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Planktic foraminifera assemblage composition and flux dynamics inferred from an annual sediment trap record in the Central Mediterranean Sea

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Abstract

The Sicily Strait, located in the Central Mediterranean Sea, represents a key point for the regional oceanographic circulation as it is considered the sill that separates the western and eastern basins. Therefore, it is considered a unique zone regarding the well-documented west-to-east Mediterranean productivity gradient. Here we document the planktic foraminifera assemblages retrieved by the C01 sediment trap between November 2013 and October 2014. 19 samples from the sediment trap deployed at a water depth of around 400 m have been used. More than 3700 individuals and 15 different species have been identified. *Globorotalia inflata*, *Globorotalia truncatulinoides*, *Globigerina bulloides*, *Globigerinoides ruber* and *ruber* (pink) were the five main species identified, accounting for more than 85% of the total foraminifera.

The total planktic foraminifera flux mean value was 630 shells m^{-2} d^{-1}, with a minimum value of 45 shells m^{-2} d^{-1} displayed during late autumn 2013 and a maximum of 1890 shells m^{-2} d^{-1} reached during spring 2014. Most of the species fluxes followed a similar pattern. This is likely the result of the regional oceanographic configuration and the marked seasonality in the surface circulation. During spring and winter, the Atlantic waters dominate the surface circulation, bringing cool and nutrient enriched waters. This results in a planktic foraminifera flux increase and a dominance of western basin taxa. During summer and autumn, the circulation is dominated by the eastern warm and oligotrophic Levantine water, which results in planktic foraminifera flux decrease and the dominance of easter basin species. Our comparison with satellite derived SST and chlorophyll-*a* data showed that *G. inflata* was associated with cool and nutrient rich conditions, while both *G. ruber* morphotypes were associated with warm and oligotrophic conditions. However, no trends were identified for *G. truncatulinoides* or *G. bulloides*.

In addition, a comparison of the Sicily Strait data with other Mediterranean time series located in the Alboran Sea, Gulf of Lions and the Levantine basin was carried out. Our data indicated that the annualized planktic foraminifera flux was lower than in the westernmost Alboran Sea but higher than in the easternmost Levantine basin. However, the Sicily Strait species diversity was the highest

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among the compared zones, highlighting the influence of the different basins and its transitional aspect from a planktic foraminifera population perspective.
Finally, we compared the sediment trap planktic foraminifera assemblage with the assemblages from seabed sediment located in the vicinity of the Sicily Strait. Our results showed that the sediment trap population significantly differed from the assemblages in the seabed sediment. The deep-dwelling species dominated the sediment trap samples, while eutrophic and oligotrophic species were significantly more abundant in the core-tops, highlighting a potential effect of the recent Mediterranean environmental change, such as warming and a potential shift in the oceanographical conditions on the planktic foraminifera population.

1. Introduction

Planktic foraminifera are a group of marine calcareous single-celled protozoans with a cosmopolitan distribution. Around 50 morphospecies of planktic foraminifera have been described in today's oceans (Schiebel and Hemleben, 2017), and although most of those species are surface dwellers, some species can be found in waters below 2000 m (Schiebel and Hemleben, 2005). Their abundance and distribution are affected by a wide array of factors, such as temperature, salinity, chlorophyll-*a* and nutrient concentrations, among others (Hemleben et al., 1989; Schiebel and Hemleben, 2005). According to Schiebel, (2002), the production and export of their calcareous shells account for 23 to 56% of the open marine $CaCO_3$ flux, thereby playing a key role in the marine carbon cycle. Moreover, the high preservation potential of their shells makes them one of the most used groups for multi-proxy studies. Numerous paleoclimatic (e.g. Barker and Elderfield, 2002; Lirer et al., 2014; Margaritelli et al., 2020; Sierro et al., 2005) and paleoceanographic (Cisneros et al., 2016; Ducassou et al., 2018; Margaritelli et al., 2022; Toucanne et al., 2007) reconstructions have used planktic foraminifera as a proxy. In addition, their capacity to reflect the water column's chemical properties has propelled studies that have focused on the impact of recent climate and environmental variability on the water column in different parts of the ocean (e.g. Azibeiro et al., 2023; Beer et al., 2010; Bijma et al., 2002; Chapman, 2010; Marshall et al., 2013; Osborne et al., 2016). As marine calcifying organisms, they are considered particularly vulnerable to the ongoing ocean warming and acidification (Bijma et al., 2002; Fox et al., 2020). Shell calcification of several foraminifera species has been showed to decrease in response to ocean acidification, and therefore, changes in the weight of their shells are considered an indicator of the ocean acidification impact on different timescales (Béjard et al., 2023; de Moel et al., 2009; Fox et al., 2020; Kroeker et al., 2013; Moy et al., 2009; Pallacks et al., 2023). In contrast, ocean warming has been proposed to produce an opposite effect on foraminifera calcification, as some studies have documented that an increase in water temperature results in larger shells and enhanced growth rates (Lombard et al., 2011, 2009; Schmidt et al., 2006).
Despite the wide array of studies focused on planktic foraminifera ecology and distribution, several aspects of their ecology remain uncertain, such as their ecological tolerance limits (Mallo et al., 2017), their geographical and temporal distributions and contribution to the marine biogeochemical cycles (Jonkers and Kučera, 2015). As major contributors to the pelagic calcite production (Schiebel, 2002), understanding their life cycle on different time scales is essential for understanding the role

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they play in the marine carbon cycle and the impact of environmental change on these organisms. In this regard, sediment traps represent a powerful tool to improve our knowledge of planktic foraminifera ecology and their impact on the biogeochemical cycles, as they allow the monitoring of foraminifera shell fluxes for extended periods, thereby allowing to document their seasonal and interannual variability and estimate their contribution to annual budgets of carbonate export to the seafloor (Jonkers et al., 2019).

The Mediterranean Sea is a semi-enclosed sea often considered a "miniature ocean" (Bethoux et al., 1999) from an oceanographic point of view or a "laboratory basin" (Bergamasco and Malanotte-Rizzoli, 2010) for studying processes occurring on a global scale. In addition, it is supersaturated regarding calcite (Álvarez et al., 2014), a key aspect in foraminifera studies, as this parameter favors shell preservation and represents one of the main environmental controls on planktic foraminifera abundance and calcification (Aldridge et al., 2012; Marshall et al., 2013; Osborne et al., 2016). These features make it an interesting zone of the global ocean to study the life cycle and seasonal response to changing environmental conditions of calcifying plankton. The Sicily Strait, in the central Mediterranean, is the sill that divides the Mediterraean into its western and easter basins. It is a choke point for the regional surface and deep-water circulation (Malanotte-Rizzoli et al., 2014) and a transition region regarding the well-known west-to-east oligotrophy gradient, functioning as a "biological corridor" (Siokou-Frangou et al., 2010) known in the Mediterranean (Navarro et al., 2017).

Despite these characteristics, time series that focused on planktic foraminifera in the Mediterranean Sea are scarce. So far, the best monitored regions are the Alboran Sea (Bárcena et al., 2004; Hernández-Almeida et al., 2011), the Gulf of Lions (Rigual-Hernández et al., 2012), and more recently, the Levantine Basin (Avnaim-Katav et al., 2020). The latter studies showed that planktic foraminifera followed an unimodal distribution with maximum shell export occurring during the months of April-May, February-March and February respectively, which agreed with the local hydrographic conditions. However, the central Mediterranean remains understudied and poorly documented regarding both continuous time series and planktic foraminifera dynamics.

Therefore, this work aims to provide new planktic foraminifera data from a sediment trap mooring line located in the Strait of Sicily to improve the current knowledge about their community composition and seasonal patterns in the central Mediterranean. For that purpose, here we document the magnitude and composition of planktic foraminifera fluxes identified in the >150 μm fraction (i.e. the most commonly used size fraction for studying planktic foraminifera distribution) from November 2013 to October 2014. We compare our planktic foraminifera data with a suite of environmental parameters to assess the main environmental drivers that control the seasonal variations in the composition and abundance of the sinking planktic foraminifera assemblages. Lastly, to provide further insight on a regional and global scale of the planktic foraminifera association and fluxes identified here, we compare our data with other time series from the Mediterranean, Atlantic Ocean and other regions of the world's oceans.

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2. Study area

The Mediterranean is an elongated, semi-enclosed sea with an anti-estuarine circulation. The Mediterranean Sea is a concentration basin (Bethoux et al., 1999) in which the evaporation exceeds the freshwater inputs, forcing a negative hydrological balance (Robinson and Golnaraghi, 1994). This negative balance is compensated by the entrance of surface oceanic water from the Atlantic Ocean through the Strait of Gibraltar. The colder and nutrient richer Atlantic Waters (AW) spread eastward into the Mediterranean basin (Millot, 1991), where they progressively become warmer, saltier and more oligotrophic as they mix with resident waters (Modified Atlantic Waters – MAW. Also known as Atlantic Waters – AW). MAW circulate following a cyclonic circuit along the Algerian coast (Algerian Current – AC) (Malanotte-Rizzoli et al., 2014; Millot, 1999) and divide into two main branches at the entrance of the Sicily Strait (Figure 1a). One of these branches spreads into the northwestern part of the basin, into the Tyrrhenian Sea, where it continues its path cyclonically. The second branch flows south of Sicily into the Ionian Sea (Lermusiaux and Robinson, 2001). In the Sicily channel itself, the water masses are split again in two different streams (Béranger et al., 2004): (i) the Atlantic Tunisian Current (ATC) that flows to the southeast following the African coast; and (ii) the Atlantic Ionian Stream (AIS) that flows into the deep eastern part of the basin (Figure 1b) and contributes to the MAW transport in the eastern Mediterranean (Jouini et al., 2016; Lermusiaux and Robinson, 2001).

The Sicily Strait is located in the central Mediterranean (Figure 1a) and acts as a sill that topographically separates the western and eastern Mediterranean basins. The circulation through the Sicily Strait is characterized by water masses that flow in opposite directions at different depths of the water column (Béranger et al., 2004). The Levantine Intermediate Water (LIW), which enters the strait from the Ionian Sea, occupies the deeper part of the water column along with occasional thin Eastern Mediterranean Deep Water layers (Gasparini et al., 2005; Lermusiaux and Robinson, 2001). The Ionian Water (IW) can be present at intermediate depths (Figure 1), while the MAW cover the surface to subsurface part of the water column (Warn-Varnas et al., 1999). Temperature and salinity range from 15-17 °C and 37.2-37.8 psu for the MAW, 15-16.5 °C and 37.8-38.4 psu for the IW and 13.7-13.9°C and 38.7-38.8 psu for the LIW (Astraldi et al., 2002; Bouzinac et al., 1999; Robinson et al., 1999). Lastly, it is important to note, that the surface circulation in the Sicily Strait presents a large seasonal variability concerning the water masses distribution (Béranger et al., 2004; Lermusiaux and Robinson, 2001). Surface circulation experiences a substantial seasonality in the Sicily Strait: during late autumn to late spring, the MAW dominate the surface circulation, allowing nutrient and chlorophyll-enriched waters to enter the strait (Astraldi et al., 2002; D'Ortenzio, 2009). In turn, summer and autumn are dominated by LIW waters. Deep-water circulation remains relatively stable on a seasonal scale (Béranger et al., 2004) with a continuous LIW presence over the year. Finally, during summer, an upwelling settles in the Sicily Strait, allowing the impoverished LIW to reach the surface (Lermusiaux and Robinson, 2001).

