technique, on the other hand, shows little to negligible influence of the morphometric parameters, and therefore, can be considered a reliable calcification proxy.

ii. Analysis of the seasonal variability of planktic foraminifera calcification revealed important differences between species. *G. bulloides* exhibited

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peak calcification during winter, *N. incompta* during mid-summer and *G. truncatulinoides* during late summer to autumn. Correlations with environmental parameters indicate that Optimum Growth Conditions (OGC), Sea Surface Temperatures (SST) and [CO_3^{2-}] are the most likely parameters influencing seasonal calcification variability in the Gulf of Lions.

iii. Interannual analysis suggest that *G. bulloides* and *N. incompta* tend to show a slight calcification reduction from 1994 to 2005, on the other hand, *G. truncatulinoides* displays a constant and steady calcification increase over the years.

iv. Finally, sediment trap and seabed sediment data comparisons between pre-industrial and post-industrial foraminifera assemblages. Our data shows that all three species experienced a clear and conspicuous calcification reduction with modern *G. bulloides* populations being 18-24% less calcified and a reduction of 20-27% and 32-40% for *N. incompta* and *G. truncatulinoides*, respectively.

As planktic foraminifera represent roughly about 50% of pelagic calcite production (Schiebel, 2002) in the world's oceans, and therefore, an important component of the marine carbon cycle, a reduction in the calcification of their shell could induce important changes in the future carbon cycle with feed-backs on climate. Our results call for increasing efforts in monitoring planktic foraminifera calcification the Mediterranean in order to determine if the trends suggested by our data will be sustained over time.

The Supplement related to this article is available at…

Competing interests. The authors declare that they have no conflict of interest.

Author contributions. ASRH, FJS and TMB designed the study and performed the numerical analyses. JPT designed Figures 1 and 2. XDM provided Planier core-top and Lacaze-Duthiers seabed sediment samples. IC provided the Minorca promontory seabed sediment samples. NH and TE carried out the ^{14}C measurements. TMB led the sample processing as well as the microscopy and image analysis, the foraminifera study and wrote the manuscript with feedback from all authors.

Acknowledgments. Authors would like to thank Blanca Ausín for her insight on radiocarbon dating and Serge Heussner for the retrieval of the sediment trap collected within the French national MOOSE program supported by CNRS-INSU and ALLENVI. This study was funded by by the Spanish "Ministerio de Ciencia e Innovación" through a grant number PRE2019-089091 and through the project RTI2018-099489-B-100; PID2021-128322NB-I00.

https://doi.org/10.5194/egusphere-2022-711
Preprint. Discussion started: 22 August 2022

References

Aldridge, D., Beer, C.J., Purdie, D.A., 2012. Calcification in the planktonic foraminifera Globigerina bulloides; linked to phosphate concentrations in surface waters of the North Atlantic Ocean. Biogeosciences 9, 1725–1739. https://doi.org/10.5194/bg-9-1725-2012

Álvarez, M., Sanleón-Bartolomé, H., Tanhua, T., Mintrop, L., Luchetta, A., Cantoni, C., Schroeder, K., Civitarese, G., 2014. The CO_2 system in the Mediterranean Sea: a basin wide perspective. Ocean Sci. 10, 69–92. https://doi.org/10.5194/os-10-69-2014

Barker, S., Elderfield, H., 2002. Foraminiferal Calcification Response to Glacial-Interglacial Changes in Atmospheric CO_2. Science 297, 833–836. https://doi.org/10.1126/science.1072815

Barker, S. & Ridgwell, A. Ocean Acidification. Nature Education Knowledge 3(10), 2 (2012).

Beaufort, L., Probert, I., Buchet, N., 2007. Effects of acidification and primary production on coccolith weight: Implications for carbonate transfer from the surface to the deep ocean. Geochemistry, Geophysics, Geosystems 8.

