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Planktonic response to main oceanographic changes in the Alboran Sea (Western Mediterranean) as documented in sediment traps and surface sediments

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Abstract

In order to determine the influence of seasonal oceanographic changes to the export of particulates and the flux of organisms as well as its corresponding integrated signal left in the bottom sediments of the Alboran Sea (Western Mediterranean), two mooring lines, ALB-1F and ALB-1D, were deployed from July 1997 to May 1998 on the continental slope south of Malaga at 36°01' N/04°16' W and 36°14' N/04°28' W, and a water depth of 1004 and 958 m, respectively. The mooring locations are under the influence of the incoming Atlantic Surface Water (ASW), at the northern and productive edge of the Western Alboran Gyre (WAG), and of the wind-induced upwelling offshore the Spanish coast. Additionally, a total of five core tops located in the same area were studied. The results are compared to information based on SeaWiFS images of chlorophyll-*a* concentration, SST, meteorological data on wind direction and intensity, and fluvial discharges from the main rivers of the Alboran Basin.

The temporal oceanographic evolution of the Alboran Sea during the studied period was divided into five episodes: E1 (July 1997), E2 (August–October 1997), E3 (November to mid-December, 1997), E4 (December–March 1998) and E5 (April–May 1998). The episodes represent different oceanographic conditions in the Alboran Sea during the studied period. Detailed analyses of the recorded pattern of bulk components, calcareous nannoplankton, planktonic foraminifera, diatoms and phytoliths reflect seasonal changes in the main hydrographic regimes in the western Alboran Sea. All biogenic bulk components, as well as the annual evolution of the floral and faunal assemblages follow a tri-modal pattern, with maximum fluxes recorded during E1, E3 and E5, representing periods of higher productivity and wind-induced upwelling. During these periods, species such as the Small *Gephyrocapsa* Group, *Gephyrocapsa muelleriae* and *Calcidiscus leptoporus*, the foraminifer *Globigerina bulloides* and the diatom *Chaetoceros* resting spores (RS) were dominant. *Gephyrocapsa oceanica* and *Globorotalia inflata* were coupled to the evolution of the Atlantic Surface Water (ASW) or related to surface water stability (E2

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and E4). The diatom *Leptocylinthus danicus* responded to upwelling relaxation, and water stratification (E1, E2 and E4) and benthic diatoms were related to eddy intensity at bottom. Phytolith fluxes were directly related to wind intensities and the prevailing westerly winds (E3 and E5).

The distribution of microfossils in surface sediments differs from the biogenic assemblages recorded in the sediment traps. In this sense, during 1997–1998 the strongest El Niño Event in the last century took place, which could have forced an unusual seasonality in the Alboran Sea, reflecting an exceptional micropaleontological signal not observed in the surface sediments.

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Keywords: particulate fluxes; microfossil fluxes; oceanographic response; surface sediments; chlorophyll-*a* concentrations; Alboran Sea

1. Background and objectives

The Alboran Sea is the westernmost basin of the Mediterranean Sea and its particular position, as the entrance of ASW into the Mediterranean, has motivated its selection as a site for intensive paleoceanographic and paleoclimatic research.

Unlike the general oligotrophy that dominates most of the Mediterranean, the Alboran Sea has two systems of high biological productivity, which are associated with the Western Alboran Gyre (WAG) and the Almeria-Oran density front (AOF), respectively (Fig. 1).

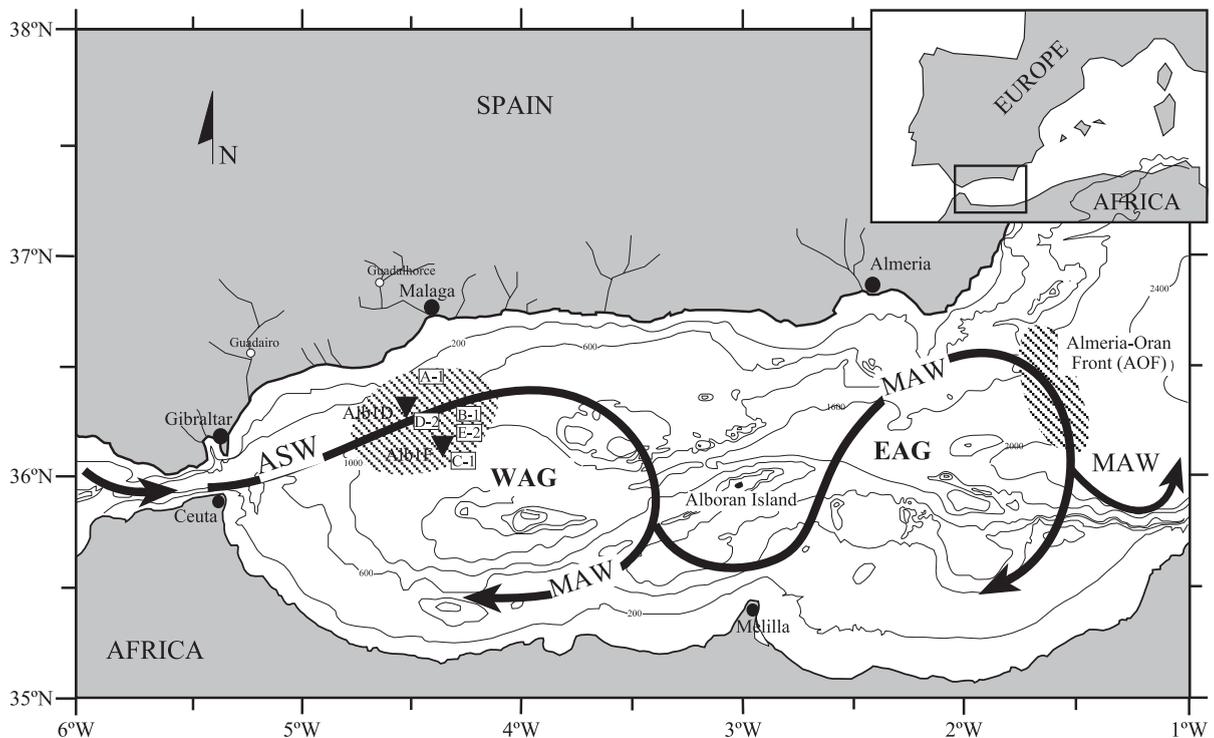


Fig. 1. Geographical setting of the study area. Bathymetric map of the Alboran Sea, inverted black triangles represent the position of the sediment traps; black dots correspond to the main localities; open squares represent the position of surface sediment samples, open dots show the locations of the two rivers considered in the discussion. 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, WAG, Eastern Alboran Gyre (EAG) and AOF.

High primary production in the Western Alboran Sea is mainly associated with the local circulation pattern, which is controlled by the WAG. According to García-Gorriz and Carr (2001), two types of upwelling occur in the basin: wind-induced upwelling, mainly on the northern side of the WAG off the Spanish coast, and gyre-induced upwelling at the periphery of the gyres. Previous studies that evidence the linkage between high productivity and the sedimentary record have already been provided by Bárcena and Abrantes (1998). Changes related to variations in climatic and paleoceanographic conditions have been studied in some depth in the area by Abrantes (1988) and Weaver and Pujol (1988), and more recently by Cacho et al. (1999), Bárcena et al. (2001), Sánchez-Goñi et al. (2002), Moreno et al. (2002), Pérez-Folgado et al. (2003), Colmenero-Hidalgo et al. (2004), among others.

Although intense paleoceanographic and paleoclimatic research has been carried out in recent years, little information is available about the dynamics and ecological characteristics of the particle fluxes. Only a very limited number of studies have been devoted to downward particle fluxes in the Alboran Sea. In this sense, Peinert and Miquel (1994) reported some flux measurements from two short-term flux experiments in the AOF. Dachs et al. (1998) reported a detailed study of lipid compounds during a 3-month trap experiment in the WAG. Recent sedimentological studies have been performed by Fabres et al. (2002) in the WAG, and by Sánchez-Vidal et al. (in press) at the AOF. However, this is the first coupled study of main constituents and organism fluxes for the Alboran Sea.

Here we analysed a 1-year time series of particle flux collected between July 1997 and May 1998 in the WAG. We describe the seasonal evolution of total mass, bulk components, coccolithophores, foraminifers, siliceous phytoplankton and phytoliths, and we compare the seasonal particle flux pattern to chlorophyll-*a* concentrations as provided by SeaWiFS satellite images (chl-*a* mg · m⁻³). In addition, trapped organism assemblages and bulk component compositions are compared to those preserved in surface sediments in order to aid in the interpretation of paleoceanographic signals downcore.

Thus, the main objective of our work has been to determine the effect of seasonal oceanographic changes on the export of particulates and flux of

organisms and the corresponding integrated signal left in the bottom sediments of the Alboran Sea. Knowledge of present-day patterns is relevant for further paleoceanographic investigations; we therefore introduce data from surface sediments as an integrated signal of current oceanographic processes in order to identify proxies for long time series.

2. Study area: oceanographic and meteorological considerations

2.1. General oceanographic aspects

The Alboran Sea could be considered a transition area between the Atlantic Ocean and the Mediterranean Sea. The pattern of circulation is very intense, subject to strong seasonal variations, and related to fluctuations in the intensity of water exchange through the Strait of Gibraltar. At the surface, the main oceanographic feature of the area is the presence of two anticyclonic gyres: the WAG and the Eastern Alboran Gyre (EAG), controlled by a jet of ASW (Fig. 1). Associated to the gyres the Alboran Sea has two systems of high biological productivity (Fig. 1). For detailed description of physiography and oceanography see Parrilla and Kinder (1987), Bárcena et al. (2001), Fabres et al. (2002), and Masqué et al. (2003).

In terms of sea surface productivity, the persistence of four main regimes is noticeable during the year: the *winter bloom regime* (November to March), the *summer non-bloom regime* (May to September), and two *transition periods*, April to May, when thermal stratification starts, and October–November, coinciding with the highest wind variability and water-column de-stratification (García-Gorriz and Carr, 2001).

