



Research paper

Microplankton response to environmental conditions in the Alboran Sea (Western Mediterranean): One year sediment trap record

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ABSTRACT

The present work analyses the seasonal evolution of planktonic assemblages and particle fluxes through the water column in the Eastern Alboran Sea (Western Mediterranean) at 35°55.47'N/01°30.77'W. A Sediment trap was deployed below the influence of the Almeria-Oran Front (AOF), a semi-permanent geostrophic front, during July 1997 to June 1998. Overall, the temporal variability of coccolithophore, planktonic foraminifer, diatom, benthic and wind-carried biogenic particle fluxes is linked to the seasonal evolution of sea surface hydrological structures. Maximum planktonic fluxes were found during high-productivity periods and wind-induced upwelling, following a trimodal pattern, with maximum fluxes in July 1997, November–December 1997, and April–May 1998. These periods were characterized by vertical mixing and the full development of anticyclonic gyres in the Alboran Sea. The annual flux of coccolithophores was dominated by the “small *Gephyrocapsa* Group” and *Emiliania huxleyi*, whereas *Turborotalita quinqueloba* and *Globigerina bulloides* dominated the foraminiferal fluxes, and *Chaetoceros* Resting Spores (RS) were predominant in the diatom assemblage. Benthic specimens were also collected with the sediment trap, suggesting a variable influence of bottom water activity. Wind-driven particles (phytoliths and fresh-water diatoms) were collected along the year, but their fluxes followed the local wind regime.

The high Sea Surface Temperature (SST) during fall due to weaker than usual westerly winds, and the pressure anomaly prevailing in the Alboran Sea during early winter, were reflected in the planktonic assemblages by the proliferation of warm, lower photic layer inhabitants and/or oligotrophic taxa of coccolithophores (*Florisphaera profunda*), planktonic foraminifers (*Globigerinoides ruber* and *Globorotalia inflata*) and diatoms (*Leptocylindrus danicus*). These unusual climatic conditions in the eastern Alboran Sea must have been caused by the 1997–1998 ENSO event.

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1. Introduction

Planktonic communities are important tracers of oceanographic changes, as they appear to be sensitive indicators of surface water conditions. Every group/species have specific spatial and temporal distributions in surface waters depending of factors such as upwelling, temperature, salinity, nutrients and light (Margalef, 1978). For this reason planktonic studies based on water samples and sediment trap records have emerged as an important tool in order to infer past global change and to determine climatic indicators in longer time-series (Okada and Honjo, 1973; Okada and McIntyre, 1979; Giraudeau and Rogers, 1994; Knappertsbusch, 1993; Abrantes and Moita, 1999). During the last decades, several studies based on downward particle fluxes have been focused in the Mediterranean Sea (Pujol and Vergnaud-Grazzini, 1995;

Rutten et al., 2000; Ziveri et al., 2000; Schiebel et al., 2004) and more specifically in the Alboran Sea (Peinert and Miquel, 1994; Fabres et al., 2002; Bárcena et al., 2004; Sanchez-Vidal et al., 2004; 2005). Results obtained in these works highlighted the control of physical-chemical characteristics of the water column on the development of certain planktonic communities; providing a useful information in order to interpret the Mediterranean fossil record (Flores et al., 2000; Bárcena et al., 2001; Colmenero-Hidalgo et al., 2004).

The Alboran Sea is a relevant area to study flux of organisms since it has a relative high productivity that contrast with the generalized oligotrophy of the Mediterranean Sea. Primary productivity in Alboran Sea is mainly related to the local circulation pattern, which is controlled by the entrance of Atlantic surface waters into the Mediterranean basin and the development of anticyclonic gyres, stimulating phytoplankton productivity in the area (Packard et al., 1988).

As part of the MTP II-MATER project (Mediterranean Targeted Project II-MAss Transfer and Ecosystem Response), sediment traps were deployed in the Almeria-Oran Front (AOF) from July 1997 to May 1998 to record the annual evolution of biogenic flux in the area. In this paper we

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describe the seasonal evolution of coccolithophores, planktonic foraminifers, diatoms and phytoliths, and compare them with other biological (chlorophyll-*a* concentration) and environmental records (sea surface temperature –SST–, bottom current and wind data) from previous studies in the Alboran Sea for the same time period (García-Gorriz and Carr, 2001; Vargas-Yañez et al., 2002; Sanchez-Vidal et al., 2005). The objective of this study is to describe the phytoplankton abundance and composition in the AOF and its relationship to short-term hydrographical changes in the Mediterranean region and with other ocean-wide processes.

2. Study area: hydrographic and meteorological considerations

The Alboran Sea is a transitional region between two oceanic domains: the Atlantic Ocean and the Mediterranean Sea. Surface circulation is very active and is characterized by the presence of two semi-permanent gyres, which are formed after the entrance of North Atlantic Surface Waters (NASW) through the Strait of Gibraltar. Once the NASW has entered the Alboran Basin, as a result of mixing with the dwelling Mediterranean waters these water mass changes its characteristics and is known as Modified Atlantic Waters (MAW). Both anticyclonic gyres are highly variable in terms of structure and permanence and, moreover, their development is controlled by several factors such as atmospheric pressure, temperature, salinity, etc. (Heburn and La Violette, 1990; Viúdez et al., 1998; Vargas-Yañez et al., 2002) (Fig. 1).

Unlike the general oligotrophy of the Mediterranean Sea, the Alboran Sea has two systems of high productivity associated with the gyres and with periods of intense westerlies activity: one located in the northern area of the Western Alboran Gyre (WAG) (Minas et al., 1991; Sarhan et al., 2000), and the Almeria-Oran Front (AOF) (Viúdez

et al., 1998), related to the Eastern Alboran Gyre (EAG) (Fig. 1). The AOF is a semi-permanent geostrophic front that results from the interaction between Atlantic waters and denser Mediterranean waters (Tintore et al., 1988). Moreover, the incoming NASW introduce and transport to the east high amounts of nutrients and biogenic material produced in the western sector of the basin (La Violette, 1984; Minas et al., 1991; García-Gorriz and Carr, 2001).

According to García-Gorriz and Carr (2001), the temporal evolution of the Alboran basin productivity is characterized by the succession of four regimes during the year: bloom regime from November to March, the non-bloom, from May to September and two transitional periods, in April–May, when thermal stratification starts, and in October–November, coinciding with maximum wind variability and de-stratification within the basin. Former authors also defined a temperature range that separates the bloom regime (for $SST \leq 17.4^\circ\text{C}$) from the non-bloom ($SST \geq 19.5^\circ\text{C}$) (Fig. 2a). Fluvial run-off is negligible in the Alboran Sea since no significant rivers flow into the AOF region (Sanchez-Vidal et al., 2005) (Fig. 1).

