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## 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

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## ABSTRACT

In order to investigate the seasonal and interannual variability of planktic foraminiferal fluxes in the NW Mediterranean, 266 samples from two 12-year-long sediment traps were analyzed. Two mooring lines were deployed at the east (Station Planier) and the west (Station Lacaze Duthiers) of the Gulf of Lions. The moorings were deployed at a water depth of around 1000 m and were equipped with sediment traps at 500 m above bottom (mab). In addition, an array of 13 core-tops recovered from different key areas of the Gulf of Lions is described. At Lacaze Duthiers, average foraminiferal fluxes were about double ( $411.8 \text{ shells m}^{-2} \text{ d}^{-1}$ ) those found at the Planier sampling site ( $225.4 \text{ shells m}^{-2} \text{ d}^{-1}$ ), probably due to the fertilizing effect of the Rhone river plume and the general oceanographic circulation. The annual total foraminiferal fluxes exhibited a unimodal trend, with maxima recorded during the winter–spring transition, i.e. the spring bloom, and minima during summer. Therefore, planktic foraminifers found in the sedimentary record in the Gulf of Lions may reflect the flux during the winter–spring period, rather than throughout the annual cycle. A total of eleven planktic foraminiferal species were identified in the sediment trap and core-top samples but only four species were dominant in the assemblages: *Globigerina bulloides*, *Neoglobobulimina papyroderma* (dex.), *Globorotalia inflata* and *Globorotalia truncatulinoides*. The foraminiferal assemblages in the Gulf of Lions reflected the relatively cold conditions of the Northern Basin. No clear relationship between the NAO (North Atlantic Oscillation) and planktic foraminiferal fluxes was found in the sediment trap records. The low planktic foraminiferal fluxes recorded during the spring of 1998 were probably related to the anomalous environmental conditions triggered by the 1997–98 El Niño event. Furthermore, sediment trap samples were compared with surficial sediments recovered from different environmental and sedimentary settings of the Gulf of Lions and the application of these results in paleoceanographic reconstructions is discussed.

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### 1. Introduction

Planktic foraminifers have been widely used for paleoceanographic and paleoclimatic reconstructions. The diversity and abundance of modern foraminiferal assemblages are intimately related to the hydrographic conditions prevailing in the region where they live (e.g., temperature, salinity and food availability). These environmental preferences eventually facilitate the reconstruction of past oceanographic conditions. However, in order to make meaningful interpretations of the fossil record it is essential to fully understand the ecology and environmental factors controlling the spatial and temporal distribution of foraminifers. In this regard, several lines of research that shed light on different aspects of the biology and sedimentary processes of living planktic

foraminifers have been developed over the years: (1) Laboratory cultures, to determine the effects of different simulated environmental conditions on the growth and reproductive potential of planktic foraminifers (e.g., Bé et al. (1981), Bemis et al. (2000), Bijma et al. (1990b), Bijma et al. (1992), Dueñas-Bohórquez et al. (2009)); (2) Studies of living assemblages collected by plankton tows, which provide information about the magnitude and composition of planktic foraminifers standing stocks, their depth habitat and seasonal distribution (e.g. Bé and Tolderlund (1971), Lončarić et al. (2006), Peeters et al. (2002), Pujol and Vergnaud Grazzini (1995), Retailleau et al. (2009), Schiebel (2002), Schiebel et al. (1997), Williams et al. (1981)). Recently living specimens have also been analyzed for genetic studies (e.g., Darling et al. (2006), Darling et al. (2003), Darling and Wade (2008)); (3) Sediment trap experiments, which record the integrated faunal flux bridging the gap between living populations and the fossil foraminiferal record (e.g. Asahi and Takahashi (2007), Deuser et al. (1981) Kincaid et al. (2000), King and Howard (2003), Thunell and Reynolds (1984)); (4) Studies of

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foraminifers from the recent deep-sea cores to draw meaningful inferences for reconstructing paleoceanographic conditions using modern analog techniques (e.g. Hayes et al. (2005), Kallel et al. (1997), Rohling and De Rijk (1989), Rohling et al. (2004), Thiede (1978), Thunell (1978)).

The Mediterranean Sea has been the object of numerous paleoclimatic studies in which planktic foraminifers have played a vital role (Cacho et al., 1999; Perez-Folgado et al., 2003; Schilman et al., 2001; Sierro et al., 2009; Sierro et al., 2005; Thiede, 1978). Nonetheless, as pointed out by Pujol and Vergnaud Grazzini (1995) few studies have been focused on living foraminiferal populations in the Mediterranean Basin (Bárcena et al., 2004; Cifelli, 1974; Hernández-Almeida et al., 2011; Pujol and Vergnaud Grazzini, 1995).

In this work, we present the results of the first long-term study of planktic foraminiferal fluxes in the Western Mediterranean by analyzing two 12-year-long sediment trap records and a set of 13 core-tops along a transect covering key physiographic regions of the Gulf of Lions (i.e., continental shelf, open slope, submarine canyons, and deep basin). The main objectives of this research are (1) to determine the effect of seasonal oceanographic changes on the export of particulates and the foraminiferal flux of sediment traps and the corresponding core top sediments of the Gulf of Lions; (2) to assess the influence of primary productivity and river runoff on the abundance and composition of foraminiferal fluxes; (3) to infer the impact of recent climatic events such as the NAO and ENSO on the foraminiferal fluxes of the northwestern Mediterranean.

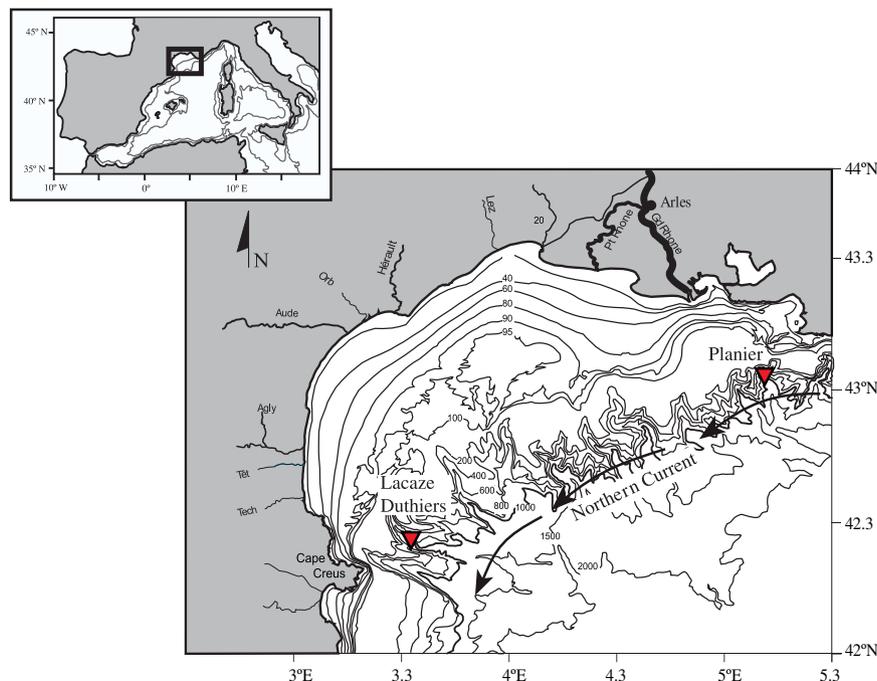
## 2. Oceanographic setting

The Gulf of Lions, located in the northwestern part of the Mediterranean Sea, has a broad crescent-shaped continental shelf and a continental slope incised by an intricate network of submarine canyons (Fig. 1). The general circulation in this area is governed by the Northern Current (NC) that enters the Gulf from its eastern side and flows to the south along the shelf break in a counter-clockwise direction (Millot, 1991) (Fig. 1). During the

winter, cold, dry continental northwesterlies (the Mistral and Tramontana) blow with intensity over the Gulf, and are responsible for the formation of dense water both on the shelf and offshore. The homogenization of the water column during winter facilitates the exchange of particulate matter between the shelf and the open sea (Durrieu de Madron et al., 2005; Heussner et al., 2006). During extreme cold and windy winters (e.g. 1999 and 2005), large volumes of dense water are formed over the shelf, drawing a large amount of sediment and organic matter from the continental shelf to the deep basin (Canals et al., 2006). This phenomenon is called Dense Shelf Water Cascading (DSWC) and occurs along the entire shelfbreak, although it is more pronounced at the southwestern exit of the Gulf (Canals et al., 2006; Heussner et al., 2006).

The suspended particulate matter in the waters of the Gulf of Lions have different sources: river input, Saharan dust deposition, biological production and particle resuspension (Heussner et al., 2006). The river input is the main source of suspended particles over the Gulf, mainly due to the Rhone which is the river with greatest discharge in the Western Mediterranean (Ulses et al., 2008). Owing to the predominance of river inputs, suspended particle concentrations present a strong, seaward-decreasing gradient all year round, however with a significant seasonal variation (Heussner et al., 2006).

The annual range of Sea Surface Temperature (SST) varies between 12 and 26 °C in both stations (See Figs. 4–7) while the annual Sea Surface Salinity (SSS) values range between 38 and 38.5 psu (MEDAR Group, 2002). The annual cycle of the thermal structure of the water column in the northwestern Mediterranean follows the classic seasonal evolution of a temperate ocean (See Figs. 6 and 7). After summer, seasonal cooling breaks up the strong stratification. During winter, the persistent northwesterlies promote dense water formation and deep mixing, advecting nutrients to the surface and setting the stage for the spring bloom. By late winter to early spring, surface waters are enriched in nutrients and solar radiation increases, triggering primary production. Finally, the gradual increase in insolation in spring causes stratification and nutrient depletion of surface waters in summer.



**Fig. 1.** Geographic setting and bathymetric map of the Gulf of Lions. Triangles represent the position of the Planier and Lacaze-Duthiers sediment traps; arrows represent the theoretical surface circulation.