Beer, C. J., Schiebel, R., Wilson, P.A., 2010. Technical Note: On methodologies for determining the size-normalised weight of planktic foraminifera. Biogeosciences 7, 2193–2198. https://doi.org/10.5194/bg-7-2193-2010

Beer, Christopher J., Schiebel, R., Wilson, P.A., 2010. Testing planktic foraminiferal shell weight as a surface water [CO32–] proxy using plankton net samples. Geology 38, 103–106. https://doi.org/10.1130/G30150.1

Béranger, K., Mortier, L., Gasparini, G.-P., Gervasio, L., Astraldi, M., Crépon, M., 2004. The dynamics of the Sicily Strait: a comprehensive study from observations and models. Deep Sea Research Part II: Topical Studies in Oceanography 51, 411–440. https://doi.org/10.1016/j.dsr2.2003.08.004

Bethoux, J.P., Gentili, B., Morin, P., Nicolas, E., Pierre, C., Ruiz-Pino, D., 1999. The Mediterranean Sea: a miniature ocean for climatic and environmental studies and a key for the climatic functioning of the North Atlantic. Progress in Oceanography 44, 131–146. https://doi.org/10.1016/S0079-6611(99)00023-3

Bethoux JP, Boukhary MS, Ruiz-Pino D, Morin P, Copin Montegut C (2005) Nutrient, Oxygen and Carbon Ratios, CO2 sequestration and anthropogenic forcing in the Mediterranean Sea. Hdb Environment Chemical, 5, 67–86.

Burke, J.E., Renema, W., Henehan, M.J., Elder, L.E., Davis, C.V., Maas, A.E., Foster, G.L., Schiebel, R., Hull, P.M., 2018. Factors influencing test porosity in planktonic foraminifera. Biogeosciences 15, 6607–6619. https://doi.org/10.5194/bg-15-6607-2018

Canals, M., Puig, P., de Madron, X.D., Heussner, S., Palanques, A., Fabres, J., 2006. Flushing submarine canyons. Nature 444, 354–357. https://doi.org/10.1038/nature05271

Chapman, M.R., 2010. Seasonal production patterns of planktonic foraminifera in the NE Atlantic Ocean: Implications for paleotemperature and hydrographic reconstructions: CURRENTS. Paleoceanography 25. https://doi.org/10.1029/2008PA001708

Cisneros, M., Cacho, I., Frigola, J., Canals, M., Masqué, P., Martrat, B., Casado, M., Grimalt, J.O., Pena, L.D., Margaritelli, G., Lirer, F., 2016. Sea surface temperature variability in the central-western Mediterranean Sea during the last 2700 years: a multi-proxy and multi-record approach. Clim. Past 12, 849–869. https://doi.org/10.5194/cp-12-849-2016

Cléroux, C., Lynch-Stieglitz, J., Schmidt, M.W., Cortijo, E., Duplessy, J.-C., 2009. Evidence for calcification depth change of Globorotalia truncatulinoides between deglaciation and Holocene in the Western Atlantic Ocean. Marine Micropaleontology 73, 57–61. https://doi.org/10.1016/j.marmicro.2009.07.001

de Moel, H., Ganssen, G.M., Peeters, F.J.C., Jung, S.J.A., Kroon, D., Brummer, G.J.A., Zeebe, R.E., 2009. Planktic foraminiferal shell thinning in the Arabian Sea due to anthropogenic ocean acidification? 9.

https://doi.org/10.5194/egusphere-2022-711
Preprint. Discussion started: 22 August 2022

de Villiers, S., 2004. Optimum growth conditions as opposed to calcite saturation as a control on the calcification rate and shell-weight of marine foraminifera. Marine Biology 144, 45–49. https://doi.org/10.1007/s00227-003-1183-8

Demes, K.W., Bell, S.S., Dawes, C.J., 2009. The effects of phosphate on the biomineralization of the green alga, Halimeda incrassata (Ellis) Lam. Journal of Experimental Marine Biology and Ecology 374, 123–127. https://doi.org/10.1016/j.jembe.2009.04.013

Dickson, A.G., 1990. Standard potential of the reaction: AgCl(s) +iH,(g) = Ag(s) + HCl(aq), and and the standard acidity constant of the ion HSOh in synthetic sea water from 273.15 to 318.15 K 15.

Dickson, A.G., Millero, F.J., 1987. A comparison of the equilibrium constants for the dissociation of carbonic acid in seawater media 11.

Dittert, N., Baumann, K.-H., Bickert, T., Henrich, R., Huber, R., Kinkel, H., Meggers, H., 1999. Carbonate dissolution in the deep-sea: methods, quantification and paleoceanographic application, Use of proxies in paleoceanography. Springer, pp. 255-284.