2.1. Special conditions during the 1997–1998 period

According to McPhaden (1999), the 1997–1998 El Niño–Southern Oscillation (ENSO) event was the strongest for the last century. The former author suggested that unusual climatic conditions around the world were related to this event. In the Alboran Sea, this special conditions consist in the high SST ($>19.5^\circ\text{C}$) and thermal stratification during late summer and early fall 1997, that increased until mid-fall, with unusually warm SST (reaching up to 22.5°C) and weak winds during October 1997 (García-Gorriz and Carr, 2001; Bárcena et al., 2004; Sanchez-Vidal et al., 2005). Therefore, the unusual fall conditions prevented the normal development

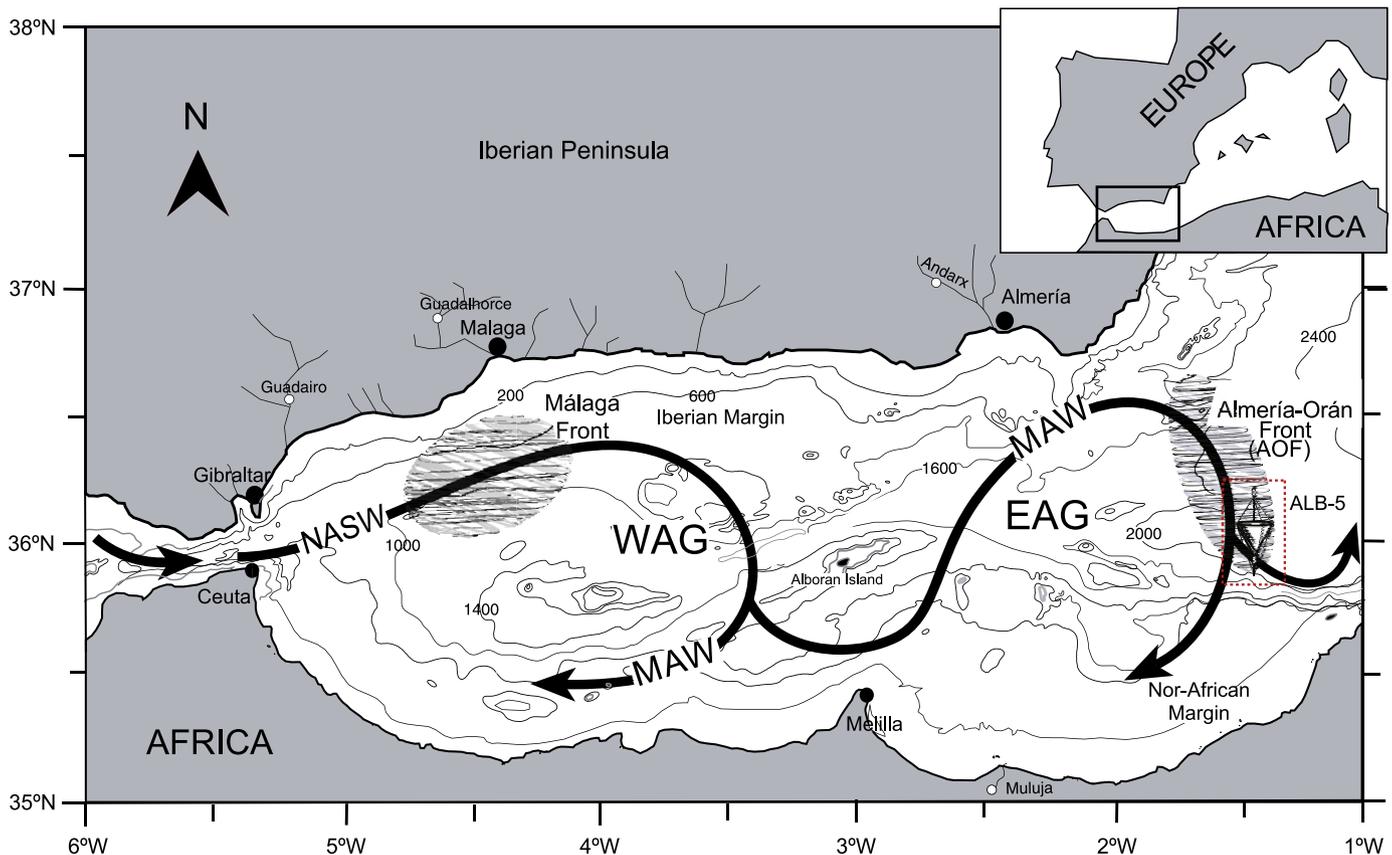


Fig. 1. Geographic and oceanographic location of the study area. Scheme of surface circulation in the Alboran Sea and position of sediment trap ALB-5. Arrows indicate the theoretical trajectories of water masses and dashed areas indicate high productivity zones. Dashed areas represent the northern border of the Western Alboran Gyre (WAG) and Almeria-Oran Front (AOF). Arrows represent the theoretical surface circulation in the Alboran Sea, North Atlantic Surface Waters (NASW), Modified Atlantic Waters (MAW), Western Alboran Gyre (WAG), Eastern Alboran Gyre (EAG) and AOF.

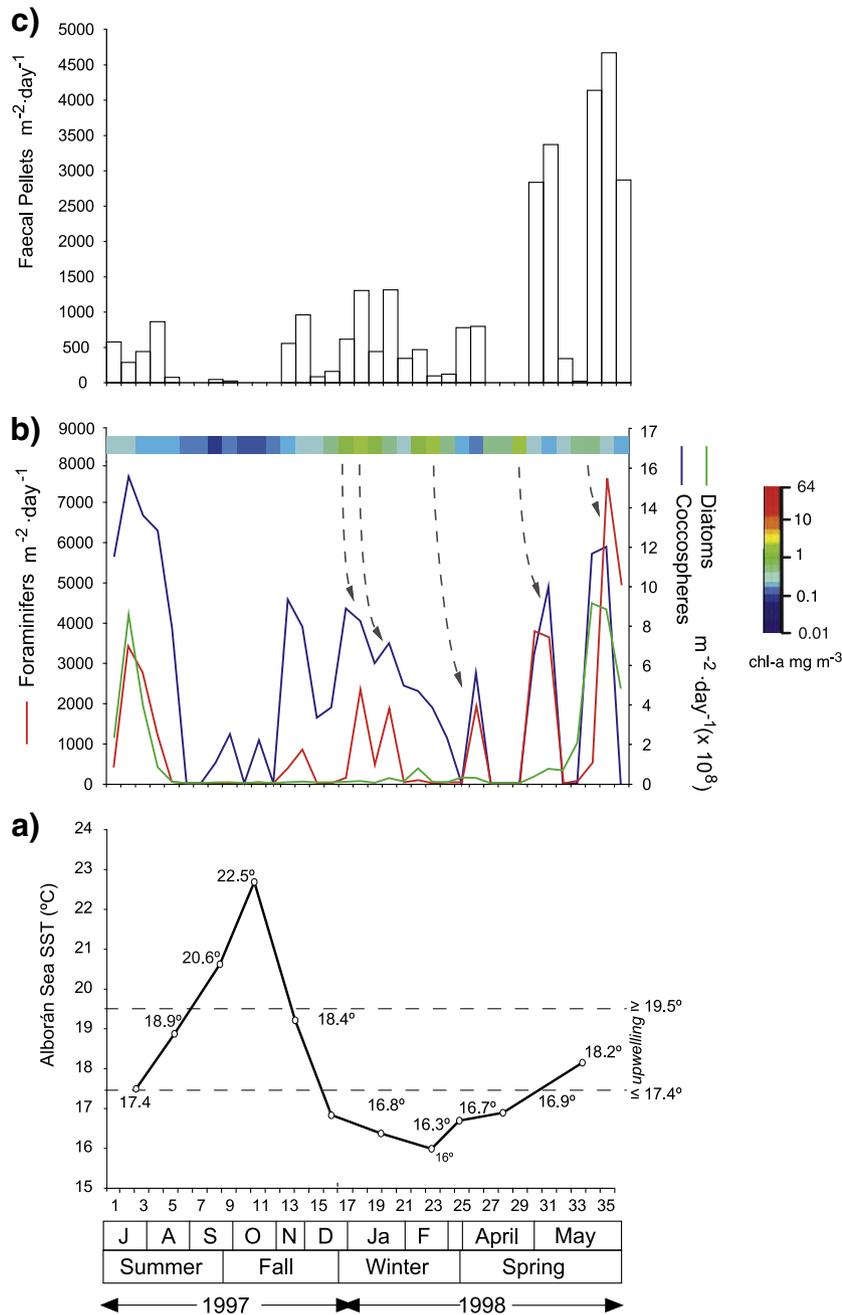


Fig. 2. Temporal evolution of a) surface temperature in the western gyre region (data obtained from Garcia-Gorriz and Carr, 2001), b) fluxes of main planktonic groups and chlorophyll-*a* concentration in surface waters and c) fluxes of faecal pellets recorded by the sediment trap ALB-5F, located in the Alborán Sea, between July 1997 and May 1998. Upper coloured bar at b) is an estimation of the chlorophyll-*a* concentration derived from SeaWiifs images (Melin, 2000). Grey dashed arrows indicate the lag between associated pigment maxima at sea surface and the planktonic flux maxima in the sediment trap.

of the winter upwelling. Later, a southward drift of warmer than usual NASW getting into the Alborán Sea forced the collapse of the gyre from February to March 1998 (Vargas-Yañez et al. 2002).

