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CAPÍTOL 3

PARTICLE FLUXES AND ORGANIC CARBON BALANCE ACROSS THE EASTERN ALBORAN SEA (SW MEDITERRANEAN SEA)

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Continental Shelf Research (In press)
Received 7 October 2003; Revised 27 July 2004

0278-4343/$

ABSTRACT

As part of the “Mediterranean Targeted Project II - MAss Transfer and Ecosystem Response” (MTPII-MATER) EU-funded research project, particle flux data was obtained from three instrumented arrays moored along the 1º30’ W meridian in the Eastern Alboran Sea. The mooring lines were deployed over 11 months, from July 1997 to May 1998, and were equipped with sediment trap-current meter pairs at 500-700 m, 1000-1200 m and 2000-2200 m of water depth. The settling material was analysed to obtain total mass, lithogenic, calcium carbonate, organic carbon and opal fluxes.

Integrated analysis of sediment trap and current meter data with sea-surface satellite images reveals that particle flux distribution is a function of primary production, mid-water lateral advection and near bottom nepheloid input. The spreading to the east and to the south of phytoplankton-rich water from the upwelling off the Spanish coast is controlled by the position and size of the Western and Eastern Alboran gyres, and drives the seasonal arrival of biogenic material down to the sea floor. Discrete lateral advection events unrelated to vertical entries of material can also supply particulate matter at 1000-1200 m and 2000-2200 m of water depth as noted at the northern and southern stations.

To achieve a better understanding of the carbon cycle in the area we have attempted to constrain the production, transfer and burial of particulate organic carbon, providing the first estimates of particulate organic carbon export in the Alboran Sea. Results suggest that sea surface circulation and associated productivity signal control the efficiency of the biological pump in the area. The export production in the Eastern Alboran Sea is higher than in other Mediterranean sites, with 0.5-0.9% of the carbon fixed during photosynthesis transferred down the water column and buried in the deep sediments. In addition, a large portion is supplied by lateral advection and through a benthic nepheloid layer, which represent a significant source of organic carbon to the deep Eastern Alboran Sea.

Keywords: Particulate flux; Organic carbon; Export production; Alboran Sea; Almeria-Oran Front.

3.1. INTRODUCTION

It is well known that hydrodynamical singularities and physical processes in the upper ocean influence growth rates and population dynamics of the phytoplankton communities. Upwelling, jets and gyres may supply new nutrients to the euphotic zone due to water vertical motion leading to phytoplankton blooming and determining the distributions of primary production in broad temporal and spatial scales. These phenomena are observed in the Alboran Sea, a dynamic area of the Western Mediterranean characterised by the entrance of an Atlantic water jet that forms two almost permanent anticyclonic gyres, the Western and the Eastern Alboran Gyres (WAG and EAG), and the geostrophic Almeria-Oran Front (AOF) located at the eastern boundary of the EAG (Tintore et al., 1988). Several studies on interactions between physical and biological processes have revealed high fertility and enhanced production at the coastal upwelling along the northern edge of the WAG (Packard et al., 1988; Minas and Coste, 1991; Garcia-Gorriz and Carr, 1999, 2001; Ruiz et al., 2001) and through the AOF (Lohrenz et al., 1988; Arnone et al., 1990; Raimbault et al., 1993; Claustre et al., 1994; Fiala et al., 1994; Videau et al., 1994; Zakardjian and Prieur, 1998, Fielding et al., 2001). In this context, the study of particle fluxes in the Alboran Sea has provided important insights into the influence of these hydrological structures in the amount and character of the settling material. Fabres et al. (2002) and Fabres et al. (submitted) described enhanced biogenic particle fluxes linked to upwelling and development of small eddies on the edge of WAG from two mooring lines deployed in the Western Alboran Sea. Also, Sanchez-Vidal et al. (2004) suggested the influence of the southern Spanish coast upwelling in the downward particle flux from one single mooring line deployed in the central Eastern Alboran Sea.

In this contribution we present the results from a year-round particle flux and deep currents monitoring experiment along a North-South transect (1º30' W) in the Eastern Alboran Sea. Lithogenic, calcium carbonate, organic carbon and opal fluxes obtained from three mooring lines are reported and related to physical and biological forcing. Primary production, organic carbon fluxes and accumulation rates in bottom sediments are also used to construct the first vertical organic carbon balance in this key area at the transition between the Atlantic Ocean and the Mediterranean Sea.

3.2. METHODS

3.2.1. Mooring description and sample collection

Three mooring lines, ALB3, ALB4 and ALB5, were deployed from July 1997 to May 1998 in the deep easternmost Alboran Sea following a north-south transect along the 1º30' W meridian (Fig. 3.1, Table 3.1). ALB3 was deployed at 2260 m of water depth into the axis of the Gata Canyon lower course, ALB4 at 2240 m of water depth in the Oran rise, and ALB5 at 2100 m of water depth on the foot of the North African continental slope.

Each mooring line was equipped with three Technicap PPS3 sediment trap-Aanderaa RCM 7/8 current meter pairs at 500-700 m depth (upper trap, U), 1000-1200 m depth (middle trap, M), and 30 m above bottom (lower trap, L) (Table 3.1). Samples were collected over 11 months divided into three successive deployments: periods (I) July 1st 1997-October 31st 1997, (II) November 15th 1997-March 10th 1998, and (III) April 1st 1998-May 22nd 1998. Sampling intervals were 10-11 days except for April 11th to May 16th 1998 when sampling was performed at 3-day intervals, which have been averaged over 9-day intervals to get a similar resolution for the entire sampling period.

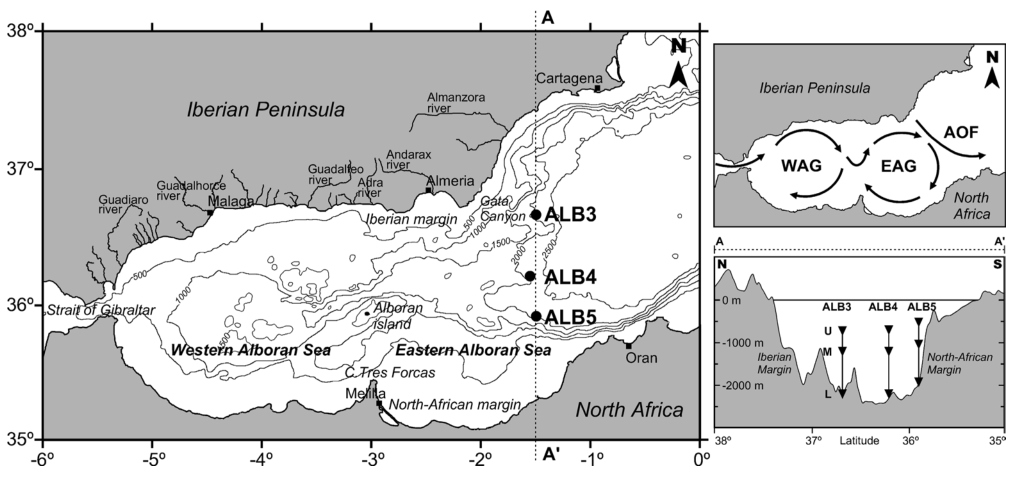

Figure 3.1. Bathymetric map of the Alboran Sea with the location of ALB3, ALB4 and ALB5 mooring lines. Countours are every 500 m. A sketch of the surface circulation pattern is shown in the upper right box. WAG: Western Alboran Gyre; EAG: Eastern Alboran Gyre; AOF: Almeria-Oran Front. Cross-section view A-A' along the 1º 30' W meridian with the location of the mooring lines is shown in the lower right box (U: upper level, M: middle level, L: lower level).

Traps are designated from station name and level, i.e. ALB3-U refers to the upper trap of station ALB3. The same procedure has been applied to designate the current meters. A total of 36 samples representing 291 days were recovered from each trap except the ALB4-L trap where only 24 samples representing 123 days (periods II and III) were obtained. The accidental collapse of a glass buoy above ALB3-L during period I hindered exact determination of total mass flux, thus fluxes are probably overestimated. Also, problems during carbon analyses caused a lack of organic carbon and calcium carbonate data for the samples corresponding to the period III in ALB3-M. The design of PPS3 traps (0.125 m^2, cylindroconical shape), its preparation and maintenance, and the assemblage of the mooring lines are described in Heussner et al. (1990).