From the productivity point of view, the Northern Basin can be considered an exception to the general oligotrophy of the Mediterranean owing to several features that contribute to an increase of its potential fertility, such as the mesoscale variability of the NC, the winter vertical mixing, and the nutrient-rich waters from the Rhone (Estrada, 1996).

### 3. Material and methods

#### 3.1. Sampling

Two mooring lines were deployed in the NW Mediterranean: one in the Northeast of the Gulf of Lions, in the axis of the Planier Canyon (43.02°N, 5.18°E) and one at the Southwest, in the axis of the Lacaze Duthiers Canyon (42.41°N, 3.54°E) (Fig. 1). Both moorings were deployed at ca. 1000 m water depth and were equipped with two sediment traps (500 and 1000 mab) and paired with current meters (Heussner et al., 2006). These traps were PPS 3 Technicap sediment traps: cylindrical–conical in shape with 0.4 m opening diameter (2.5 height/diameter aspect ratio for the cylindrical part) and equipped with 6 or 12 sampling cups (Heussner et al., 1990).

Here we present the data recorded by the two sediment traps set at 500 mab from October 1993 until January 2006. The experiments can be divided in two phases based on the collecting periods: a first phase with a sampling interval at 14 day until early 1997, and at one month onwards until the beginning of 2006. Gaps in the time series were caused by mooring recovery periods or by problems in sediment trap functioning. Despite these gaps, the foraminiferal test flux data represent more than 75% and 82% of the deployment time for the Planier and Lacaze Duthiers stations, respectively.

#### 3.2. Core tops

The relative abundance of planktic foraminifers of thirteen core tops (0–0.5 cm) from various physiographic areas of the Gulf of Lions is presented (Figs. 2 and 3). The data of eleven core tops were taken from the Core top database of Kallel et al. (1997) and two core tops were analyzed during this study (Table 1).

#### 3.3. General processing of the sediment trap and core top samples

The general sample processing and a detailed description of the PPS3 sediment traps can be found in Heussner et al. (1990, 2006),

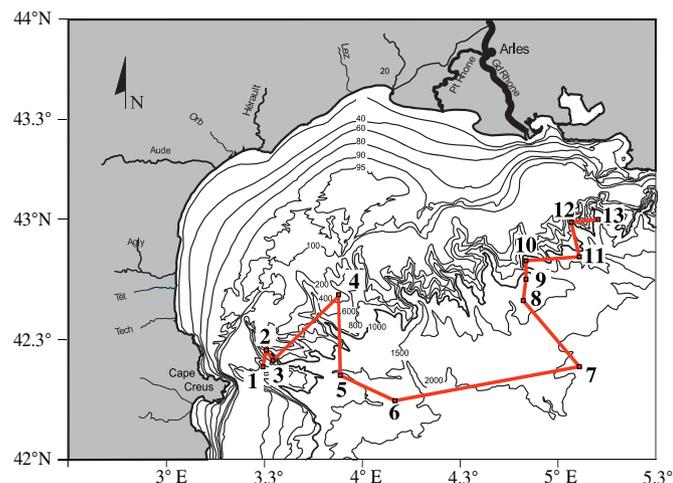


Fig. 2. Bathymetric map of the Gulf of Lions with the location of the core tops. The red line represent the core top transect. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

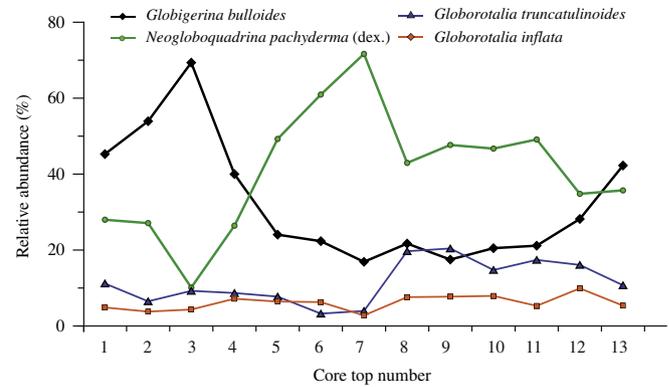


Fig. 3. Relative abundance of the four main taxa along the core top transect.

while the specific treatment for the foraminiferal analysis is described. Different aliquots of trap samples were used for the micropaleontological analyses. The most common aliquot was 1/8, although other fractions were also used depending on sample availability, which ranged from 1/64 to 3/4.

The samples were wet-sieved into two size fractions: 63–150  $\mu\text{m}$  and  $> 150 \mu\text{m}$  using a potassium phosphate-buffered solution (pH=7.5). The aim of this solution was to prevent carbonate dissolution during the sieving process without affecting shell composition. After the wet-sieving process, the  $> 150 \mu\text{m}$  fraction was filtered with cellulose filter paper and then dried at ambient temperature. Most of the core-top foraminiferal data were taken from the Mediterranean data base (Core top database of Kallel et al. (1997)), with the exception of two samples, which were sieved through a 63- $\mu\text{m}$  screen and dry-sieved through a 150- $\mu\text{m}$  screen. The  $> 150 \mu\text{m}$  fraction was then split as many times as necessary to obtain an aliquot of 400 or more planktic foraminifers. In all, 278 sediment trap samples and 2 core-top samples ( $> 150 \mu\text{m}$ ) were examined under a stereomicroscope for species identification and counting. Owing to the high seasonal flux variations, there were some periods when almost no foraminifers were present in the water column or in the traps. Consequently, the number of tests in the samples was highly variable, ranging from zero to 1946. The foraminiferal flux data are given in shells  $\text{m}^{-2} \text{d}^{-1}$ , which were calculated based on the duration of each collection period, the aliquot of the original sample, and the diameter of the sediment trap (0.4 m diameter).

Monthly averages of planktic foraminiferal fluxes, chlorophyll-a and SST changes were elaborated to discern their general seasonal trends (See Figs. 6 and 7). To calculate the monthly average flux, an average daily flux value was assigned to each day of the collecting period. Thus, the total flux for a particular month was the result of the addition of all daily fluxes during that month.

#### 3.4. Satellite imagery and meteorological and oceanographic data

SeaWiFS derived monthly chlorophyll-a concentrations from September 1997 to March 2006 (Figs. 3 and 4) were obtained from NASA's Giovanni program (Acker and Leptoukh, 2007). The chlorophyll-a concentration was averaged over an area of  $0.2^\circ \times 0.2^\circ$  around the mooring location. Weekly sea surface temperatures (SSTs) from October 1993 until March 2006 (Figs. 4 and 5) were obtained from NOAA Optimum Interpolation Sea Surface Temperature Analysis (Reynolds et al., 2002). Seasonal variation of the vertical structures of temperature of the upper 300 m for the 1996–2006 period were obtained for both sampling locations from the World Ocean Atlas 2009 (Locarnini et al., 2010).

**Table 1**  
Location, water depth and relative abundances of planktic foraminiferal species of the core tops and sediment traps.

	Core tops													Sediment traps		
	1	2	3	4	5	6	7	8	9	10	11	12	13	Planier	L D	
Latitude	42.27N	42.29N	42.26N	42.69N	42.23N	42.14N	42.24N	42.48N	42.51N	42.5N	42.56N	42.59N	43.1N	43.02N	42.41N	
Longitude	3.31 E	3.29 E	3.32 E	3.84 E	3.53 E	4.1 E	4.57 E	4.39 E	4.5 E	4.49 E	5.06 E	5.04 E	5.12 E	5.18 E	3.54 E	
Water depth (m)	958	650	990	300	1200	1740	1875	1130	1040	1012	1310	1035	1095	1000 (500 mab)	1000 (500 mab)	
<b>Relative abundance (%)</b>																
<i>G. bulloides</i>	45.3	53.9	69.4	40.0	24.1	22.3	16.9	21.7	17.5	20.5	21.2	28.2	42.3	36.5	50.8	
<i>N. pachyderma</i> (dex.)	28.0	27.1	10.1	26.4	49.3	61.0	71.7	43.0	47.7	46.7	49.1	34.8	35.7	18.7	16.0	
<i>G. inflata</i>	4.9	3.8	4.3	7.2	6.4	6.3	2.8	7.6	7.7	7.9	5.3	9.9	5.4	10.1	9.2	
<i>G. truncatulinoides</i>	11.2	6.5	9.2	8.7	7.7	3.3	4.0	19.7	20.4	14.8	17.4	16.1	10.7	30.3	17.5	
<i>O. universa</i>	1.2	1.1	3.5	0.8	0.3	0.4	0.2	0.9	0.7	0.8	1.1	1.5	1.0	1.3	2.4	
<i>G. siphonifera</i>	0.2	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.3	1.1	
<i>G. ruber</i> (white)	4.1	3.5	1.2	11.3	5.9	0.9	0.4	4.3	2.7	6.3	2.4	6.0	2.4	0.2	0.3	
<i>G. ruber</i> (pink)	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.1	
<i>G. sacculifer</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.5	1.7	
<i>G. glutinata</i>	1.0	1.4	0.3	0.0	2.3	2.6	1.6	1.1	1.0	0.3	0.7	0.9	0.6	0.2	0.3	
<i>G. digitata</i>	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.2	0.3	
<i>T. quinqueloba</i>	0.0	0.5	0.0	1.1	0.8	0.2	0.9	0.0	0.0	0.0	0.2	0.2	0.0	0.7	0.2	

### 3.5. Sample analyses

To investigate the periodicity of the flux of total foraminifers at the Planier and Lacaze Duthiers stations, the maximum entropy spectral method (MEM) was applied using the “Analysis Series” program, Version 1.1 (Paillard et al., 1996). Before the spectral analyses, the data sets were normalized and linearly detrended. Owing to the gaps up to 1997 in the Planier time-series (Fig. 4), the analysis was performed only for the 1997–2006 period for this station, while for Lacaze Duthiers the complete data set was used. The MEM analysis afforded only one significant 12-month cycle at both stations (Figs. 4 and 5). Additionally, a dissimilarity matrix was calculated in order to measure the faunal similarity between sediment-trap foraminiferal assemblages and those of core tops (Table 2).