This special regime characterized by high temperatures likely yielded changes in the planktonic assemblage along the Mediterranean region during the 1997–1998 period. Rigual-Hernández et al. (2010) observed lower silica organisms fluxes during the winter 1997–1998 in a 12 years sediment trap record from the Gulf of Lion (Western Mediterranean). Mercado et al. (2005, 2007) observed extraordinary warm conditions during the 1997 fall that produced a shift in the phytoplanktonic community of the Alborán Sea. Bárcena et al. (2004) reported low productive conditions during the 1997–1998 year. We therefore suggest that 1997–1998 ENSO event had promoted unusual meteorological and

hydrographic conditions through remote teleconnections that affected the Mediterranean region, and in our particular case, to the planktonic assemblages of the Alborán Sea.

3. Materials and methods

3.1. Mooring configuration

Sediment trap ALB-5F was deployed on the north-Africa continental margin located at 35°55.47'N/01°30.77'W below a water column of 2070 m and 30 m above the sea floor (Fig. 1). The mooring line was equipped with a Technicap PPS3 sediment trap and Aanderaa current meters at several levels of the water column. A complete

Table 1
Daily flux (expressed as organisms m⁻² day⁻¹) of coccolithophore taxa taxa, *Emiliania huxleyi*, *Gephyrocapsa oceanica*, small *Gephyrocapsa* group, Warm coccolithophore group, *Helicosphaera carteri*, *Syracosphaera* spp., *Gephyrocapsa muelleriae*, *Florisphaera profunda*, *Calcidiscus leptoporus*, most abundant planktonic foraminifers, *Turborotalita quinqueloba*, *Globigerina bulloides*, *Globigerinoides ruber*, *Globorotalia inflata*, the main diatom groups, *Chaetoceros* RS, Marine Planktonic Group, *Leptocylindrus danicus*, Benthic and Neritic group, Fresh-water diatoms and Phytoliths, at the mooring site in the Almeria-Oran Front from July 1997 through May 1998.

Period	Sample	Total coccosph. (×10 ⁸)	SGG (×10 ⁷)	<i>E. huxleyi</i> (×10 ⁷)	<i>F. profunda</i> (×10 ⁶)	WCCG (×10 ⁶)	<i>C. leptop.</i> (×10 ⁵)	<i>H. carteri</i> (×10 ⁶)	Syracos. spp. (×10 ⁶)	Total forams (×10 ³)	<i>T. quinquel.</i> (×10 ³)	<i>G. bulloides</i> (×10 ³)	<i>G. inflata</i> (×10 ²)	<i>G. ruber</i> (×10)	Total diatoms (×10 ⁷)	Chaet. RS (×10 ⁷)	MPG (×10 ⁶)	NBG (×10 ⁶)	<i>L. danicus</i> (×10 ³)	Phytoliths (×10 ⁵)	Fresh-water (×10 ⁵)	
I	1	1.13	6.67	2.86	3.29	0.82	2.52	1.96	5.42	0.40	0.16	0.16	0.19	3.20	2.29	2.00	2.35	0.55	2.35	0.00	0.29	
	2	1.52	9.91	3.02	1.74	1.83	19.9	2.57	3.55	3.33	1.14	1.59	2.88	5.76	8.38	7.24	9.96	1.20	14.4	6.00	3.60	
	3	1.33	8.68	3.22	2.53	0.0	11.5	2.37	0.00	2.72	1.29	1.18	1.57	3.49	3.83	3.27	4.68	0.56	9.95	1.49	3.48	
	4	1.25	8.45	2.54	1.95	7.04	13.6	3.23	1.90	0.98	0.54	0.34	0.19	2.56	0.79	0.63	1.06	0.36	3.81	1.76	2.49	
	5	0.76	3.73	1.70	2.37	15.3	1.42	1.47	0.93	0.03	0.00	0.00	0.19	6.40	0.06	0.02	0.11	0.12	0.17	0.59	1.47	
	6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	8	0.10	0.31	0.60	0.37	0.11	0.23	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.06	0.07	0.04	0.58	0.34	
	9	0.24	1.67	0.42	1.22	0.92	1.42	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.04	0.02	0.09	0.01	0.00	1.06	0.76	
	10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	11	0.21	0.96	0.84	1.71	0.50	2.58	0.06	0.24	0.02	0.00	0.00	0.00	1.92	0.04	0.02	0.12	0.04	0.00	0.53	0.88	
II	12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	13	0.91	6.92	0.63	0.55	3.27	3.78	2.44	2.37	0.37	0.03	0.16	0.32	9.60	0.05	0.01	0.19	0.09	0.10	0.49	0.78	
	14	0.77	5.70	0.47	3.13	3.77	11.4	1.83	1.02	0.83	0.20	0.29	1.28	3.84	0.08	0.04	0.18	0.08	0.00	0.29	0.94	
	15	0.32	2.48	0.42	1.62	0.23	0.71	0.00	0.29	0.01	0.00	0.00	0.12	0.00	0.03	0.00	0.11	0.08	0.00	0.29	1.17	
	16	0.37	2.78	0.39	2.28	0.00	4.06	0.00	0.19	0.00	0.00	0.00	0.00	0.00	0.05	0.01	0.19	0.10	0.00	0.53	0.94	
	17	0.86	7.19	0.44	2.04	0.56	6.88	1.56	0.61	0.12	0.00	0.06	0.40	0.00	0.06	0.01	0.25	0.22	0.09	1.07	1.07	
	18	0.80	6.81	0.40	2.42	1.14	17.5	1.13	1.56	2.32	1.32	0.64	1.66	6.40	0.10	0.03	0.32	0.32	0.06	0.88	1.47	
	19	0.59	4.91	0.27	1.34	0.91	6.81	0.73	0.40	0.45	0.31	0.12	0.00	0.00	0.02	0.01	0.07	0.01	0.06	0.23	0.29	
	20	0.69	5.80	0.31	1.50	1.40	7.37	1.71	1.41	1.84	0.97	0.61	0.75	2.33	0.25	0.15	0.62	0.26	0.64	0.58	1.17	
	21	0.48	3.55	0.40	1.22	0.50	15.5	0.80	2.03	0.01	0.00	0.01	0.00	0.00	0.08	0.05	0.15	0.15	0.17	0.35	0.58	
	22	0.45	3.89	0.12	0.96	0.46	13.2	0.61	0.67	0.07	0.00	0.06	0.00	0.00	0.73	0.43	2.35	0.51	0.88	1.03	2.64	
23	0.37	3.01	0.10	0.74	0.12	3.15	1.43	1.69	0.00	0.00	0.00	0.00	0.00	0.06	0.03	0.16	0.09	0.12	0.36	0.73		
III	24	0.22	1.59	0.19	0.04	0.06	0.40	0.00	0.02	0.02	0.00	0.00	0.12	0.00	0.04	0.02	0.17	0.09	0.00	0.29	0.23	
	25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.19	0.53	0.20	0.15	1.23	1.00	
	26	0.54	3.48	1.08	0.98	1.83	8.41	1.63	1.00	1.90	1.36	0.12	0.99	1.42	0.25	0.17	0.54	0.30	0.13	2.41	0.39	
	27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
	30	0.63	3.86	1.18	0.77	0.94	0.14	3.51	0.91	3.73	2.41	0.87	1.49	0.00	0.32	0.24	0.36	0.38	0.00	1.37	0.68	
	31	0.97	6.82	1.73	1.47	1.53	0.17	2.20	1.24	3.54	2.58	0.32	1.49	4.27	0.71	0.59	0.74	0.39	0.20	4.89	0.19	
	32	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.48	0.92	0.42	0.49	1.47	1.30	
	33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.00	2.13	2.00	1.77	1.71	0.55	1.47	0.98	0.00	
	34	1.14	7.64	2.14	2.51	1.91	0.23	2.44	3.67	0.02	0.00	0.02	0.00	0.00	8.93	8.13	6.36	1.51	1.99	3.98	0.00	
	35	1.17	8.45	2.04	2.89	0.36	4.73	2.75	0.70	7.40	2.77	3.9	3.63	0.00	8.64	8.07	4.15	1.44	13.1	2.19	0.00	
	36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.85	2.70	1.7	0.74	0.00	4.74	4.24	3.99	0.90	2.64	4.28	1.65	
Annual Flux Average		17.9	125	27.6	46.7	45.5	21.2	36.4	32.2	35.1	17.8	12.2	18.1	47.6	43.6	38.0	42.6	11.1	53.1	41.2	30.6	
		0.49	3.48	0.76	1.30	1.26	0.58	1.01	0.89	0.97	0.49	0.33	0.50	1.32	1.21	1.05	1.18	22.2	1.48	1.14	0.84	