Table 3.1. Summary data on the Almeria-Oran Front moored arrays including location, seafloor depth, and water depth of sediment traps in each of the moorings (upper U; middle M, and lower L).

Mooring line	Latitude	Longitude	Seafloor depth	Trap levels	Trap depths
ALB3	36° 40.49' N	1° 30.60' W	2260 m	**ALB3-U**	680 m
				ALB3-M	1190 m
				ALB3-L	2230 m
ALB4	36° 13.06' N	1° 33.53' W	2240 m	**ALB4-U**	645 m
				ALB4-M	1170 m
				ALB4-L	2210 m
ALB5	35° 55.47' N	1° 30.77' W	2100 m	**ALB5-U**	510 m
				ALB5-M	1050 m
				ALB5-L	2070 m

Current meters recorded current speed and direction with an hourly frequency during the three deployment periods. Recording of current direction failed during period II at the three depths of the ALB4 mooring line, and during period III at the upper traps of ALB3 and ALB5 and middle trap of ALB4.

3.2.2. Sample treatment and analytical procedures

Sediment trap samples were processed in the laboratory according to the procedure described by Heussner et al. (1990). Large swimming organisms were removed by wet sieving through a 1 mm nylon mesh, while organisms <1mm were hand-picked under a microscope with fine-tweezers. Samples were (i) repeatedly split into aliquots using a high precision peristaltic pump robot to obtain 10-20 mg sub-samples, (ii) filtered through glass-fibre prefilters for carbon and nitrogen analysis and 0.45 μm pore size cellulose membranes for total mass determination and biogenic Si analysis, (iii) rinsed with distilled water and, finally, (iv) dried at 40ºC during 24 h for dry weight determination. The precision of mass estimates, as measured by the coefficient of variation, was 4.1% (Heussner et al., 1990).

Total and organic carbon, and total and organic nitrogen were measured with a Fisons 1500 elemental analyser. Samples for organic carbon analysis were first decarbonatated using repeated additions of 100 μl 25% HCl with 60ºC drying steps in between until no effervescence was observed. Calcium carbonate content was calculated as (%total carbon-%organic carbon)*8.33, assuming that all the inorganic carbon is contained within the calcium carbonate fraction. Carbon measurements were tested against the certified sediment MESS-1 of the Canadian National Research Council. Analytical precision of the measurement of carbon in the sediment sample was 2.9% (n=24), which lay within the 95% confidence limits. The overall precision of carbon measurements in filtered sediment trap samples was 5.8%.

Biogenic Si was analysed using a two-step extraction with 0.5M Na_2CO_3 (2.5 hours each) separated after filtration of the leachate. Inductive Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) was used to analyse Si and Al contents in the leachates, and a correction of the Si of the first leachate by the Si/Al relation of the second leachate was applied to obtain the opaline Si concentration. Corrected Si concentrations were transformed to opal after multiplying by a factor of 2.4 (Mortlock and Froelich, 1989). Analytical precision of opal measurements was 4.5%.

The lithogenic fraction was calculated assuming %lithogenics = 100-(%organic matter, taken as twice the organic carbon+%calcium carbonate+%opal).

3.3. RESULTS

3.3.1. Atmospheric and oceanographic conditions

Climatic and hydrographic data have been collected from various sources during the 1997-1998 monitoring period. Daily E-W wind speed and frequency of westerlies data from the Almeria meteorological station, provided by the Spanish "Instituto Nacional de Meteorología", depict 5 main westerly pulses in June-July 1997, November 1997, December 1997 and April 1998 (Fig. 3.2).

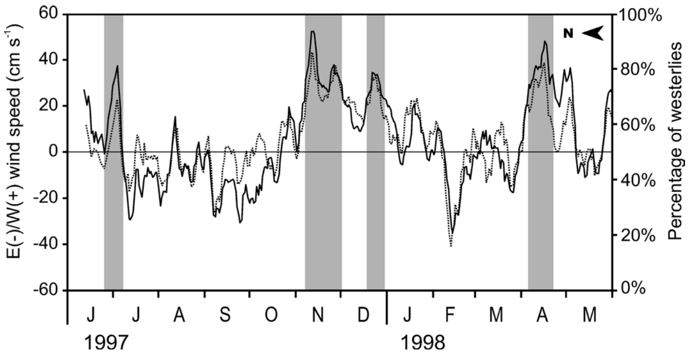

Figure 3.2. Wind data from the Almeria meteorological Station (36º 50'N, 02º 23'W) showing the maximum daily wind speed moving average (period 10 days) (solid line) and the percentage of westerlies (dotted line). Vertical shaded bars underline periods of westerlies intensification.

Reverse winds prevailed during few time intervals, with a pronounced peak in February 1998. As reported by Sarhan et al. (2000) when westerlies blow upwelling of cool subsurface waters off the southern Spanish coast fertilizes this zone. In addition, chlorophyll-a and sea surface temperature maps suggest a southeastward transfer of the fertilized waters by the Atlantic jet (La Violette, 1984; Minas and Coste, 1991; Baldacci et al., 2001; Garcia-Gorriz and Carr, 2001). Four events of increased chlorophyll-a have been tracked from June 1997 to May 1998 (Fig. 3.3) according to the satellite images covering the entire sampling interval.

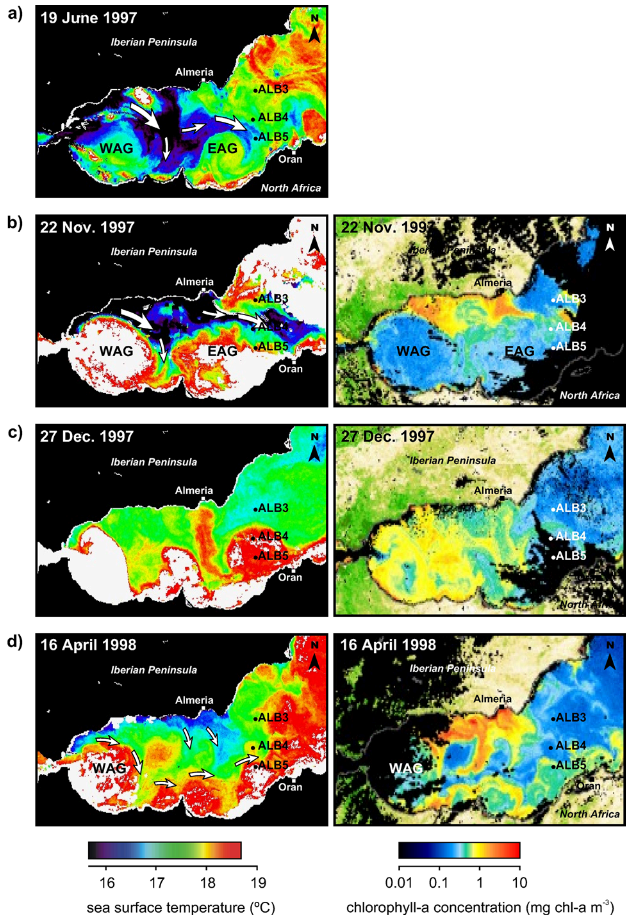

Figure 3.3. Sea Surface Temperature (AVHRR, left) and chlorophyll-a concentration (SeaWiFS, right) images illustrating the four high productive events that occurred during the particle flux monitoring experiment in the Alboran Sea: a) June 1997, b) November 1997, c) December 1997 and d) April 1998. SeaWiFS was not in operation yet in June 1997. Arrows show the spreading of the fertilised waters to the east and the south, as described in Sanchez-Vidal et al. (2004). SST images are obtained from the Intelligent Satellite Data Information System (ISIS) of the Deutschen Zentrum für Luft- und Raumfahrt (DLR); chlorophyll-a concentration images are obtained through the website of the Marine Environment Unit of the Space Applications Institute (Joint Research Centre, European Comission) (Melin, 2000).

Three of them (June 1997, November 1997 and April 1998) were upwelling events leading to the development of a nutrient-rich jet, that spread the fertilised upwelled waters to the east and to the south controlled by the position and development of the Western and Eastern Alboran gyres. The fourth event corresponded to a rather uniform bloom due to destratification covering most of the Alboran Sea in December 1997 and January 1998, as described in Garcia-Gorriz and Carr (2001).