Regarding its nutrient distributions, the Mediterranean Sea is generally considered an oligotrophic to ultraoligotrophic sea (Krom et al., 1991). However, this oligotrophy is not homogenous and displays a clear west-to-east gradient which is reflected in the nutrient concentration and algal biomass accumulation derived from colour remote sensing (Navarro et al., 2017; Siokou-Frangou et

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al., 2010). The eastern part of the Mediterranean is considered to be more nutrient depleted than the western part of the basin (Krom et al., 2005; Raimbault et al., 1999), with N:P ratios around 50:1 (Krom et al., 2005). At times of maximum annual algal concentration, primary productivity (PP) in the Levantine Basin reaches values of ca. 0.1 g C $m^{-2}d^{-1}$ (Hazan et al., 2018). This value is substantially lower than those recorded in the high productivity regions of the western basin such as the Gulf of Lions, ca. 0.4-0.65 g C $m^{-2}d^{-1}$ (Gaudy et al., 2003; Rigual-Hernández et al., 2012), or the Alboran Sea, ca. 0.3-1.3 g C $m^{-2}d^{-1}$ (Bárcena et al., 2004; Morán and Estrada, 2001) during the corresponding period.

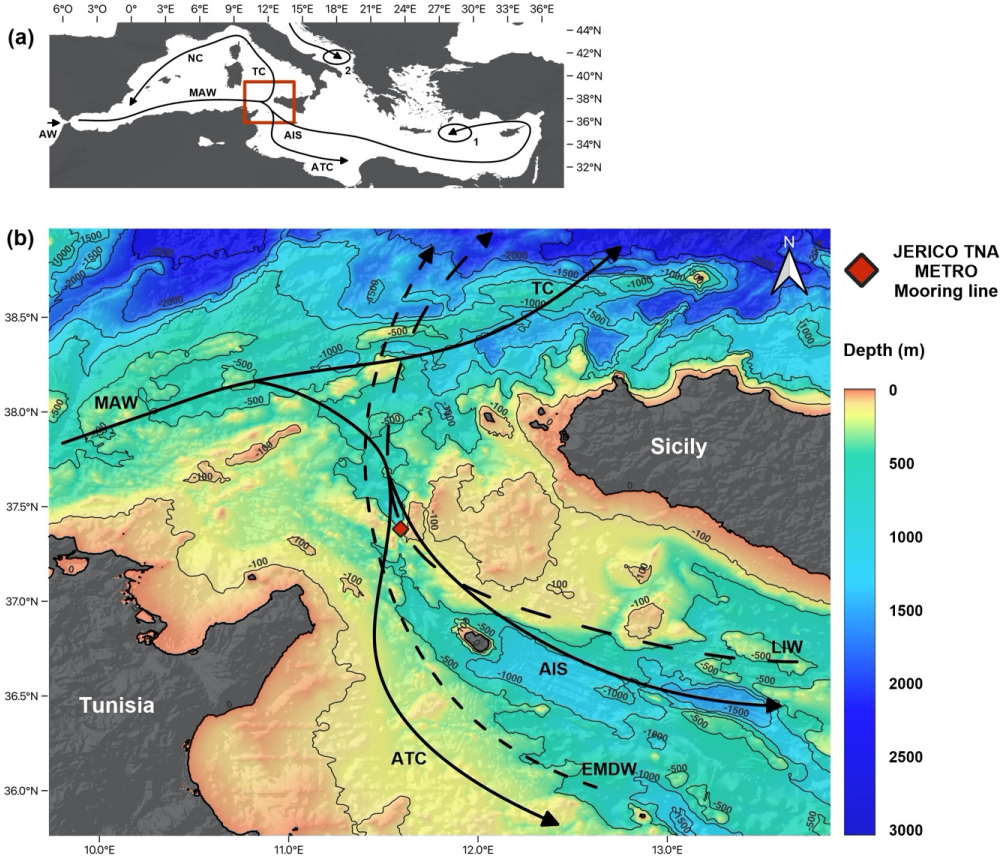

Figure 1. (a) Mediterranean Sea general surface circulation (Astraldi et al., 2002; Béranger et al., 2004; Incarbona et al., 2011; Macias et al., 2019) and location of the study zone. The ellipses show the deep-water formation zones for the LIW (1) and the EMDW (2). **(b)** Regional oceanographic and geographic setting of the Sicily Strait. The red diamond represents the location of the JERICO TNA METRO mooring line in which the C01 sediment trap is located. Black continuous lines represent surface circulation, while dashed lines show deep-water circulation. The difference in the dashed lines period stands for the occasional aspect of the EMDW. The topographic model was downloaded from the GEBCO database.

3. Material and methods

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3.1. Field experiments

The C01 sediment trap is part of the JERICO TNA METRO mooring line (Figure 1b) which is maintained by ISMAR-CNR in the Sicily Channel (37.38°N, 11.59°E) thanks to TransNational Access activity in the FP7 JERICO project (Mediterranean sediment Trap Observatory). The mooring line was equipped with a sediment trap located 413 m below the sea surface in a water column of around 450 m deep. The sediment trap was a PPS3/3 model, conical in shape with a 2.5 height/diameter ratio and equipped with 12 sampling cups. Further information about this sediment trap configuration and model can be found in Heussner et al., (2006, 1990).

Here we present data from November 2013 to mid-October 2014. The sampling period was 15 to 16 days from November 2013 to July 2014 and from September 2014 to October 2014. Between July 2014 and September 2014, the sampling was set to 31 days. Before deployment and to limit the degradation of the material caught, sampling cups from both mooring lines were filled with a 5% formalin solution prepared with 40% formaldehyde mixed with 0.45 μm filtered seawater. The solution was then buffered with sodium borate to keep the pH stable and avoid the dissolution of carbonate.

3.2 Processing of sediment trap samples

After the recovery, the cups were stored at 2-4°C until their processing. First, the few swimmers that entered the trap were removed with a 1 mm nylon mesh for the big individuals. Then, the formaldehyde was removed by centrifugation and the cup samples were freeze-dried and weighted. A total of 19 samples from the sediment trap were processed for micropaleontological analyses in the micropaleontology laboratory of the Geology department at the University of Salamanca. The samples consisted of aliquots of 1/6 of the original mooring line cups and were preserved in seawater, with a pH between 7.6 and 7.8. All samples were first wet sieved to separate the <63μm fraction and then dry sieved to separate the 63-150 and >150 μm fractions. The washing was carried out with a potassium phosphate-buffered solution (pH= 7.5) to prevent carbonate dissolution.

3.3 Planktic foraminifera identification, flux calculations and imaging

The planktic foraminifera identification (Plate 1) and counting to the species level were carried out in the >150 μm fraction using a microscope (Leica Wild M3B). To have a representative picture of the planktic foraminifera population, the complete samples were analyzed (i.e. no splits were applied). Identification was carried out according to Schiebel and Hemleben, (2017). A total of 15 species were identified (Plate 1): *Globigerinella siphonifera*, *G. calida*, *Globigerinoides sacculifer*, *G. ruber*, *G. ruber* (pink), *Globoturborotalita tenella*, *G. rubescens*, *Orbulina universa, Globorotalia truncatulinoides*, *G. inflata*, *G. scitula*, *Globigerina bulloides* (+ *G. falconensis*), *Neogloboquadrina incompta* and *Turborotalita quinqueloba* (Plate 1). In addition, benthic foraminifera shells were identified to the lowest taxonomic level possible and counted.

The foraminifera fluxes were calculated according to the following formula:

$$PF\ (shells\ m^{-2}\ d^{-1}) = \frac{(N\ x\ aliq.)\ x\ SD^{-1}}{0.1256}$$

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"PF" stands for planktic foraminifera, "N" accounts for the number of individuals identified, "aliq." refers to the aliquot (1/6 for all samples) and "SD" represents the sampling interval that the sediment trap cup stayed open. Relative abundance for each species was also calculated for all samples.

To showcase the species collected by the traps (Plate 1), foraminifera imaging was carried out using a Nikon SMZ18 stereomicroscope equipped with a Nikon DS-Fi3 camera and the image processing software NISElements (version 5.11.03).

3.4 Environmental and planktic foraminifera data

To assess the possible relationship of planktic foraminifera fluxes with environmental variability, key environmental parameters, namely satellite-derived chlorophyll-*a* and Sea Surface Temperatures (SSTs) were retrieved from global data sets. Satellite-derived chlorophyll-*a* concentration (mg m^{-3}) were obtained from MODIS L3m satellite through NASA's Giovanni web interface with an 8-day and 4 km resolution for a 0.2 x 0.2° area around the mooring location between 01/10/2013 to 01/11/2014. Additionally, sea surface temperature SST (°C) were also obtained from the same site with the same resolution to use as a proxy for water temperature and water column stratification.

Additionally, to put into context our observations with the regional variability of planktic foraminifera communities in the Mediterranean Sea, modern planktic foraminifera flux datasets were retrieved from different sites. Levantine basin foraminifera fluxes (LevBas) were obtained from Avnaim-Katav et al., (2020), the Gulf of Lions ones (LCD and PLA) from Rigual-Hernández et al., (2012) and finally the Alboran Sea fluxes (ALB 1F and ALB 5F) from both Bárcena et al., (2004) and Hernández-Almeida et al., (2011). All the foraminifera fluxes concerned the >150 μm fraction, except the ones from the Levantine basin, which represented the >125 μm fraction (Figure 6).

Finally, core-top data from the ForCenS database (Siccha and Kucera, 2017) was used to compare the planktic foraminifera abundance patterns from the C01 sediment trap with the seabed sediment. Only seabed sediment located on a 2.5 degree difference in both latitude and longitude was selected to compare our data with sites in the vicinity of the Sicily Strait. This corresponded to a total of 16 core-tops part of the MARGO database. The complete details of the latter can be found in the Supplementary data.

3.5 Statistical analysis

To have uninterrupted monthly and daily values from NASA's Giovanni environmental parameters that coincide with the mean sampling date from the sediment traps, a daily resampling has been carried out using QAnalySeries software.

Pearson correlation and *p*-value tests were carried out with the Past4 program. A $p < 0.05$ was used to denote statistical significance.

In addition, a canonical correspondence analysis (CCA) was also used to estimate the influence of both SST and chlorophyll-*a* on foraminifera fluxes. A CCA is a correspondence analysis of a species matrix where each site has given values for one or more environmental variables (SST and chlorophyll-*a* concentration in this case). The ordination axes are linear combinations of the

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environmental variables. A CCA is considered an example of direct gradient analysis, where the gradient in environmental variables is known and the species abundances/fluxes are considered to be a response or to be affected by this gradient (Nielsen, 2000).

Additionally, to evaluate the magnitude of the foraminifera fluxes across major regions of the Mediterranean, an estimation of the annual planktic foraminifera flux (shells m^{-2} y^{-1}) was calculated using the sediment trap data from the literature review and our study. To that purpose, the data was annualized according to the following formula:

$$Annual\ PFF = \sum(PF\ x\ SD + cPF\ x\ mSD)$$

Where "PFF" stands for planktic foraminifera flux (shells m^{-2} d^{-1}), "SD" accounts for sampling days, "cPF" represents calculated planktic foraminifera flux (shells m^{-2} d^{-1}) and "mSD" stands for missing sampling days. "cPF" calculation depended on the site. For the datasets retrieved from the Sicily Strait and the Levantine basin, less than 20 sampling days were missing, so the corresponding planktic foraminifera fluxes were replaced by the mean of the first and last flux values recorded. The two datasets from the Alboran Sea displayed more than 70 missing days, so the corresponding flux values used were a mean of the two closest months to the missing data. Concerning the two time series from the Gulf of Lions, they covered more than one year. Therefore, a mean year was estimated: a mean monthly flux value was calculated for all 12 months based on all the available measurements and then multiplied by the corresponding mean duration of each month, and then, all monthly fluxes were added together.