Doney, S.C., Fabry, V.J., Feely, R.A., Kleypas, J.A., 2009. Ocean Acidification: The Other CO 2 Problem. Annu. Rev. Mar. Sci. 1, 169–192. https://doi.org/10.1146/annurev.marine.010908.163834

Durrieu de Madron, X., Houpert, L., Puig, P., Sanchez-Vidal, A., Testor, P., Bosse, A., Estournel, C., Somot, S., Bourrin, F., Bouin, M.N., Beauverger, M., Beguery, L., Calafat, A., Canals, M., Cassou, C., Coppola, L., Dausse, D., D'Ortenzio, F., Font, J., Heussner, S., Kunesch, S., Lefevre, D., Le Goff, H., Martín, J., Mortier, L., Palanques, A., Raimbault, P., 2013. Interaction of dense shelf water cascading and open-sea convection in the northwestern Mediterranean during winter 2012: shelf cascading and open-sea convection. Geophys. Res. Lett. 40, 1379–1385. https://doi.org/10.1002/grl.50331

Durrieu de Madron, X., Ramondenc, S., Berline, L., Houpert, L., Bosse, A., Martini, S., Guidi, L., Conan, P., Curtil, C., Delsaut, N., Kunesch, S., Ghiglione, J.F., Marsaleix, P., Pujo-Pay, M., Séverin, T., Testor, P., Tamburini, C., the ANTARES collaboration, 2017. Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection: bnl generation by open-ocean convection. J. Geophys. Res. Oceans 122, 2291–2318. https://doi.org/10.1002/2016JC012062

Durrieu de Madron, X., Zervakis, V., Theocharis, A., Georgopoulos, D., 2005. Comments on "Cascades of dense water around the world ocean." Progress in Oceanography 64, 83–90. https://doi.org/10.1016/j.pocean.2004.08.004

Estrada, M., Marrasé, C., Latasa, M., Berdalet, E., Delgado, M., Riera, T., 1993. Variability of deep chlorophyll maximum characteristics in the Northwestern Mediterranean. Mar. Ecol. Prog. Ser. 92, 289–300. https://doi.org/10.3354/meps092289

Fox, L., Stukins, S., Hill, T., Miller, C.G., 2020. Quantifying the Effect of Anthropogenic Climate Change on Calcifying Plankton. Sci Rep 10, 1620. https://doi.org/10.1038/s41598-020-58501-w

Hassoun, A. E. R., Gemayel, E., Krasakopoulou, E., Goyet, C., Abboud-Abi Saab, M., Guglielmi, V., Touratier, F. and Falco, C.: Acidification of the Mediterranean Sea from anthropogenic carbon penetration, Deep Sea Res. Part I Oceanogr. Res. Pap., 102, 1–15, doi:10.1016/J.DSR.2015.04.005, 2015.

Hemleben, C., Spindler, M., Anderson, O.R., 1989. Modern Planktic Foraminifera.

Heussner, S., Durrieu de Madron, X., Calafat, A., Canals, M., Carbonne, J., Delsaut, N., Saragoni, G., 2006. Spatial and temporal variability of downward particle fluxes on a continental slope: Lessons from an 8-yr experiment in the Gulf of Lions (NW Mediterranean). Marine Geology 234, 63–92. https://doi.org/10.1016/j.margeo.2006.09.003

Houpert L., X. Durrieu de Madron, P. Testor, A. Bosse, F. D'Ortenzio, M.N. Bouin, D. Dausse, H. Le Goff, S. Kunesch, M. Labaste, L. Coppola, L. Mortier, P. Raimbault(2016)

https://doi.org/10.5194/egusphere-2022-711
Preprint. Discussion started: 22 August 2022

Observations of open-ocean deep convection in the NorthwesternMediterranean Sea seasonal and interannual variability of mixing and deep water masses for the 2007-2013 period. Journal of Geophysical Research - Oceans. doi : 10.1002/2016JC011857

Ipcc, 2022. The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009157964

Jonkers, L., Hillebrand, H., Kucera, M., 2019. Global change drives modern plankton communities away from the pre-industrial state. Nature 570, 372–375. https://doi.org/10.1038/s41586-019-1230-3