Current speeds and directions recorded by current meters below each sediment trap are shown in Table 3.2. The current meters at ALB3 and ALB4 were fully consistent, recording a mean flow directed towards the southeast, with the exception of the lower depth of ALB3 that recorded a flow towards the southwest. Contrarily, the current meters at the southern station ALB5 showed a mean flow directed towards the Strait of Gibraltar at the three depths. In this site the current field was more energetic than in the other stations, with maximum discrete values up to 19.12 cm s^{-1}.

Table 3.2. Current meter data statistics. The rightmost column corresponds to the percentage of individual measurements with absolute speed above 12 cm s^{-1}. This is the threshold value above which currents could significantly affect the collection of settling particles by sediment traps according to Gardner et al. (1997).

Trap	Depth	Recording periods	Average speed ± stand. dev.	Max. absolute speed (cm s^{-1})	Max. W-E speed (cm s^{-1})	Max. S-N speed (cm s^{-1})	Residual direction (degrees from N)	Percent. values > 12 cm s^{-1}
	680 m	I, II	2.37 ± 1.34	12.14	11.74	-10.10	171º	0%
ALB3-M	1190 m	I, II, III	1.48 ± 0.76	7.78	6.63	-7.63	170º	0%
ALB3-L	2230 m	I, II, III	2.17 ± 1.37	10.11	-9.77	-9.48	215º	0%
ALB4-U	645 m	I, III	2.78 ± 1.99	8.95	8.93	-8.44	150º	0%
ALB4-M	1170 m	I	2.54 ± 1.58	10.40	10.20	-5.76	134º	0%
ALB4-L	2210 m	I, III	3.19 ± 1.91	11.85	11.60	8.28	136º	0%
ALB5-U	510 m	I, II	3.11 ± 2.64	15.92	-15.90	-7.49	284º	0.81%
ALB5-M	1050 m	I, II, III	2.71 ± 2.38	18.54	-17.59	15.92	242º	1.33%
ALB5-L	2070 m	I, II, III	3.93 ± 3.14	19.12	-18.58	12.30	276º	2.02%

3.3.2. Temporal variability of particle fluxes

Particle fluxes at all stations show important mass peaks synchronous at the three stations and at the three depths in spring (April-May 1998) and summer (July 1997) (Fig. 3.4). Total mass flux peaks are also observed in fall and winter, particularly at ALB4 and ALB5 in December 1997 and January-February 1998.

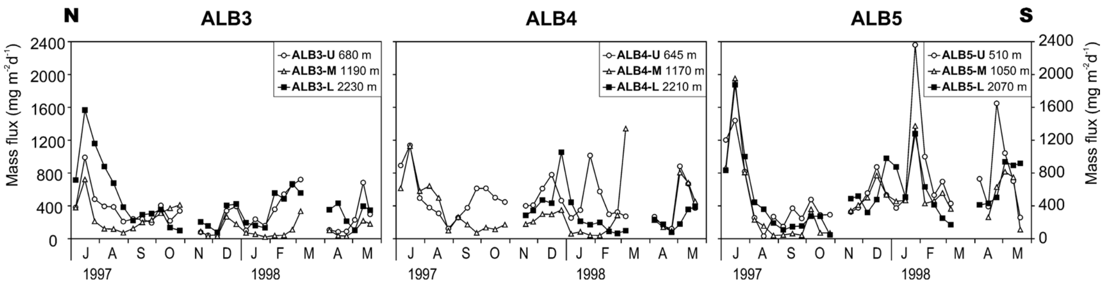

Figure 3.4. Temporal evolution of total mass flux (mg m^{-2} d^{-1}) at the three mooring lines.

Main constituent fluxes and their relative contributions (lithogenic, calcium carbonate, organic carbon and opal) time series are shown in Figures 3.5 and 3.6. Lithogenics were the most abundant constituent, followed by calcium carbonate. Both constituents showed a similar pattern and essentially matched total mass fluxes at the three stations (Figs. 3.4, 3.5a, b, and 3.6a, b). Lithogenic fluxes ranged from 14 mg m^{-2} d^{-1} to 1591 mg m^{-2} d^{-1} (August 1997 and January 1998, both in the ALB5 upper trap), and relative contributions never fell below 39%. Calcium carbonate fluxes peaked at 532 mg m^{-2} d^{-1} (ALB5-U in January 1998) and had lowest values of 8 mg m^{-2} d^{-1} (ALB4-M in January 1998).

Organic carbon and opal followed a rough seasonal pattern, with their relative abundances increasing during the summer 1997 (July) and spring 1998 (May) peaks at ALB4 and ALB5 (Fig. 3.6c, d). Although flux peaks at the beginning and at the end of the time-series were recorded for all the main constituents, lithogenic and calcium carbonate peaks were not essentially different from those through the rest of the year. This would imply that the seasonal cycle in the study area was associated to the biogenic constituents. Organic carbon fluxes varied between 1 mg m^{-2} d^{-1} (ALB3-M) and 137 mg m^{-2} d^{-1} (ALB5-M), with percentages ranging from 2% (ALB3-L) and 13% (ALB4-U) (Figs. 3.5c and 3.6c).

The organic carbon flux time-series highlights the two main increases in July 1997 and May 1998 that were found in all the stations and water depths, though they were particularly noticeable at ALB4 and ALB5. Other lower peaks were observed between these two main events, in December 1997 (ALB3, ALB4 and ALB5) and January 1998 (ALB4 and ALB5). Opal fluxes fluctuated from 0.38 mg m^{-2} d^{-1} (ALB3-U) to 217 mg m^{-2} d^{-1} (ALB5-M) (Fig. 3.5d), and also presented the seasonal signal, as it was the case for the organic carbon. In spring and summer (July 1997 and May 1998) dramatic increases were recorded at ALB4 and ALB5, leading to percentages above 14% (Fig. 3.6d). Autumn and winter values tended to be lower (occasionally down to 1%) although relatively minor peaks were observed too. This was the case of one of the winter peaks in December 1997.

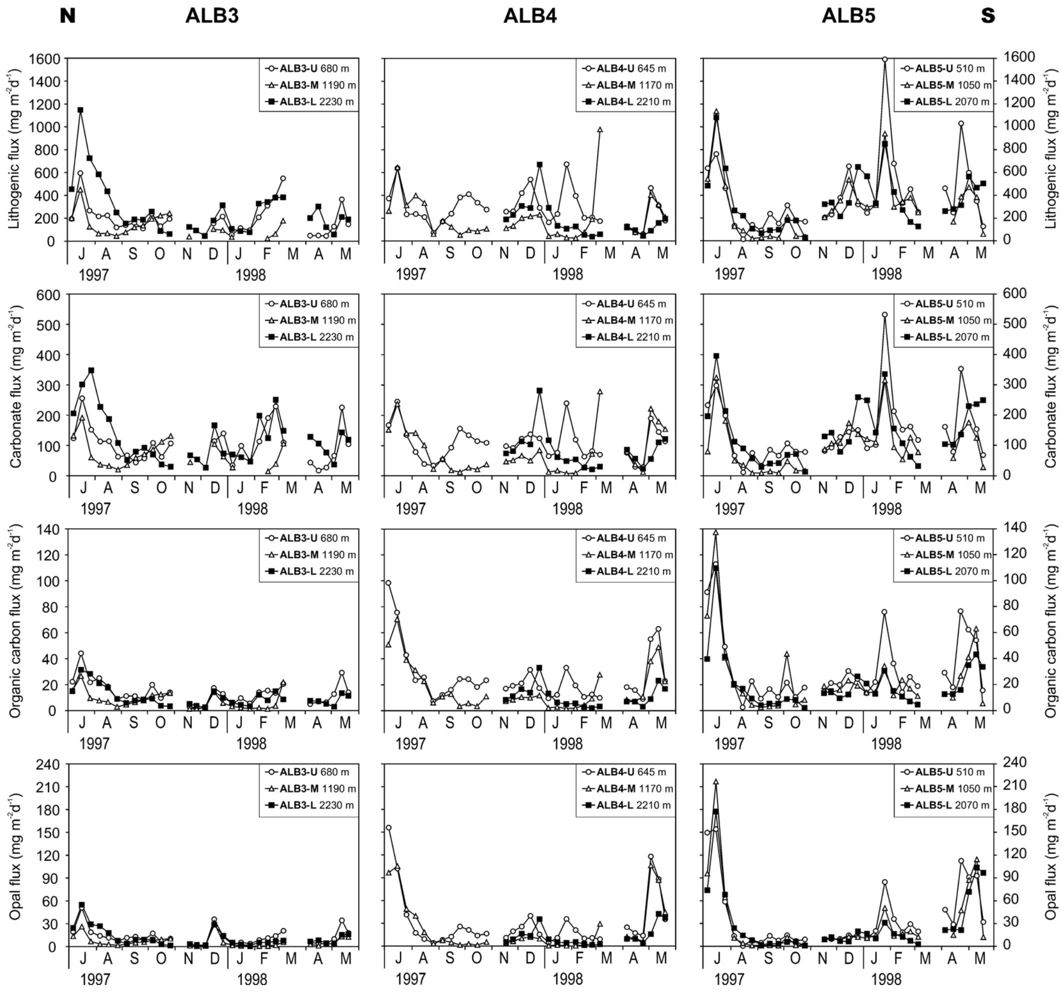

Figure 3.5. Temporal evolution of lithogenic, calcium carbonate, organic carbon and opal flux (mg m^{-2} d^{-1}) at the three stations.

