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CAPÍTOL 2

PARTICLE FLUXES IN THE ALMERIA-ORAN FRONT: CONTROL BY COASTAL UPWELLING AND SEA-SURFACE CIRCULATION

Anna Sanchez-Vidal, Antoni Calafat*, Miquel Canals, Joan Fabres

GRC Geociències Marines, Dept. d'Estratigrafia, Paleontologia i Geociències Marines, Universitat de Barcelona, E-08028, Barcelona, Spain.

* Corresponding author: Tel +34-934021361; Fax +34-934021340.
E-mail address: tonim@natura.geo.ub.es (A. Calafat)

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ABSTRACT

Particle flux data were obtained from one instrumented array moored under the direct influence of the Almeria-Oran Front in the Eastern Alboran Sea, Western Mediterranean Sea, within the frame of the “Mediterranean Targeted Project II – MAss Transfer and Ecosystem Response” (MTPII-MATER) EU-funded research project. The mooring line was deployed from July 1997 to May 1998 and was equipped with three sequential sampling sediment trap-current meter pairs at 645 m, 1170 m and 2210 m (30 m above the seafloor). The settling material was analysed to obtain total mass, organic carbon, opal, calcium carbonate and lithogenic fluxes. Qualitative analyses of SST and SeaWiFS images allowed monitoring the location and development of the Western and Eastern Alboran Sea gyres and associated frontal systems to determine their influence on particle fluxes.

Particle flux time series obtained at the three depths showed a downward decrease of the time-weighed total mass flux annual means, thus illustrating the role of pelagic particle settling. The total mass flux was dominated by the lithogenic fraction followed by calcium carbonate, opal and organic carbon. The time series at the various depths were rather similar, with two strong synchronous biogenic peaks (up to 98 mg $m^{-2}d^{-1}$ of organic carbon and 156 mg $m^{-2}d^{-1}$ of opal) recorded in July 1997 and May 1998. Through comparing the fluctuations of the lithogenic and calcium carbonate-rich fluxes with the biogenic flux we observed that the non-biogenic fluxes remained roughly constant, while the biogenic flux responded strongly to seasonal variations throughout the water column.

Overall, the temporal variability of particle fluxes appeared to be linked to the evolution of several tens of kilometres in length sea surface hydrological structures and circulation of the Alboran Sea. Periodic southeastward advective displacements of waters from upwelling events off the southern Spanish coast were observed on SST and SeaWiFS images. In between these periods, widespread phytoplankton blooms were observed. The influence of the varying surface structures resulted in changes in the biogenic particle flux. For example, we observed an opal pulse in April 1998 that resulted from a diatom-rich highly productive frontal surface situation above the mooring line.

Estimation of the annual organic carbon export and calculation of a seasonality index indicate that the overall dynamics of the carbon reservoir within the Eastern Alboran Sea appears to be strongly influenced by the sea surface hydrological structures.

***Keywords*:** Particle fluxes; Organic carbon; Sediment traps; Satellite imagery; Mediterranean Sea; Almeria-Oran Front

2.1. INTRODUCTION

The Alboran Sea is the transitional area connecting the Atlantic Ocean to the Mediterranean Sea. It is bounded by the Iberian margin to the north and the North African margin to the south. Surface circulation in the Alboran Sea is characterised by the entrance of a 200-300 m thick jet of Atlantic Surface Water, which becomes more saline by mixing with water of Mediterranean origin thus forming the Modified Atlantic Water (MAW) as it travels into the Alboran Basin. This Atlantic jet forms two almost permanent anticyclonic gyres, namely the Western Alboran Gyre (WAG) and the Eastern Alboran Gyre (EAG), before it flows eastwards along the Algerian coast. Both gyres exhibit large variations in structure and can disappear entirely for periods of weeks to months (Heburn and La Violette, 1990; Viudez et al., 1998).

The interaction of the Atlantic jet with the denser and more saline Mediterranean water results in the formation of a quasi-continuous geostrophic front along the northern edge of the gyres and at the eastern boundary of the EAG, which is known as the Almeria-Oran Front (AOF) (Tintore et al., 1988). The AOF can be clearly observed on satellite images (Arnone et al., 1990; Folkard et al., 1994), its position and intensity depending on the development and extension of the EAG. The AOF northern end detaches from the Spanish coast between Almeria and Cartagena, while its southern end terminates around Oran on the North African coast.

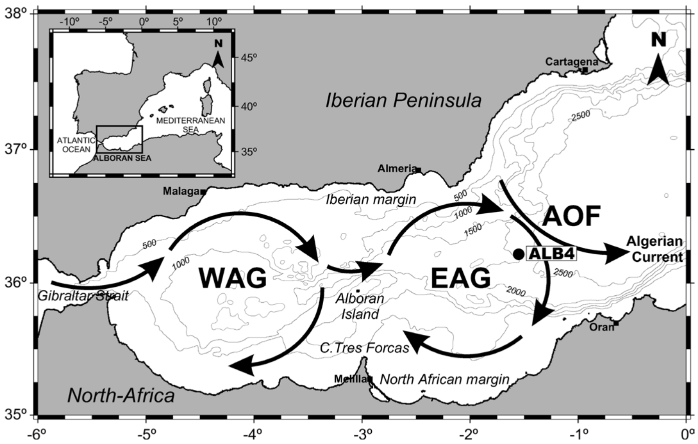

Figure 2.1. Geographical, physiographic and oceanographic settings of the study area. The location of the mooring line ALB4 deployed from June 1997 to May 1998 in the Eastern Alboran Sea as part of the EU MTP II-MATER project, and the theoretical surface circulation in the Alboran Sea (WAG, Western Alboran Gyre; EAG, Eastern Alboran Gyre; AOF, Almeria-Oran front) are shown. Countours are every 500 m.