To compare the species richness and diversity across the previously described sites, Simpson (D) and Shannon/Weiner (H/W) indexes were calculated. Here, we reported the inverse Simpson index (1-D). None of these indexes were calculated for the Alboran Sea sites (ALB 1F and ALB 5F) because only information about the four main species was documented (Bárcena et al., 2004; Hernández-Almeida et al., 2011).

Finally, the squared chord distance (SCD) between the C01 sediment trap and every core top sample downloaded from the ForCenS database (Siccha and Kucera, 2017) planktic foraminifera relative abundance was calculated. It is a widely used metric in palaeoecological and paleontological studies as it is the most effective index for identifying the closest analogues in planktic foraminifera datasets (Prell, 1985). This is mainly because it shows the best balance in weighing the contribution of abundant and rare species in a given association (Jonkers et al., 2019). In this study, SCD values lower than 0.25 have been considered as reliable analogues (Ortiz and Mix, 1997).

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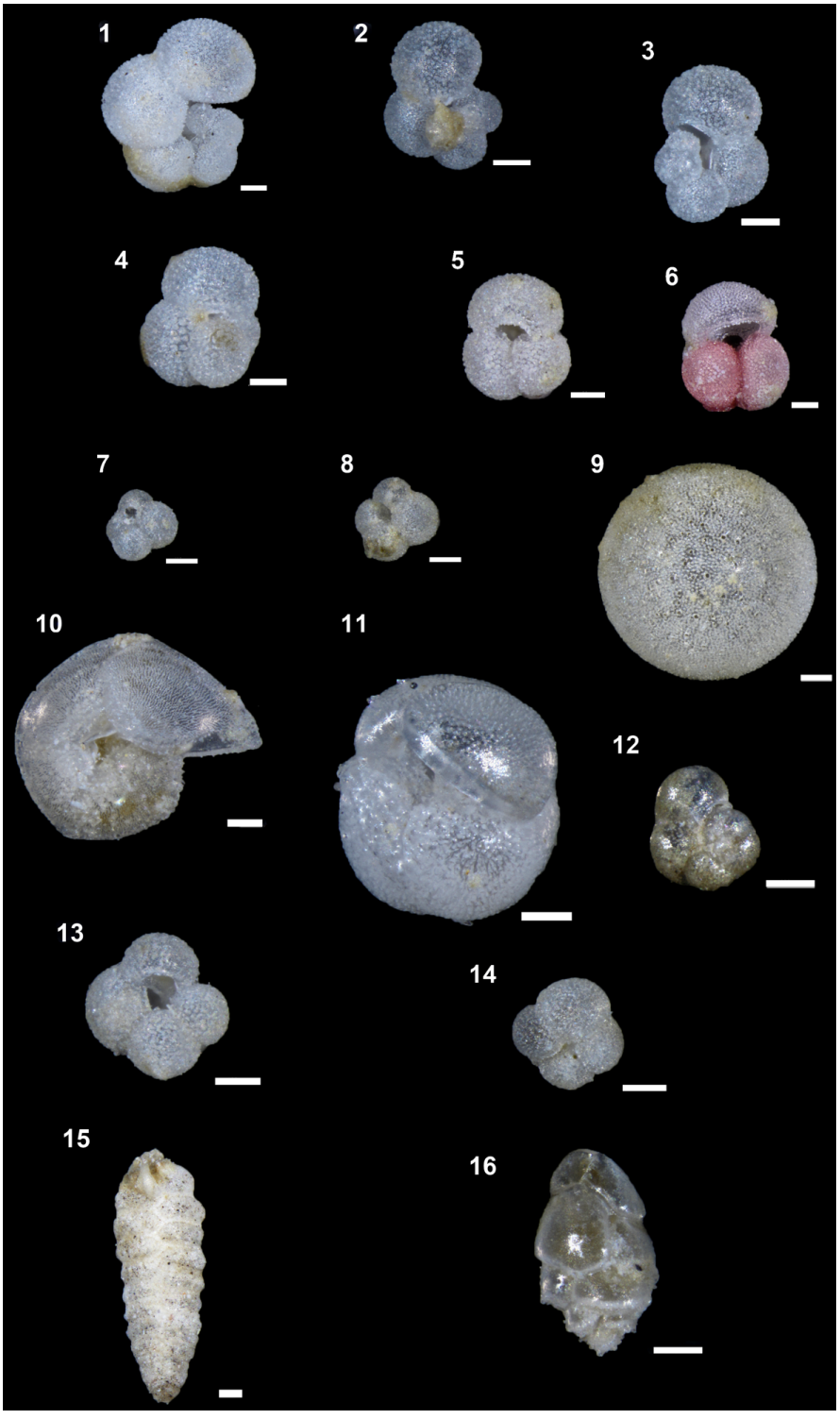

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Plate 1. Planktic **(1-14)** and the most common benthic foraminifera **(15-16)** species collected from the C01 sediment trap. The white scale bars on all figures represent 100 μm. **(1)** *G. siphonifera,* side view. **(2)** *G. calida*, umbilical view. **(3)** *G. calida*, apertural view. (**4**) *G. sacculifer*, umbilical view. (**5**) *G. ruber*, umbilical view. **(6)** *G. ruber* (pink), umbilical view. **(7)** *G. tenella*, umbilical view. **(8)** *G. rubescens*, umbilical view. **(9)** *O. universa*. **(10)** *G. truncatulinoides*, umbilical view. **(11)**. *G. inflata*, apertural view. **(12)** *G. scitula*, umbilical view. **(13)** *G. bulloides*, umbilical view. **(14)** *N. incompta*, umbilical view. **(15)** *Textularia spp.* **(16)** *Bulimina marginata*, apertural view.

4. Results

4.1 General considerations of the planktic foraminifera assemblages

Table 1. Counts and key statistics of the planktic foraminifera species and the benthic foraminifera group from the > 150 μm fraction identified in the 19 sediment trap cups of the JERICO site. Mean, maximum (Max), minimum (Min), standard deviation (SD) of the relative abundance and fluxes. Raw counts also include a total and % of the total description.

	G. sipho.	*G. cal.*	*G. sacc.*	*G. rub.*	*G. rub. (p.)*	*G. ten.*	*G. rubesc.*	*O. univ.*	*G. truncat.*	*G. inf.*	*G. sci.*	*G. falco.*	*G. bull.*	*N. inc.*	*T. quin.*	Benthics	Total planktic
COUNTS (N)																	
Mean	2.5	3.1	4.1	6.5	5.2	1.1	3.7	3.9	37.0	109.2	1.3	0.1	16.2	1.5	0.5	7.4	195.9
Max	6	11	10	22	40	5	9	15	118	456	7	1	111	8	3	42	633
Min	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	1	14
SD	1.8	2.8	3.2	5.6	9.2	1.5	2.5	4.1	33.2	132.5	2.3	0.2	26.4	2.3	1.1	9.2	
Total	48	59	78	124	99	21	71	74	703	2075	24	1	307	29	10	141	3723
% of total	1.3	1.6	2.1	3.3	2.7	0.6	1.9	2.0	18.9	55.7	0.6	0.0	8.2	0.8	0.3	3.6	
ABUNDANCES (%)																	
Mean	2.0	2.7	2.8	5.5	5.7	0.9	4.0	3.0	20.5	41.6	1.9	0.1	7.3	1.8	0.2	5.2	
Max	7.4	10.2	8.1	16.0	32.5	8.5	14.3	16.9	46.1	72.0	8.8	1.6	26.7	21.4	1.7	12.5	
Min	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	7.1	1.6	0.0	0.0	0.0	0.0	0.0	0.6	
SD	2.0	2.7	2.4	4.7	10.1	1.9	4.3	3.9	9.0	24.0	3.2	0.4	6.5	4.8	0.4	3.9	
FLUXES (shells m^{-2} d^{-1})																	
Mean	7.9	10.2	13.2	19.6	15.8	3.6	12.0	11.0	113.8	354.9	3.3	0.2	57.2	5.3	1.8	24.8	629.8
Max	26.1	47.8	34.7	65.7	127.4	21.7	28.7	35.0	368.5	1361.5	22.3	3.2	482.0	34.7	13.0	182.4	1889.9
Min	0.0	0.0	0.0	3.2	0.0	0.0	0.0	0.0	3.2	3.2	0.0	0.0	0.0	0.0	0.0	3.0	44.6
SD	6.5	11.1	11.3	17.7	29.6	5.8	8.6	10.7	107.2	426.4	6.3	0.7	110.7	8.8	3.9	39.9	

A total of 3723 planktic foraminifera shells and 141 benthic foraminifera were counted. Planktic foraminifera were identified at the species level, resulting in a total of 15 different species identified (Plate 1). A mean of 196 planktic foraminifera specimens per sample were identified, with a minimum of 14 individuals in November 2013 and a maximum of 633 individuals in mid-March 2014 (Table 1).

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According to the raw counts results, the most abundant species was *G. inflata*, which represented 55.7% of the total planktic foraminifera individuals. The second most represented species was *G. truncatulinoides*, with 18.9%, followed by *G. bulloides* with 8.2%. These three species alone accounted for more than 80% of the planktic foraminifera identified. The remaining species abundances were below 5%. *G. ruber*, *G. ruber* (pink), *O. universa*, *G. rubescens* and *G. sacculifer* represented between 2 and 3.3 % of the total individuals. Species like *G. tenella*, *G. scitula*, *N. incompta* and *T. quinqueloba* were very scarce and accounted individually for less than 1% of the total planktic individuals (Table 1). Note that *G. inflata*, *G. truncatulinoides* and *G. ruber* were the only species present in all samples.

4.2 Total mass and planktic foraminifera fluxes

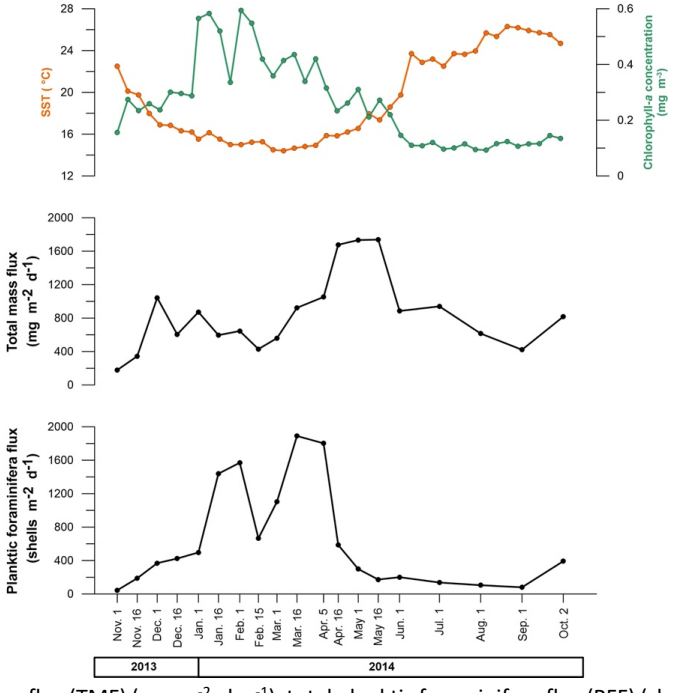

Figure 2. Total mass flux (TMF) (mg m^{-2} day^{-1}), total planktic foraminifera flux (PFF) (shells m^{-2} day^{-1}), SST (°C) and chlorophyll-*a* concentration (mg m^{-3}) changes between November 2013 and October 2014.