The exception to the general tendency of larger opal fluxes at spring-summer was the high single peak recorded by ALB3 in December 1997, with values between 7% and 12% at the three depths within the same sampling period (maximum values found in this mooring).

3.3.3. Annual fluxes

Time-weighted mean of total mass fluxes (TWF) and fluxes of main constituents (lithogenics, calcium carbonate, organic carbon and opal) at the three stations are shown in Table 3.3.

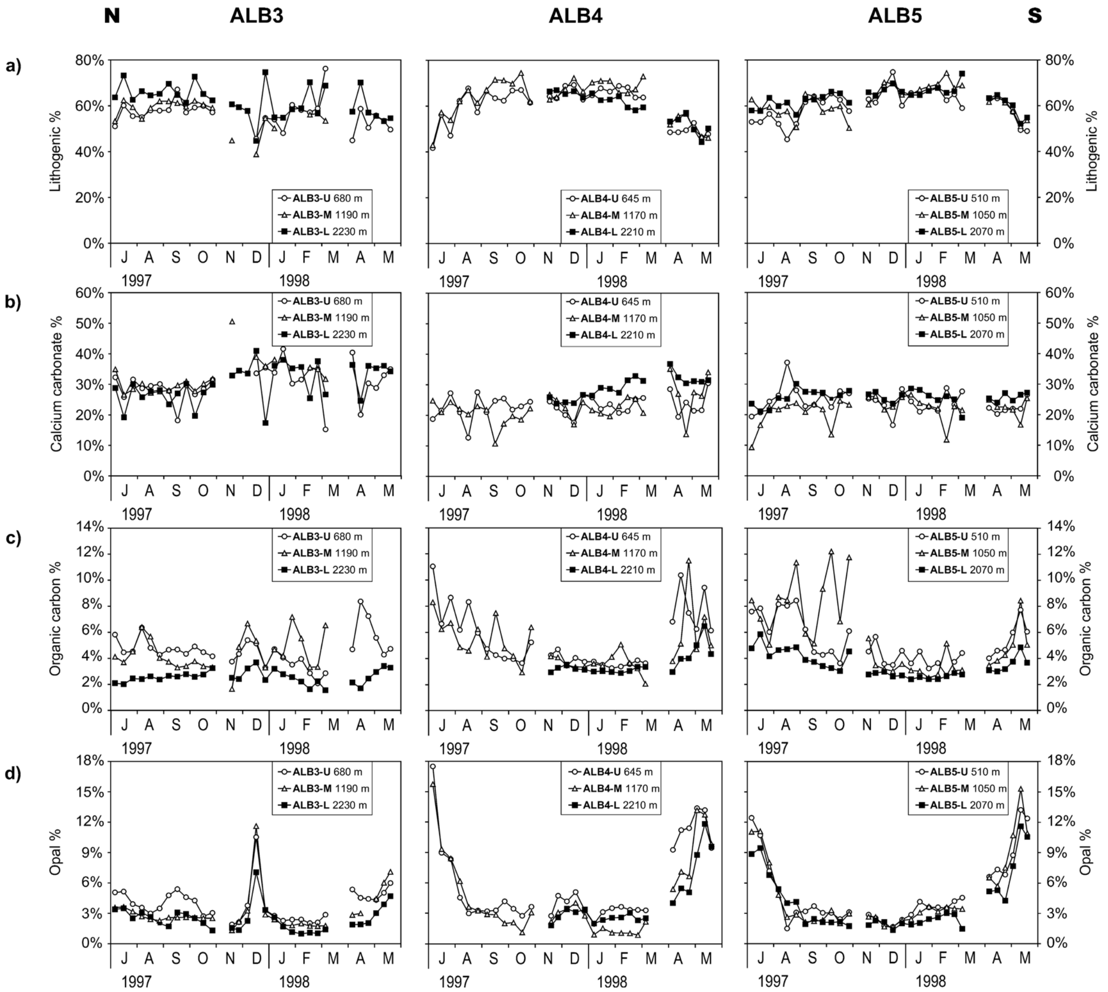

Figure 3.6. Temporal evolution of lithogenics, calcium carbonate, organic carbon and opal relative contributions (%) at the three stations.

On an annual basis, the total mass fluxes decreased from south to north along the latitudinal transect that crosses the Eastern Alboran Sea. The highest TWF (647 mg m^{-2} d^{-1}) was recorded at ALB5-U, and the lowest TWF (176 mg m^{-2} d^{-1}) was recorded by the northernmost station ALB3-M. Particle flux patterns from ALB3 and ALB5 were similar, with a decrease from the upper to the middle trap (25% and 46% of mass flux reduction in ALB5 and ALB3 respectively) and an increase from the middle to the lower trap (Fig. 3.7). However, this mass flux increase with depth was much lower (14%) at ALB5 than it was at ALB3 (142%). Such near-bottom increases of particle fluxes suggest variable contributions by advection. ALB4 TWF displayed a different behaviour, with reduced lateral input illustrated by a 30% and 11% of reduction of fluxes from the upper to the middle trap, and from the middle to the lower trap, respectively.

Table 3.3. Time averaged total mass flux and fluxes of main constituents, plus organic nitrogen. Main constituents are also expressed as time averaged relative contributions in percentages.

Trap	Mass flux (mg $m^{-2}d^{-1}$)	Lithogenic (mg $m^{-2}d^{-1}$) (%)	$CaCO_3$ (mg $m^{-2}d^{-1}$) (%)	Organic carbon (mg $m^{-2}d^{-1}$) (%)	Organic nitrogen (mg $m^{-2}d^{-1}$) (%)	Opal (mg $m^{-2}d^{-1}$) (%)
ALB3-U	323.24	204.16 (58%)	104.96 (30%)	13.82 (4%)	1.93 (0.6%)	12.93 (4%)
ALB3-M	176.09	133.89 (57%)	72.76 (31%)	7.93 (4%)	1.12 (0.6%)	6.32 (3%)
ALB3-L	426.59	276.02 (64%)	122.43 (28%)	10.16 (2%)	1.39 (0.3%)	11.34 (3%)
ALB4-U	482.86	290.34 (60%)	108.53 (22%)	26.43 (5%)	3.72 (0.8%)	31.12 (6%)
ALB4-M	337.80	206.18 (60%)	78.91 (23%)	16.61 (5%)	2.26 (0.7%)	22.39 (7%)
ALB4-L	299.60	188.86 (61%)	85.79 (28%)	10.54 (4%)	1.37 (0.5%)	12.35 (4%)
ALB5-U	646.79	397.86 (62%)	147.15 (23%)	32.29 (5%)	5.07 (0.8%)	37.21 (6%)
ALB5-M	486.40	307.00 (63%)	99.09 (20%)	24.99 (5%)	3.70 (0.8%)	30.35 (6%)
ALB5-L	555.65	347.79 (63%)	139.47 (25%)	20.08 (4%)	2.98 (0.5%)	28.21 (5%)

The dominant constituents of the total mass flux were the lithogenic fraction and the calcium carbonate. Both components displayed a similar behaviour than total mass flux, with a near bottom increase at the stations closer to the margins (ALB3 and ALB5) (Fig. 3.7). Overall, organic carbon and opal fluxes decreased downwards and northward thus reaching the highest value in the upper ALB5 trap off the Algerian coast. At ALB5 and ALB4 the flux of organic carbon and opal between upper, middle and lower traps decreased 10-40% (Fig. 3.7), representing an exception to the general behaviour of the ALB5 southern site as far as TWF, lithogenic and calcium carbonate fluxes are concerned. In contrast, at ALB3 organic carbon and opal fluxes followed the same tendency than the total mass flux, with a decrease with depth between the two upper traps (40-50% down) and a significant increase near the bottom level (30-80% up).