## 4. Results

### 4.1. Total particle flux and bulk composition

The total particulate flux and its bulk compounds at both stations from October 1993 until June 2001 is discussed in detail by Heussner et al. (2006). In addition, a complementary dataset of the total particle flux June 2001 till March 2005 is reported (Figs. 4 and 5). The patterns observed in total mass flux are closely related to seasonal hydrographic variability in the upper water column. A distinct maximum occurred every year during February and March (Figs. 4 and 5) and the magnitude of the maximum varied from year to year. The 12-year average of total mass flux was approximately 2.5 times higher in Lacaze Duthiers ( $1765 \text{ mg m}^{-2} \text{ d}^{-1}$ ) than in Planier ( $679 \text{ mg m}^{-2} \text{ d}^{-1}$ ) site.

### 4.2. Total planktic foraminiferal fluxes

Total planktic foraminiferal fluxes exhibited maximum fluxes during winter–spring transition and minimum during summer (Figs. 4 and 5). At the Planier station, total planktic foraminiferal fluxes ranged from 0 to  $2144 \text{ shells m}^{-2} \text{ d}^{-1}$ , while at Lacaze Duthiers they ranged from 2 to  $4268 \text{ shells m}^{-2} \text{ d}^{-1}$ . The 12-year average of the total foraminiferal fluxes ( $> 150 \mu\text{m}$ ) at the Planier

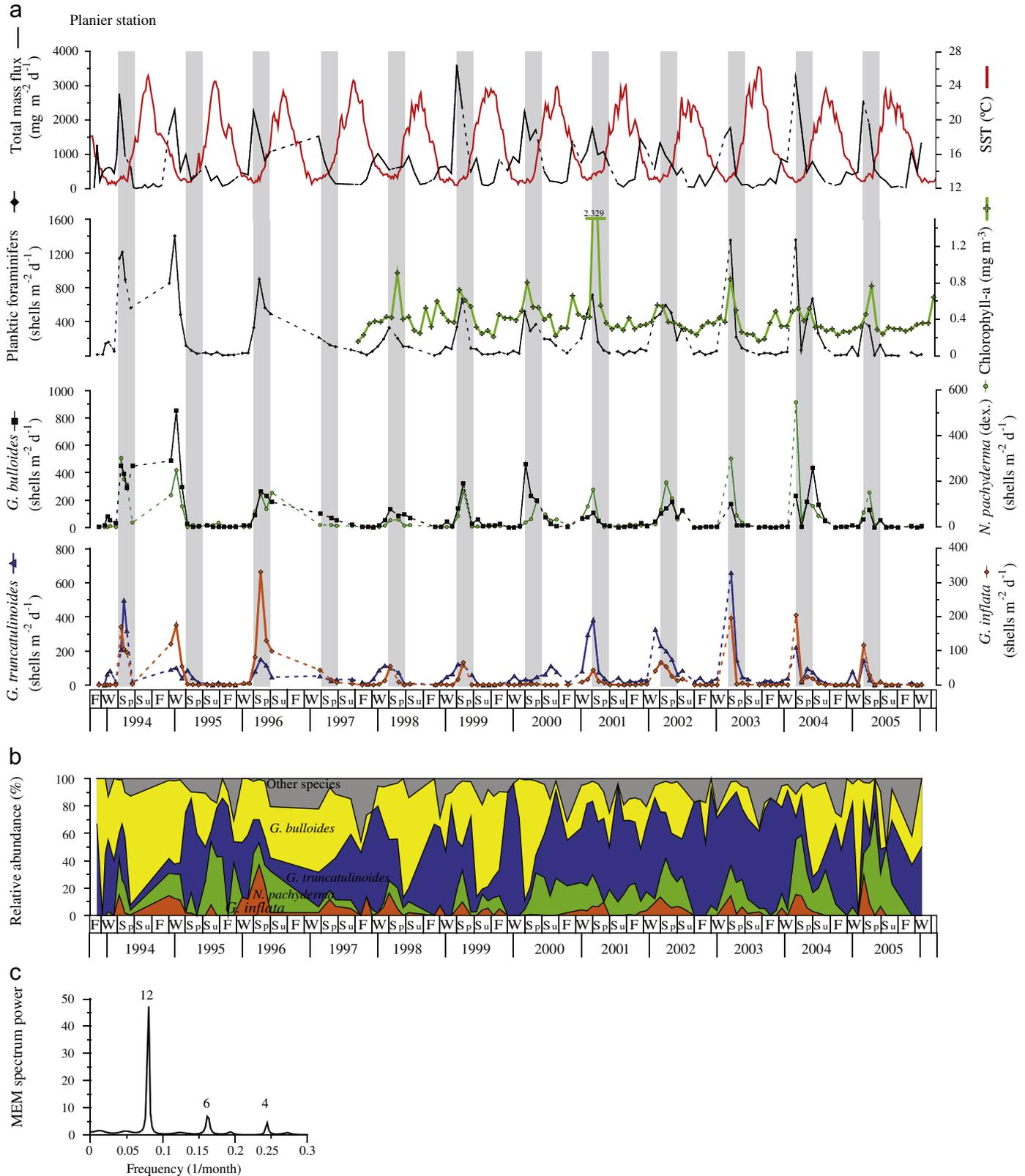
site was  $225.4 \text{ shells m}^{-2} \text{ d}^{-1}$  while at the Lacaze Duthiers station it was approximately double ( $411.8 \text{ shells m}^{-2} \text{ d}^{-1}$ ).

The highest fluxes were recorded at Planier during December 1994 ( $1405 \text{ shells m}^{-2} \text{ d}^{-1}$ ), March 2004 ( $1360 \text{ shells m}^{-2} \text{ d}^{-1}$ ), and March 2003 ( $1356 \text{ shells m}^{-2} \text{ d}^{-1}$ ) (Fig. 4), while at the Lacaze Duthiers site, the highest values were recorded during March 1994 ( $4268 \text{ shells m}^{-2} \text{ d}^{-1}$ ), March and April 2000 ( $3998$  and  $3565 \text{ shells m}^{-2} \text{ d}^{-1}$ ), and March 1996 ( $2603 \text{ shells m}^{-2} \text{ d}^{-1}$ ) (Fig. 5).

### 4.3. Foraminiferal assemblages

Eleven species of planktic foraminifers were identified, but the assemblages at both stations were mainly represented by only four taxa: *Globigerina bulloides*, *Neogloboquadrina pachyderma* (dex.), *Globorotalia inflata* and *Globorotalia truncatulinoides*. These four species accounted for 94.5% and 87.8% of the planktic foraminiferal assemblages recorded at the Planier and Lacaze Duthiers sites, respectively. Besides, the less abundant species: *Globigerinella siphonifera*, *Neogloboquadrina pachyderma* (sin.), *Globigerinoides ruber* white and pink, *Globigerinoides sacculifer*, *Globigerinella glutinata*, *Orbulina universa* and *Turborotalita quinqueloba* were also identified and counted.

The main planktic foraminiferal species showed a similar annual unimodal distribution pattern at both the sites; yet, they displayed slightly different annual patterns (Figs. 6 and 7). Owing to the negligible quantity of other species the changes in their fluxes are not as significant as for the major taxa. Among the “other species” group the main species were *O. universa* (1.3%), *G. siphonifera* (1.3%) for Planier and *O. universa* (2.4%), *G. sacculifer* (1.7%) and *G. siphonifera* (1.1%) for the Lacaze Duthiers site (Table 1). These species exhibited different annual distribution patterns at each sampling station (Figs. 6 and 7). In this sense, *O. universa* exhibited its maximum fluxes at the end of spring and summer at the Planier station (Fig. 6), and during fall at Lacaze Duthiers (Fig. 7). *G. siphonifera* fluxes were highest during spring at Planier (Fig. 6), and during winter at Lacaze Duthiers (Fig. 7). Regarding *G. sacculifer* and *G. ruber* (white), their fluxes at the Planier station were lower and more dispersed than at the Lacaze Duthiers site, where they had higher values and clear seasonal maximum values in fall (Figs. 6 and 7).



**Fig. 4.** Planier station a. Total mass flux ( $\text{mg m}^{-2} \text{d}^{-1}$ ), SST ( $^{\circ}\text{C}$ ), total foraminiferal flux ( $\text{shells m}^{-2} \text{d}^{-1}$ ), chlorophyll-a concentration ( $\text{mg m}^{-3}$ ) and flux of *G. bulloides*, *N. pachyderma*, *G. inflata* and *G. truncatulinoides* ( $\text{shells m}^{-2} \text{d}^{-1}$ ). Gaps in the time series are represented by a dotted line. Gray bars represent spring. b. Relative abundance of the foraminiferal assemblage c. Frequency versus power from the maximum entropy method for total foraminiferal flux at the Planier site.