2.2. 1997–1998: seasonal oceanographic and meteorological variations

Sets of SeaWiFS chlorophyll-*a* concentration images show the temporal evolution of biological productivity for the whole of the Alboran Sea (Fig. 2). The set of images covers almost the whole period, except for July and August 1997. Accordingly, we used the composite images from June–

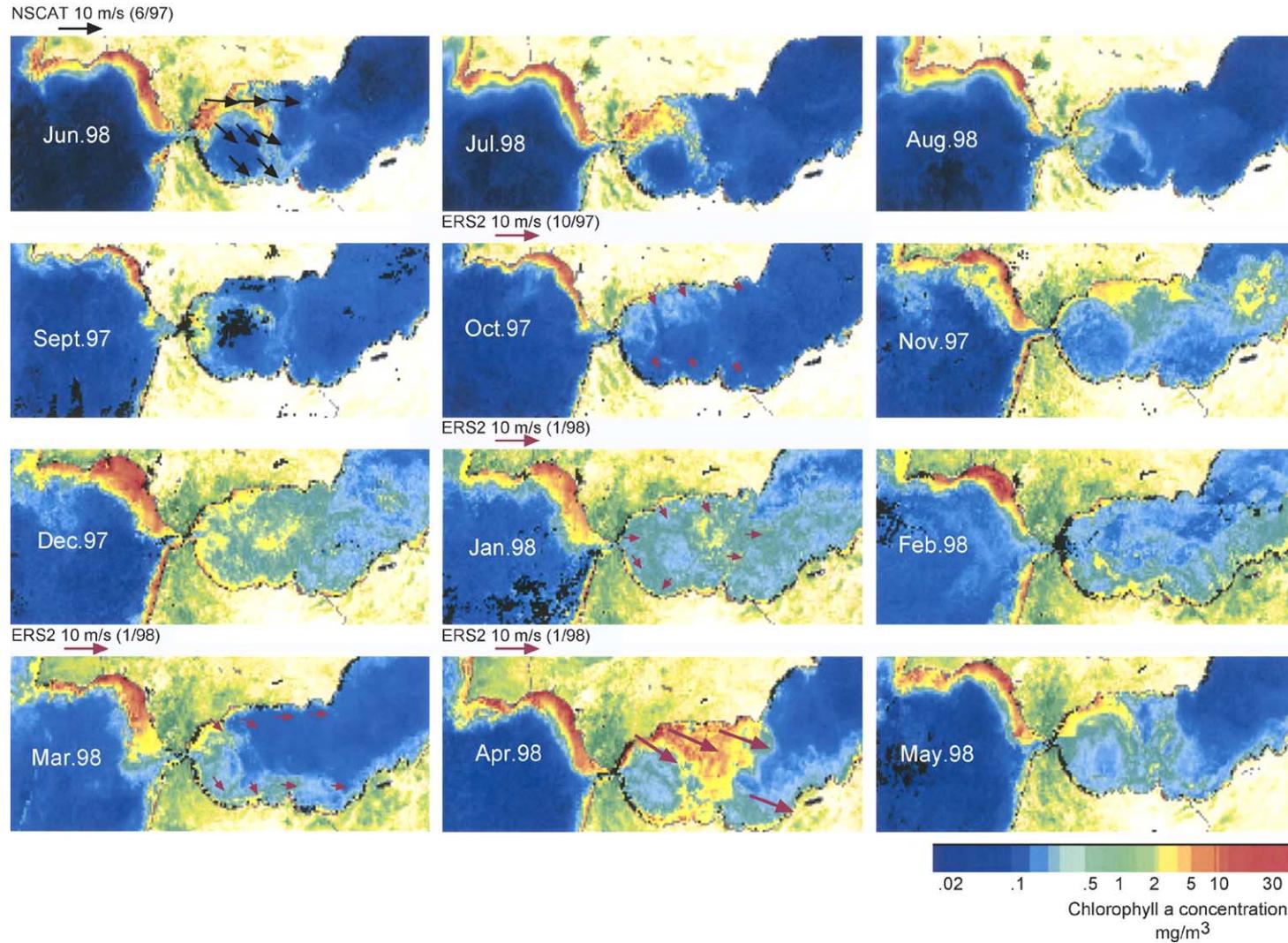


Fig. 2. Chlorophyll-*a* concentrations for the Western Alboran Sea between September 1997 and August 1998. SeaWiFS images are averaged over 1-month periods. Images were obtained from the Space Applications Institute (SAI), Marine Environment Unit (ME), Joint Research Centre (JRC); the online dataset can be obtained from http://me-www.jrc.it/me-website/contents/shared_utilities/frames/archive_seawifs.htm. Overlapped arrows represent the intensities and directions of available satellite-measured winds, black arrows by NSCAT, and pink arrows by ERS-2 (after García-Gorriç and Carr, 2001).

August 1998 in order to tentatively approach the dynamics of the WAG. Data from June and July 1997 related to chlorophyll-*a* concentration and SST was published by García-Gorrioz and Carr (2001) and Vargas-Yáñez et al. (2002), respectively. The information provided by these authors reveal that both summers, 1997 and 1998, displayed a similar oceanographic scenario.

For the time interval considered in the present study, seasonal chlorophyll-*a* images reveal two periods of maximum concentration: summer (July, 1997) and spring (April–May, 1998), induced by strong upwelling-favourable winds (García-Gorrioz and Carr, 2001). These periods are related to the formation of the WAG, and to the upwelling of subsurface waters off the SW Spanish coast (Fig. 2).

Furthermore, increased but anomalous phytoplankton activity was also observed during November–December (Fig. 2). In 1997 summer SST prevailed in the Alboran Sea until October (García-Gorrioz and Carr, 2001; Vargas-Yáñez et al., 2002). During October 1997, SST were around 22.5 °C (3 °C warmer than summer average temperature), and winds were unusually weak, favouring a strong water stratification (Fig. 2). Thus, combination of both factors, delayed the typical winter destratification and fertilisation events, resulting in a weaker than usual *winter bloom regime*. The sampling period falls within the 1997–1998 El Niño Event (McPhaden, 1999); according to the former author the event was the strongest for the last century, and resulted in highest positive SST anomalies in the SE Pacific, nearly 4°C. McPhaden (1999) suggested that major climatic impacts around the world were related to this event. This could be the case for the anomalous high summer and fall SST recorded in the Alboran Sea.

Additional meteorological information reveals the prevalence of a westerly wind regime with upwelling-favourable winds ending in November–December of 1997 and April 1998 (García-Gorrioz and Carr, 2001) (Fig. 2). Moreover, maximum rainfall and fluvial discharges occurred during fall and winter. Four important discharges were observed, two of them relatively weak (around 120 m³ s⁻¹), occurred in September and October–November 1997, while the strongest took place towards the end of December 1997 and the beginning of February 1998 (higher than 350 m³ s⁻¹). According

to Fabres et al. (2002), none of them left clear evidence in the sediment traps.

3. Materials and methods

3.1. Sediment traps

Two mooring lines, ALB-1F and ALB-1D, were deployed on the continental slope at 1004 m and 958 m depth, and located at 36°01' N/04°16' W and 36°14' N/04°28' W, respectively (Fig. 1, Table 1). The cups were deployed at 30 m above the sea floor. Mooring lines were equipped with coupled pairs of Technicap PPS3 sediment traps and Aanderaa current meters at several levels in the water column. The design of the PPS3 sediment trap, its preparation, maintenance and the configuration of the mooring lines are described in Heussner et al. (1990) and Fabres et al. (2002). The mooring locations are under the influence of both the incoming ASW, at the northern border of the WAG, and of the wind-induced upwelling off the Spanish coast.

The ALB-1F sediment trap was deployed from July 1997 to May 1998 during three different periods (Table 2); ALB-1D was deployed exclusively during the third period. The sampling interval was 10–11 days for the whole period, except between April 20th and May 16th (third period), when the sampling interval was 3 days (Table 2). ALB-1D was only used for foraminifer counts. For technical reasons, the record of foraminifers in the ALB-1F trap for the third period was lost.

Additionally, five core tops recovered during the BIO-Hespérides MATER-1 leg were studied (Table 1).

Table 1
Position of the mooring sites and surface sediment samples

Site	Latitude (N)	Longitude (W)	Depth (m)
ALB-1F	36°01'	04°16'	1004
ALB-1D	36°14'	04°28'	958
A-1	36°23'	4°23'	659
B-1	36°15'	4°14'	948
C-1	36°00'	4°16'	1319
D-2	36°15'	4°28'	973
E-2	36°13'	4°20'	1055

Table 2

Daily flux of total mass, lithogenic, calcium carbonate, opal, and OC at the mooring site in the Alboran Sea from July 1997 through May 1998

Period	Opening day	Sampling days	Mass flux	Lithogenic flux	Carbonate flux	Opal flux	TOC flux	
I	30/06/1997	10	0.914	0.627	0.167	0.052	0.034	
	10/07/1997	10	1.225	0.722	0.298	0.098	0.053	
	20/07/1997	11	1.234	0.746	0.279	0.109	0.049	
	31/07/1997	10	0.651	0.483	0.073	0.048	0.024	
	10/08/1997	10	0.495	0.305	0.117	0.035	0.019	
	20/08/1997	11	0.463	0.249	0.146	0.031	0.018	
	31/08/1997	10	0.424	0.226	0.140	0.023	0.017	
	10/09/1997	10	0.306	0.145	0.121	0.013	0.013	
	20/09/1997	10	0.385	0.260	0.073	0.020	0.016	
	30/09/1997	10	0.359	0.259	0.055	0.017	0.014	
	10/10/1997	10	0.435	0.321	0.066	0.017	0.016	
	20/10/1997	11	0.539	0.435	0.042	0.019	0.021	
	II	14/11/1997	6	1.175	0.941	0.078	0.021	0.067
		20/11/1997	10	1.461	1.142	0.216	0.030	0.036
30/11/1997		10	1.703	1.302	0.260	0.057	0.041	
10/12/1997		10	1.007	0.691	0.209	0.053	0.027	
20/12/1997		11	0.717	0.460	0.170	0.043	0.022	
31/12/1997		10	0.607	0.372	0.179	0.020	0.018	
10/01/1998		10	0.415	0.317	0.030	0.018	0.025	
20/01/1998		11	0.394	0.274	0.073	0.021	0.013	
31/01/1998		10	0.247	0.169	0.051	0.012	0.008	
10/02/1998		10	0.245	0.154	0.065	0.008	0.009	
20/02/1998		8	0.332	0.224	0.077	0.008	0.012	
28/02/1998		10	0.524	0.381	0.099	0.013	0.016	
III		31/03/1998	10	0.601	0.404	0.132	0.029	0.019
		10/04/1998	9	1.011	0.731	0.186	0.038	0.028
	19/04/1998	3	1.152	0.844	0.200	0.038	0.035	
	22/04/1998	3	1.196	0.863	0.220	0.036	0.038	
	25/04/1998	3	1.011	0.738	0.174	0.034	0.033	
	28/04/1998	3	1.082	0.730	0.233	0.040	0.039	
	01/05/1998	3	1.361	0.924	0.201	0.102	0.067	
	04/05/1998	3	1.618	1.065	0.254	0.143	0.078	
	07/05/1998	3	1.697	1.129	0.316	0.120	0.066	
	10/05/1998	3	1.001	0.686	0.160	0.067	0.044	
	13/05/1998	3	1.628	1.018	0.296	0.154	0.080	
	16/05/1998	6	1.143	0.739	0.191	0.107	0.053	

Periods sampled, trap-cup opening day, as well as the days of sampling for each sample are indicated. Fluxes are expressed as $\text{g m}^{-2} \text{day}^{-1}$.

Cores were recovered at five different positions; which are under the influence of the WAG (Fig. 1, Table 1).

3.2. Sample treatment and analytical methods

For the sample splitting procedure, the method proposed by Heussner et al. (1990) was followed. A detailed description of the analytical procedures of the geochemical analyses (total carbon, organic carbon, calcium carbonate, and biogenic silica) is given in Fabres et al. (2002).

For micropaleontological analysis, the original total dry mass was known, and 1/8 aliquots were used. Original samples were wet-sieved onto a 150- μm mesh in order to separate foraminifera larger than 150- μm from smaller diatoms and coccolithophores. The scarcity of the material collected obliged us to carry out all micropaleontological studies on the same sample aliquot, with no loss of information from the total sample. The sample fraction of less than 150 μm was rinsed with distilled water. From this untreated solution, 1 cc was used to mount permanent slides for coccolithophore analysis according to the method-

ology proposed by Flores and Sierro (1997). For diatom and silicoflagellates analyses Schrader and Gersonde's (1978) recommendations were followed, qualitative and quantitative analyses were done at 1000 magnifications using a Leica DMLB with phase-contrast illumination. For surface sediment samples, the standard treatment was performed for siliceous and calcareous microfossils.

3.3. Satellite imagery, meteorological and oceanographic data

SeaWiFS images of chlorophyll-*a* concentrations were obtained from the Marine Environment Unit of the Space Applications Institute (Joint Research Centre, European Commission) (Melin, 2000). The series of 1-month images covers the whole Alboran Sea.