description of the sediment trap as well as of the technical procedures of maintenance and configuration of the mooring line was described in Heussner et al. (1990) and Sanchez-Vidal et al. (2005). Current meters recorded water speed and direction every hour throughout the experiment (291 days); average speed was $3.93 (\pm 3.14) \text{ cm s}^{-1}$ (Sanchez-Vidal et al., 2005).

3.2. Sampling period

The ALB-5F sediment trap was deployed from July 1997 to May 1998 during three different periods: (I) from 1st of July to 3rd October 1997, (II) from 15th November 1997 to 10th of March 1998, and (III) from 1st April to 22nd May 1998. The samples were taken every ten days throughout the study period, except between April and May (third period), when the sampling interval was three days (Table 1). A total of 29 samples were studied; unfortunately, owing to technical reasons seven samples from September to October 1997 were invalid for performing micropaleontological analyses, since they had not collected a sufficient amount of material. Sediment trap efficiency was 80.5% for the first two periods and 100% for the third.

3.3. Sample treatment and calculations

A high-precision peristaltic pump was used to split each sample into eight identical and homogeneous sub-samples, following Heussner et al. (1990). For geochemical treatments, we followed the methodology described in Fabres et al. (2002).

For micropaleontological analyses, the original dry mass was known, and 1/8 aliquots were used. The original samples were wet-sieved onto a $63 \mu\text{m}$ mesh in order to separate foraminifer from smaller diatoms and coccolithophores. The reduced amount of collected sediment made it necessary to carry out the micropaleontological investigations on the same sample aliquot, thus avoiding loss of information from the total sample. The methodological laboratory treatment can be found in Bárcena et al. (2004). Qualitative and quantitative analyses were done with a Nikon Eclipse 80-I petrographic microscope with a phase contrast device. For diatom studies, we used a 1000 magnification, while $\times 1250$ was used for coccolithophore analyses.

In order to convert coccoliths into coccospheres, we used the Knappertbusch formula (1993) using the specific relationship between coccoliths/coccospheres for each species. Due to the different planktonic foraminifer species represented in the coarse and fined fraction ($>150 \mu\text{m}$ and $63-150 \mu\text{m}$) in our samples, we have grouped both fractions to avoid any loss of information (Carstens et al., 1997; Smart, 2002).

4. Results

4.1. Transport mechanism of planktonic shells

Faecal pellets, derived of high zooplanktonic activity (Quétel et al., 1993; Rutten et al., 2000), provided an effective mechanism of vertical transport for biogenic particles recorded in our sediment trap, as seen in the short time elapsed (2–3 weeks) between the periods of high chlorophyll-*a* concentration, increase of faecal pellets and interception of planktonic shells in the sediment trap ALB-5F (2070 m depth) (Fig. 2b and c). These aggregates sink faster than single particles such as coccolithophores or clay minerals, which can remain suspended in the water column for long time, increasing vertical transport to the sea floor over several months (Ziveri et al., 1995). Furthermore, the temporal agreement between biogenic and lithogenic fluxes (Sanchez-Vidal et al., 2005) may indicate the incorporation of mineral particles into faecal pellets, producing a ballast effect (Armstrong et al., 2002) on settling particles, as reported by Sanchez-Vidal et al. (2005). An additional source of material would be the particles (mainly benthic and neritic diatoms)

supplied by bottom currents and wind-carried opaline particles from the continent (phytoliths and fresh-water diatoms), which have a minor contribution and their significance will be discussed further.

4.2. Calcium carbonate fraction

Coccolithophores and foraminifers were the main components of this fraction, although other calcareous organisms, such as pteropods and bivalves also contributed to it, but in very low quantities.

4.2.1. Coccolithophores

The total coccolithophore flux also followed a tri-modal pattern, exhibiting the same trend as calcium carbonate (Sanchez-Vidal et al., 2005), decreasing trends at the end of summer and beginning of fall, while during spring and early summer an increase of calcareous flora productivity was observed (Fig. 3a). The daily flux of coccospheres ranged between 15.2×10^7 and 1.0×10^7 (average: 4.9×10^7 coccospheres $\text{m}^{-2} \text{day}^{-1}$) (Fig. 3a).

The main component of the assemblage was the “small *Gephyrocapsa* Group” (sGG) ($<3 \mu\text{m}$), representing 49% of the total assemblage (Fig. 3b). The highest relative values were recorded between mid-fall and early winter, but high relative contributions were also recorded during middle spring and early summer. In terms of flux, the most significant contribution occurred in early summer, with values of 10×10^7 coccospheres $\text{m}^{-2} \text{day}^{-1}$. The sGG also displayed secondary peaks during spring and mid-fall to early winter (Fig. 3b).

Emiliania huxleyi (average: 11%), in terms of both flux and relative contribution, shows a variable pattern. The highest contribution was recorded during fall, reaching up to 60% of the total assemblage, while highest fluxes recorded during summer (3.2×10^7 coccospheres $\text{m}^{-2} \text{day}^{-1}$) (Fig. 3c).