#### 4.4. Core tops

The core-top transect covers different environmental and sedimentary settings of the Gulf of Lions (Fig. 2). The relative abundance

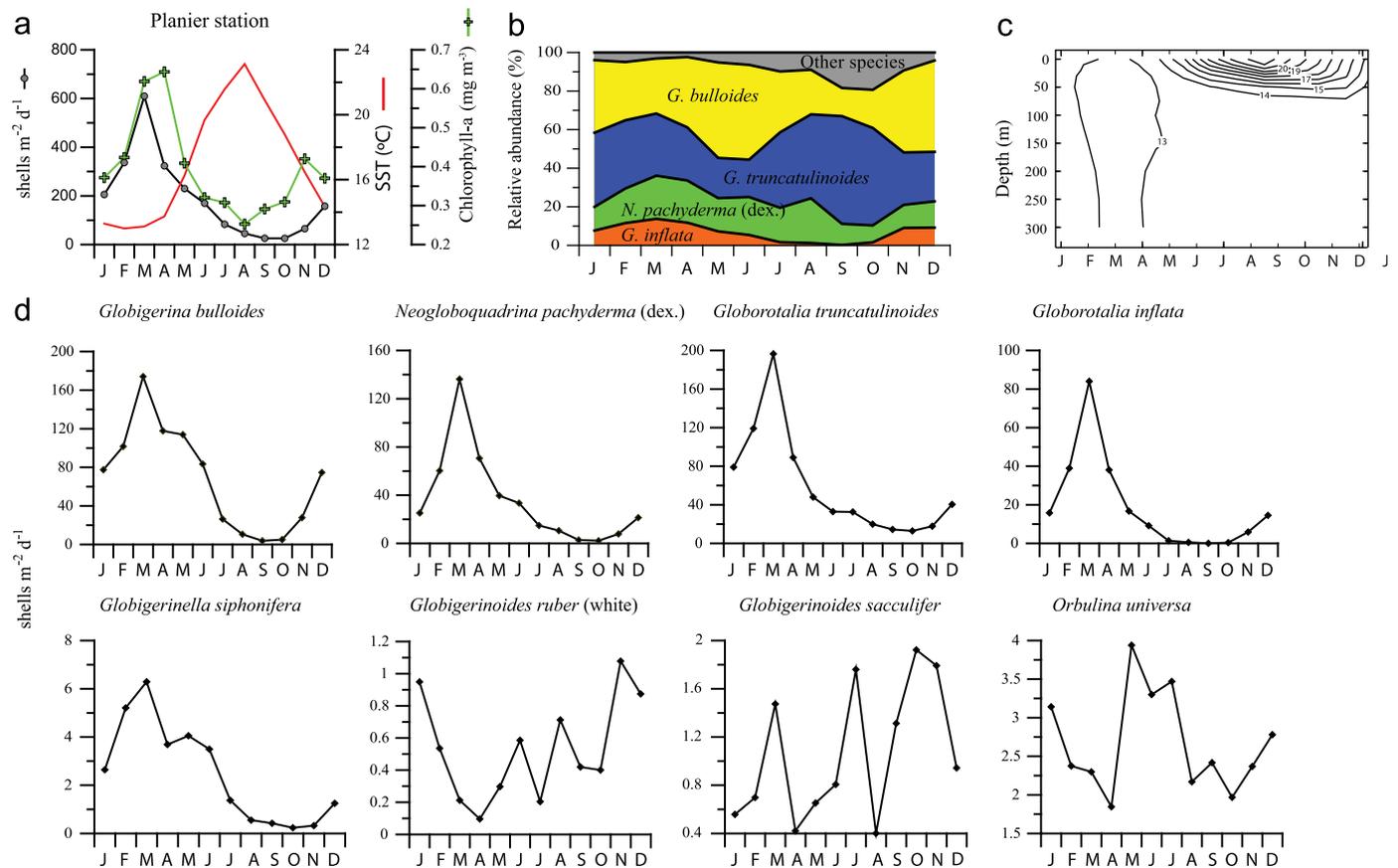
of all the foraminiferal species observed in the sediment samples are summarized in Table 1, and the relative abundances of the major taxa along the transect are plotted in Fig. 3. The same four taxa that dominated the planktic foraminiferal fluxes in the sediment traps



**Table 2**

Matrix of dissimilarity (squared chord distance) between each of the core-tops and the sediment trap sites. The closest analogs are highlighted.

	1	2	3	4	5	6	7	8	9	10	11	12	13	Planier	L D
1	0														
2	0.019	0													
3	0.169	0.104	0												
4	0.028	0.054	0.233	0											
5	0.300	0.402	0.857	0.276	0										
6	0.441	0.540	1.039	0.434	0.027	0									
7	0.599	0.714	1.256	0.591	0.072	0.018	0								
8	0.296	0.439	0.843	0.291	0.062	0.131	0.178	0							
9	0.414	0.572	1.020	0.411	0.071	0.111	0.131	0.012	0						
10	0.335	0.470	0.918	0.309	0.024	0.070	0.107	0.015	0.018	0					
11	0.344	0.482	0.926	0.348	0.037	0.073	0.101	0.013	0.009	0.010	0				
12	0.133	0.239	0.555	0.122	0.095	0.206	0.305	0.045	0.101	0.069	0.084	0			
13	0.022	0.062	0.298	0.050	0.171	0.276	0.407	0.184	0.273	0.205	0.209	0.073	0		
Planier	<b>0.199</b>	<b>0.289</b>	0.346	<b>0.255</b>	0.561	0.755	0.905	0.346	0.454	0.472	0.456	<b>0.219</b>	<b>0.242</b>	0	
L D	<b>0.080</b>	<b>0.082</b>	<b>0.069</b>	<b>0.137</b>	0.617	0.802	1.000	0.528	0.677	0.620	0.622	0.302	<b>0.165</b>	0.120	0



**Fig. 6.** (a) Mean yearly values of total foraminiferal flux ( $\text{shells m}^{-2} \text{d}^{-1}$ ), temperature and chlorophyll-a concentration ( $\text{mg m}^{-3}$ ) for the Planier site. (b) Mean yearly values of relative abundance of the main foraminiferal groups of Planier site. (c) Seasonal variation in the vertical structure of temperature at Planier. (d) Mean yearly values of the main foraminiferal fluxes ( $\text{shells m}^{-2} \text{d}^{-1}$ ) at the Planier site.

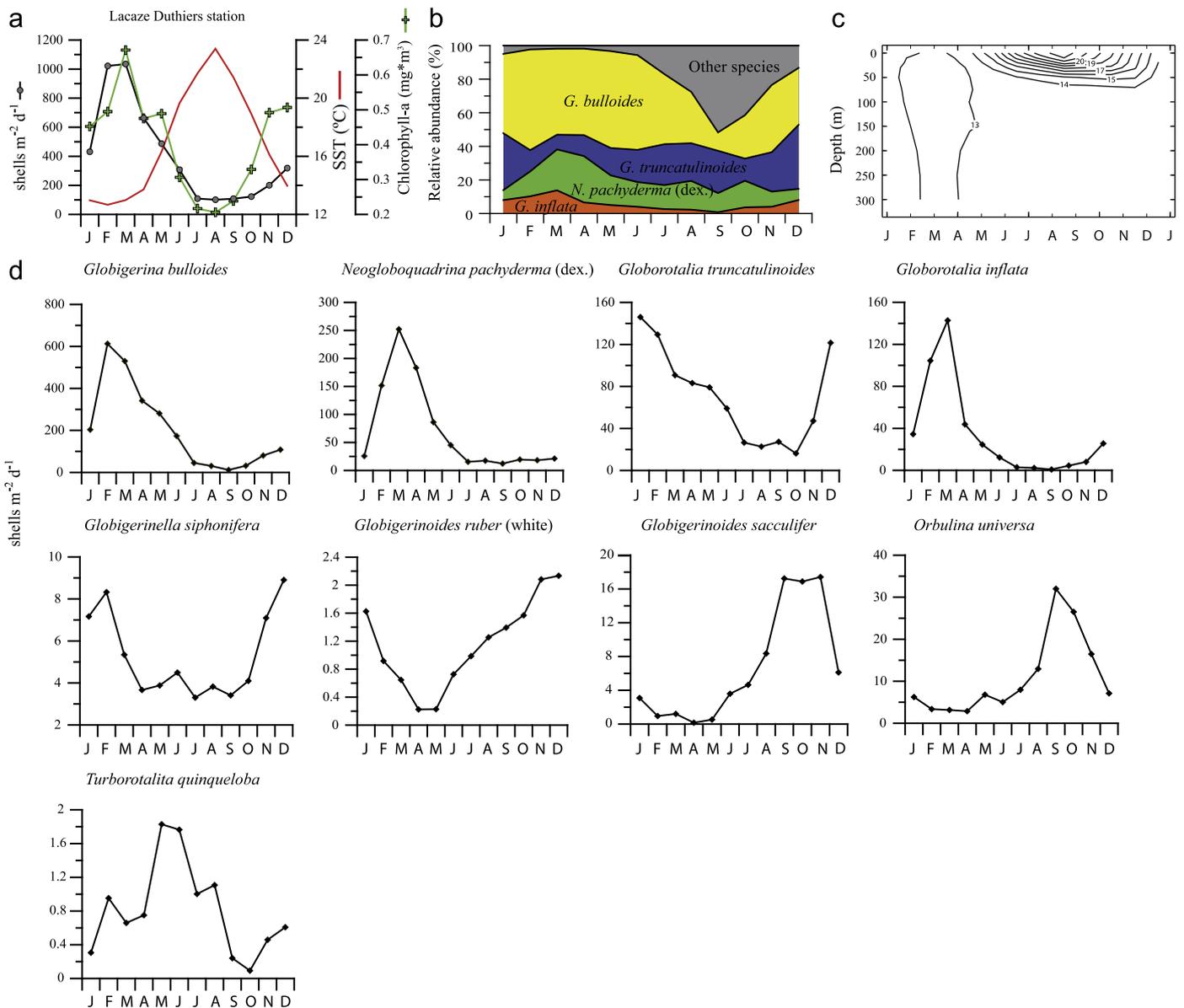
recorded in the southwestern part of the Gulf. *G. inflata* was the fourth most important planktic foraminiferal species and its contribution was relatively constant in all the samples of the array.

Similarity between the sediment trap and the core top foraminiferal assemblages is determined by the squared chord dissimilarity (Table 2). A squared chord distance dissimilarity of  $< 0.2$  is considered to indicate a close analog (King and Howard, 2001; King and Howard, 2003; Ortiz and Mix, 1997). At Planier, the closest analogs are core tops 1, 2, 4, 12 and 13 ( $< 0.3$ ), located at the upper continental slope. The closest analogs to the Lacaze Duthiers trap are 1, 2, 3, 4 and 13, similar to those of Planier, however they showed lower distance dissimilarity values ( $< 0.16$ ).