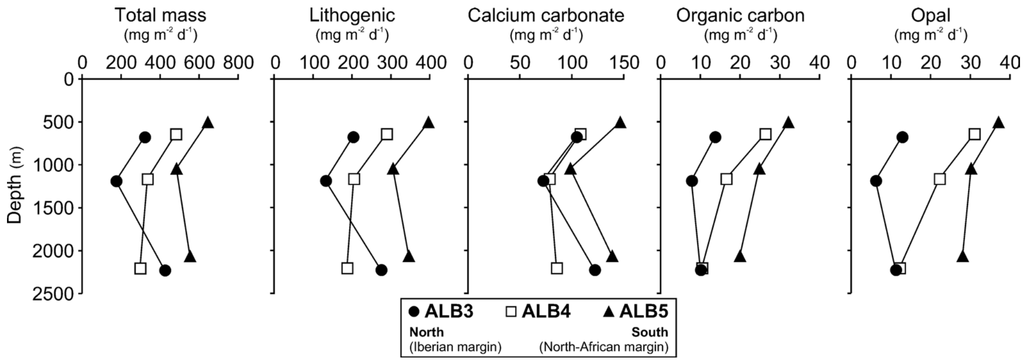

Figure 3.7. Time averaged total mass flux and fluxes of main constituents (mg m^{-2} d^{-1}) at the three stations.

A rough calculation of the difference between fluxes of lithogenics, calcium carbonate, organic carbon and opal between the upper traps (500-700 m) and the middle traps (1000-1200 m) indicate that vertical transfer dominated fluxes of the above main constituents at middle depths in the three stations (Fig. 3.7). Annual particle fluxes near the bottom do not mirror the pattern recorded in upper waters, as they descended towards the centre of the basin. Lateral input at 30 meters above bottom was considerable at the southern and northern stations, the later particularly higher, endorsing substantial lateral input at short distance from the seafloor. Contrarily, at the central station the total mass flux descended in between the middle and the lower trap (Fig. 3.7).

3.4. DISCUSSION

3.4.1. Biological and physical processes influencing particle fluxes to upper depths

Enhancement of phytoplankton populations in frontal areas of the Alboran Sea due to the vertical supply of nutrients is well known after the studies of Lohrenz et al. (1988), Claustre et al. (1994) and Fielding et al. (2001). In addition, an eastward transfer of chlorophyll-rich water from the upwelling area off the Spanish coast is shown by satellite images as reported by Baldacci et al. (2001) and Garcia-Gorriz and Carr (2001). Sanchez-Vidal et al. (2004) found, in addition, a north to south transfer that combined with the former results in a net southeastward transfer of water, nutrients and chlorophyll. As described by Garcia-Gorriz and Carr (2001), eddy-induced nutrient supply in the periphery of the WAG can account for 20-60% of that advected from the coastal upwelling sites.

It is easy to recognise the link between the presence of the fertilised jet in surface waters and increased opal relative contributions (%) and fluxes (mg m^{-2} d^{-1}) at 500-700 m of water depth. In June 1997 and April 1998 SST images clearly recorded an upwelling off the Spanish coast (Fig. 3.3a and 3.3d). A chlorophyll-rich southeastward-directed jet associated to a southward shift of the gyres was evident in April 1998, and, although there is no SeaWiFS image from June 1997, a highly productive event was identified by Garcia-Gorriz and Carr (1999) by means of the Ocean Color and Temperature Scanner (OCTS). In these two occasions, particle fluxes peaked at all traps few days later, especially opal and organic carbon, which in addition display a pronounced increasing trend from north to south (Fig. 3.5c, 3.5d). Opal flux peaks should follow from the development of diatom-rich phytoplankton communities, as evidenced by the high abundances of diatoms found along the frontal regions in the Alboran Sea during the studied period in July 1997 and April 1998 by Barcena et al. (2001) and in May 1998 by Arin et al. (2002). The resemblance of opal fluxes between station ALB1 (Fabres et al., 2002) in the northern side of the WAG (36º 14.39'N, 04º 15.41'W), and our stations ALB4 and ALB5 (Fig. 3.5d), supports that the physical processes responsible for the supply of nutrients should be essentially the same in both Eastern and Western Alboran basins.

In mid-late November 97, the centred position and the significant development of the two gyres resulted in an eastward-directed jet (Fig. 3.3b) that manifests as another opal pulse at the central station ALB4 about one month later (Fig. 3.5d and 3.6d). Also, advection of cool and phytoplankton rich waters between 1º and 0ºW from the southern Spanish coast (Fig. 3.3b), could be responsible for the exceptional opal relative contribution peak at the northern station ALB3 (Fig. 3.6d).

The mid-late December 1997 hydrological situation (Fig. 3.3c) is different (section 3.3.1). Fertilisation of the entire basin at that time has been attributed to water column destratification (Garcia-Gorriz and Carr, 2001), with three surface gyres becoming compressed close to the North-African coast. Approximately 1 month later, by the end of January 1998, large calcium carbonate fluxes and moderate organic carbon and opal fluxes were recorded at the upper traps of the southern stations ALB4 and ALB5. Sanchez-Vidal et al. (2004) interpreted this calcium carbonate flux peak at ALB4 as due to the development of calcareous phytoplankton communities in extensive phytoplankton blooms affecting large parts of the Alboran basin. This is further supported in the present study, as we recorded a larger calcium carbonate peak at the southern station ALB5, under the influence of the uniform bloom (Fig. 3.3c), and a very minor increase at the northern station ALB3. The changing nature of the nutrient enrichment in the frontal area would thus allow for differential growth of phytoplankton populations (siliceous vs. calcareous phytoplankton) as postulated by Claustre et al. (1994).

The biogenic signal in the particulate matter has been recognised even when the lithogenic fluxes were high (Fig. 3.5a). This supports the idea of scavenging of fine lithogenic material into faecal pellets and organic aggregates as the principal mechanism controlling the lithogenic flux. The large contribution of lithogenics in the total mass flux in both Western and Eastern Alboran Sea has been linked to fluvial sediment transport and airborne dust biologically scavenged and transferred through the water column down to the seafloor (Fabres et al., 2002; Sanchez-Vidal et al., 2004).

3.4.2. Variability in transfer to middle and near bottom depths

The seasonal signal linked to the biogenic components was still noticeable at middle (1000-1200 m) and near bottom levels (2000-2200 m) as recorded by the corresponding sediment traps (Fig. 3.5c, d). Opal shows sharp increases in both percentage and flux in July 1997 and April-May 1998 at all levels of ALB4 and ALB5, and in December 1997 at all levels of ALB3 (Figs. 3.5c, d, 3.6c, d), which roughly correlate with the location of the jet above the various stations (Figs. 3.3a, d). Sanchez-Vidal et al. (2004) estimated a settling velocity for organic carbon and opal particles at ALB4 mooring station of 87-117 m d^{-1}. The opal maxima of December 1997 at station ALB3 and July 1997 at station ALB5 allow an estimate of minimum settling velocity of 155-156 m d^{-1}. This supports a rapid transfer of the material from 500-700 m to depths >2000 m linked to the hydrological conditions along the Eastern Alboran Sea. Such control of the biophysical processes to the organic matter exportation should have important implications for the organic carbon cycle en the study area, that will be discussed in section 3.4.3.

Lateral advection was also considerable in some periods of the year, particularly at the stations close to the margins. The July 1997 peak at ALB5 was higher at the middle and lower traps than at the upper trap (Fig. 3.4). The similar composition of the downward flux of this event at the three depths suggests a common source of the settling particles. Thus, this situation most likely results from a widespread productive situation in the southern part of the Eastern Alboran Sea, not far from the North-African shelf edge as intuited by the position of the jet (Fig. 3.3a), which would export fresh biogenic material from the continental shelf towards the base-of-slope middle and near-bottom depths.