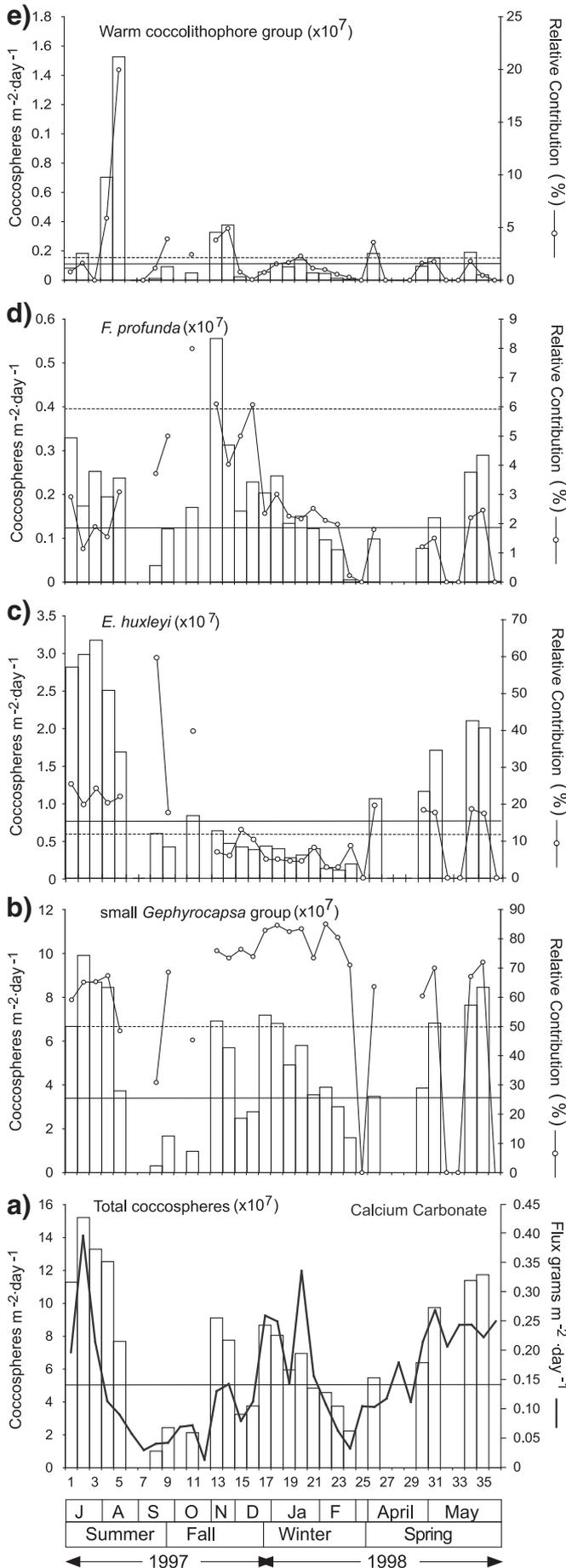
Florisphaera profunda (average: 2.5%) showed highest contribution (8%) and daily flux (0.55×10^7 coccospheres $\text{m}^{-2} \cdot \text{day}^{-1}$) during fall (Fig. 3d). Several taxa (contributions between 2.8 and 1.4%; see Table 1), such as *Syracosphaera* spp., *Calcidiscus leptoporus*, *Helicosphaera carteri*, *Gephyrocapsa muelleri* and *Gephyrocapsa oceanica*, followed a similar temporal pattern along the sampling period, with their highest daily flux recorded at the beginning of summer and during spring. *Umbilicosphaera* spp., *Rhabdosphaera clavigera*, *Umbellosphaera* spp. and *Discosphaera tubifera* represent the “Warm Coccolithophore Group” (WCCG) (Okada and McIntyre, 1979). The warm group accounted for 1.7% of the total assemblage. Mid-summer is the most productive period for this group, with a relative contribution up to 20% and a daily flux of 1.6×10^7 coccospheres $\text{m}^{-2} \text{day}^{-1}$ (Fig. 3e).

4.2.2. Planktonic foraminifers

Planktonic foraminifers were present throughout the year. Maximum fluxes occurred in three peaks at the beginning of summer, winter and during spring, with values of 3400, 2300 and 7500 foraminifers $\text{m}^{-2} \text{day}^{-1}$ respectively (Fig. 4a) (average: 1000 foraminifers $\text{m}^{-2} \text{day}^{-1}$).

Around 85% of the total planktonic foraminifera assemblage was composed by two species, *Turborotalita quinqueloba* (average 20%) (Fig. 4b) and *Globigerina bulloides* (average 18%) (Fig. 4c). The first one, *T. quinqueloba*, displayed the highest average relative contribution for the studied period. The highest fluxes of the species were recorded during summer, winter and spring; while the maximum contribution (both, relative and absolute) was observed during spring, with values of 72% and 2700 foraminifers $\text{m}^{-2} \text{day}^{-1}$ respectively (Fig. 4b). *T. quinqueloba* contributed to the foraminiferal assemblage with an average flux of 490 foraminifers $\text{m}^{-2} \text{day}^{-1}$.

Globigerina bulloides showed a clear seasonal component; during fall, the contribution of *G. bulloides* was negligible, but during summer, winter and spring it showed the highest daily fluxes, especially during May 1998, with 3900 foraminifers $\text{m}^{-2} \text{day}^{-1}$. Moreover, the



maximum relative contribution (83%) was recorded during winter (January–February). The average flux and relative contribution was 339 foraminifers $m^{-2} day^{-1}$ and 17% respectively (Fig. 4c).

Globorotalia inflata (average: 8.8%) was especially important during fall and late winter. The most significant daily flux was recorded during May 1998, with 360 foraminifers $m^{-2} day^{-1}$ (Fig. 4d). The main flux contribution of *Globigerinoides ruber* (both varieties: white and pink) was observed in November 1997 (up to 100 foraminifers $m^{-2} day^{-1}$), although the species was scarcely represented in the rest of the studied period. The relative contribution of this species reached up to 75% of the assemblage during fall (Fig. 4e).

4.3. Biogenic opal fraction

Diatoms, radiolarians, silicoflagellates, sponge spicules, siliceous dinoflagellates and phytoliths were the major components of the biosiliceous particles that settled in the Alboran Sea during the studied period. In our analyses, diatoms were numerically the main contributors to the opal fraction; their daily flux was several orders of magnitude higher than that of the rest of the siliceous microorganisms. Silicoflagellates (mainly *Dictyocha fibula*), dinoflagellates (*Actiniscus pentasterias*) sponge spicules and radiolarians displayed maxima fluxes at the beginning of summer 1997 and mid-spring 1998.

4.3.1. Diatoms

The flux of diatoms is expressed as the number of valves $m^{-2} day^{-1}$. Daily diatom flux displayed a bi-modal pattern, with two peaks at the beginning of summer 1997 and during late spring 1998, reaching values of around 8×10^7 valves $m^{-2} day^{-1}$. During the rest of the year, diatom flux was three orders of magnitude lower. The diatom flux followed the same pattern as opal (Fig. 5a). A slight increase in both diatom and opal levels, was observed during mid-winter. The mean daily flux was 1.2×10^8 valves $m^{-2} day^{-1}$ (Fig. 5a).