In order to evaluate wind direction and intensity we used the monthly wind fields measured by NSCAT (NASA Scatterometer, June 1997) and ERS-2 (second European Remote Sensing Satellite, from October 1997 to June, 1998) published by García-Gorrioz and Carr (2001). Fluvial discharge data for the two small rivers flowing into the Western Alboran Sea, Guadairo and Guadalhorce (Fig. 1) were discussed by Fabres et al. (2002).

The former authors have also discussed current meter data derived from ALB1-F current meter deployed with the trap. The current meter was deployed during 332 days, the average speed recorded was of $4.96 (\pm 3.29) \text{ cm s}^{-1}$. According to these authors, the mooring was in the vertical position throughout the whole experiment and therefore, the efficiency of trap collection is high.

4. Results

4.1. Bulk composition

The temporal evolution of the total mass flux reveals a tri-modal distribution with the highest values during July 1997, November–December 1997, and April–May 1998 (Fig. 3a, Table 2). The total flux ranged from a maximum value of $1.70 \text{ g m}^{-2} \text{ day}^{-1}$ to a minimum value of $0.25 \text{ g m}^{-2} \text{ day}^{-1}$ (mean: $0.85 \text{ g m}^{-2} \text{ day}^{-1}$). The lithogenic fraction was the dominant

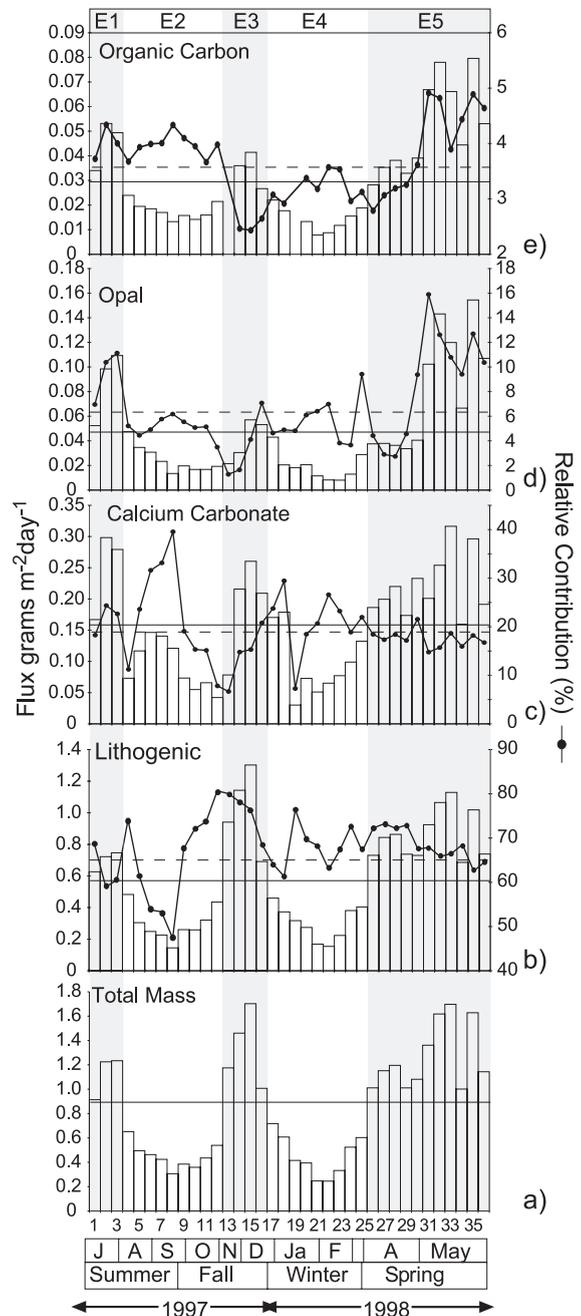


Fig. 3. White bars represent the seasonal pattern of flux of (a) total mass, (b) lithogenics, (c) calcium carbonate, (d) opal, (e) organic carbon. Solid lines represent the relative contribution of lithogenics, calcium carbonate, opal, and organic carbon at the mooring site in the Alboran Sea between July 1997 and May 1998. Grey vertical areas indicate the oceanographic episodes E1, E3 and E5 described in the discussion for the same time span; episodes E2 and E4 in white.

bulk component, on average representing more than 65% of the total mass. Maximum values of the lithogenic component were recorded from late October through late December 1997, the relative contribution being in the 70–80% range of the total mass. In terms of flux, the lithogenic component also followed the tri-modal pattern, maximum values reaching up to $1.3 \text{ g m}^{-2} \text{ day}^{-1}$ and minimum decrease to $0.15 \text{ g m}^{-2} \text{ day}^{-1}$, and it followed the same trend as that of the total mass flux (Fig. 3b, Table 2).

Biogenic components are secondary contributors. Calcium carbonate, on average, accounted for 20% of the total flux (range 39.5–7.8%). Calcium carbonate concentration showed a main relative peak in September 1997 and three secondary peaks in July 1997, January 1998 and February 1998. The calcium carbonate flux-pattern followed the same trend as the total mass flux; the highest values being found for July 1997, November–December 1997 (10 days displaced into November with respect to the total mass flux), and April–May 1998. A minor peak occurred in late August–early September. The average daily flux ranged from 0.03 to $0.29 \text{ g m}^{-2} \text{ day}^{-1}$ (average $0.16 \text{ g m}^{-2} \text{ day}^{-1}$) (Fig. 3c, Table 2).

Biogenic silica and organic carbon (OC) constitute a minor fraction of the bulk flux. Opal contribution ranges from 1.3% to 15.9% (mean 5.2%). The seasonal pattern displayed two main relative maxima—during late mid July–August 1997 and May 1998—with relative secondary peaks during late December 1997 and mid January 1998. Opal flux ranged from $0.158 \text{ g m}^{-2} \text{ day}^{-1}$ during May 1998 to $0.008 \text{ g m}^{-2} \text{ day}^{-1}$ during February 1998 (average $0.5 \text{ g m}^{-2} \text{ day}^{-1}$). During mid–late July and early mid–December 1997 two peaks in opal flux were also observed (Fig. 3d, Table 2).

Organic carbon represented between 2.4% and 4.9% of the total mass (3.5% average). The maximum relative contribution occurred during May 1998 and summer of 1997 (when the lithogenic contribution was minimum) (Fig. 3e, Table 2). In terms of flux, OC followed the same pattern as that described for the total mass during July 1997, but partially displaced in time during the fall and spring, with maxima during late November–early December 1997 and May 1998. The OC average was close to $0.03 \text{ g m}^{-2} \text{ day}^{-1}$, ranging from 0.008 to $0.08 \text{ g m}^{-2} \text{ day}^{-1}$.

4.2. Calcium carbonate fraction

4.2.1. Coccolithophores

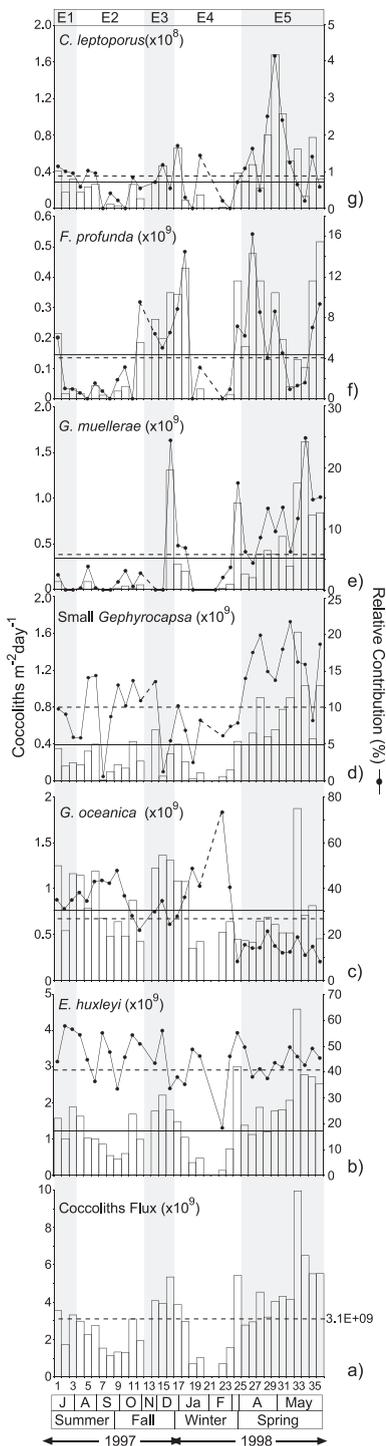
Most biogenic carbonate particles recorded in the sediment traps were coccoliths and planktonic foraminifera (pteropod abundance was negligible). The daily flux of coccoliths, expressed as the number of coccoliths $\text{m}^{-2} \text{ day}^{-1}$, ranged from 9.9×10^9 to 7.1×10^8 (3.1×10^9 average). The total coccolith flux also followed a tri-modal pattern, following the same trend as calcium carbonate and OC fluxes, the highest values being observed during November–December 1997 and March through May 1998. A secondary peak was observed during July 1997 (Fig. 4a, Table 3).

The main component of the coccolithophore association was *Emiliania huxleyi*, whose contribution ranged from 58% to 18% of the total assemblage (41% mean). In terms of fluxes, *E. huxleyi* showed two maxima, November–December 1997, and the highest daily flux in May 1998, fluxes ranging from 4.6×10^9 to 1.3×10^8 (1.4×10^9 coccoliths $\text{m}^{-2} \text{ day}^{-1}$ average); a peak in March 1998 was also recorded (Fig. 4b, Table 3).

Gephyrocapsa oceanica was the second main component of the assemblage (8–73%, mean of 27%, Fig. 4c, Table 3). The abundance pattern, as regards both fluxes and percentages, varied considerably along the year. The highest percentages were recorded during August–October 1997 and February 1998. The highest flux peak was recorded in May 1998 (1.9×10^9 coccoliths $\text{m}^{-2} \text{ day}^{-1}$), although two secondary flux peaks were recorded during July–August and November–December 1997.

The “Small *Gephyrocapsa* Group” (*Gephyrocapsa ericsonii* and *Gephyrocapsa aperta*) contributed to the assemblage with values from 0% to 22% (10% average). Maximum percentage values were reached at mid–late August 1997, late September to end–November 1997, and April–May 1998. Daily fluxes reached the highest values during April–May 1998 (3.7×10^8 coccoliths $\text{m}^{-2} \text{ day}^{-1}$ average, maximum 1.6×10^9 coccoliths $\text{m}^{-2} \text{ day}^{-1}$ during May 1998) (Fig. 4d, Table 3).

Gephyrocapsa muellerae represented 6% (range 0–25%) of the assemblage. The seasonal distribution of the species showed four peaks of higher percentage contribution: mid December 1997, March 1998, and



April–May 1998, increasing progressively from 13% to 25%. The absolute contribution into the flux also followed the same temporal pattern, with mean values of 2.8×10^8 coccoliths $\text{m}^{-2} \text{day}^{-1}$ (ranging from 0 to 1.2×10^9) (Fig. 4e, Table 3). *Florisphaera profunda* accounted for 4% of the assemblage on average (range, 0 to 16%) (Fig. 4f, Table 3). Percentages and fluxes showed a seasonal distribution, with three maxima from late mid-October 1997 to early mid-January 1998, March–April 1998, and late mid-May 1998. *Calcidiscus leptoporus* was a minor component of the coccolithophore assemblage: a prominent peak in both relative and absolute records was observed from late mid-April to early mid-May 1998 (Fig. 4g, Table 3).