In December 1997, a higher total mass flux peak was also observed in the near bottom trap of ALB5, which was delayed 10 days with respect to the upper and middle traps record (Fig. 3.4). In this case, calcium carbonate and lithogenic peaks were of considerable magnitude (Fig. 3.5a, b), in contrast to lowered opal and organic carbon fluxes. Lateral supply of lithogenic and carbonate-rich material, or collection by the lower trap of resuspended sediments, or some combination of two must be invoked to explain this observation. In a geochemical study of the uppermost sediments from short sediment cores below each mooring line Masque et al. (2003) revealed that surface sediments in the Eastern Alboran Sea are mostly made of lithogenic (70%) and carbonate (30%) particles, with minor organic carbon and opal contributions. The intensification of the westward-eastward current reversal at ALB5 in winter (Fig. 3.8) suggests that the particles collected by the sediment trap were in part derived from resuspended bottom sediments from the nearby margin.

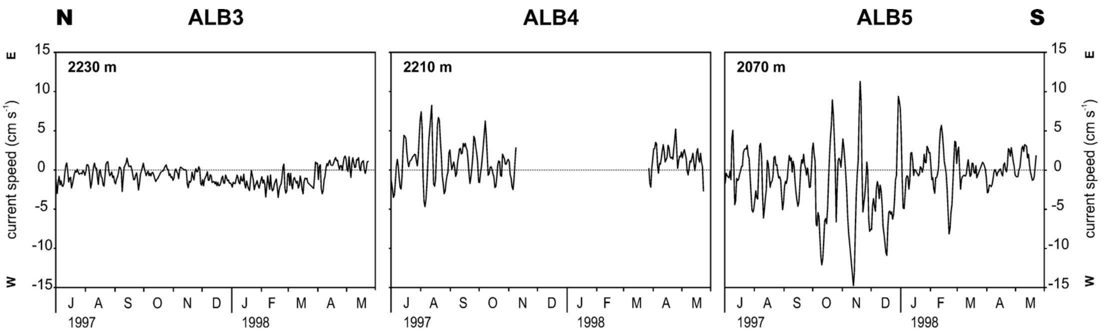

Figure 3.8. Temporal evolution of the West-East low-pass filtered component (cut-off period of 48h) of the current speed (cm s^{-1}) at the three near bottom current meters.

Despite of the higher distance to the North-African and the Iberian margins (Fig. 3.1) a similar scenario has been considered to explain the lower-trap increase in mass flux measured at ALB4 in December 1997 (Sanchez-Vidal et al., 2004). In the Western Alboran Sea, Fabres et al. (2002) also found pulses of increased fluxes of lithogenic and carbonate nature, which they associated to deep advective input of particles by intermediate and benthic nepheloid layers detaching from the slope regions. Hydrological profiles of temperature and light transmission carried out during the sampling period clearly illustrated the process (see Fig. 4 on Fabres et al., 2002 or Fig. 4.4 in this volume).

The existence of a nepheloid layer suggests that part of the increased fluxes near the bottom in periods of high productivity could also be attributed to scavenging of benthic nepheloid layer material by the settling organic aggregates. The resulting material should be richer in organic matter but also in calcium carbonate and lithogenic. Although we do not have the appropriate hydrographic data that supports it, during summer 1997 and spring 1998 this sweeping effect may be the responsible for part of the increased fluxes at the lower traps of station ALB5 and ALB3 (Fig. 3.5).

In station ALB3 there is an overall parallelism between the various flux curves at the three levels, with the exception of enhanced total mass fluxes at the lower level (2230 m) in July and August 1997 (Fig. 3.4). The accidental collapse of a glass buoy above the ALB3 lower sediment trap could respond for these high fluxes (see section 3.2.1), but the similar behaviour with upper and middle traps fluxes suggests it was not major. The location of ALB3 within the axis of the lower Gata Canyon may have an influence on particle fluxes, as is well known that they are preferential pathways for the transport of sediment from the continental shelves to the deep sea. The fact that the canyon is not directly fed by any significant fluvial system (Fig. 3.1) discards floods and river plumes to play a major role in the delivery of terrigenous sediments to the axis of the canyon. Particulate matter collected during that event was of lithogenic and calcium carbonate origin (Fig. 3.5a, b), which in turn suggests the influence of resuspended sediments, as is the case of the other stations. Bottom nepheloid layers fed by resuspension at the upper slope have been observed in other submarine canyons of the Western Mediterranean Sea such as the Grand-Rhône canyon in the Gulf of Lions (Durrieu de Madron et al., 1994), the Foix canyon in the Balearic Sea (Puig and Palanques, 1998), or the nearby Guadiaro canyon in the western Alboran Sea (Puig et al., 2002). Even though we have no way to formally demonstrate the presence of nepheloid layers in the study area, the coincidences suggest that they could play a major role in transporting sediment towards lower levels.

3.4.3. Organic carbon balance

To achieve a better understanding on biogeochemical cycles in the Alboran Sea it is necessary to constraint the production, transfer and burial of organic carbon. By combining measurements of primary production data, algorithm-generated fluxes below the upper sediment trap, fluxes measured at the three sediment trap-levels, and mean accumulation rates measured from sediment cores, a balance of carbon is constructed in the Eastern Alboran Sea. The vertical particulate organic carbon flux derived from primary productivity, and the difference between the calculated flux and the flux measured by the sediment traps are named from here onwards “primary flux” and “lateral flux”, respectively (Antia et al., 1999). The “primary export ratio” is defined as the proportion of primary production exported vertically from the surface layer as sinking organic carbon.

Fluxes from the upper traps best represent primary fluxes. The expected vertical distribution of organic carbon can be calculated using the algorithm of Martin et al. (1987):

$$F = F_d \, (z/d)^b, \qquad (3.1)$$

where F is organic carbon flux calculated at depth z, F_d is organic carbon flux measured at the upper trap (depth d) and b is the open ocean composite fitting parameter (b=-0.858). To achieve our goal, we have used ALB4 as a reference mooring dominated by pelagic particle settling (Sanchez-Vidal et al., 2004). ALB4 organic carbon data fit almost perfectly with the Martin et al. (1987) curve, with 16.61 and 10.54 mg organic carbon m^{-2} d^{-1} measured and 15.86 and 9.19 mg organic carbon m^{-2} d^{-1} calculated at middle and lower traps, respectively. These results support the use of ALB4 as a reference mooring. In addition, we have adjusted exponent b to achieve the best fitting of ALB4 curve after applying Martin's et al. (1987) equation to our data, and the result is b=-0.753 (r^2= 0.999). The same procedure has been used to calculate the curve for organic nitrogen data shown in Table 3.3, obtaining a value b=-0.815 (r^2= 0.999). The b values obtained are lower than those for the open ocean given by Martin et al. (1987), which in turn suggests a higher transfer efficiency of carbon to the deep sea.

Recently, Armstrong et al. (2002) questioned the Martin et al. (1987) concept that particulate organic carbon transfer down the water column is only a function of depth. They proposed that sinking POC is composed of two fractions: a fraction quantitatively associated with ballast minerals with an asymptotic comportment, and a free fraction that is remineralized before reaching the sediments. Klaas and Archer (2002) extended the application of the model by distinguishing the different forms of mineral ballast (carbonate, opal and lithogenic material). However, there are significant uncertainties in the mesopelagic zone above 2000 m (Francois et al., 2002) and in areas with significant input of fluvial and/or resuspended lithogenic material (Passow 2004). Francois et al. (2002) suggests that the algorithm proposed by Martin et al. (1987) can be used to predict organic carbon flux at depths <2000 m if the exponent b is adjusted in each region. Whether the vertical flux of organic carbon in shallow (>2000 m) areas is controlled by ballasting, remineralization, or other processes, is not clear and need further studies.

Primary production, new production and export production through the euphotic zone

Integrated primary production in the upper layer from October 1997 to May 1998 has been obtained following Garcia-Gorriz and Carr (2001) using chlorophyll concentration from SeaWiFS, mixed layer depth, sea surface temperature and photosynthetic active radiation values (Garcia-Gorriz, personal communication). The values obtained indicate that primary production increased southward, from 415 mg organic carbon m^{-2} d^{-1} in the northern station ALB3, to 531 mg organic carbon m^{-2} d^{-1} at ALB4, and 562 mg organic carbon m^{-2} d^{-1} at ALB5 (Fig. 3.9).