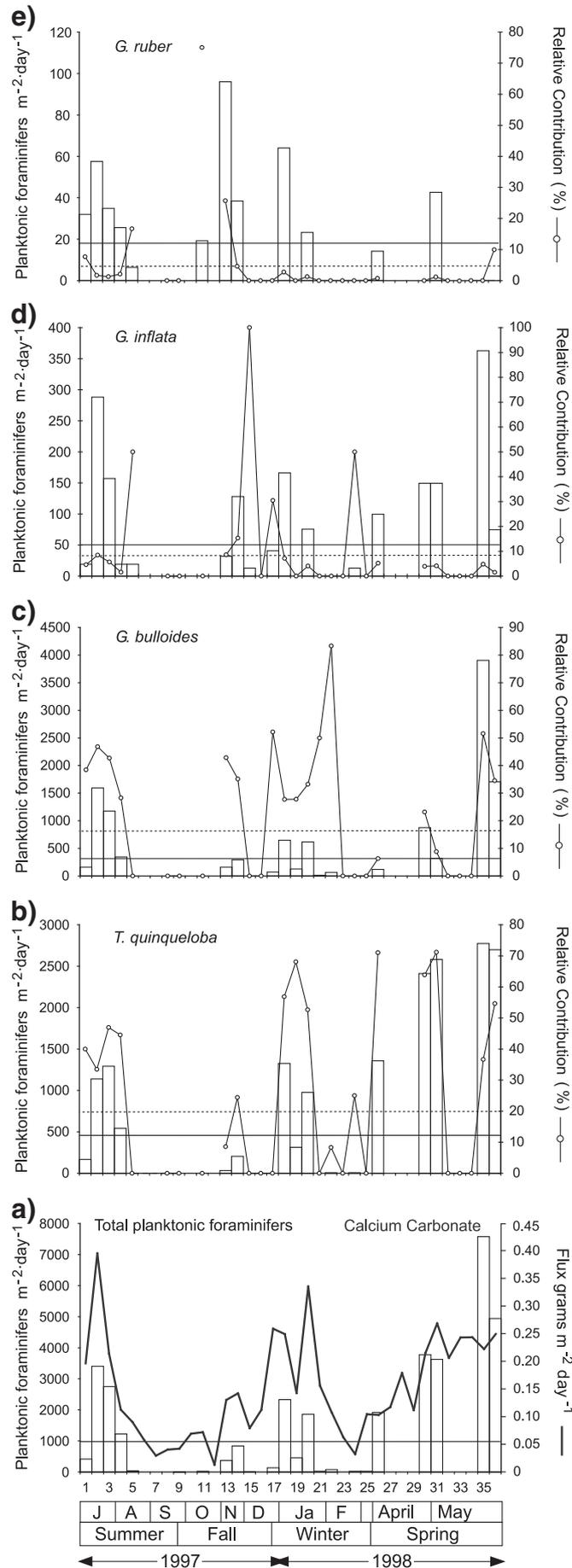
A total of 66 diatom taxa were recognised in the samples. Diatoms were grouped as a function of their ecological significance into planktonic, neritic and benthic, and fresh-water, following Bárcena et al. (2004) considerations. Likewise, other species were treated individually due to their higher abundances or important ecological significance, such as *Chaetoceros* resting spores (RS) and *Leptocylindrus danicus*, respectively.

Chaetoceros RS was the main contributor to the diatom assemblage with daily fluxes of 1×10^7 valves $m^{-2} day^{-1}$ (average). Its relative contribution represented more than 56% of the total, ranging from 27% to 98%. In terms of fluxes, *Chaetoceros* RS shoed two maxima, early summer, and the highest daily flux during spring, with 8.1×10^7 valves $m^{-2} day^{-1}$ (Fig. 5b).

The Marine Planktonic Group (MPG), followed the opposite trend to that of *Chaetoceros* RS. The highest relative contribution was observed during the second half of fall and the first half of winter (up to 60%), while the lowest was recorded during spring and summer (Fig. 5c). The mean relative contribution was 20%. The flux followed a bi-modal pattern, with maxima during July 1997 and May 1998. The group contributed with daily fluxes of 1.2×10^6 valves $m^{-2} day^{-1}$ (average).

Neritic and benthic diatoms (Neritic and Benthic group –NBG–) showed their highest relative contributions at the end of summer 1997 and early winter 1997–98 (average up to 10%). The highest flux was recorded during spring 1998 with daily fluxes of 1.5×10^6 valves $m^{-2} day^{-1}$ (Fig. 5d). The most significant fluxes of *L. danicus* were recorded during early summer 1997 (14×10^5 valves $m^{-2} day^{-1}$) and

Fig. 3. Seasonal evolution of coccolithophore flux (bars) and relative contribution (lines) of the most significant species, a) total coccosphere and calcium carbonate (solid grey line), b) sGG, c) *Emiliana huxleyi*, d) *Florisphaera profunda*, e) Warm Coccolithophore Group (WCCG), in the sediment trap ALB-5F, located in the Alboran Sea, between July 1997 and May 1998. Horizontal solid lines indicate the average flux, and horizontal dashed lines indicate the average relative contribution.



during mid-spring (Fig. 5e). For the rest of the year the contribution of this species was negligible, with the exception of a relative high during August 1997 (5%). The annual average contribution was around 1% (Fig. 5e).

Fresh-water diatoms (mainly *Aulacoseira granulata*) and phytoliths represent continental input to the sediment trap (origin and transport mechanism discussed in section 5.3). Fresh-water diatoms are mainly represented during early summer 1997 (up to 3.6×10^5 valves $m^{-2} \cdot day^{-1}$), while phytoliths show two peaks, early summer 1997 and spring 1998 (more than 5×10^5 phytoliths $m^{-2} \cdot day^{-1}$) (Fig. 6).

5. Discussion

5.1. Microplanktonic communities as response to environmental conditions

Oceanographic and atmospheric variability in the Alboran Sea during the 1997–1998 period provided different scenarios featured by the ecological succession of different planktonic species and phytoplankton groups. The occurrence of these scenarios are dependent of development of upwelling, a favourable wind-regime (westerly winds), nutrient availability, sea surface temperature and surface circulation of the Alboran Sea (García-Gorrioz and Carr, 2001; Sanchez-Vidal et al., 2004).

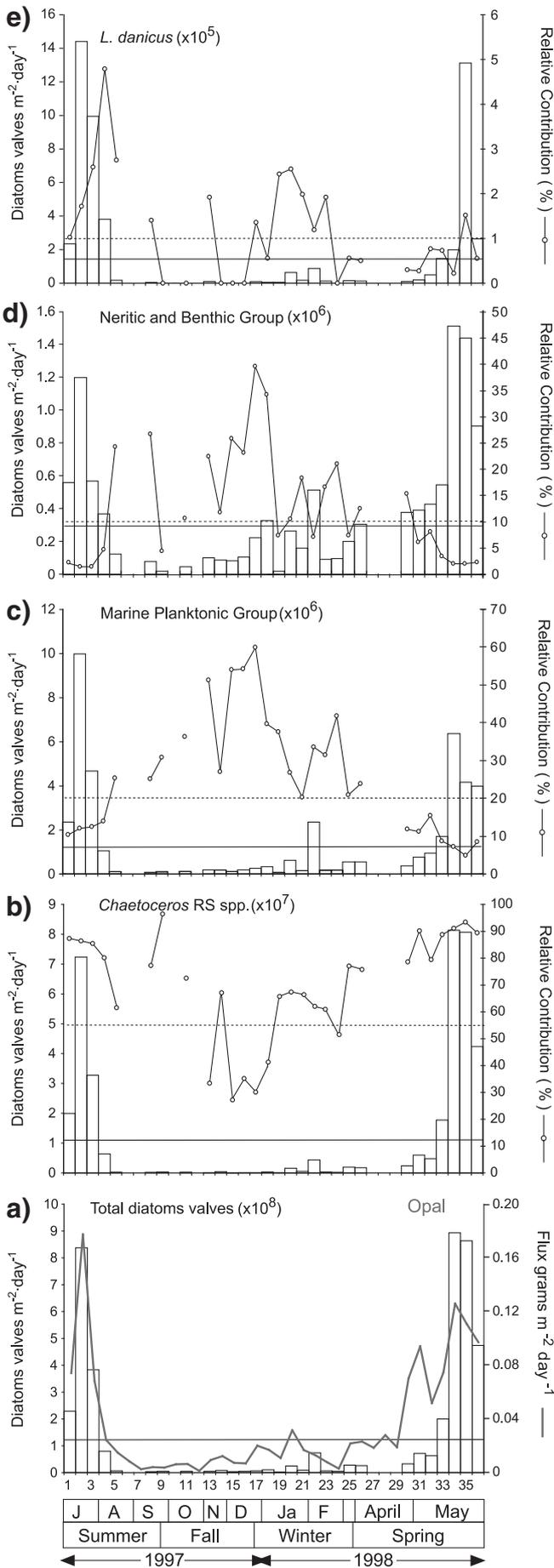
Highest biogenic particle fluxes recorded by sediment trap ALB-5F (Sanchez-Vidal et al., 2005) are related with high-chlorophyll-*a* concentrations events observed in previous weeks in the Alboran basin (WAG and/or EAG) by satellite images (García-Gorrioz and Carr, 2001) during the 1997–1998 period. These high productivity events correspond in our study with specific planktonic assemblages. Several opportunistic taxa show a rapid response to nutrients availability, such as sGG and *E. huxleyi* (Knappertsbusch, 1993; Brand, 1994), or the genus *Chaetoceros* (Abrantes, 1988; Abrantes and Moita, 1999), which appears at ALB-5F as resting spore stage in response to environmental stress (water column turbulence) during the upwelling events (Hargraves and French, 1983; Sautter and Sancetta, 1992). This enhanced productivity of coccolithophores and diatom cells serves as food-resource for zooplankton (Hemleben et al., 1989), such as the planktonic foraminifer *G. bulloides*, a taxon with multiple trophic strategies (Schiebel et al., 2001; Sautter and Sancetta, 1992) and *T. quinqueloba*, a characteristic species of spring blooms and upwelling stages (Weaver and Pujol, 1988; Sautter and Sancetta, 1992; Schiebel et al., 2004).