## 5. Discussion

### 5.1. Seasonal and geographical variability of planktic foraminiferal fluxes

The planktic foraminiferal fluxes showed consistent annual cycles and variable interannual fluctuations that mirrored the hydrographic and atmospheric conditions off the Northwestern Mediterranean. The MEM power spectrum analysis identified one significant cycle of a 12-month period at both stations (Figs. 4 and 5) that referred to the winter–spring maxima of the total foraminiferal flux. This maximum of the total foraminiferal flux was always



**Fig. 7.** (a) Mean yearly values of total foraminiferal flux (shells  $m^{-2} d^{-1}$ ), temperature and chlorophyll-a concentration ( $mg m^{-3}$ ) for the Lacaze Duthiers site. (b) Mean yearly values of relative abundance of the main foraminiferal groups at the Lacaze Duthiers station. (c) Seasonal variation in the vertical structure of temperature at the Lacaze Duthiers station. (d) Mean yearly values of the main foraminiferal fluxes (shells  $m^{-2} d^{-1}$ ) at the Lacaze Duthiers site.

associated with the spring phytoplankton bloom when the highest annual chlorophyll-a concentration (Figs. 6 and 7) and annual maximum fluxes of silicoflagellates (Rigual-Hernández et al., 2010), coccoliths and diatom valves (Rigual-Hernández, et al. submitted and unpublished results) were registered. By contrast, the minimum annual foraminiferal fluxes were always recorded during summer and autumn at both locations, i.e., the period of lowest primary productivity and strongest stratification (Figs. 6 and 7). The strong seasonality of the planktic foraminiferal flux and the relationship with chlorophyll in sea surface water strongly argues in favor of a downward settling of foraminiferal tests at times of maximum phytoplankton productivity as the major process involved in the planktic foraminiferal sedimentation in the Gulf of Lions.

This is in agreement with the previous studies, where a strong relationship between foraminiferal growth and food availability has been described (e.g. Deuser (1986), Hemleben et al. (1989), Lončarić et al. (2007), Schiebel (2002), Schiebel and Hemleben (2000), Schiebel and Hemleben (2005)). Moreover, in the Western

Mediterranean the planktic foraminiferal production is strongly affected by seasonality and annual maximum abundance of foraminifers has consistently been associated to the spring bloom (Bárcena et al., 2004; Hernández-Almeida et al., 2011; Pujol and Vergnaud Grazzini, 1995). The entrainment of nutrients and the redistribution of chlorophyll during the spring phytoplankton bloom stimulate the growth and the increase of planktic foraminifers (Schiebel et al., 1995). During this period foraminifers may migrate around the pycnocline to reproduce, where after gametogenesis their empty tests sink to the sea bed (Schiebel and Hemleben, 2005). This would lead to a major contribution of foraminiferal tests to the total annual foraminiferal flux during the winter–spring transition in the Gulf of Lions.

Despite the fact that both sites have a similar seasonal cycle, two-fold total foraminiferal fluxes were recorded at the Lacaze Duthiers station (a 12-year average of  $411.8 \text{ shells } m^{-2} d^{-1}$ ) relative to the Planier station (a 12-year average of  $225.4 \text{ shells } m^{-2} d^{-1}$ ). Owing to the general oceanographic circulation in the Gulf of Lions, Lacaze Duthiers site is under the influence of the dilution zone of the

Rhone river plume, which is an area of elevated primary productivity due to the permanent nutrient supply (Lefevre et al., 1997). The regional setting of this station would stimulate foraminiferal growth and explains, at least partly, the higher values recorded at Lacaze Duthiers. The higher productivity is also reflected in the diatom and silicoflagellate fluxes recorded in Lacaze Duthiers trap that were also the double of those in Planier (Rigual-Hernández et al., 2010 and Rigual-Hernández not published results). Furthermore, it is worth noting that, on average, the foraminiferal fluxes observed in both traps of this study are in the same order of magnitude as those observed in other areas of elevated primary productivity in the Western Mediterranean, such as the Alboran Sea where Bårçena et al. (2004) observed total foraminiferal fluxes of  $783 \text{ shells m}^{-2} \text{ d}^{-1}$  in the Western Alboran Gyre and Hernández-Almeida et al. (2011) recorded  $970 \text{ shells m}^{-2} \text{ d}^{-1}$  in the Eastern Alboran Gyre, further confirming our interpretations.

Nevertheless, it should be taken into consideration that previous studies in the Gulf of Lions suggest that lateral particulate advection may also have played a secondary role on the accumulation of planktic foraminiferal tests in our traps, especially in the southwest of the Gulf of Lions. Planier station is considered as the most marine site of all the sampling stations studied by Heussner et al. (2006), and free from influence of the Rhone river plume as inferred from the study of Durrieu de Madron et al. (1990) in the nearby Marseille canyon. In consequence, we argue that planktic foraminiferal fluxes at Planier mainly recorded changes in population dynamics of this group of protozoans in the water column. With regard to Lacaze Duthiers site, this area has been reported to be more influenced by particulate matter from the shelf. The dominant surface water circulation concentrates suspended particles in the water column, including foraminiferal shells around the location of this site (Heussner et al., 2006). As a consequence of these factors, it can be argued that accumulation of foraminiferal shells as well as other biogenic and lithogenic particles at Lacaze-Duthiers is increased due to lateral advection of particles originated in other areas of the Gulf of Lions, including the Rhone plume and possibly a fraction of resuspended particles from the shelf. However, the straight similarity between the average seasonal cycle of the planktic foraminiferal fluxes in Planier and Lacaze-Duthiers with maximum fluxes occurring in both sites at times of phytoplankton bloom in early spring indicates that changes of surface water productivity in the Gulf of Lions can be considered as the main mechanism driving planktic foraminiferal sedimentation at Lacaze-Duthiers, even though a westward transport of particles concentrated planktic foraminiferal shells in that region.

## 5.2. Sinking rates and preservation of trap-collected planktic foraminifers

A point to consider when analyzing sediment trap foraminiferal assemblages, is the time lag between the gametogenesis or death and the recording of the foraminiferal test by the sediment trap. The sinking velocity of the empty tests is variable and is mainly governed by shell weight and presence/absence of spines (Takahashi and Bé, 1984). A general estimation derived from the studies of Takahashi and Bé (1984) and Schiebel and Hemleben (2000) is that most planktic foraminifers  $> 150 \mu\text{m}$  would reach the ocean depth of 500 m in two days or less.

Owing to the saturation of calcite and aragonite of western Mediterranean waters (Millero et al., 1979; Schneider et al., 2007) and the presence of good preserved foraminiferal tests, the possibility of carbonate dissolution during the first 500 m is ruled out.

## 5.3. Interannual planktic foraminiferal fluctuations

Although most of the spectral energy in the data on the planktic foraminiferal fluxes in the Gulf of Lions is concentrated in the annual

period, these fluxes also exhibit an evident interannual variability (Figs. 4 and 5). Several oceanographic and climatic phenomena recorded in the North Atlantic and Mediterranean, such as DSWC events, the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO), with recurrent periodicities longer than one year can leave an imprint on the variability of planktic foraminiferal fluxes.

### 5.3.1. Dense shelf water Cascading

The Gulf of Lions is one of the few areas of the Mediterranean where dense water formation occurs (Durrieu de Madron et al., 2005). During anomalously cold and windy winters, large volumes of dense water are formed over the shelf and are funneled to the deep ocean along the submarine canyons of the continental slope (Canals et al., 2006). This process occurs along the entire shelfbreak, although it is more pronounced at the exit of the Gulf of Lions (Heussner et al., 2006). The strongest cascading events along our record took place during the winters of 1999 and 2005 (Canals et al., 2006; Heussner et al., 2006). These intense DSWC events could have altered the planktic foraminiferal fluxes recorded by both sediment traps, dragging planktic foraminiferal tests previously deposited over the shelf sediments and/or enhancing the growth of the living planktic foraminiferal assemblages by means of an increase in food supply. However, during these two years no remarkably high pulses of planktic foraminifers were recorded at the stations, meaning that intense cascading events did not significantly alter planktic foraminiferal fluxes at 500 mab.

### 5.3.2. North Atlantic Oscillation

The North Atlantic Oscillation (NAO) can be defined as a north-south see-saw oscillation in atmospheric mass, with centers of action near Iceland and over the subtropical Atlantic, being the dominant mode of winter climate variability in the North Atlantic region. The NAO winter positive phase (Hurrell, 1995) is associated with warm and moist air masses conveyed towards the NW Mediterranean, resulting in mild winters and a decrease in the NC flow. In contrast, negative NAO winter values are related to severe weather conditions; i.e., cold and dry air masses from polar regions prevail, leading to an intensification of heat losses to the atmosphere and an intensification of the NC circulation (Vignudelli et al., 1999). It has been observed that low or negative NAO winter indices are often associated with strong diatom blooms while positive values are normally coupled with weak diatom blooms (Gómez and Gorsky, 2003). Therefore, an enhancement of the planktic foraminiferal fluxes due to increased food supply (nutrients and phytoplankton) is expected in winters with the most negative NAO values along our record; i.e., 1996 and 2001 (Fig. 8). Nevertheless, planktic foraminifers did not significantly intensify their fluxes during those years at either of the sampling stations, which suggests that the processes driving foraminiferal flux variability are not controlled by the NAO.