In order to compare the annual record of the species in the trap with the multi-annual record obtained from surface sediments, a tentative calculation was made considering the total number of coccolithophores trapped during the year-round sampling period (291 days) and the relative contribution of the taxa considered above. Thus, a total of 9.2×10^{10} coccolithophores were trapped; *Emiliania huxleyi* reached 29.5%, *Gephyrocapsa oceanica* represented 15.3%, the Small *Gephyrocapsa* Group reached 6.4%, *Gephyrocapsa muelleriae* attained 5.9%, *Florisphaera profunda* reached 3.5%, and *Calcidiscus leptoporus* represented 0.55% of the assemblage trapped (Fig. 7a).

4.2.2. Planktonic foraminifers

Planktonic foraminifers were present throughout the year (Fig. 5a, Table 3). Maximum fluxes occurred in a single peak during mid–late May 1998, with values up to 6.2×10^3 foraminifers $\text{m}^{-2} \text{day}^{-1}$. Two minor peaks also occurred during mid-July 1997 and mid-November–early January (Fig. 5a). The main flux event was due to the high proliferation of *Globigerina bulloides*.

Fig. 4. Seasonal pattern of flux (bars) and relative abundance (solid lines) of the most significant species of coccolithophores, (a) total coccoliths, (b) *Emiliania huxleyi*, (c) *Gephyrocapsa oceanica*, (d) Small *Gephyrocapsa* group, (e) *Gephyrocapsa muelleriae*, (f) *Florisphaera profunda*, (g) *Calcidiscus leptoporus* at the mooring site in the Alboran Sea between July 1997 and May 1998. Grey vertical areas indicate the oceanographic episodes E1, E3 and E5 described in the discussion for the same time span; episodes E2 and E4 in white.

Table 3

Daily flux of the main coccolithophore taxa, *Emiliania huxleyi*, *Gephyrocapsa oceanica*, Small *Gephyrocapsa* group, *Gephyrocapsa muellerae*, *Florisphaera profunda*, *Calcidiscus leptoporus*, most abundant planktonic foraminifers, *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

Period	Sample	Total nanno ($\times 10^9$)	<i>E.</i> <i>huxleyi</i> ($\times 10^9$)	<i>G.</i> <i>oceanica</i> ($\times 10^9$)	SGG ($\times 10^9$)	<i>G.</i> <i>mueller.</i> ($\times 10^9$)	<i>F.</i> <i>profim</i> ($\times 10^9$)	<i>C.</i> <i>lepto.</i> ($\times 10^8$)	Total forams ($\times 10^3$)	<i>G.</i> <i>bulloides</i> ($\times 10^3$)	<i>G.</i> <i>inflata</i> ($\times 10^2$)	<i>G.</i> <i>ruber</i> ($\times 10^2$)	Total diatoms ($\times 10^7$)	<i>Chaet.</i> RS ($\times 10^7$)	Marine plankt. ($\times 10^6$)	<i>L.</i> <i>danicus</i> ($\times 10^6$)	Benthic Neritic ($\times 10^5$)	Fresh- water ($\times 10^5$)	Phytol ($\times 10^4$)
I	1	3.56	1.57	1.25	0.35	0.09	0.22	0.41	0.09	0.00	0.58	0.06	2.11	1.92	0.55	0.55	3.03	1.01	0.00
	2	1.74	1.01	0.54	0.16	0.00	0.02	0.17	0.28	0.02	2.30	0.13	4.53	4.07	0.91	3.12	2.99	0.00	0.00
	3	3.32	1.88	1.16	0.20	0.00	0.03	0.32	0.05	0.01	0.47	0.00	5.32	4.65	1.19	4.20	5.43	0.00	0.00
	4	2.99	1.63	1.15	0.17	0.01	0.02	0.17	0.03	0.00	0.19	0.00	2.29	1.98	0.40	1.71	5.04	1.01	0.00
	5	2.27	1.02	0.78	0.32	0.09	0.00	0.23	0.05	0.01	0.32	0.00	1.23	1.09	0.45	0.50	0.49	0.49	0.00
	6	2.76	1.00	1.19	0.40	0.01	0.04	0.26	0.05	0.01	0.29	0.12	1.08	0.94	0.32	0.64	2.28	0.00	0.00
	7	1.55	0.85	0.67	0.01	0.00	0.01	0.00	0.04	0.01	0.32	0.00	0.35	0.31	0.10	0.07	1.34	0.33	0.00
	8	1.13	0.54	0.48	0.10	0.00	0.00	0.05	0.01	0.00	0.06	0.06	0.14	0.11	0.00	0.08	1.01	0.13	0.00
	9	1.34	0.45	0.64	0.17	0.02	0.02	0.03	0.01	0.00	0.00	0.06	0.37	0.31	0.12	0.10	1.67	0.00	0.63
	10	1.31	0.60	0.48	0.13	0.04	0.04	0.00	0.01	0.00	0.13	0.00	0.26	0.22	0.04	0.12	0.60	0.00	0.25
	11	3.10	1.69	0.87	0.42	0.02	0.00	0.26	0.04	0.01	0.00	0.32	0.27	0.21	0.16	0.04	1.82	0.00	0.50
	12	1.94	0.99	0.42	0.21	0.05	0.18	0.11	0.06	0.02	0.17	0.23	0.32	0.25	0.08	0.15	2.38	0.55	0.23
II	13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.25	0.29	0.12	5.50	0.24	0.60	
	14	4.08	1.77	1.22	0.55	0.00	0.26	0.29	0.24	0.03	0.51	1.28	0.41	0.27	0.16	0.12	7.49	0.20	1.51
	15	3.94	2.21	1.37	0.05	0.00	0.20	0.47	0.40	0.18	1.60	0.45	1.10	0.87	0.93	0.33	5.97	1.01	2.83
	16	5.36	1.80	1.31	0.29	1.31	0.35	0.29	0.29	0.00	2.88	0.00	0.87	0.57	2.23	0.18	2.21	0.20	0.50
	17	3.89	1.48	1.08	0.40	0.28	0.34	0.66	0.74	0.24	4.60	0.23	1.39	0.86	3.84	0.14	8.70	0.46	0.57
	18	2.97	1.05	1.08	0.20	0.20	0.43	0.09	0.30	0.01	2.75	0.00	0.22	0.14	0.32	0.13	1.35	0.52	0.00
	19	0.72	0.35	0.35	0.02	0.00	0.00	0.00	0.04	0.00	0.45	0.00	0.13	0.08	0.17	0.08	1.45	0.19	0.00
	20	1.03	0.48	0.42	0.08	0.00	0.03	0.15	0.02	0.00	0.17	0.00	0.34	0.22	0.52	0.07	2.60	0.00	0.21
	21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.06	0.14	0.02	0.91	0.00	0.00
	22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.58	0.00	0.05	0.04	0.03	0.03	0.00	0.00	0.00
	23	0.71	0.13	0.52	0.04	0.01	0.00	0.01	0.06	0.00	0.56	0.00	0.02	0.01	0.00	0.00	0.25	0.25	0.63
	III	24	1.58	0.73	0.64	0.12	0.06	0.01	0.00	0.07	0.00	0.70	0.00	0.06	0.01	0.14	0.00	0.97	0.00
25		5.44	3.00	0.45	0.43	0.95	0.39	0.39	0.20	0.10	0.77	0.00	0.24	0.13	0.23	0.08	2.73	0.71	0.25
26		2.78	1.38	0.43	0.39	0.17	0.17	0.30	0.30	0.21	0.28	0.57	0.45	0.29	0.46	0.03	3.99	0.98	0.35
27		2.95	1.12	0.41	0.52	0.13	0.48	0.48	0.34	0.23	0.43	0.64	0.42	0.30	0.20	0.00	5.22	1.31	0.70
28		4.55	1.87	0.65	0.90	0.39	0.39	0.22	1.00	0.77	0.21	1.28	0.38	0.20	0.63	0.00	10.16	0.00	0.00
29		3.21	1.20	0.68	0.48	0.43	0.13	0.80	0.38	0.26	0.64	0.21	0.31	0.23	0.23	0.00	2.34	2.34	0.84
30		4.06	1.77	0.61	0.56	0.39	0.35	1.68	0.30	0.28	0.00	0.21	0.46	0.28	0.39	0.00	8.59	0.78	0.84
31		4.31	1.81	0.52	0.78	0.58	0.19	1.03	2.26	1.96	1.92	0.85	1.43	1.09	1.64	0.04	10.77	0.86	0.00
32		4.16	2.07	0.52	0.90	0.26	0.04	0.52	1.45	1.30	0.21	0.00	1.78	1.49	1.39	0.11	6.09	1.65	0.00
33		9.97	4.59	1.87	1.61	1.16	0.13	0.65	1.26	1.11	0.64	0.43	1.96	1.63	1.82	0.00	7.75	0.00	1.20
34		6.51	2.78	0.71	1.03	1.61	0.10	0.13	5.87	5.50	2.56	0.85	3.65	3.42	1.18	0.13	0.00	0.00	0.00
35		5.53	2.71	0.81	0.45	0.81	0.39	0.78	6.21	6.04	0.85	0.64	4.71	4.24	3.52	0.13	2.64	3.91	1.40
36	5.54	2.52	0.45	1.03	0.84	0.52	0.32	5.70	5.51	1.28	0.53	7.26	6.30	6.26	0.20	11.75	0.00	2.10	
Annual flux	92	27	14	5.9	5.5	3.2	0.5	16	11.7	3.0	0.5	4.2	3.5	2.6	1.7	1.2	1.4	1.2	
		($\times 10^9$)	($\times 10^9$)	($\times 10^9$)	($\times 10^9$)	($\times 10^9$)	($\times 10^9$)	($\times 10^9$)	($\times 10^3$)	($\times 10^3$)	($\times 10^3$)	($\times 10^3$)	($\times 10^8$)	($\times 10^8$)	($\times 10^7$)	($\times 10^7$)	($\times 10^7$)	($\times 10^6$)	($\times 10^6$)
Average			29.5	15.3	6.4	5.9	3.5	0.5		73.1	19	3.3		83.3	6.4	4.0	2.8	0.3	

Fluxes are expressed as numbers of coccoliths, individuals or diatom valves $m^{-2} day^{-1}$.