New production is equivalent to the organic carbon escaping from the photic layer as assumed since Eppley and Peterson (1979). If we calculate the expected fluxes of organic carbon and organic nitrogen at 100 m depth of the central station ALB4 we obtain 108 mg organic carbon m^{-2} d^{-1} and 17 mg organic nitrogen m^{-2} d^{-1}. Based on ^{15}N uptake rates

L'Helguen et al. (2002) estimated a new production of 19 mg organic nitrogen m^{-2} d^{-1} for the three water masses in the Eastern Alboran Sea (Atlantic, Mediterranean and frontal waters), which is close to the flux obtained from our calculations. Also, the organic nitrogen new production obtained for ALB3 is in very good agreement with Mediterranean waters new production, and ALB5 data fall within the range of the frontal waters (L'Helguen et al., 2002). The similarity of values obtained from two independent approaches suggests that calculated organic carbon fluxes at 100 m are a good approximation to new production, and validate our upper-trap data as reliable estimates of the actual vertical particle flux.

Data reveal that 14-20% of the photosyntetically produced organic carbon is available to export below the euphotic zone (last column of Table 3.4 and Fig. 3.9). This is the same that 80-86% of the carbon fixed during photosynthesis has been respired back to inorganic carbon or released as dissolved organic carbon in the first 100 m of the water column. The fraction of primary production exported from the euphotic zone has also been defined as f-ratio (Eppley and Peterson, 1979), which is a good indicator of how efficient is biological recycling in the upper layers. The f-ratios obtained are within the range of the values reported in the literature. In particular, the ratio in the northern station is equivalent to that in the open-ocean, and values at ALB4 and ALB5 are equivalent to those found in upwelling systems as reported by Martin et al. (1987). The difference between ALB4/ALB5 and ALB3 ratios would suggest a more efficient carbon export to 100 m at the southern half of the Eastern Alboran Sea versus a more intense surface recycling to the north. Sea-surface temperature and chlorophyll-a satellite images have revealed that the phytoplankton-rich jet of Modified Atlantic Water is more often present in the southern half of the latitudinal transect where ALB4 and ALB5 are located than in the northern half, were ALB3 is located, as seen in the four productive events recorded during the 1997-1998 monitoring period (Fig. 3.3). Thus, the higher spatial and temporal variability of the productivity signal above stations ALB4 and ALB5 has important implications on the amount of material that sinks out of the euphotic zone and is potentially available to be transferred through the water column.

Organic carbon transport through the water column: the role of lateral advection

Vertical organic carbon fluxes (or primary fluxes) calculated with the modified equation of Martin et al. (1987) follow those at the upper traps, with larger fluxes at ALB5 and lower at ALB3. Lateral organic carbon fluxes are also higher at the southern station, where inputs of 6.24 mg organic carbon m^{-2} d^{-1} and 8.84 mg organic carbon m^{-2} d^{-1} have been measured at 1050 and 2070 m of water depth, respectively (lateral organic carbon flux on Table 3.4). These non-vertical fluxes represent 25% and 44% of the total organic carbon flux (Fig. 3.9). In the northern site ALB3 we have not observed lateral input of organic carbon between the upper and the middle levels, but a loss that accounts for 14% of the organic carbon (negative values of lateral organic carbon flux on Table 3.4). Lateral input reappears between the middle and lower traps, with an input of 4.51 mg organic carbon m^{-2} d^{-1}, that is 44% of the organic carbon collected by the lower sediment trap.

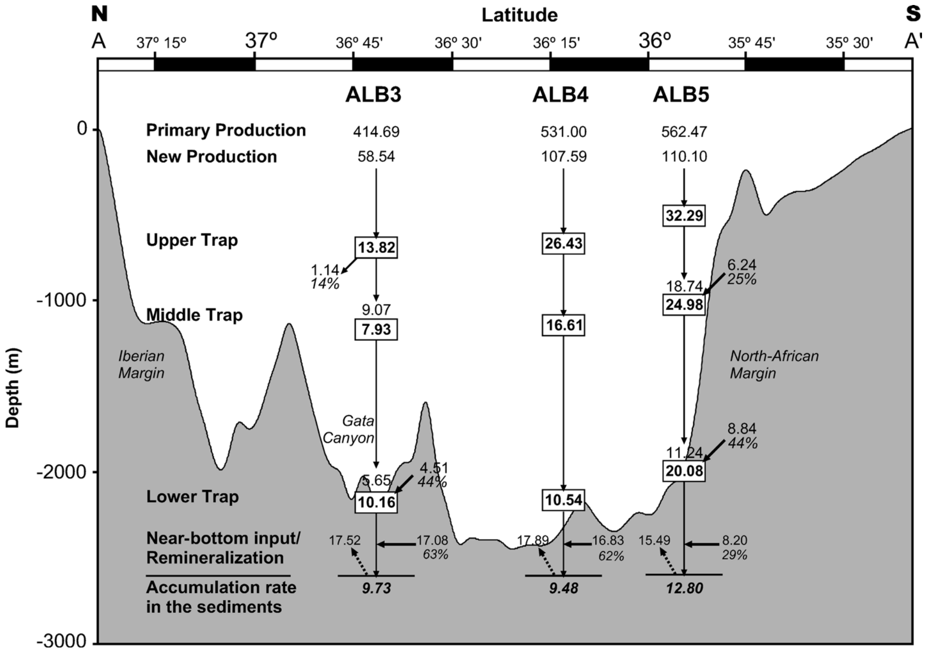

Figure 3.9. Organic carbon balance across the Eastern Alboran Sea, following a North-South transect along the 1º30' W meridian (A-A' in Figure 1). Bold data within rectangles represent measured organic carbon fluxes by the sediment traps; data on top of rectangles represent primary organic carbon fluxes calculated with a modified version of the Martin et al. (1987) equation; data among arrows represent lateral organic carbon fluxes (inputs/losses). Organic carbon accumulation rates and remineralization rates of the sediment cores below each mooring line are also shown. All organic carbon fluxes are in mg m^{-2} d^{-1}. See text for details on calculations.

It is hard to distinguish between lateral advection of organic matter from primary productivity and resuspension of modern or past supply from the annual flux values alone. However, the influence of the local topography in the lateral advection of particles has been noticed from the study of the temporal evolution of particle fluxes (section 3.4.2). Thus, shelf export of organic matter derived from primary productivity should account in part for the observed lateral inputs in the middle and lower traps of ALB5, which reflects the proximity of the sediment trap array to the North-African margin. In addition, deep advective input of resuspended sediments should also account for the increased fluxes at the lower traps of ALB3 and ALB5, in accordance with the location of ALB3 within the axis of the Gata Canyon and ALB5 on the foot of the continental slope.

Table 3.4. Organic carbon balance data. Total organic carbon fluxes are those measured by the sediment traps. Primary organic carbon fluxes have been estimated following a modified version of Martin's et al. (1987) (see section 3.4.1.2 of the main text). Lateral organic carbon flux has been obtained from the difference between measured total flux and calculated primary flux. Total and primary export ratio are calculated as total organic carbon flux normalized to primary production, and primary organic carbon flux normalized to primary production, respectively. Propagation of uncertainty associated with organic carbon and total mass flux measurements results in a precision better than 7.2% for organic carbon flux.

	Percentage organic carbon (%)	**Total** organic carbon flux (mg $m^{-2}d^{-1}$)	**Primary** organic carbon flux (mg $m^{-2}d^{-1}$)	**Lateral** organic carbon flux (mg $m^{-2}d^{-1}$)	**Total Export ratio**	**Primary Export ratio**
ALB3						
upper layer			414.69 P	-365.15		
100 m			58.54			14.12% FR
680 m	4.28%	13.82	13.82		3.33%	3.33%
1190 m	4.15%	7.93	9.07	-1.14	1.91%	2.19%
2230 m	2.38%	10.16	5.65	4.51	2.45%	1.36%
Bottom	0.69%	9.73	5.59	17.08 B, -17.52 R	2.35%	0.48%
ALB4						
upper layer			531.00 P	-423.41		
100 m			107.59			20.26% FR
645 m	5.47%	26.43	26.43		4.98%	4.98%
1170 m	4.92%	16.61	16.61		3.13%	3.13%
2210 m	3.52%	10.54	10.54		1.98%	1.98%
Bottom	0.67%	9.48	10.35	16.83 B -17.89 R	1.79%	0.68%
ALB5						
upper layer			562.47 P	-452.36		
100 m			110.10			19.58% FR
510 m	4.99%	32.29	32.29		5.74%	5.74%
1050 m	5.14%	24.99	18.74	6.24	4.44%	3.33%
2070 m	3.61%	20.08	11.24	8.84	3.57%	2.00%
Bottom	0.74%	12.80	11.12	8.20 B 15.49 R	2.28%	0.89%

P: Primary Production as given by Garcia-Gorriz and Carr (2001).
R: Remineralizated organic carbon calculated using diffusive oxygen uptake rates from Bianchi et al. (2003).
B: Near-bottom input calculated as remineralizated organic carbon plus accumulated organic carbon minus lower traps total organic carbon flux.
FR: Known as f-ratio, new production/primary production (Eppley and Peterson, 1979).