Planktonic organism density and species found in the AOF are comparable to those recorded in the WAG by Bárcena et al. (2004). The differences in fluxes between both records may be related to less intense upwelling events at AOF, as inferred from the lower chlorophyll-*a* concentrations at ALB 5-F.

5.1.1. Early-summer period

The increase in the fluxes of *T. quinqueloba* and *G. bulloides*, sGG and *E. huxleyi*, *Chaetoceros* RS and the diatoms MPG (Figs. 3–5) indicates the advection of cold upwelled waters south-eastwards resulting in a period of high nutrient availability with a favourable water-mixing at the AOF, then transported to the AOF, due to a westerly wind regime during June 1997. Other minor components of the coccolithophore assemblage, *Syracosphaera* spp., *Helicosphaera carteri* and *Calcidiscus leptoporus*, showed a very similar trend (Table 1), indicating a clear preference for productive periods, in

Fig. 4. Seasonal evolution of planktonic foraminifers flux (bars) and relative contribution (lines) of the most important species, a) total foraminifers and calcium carbonate (solid grey line), b) *Turborotalita quinqueloba*, c) *Globigerina bulloides*, d) *Globobulimina inflata*, e) *Globobuliminoides ruber*, in the sediment trap ALB-5F, located in the Alboran Sea, between July 1997 and May 1998. Horizontal solid lines indicate the average flux, and horizontal dashed lines indicate the average relative contribution.



clear agreement with Ziveri et al. (1995, 2000) findings, who observed a significant increase in the coccosphere flux of these three coccolithophore species during upwelling episodes. In the same sense, *Gephyrocapsa muelleriae* and *G. oceanica* fluxes seem to be directly controlled by nutrient availability. These species has been related to cold and fertile waters associated with upwelling conditions (Giraudeau, 1992; Ziveri et al., 1995; Broerse et al., 2000). This behaviour is supported by oceanographic-satellite observations since Garcia-Goriz and Carr (2001) reported this period as one of the most intense productivity events with an increase of nutrients from spring to summer, related with a wind-induced upwelling.

5.1.2. Late summer and fall period

The anomalous sea-surface warmer conditions during this period (up to 22.5 °C) (Garcia-Goriz and Carr, 2001) promoted a water-column stratification and caused deepening of the thermocline. These conditions contributed to the proliferation of several taxa, such as WCCG (*Umbilicosphaera* spp., *R. clavigera*, *Umbellosphaera* spp. and *D. tubifera*) (Okada and McIntyre, 1979), which are typical dwellers of warm and oligotrophic waters during mid-summer in the Mediterranean Sea (Ziveri et al., 2000). In the same sense, increase in *L. danicus* percentages (Fig. 5e) agrees with the upwelling relaxation and the beginning of a thermal stratification in the upper water column (Varela et al., 2003, Bárcena et al., 2004). This scenario with poor nutrient content in surface waters induces oligotrophic conditions, favouring development of predatory and grazing species, such as *Globigerinoides ruber* and *Globorotalia inflata* (Hemleben et al., 1989; Pujol and Vergnaud-Grazzini, 1995) (Fig. 4). Moreover, opportunistic and multi-diet character of *G. bulloides* (Sautter and Sancetta, 1992; Pujol and Vergnaud-Grazzini, 1995; Schiebel et al., 2001) allowed it to reach more than 40% in this period. Summarizing, 1997–1998 ENSO event likely led to warm SST and weak winds in the Alboran region during this period (Garcia-Goriz and Carr, 2001; Sanchez-Vidal et al., 2005) favoured the proliferation of taxa typical of warm and oligotrophic environments better adapted to stratified waters.

The typical deep-dwelling species, *F. profunda* (Okada and Honjo, 1973), exhibits higher percentages during November and December 1997 (Fig. 3d). Bárcena et al. (2004) reported two peaks of this taxon in the WAG during the same period, and related them to times of maximum rainfall and river discharge. In the AOF, high wind speed recorded during these months (Sanchez-Vidal et al., 2005) likely created an environment with high turbulence in the upper photic zone and low light intensity, conditions favourable for *F. profunda* development (Ahagon et al., 1993; Schiebel et al., 2004).

This low-productive scenario lasted until November 1997, when the development of WAG and EAG favoured the water column destratification and advection nutrient-rich waters into the Eastern Alboran Sea (Garcia-Goriz and Carr, 2001; Sanchez-Vidal et al., 2004). This upwelling event triggered a planktonic bloom in the WAG as reported by Bárcena et al. (2004), and recorded at our sediment trap, ALB-5F, with high relative and absolute fluxes values of eutrophic to mesotrophic species.

5.1.3. Winter period

This period was characterized by a massive destratification of the water column during late December 1997–January 1998; strong winds affected large parts of the Alboran Basin and caused an extensive bloom (Garcia-Goriz and Carr, 2001; Sanchez-Vidal et al., 2004) (Fig. 2b), but with pigment concentrations lower than those

Fig. 5. Seasonal evolution of planktonic diatoms flux (bars) and relative contribution (lines) of the most significant species, a) total diatoms valves and opal (solid grey line), b) *Chaetoceros* RS, c) Marine planktonic Group, d) Neritic and Benthic Group, e) *Leptocylindrus danicus*, in the sediment trap ALB-5F, located in the Alboran Sea, between July 1997 and May 1998. Horizontal solid lines indicate the average flux, and horizontal dashed lines indicate the average relative contribution.