The mean total mass flux for the whole period of the study was 772.5 mg m^{-2} d^{-1}, with a maximum value of 1737.7 mg m^{-2} d^{-1} and a minimum value of 179.5 mg m^{-2} d^{-1} reached in mid-May 2014 and November 2013 respectively (Figure 2). Higher total mass flux values were reached during spring 2014, while lower values appeared during both autumn 2013 and 2014.
Planktic foraminifera mean flux across the interval studied was 629.8 shells m^{-2} d^{-1} with a maximum value of 1889.9 shells m^{-2} d^{-1} and a minimum of 44.6 shells m^{-2} d^{-1} reached in mid-March 2014 and in November 2013 respectively. Higher values occurred during two periods, early spring and winter

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2014, while the lower ones occurred from late spring to fall 2014. Overall, the seasonal mean values were 1194.3 shells m^{-2} d^{-1} for the winter period, 612.3 shells m^{-2} d^{-1} for spring, 283.5 shells m^{-2} d^{-1} for autumn and finally 107.2 shells m^{-2} d^{-1} for summer.

SST mean value was 19.2 °C and values ranged between a maximum of 26.1 and a minimum of 14.5 °C. The mean chlorophyll-*a* value was 0.27 mg m^{-3}, the maximum value displayed was 0.56 mg m^{-3} while the minimum one was 0.09 mg m^{-3} (Figure 2).

4.3 Foraminifera species fluxes

Overall, most of the planktic foraminifera species collected by the trap exhibited either a uni-modal or bi-modal flux distribution with a few exceptions (Figure 3).

Globorotalia inflata exhibited the highest fluxes of all species, with a mean flux of 368 shells m^{-2} d^{-1} throughout the record, with peak values in mid-March 2014 (1361 shells m^{-2} d^{-1}) and minimum in November 2013 (3 shells m^{-2} d^{-1}). *G. truncatulinoides* was the second most important contributor (mean of 114 shells m^{-2} d^{-1}), with a maximum in mid-February and a minimum in November 2013 (368 and 3 shells m^{-2} d^{-1}, respectively). *G. bulloides* was the third most important contributor to the total planktic foraminifera fluxes with a mean flux of 57.2 shells m^{-2} d^{-1} and maximum values registered in April 2014 and minima in November 2013 (482 and 0 shells $m^{-2}d^{-1}$, respectively).

The remaining species displayed mean fluxes lower than 50 shells m^{-2} d^{-1}. *G. calida*, *G. ruber*, *G. ruber* (pink), *G. rubescens* and *O. universa* mean fluxes were comprised between 10 and 20. Among these species, *G. ruber* and *G. ruber* (pink) stood out and showed maximum fluxes of 66 shells m^{-2} d^{-1} in February 2014 and 127 shells m^{-2} d^{-1} in October 2014, respectively. The remaining species, *G. siphonifera*, *G. scitula*, *G. falconensis*, *N. incompta* and *T. quinqueloba* mean and maximum fluxes were lower than 10 and 35 shells m^{-2} d^{-1}, respectively, thereby representing a low contribution to the total foraminifera fluxes.

Finally, it is worth noting that benthic foraminifera were also collected by the trap, displaying a mean flux of 25 shells m^{-2} d^{-1}. The peak contribution of these taxa was recorded in April 2014 (182 shells m^{-2} d^{-1}), and a minimum value in January 2014 (3 shells m^{-2} d^{-1}).

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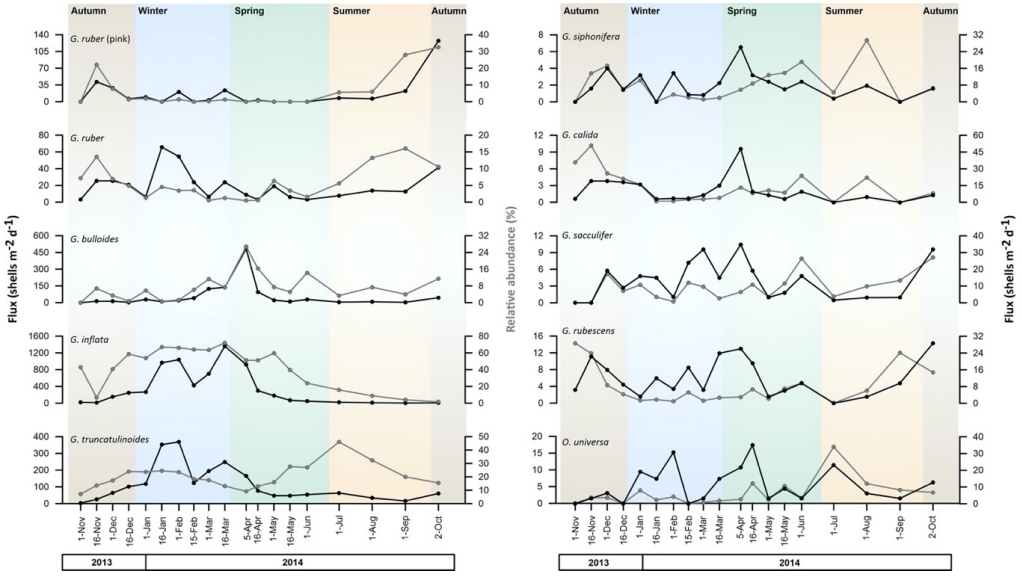

Figure 3. Planktic foraminifera fluxes (shells m^{-2} d^{-1}, black lines) and relative abundances (%, grey lines) from November 2013 to October 2014 of the 10 most abundant species identified. Note that the scale of the fluxes and abundances depend on the species. Background colour filling represents the different seasons: brown for autumn, blue for winter, green for spring and orange for summer.

The variations in relative abundance differed according to the species. Most of the species displayed a unimodal distribution across the studied interval (Figure 3), with some exceptions such as *G. siphonifera*, *G. calida* or *G. ruber*.

Overall, *G. inflata* dominated the association from late autumn until mid-spring. Its relative abundance was comprised between 72% reached in mid-March 2014 and around 2% in mid-November 2013 (Figure 3). *G. truncatulinoides* relative abundance pattern was different from any other species. The lowest relative abundance was reached in November 2013: around 7%, while the highest abundance was 46% in July 2014. Note that despite the seasonality of its abundance, the amplitude of its relative abundance change was low compared to other species (Figure 3). In turn, the third most abundant foraminifera species, *G. bulloides*, displayed a pronounced seasonal change in its relative abundance reaching values up to 27% in early spring (April 2014) and dropping to about 5-8% in November 2014.

Secondary contributors, such as *G. siphonifera* and *G. sacculifer* reached their maximum contributions (~8%) in August and June 2014, respectively, *G. calida* in mid-November 2013 (10%), *G. ruber* in November 2013 (16%), *G. ruber* pink in October 2014 (32.5%) and both *G. rubescens* and *O. universa* exhibited their maximum contributions (with 14-15% for both species) in November 2013 and in July 2014, respectively.

Overall, *G. inflata* is the only species that displayed its maximum mean relative abundance during winter: 64%. *G. siphonifera*, *G. sacculifer*, and *G. bulloides*, maximum mean relative abundances were reached during spring: 3%, 3.5%, 14% respectively. *G. calida*, *G. tenella*, *G. rubescens* and *N. incompta* maximum mean abundances appeared to be in autumn: 5.7%, 2.2%, 8% and 4.8%

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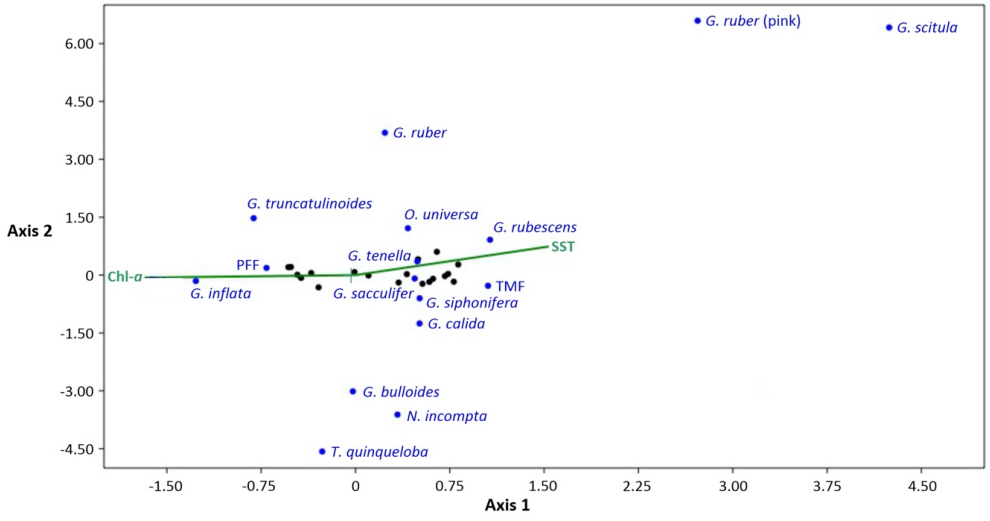
397 respectively. Finally, *G. ruber*, *G. ruber* (pink), *O. universa*, *G. truncatulinoides* and *G. scitula*
398 maximum mean relative abundances were displayed in summer: 11.6%, 13.2%, 8.9%, 32.8% and
399 6.4% respectively.
400
401 **4.4 Chlorophyll-*a* and SST impact on foraminifera fluxes**
402



403
404 **Figure 4.** CCA analysis of all the planktic foraminifera species flux with the SST (°C) and the chlorophyll-*a*
405 ("chl-*a*" in the CCA, in mg m^{-3}) as the explanatory variables. The total mass flux ("TMF") and planktic
406 foraminifera flux ("PFF") are also included. Black dots represent the 19 sediment trap samples studied.
407
408 A CCA (see section 3.4) was carried out to characterize the impact of both the SST and the
409 chlorophyll-*a* on the planktic foraminifera fluxes (Figure 4).
410 Total planktic foraminifera flux and the fluxes of *G. inflata* and *G. truncatulinoides* are positively
411 affected by the chlorophyll-*a* concentration and negatively affected by the SST. On the other hand,
412 *G. ruber*, *G. ruber* (pink) and *G. scitula* fluxes showed an opposite pattern, being positively related
413 with the SST and negatively with the chlorophyll-*a* concentration. *O. universa*, *G. rubescens*, *G.*
414 *tenella*, *G. sacculifer, G. siphonifera* and *G. calida* fluxes are positively correlated with the SST and
415 negatively with chlorophyll-*a* concentration, nonetheless, the impact of these parameters is weaker
416 compared with the previous species. Finally, *G. bulloides*, *N. incompta* and *T. quinqueloba* fluxes are
417 positively influenced by the chlorophyll-*a* concentration, however, (arguably excepting for *G.*
418 *bulloides*) no clear effect of the SST was displayed on these species fluxes.
419
420 **5. Discussion**
421
422 **5.1 Seasonal variations in the magnitude of planktic foraminifera fluxes in the Sicily Strait**
423

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The strong seasonality in the planktic foraminifera fluxes registered by the trap is generally similar in amplitude to previous studies in the Mediterranean (Bárcena et al., 2004; Rigual-Hernández et al., 2012) and other temperate settings (Rembauville et al., 2016; Wilke et al., 2009), thereby suggesting the C01 record mainly reflects the temporal variations in planktic foraminifera abundance in the upper water column. Therefore, next, we discuss the influence of oceanographic controls on the planktic foraminifera fluxes.