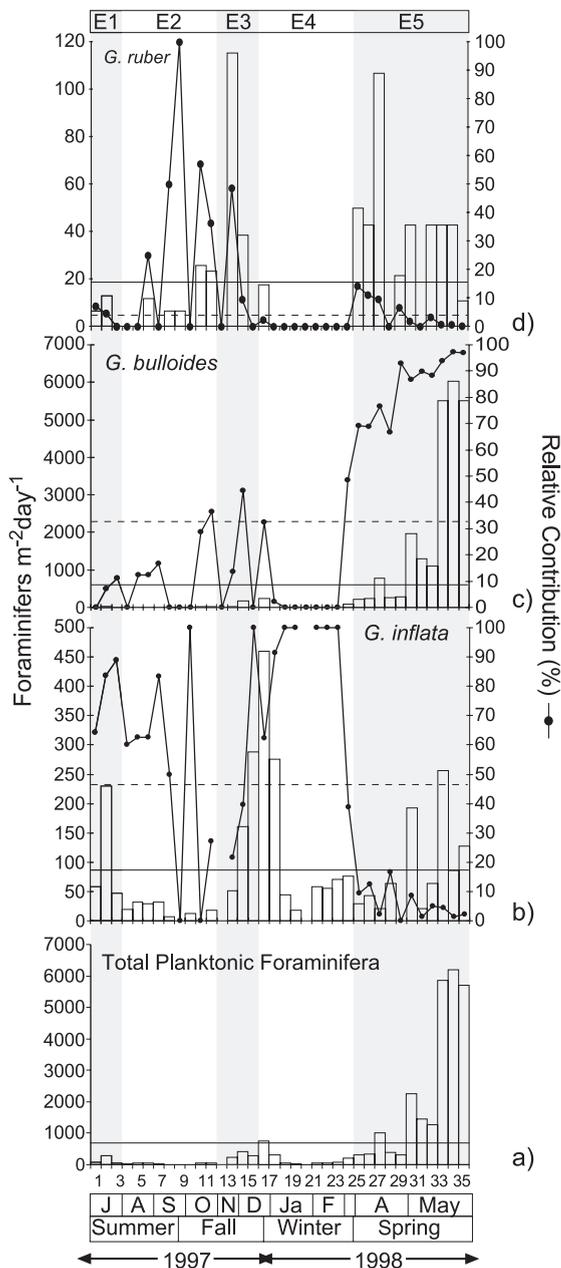


Fig. 5. Seasonal pattern of flux (bars) and relative abundance (solid lines) of the most significant group of foraminifera, (a) total foraminifera, (b) *Globigerina bulloides* (c) *Globigerinoides ruber* (d) *Globorotalia inflata*. These species are the main component of the foraminifer assemblage during the mooring period (between July 1997 and May 1998) at the site on the northern edge of the WAG. Grey vertical areas indicate the oceanographic episodes E1, E3 and E5 described in the discussion for the same time span; episodes E2 and E4 in white.

A few species of planktonic foraminifera were recorded in the sediment traps along the year. However, three of those species accounted for more than 90% of the whole foraminiferal assemblage. *Globorotalia inflata*, typically found along the gyre-margin region of North Atlantic, mostly followed the seasonal pattern of the total accumulation rate (Fig. 5b, Table 3), and was the major relative contributor during early summer (July–August 1997) and winter (late December 1997 to the end of February 1998), where *G. inflata* was the only contributor to the foraminiferal assemblage. The species had a mean relative abundance of 47% of the assemblage. The highest fluxes of the species were reached during December 1997–early January 1998.

Globigerina bulloides displayed the highest relative abundance for the period studied, although its annual distribution showed a strong seasonal trend, since the numbers of individuals observed in the trap during summer and winter were negligible, whereas they increased dramatically during spring. The highest *G. bulloides* flux was reached during April and May, with daily fluxes of 5 and 6.2×10^3 individuals $m^{-2} day^{-1}$, and a mean relative contribution of 70% and 90%, respectively (Fig. 5c, Table 3). Nevertheless, the mean relative contribution of the species accounted for 32% of the total assemblage. Apart from the spring peak, a small increase in the *G. bulloides* flux was observed during fall (November–December 1997), with values of around 238 individuals $m^{-2} day^{-1}$.

Globigerinoides ruber white was a secondary significant component of the foraminiferal assemblage, with a mean relative abundance of 3%. Its main flux contribution was observed in fall and spring, reaching values of 115 and 106 individuals $m^{-2} day^{-1}$ during November 1997 and April 1998, respectively (18.5 individuals $m^{-2} day^{-1}$, average) (Fig. 5d, Table 3). This species was the dominant contributor to the foraminiferal assemblage only in fall, when it replaced *Globorotalia inflata*. In contrast, *G. ruber* showed a minor relative contribution in winter because of the extremely high fluxes of *G. inflata* in that season.

A tentative calculation was made considering the total planktic foraminifera trapped during the sampling period and the relative contribution of the taxa considered above. Thus, from a total of 1.5×10^5 foraminifera trapped, *Globigerina bulloides* accounted for 73%, *Globorotalia inflata* represented

19%, and *Globigerinoides ruber* reached 3.3% of the assemblage (Fig. 7b).

4.3. Biogenic opal fraction

Diatoms, silicoflagellates, radiolarians, phytoliths and the siliceous dinoflagellate *Actiniscus* are the major constituents of siliceous biogenic particles settling in the Alboran Sea. According to our data, diatoms were the most significant contributors to the opal biogenic fraction. The daily flux of silicoflagellates was three orders of magnitude lower than that of diatoms; although the silicoflagellate species *Dictyocha* dominated the assemblage during most of the year, *Octactis* showed an important peak in winter (from mid November 1997 to January 1998), representing up to 60% of the assemblage. Additionally, radiolarians (fraction $>62\ \mu\text{m}$) displayed a daily average flux of $70\ \text{individuals m}^{-2}\ \text{day}^{-1}$, contributing secondarily to the opal content.

4.3.1. Diatoms

The daily flux of diatoms is expressed as the number of valves $\text{m}^{-2}\ \text{day}^{-1}$. Diatom fluxes followed the same tri-modal pattern as opal, the OC fluxes and the seasonal trend observed in foraminifers and coccolithophores.

Total diatom flux reached the highest values in spring (late May 1998) and early summer (mid–late July 1997) (5.31×10^7 and 7.3×10^7 valves $\text{m}^{-2}\ \text{day}^{-1}$), respectively, and underwent a moderate increase during December 1997 (fluxes of up to 1.4×10^7 valves $\text{m}^{-2}\ \text{day}^{-1}$) (Fig. 6a, Table 3). Minimum fluxes were recorded during August–November 1997 and January–April 1998.

Three main diatom groups were defined, based on their ecological requirements: (a) the *Chaetoceros* resting spore (RS) group as representing high

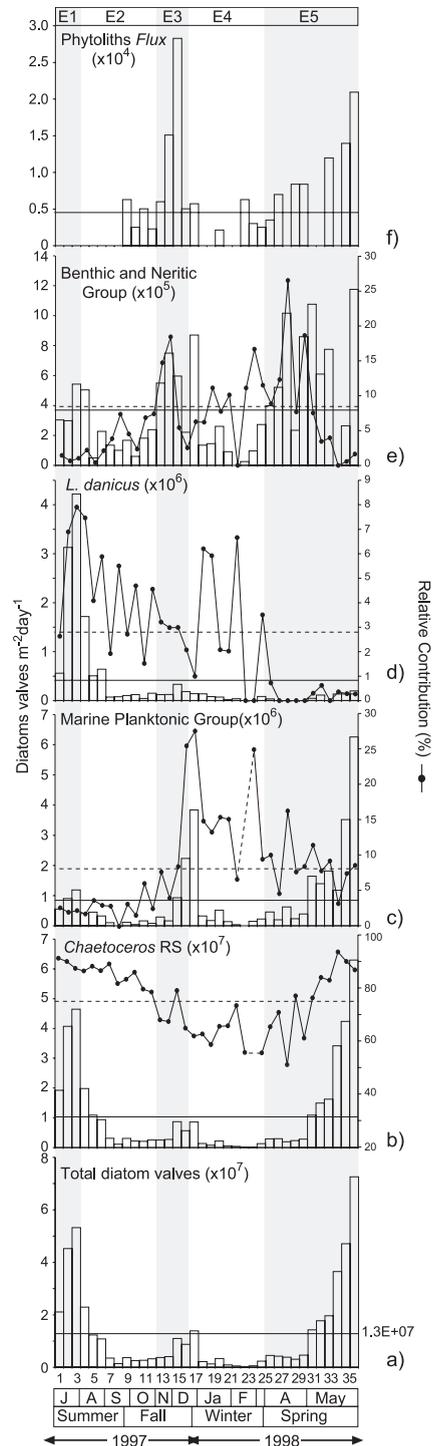


Fig. 6. Seasonal pattern of flux (bars) and relative abundance (solid lines) of the most significant group of diatoms, (a) total diatoms, (b) *Chaetoceros* RS, (c) Marine Planktonic Group, (d) *Leptocylindrus danicus*, (e) Benthic and Neritic Group, (f) Phytoliths at the mooring site in the Alboran Sea during July 1997 and May 1998. Grey vertical areas indicate the oceanographic episodes E1, E3 and E5 described in the discussion for the same time span; episodes E2 and E4 in white.

sea-surface productivity under coastal upwelling conditions, (b) the Marine Planktonic Group is a wide ecological group of diatoms, including species that dwell as planktonic forms related to moderate surface productivity (Table 3 and Taxonomic appendix), and (c) the Benthic and Neritic Group, including diatoms living attached to a substratum or those that live associated with sediments (Table 3). The species *Leptocylinthus danicus*, although not dominant, was also considered because it is the most important contributor to the sedimentary record in the Alboran Sea along the last climatic cycle, probably related to the entrance of cool waters into the Alboran Sea and water-column stratification (Bárcena et al., 2001).

Chaetoceros RS was the main component of the diatom assemblage. Its relative contribution represented more than 75% of the total, and it was more abundant during July–October 1997 and May 1998 (Fig. 6b, Table 3). In a general pattern, *Chaetoceros* RS followed a decreasing trend from July 1997 to

March 1998, increasing from April to May 1998. *Chaetoceros* RS contributed with daily fluxes of 1.3×10^7 valves $m^{-2} day^{-1}$ (average), ranging from 1.3×10^5 valves $m^{-2} day^{-1}$ in February 1998 to 6.3×10^7 valves $m^{-2} day^{-1}$ in May 1998.

The Marine Planktonic Group followed the opposite trend to that of *Chaetoceros* RS. The lowest relative contribution was observed from July to mid-December 1997 and May 1998, with values below 10%. The group had its highest relative contribution from mid-December 1997 until April 1998, with values from 10% to 28%. The mean annual relative contribution of the group was 8% of the total assemblage. The flux followed a tri-modal pattern, with maxima during late December 1997 and late May 1998 (Fig. 6c, Table 3).

The daily flux of *Leptocylinthus danicus* reached the highest value in late July–early August 1997 (up to 4.2×10^6 valves $m^{-2} day^{-1}$), accounting for 9% of the total diatom association, whereas the lowest value was observed in April–May 1998 (Fig. 6d, Table 3).

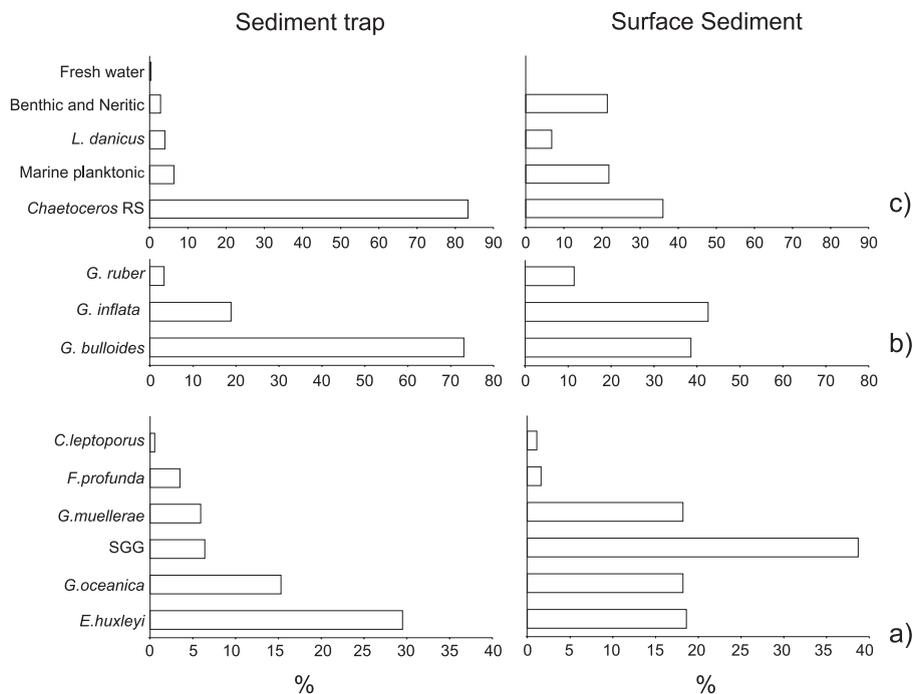


Fig. 7. Annual average distribution of the main taxa recorded during the year-round (291 days) in the sediment trap (left column), and average value of the same taxa accumulated in surface sediments at the northern edge of the WAG (right column), (a) coccolithophores, (b) foraminifers and, (c) diatoms.