### 5.3.3. El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) is a quasi-periodic climate fluctuation whose major effects are recorded over the Pacific Ocean. El Niño events are characterized by a warming of the tropical Pacific and a weakening of the trade winds. It has been suggested that severe El Niño events could raise global mean temperatures (McPhaden, 1999a) and/or modify the climate of the North Atlantic and Europe (Wanner et al., 1997). During 1997–98, the strongest El Niño event of the last century took place (Fig. 8), and major climatic impacts felt around the world were related to this event (McPhaden, 1999b). In this regard, anomalously high SST and weak winds were recorded during the summer and fall of 1997 in the Alboran Sea (Western Mediterranean) (García-Goriz and Carr, 2001), which led to the development of a weaker than usual winter bloom

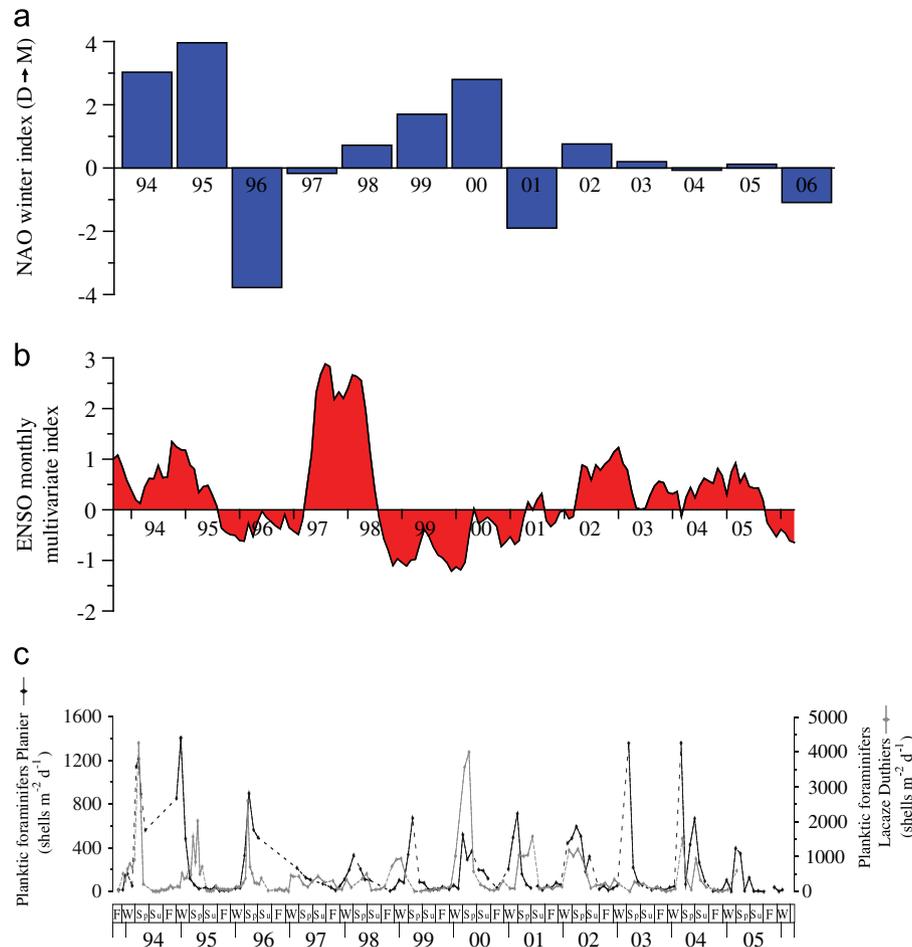


Fig. 8. (a) NAO Winter index. (b) monthly multivariate ENSO index.

regime and important changes in living planktic assemblages (Mercado et al., 2007; 2005) and in the downward fluxes of plankton remains (Bárcena et al., 2004; Hernández-Almeida et al., 2011). In the NW Mediterranean, abnormally high SST were recorded during the fall of 1997 ( $\sim 1.6$  °C higher than the 12-year average) and winter of 1997–98 (the highest winter temperatures of the record and  $\sim 0.7$  °C higher than the 12-yr winter average) (Figs. 4 and 5). The elevated winter SSTs, together with low wind intensity (Rigual-Hernández et al., submitted for publication), could have resulted in a weaker winter mixing. The planktic foraminiferal fluxes at both stations exhibited low values during this period, probably due to this weak winter mixing and a subsequent limited food supply. Our results suggest that the anomalous meteorological and hydrographic conditions induced by the El Niño event 1997–98 had a direct influence on the planktic foraminiferal fluxes in the Gulf of Lions. A similar effect has been detected in the siliceous plankton where low fluxes (Rigual-Hernández et al., 2010) and remarkable changes in the diatom assemblages (Rigual-Hernández et al., submitted for publication) have been registered in the NW Mediterranean during this specific period.

#### 5.4. Foraminiferal faunal composition in the sediment trap records

The foraminiferal assemblages at the Planier and Lacaze Duthiers stations are mainly composed of four species: *G. bulloides*, *N. pachyderma* (dex.), *G. inflata* and *G. truncatulinoides* (Table 1). This assemblage is characteristic of the NW Mediterranean (Hayes et al., 2005; Core top database of Kallel et al. (1997); Pujol and Vergnaud Grazzini, 1995) and reflects the relatively cold and high fertility

conditions of the Gulf of Lions. The maximum fluxes of all these species were always recorded during periods of maximum primary productivity, i.e. the winter–spring transition. During this period the main taxa may move to a specific depth close to the pycnocline to enhance the possibilities of successful fertilization and to optimize the food availability for the offsprings (Schiebel and Hemleben, 2005). Following reproduction, the empty tests of the parental generation settle to the sea bed which yields in a record of a major flux pulse of planktic foraminifera during the spring phytoplankton bloom. High spring fluxes of similar faunal assemblages have already been observed in other settings with large seasonal changes in water stratification such as the Southern Ocean (Northcote and Neil, 2005).

##### 5.4.1. *Globigerina bulloides*

*Globigerina bulloides* was by far the most abundant species in both sediment trap records, with a mean relative abundance of 36% and 50% at the Planier and Lacaze Duthiers sampling sites, respectively (Table 1). *G. bulloides* is a subpolar and transition species but also associated to upwelling environments (Bé and Hutson, 1977; Bé and Tolderlund, 1971; Naidu and Malmgren, 1996; Schiebel et al., 2004; Thiede, 1975). This species is considered opportunistic and may feed on any organic matter (Schiebel and Hemleben, 2005), particularly algae (Schiebel et al., 1997). *G. bulloides* is a shallow-dwelling species that has been shown to reproduce once per month triggered by the synodic lunar cycle (Bijma et al., 1990a; Schiebel et al., 1997; Schiebel and Hemleben, 2005). In the Western Mediterranean, *G. bulloides* occurs at significant abundances (Bé, 1977; Core top database of

Kallel et al., 1997), especially during periods of elevated primary productivity (Bárcena et al., 2004; Hernández-Almeida et al., 2011), while in the Eastern Mediterranean, typically associated with more permanent oligotrophic conditions, its abundance gradually decreases, showing a clear temperature and nutrient dependence (Core top database of Kallel et al. (1997), Thunell (1978)).

In our study, the enhanced availability of nutrients and prey during spring was always mirrored by the highest annual fluxes of *G. bulloides* (Figs. 4 and 5). Maximum fluxes of *G. bulloides* occurred from February to April in both stations, indicating that *G. bulloides* is an indicator for the whole period of elevated primary productivity, as already observed by Schiebel et al. (2004) in the Arabian Sea. The higher relative contribution and threefold fluxes of *G. bulloides* in the Lacaze Duthiers station were possibly related to the fertilizing effect of the Rhone river plume, which points towards a tight link of this taxon to its food supply.

#### 5.4.2. *Globorotalia truncatulinoides*

*Globorotalia truncatulinoides* is the second most abundant foraminiferal species (30.3%) at the Planier site. At Station Lacaze Duthiers, it is also the second most abundant species but together with *N. pachyderma* (dex.) (17.3%) (Table 1). Fluxes of *G. truncatulinoides* were higher at the Lacaze Duthiers than at the Planier trap (average flux for the entire sampling period = 58.6 and 70.75 shells  $m^{-2} d^{-1}$ , respectively). However, the difference between sites is not as remarkable as for other species, such as *G. bulloides*, which fluxes increase three times at the Lacaze Duthiers site. In the Gulf of Lions, *G. truncatulinoides* populations were dominated by left-coiling specimens. Only a handful of right-coiling forms were identified in both records (< 1%). *G. truncatulinoides* is a deep-dwelling species (Hemleben et al., 1989; Hemleben et al., 1985) that has been described as a tracer for intermediate to deep water masses (Schmuker and Schiebel, 2002). In the Mediterranean, maximum abundances of *G. truncatulinoides* have been observed in areas of intense water mixing during winter, i.e. the North Western Basin (Pujol and Vergnaud Grazzini, 1995), while in the more stratified waters of the Eastern Basin it is rarely found (Core top database of Kallel et al. (1997)). *G. truncatulinoides* possibly follows an annual reproduction cycle: during the beginning of the spring this species migrates from deep water masses to the pycnocline for reproduction, afterwards, the new generation descends to deep waters where it spends most of its life span (Hemleben et al., 1985; Schiebel and Hemleben, 2005; Schiebel et al., 2002). In this regard, the elevated fluxes and high relative contribution of *G. truncatulinoides* noted in this study during the winter–spring transition (Figs. 6 and 7) point towards an affinity of this taxon for the intense mixing conditions in the Gulf of Lions. The break-down of the thermocline during winter coupled with the deep turbulent mixing and vertical mixing would facilitate the ascent of *G. truncatulinoides* to the euphotic zone, where it reproduces and proliferates due to the increased primary productivity. After the spring bloom, the offsprings of *G. truncatulinoides* possibly sink to waters deeper than 500 m. Therefore, it should be taken into account that the annual flux of *G. truncatulinoides* to the sea floor inferred from our sediment traps might be biased.