Kiss, P., Jonkers, L., Hudáčková, N., Reuter, R.T., Donner, B., Fischer, G., Kucera, M., 2021. Determinants of Planktonic Foraminifera Calcite Flux: Implications for the Prediction of Intra- and Inter-Annual Pelagic Carbonate Budgets. Global Biogeochem Cycles 35. https://doi.org/10.1029/2020GB006748

Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M., Gattuso, J., 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Glob Change Biol 19, 1884–1896. https://doi.org/10.1111/gcb.12179

Kuroyanagi, A., Kawahata, H., 2004. Vertical distribution of living planktic foraminifera in the seas around Japan. Marine Micropaleontology 53, 173–196. https://doi.org/10.1016/j.marmicro.2004.06.001

Lazzari, P., Mattia, G., Solidoro, C., Salon, S., Crise, A., Zavatarelli, M., Oddo, P. and Vichi, M.: The impacts of climate change and environmental management policies on the trophic regimes in the Mediterranean Sea: Scenario analyses, J. Mar. Syst., 135, 137–149, doi:10.1016/j.jmarsys.2013.06.005, 2014.

Lejeusne C, Chevaldonné P, Pergent-Martini C, Boudouresque CF, PérezT(2009) Climate change effects on a miniature ocean: the highly diverse, highly impacted Mediterranean Sea. Trends in Ecology & Evolution, 25, 250–260.

Lirer, F., Sprovieri, M., Vallefuoco, M., Ferraro, L., Pelosi, N., Giordano, L., Capotondi, L., 2014. Planktic foraminifera as bio-indicators for monitoring the climatic changes that have occurred over the past 2000 years in the southeastern Tyrrhenian Sea. Integrative Zoology 9, 542–554. https://doi.org/10.1111/1749-4877.12083

Lombard, F., da Rocha, R.E., Bijma, J., Gattuso, J.-P., 2010. Effect of carbonate ion concentration and irradiance on calcification in planktic foraminifera. Biogeosciences 7, 247–255. https://doi.org/10.5194/bg-7-247-2010

Lombard, F., Erez, J., Michel, E., Labeyrie, L., 2009. Temperature effect on respiration and photosynthesis of the symbiont-bearing planktic foraminifera Globigerinoides ruber , Orbulina universa , and Globigerinella siphonifera. Limnol. Oceanogr. 54, 210–218. https://doi.org/10.4319/lo.2009.54.1.0210

Lombard, F., Labeyrie, L., Michel, E., Bopp, L., Cortijo, E., Retailleau, S., Howa, H., Jorissen, F., 2011. Modelling planktic foraminifer growth and distribution using an ecophysiological multi-species approach. Biogeosciences 8, 853–873. https://doi.org/10.5194/bg-8-853-2011

Loulergue, L., Parrenin, F., Blunier, T., 2007. New constraints on the gas age-ice age difference along the EPICA ice cores, 0–50 kyr. Clim. Past 14.

Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K., Stocker, T.F., 2008. High-resolution carbon dioxide concentration record 650,000–800,000 years before present. Nature 453, 379–382. https://doi.org/10.1038/nature06949

Margaritelli, G., 2020. Globorotalia truncatulinoides in Central - Western Mediterranean Sea during the Little Ice Age. Marine Micropaleontology 11.

Marshall, B.J., Thunell, R.C., Henehan, M.J., Astor, Y., Wejnert, K.E., 2013. Planktic foraminiferal area density as a proxy for carbonate ion concentration: A calibration study

https://doi.org/10.5194/egusphere-2022-711
Preprint. Discussion started: 22 August 2022

using the Cariaco Basin ocean time series: foraminiferal area density [CO_3^{2-}] proxy. Paleoceanography 28, 363–376. https://doi.org/10.1002/palo.20034

Marty, J.-C., Chiavérini, J., Pizay, M.-D., Avril, B., 2002. Seasonal and interannual dynamics of nutrients and phytoplankton pigments in the western Mediterranean Sea at the DYFAMED time-series station (1991–1999). Deep Sea Research Part II: Topical Studies in Oceanography 49, 1965–1985. https://doi.org/10.1016/S0967-0645(02)00022-X