Our data shows that, despite differences in the magnitude of their fluxes, most of the species identified display their maximum flux during winter, winter/spring transition or spring (Figure 3) thereby coinciding with the period of maximum algal biomass accumulation and coldest SSTs (Figure 2). The enhanced primary productivity during winter and spring is mostly related to an intensification of the chlorophyll-*a* and nutrient richer MAW flow into the Eastern Mediterranean basin (D'Ortenzio, 2009; Siokou-Frangou et al., 2010). Our CCA results (Figure 4) show that, although the flux patterns increase during winter and spring, only the planktic foraminifera flux, *G. inflata*, *G. truncatulinoides* and arguably *G. bulloides* (further discussed below) fluxes are negatively related to SSTs and positively with the chlorophyll-*a* concentration. The dominance of the planktic foraminifera fluxes by these three species and their affinity for mesotrophic waters is not surprising as *G. inflata* and *G. truncatulinoides* are typically associated with the MAW, winter water mixing events and hydrologic fronts in the western Mediterranean, while *G. bulloides* is generally associated with eutrophic environments linked to upwelling conditions (Azibeiro et al., 2023). Overall, these three taxa have been described to be dominant during winter in various western regions of the Mediterranean, such as the Alboran Sea (Bárcena et al., 2004; Hernández-Almeida et al., 2011), the Provençal basin and in the Gulf of Lions (Pujol and Grazzini, 1995; Rigual-Hernández et al., 2012). Interestingly *G. inflata*, *G. truncatulinoides* and *G. bulloides* are almost absent in the eastern part of the basin, most likely due to the low algal biomass accumulation (Avnaim-Katav et al., 2020; Thunell, 1978).

Conversely, species such as *G. ruber*, *G. ruber* (pink), *G. scitula*, *G. rubescens* and *G. sacculifer* display their maximum fluxes in summer or autumn (Figure 3). During the warm periods, summer and autumn, the eastward advection of Atlantic waters in the Sicily Strait is weakened due to an increased meandering of the ATC (Figure 1) and the local hydrography patterns (Béranger et al., 2004), leading to a local water column stratification period which is also well documented in the whole Mediterranean basin during summer (Siokou-Frangou et al., 2010). This translates into a reduced MAW influence, and a larger influence of the LIW at intermediate depths (Astraldi et al., 2002, 2001; Jouini et al., 2016). Therefore, the water column becomes warmer, saltier and more nutrient depleted than the general conditions of the western basin (Gasparini et al., 2005; Navarro et al., 2017; Siokou-Frangou et al., 2010) and provides the necessary environmental and oceanographical configuration for eastern basins taxa to develop or being transported from the easternmost part of the Mediterranean. Indeed, our CCA results (Figure 4) support these observations (Figure 3). The latter species have been described to reach their maximum abundances in the eastern part of the Mediterranean, specifically in the Ionian and Levantine basins during both summer and autumn (Avnaim-Katav et al., 2020; Pujol and Grazzini, 1995).

Some species, such as *O. universa* or *G. calida*, do not display a clear flux pattern over the period studied. CCA results suggest that these species have an affinity for warm and less productive

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conditions. These taxa are considered widespread in the Mediterranean basin, although their relative contributions are generally higher in the eastern part of the basin (Avnaim-Katav et al., 2020; Pujol and Grazzini, 1995; Thunell, 1978). Lastly, it is important to note that the low number of specimens of *G. falconensis*, *N. incompta*, *T. quinqueloba* and *G. tenella* found in our samples, makes the estimation of shell fluxes for these species unreliable. These results are not surprising, since *N. incompta* is mainly found in the northwestern part of the basin owing to cold and eutrophic conditions (Azibeiro et al., 2023; Millot and Taupier-Letage, 2005) while *T. quinqueloba* has generally been associated to cool Atlantic waters or cool marginal seas (Azibeiro et al., 2023).

The record of benthic foraminifera (Figure 3) indicates that the trap also collected resuspended sediments. The main benthic species identified were *T. saggitula* spp. and *B. marginata* (Plate 1) which are considered infaunal species, i.e. they live buried in the sediment (Balestra et al., 2017; Milker and Schmiedl, 2012) and are commonly found in continental shelves and slopes. Overall, benthic foraminifera accounted only for a mean of 3.4% of the total foraminifera identified in the C01 sediment trap (Table 1) and the % of planktic oscillated between 87.5 and 99.4%. Therefore, it can be assumed that the C01 mooring line recorded mainly a pelagic signal.

In summary, planktic foraminifera flux was maximum during winter and spring, coinciding with the maximum seasonal eastward advection that brings MAW further east into the Sicily Strait. These waters are less saline and nutrient enriched compared to the easternmost waters from the Levantine basin. *G. inflata*, *G. truncatulinoides* and *G. bulloides* (the three most abundant species that dominate the PFF), which are species described to come from the western basins, are probably brought by the MAW and then dominate the planktic foraminifera population. On the other hand, during summer and autumn, the eastward advection weakens, allowing the LIW and AIS to dominate the surface circulation due to the water column stratification and set favourable conditions for eastern basin dominant taxa such as both morphotypes of *G. ruber*, *G. rubescens*, *G. sacculifer*. This results in a significantly decreased planktic foraminifera flux due to the absence of western basin dominant species.

5.2 Species succession, ecology and impact of the SST and chlorophyll-*a*

The annual planktic foraminifera assemblage collected by the C01 trap reflects a diverse planktic foraminifera assemblage with species with contrastingly different ecological preferences, encompassing a wide range of depth habitats and diverse feeding strategies. Overall, the annual assemblage composition agrees well with previous ship-board observations (Pujol and Grazzini, 1995) in the Strait of Sicily during VICOMED 1988 cruise, where *G. inflata*, *G. truncatulinoides* and *G. bulloides* were documented as the most abundant taxa.

Next, we discuss the ecology of the most abundant species and the impact of chlorophyll-*a* and SST on their distribution. We also discuss the foraminifera groups suggested by Jonkers and Kučera, (2015), to explore their correlation with the previous parameters on an interannual scale. The latter work proposed 3 groups: group 1 is formed by tropical and subtropical species, group 2 consists of temperate to subpolar taxa, and group 3 represents the deep-dwelling species. These groups were described as a result of the seasonal maximum fluxes timing of each species and their relationship with both temperatures and nutrients (amongst other parameters) in different time-series across

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the world ocean. Therefore, here we also used this grouping to compare and complete this classification from a new time-series dataset.

Globorotalia inflata is the most abundant taxon in our samples. Our data shows that maximum fluxes and relative abundances of this species are reached during winter and the winter-spring transition (Figure 3). The relative abundances showed strong positive and negative significant (p <0.05) correlations with the chlorophyll-*a* concentration and the SST: 0.808 and -0.896 respectively (Figure 5). It is a non-spinose species and is considered a deep dweller (Hemleben et al., 1989; Schiebel and Hemleben, 2017). Generally regarded as showing limited opportunistic behaviour and it has been often associated with eddies and hydrological fronts (Chapman, 2010; Retailleau et al., 2011). Concerning the Mediterranean, its maximum stocks and abundances have been recorded along the southern margin of the western Mediterranean basin (Azibeiro et al., 2023), especially during winter (Bárcena et al., 2004; Pujol and Grazzini, 1995; Rigual-Hernández et al., 2012); while it is poorly represented in the eastern part, even absent in the Levantine basin (Avnaim-Katav et al., 2020). As a consequence, *G. inflata* can be considered as a mesotrophic species, which is dominant in regions with some degree of stratification of the water column and an intermediate amount of nutrients and it has been used as a tracer of the Atlantic inflow in the Mediterranean basin (Azibeiro et al., 2023), which agrees with the local hydrography in the Sicily Strait during winter and spring. As *G. inflata* appeared in periods of cool and nutrient enriched waters (Figure 3), which coincide with the periods of higher MAW influence in the Sicily Strait (Béranger et al., 2004), we consider that our results further confirm *G. inflata* as tracer of the MAW in the Sicily Strait.

Globorotalia truncatulinoides is the second most abundant species in our record. However, our CCA results suggest that the seasonal variations in *G. truncatulinoides* are not directly correlated with either chlorophyll-*a* concentration or SSTs (r= -0.162 and 0.256, respectively, p >0.05) (Figure 5). This highlights the fact that environmental controls other than the ones considered here may be affecting its distribution. This taxon is a cosmopolitan species found in all major oceans (Schiebel and Hemleben, 2017) and is considered a deep dweller with an affinity for water-mixing conditions (Margaritelli et al., 2020; Schiebel and Hemleben, 2005). It is a non-spinose species with a complex life cycle. In the Mediterranean, peak abundances of this species are found in the northwestern part of the basin, where it represents a major component of the assemblages (Pujol and Grazzini, 1995; Rigual-Hernández et al., 2012), while it is absent in the easternmost part of the basin (Avnaim-Katav et al., 2020). This species has been documented to have a complex life cycle and reproductive strategy. *G. truncatulinoides* has been described to reproduce once a year in the upper layers of the water column, generally when the water mixing allows the migration of juvenile individuals to the surface (Lohmann and Schweitzer, 1990; Schiebel et al., 2002). Then, adult individuals migrate downward the water column and spend the rest of their life cycle (Rebotim et al., 2017; Schiebel and Hemleben, 2005). Hence, we speculate that these complex migratory patterns may be playing a role here. As its reproduction cycle is mainly controlled by the gametogenesis process, and as described previously, it reproduces once a year (a slower rate than the majority of the planktic foraminifera species) (Schiebel and Hemleben, 2017), then, although different stages of its life cycle could be affected by SST and chlorophyll-*a*, this is not necessarily registered by the sediment traps in every stage of its growth.

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Globigerina bulloides was the third most abundant planktic foraminifera species identified here. It is a surface to subsurface dweller and one of the most common species across the world ocean (Schiebel and Hemleben, 2017). Interestingly, our analysis showed no significant correlation between changes in *G. bulloides* relative abundance and chlorophyll-*a* concentration or SST (r= -0.145 and -0.111 respectively, p >0.05). However, across the time span studied, this taxon showed its maximum abundance and fluxes during relatively high chlorophyll-*a* and cool SST conditions (Figure 3). This highlights that other environmental parameters than the ones considered here might be playing a role in its distribution. It is a spinose species known for its opportunistic feeding strategy (Schiebel et al., 2001) and affinity for upwelling and eutrophic environments (Azibeiro et al., 2023; Bé et al., 1977). Within the Mediterranean Sea, it displays peak export fluxes to the deep sea in areas of high productivity such as the Gulf of Lions and the Alboran Sea during the high productivity period in late winter to spring (Azibeiro et al., 2023; Bárcena et al., 2004; Hernández-Almeida et al., 2011; Rigual-Hernández et al., 2012), while few individuals are found in the eastern part of the Mediterranean (Avnaim-Katav et al., 2020). We surmise that owing to its multiple trophic strategies and its multi-diet characteristics, it could adapt and feed on varying chlorophyll-*a* concentrations. Also, the lack of correlation with both parameters could be explained by the fact that this taxon is associated with eutrophic conditions. In the Sicily Strait, the high productivity period ranges from winter to spring, and the conditions allow deep mesotrophic dwellers (i.e. *G. inflata*) to dominate the assemblage; while in summer and autumn, the upwelling setting brings oligotrophic conditions that are not favourable for this species. In addition, the maximum abundances of *G. bulloides* are displayed coincidently with the highest number of benthic foraminifera identified (see Supplementary data), which in turn could mean that some of the *G. bulloides* specimens during their maximum abundance have a resuspended origin.