#### 5.4.3. *Neogloboquadrina pachyderma* (dex.)

*Neogloboquadrina pachyderma* (dex.), or *N. incompta* (Darling et al., 2006), is the third most abundant taxon in the Planier site record (18.6%) and the second in Lacaze Duthiers site, together with *G. truncatulinoides* (17.3%) (Table 1). *N. pachyderma* (dex.) is a planktic foraminiferal species characteristic of subpolar and transitional waters (Bé and Tolderlund, 1971; Cifelli, 1973). It is considered a deep-dweller (Fairbanks and Wiebe, 1980) that reproduces on a synodic cycle (Schiebel and Hemleben, 2005)

that could well live at or below the thermocline (Bé, 1960, 1977; Bé and Ericson, 1963).

Few left-coiling specimens were found in the samples (< 1%). Although the Gulf of Lions is among one of the coldest regions of the Mediterranean, its conditions are too warm for the development of the polar species *N. pachyderma* (sin.). Thus, these left-coiling specimens are probably aberrant coiling forms of *N. pachyderma* (dex.). The distribution of *N. pachyderma* in the Mediterranean is almost restricted to the Northern Basin (Core top database of Kallel et al., 1997), where it reaches high concentrations in surface waters and at mesopelagic depth during winter (Pujol and Vergnaud Grazzini, 1995). Pujol and Vergnaud Grazzini (1995) suggested that the distribution of this species in the Mediterranean would mainly be controlled by temperature, only being present in those areas where annual SST reach temperatures below 13 °C. In our study, maximum annual fluxes of *N. pachyderma* (dex.) occur during March in both sediment traps, period with maximum phytoplankton productivity.

At the Lacaze Duthiers site *N. pachyderma* (dex.) fluxes are the double of those seen at Planier, which indicates a positive response of this taxon to the nutrient supply from the Rhone river plume.

#### 5.4.4. *Globorotalia inflata*

The fourth most abundant species in the Gulf of Lions was *Globorotalia inflata*. The mean relative abundance of this species was 10% at Planier and 8.3% at the Lacaze Duthiers site (Table 1). *G. inflata* is a foraminiferal species indigenous to the transitional zone between the subpolar and subtropical regions of the Atlantic (Bé and Tolderlund, 1971). It is considered a deep dwelling species (Hemleben et al., 1989; Hemleben et al., 1985) that has been used as an indicator of a cool, deep, homogenous and relatively eutrophic winter mixed layer in the Mediterranean (Rohling et al., 2004). Large standing stocks of *G. inflata* are found in the Western Basin during winter (Bárcena et al., 2004; Cifelli, 1974; Pujol and Vergnaud Grazzini, 1995), while in the Eastern Mediterranean it is poorly represented (Pujol and Vergnaud Grazzini, 1995). Regarding its distribution in surface sediments, the highest contribution of this taxon occurs in the Alboran Sea and along the North African coast (Core top database of Kallel et al. (1997)), coinciding with the path of the Modified Atlantic Waters. Maximum fluxes of this species occur during March in both sediment traps (Figs. 6 and 7) which indicate that during this period *G. inflata* possibly migrate from deep waters to the photic zone to reproduce. The higher fluxes of *G. inflata* registered in Lacaze Duthiers station (Fig. 7) reflects the positive response of this taxon to food supply.

#### 5.4.5. Other species

Regarding the other planktic foraminiferal species, these only represent a small fraction of the 12-year assemblage (4.4% for Planier and 6.4% for Lacaze Duthiers) (Table 1). However, their relative contribution to the foraminiferal faunal assemblages was often important during periods of low total planktic foraminiferal flux; i.e., the end of summer and the beginning of fall, especially at Lacaze Duthiers, the station where they represented ca. 50% of the assemblage (Fig. 7). Most of the components of the “other species” group are warm-water, oligotrophic species such as *O. universa*, *G. siphonifera*, *G. sacculifer* and *G. ruber*, and therefore they exhibit their maximum relative abundance values during the stratification period; i.e., summer and part of fall. Two of the main components of the other species group require special attention: *O. universa* and *G. sacculifer*. *O. universa* has been defined as a subtropical species (Bé, 1977) that, in the Mediterranean, is more prolific at the end of the summer (Pujol and Vergnaud Grazzini,

1995), while *G. sacculifer* is a tropical taxon that dwells in superficial and oligotrophic waters and reaches its maximum abundances in the Eastern Basin (Core top database of Kallel et al. (1997); Pujol and Vergnaud Grazzini, 1995). These two species were the main components of a remarkable pulse of the other species group recorded during the fall of 1997 at both sampling sites (Figs. 4 and 5). *O. universa* reached up to 25% at Planier and up to 57.5% at the Lacaze Duthiers station while (2) *G. sacculifer* reached up to 13.3% at Planier and 52.6% at Lacaze Duthiers. The average fluxes of these two species were also high in the fall of that year. As already mentioned in Section 5.2, during the fall of 1997 anomalous atmospheric and hydrographic conditions were recorded in the Western Mediterranean that were probably related to the intense 1997–98 El Niño event. We surmise that the increase in the relative contribution of these warm water taxa would have been induced by the exceptional hydrographic conditions in the NW Mediterranean seen during this period. Although in a distant and different environment, a drop in the total planktic foraminiferal fluxes, accompanied by pulse of the warmer dwelling *O. universa*, was recorded in the central subarctic Pacific by Asahi and Takahashi (2007) at the end of 1997. The former authors related the appearance of this taxon to the anomalously warm conditions elicited by the 1997–98 El Niño event.

The other species group, however, is the main component of the core top foraminiferal assemblages from the Eastern Mediterranean and reflect the strong, annually permanent water stratification in that region. Most of the Eastern Mediterranean is oligotrophic because there is no vertical mixing in winter or spring and, consequently, the planktic foraminiferal species that usually benefit from the high nutrient content of surface waters do not thrive in that region. By contrast, the intense vertical mixing in the Gulf of Lions during winter and the subsequent high food availability in surface waters in winter and spring lead to the proliferation of typically eutrophic species such as *G. bulloides* or *N. pachyderma*, reducing the relative abundance of oligotrophic species such as *O. universa*, *G. sacculifer*, and *G. ruber*.

##### 5.5. Foraminiferal assemblages in the sediment traps and the recent sediments: implications for paleoreconstructions

Sediment traps are a useful tool to validate paleoreconstructions based on the fossil record. Unless major changes have occurred during or after sedimentation, the composition of planktic foraminiferal assemblages preserved in sediments should reflect the relative concentration of the foraminifers living in the water column. In this study, the planktic foraminiferal assemblages from the core tops were mainly composed of the same four species that dominated the sediment trap records. The closest analogs to the trap assemblages are the core tops located nearby the sediment traps (Figs. 1 and 2) and are situated in the most productive areas of the Gulf of Lions: The southwestern zone, affected by the Rhone river plume, and the continental slope, which is under the influence of the permanent shelf-slope density front. The most abundant species in these samples is *G. bulloides* that, as previously mentioned, is a good indicator of productivity. On the other hand, the most distal core tops, located towards the center of the Catalano-Balearic Basin (Fig. 3), exhibited the highest dissimilarities (Table 2) and showed maximum abundances of *N. pachyderma* (dex.) and *G. truncatulinoides*. Probably this is due to the fact that these areas have a lower primary productivity leading to a drop in the abundance of the opportunistic species *G. bulloides* and an increase of the planktic foraminiferal diversity.

Nevertheless, other factors apart from the geographical location can cause discrepancies between sediment trap and surficial sediment samples. An important factor is the difference in time scale: while our sediment trap records cover 12 years, surface sediments represent an integrated signal of several hundreds or thousands years. In particular, in some areas of the Gulf of Lions the

sedimentation rates on the continental slope were extremely slow during the Holocene because of the low supply of detrital material from the Rhone river at this distance from the coast (Sierro et al., 2009). More precisely, the mixed layer formed by the uppermost 10 cm of sediment in the upper slope may represent a few millennia due to the extremely low sediment input to this area (Sierro et al., 2009), while in the southeastern deeper settings, far from the continental slope, the same mixed layer can be deposited in a few decades or centuries because of the high sedimentation rates in the Rhone deep sea fan. Additionally, the modern thanatocenosis found in the sediments could have been altered by different sedimentary processes (Véneç-Peyré, 1990), specially when the burying rates are low. The presence of planktonic foraminiferal tests during centuries or millennia near the sediment-water interface make them prone to differential transport by bottom currents or differential preservation, even though the Western Mediterranean is oversaturated with respect to calcite and aragonite (Millero et al., 1979; Schneider et al., 2007). The activity of different generations of macrobenthic organisms can bioturbate sediments and mix older shells, which may have lived under different conditions, towards the surface. For example, in coretop 5 high abundances of *G. ruber* (11.3%) have been registered. *G. ruber* is scarce in the present assemblages, as inferred from the sediment trap samples, but has been more abundant in the last 15 ka in the Gulf of Lions (Melki et al., 2009). Therefore, the high values of this species in surficial sediments can be related to sediment bioturbation.

However, the close match between the trap samples and the core tops recovered along the continental slope, as expressed by the low square chord distances, indicates that core top sediments recovered over the continental slope do reflect modern planktic foraminiferal assemblages currently living in the most productive areas of the Gulf of Lions. Nonetheless, the strong seasonal cycles observed in this study indicates that most of the total planktic foraminiferal flux was recorded during the winter and spring (81.7% at Planier and 80.6% at the Lacaze Duthiers station) (Table 3). Thus, when analyzing the fossil record it should be taken into consideration that the foraminiferal assemblages registered in the sediments represent flux during the winter–spring period, instead of the annual cycle. Nonetheless, a few taxa with low relative abundance, such as *G. ruber* and *G. sacculifer*, exhibited a different seasonal behavior. The fluxes of these two taxa showed a less clear pattern and were more widespread along the year. *G. ruber* showed its maximum values from late-summer to early-winter (SST 13–23 °C) while *G. sacculifer* did so during the summer until mid-fall (SST ca. 16–23 °C).