The mean annual relative contribution was 3% of the total diatom assemblage recorded.

The relative contribution of the Benthic and Neritic Group was moderately high in late November 1997 and mid April 1998, minima being observed during July to October 1997 and May 1998 (8% average) (Fig. 6e, Table 3).

Freshwater diatoms were observed in the traps, but their abundance was negligible. The main contributor of fresh-water diatoms in the Alboran Sea was *Aulacoseira granulata*. The maximum flux was reached at the end of May (3.9×10^5 valves m^{-2} day $^{-1}$) (Table 3).

Tentative calculation of the year-round downwards accumulation of trapped diatoms reflected a total of 4.2×10^8 valves; *Chaetoceros* RS reached up to 83%, the Marine Planktonic Group represented 6.4%, *Leptocylindrus danicus* reached 4.0%, the Benthic and Neritic Group represented up to 2.8%, and Fresh-water diatoms were poorly represented (0.34% of the assemblage) (Fig. 7c).

4.3.2. Phytoliths

Phytoliths are silica-rods derived from the epidermal cells of grasses, introduced in the Alboran Basin by winds. The phytolith flux followed a seasonal pattern, with two main peaks: one in late November–early December 1997, reaching daily fluxes of up to

2.8×10^4 (bodies m^{-2} day $^{-1}$), and the other in mid-May 1998, with values around 2.1×10^4 (bodies m^{-2} day $^{-1}$) (Fig. 6f, Table 3).

4.4. Surface sediments: bulk composition and microfossil assemblages

The relative abundance of the main microfossil groups studied shows significant differences between the traps and core tops (Table 4). The coccolithophore assemblage was dominated by the “Small *Gephyrocapsa* Group” ($\approx 38.7\%$) and *Emiliania huxleyi* (18.6%), while *Gephyrocapsa muelleriae* (18.2%) and *Gephyrocapsa oceanica* (18.2%) were secondary components. The relative abundances of *Florisphaera profunda* and *Calcidiscus leptoporus* were negligible (1.6% and 1.1%, respectively) (Table 4, Fig. 7a).

The planktic foraminifer assemblage at the WAG had values of 47% (on average) for *Globorotalia inflata*, while *Globigerina bulloides* represented 38.6% of the total assemblage. *Globigerinoides ruber* had mean values of 10% (Table 4, Fig. 7b).

The most noteworthy differences were observed for the fossil diatom assemblage (Table 4, Fig. 7c). *Chaetoceros* RS represented up to 36%. The Marine Planktonic Group was more abundant, with relative values of up to 33.5%. *Leptocylindrus danicus*

Table 4
Relative contribution of the main groups recorded in surface sediment samples

	Samples	B-1	A-1	C-1	D-2	E-2	Average
Coccoliths	<i>E. huxley</i>	19.1	16.1	28.1	20.9	8.8	18.6
	SGG	41.6	41.4	29.1	36.6	44.8	38.7
	<i>G. muelleriae</i>	15.2	17.1	25.3	14.9	18.5	18.2
	<i>G. oceanica</i>	15.8	18.6	13.1	23.2	20.4	18.2
	<i>F. profunda</i>	4.2	2.4	0.0	0.7	1.0	1.6
	<i>C. leptoporus</i>	0.6	0.4	1.9	0.4	1.7	1.1
Forams	<i>G. inflata</i>	50.27	38.17	41.57	44.91	38.33	42.6
	<i>G. bulloides</i>	31.82	49.18	36.58	31.07	44.44	38.6
	<i>G. ruber</i>	9.09	6.09	12.59	14.62	7.5	10.0
Diatoms	Valves/g	1.8E+05	6.1E+05	7.7E+05	5.0E+05	7.3E+05	7.3E+05
	Benthic/Neritic	22.1	9.9	28.5	25.5	20.9	21.4
	<i>Chaetoceros</i> RS	27.4	57.4	23.5	29.5	42.2	36.0
	<i>L. danicus</i>	8.2	5.9	10.0	3.5	6.2	6.8
	Marine Plank. G	22.1	14.9	26.5	24.0	21.3	21.8
Windblown	FWD/g	9.1E+04	0.0E+01	0.0E+01	0.0E+01	1.4E+05	4.5E+05
	Phytoliths/g	1.8E+05	1.0E+05	1.8E+05	2.3E+05	9.1E+04	1.5E+05

represented up to 6.8% of the assemblage. The Benthic and Neritic Group represented 21.4% of the diatom assemblage in surface sediments.

Phytoliths were of nearly similar abundance as diatoms in surface sediments from the Alboran Sea, with mean values of 1.5×10^5 bodies g^{-1} . The fresh-water diatom group accounts with values of around 4.5×10^5 (Table 4). The major component of the fresh-water diatom group was *Aulacoseira granulata*.

5. Discussion

According to satellite data, meteorological information, and the data collected from the sediment traps, five oceanographic episodes governed the settling of biogenic particles in the area (Figs. 2 and 8).

E1 (July 1997), the last steps or/and the relaxation of a high productivity period were recorded at the trap position due to cold upwelling waters induced by strong favourable winds. Thus, E1 represents the beginning of the thermal stratification.

E2 (August to October 1997) represented a typical *summer non-bloom regime* with water stratification and high SST (>19.5 °C) (García-Gorriz and Carr, 2001). During October SST were unusually warm (22.5 °C), instead of the first step of the *Transition period* of 1997, it could be considered as a continuation of E2 as thermal stratification persists.

Episode 3 (E3) (November–December 1997) represented a *transition period*, with SST of around 18.5 °C, and upwelling-favourable winds inducing a low increase in chlorophyll-*a* concentration at the northern part of the western gyre (off the Spanish coast).

Episode 4 (E4) (December 1997–March 1998). The unusual fall of 1997 forced anomalous conditions during winter, which is usually characterized by a *bloom regime*. A warmer ASW entered the Alboran basin and followed the African coast, remaining in this situation until April 1998 (Vargas-Yáñez et al., 2002). The anomalous oceanographic situation forced the collapse of the gyre from January to March 1998.

Episode 5 (E5) (April to May, 1998), the gyre was fully developed in April, and gyre reestablishment together with upwelling-favourable winds induced high productivity at the mooring position during the *transition period* of April–May 1998.

5.1. Seasonal patterns of the bulk components

The recorded patterns of the bulk and various component fluxes are well correlated with the annual cycle of the described oceanographic features related to the entrance of ASW, and with the wind-induced upwelling from the northern edge of the WAG. The highest fluxes of bulk components were recorded during episodes E1, E3 and E5 (Fig. 3). Maximum export of particles occurred during E3, although Fabres et al. (2002) failed to find any direct correspondence between the temporal evolution of the local river flows and increasing fluxes of lithogenic particles at the ALB-1F and ALB-1D sediment traps. Additionally, those authors stated that the aeolian input of lithogenic material played a limited role in the total lithogenic flux into the basin. By contrast, our results reveal that aeolian input could have played an important role, at least regarding microfossil assemblage, during E3 and E5, since the highest values of wind-blown phytolith particles were recorded at times of prevailing strong westerly winds (Fig. 6) (García-Gorriz and Carr, 2001). Moreover, based on current-meter data, Fabres et al. (2002) related these episodes of high fluxes during E3 and E5 to well-marked periods of more intense eddy-like activity near the sea floor, which is supported by the highest flux of resuspended benthic diatoms at the sediment trap (Fig. 6). In this sense, Fabres et al. (2002) have observed the development of a bottom nepheloid layer related to a slope gradient break located close to the trap position. The former authors suggested that down slope transport is the principal mechanism that injects and spreads supplementary amounts of settling particles at depth.

Sedimentation of biogenic particles also reached three maxima in episodes E1, E3 and E5, although the E3 peak is displaced towards the end of the episode (Fig. 3). Since the flux of planktic foraminifers was low during E2 (Figs. 5 and 8), coccolithophores must have been responsible for the moderate values of calcium carbonate observed (Figs. 4 and 8). Likewise, the parallel trend of the fluxes of opal and diatoms leads us to infer that diatoms were the main contributors to the biogenic silica flux (Fig. 6).

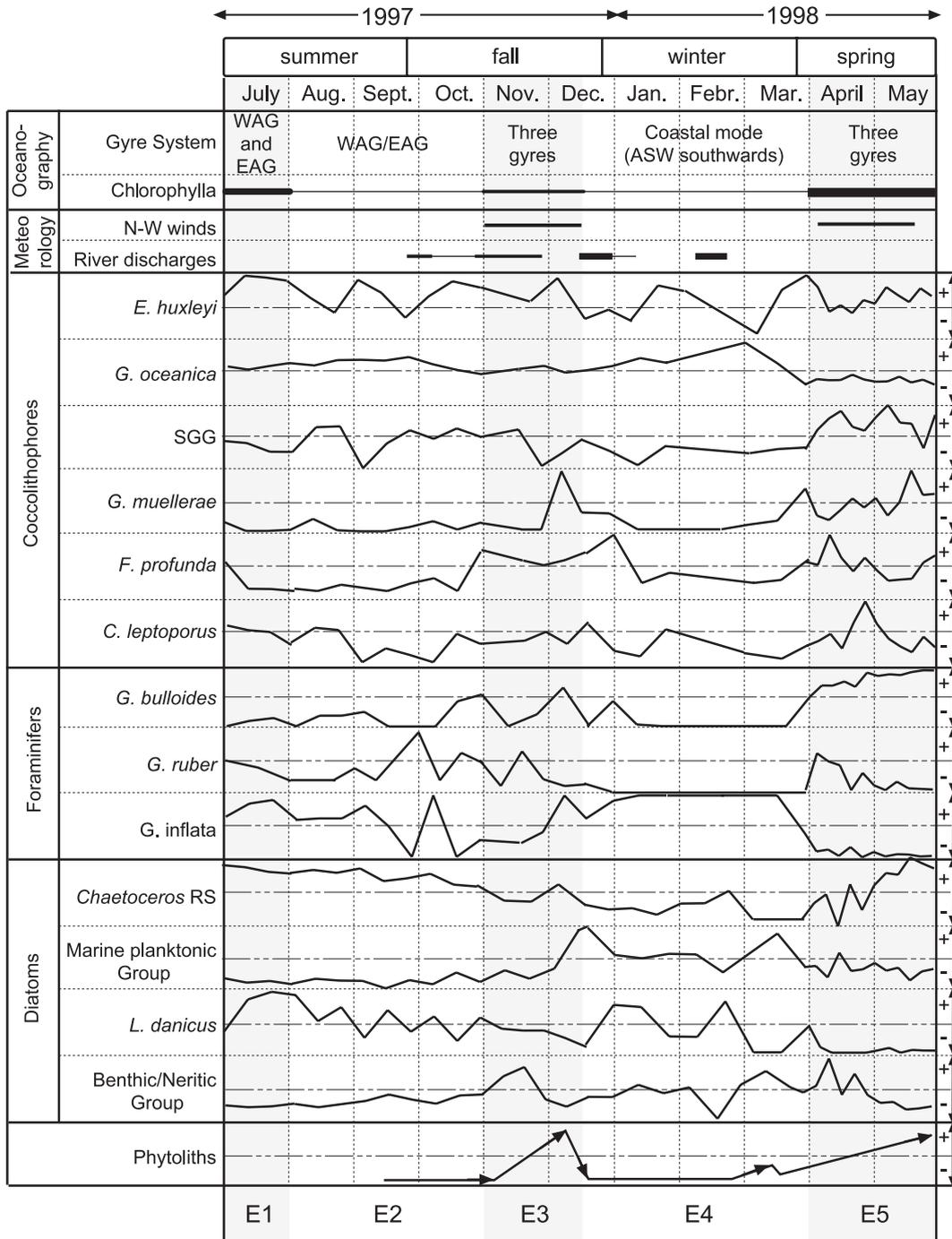


Fig. 8. Diagrammatic representation of the main oceanographic and meteorological features, situation of the Gyre, chlorophyll-*a* concentration, wind and river discharges, as well as the main seasonal pattern evolution of the different planktonic groups or/and species analyzed in this work. Grey vertical areas indicate the oceanographic episodes E1, E3 and E5 described in the discussion for the same time span; episodes E2 and E4 in white.