Primary export ratio to the three trap-levels (last column of Table 3.4) matches the general north to south increasing pattern of the primary productivity. This is not noticed from the total export ratio alone (second last column of Table 3.4), indicating the importance of the calculations made in order to discriminate the influence of vertical and horizontal inputs of organic carbon. The non-inclusion of the lateral flux in our export efficiency estimation is also useful to place the Alboran Sea in a regional and a global context of carbon export. The fraction of primary production exported below 1000 m depth is larger in the southern part of the Eastern Alboran Sea than in other Mediterranean sites, such as the Ligurian Sea (Miquel et al., 1994) or the Ionian Sea (Miserocchi et al., 1999). In the northern station the primary export ratio is lower, and falls within the range of the typical oligotrophic open Mediterranean sites. The estimated export efficiencies to depths >1500 m are also higher than the mean global average of 1.1 % reported recently by Lutz et al. (2002) but similar to values obtained in other margin systems such as the Arabian Sea or the Panama Basin (see compilation in Lutz et al., 2002).

Organic carbon burial

Benthic studies from sediment cores below each sediment trap array have been carried out by Masque et al. (2003) and Bianchi et al. (2003). The accumulation rates of organic carbon in the sediment assessed by means of ^{210}Pb concentration profiles are reported by Masque et al. (2003), and will be used as suitable indicators of what is exported from the water column and buried efficiently in the sediment. Diffusive oxygen uptake rates have been reported by Bianchi et al. (2003), and are converted into remineralizable organic carbon flux by applying the mean elemental Redfield ratio ($O_2/C=138/106$) (Table 3.4).

The three sediment cores have similar organic carbon accumulation rates, a situation that has been attributed to the spatial homogenisation capacity of near bottom transport (Masque et al., 2003). Benthic remineralization rates are largely higher than the organic carbon fluxes collected by the lower sediment traps. Thus, a strong input of particulate organic carbon is supposed to occur below the lower and the sea floor to account for the difference between burial plus remineralization rates and supply rates. This lateral input accounts for 29-63% of the total organic carbon supply (Table 3.4). The minor lateral input at station ALB5, almost half of the other stations, indicates that the amount of resuspended material collected by the lower trap was higher than at the other stations, thus causing the lateral input versus total supply to be lower in the last 30 m of the water column. This suggests that the benthic nepheloid layer at the station close to the southern margin was thicker, probably due to a dispersion effect as a result of the more energetic current field (Table 3.2). In order to avoid this bias we have calculated the integrated lateral advection below 1000-1200 m, depth at which is located the middle sediment trap. The results obtained show that the lateral organic carbon input in the last 1000 m of the water column, which could be attributed almost certainly to a benthic nepheloid supply (section 3.4.2), is higher at the station located within the axis of the Gata Canyon (79%), than at stations ALB4 and ALB5 (60-62%). Thus, local topography plays a very important role in the lateral input of organic carbon also near the bottom.

Computation of the total export ratio, which is the proportion of primary production exported from the surface layer and buried in the sediments after arriving at the sea floor either vertically or advectively, yields the following values of 2.35% (ALB3), 1.79% (ALB4) and 2.28% (ALB5). However, the primary export ratio, which is the organic carbon supplied vertically, is 0.48%, 0.68% and 0.89% for ALB3, ALB4 and ALB5, respectively (Table 3.4). Therefore, most of the organic carbon buried in the deep Eastern Alboran Sea sediments is supplied by lateral transport rather than by settling from the overlying euphotic zone. However, even if only vertical fluxes are considered, the values registered in Eastern Alboran Sea are higher than those recorded in other Mediterranean sites such as the Adriatic Sea (0.5% of the primary production is buried at 1200 m of water depth) and the Ionian Sea (0.1% is buried at 2360 m of water depth) (Giordani et al., 2002).

3.5. CONCLUSIONS

Spatial trends and temporal evolution of sediment trap data obtained during the MTP-II MATER Project have provided important information about the sources and particle transfer processes in the Eastern Alboran Sea. Several conclusions can be drawn from the combined analyses of meteorological data, remote sensing images, current meter and sediment trap data.

The delivery of particles to the sea floor is controlled primarily by hydrological structures in surface waters. The temporal evolution of total mass and main constituents fluxes suggests that a close connection exists between both Western and Eastern Alboran Seas although the sea surface circulation in both areas presents high temporal and spatial variability. The spreading to the east and to the south of phytoplankton rich water from the upwelling off the Spanish coast by the Atlantic jet, together with vertical supply of nutrients due to vertical motion, triggers development of diatom-rich phytoplankton communities and the arrival of biogenic material at either part of the Eastern Alboran Sea. Furthermore, a particle transfer scenario of lateral transport of biogenic material from the southern continental shelf to the station close to the north-African margin, and a deep advective input of particulate matter by a benthic nepheloid layer has been suggested to explain middle-depth and near-bottom increases of particle flux.

An annual balance of organic carbon in the Eastern Alboran Sea is achieved through the use of primary production, fluxes measured at three sediment trap-levels, and mean accumulation rates measured from sediment cores. Data obtained have provided evidence of the control exerted by the sea surface circulation and associated productivity signal over the downward transfer of organic carbon. The higher spatial and temporal variability of the

Alboran gyres at the southern half of the Eastern Alboran Sea is translated in increased organic carbon export efficiency at stations ALB4 and ALB5, bringing clear evidence that hydrodynamic structures in the area behave as efficient conveyor belts of organic carbon down to the sea floor. In the northern part of the Eastern Alboran Sea less episodes of increased productivity are recorded, thus organic carbon export efficiency at station ALB3 is lower, typical of an oligotrophic area and within the range of other Mediterranean sites. In addition, a large portion of the organic carbon is supplied by lateral advection and through a benthic nepheloid layer, suggesting a strong control of the local topography on the transport and deposition of organic carbon. Lateral advection from the nearby margins and deep advective input of resuspended sediments constitute a significant source of organic carbon to the deep Eastern Alboran Sea.

The data presented suggests that lateral flux of organic carbon supplies 60-80% of the total organic carbon that reaches the deep sea floor and is buried forming the sedimentary record. Thus, the variability of primary production in surface waters is overridden when looking at organic carbon fluxes near the bottom or organic carbon accumulation rates in the sediments. However, integrated studies of particle dynamics such as those made in this study allow discriminate the influence of lateral particle transport, and SeaWiFS imagery becomes useful to estimate efficiency of the organic carbon exportation.

Acknowledgements

Authors would like to thank E. Garcia-Gorriz and F. Melin of the Inland and Marine Waters Unit, IES-Joint Research Centre of the EC at Ispra, for providing primary production data and SeaWiFS images, and M. Guart and the Elemental Analysis and Optic Plasma teams of the "Serveis Científico-Tècnics" (University of Barcelona) for invaluable help in trap sample preparation and carbon-nitrogen and silica analyses. We gratefully acknowledge people on board R/V Garcia del Cid during the various MATER cruises for their help and dedication. We also thank Dr. G.B. Shimmield and two anonymous reviewers for constructive comments. This research was part of the EC MTPII-MATER (MAS3-CT96-0051) and ADIOS (EVK3-CT-2000-00035) projects. A.S. is indebted to the "Departament d'Universitats, Recerca i Societat de la Informació" for providing a predoctoral fellowship. GRCGM is additionally funded by a Generalitat de Catalunya grant (ref. 2001 SGR-00076) and the Thematic Network "Barcelona Consortium on Marine Geosciences" (2003 XT-0025).

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