These data are specially relevant for paleobiogeochemical studies, in particular trace element and stable isotope analyses of planktic foraminifera shells and when comparing biogeochemical records from different Mediterranean regions. From our data, we can infer that in the NW Mediterranean, most of the planktic foraminifers (> 80%) grow during the coldest period of the year, when SST range between 13–14.5 °C (Table 3). Consequently oxygen isotope or trace element records obtained from planktic foraminifers like *G. bulloides*, *N. pachyderma*, *G. truncatulinoides* or *G. inflata* should reflect SST during this period. In contrast, the same trace element and stable isotope analyses in other areas of the Mediterranean, such as the Alboran Sea should record surface conditions in May and June, because this is the season with the highest fluxes of *G. bulloides* and *G. inflata* in that region (Bárcena et al., 2004; Hernández-Almeida et al., 2011).

## 6. Conclusions

Two long term sediment trap records in the Gulf of Lions provide reliable information on the seasonal and regional variations of planktic foraminiferal flux in the NW Mediterranean. Planktic

**Table 3**  
Monthly and seasonal distribution of foraminiferal species flux (%). The monthly average surface temperature is also shown.

<b>Planier</b>	J	F	M	A	M	J	J	A	S	O	N	D	Fall	Winter	Spring	Summer
Total foraminifers	9.0	14.8	26.8	14.2	10.1	7.5	3.7	2.0	1.1	1.1	2.9	6.9	5.1	30.7	<b>51.0</b>	13.1
<i>G. bulloides</i>	9.5	12.5	21.3	14.4	13.9	10.2	3.2	1.3	0.5	0.6	3.4	9.1	4.5	31.1	<b>49.7</b>	14.7
<i>G. siphonifera</i>	8.9	17.6	21.3	12.5	13.7	11.8	4.7	1.9	1.4	0.8	1.1	4.2	3.3	30.8	<b>47.5</b>	18.4
<i>N. pachyderma</i> (dex.)	5.9	14.2	32.0	16.6	9.3	7.9	3.5	2.5	0.7	0.5	1.8	5.0	3.0	25.2	<b>58.0</b>	13.9
<i>N. pachyderma</i> (sin.)	10.6	10.8	69.3	9.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.4	<b>78.6</b>	0.0
<i>G. inflata</i>	7.0	17.3	37.2	16.9	7.4	4.1	0.6	0.3	0.0	0.2	2.6	6.4	2.8	30.7	<b>61.5</b>	4.9
<i>G. ruber</i> (white)	14.9	8.4	3.3	1.5	4.7	9.2	3.2	11.2	6.6	6.3	16.9	13.7	29.8	<b>37.1</b>	9.5	23.6
<i>G. ruber</i> (pink)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.9	10.0	38.8	43.4	0.0	<b>92.1</b>	0.0	0.0	7.9
<i>G. sacculifer</i>	4.4	5.5	11.6	3.3	5.1	6.3	13.8	3.1	10.3	15.1	14.1	7.4	<b>39.4</b>	17.3	20.0	23.3
<i>G. glutinata</i>	4.9	10.3	23.9	11.2	18.8	17.8	10.9	0.0	0.0	0.0	0.0	2.3	0.0	17.4	<b>53.9</b>	28.6
<i>G. truncatulinoides</i>	11.2	16.9	28.0	12.7	6.8	4.7	4.6	2.8	2.1	1.8	2.5	5.8	6.4	33.9	<b>47.5</b>	12.2
<i>G. digitata</i>	6.6	19.6	10.2	13.1	17.8	18.3	3.1	1.2	2.8	3.1	0.0	4.3	5.9	30.5	<b>41.1</b>	22.5
<i>O. universa</i>	9.8	7.4	7.2	5.8	12.3	10.3	10.8	6.8	7.5	6.1	7.4	8.7	21.1	25.9	25.2	<b>27.9</b>
<i>T. quinqueloba</i>	1.4	36.4	36.9	2.3	7.5	6.2	4.6	0.9	0.0	0.1	1.4	2.1	1.6	40.0	<b>46.7</b>	11.7
Temperature	13.3	13.0	13.1	13.7	16.2	19.7	21.6	23.1	20.9	18.8	16.5	14.3	18.7	13.5	14.4	21.5
<b>Lacaze Duthiers</b>	J	F	M	A	M	J	J	A	S	O	N	D	Fall	Winter	Spring	Summer
Total foraminifers	8.8	20.8	21.1	13.5	9.9	6.3	2.2	2.1	2.2	2.5	4.1	6.5	8.8	36.1	<b>44.5</b>	10.5
<i>G. bulloides</i>	8.3	25.0	21.6	13.9	11.5	7.1	1.9	1.3	0.5	1.3	3.3	4.4	5.1	37.7	<b>47.0</b>	10.2
<i>G. siphonifera</i>	11.3	13.1	8.4	5.8	6.1	7.1	5.2	6.0	5.4	6.5	11.2	14.0	23.0	<b>38.4</b>	20.3	18.3
<i>N. pachyderma</i> (dex.)	3.0	17.9	29.7	21.6	10.2	5.3	1.8	2.0	1.5	2.3	2.1	2.5	5.9	23.4	<b>61.5</b>	9.2
<i>N. pachyderma</i> (sin.)	10.7	42.0	18.4	1.9	6.2	3.7	0.0	0.0	1.9	3.3	7.0	4.9	12.1	<b>57.7</b>	26.5	3.7
<i>G. inflata</i>	8.5	25.7	35.1	10.8	6.1	3.0	0.7	0.6	0.2	1.1	2.0	6.3	3.3	40.5	<b>51.9</b>	4.3
<i>G. ruber</i> (white)	11.8	6.7	4.7	1.6	1.7	5.3	7.2	9.1	10.1	11.4	15.1	15.5	36.6	33.9	8.0	21.5
<i>G. ruber</i> (pink)	3.8	0.0	0.0	0.0	4.4	0.0	0.0	3.6	16.5	16.4	37.1	18.1	<b>70.0</b>	21.9	4.4	3.6
<i>G. sacculifer</i>	3.8	1.2	1.5	0.2	0.6	4.5	5.8	10.4	21.5	21.1	21.7	7.6	<b>64.3</b>	12.7	2.3	20.7
<i>G. glutinata</i>	10.3	18.4	19.0	13.2	11.5	8.9	3.7	1.3	0.0	0.0	4.1	9.7	4.1	38.4	<b>43.7</b>	13.9
<i>G. truncatulinoides</i>	17.2	15.2	10.7	9.8	9.3	7.0	3.1	2.7	3.2	1.9	5.6	14.3	10.7	<b>46.8</b>	29.8	12.8
<i>G. digitata</i>	3.6	25.8	29.8	16.5	3.3	2.2	0.0	0.2	4.5	4.7	4.2	5.3	13.4	34.6	<b>49.5</b>	2.4
<i>O. universa</i>	4.8	2.6	2.4	2.2	5.2	3.9	6.1	9.9	24.5	20.3	12.6	5.4	<b>57.5</b>	12.8	9.8	19.9
<i>T. quinqueloba</i>	3.1	9.7	6.7	7.7	18.7	18.1	10.3	11.3	2.5	1.0	4.7	6.2	8.1	19.1	33.1	<b>39.6</b>
Temperature	13.0	12.7	13.0	13.7	16.3	19.7	21.7	23.4	21.4	18.9	16.1	14.0	18.8	13.2	14.3	21.5

foraminiferal fluxes underwent consistent annual cycles that mirrored the hydrographic conditions and nutrient availability of the upper water column. Total foraminiferal fluxes showed an annual unimodal maximum in the winter–spring transition at both stations, coinciding with the phytoplankton bloom, while minimum values were always recorded during the summer. The phytoplankton growth and the entrainment of nutrients in the surface waters during the winter–spring stimulate the foraminiferal growth and reproduction which yields in a major contribution of tests to the deep-sea sediments during this particular period. Therefore, the planktic foraminiferal assemblages found in the sedimentary record in the NW Mediterranean are mainly composed (> 80%) by shells accumulated during the winter–spring period. The mean foraminiferal flux was about double at Lacaze-Duthiers ( $411.8 \text{ shells m}^{-2} \text{ d}^{-1}$ ) than at the Planier station ( $225.4 \text{ shells m}^{-2} \text{ d}^{-1}$ ), probably owing to the fertilizing effect of the Rhone river plume and the general oceanographic circulation. No clear relationship between planktic foraminiferal fluxes and the Dense Water Cascading events or the winter state of the NAO was observed. Nonetheless, the anomalous condition elicited by the 1997–98 El Niño event could have been the cause of the pulse of warm water species during fall 1997 and the low foraminiferal fluxes during spring 1998 in both stations. Foraminiferal fluxes at the study sites were mainly comprised of four species: *G. bulloides*, *N. pachyderma* (dex.), *G. inflata* and *G. truncatulinoides*, which reflect the relatively cold conditions of the Northern Basin inside the Mediterranean. The opportunistic species *G. bulloides* exhibited a tight relationship with nutrient supply, being the main contributor to the winter–spring foraminiferal assemblages. The significant relative abundance of deep-dwelling species *G. truncatulinoides* in both stations supports the idea of the affinity of this taxon for areas of deep water mixing. Planktic foraminiferal species typically living in warm-waters, such as *G. sacculifer*, *G. ruber* or *O. universa* are scarce throughout the year but they reach maximum fluxes and relative abundances in fall, after the strong summer stratification. The analysis of the core-top assemblages revealed that the closest analogs to the sediment trap sites were those core tops located nearby the traps. This indicates that the sedimentary record in this area retains an integration of the seasonal flux patterns of the planktic foraminifers living in the upper water column.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at <http://dx.doi.org/10.1016/j.dsr.2012.03.011>.

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