5.2. Seasonal patterns of calcium carbonate and siliceous microfossil assemblages

5.2.1. Coccolithophores

Previous studies on living Mediterranean coccolithophorids have suggested that only a few species, such as *Emiliania huxleyi*, “Small *Gephyrocapsa* Group”, *Gephyrocapsa oceanica*, *Florisphaera profunda*, were dominant in the water column, while *Gephyrocapsa muelleriae* and *Calcidiscus leptoporus* were less abundant (Knappertsbusch, 1993). This latter author also recognized that the coccolithophore assemblage changed dramatically from summer to winter and from the eastern to the western Mediterranean. While the calcareous flora showed a patchy distribution during the summer, the distribution of species in winter displayed a consistent pattern from west to east: *E. huxleyi* was dominant in the eastern assemblage (abundance values are double in this region), while the “Small *Gephyrocapsa* Group” and *G. oceanica* occurred mainly in the Western Mediterranean. On the other hand, *F. profunda*, a typical deep dwelling species from the lower photic zone (LPZ), showed a rather patchy distribution throughout the Mediterranean (Knappertsbusch, 1993).

Our results reveal that *Emiliania huxleyi* was the dominant species in the assemblage (Figs. 4 and 8). The species did not show significant seasonal differences throughout the year, but increased from pre-bloom to bloom conditions, with peaks during March and October, immediately before the higher productive periods E3 and E5 (Figs. 4 and 8). This pattern agrees with the ecological requirements reported by several authors, who consider *E. huxleyi* as an opportunistic species (Knappertsbusch, 1993; Girardeau and Bailey, 1995; Broerse et al., 2000). Our data clearly show that *E. huxleyi* rapidly responds to nutrient enrichment in surface waters, as previously observed by Knappertsbusch (1993).

The seasonal distribution of *Gephyrocapsa oceanica*, which increased in episodes E2 and E4, is opposite to that observed for *Emiliania huxleyi*, suggesting a close relationship with the oceanographic evolution of the ASW jet (Figs. 4 and 8). In contrast, the flux of *G. oceanica* decreased when wind-induced upwelling became more intense in the Alboran Sea (E3 and E5). According to Knappertsbusch (1993), *G. oceanica* is an allochthonous species transported and

introduced into the Alboran Sea by the ASW current. Although little information is available about the ecology of this species, most authors agree on its close relationship with high productivity conditions (Girardeau, 1992; Broerse et al., 2000; Ziveri et al., 1995). While for Broerse et al. (2000) this species exhibits an opportunistic behaviour similar to that of *E. huxleyi*, and therefore both species are good proxies for upwelling conditions, Ziveri et al. (1995) reported that temperature may also play a role in the distribution of the species. Taking into account our results, as well as the previous considerations of Knappertsbusch (1993), we interpret this species as a good ASW tracer for the Alboran Sea, and hence it could be used as a tool for paleoceanographic reconstruction, but not as proxy for upwelling conditions in this region.

“Small *Gephyrocapsa* Group”, *Gephyrocapsa muelleriae* and *Calcidiscus leptoporus* showed high values during E1, E3 and E5 (Figs. 4 and 8). According to our results, the “Small *Gephyrocapsa* Group” shows the opposite trend to that of *Gephyrocapsa oceanica*, since that group increased when *G. oceanica* decreased (E5). As well as *G. oceanica*, Knappertsbusch (1993) also considered “Small *Gephyrocapsa* Group” as being transported by the ASW jet into the Mediterranean. Nevertheless, taking into account our own data, we consider that, at least in the Alboran Sea, species respond to high nutrient concentrations rather than to the ASW.

Gephyrocapsa muelleriae and *Calcidiscus leptoporus* increased during E3 and E5, in clear response to nutrient-rich waters during the wind-induced upwelling (Figs. 4 and 8). Several authors have considered these taxa as indicators of cold water and/or waters of moderate to high productivity (Ziveri et al., 1995; Colmenero-Hidalgo et al., 2004), in agreement with our data.

Florisphaera profunda requires special consideration. This species dwells at the lower photic zone (LPZ) and, from a paleoceanographic point of view its abundance in fossil sediments has been used as a good proxy for water stratification and/or oligotrophic conditions (Molfini and McIntyre, 1990). Knappertsbusch (1993) found a patchy distribution of this species in the water column, although it was one of the two most abundant species in surface sediments. According to our data, *F. profunda* shows minima

during water stratification (E2 and E4) and maxima during high productivity periods (E3 and E5) (Figs. 4 and 8). Two prominent peaks were observed just before and after episode E3 (Figs. 4 and 8), coinciding with times of maximum rainfall and river discharge. The resulting high water turbidity, which is also reflected by high values of benthic diatoms (Fig. 6), may have favoured the proliferation of *F. profunda*. Higher records of this species were also obtained in April and May, when the gyre was totally developed and upwelling-favourable winds induced high productivity. However, both the flux and relative contribution of *F. profunda* also parallel the benthic diatom values (Figs. 4 and 6). An equivalent situation was also observed for the Arabian Sea by Ahagon et al. (1993) and Broerse et al. (2000). These authors explained the relative success of deep-living coccolithophores as a result of the unfavourable conditions created in the upper photic zone due to high wind speeds and strong turbulence.

5.2.2. Planktonic foraminifers

The seasonal evolution of planktic foraminifers also responds to the annual evolution of oceanographic regimes (Figs. 5 and 8). *Globigerina bulloides*, which is the main component of the assemblage, follows a trend very similar to that found for the total abundance of foraminifera. The highest fluxes of this species were recorded during E5, when upwelling conditions were more intense in the region, in agreement with previous data from the Alboran Sea, indicating that this species dwells preferentially below the thermocline at the end of spring and early summer, even after the onset of summer stratification (Cifelli, 1974; Pujol and Vergnaud-Grazzini, 1995). The secondary peak recorded during E3 (Figs. 5 and 8) also reflects the response to wind-induced upwelling and an unstratified water-column marked by high pigment concentration, as deduced from satellite imagery (García-Gorrioz and Carr, 2001; Vargas-Yáñez et al., 2002). All this demonstrates that *G. bulloides* is well adapted to high food availability.

The fluxes of other significant species of the assemblage, such as *Globorotalia inflata* and *Globigerinoides ruber*, also peak during E1, E3 and E5 characterized by high productivity in surface waters, however, their relative contribution is high during E1, E2 and E4, when the production of *Globigerina*

bulloides is low. Although the three species increase in abundance as food becomes available for plankton consumption, it seems that *G. bulloides* reproduces faster than *G. inflata* and *G. ruber*, which proliferate under conditions of low fertility. In this sense, Giraudeau (1993) assesses that *G. inflata* is deep-living planktonic foraminifera and reflects oligotrophic and reduced upwelling conditions. During E2, the warmer SST associated with El Niño Event caused water stratification that favours the development of the warm and oligotrophic assemblage, represented by *G. ruber* (Figs. 5 and 8). The high relative abundance of *G. inflata* during E4 is related to the collapse of the gyre caused by an ASW jet warmer than Alboran waters. During winter, sea surface stability allowed the development of *G. inflata* in the area, but the SST was not warm enough to allow the development of *G. ruber* (Fig. 5). Previous data from investigations on plankton in the Alboran Sea have shown that *G. inflata* is present throughout the year, but only in winter and spring does it become a dominant species (Cifelli, 1974; Pujol and Vergnaud-Grazzini, 1995); this agrees only partially with our observations as the development of *G. bulloides*, due to the surface water instability created by westerly winds during April–May, diminished the relative abundance of *G. inflata*.

According to Cifelli (1974) and Pujol and Vergnaud-Grazzini (1995), *Globigerinoides ruber* appears at the end of the summer, related to the southern edge of the WAG close to the north-African coast; here the species may reach up to 80% of the planktonic assemblage. Our data agree with the above investigations, but due to the exceptionally high SSTs observed during the first part of the fall of 1997, *G. ruber* was still abundant at that time of the year (October, 1997).

5.2.3. Diatoms and phytoliths

Qualitative variations in the diatom assemblage also reflect oceanographic changes in the water column. The daily diatom flux followed the same trend as the opal fraction, with maximum values during E1, end of E3 and the second half of E5 (Fig. 6). This tri-modal pattern is similar to that previously described for the rest of the planktonic community. The most remarkable feature was the decreasing trend of the relative contribution of *Chaetoceros* RS

from E1 to E4, while it increased again during E5 (Figs. 6 and 8). The relative variation in *Chaetoceros* RS may have been governed by changing rates of opal preservation at the uppermost part of the water column during periods of lower surface productivity: late E1, E2 and E4. During low productive periods, diatom production at the photic zone is lowered, and diatoms may be dissolved in the upper part of the water column; thus, only highly silicified diatoms would be trapped and preserved. On the other hand, the high values of *Chaetoceros* RS during E3 and E5 reflect a clear response to the oceanographic regime. The Marine Planktonic Group was present throughout the year, its highest daily fluxes followed the tri-modal pattern, but in terms of relative contribution the group seems to have had a preference for conditions of moderate productivity during E3 and the water column stability observed during E4 (Figs. 6 and 8).

The highest value of *Leptocylindrus danicus* recorded at the end of E1 agrees with upwelling relaxation and the beginning of stratification, which continued during E2 (Figs. 6 and 8). Nutrient depletion after E3 resulted in an increase in *L. danicus* that continued during E4 with a collapsed gyre and partial water stratification due to the exceptionally warm ASW coming into the basin. In agreement with our data, plankton observations have revealed that *L. danicus* increases during upwelling relaxation and its spore production is related to nutrient depletion (Varela et al., 2003). Moreover, the observation of plankton in the Alboran Sea points to increases in *L. danicus* during January (Delgado, 1990). Hobson and McQuoid (1997) related the species to the stratified phase of a turbulent environment.

The record of benthic and neritic diatoms must be linked to the activity of bottom currents along the shelf rather than sea surface oceanography. The highest values of the group recorded during E3 and beginning of E5 could be related to the well-marked periods of more intense eddy-like activity near the bottom recorded by Fabres et al. (2002). On the other hand, rainfall events had no impact either on the diatom assemblage or on other components of the sediment recovered in the trap.