Globigerinoides ruber and *G. ruber* (pink) were the fourth and fifth most abundant species in our samples (Table 1). Our correlation analyses showed a significant positive effect of SST (r= 0.803 and 0.678, p <0.05) and a significant negative effect of chlorophyll-*a* (r= -0.567 and -0.464 respectively, p <0.05) on both *G. ruber* and *G. ruber* (pink) respectively (Figure 5). These species have been described as tropical to subtropical taxa, with an affinity for oligotrophic and stratified waters (Bé et al., 1977). Both of these species are among the shallowest dwellers of the extant planktic foraminifera species and are considered one of the most adaptable to varying surface water conditions (Kemle-von Mücke and Oberhänsli, 1999; Schiebel and Hemleben, 2017). Due to its temperature and salinity limits for food acceptance, the white variety is one of the most studied foraminifera species in culture experiments, which highlight their euryhaline and eurythermal life cycle (Bijma et al., 1990; Lombard et al., 2009). In today's ocean, the white variety is substantially more abundant than the pink one (Schiebel and Hemleben, 2017). In the case of the Mediterranean basin, *G. ruber* is generally associated with warm and oligotrophic waters (Pujol and Grazzini, 1995) and is abundant in the eastern oligotrophic basin, where it dominates the assemblages in the Levantine basin during spring and fall (Avnaim-Katav et al., 2020). However, although present in the western basin, its abundance is much lower in the Gulf of Lions (Rigual-Hernández et al., 2012) and in the Alboran Sea (Bárcena et al., 2004). Overall, the correlation data agrees with the previous work that linked *G. ruber* (both varieties) to warm and oligotrophic conditions generally displayed during a higher stratification of the water column (Schiebel et al., 2004) as they appear mainly during

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summer and autumn, coincidently with the increased LIW and eastern basin waters influence in the Sicily Strait.

According to Jonkers and Kučera, (2015), the foraminifera fluxes can be predicted on a seasonal scale for three different groups of planktic foraminifera. Following this approach, we explore the relative abundance of these three aggrupations to explore if these correlate with both SST and chlorophyll-*a* concentration (see Supplementary Table 1) on the period covered by the sediment trap (Figure 5). The first group (group 1) consists of both *G. ruber* varieties, *G. sacculifer*, *O. universa*, *G. siphonifera*, *G. rubescens* and *G. tenella*. The second group (group 2) is formed by *G. bulloides*, *T. quinqueloba*, *N. incompta*, *G. scitula* and *G. calida*. In our record, however, either *G. bulloides* or *G. calida* displayed a similar trend, and the remaining three species abundance was <1.5%, making any significant assumption difficult (Table 1). The third (group 3) is composed by the deep dwellers *G. inflata* and *G. truncatulinoides*. Group 1 showed a strong and significant positive correlation with the SST (Figure 5) and a negative with the chlorophyll-*a* (r= 0.828 and -0.668 respectively, p <0.05, see Supplementary Table 1). This is not surprising as the majority of the group is formed by species not only considered tropical but also well adapted to oligotrophic and nutrient impoverished environments (Chapman, 2010; Hemleben et al., 1989; Schiebel and Hemleben, 2017). In addition, most components of this group are symbiont bearing species (Takagi et al., 2019), which have been described to be more adapted to nutrient depleted and oligotrophic conditions. Group 2 on the other hand did not show any strong correlation to either SST and chlorophyll-*a* concentration, although a significant negative correlation was displayed between the group abundances and the latter parameter (r= -0.525, see Supplementary Table 1). This result is not surprising as the main component of this group is *G. bulloides*, which previously showed a lack of correlation with both SST and chlorophyll-*a*, while the remaining species of this group were taxa that tend to be outnumbered by more opportunistic species (i.e. *N. incompta* and *T. quinqueloba*) (Kuroyanagi and Kawahata, 2004; Schiebel, 2002). Also, the overall abundance of these taxa was very low in our samples compared to the other two groups, which in turn could affect the correlation results. Here we propose that the mesotrophic conditions of the Sicily Strait developed during the relatively high productivity period are not favourable enough for the development of the taxa comprised in group 2. Finally, group 3 displayed a strong and significant positive correlation with chlorophyll-*a* concentration (r= 0.771, p <0.05), which is an expected trend according to the affinity showed to mesotrophic conditions by the two species that constitute this group, however, as compared to Jonkers and Kučera, (2015), we showed a strong and significant negative correlation of these two species abundances with the SST (Figure 5). The latter work stated that the cycles of these species were independent of the temperature changes, however, these two species tend to be used as tracers of cool and deep mesotrophic waters in the Mediterranean, generally associated with the MAW (Azibeiro et al., 2023).

In summary, our data showed that in the Sicily Strait, the three major ecological groups proposed by Jonkers and Kučera, (2015), exhibited a different response to environmental variability. Overall, groups 1 and 3 showed significant correlation with the latter parameters and were in accordance with their corresponding species ecologies. However, group 2 did not show any significant correlation, which we interpreted as the result of very low abundances of the taxa comprised within this group. This translates into the dominance of group 1 during summer and autumn when

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oligotrophic and warm eastern waters dominate the water column, while the mesotrophic taxa from group 3 dominate during winter and spring, coincidently with higher primary productivity, yet not eutrophic enough for the opportunistic taxa comprised in the group 2, which is less well represented in the Sicily Strait.

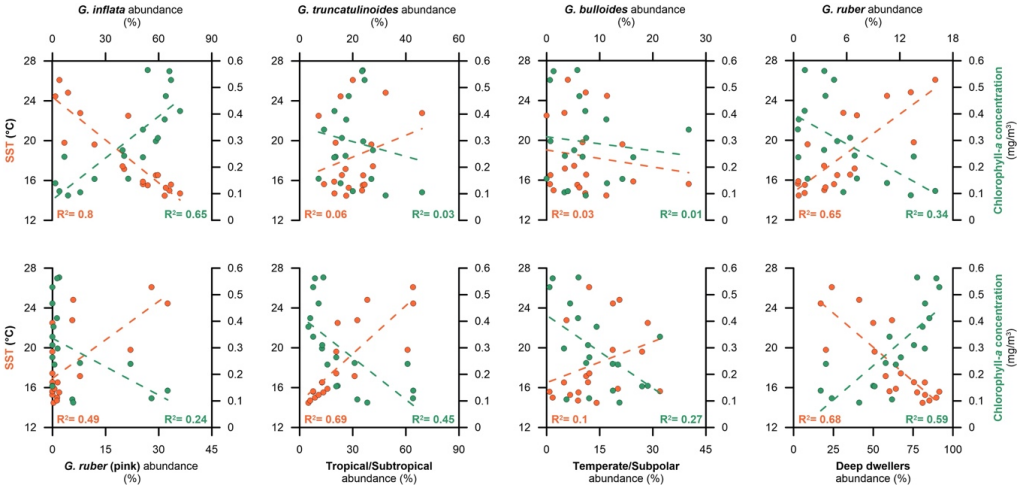

Figure 5. SST and chlorophyll-*a* concentration against the relative abundance of the five most abundant species and the three ecological groups proposed by Jonkers and Kučera (2015). Orange dots stand for SST while the green ones correspond to chlorophyll-*a*.

5.3 Geographical variability in the magnitude and composition of planktic foraminifera fluxes across the Mediterranean

The comparison of the Sicily Strait planktic foraminifera sediment trap record with the ones retrieved from different parts of the Mediterranean offers a unique opportunity to provide further insight into the dynamics and ecology of this group on a basin-wide scale.

As stated previously, the planktic foraminifera flux in the Sicily Strait was higher from mid-January to mid-March, which coincided with the highest chlorophyll concentrations and the coolest SST recorded (Figure 2). This seasonality is similar to the one observed in the Gulf of Lions, where the planktic foraminifera flux reached its highest values from mid-February to mid-March during different years (Rigual-Hernández et al., 2012). Although slightly different, the planktic foraminifera fluxes patterns from both the Levantine basin and the Alboran Sea also displayed maximum values between mid-February to mid-March and mid-January to mid-February respectively (Avnaim-Katav et al., 2020; Hernández-Almeida et al., 2011). However, the magnitude of the planktic foraminifera flux values displayed some differences between the sites (see Supplementary Figure). Overall, for the Sicily Strait, values ranged between 0-1889 shells m^{-2} d^{-1} with a mean value of 629 shells m^{-2} d^{-1}. These values were comparable to the ones from the Gulf of Lions: 0-2114 and 4268 shells m^{-2} d^{-1} with a mean value of 225.4 in Planier sediment trap to 419 shells m^{-2} d^{-1} in Lacaze-Duthiers sediment trap. On the other hand, the Levantine basin values were lower: 0-429 shells m^{-2} d^{-1}, with a mean value of 93 shells m^{-2} d^{-1}. Finally, the highest values belonged to the Alboran Sea: 0-6000 shells m^{-2}

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d^{-1} with a mean value of 783 to 970 shells m^{-2} d^{-1} depending on the gyres. Note that the planktic foraminifera flux values from the Levantine basin used here represent the foraminifera shells from the >125 μm fraction, which highlights the fact that compared to the >150 μm, the flux values should be even lower. The corresponding chlorophyll-*a* values registered in the latter sites were 0.2-0.65 mg m^{-3} for the Sicily Strait (Figure 5), 0.25-0.85 mg m^{-3} for the Gulf of Lions (0-0.65 mg m^{-3} in the Planier site, 0.25-0.85 mg m^{-3} for Lacaze-Duthiers) (Rigual-Hernández et al., 2012), 0.02-0.4 mg m^{-3} for the Levantine basin (Avnaim-Katav et al., 2020) and 0.1-1.2 mg m^{-3} in the Alboran Sea (Hernández-Almeida et al., 2011), indicating a similar productivity in terms of chlorophyll-a between the Gulf of Lions and the Sicily Strait. In addition, here we calculated an annualized planktic foraminifera flux (section 3.4) for each of the 6 sites compared here (Figure 6). Overall, the highest annualized fluxes were displayed in the Alboran Sea (Figure 6): around $3x10^5$ and $4.4x10^5$ shells m^{-2} y^{-1}, while the lowest one was displayed in the Levantine Basin: a little over 30000 shells m^{-2} y^{-1} (Figure 6). The Gulf of Lions and the Sicily Strait displayed comparable annualized fluxes although higher for the latter: around $1.5x10^5$ and $1.85x10^5$ shells m^{-2} y^{-1} respectively. Note that PLA site values were significantly lower: around $7x10^4$ shells m^{-2} y^{-1} (Figure 6). Previous work showed that these planktic foraminifera patterns were mainly linked to specific regional oceanographic processes. First of all, the Levantine basin is well known for being an ultra-oligotrophic region and being the warmest and saltiest of the Mediterranean basins (Ozer et al., 2017), mainly due to the W-E anti-estuarine circulation. On the other hand, the Gulf of Lions is considered an exception to the general oligotrophy of the Mediterranean. Seasonal vertical mixing phenomenon occurs in winter, generated by cold winds. This winter mixing recharges the surface waters with nutrients, allowing a winter/spring productivity bloom (Durrieu de Madron et al., 2013; Houpert et al., 2016). Finally, the Alboran Sea is a transitional region between the Atlantic Ocean and the Mediterranean Sea (Hernández-Almeida et al., 2011), and unlike the latter, is not an oligotrophic region due to the two systems of high productivity related to the gyres generated by an intense westerlies activity, which allow nutrients enriched (compared to the resident waters) Atlantic waters to spread into the Mediterranean. This results in an enhanced primary productivity period from November to March. According to the PFF patterns displayed in this study, the Sicily Strait presents similar values and fluxes distributions to the Gulf of Lions, however, its oceanographic circulation is significantly different from the latter. These observations agree with the work of Mallo et al., (2017) carried out with plankton tows in the whole Mediterranean basin. The latter work found that the Alboran Sea displayed the highest standing stocks of planktic foraminifera, while the easternmost part of the Mediterranean showed the minimum values. Also, the Gulf of Lions and the Strait of Sicily displayed similar stocks, although slightly superior for the Strait of Sicily.