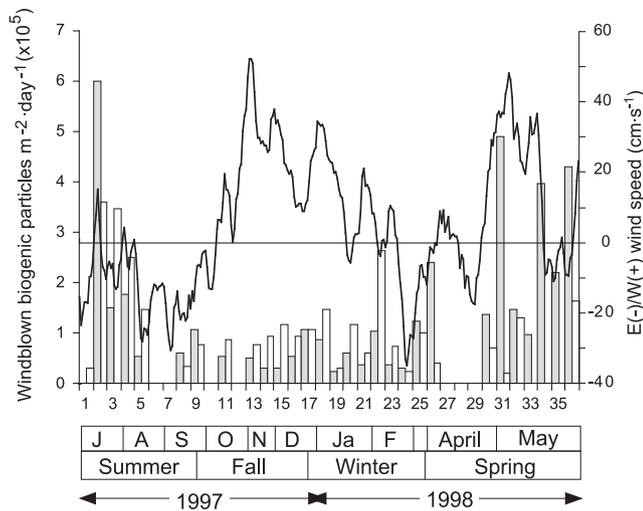


Fig. 6. Seasonal evolution of flux of the windblown biogenic particles, fresh-water diatoms (grey) and phytoliths (black), in the sediment trap ALB-5F, located in the Alboran Sea, between July 1997 and May 1998. Wind data from the Almeria meteorological Station ($36^{\circ} 50'N$, $021^{\circ} 23'W$) showing the maximum daily wind speed moving average (period 10 days).

recorded in summer 1997 and spring 1998 (García-Gorrioz and Carr, 1999). Planktonic communities in the AOF did not respond equally, while coccospheres and planktonic foraminifers increased their fluxes; diatoms did not flourish with the same intensity (Figs. 3–5). An equivalent situation was also detected for the same period in the Alboran Sea by Sanchez-Vidal et al. (2004) and Mercado et al. (2005, 2007). These authors explained this shift from opal to calcareous phytoplankton domain as a response to the weak upwelling conditions and low-nutrient concentration in the surface waters, that favoured coccolithophores development, better adapted to this conditions than diatoms (Eppley et al., 1969; Bethoux et al., 2002; Schiebel et al., 2004). In this sense, LeBlanc et al. (2004) and Sanchez-Vidal et al. (2005) found lower opal values in the Alboran Sea during 1997 winter than those recorded during summer and spring, indicative of a decline of the siliceous phytoplankton.

Opposite distribution of *Chaetoceros* RS and MPG along the studied period responds to the different nutrient requirements of both groups. *Chaetoceros* RS prefers persistent upwelling conditions, while *Thalassionema nitzschioides*, the main component of the MPG, is a species with prevalence by weaker upwelling episodes (Blasco et al., 1981; Abrantes, 1988; Abrantes and Moita, 1999), like the winter period of our study. The high percentage values of *L. danicus* during 1997 winter are equivalent to the increase of this species in the WAG, as observed by Bárcena et al. (2004). The former author related the increase of *L. danicus* to the unfavourable surface water conditions occurring in the Alboran, with water stratification caused by a warmer than usual NASW getting into the basin (Vargas-Yañez et al., 2002).

The record of both neritic and benthic diatoms in the ALB-5F sediment trap (Fig. 5d) reveals an intense bottom current activity. Highest peaks of this group could be related to the intense westward–eastward current reversal at ALB5 mooring recorded by Sanchez-Vidal et al. (2005) during winter that would have resuspended bottom sediments from the nearby margin.

5.1.4. Spring period

The spring is characterized by planktonic bloom, with an increase in fluxes in all the main groups (diatoms, coccolithophores and foraminifers) but a reduced diversity, because only a few taxa, typical of this productive conditions were dominant (Figs. 3–5). At the beginning of March 1998 gyres are practically collapsed (García-Gorrioz and Carr, 2001) and caused a decrease in all constituents observed in ALB-5. This scenario is reversed during the following

months, when favourable conditions – developed western gyre – transported nutrient from western Alboran (García-Gorrioz and Carr, 2001) and allowed a gradual increase of foraminifer, coccolithophores and diatoms. Typical upwelling taxa (*T. quinqueloba* and *G. bulloides*, sGG, *E. huxleyi*, RS *Chaetoceros* and the diatom MPG) dominated this event. Increase in solar radiation during spring may have contributed to the phytoplanktonic flourishing (Margalef, 1978), and hence, higher prey availability favoured zooplankton development (Hemleben et al., 1989).

5.2. Additional inputs

5.2.1. Aeolian biogenic component

Phytoliths are robust bodies of opaline silica in epidermal cells of plants (Blackman, 1971) and they are injected into the atmosphere during dry-season brush fires (Pokras and Mix, 1985). Fresh-water diatoms are dispersed by deflation of Holocene basins and dry lake deposits (Pokras and Mix, 1985). Hence, the presence of a mixture of microfossils with distinct ecological requirements (terrestrial and lacustrine environments) (Fig. 6) allows us to interpret this fact as a wind-transported material rather than as a run-off origin. Moreover, there are no important river systems in the Alboran Basin (Fig. 1). Increase in windblown fresh-water diatoms and phytoliths in our sediment trap may reflect periods of enhanced deflation and wind transport (aridity) and changes in continental grass cover (Pokras and Mix, 1985).

In this sense, Saharan dust storms are considered the main process of dust particles input to the Mediterranean area (Loyé-Pilot and Martin, 1996). Guerzoni et al. (1997) and Moreno et al. (2002) have suggested that the Central Sahara and South Algeria could be the main source areas of dust particles entering the western Mediterranean Sea. These dust storms show a clear seasonal cycle, with maximums during dry and warmest seasons, spring and summer (Moulin et al., 1998; Barnaba and Gobbi, 2004), in clear correspondence with our windblown biogenic particles record (Fig. 6).

The occurrence of phytoliths and fresh-water diatoms in our sediment trap confirms the results obtained in paleostudies of the Mediterranean sediments and supports the general assumption of an eolic transport agent of this biogenic material to the Mediterranean basin (Abrantes, 1991; Flores et al., 2000; Bárcena et al., 2001).

6. Summary and conclusions

Biogenic particles flux recorded in sediment trap ALB-5F, composed by coccolithophores, planktonic foraminifers, diatoms and phytoliths, mirrors the variability of meteorological and hydrographic conditions occurred in the Alboran Sea during the period from July 1997 to May 1998.

The main fluxes in surface productivity during the studied period took place during mid-spring to early summer, and a minor bloom occurred during mid-fall to early winter. These episodes are related to local pulses of productivity forced by the development of anti-cyclonic gyres in the Alboran Basin as well as a predominance of westerly winds over the area. The good correspondence between seasonal microorganism fluxes and high pigment concentrations in surface waters suggests a control of particle export by the seasonal productivity cycle in the surface and subsurface waters transported towards the bottom by faecal pellets or/and marine snow.

Succession in coccolithophores, planktonic foraminifers and diatoms communities were related to changes of water column conditions. Species adapted to well-mixed and nutrient-rich waters, such as *Chaetoceros* RS, sGG, *G. bulloides*, *T. quinqueloba*, dominated during the upwelling conditions of early summer 1997 and mid-spring 1998. Increases in temperature, upwelling relaxation and surface water stratification during late summer to fall 1997 allowed the blooming of warm and oligotrophic planktonic taxa, like *G. inflata*,

G. ruber, *F. profunda*, WCCG and *L. danicus*. Weaker upwelling and low-nutrient conditions during 1997–1998 winter may have favoured the shift from opal to calcareous phytoplankton domain. Unusual surface warmer conditions during late summer and fall in the Alboran Sea could be related to the 1997–1998 ENSO event.

Increase in fresh-water diatoms and phytoliths in the Alboran Sea indicates a significant continental input from Sahara desert as a consequence of an intensification of westerly winds during spring and early summer. Furthermore, continuous changes in current directions (E–W) detected by the current meters deployed in the ALB-5 mooring during fall and winter suggest that an important particle input to the sediment trap came from the seafloor and neighbouring continental margin sediment by resuspension.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.marmicro.2010.09.005.

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