A clear correspondence between maximum phytolith fluxes in the traps and high wind intensities

was found. Intense westerly winds were recorded during episodes E3 and E5 (García-Gorriz and Carr, 1999, 2001; Vargas-Yáñez et al., 2002; Fabres et al., 2002). Thus, the maximum abundance of these wind-transported bodies was recorded during the same time interval, while no phytoliths were trapped in summer.

5.3. Trap versus sediments: implications for paleoreconstructions

According to our data, the plankton distribution in surface sediments agrees with the sea surface productivity detected by satellite imagery and the paleoproductivity based on the organic component signal recorded in surface sediments (Table 4). Nevertheless, some discrepancies may be observed. This fact might have been caused by several factors: (a) difference in time scale, since surface sediments represent an integrated signal of several hundred years; (b) lateral advection or resuspension processes; (c) preservation effect; (d) or anomalous oceanographic year as deduced by the influence of 1997–1998 El Niño Event.

The coccolithophore assemblages found in surface sediments are quite different from those trapped during the year-round period studied. *Emiliania huxleyi* and *Gephyrocapsa oceanica*, which were the major components in the sediment traps, were replaced by the “Small *Gephyrocapsa* Group” in surface sediments, although no evidence of dissolution was observed. Similar results were obtained for Holocene times by Colmenero-Hidalgo et al. (2004), which in clear agreement with our observations in surface sediments stated that the Group responds to SST variations and its populations could be strongly diminished with temperatures below 16 °C. Knappertsbusch (1993) considers this group as being transported by the ASW jet into the Mediterranean, although in light of our data derived from sediment traps, the species could also respond to high nutrient concentrations. *Gephyrocapsa muelleri* was also a secondary contributor to the coccolithophore assemblage in the sediment traps, but its contribution in surface sediments was threefold higher (18% of the fossil assemblage). This species has also been related to cold and nutrient-rich surface waters associated with upwelling (Ziveri et al., 1995). *Gephyrocapsa*

oceanica does not represent substantial changes in relative abundance between year-round downward fluxes and surface sediments at the northern edge of the WAG studied. The species has been reported by Giraudeau (1992) as having a preference for fertile waters and is dominant in shallow sediments in the Northern Benguela system. The external factors that forced the unusual year detected by satellite imagery (García-Gorrioz and Carr, 2001; Vargas-Yáñez et al., 2002), probably related to the strong 1997–1998 El Niño Event (McPhaden, 1999), could have induced changes in the coccolithophore assemblage; thus *E. huxleyi* became the dominant species, and the contribution of the “Small *Gephyrocapsa* Group” was dramatically decreased, while the integrated signal recorded in surface sediments revealed a coccolithophore assemblage dominated by the “Small *Gephyrocapsa* Group”, rarely recorded in the sediment traps.

The foraminiferal distribution in surface sediments indicates the co-dominance of two species—*Globigerina bulloides* and *Globorotalia inflata* (38.6% and 42.6%, respectively)—in clear discrepancy with that observed during the time period controlled with the sediment trap, when *G. bulloides* was the main contributor to the annual foraminiferal assemblage (73%). *Globorotalia inflata* was present throughout the year and responded to the stability of the water column and low nutritional needs, while *G. bulloides* mainly responded to the high nutrient concentrations during the wind-induced upwelling recorded in the spring. Since no calcite dissolution indications were observed, the integrated signal of surface sediments suggests that the spring of 1998 was exceptionally productive in terms of *G. bulloides* and/or that 1997–1998 was exceptionally unproductive in terms of *G. inflata*. In this sense, the 1997–1998 El Niño Event could force an unusual seasonality in the Alboran Sea giving an exceptional micropaleontological signal, not reflected in surface sediments.

With regard to diatoms, the same explanation can be given for the discrepancies observed between sediment trap and surface sediments. Surface sediment samples within the northern edge of the WAG also indicated a higher productivity, in agreement with the annual primary production derived from SeaWiFS images. Nevertheless, the year-round dominance in *Chaetoceros* RS reflects an unusual contribution of

the species to the diatom assemblage, more than twofold higher than in surface sediments. On the other hand, the Marine Planktonic Group was better represented in surface sediments than after the 1997–1998 year-round record, being nearly three times higher and indicating unusual oceanographic conditions during the time period considered. The relative contribution of *Leptocylinthus danicus*, related to low nutrients and surface water stratification (Hobson and McQuoid, 1997; Varela et al., 2003), was also more abundant in surface sediments. The high values obtained for the Benthic and Neritic Group in surface sediments, could reflect stronger bottom water activity, with eddy-like structures near the bottom of the shelf, but this could also be due to higher input of transported sediment at the floor than in the trap, in agreement with Masqué et al. (2003) who assessed that the advection and redistribution of sediments occur below 30 m above the bottom in the northern part of the WAG.

The differences among biogenic assemblages recorded in the sediment traps and those found in surface sediments must be considered with caution since the time span recovered by the traps was an unusual year probably related to the strong 1997–1998 El Niño Event (McPhaden, 1999). As discussed before, if no external signal of dissolution affects the microfossil assemblages information derived from surface sediment would reflect the integrated signal of normal years, not affected by external processes, but would also be influenced by bottom sedimentary transport processes.

6. Summary and conclusions

In this study we have analysed a year-round time series of particle flux collected between July 1997 and May 1998 in the WAG of the Alboran Sea (western Mediterranean), as well as surface sediment samples, in order to evaluate the seasonal signal of the oceanographic changes and the integrated record left in the surface bottom sediments that allow us to identify proxies for long time series. The parameters analysed were, Total mass, Carbonate, OC and Opal content, and the micropaleontological groups, calcareous nannoplankton, planktic foraminifera, diatoms and phytoliths.

Based on satellite and meteorological information, intra-annual variations in oceanographic conditions occurred from July 1997 to June 1998 in the Alboran Sea can be divided into five episodes, E1 to E5. Anomalous high SST's were recorded during E2 as well as the entrance of a warm ASW during E3 that could be related to the 1997–1998 El Niño Event.

The pattern of main constituent and organism fluxes correlates with the oceanographic regimes. Plankton communities respond to changes in the dominant hydrographic conditions. *Emiliania huxleyi* dominates the coccolithophore assemblages, having a rapid response to nutrient enrichment. *Gephyrocapsa oceanica* seems to be coupled with the evolution of ASW in the Alboran Sea or related to surface water stability. The “Small *Gephyrocapsa* Group”, *Gephyrocapsa muelleriae* and *Calcidiscus leptoporus* respond to nutrient-rich waters during periods of wind-induced upwelling. *Florisphaera profunda* responds to unfavourable conditions in the upper photic zone, the water column instability generated by turbulence, and/or water turbidity.

The seasonal evolution of the planktonic foraminifer assemblage follows the same trend as the oceanographic regime. *Globigerina bulloides* is the main component of the annual planktic foraminifer assemblage but has a living preference of high food availability. *Globorotalia inflata* and *Globigerinoides ruber* proliferate under low fertility conditions. *Globigerinoides ruber*, a summer species in the Alboran Sea, increased during fall 1997 due to the exceptionally high SST induced by El Niño Event.

The diatom population reflects oceanographic changes in the water column. *Chaetoceros* RS responds to high productivity conditions and showed a decreasing trend depending on the water column stratification. Its high abundance could also have been a response to opal preservation in the photic zone. The Marine Planktonic Group prefers moderate wind-induced upwelling conditions. *Leptocylinndrus danicus* is confirmed as a species that produces its sexual spore during the last phase of an upwelling period, indicating nutrient depletion and water stratification. Benthic and Neritic diatoms were related to eddy activity at the sea floor.

Phytolith fluxes in the Alboran Sea are directly related to wind intensities and the prevailing westerly winds of 1997 fall and 1998 spring.

The micropaleontological groups analysed in surface sediments were inconsistent with those observed in the sediment traps. The data show that the studied period was unusual in surface water productivity. 1997–1998 was affected by a strong El Niño Event that caused anomalies in the Alboran Sea. The monitoring year was usually high in those taxa related to high nutrient content, *Emiliania huxleyi*, *Globigerina bulloides* and *Chaetoceros* RS, while in surface sediments they were less represented. On the other hand, 1997–1998 was an unproductive year in terms of SSG, *Gephyrocapsa muelleriae*, *Globorotalia inflata*, Marine Planktonic diatoms and *Leptocylinndrus danicus*, which were well represented in surface sediments. In agreement with what is suggested by satellite images, input between the trap and the bottom may have a different micropaleontological signature than the one recorded by the trap due to a higher influence from resuspension from shallower areas.

Thus, the “Small *Gephyrocapsa* Group”, *Globorotalia inflata*, and *Chaetoceros* RS were the main planktonic groups, in agreement with the reports of other authors, and reflected the main oceanographic patterns described for the northern edge of the WAG.

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Appendix A. Taxonomic appendix

The taxonomic list includes all taxa referred in the text, as well as the main taxa identified during the present study. The taxa were grouped as a function of their ecological significance as described in the text.

Calcareous nannoplankton. The references can be found in Jordan and Kleijne (1994).

Emiliana huxleyi Lohman 1902
Gephyrocapsa oceanica Kamptner 1943
Gephyrocapsa ericsonii McIntyre and Bé 1967
Gephyrocapsa aperta Kamptner, 1963
Gephyrocapsa muelleriae Bréhéret, 1978
Florisphaera profunda Okada and Honjo, 1973
Calcidiscus leptoporus Murray and Blackman, 1898

Planktonic foraminifera: References can be found in Hemleben et al., (1988).

Globigerina bulloides (d'Orbigny, 1826)
Globorotalia inflata (d'Orbigny, 1839)
Globigerinoides ruber (d'Orbigny, 1839)

Diatoms: The cited references can be found in Round et al. (1990).

Marine Planktonic Group

Azpeitia nodulifera (Schmidt) Fryxell and Sims 1986
Coscinodiscus marginatus Ehrenberg 1841
C. radiatus Ehrenberg 1840
Nitzschia bicapitata Cleve 1901
Rhizosolenia spp. (Ehrenberg) Brightwell 1858
Thalassionema nitzschioides (Grunow) Grunow 1881
Thalassiosira eccentrica (Ehrenberg) Cleve 1903–1904
Thalassiosira lineata Jousé 1968
Thalassiosira oestrupii (Ostenfeld) Hasle, 1972
Thalassiothrix longissima Cleve and Grunow 1880

Chaetoceros (Ehrenberg 1844), traditionally have been related to coastal upwelling.

Chaetoceros-spores (RS). Spores of all *Chaetoceros* taxa were grouped together.

Leptocylindrus danicus Cleve 1889, a coastal species that indicates the last steps of an upwelling

event, and could be related to water-column stratification.

Benthic and Neritic Group

Actinocyclus octonarius Ehrenberg 1861
Actinoptychus senarius (Ehrenberg) Ehrenberg 1843
Achnantes brevipes Agardh 1824
Cocconeis spp. Ehrenberg 1837
Diploneis smithii (Brébisson) Cleve 1894
Gomphonema spp. Agardh 1824
Trachyneis aspera (Ehrenberg) Cleve 1894
Paralia sulcata (Ehrenberg) Cleve 1873

Fresh-water Group

Aulacoseira granulata (Ehrenberg) Thwaites 1848

Silicoflagellates

Octactis pulchra Schiller 1925
Dictyocha spp. Ehrenberg 1839

Dinoflagelates

Actiniscus pentasterias Ehrenberg 1843

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