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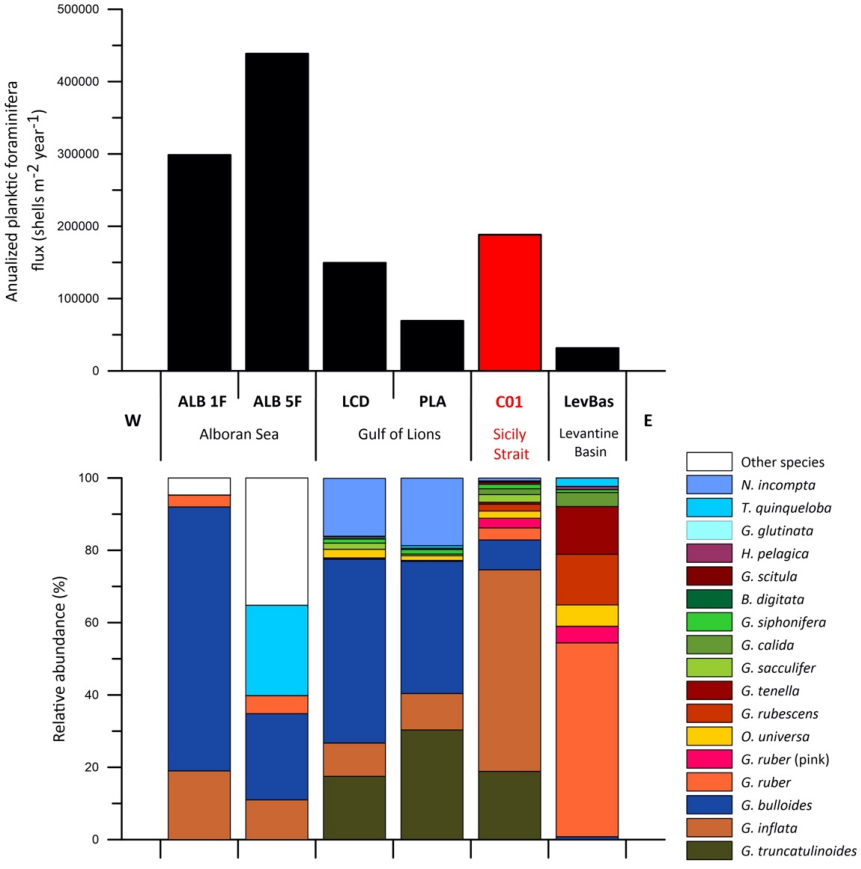

Figure 6. Comparison of the annualized (see section 3….) planktic foraminifera flux and the relative abundance of each species identified in different time-series across the Mediterranean Sea (see section 3…). The data from the Sicily Strait (C01) is depicted in red. Note that the Levantine Basin (LevBas) dataset covers the >125 μm fraction. Other species (white bar) in the Alboran Sea corresponds to any species different from the main 4 taxons identified in Bárcena et al., (2004) and Hernández-Almeida et al., (2011).

Concerning the species composition, we identified 15 planktic foraminifera species in the Sicily Strait, which is a similar species number to the one from the Gulf of Lions (14 species) and higher than in the Levantine basin (10 different species). The Sicily Strait site displayed the highest planktic foraminifera assemblage diversity among the three sites compared: a mean 1-D and S/W index of 0.68 and 1.57 respectively. (Table 2). Interestingly, despite showing a similar number of different species, the Gulf of Lions displayed the lowest diversity values, especially for the PLA site: mean 1-D of 0.55 and mean H/W of 1.08, while the LCD site 1-D and h/w were 0.58 and 1.15 respectively. These observations highlight that, although the annualized planktic foraminifera flux was similar between the Gulf of Lions (for the LCD site) and the Sicily Strait (Figure 6), the assemblage in the latter site was significantly more diverse regarding species composition. The composition of the annual planktic foraminifera population of the different species showed some differences between

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the sites compared here. In the Levantine basin, the majority of the planktic foraminifera population consisted of surface symbiont bearing species such as *G. ruber*, *G. ruber* (pink), *G. rubescens*, *G. tenella*, *O. universa*, which are well adapted to the ultra-oligotrophic conditions (Lombard et al., 2011; Schiebel and Hemleben, 2017). The latter species represented 96% of the total planktic foraminifera in the Levantine basin, while the same species in the Sicily Strait accounted for around 10% of the total individuals (Figure 6). Note that both *G. rubescens* and *G. tenella* are considered small-sized species (Chernihovsky et al., 2023) and their adult size is often smaller than 150 μm, so it is possible that some individuals of those species may not be recorded in our data. On the other hand, in the Gulf of Lions, the four main species were *G. bulloides*, *N. incompta*, *G. inflata* and *G. truncatulinoides*, which represented 88 to 95% of the total planktic foraminifera (Rigual-Hernández et al., 2012). These species tend to be associated with eutrophic to mesotrophic environments which coincides with the Gulf of Lions locally enhanced primary productivity conditions. In the Sicily Strait, the same species accounted for 83% of the total individuals, and, except for *N. incompta*, the remaining three species were also the most abundant in our samples.

Table 2. Inverse Simpson (1-H) and Shannon-Weiner indexes mean, standard deviation ("Stan. Dev.") and maximum values for the two Gulf of Lions sites (PLA and LCD), the Sicily Strait (C01, this study) and the Levantine Basin (LevBas).

	Gulf of Lions		Sicily Strait	Levantine Basin
	LCD	PLA	C01	LevBas
Simpson 1-H				
Mean	0.581	0.553	0.681	0.615
Stan. Dev.	0.168	0.180	0.132	0.144
Max	0.802	0.781	0.872	0.804
Shannon H/W				
Mean	1.151	1.078	1.572	1.230
Stan. Dev.	0.359	0.375	0.398	0.316
Max	1.789	1.630	2.188	1.759

Considering the planktic foraminifera fluxes patterns, the species diversity and the planktic foraminifera most abundant species from each of the three Mediterranean time-series with which we compared our data, we interpret that, from a planktic foraminifera population point of view, the Sicily Strait could be considered as a transition zone and a biological corridor between the western and eastern basins.

Finally, to put our data into a global context, here we compare our dataset with planktic foraminifera data from the same size fraction retrieved in the Gulf of Mexico, high latitudes North Atlantic and gyres region of the North Atlantic Ocean. In the northern Gulf of Mexico, from 2008 to 2010, the >150 μm PFF was comprised between 0 and slightly over 800 shells m^{-2} d^{-1}, with a mean value of around 250 shells m^{-2} d^{-1} (Poore et al., 2013). A total of 12 species were identified, with *G. truncatulinoides*, *G. ruber* (pink) and *N. dutertrei* as the most abundant species recorded. On the

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other hand, in the North and high-latitudes Atlantic Ocean, Wolfteich (1994), showed that the PFF oscillated between 0 and around 5000 shells m^{-2} d^{-1} for a mean value of 800 shells m^{-2} d^{-1}, while *G. bulloides* and *N. incompta* were the most abundant species. Although the latter work only focused on the most abundant species, additional work has documented more than 20 species in the vicinity of the North-Atlantic gyres (Salmon et al., 2015), but around only three to four in the high latitudes. This highlights that, from a planktic foraminifera population point of view on a wider scale, the Sicily Strait displayed a higher planktic foraminifera flux and species richness compared to the tropical to subtropical Gulf of Mexico and to the high latitudes of the North Atlantic, but lower values compared to the North Atlantic gyres region.

5.4 Recent planktonic foraminifera assemblage comparison with seabed sediment

The Mediterranean Sea is often referred to as a climate change hotspot and a "laboratory basin" where many global environmental trends are amplified (Bethoux et al., 1999). In particular, ocean warming is expected to exceed the global average (Hassoun et al., 2022, 2015; Lazzari et al., 2014) while it is considered a specially sensitive zone of the ocean to acidification due to the fast turnover of its waters and penetration of anthropogenic CO_2 (Bethoux et al., 1999; Schneider et al., 2007). One of the main questions about planktic foraminifera concerns the way they are going to react to the ongoing climate change in the global ocean (Jonkers and Kučera, 2015; Schiebel and Hemleben, 2017). Previous work suggests that global communities of planktic foraminifera have already been affected by environmental change since the onset of industrialization (Jonkers et al., 2019). Moreover, recent work has shown that the calcification of several planktic foraminifera species has decreased during the industrial era in the northwestern Mediterranean (Béjard et al., 2023). Therefore, here we aim to assess if modern planktonic foraminifera communities dwelling in the Sicily Strait differ from their pre-industrial counterparts. To do so, next, we compare the annual integrated assemblages collected by the C01 sediment trap with the ones from a set of core-tops retrieved in the vicinity of the studied zone (see Section 3.5).

As planktic foraminifera are a group of calcifying plankton, when comparing sediment trap and seabed sediment data, the possible role of calcite dissolution must be discussed. Firstly, the Mediterranean Sea is supersaturated with respect to calcite (Álvarez et al., 2014; Millero et al., 1979) and the depth of the studied material is substantially shallower than the calcite saturation horizon (Álvarez et al., 2014). Secondly, recent work suggests that calcite experiences little to negligible changes in the water column and burial in recent sediments (Béjard et al., 2023; Pallacks et al., 2023). All this evidence suggests that dissolution played a negligible role in the preservation of planktonic foraminifera preserved in the sediment record in the study region.

The core-tops with which the C01 sediment trap data is compared were part of the MARGO database (see Section 3.4 for more details). Note that the MARGO sites 3735 to 3739 seabed sediment was taken using a trigger-weight corer (Thunell, 1978). However, samples 3658, 3672 and 3673 were retrieved using a piston corer (Hayes et al., 2005). Generally, sampling with the trigger-weight method is considered to retrieve less mixed and disturbed sediment than the piston or box corer sampling methods (Skinner and McCave, 2003; Wu et al., 2020). Therefore, the foraminifera assemblages from the core-tops may likely represent a mix of Holocene foraminifera assemblages rather than exclusively modern assemblages. Although the lack of dating control makes it impossible

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to determine the exact date of the core top assemblages, our data suggest that the composition of modern foraminifera assemblages in the Sicily Strait has changed between the late Holocene and the present day. The reasons of this change are uncertain, although we speculate that ongoing warming (Lazzari et al., 2014), the consequent increasing stratification of the water column in the Mediterranean (Siokou-Frangou et al., 2010) and a shift in the oceanographical configuration could have already reduced primary production in the Sicily Strait.