Mehrbach, C., Culberson, C.H., Hawley, J.E., Pytkowicx, R.M., 1973. Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. Limnol. Oceanogr. 18, 897–907. https://doi.org/10.4319/lo.1973.18.6.0897

Meier, K.J.S., Beaufort, L., Heussner, S., Ziveri, P., Université, A.-M., 2014. The role of ocean acidification in Emiliania huxleyi coccolith thinning in the Mediterranean Sea 13. Biogeosciences, 11, 2857–2869, 2014. https://doi:10.5194/bg-11-2857-2014

Millero, F.J., Morse, J., Chen, C.-T., 1979. The carbonate system in the western Mediterranean sea. Deep Sea Research Part A. Oceanographic Research Papers 26, 1395-1404.

Millot, C., 1999. Circulation in the Western Mediterranean Sea. Journal of Marine Systems 20, 423–442. https://doi.org/10.1016/S0924-7963(98)00078-5

Millot, C., 1991. Mesoscale and seasonal variabilities of the circulation in the western Mediterranean. Dynamics of Atmospheres and Oceans 15, 179–214. https://doi.org/10.1016/0377-0265(91)90020-G

Monaco A., X. Durrieu de Madron, O. Radakovitch, S. Heussner& J. Carbonne (1999). Origin and variability of downward biogeochemical fluxes on the Rhone continental margin (NW Mediterranean)). Deep-Sea Research I, 46: 1483-1512.

Moy, A.D., Howard, W.R., Bray, S.G., Trull, T.W., 2009. Reduced calcification in modern Southern Ocean planktic foraminifera. Nature Geosci 2, 276–280. https://doi.org/10.1038/ngeo460

Nguyen, T.M.P., Petrizzo, M.R., Speijer, R.P., 2009. Experimental dissolution of a fossil foraminiferal assemblage (Paleocene–Eocene Thermal Maximum, Dababiya, Egypt): Implications for paleoenvironmental reconstructions. Marine Micropaleontology 73, 241–258. https://doi.org/10.1016/j.marmicro.2009.10.005

Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.-K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.-F., Yamanaka, Y., Yool, A., 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437, 681–686. https://doi.org/10.1038/nature04095

Osborne, E.B., Thunell, R.C., Marshall, B.J., Holm, J.A., Tappa, E.J., Benitez-Nelson, C., Cai, W., Chen, B., 2016. Calcification of the planktic foraminifera Globigerina bulloides and carbonate ion concentration: Results from the Santa Barbara Basin. Paleoceanography 31, 1083–1102. https://doi.org/10.1002/2016PA002933

Paasche, E. and Brubank, S.: Enhanced calcification in the coccol- ithophorid Emiliania huxleyi (Haptophyceae) under phosphorus limitation, Phycologia, 22, 324–330, 1994.

Pallacks, S., Anglada-Ortiz, G., Belen Martrat, P. Graham Mortyn, Grelaud, M., Incarbona, A., Schiebel, R., Garcia-Orellana, J., Ziveri, P., 2020. Western Mediterranean marine cores show that foraminiferal mass and flux are being influenced by enhanced anthropogenic pressure. https://doi.org/10.13140/RG.2.2.26245.99045

Parrenin, F., Jouzel, J., Kawamura, K., Lemieux-Dudon, B., Loulergue, L., Masson-Delmotte, V., Narcisi, B., Raisbeck, G., Raynaud, D., Ruth, U., Schwander, J., Severi, M., Spahni, R., Steffensen, J.P., Svensson, A., Udisti, R., Waelbroeck, C., Wolff, E., 2007. The EDC3 chronology for the EPICA Dome C ice core. Clim. Past 13.

https://doi.org/10.5194/egusphere-2022-711
Preprint. Discussion started: 22 August 2022

Pujol, C., Grazzini, C.V., 1995. Distribution patterns of live planktic foraminifers as related to regional hydrography and productive systems of the Mediterranean Sea. Marine Micropaleontology 25, 187–217. https://doi.org/10.1016/0377-8398(95)00002-I