Table 3. MARGO core-tops analyzed, their latitude and longitude and the squared chord distance (SCD) between the C01 sediment trap and the MARGO database core-tops. The complete SCD for all sites can be found in Supplementary data.

	MARGO database															
Site	**3655**	**3677**	**3724**	**3739**	**3737**	**3738**	**3658**	**3725**	**3654**	**3680**	**3735**	**3736**	**3673**	**3727**	**3661**	**3726**
Latitude	38.25	36.47	35.85	36.73	38.33	38.00	36.68	36.49	38.22	37.46	38.17	38.23	39.40	38.93	39.41	38.64
Longitude	13.35	11.49	13.03	13.95	11.80	11.78	12.28	13.32	13.27	11.55	11.23	11.25	13.34	10.59	13.34	10.78
SCD to C01	0.27	0.52	0.55	0.56	0.66	0.78	0.84	0.85	0.88	0.89	0.90	0.93	1.03	1.03	1.07	1.10

The SCD between the annual integrated foraminifera assemblage of the C01 sediment trap and the core-tops from the Sicily Strait and adjacent areas (see Supplementary Figure 2) ranged between 0.27 and 1.1 (Table 3). By using a dissimilarity coefficient value of <0.25 as cutoff criteria (see section 3.4 for more details), it can be concluded that none of the core-tops assemblages can be considered close analogues to the C01 sediment trap. The only exception might be MARGO site 3655, located around 180 km northeast of the sediment trap, which displayed an SCD value of 0.27, very close to our cutoff threshold. The mean SCD between all core-tops and the sediment trap is 0.8, which contrasts with the SCD between the core-tops, which exhibited an average value between them of 0.47 (see Supplementary data), indicating a higher similarity between them than with the sediment trap. Interestingly, from a geographical point of view, the geographical closest site analyzed (MARGO 3680) displayed a high SCD (0.89) despite being retrieved virtually in the underlying sediments beneath the C01 sediment trap (Table 3). Overall, the 4 most similar sites (SCD <0.6) to the sediment trap assemblage are all located eastward, while the 4 most different sites (SCD >1) are all located northward to the location of the sediment trap. This highlights the geographical variability of the Sicily Strait regarding the planktic foraminifera population and the complex oceanographic conditions. We speculate that the C01 sediment trap, in addition to registering species from both the western and eastern Mediterranean basins, could also be considered a key point in an east to west planktic foraminifera population gradient. Interestingly, the most different core-tops are located in the vicinity of the Tyrrhennian Sea and the most similar ones can be found in the easternmost part of the Sicily Strait. In combination with the dominant taxa registered, we propose that the MAW and western basin waters influence could have spread further east into the Sicily Strait. This, in combination with the resident eastern basin waters, could reconcile the planktic foraminifera assemblage described from the C01 sediment trap and the fact that it is more similar to core-tops located eastward.

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In terms of planktic foraminifera assemblage composition, the most evident observation relies on the shift of the dominant taxa when comparing the sediment trap and core-top assemblages (Figure 7). As described previously, *G. inflata* dominated the assemblages in the C01 sediment trap (Table 1), while *G. bulloides* is the best-represented species in the seabed sediment, followed by *G. inflata* and *G. ruber* (Figure 7). The latter species showed mean relative abundances of 27.5%, 23% and 20% across all core-tops, respectively. Interestingly, *G. truncatulinoides* abundance was significantly lower in the core-tops while the "other species" category, which consists of minor taxa such as *G. rubescens, G. siphonifera* and *G. calida* (amongst others) played a more significant role in the seabed sediment, reaching abundances up to 26% (Figure 7). These results lead to several observations. Firstly, *G. bulloides*, considered more susceptible to dissolution than the average planktic foraminifera species (Dittert et al., 1999), dominates the seabed sediment assemblages; and *G. inflata*, considered a less dissolution susceptible species (Schiebel and Hemleben, 2017) dominates the sediment trap population. This information reinforces the idea that calcite dissolution in the water column or sediments is negligible. In other words, if dissolution was to take place here, *G. inflata* would be overrepresented in the seabed sediment, which is not the case. Secondly, the seabed sediment planktic foraminifera populations showed a reduced influence of deep-dwelling species and a more pronounced influence of both eutrophic and oligotrophic species. These eutrophic species (such as *G. bulloides* but also *N. incompta*) are associated with MAW and western basins in the modern Mediterranean Sea, while the more oligotrophic taxa (*G. ruber*, *G. rubescens*, *G. calida*…) are considered to be transported from the easternmost part of the basin (Azibeiro et al., 2023). A possible interpretation of these results is that the MAW influence into the basin may have shifted, and instead of bringing rich and eutrophic waters that would allow the development of opportunistic species, it nowadays brings more mesotrophic water masses that favour the development of deep dwellers in the Sicily Strait. On the other hand, this could also lead to the assumption of a reduced eastward and LIW influence in the present day as seen by the significantly lower abundance of oligotrophic species in the C01 sediment trap. Also, a change in the environmental conditions could lead to the increase of deep dwellers in substitution of eutrophic species such as *G. bulloides*. As described previously, the Mediterranean Sea has already been described as a climate change "hotspot", therefore the already documented ocean warming and the consequent stratification (Malanotte-Rizzoli et al., 2014; Siokou-Frangou et al., 2010) could have led to unfavorable conditions for several taxa. A decrease in the primary production might have caused a shift in the dominance of the opportunistic *G. bulloides* by *G. inflata*. As described previously, *G. bulloides* shows a high affinity for high productivity environments, while deep dwellers such as *G. inflata* and *G. truncatulinoides* tend to prefer mesotrophic and stratified waters. In that sense, the recent warming and stratification of the Mediterranean could explain the recent trend in the planktic foraminifera population registered by the C01 sediment trap. However, in that case, species such as *G. ruber* and other oligotrophic species should be at least as much represented as in the seabed sediment. Alternatively, this could imply a change in the intensity of the water masses flowing, such as an increased mesotrophic MAW influence and a reduced oligotrophic LIW influence.

Therefore, here we theorize that a combination of environmental change and a shift in the oceanographic configuration could explain the differences in the planktic foraminifera population

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between the modern C01 sediment trap population and the seabed assemblages. Overall, these results call for increasing the monitoring of planktic foraminifera populations and accentuating the comparisons between recent and seabed sediment assemblages in the Mediterranean to determine if the trends suggested by our data are the result of the recent environmental change.

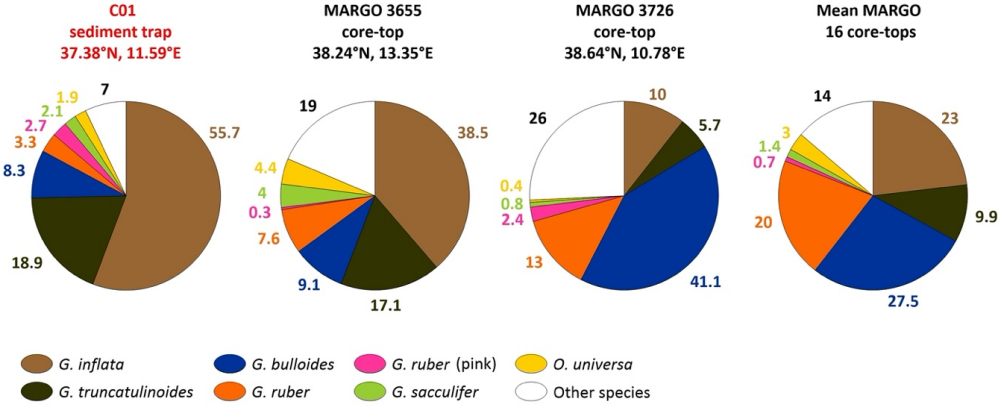

Figure 7. Comparison of the relative abundance of the planktic foraminifera from the sediment trap and seabed sediment. C01 sediment trap is depicted in red (first from the left). MARGO site 3655 corresponds to the lowest squared chord distance and MARGO site 3726 to the highest one. The last figure represents the mean relative abundance of all core-tops included in this study (see Supplementary data).

Conclusions

The C01 mooring line, located on the axis of the Sicily Strait, provided the opportunity to document the planktic foraminifera population on an interannual scale. We analyzed 19 samples that covered the timespan between November 2013 and October 2014. A total of 3723 individuals and 15 different species were identified. *G. inflata*, *G. truncatulinoides*, *G. bulloides*, *G. ruber* and *G. ruber* (pink) were the five most abundant species, representing 56, 19, 8, 3.5 and 3% of the total foraminifera. The remaining species represented less than 5% of the total individuals. Total planktic foraminifera flux ranged between 44 and 1890 shells m^{-2} d^{-1}, higher values were reached during spring while values were lower during summer. Our data indicates that the planktic foraminifera fluxes mainly reflect the oceanographic configuration of the Sicily Strait and its seasonal surface circulation variability. During winter and spring, a stronger eastward advection favours the MAW entrance in the Sicily Strait, allowing cool and nutrient enriched waters to enter the strait. This resulted in an increased planktic foraminifera flux and a higher presence of *G. inflata*, *G. truncatulinoides* or *G. bulloides*, which are taxa associated with the western basin. On the other hand, during summer, the eastward advection is reduced and the LIW dominates the water column, favorizing the increase of species associated with the eastern basin, such as *G. ruber*, and *G. ruber* (pink). Our correlation data with both SST and chlorophyll-*a* showed that *G. inflata* was associated

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with cool and nutrient rich waters. In contrast, both *G. ruber* species were associated with warm and oligotrophic waters, which agrees with their ecology. Surprisingly, no significant trends were identified for either *G. truncatulinoides* or *G. bulloides*. The comparison with integrated annual data from other sediment trap experiments conducted in in different regions of the Mediterranean basin, our fluxes and diversity data indicated that the Sicily Strait can be considered a transitional zone in regard to planktic foraminifera populations: annualized fluxes were lower compared to the westernmost Alboran Sea, but higher than in the easternmost Levantine basin. However, the Sicily Strait exhibited the highest diversity values across all the sites analyzed, highlighting the influence of both the western and eastern basins. Finally, the planktic foraminifera assemblages from the sediment trap were significantly different from the ones coming from the seabed located in the vicinity of the mooring line. In the sediment trap, deep dwellers dominated the planktic foraminifera population, while both eutrophic and oligotrophic taxa were more abundant in the seabed sediment. We propose a combination of two factors to explain these differences such as recent environmental change, most likely warming and consequent shallowing of mixed layer depths; and a shift in the oceanographical conditions in the recent Central Mediterranean.

Data availability. All data used in this study are presented in the Supplement and are available online at doi: 10.17632/tp4v6hm7dc.1 (Béjard et al., 2023).

Supplement. The supplement related to this article is available online at:

Author contributions. ASRH, FJS and TMB designed the study. JPT designed Fig. 1 and contributed to planktic foraminifera identification and imaging. ASV and ILC provided the JERICO C01 sediment trap samples and led the sample processing. TMB led the microscopy and image analysis, the foraminifera study, statistical analysis and wrote the manuscript with feedback from all authors.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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