Rigual-Hernández, A.S., Sierro, F.J., Bárcena, M.A., Flores, J.A., Heussner, S., 2012. Seasonal and interannual changes of planktic foraminiferal fluxes in the Gulf of Lions (NW Mediterranean) and their implications for paleoceanographic studies: Two 12-year sediment trap records. Deep Sea Research Part I: Oceanographic Research Papers 66, 26–40. https://doi.org/10.1016/j.dsr.2012.03.011

Rigual-Hernández, A.S., Trull, T.W., Flores, J.A., Nodder, S.D., Eriksen, R., Davies, D.M., Hallegraeff, G.M., Sierro, F.J., Patil, S.M., Cortina, A., Ballegeer, A.M., Northcote, L.C., Abrantes, F., Rufino, M.M., 2020. Full annual monitoring of Subantarctic Emiliania huxleyi populations reveals highly calcified morphotypes in high-CO2 winter conditions. Scientific Reports 10, 2594.

Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L., Wanninkhof, R., Wong, C.S., Wallace, D.W.R., Tilbrook, B., Millero, F.J., Peng, T.-H., Kozyr, A., Ono, T., Rios, A.F., 2004. The Oceanic Sink for Anthropogenic CO 2. Science 305, 367–371. https://doi.org/10.1126/science.1097403

Schiebel, R., 2002. Planktic foraminiferal sedimentation and the marine calcite budget: Marine calcite budget. Global Biogeochem. Cycles 16, 3-1-3–21. https://doi.org/10.1029/2001GB001459

Schiebel, R., Hemleben, C., 2017. Planktic Foraminifers in the Modern Ocean. Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-50297-6

Schiebel, R., Hemleben, C., 2000. Interannual variability of planktic foraminiferal populations and test flux in the eastern North Atlantic Ocean (JGOFS) 44.

Schiebel, R., Hemleben, C., n.d. Modern planktic foraminifera 14.

Schiebel, R., Waniek, J., Zeltner, A., Alves, M., 2002. Impact of the Azores Front on the distribution of planktic foraminifers, shelled gastropods, and coccolithophorids. Deep Sea Research Part II: Topical Studies in Oceanography 49, 4035–4050. https://doi.org/10.1016/S0967-0645(02)00141-8

Schiebel, R., Waniek, J., Bork, M., and Hemleben, C.: Planktic foraminiferal production stimulated by chlorophyll redistribution and entrainment of nutrients, Deep-Sea Res. Pt. I, 48, 721–740, 2001.

Schmidt, D. N., Renaud, S., Bollmann, J., Schiebel, R., and Thierstein, H. R.: Size distribution of Holocene planktic foraminifer assemblages:biogeography, ecology and adaptation, Mar.Micropaleontol., 5, 319–338, 2004.

Schneider A, Tanhua T, Körtzinger A, Wallace DWR (2010) High anthropogenic carbon content in the eastern Mediterranean. Journal of Geophysical Research, 115, C12050. doi:10.1029/2010JC006171.

Spero, H. J., Lerche, I., and Williams, D. F.: Opening the carbon isotope 'vital effect' box. 2. Quantitative model for interpreting foraminiferal carbon isotope data, Paleoceanography, 6, 639655, 1991.

Wacker L, Fülöp RH, Hajdas I, Molnár M, Rethemey- er J. 2013b. A novel approach to process carbonate samples for radiocarbon measurements with helium carrier gas. Nuclear Instruments and Methods in Physics Research B 294:214–7.

Zarkogiannis, S.D., Iwasaki, S., Rae, J.W.B., Schmidt, M.W., Mortyn, P.G., Kontakiotis, G., Hertzberg, J.E., Rickaby, R.E.M., 2022. Calcification, Dissolution and Test Properties of Modern Planktic Foraminifera From the Central Atlantic Ocean. Front. Mar. Sci. 9, 864801. https://doi.org/10.3389/fmars.2022.864801

Zeppenfeld, K., 2019. Inhibition of calcite precipitation by orthophosphate at different water flow 7.

https://doi.org/10.5194/egusphere-2022-711
Preprint. Discussion started: 22 August 2022

1124 Ziveri P (2012) Research turns to acidification and warming in the Mediterranean Sea, IMBER
1125 (Integrated Marine Biogeochemistry and Ecosystem Research). News- letter, Issue 20,
1126 May 2012. http://www.imber.info/index.php/News/Newslet- ters/Issue-n-20-May-2012.