Previous studies on the interaction between physical and biological processes in the Alboran Sea have revealed high fertility and enhanced production at the northern edge of the WAG, where the existence of a frontal system was first reported by Cheney and Doblar (1982). The upwelling of cold, nutrient-rich subsurface waters, either wind-induced or due to north-south excursions of the Atlantic jet (Sarhan et al., 2000), allows the phytoplankton communities to bloom (Packard et al., 1988; Minas and Coste 1991; Garcia-Gorriz and Carr, 1999, 2001; Ruiz et al., 2001) and reinforces biogenic particle fluxes (Fabres et al., 2002). An upwards advection of nutrients and subsequent increases of primary production have been noted by several authors also in the AOF as related to the cross-frontal circulation (Lohrenz et al., 1988; Tintore et al., 1988; Arnone et al., 1990; Raimbault et al., 1993; Claustre et al., 1994; Videau et al., 1994; Fiala et al., 1994; Zakardjian and Prieur, 1998; Fielding et al., 2001). However, only Peinert and Miquel (1994) performed actual measurements of particle fluxes in the AOF and discussed the influence of the AOF on particle export prior to our study. These measurements, carried out by means of drifting traps, were severely limited by their duration (1 to 1.5 days in mid-May 1991) and water depth (100 m to 300 m).

In this paper our aim is to demonstrate that the pronounced spatial and temporal variability of the hydrological structures off the Spanish coast in the Alboran Sea and their influence on the AOF determine the amounts and character of the downward particle fluxes below the front. We present the results from the first year-round particle flux and deep currents monitoring experiment in the Eastern Alboran Sea below the AOF. Organic carbon, opal, calcium carbonate and lithogenic fluxes were measured and cross-related to physical and biological forcing as observed on satellite imagery from this key area at the transition between the Atlantic Ocean and the Mediterranean Sea.

2.2. METHODS

2.2.1. Sediment trap and current meter array

One mooring line, named ALB4, was deployed in the Eastern Alboran Sea at a depth of 2240 m halfway between Almeria and Oran (Fig. 2.1). The line was equipped with three Technicap PPS3 sequential-sampling sediment trap – Aanderaa RCM-7/8 current meter pairs placed at 645 m (upper pair), 1170 m (middle pair), and 2210 m (near-bottom pair) of water depth. Samples were collected over 11 months, divided into three successive deployment 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 between April 11th and May 16th when sampling was performed at 3-day intervals. For the purpose of this paper, those three-day samples have been averaged over 9-day intervals to get similar resolution for the entire sampling period. A total of 36 samples representing 291 sampling days were recovered at upper and middle traps while samples from the near-bottom trap were only 24 representing 123 days because of the failure of the rotating motor during sampling period I. The design of the 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).

Current meters recorded speed and direction at an hourly frequency during the three deployment periods. Recording of current direction failed during period II at the uppermost and near-bottom levels, and data looked inconsistent at the middle level during periods II and III. For these reasons, only current data from periods I and III are presented.

2.2.2. Analytical methods

Sediment trap samples were processed in the laboratory according to the procedure described by Heussner et al. (1990), and main constituents were measured following Fabres et al. (2002). Large swimming organisms were removed by wet sieving through a 1 mm nylon mesh, while organisms <1 mm were hand-picked under a microscope with fine tweezers. Samples were (i) repeatedly split into aliquots using a high precision peristaltic pump in order to obtain 10-20 mg sub-samples, (ii) filtered through glass-fibre prefilters for carbon 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 for 24 h for dry weight determination.

Total carbon and organic carbon were measured with a Fisons 1500 elemental analyser. Samples for organic carbon analysis were first decarbonated 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 was contained within the calcium carbonate fraction. Precision and accuracy of the carbon measurements were tested against the Canadian National Research Council certified estuarine sediment MESS-1 (Berman, 1990). Short-term precision (mean standard deviation from successive runs) for the replicate analyses of carbon (n=8 samples) averaged ±2.3% of the measured values, and mid term precision from runs during three months (n=24 samples) was ±2.9%. The correspondence between measured carbon values, 3.05 ± 0.04% (95% confidence interval), and the standard certified carbon values, 2.99 ± 0.09%, indicates excellent accuracy.

Biogenic silica 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 was applied to obtain the opaline Si concentration. Corrected Si concentrations were transformed to opal after multiplying the first by a factor of 2.4 (Fabres et al., 2002). Short-term precision of opal measurements averaged 4.5% of the measured values as determined from replicate analysis (n=3 or 4 samples) of seven trap samples covering a broad composition range (1.07% - 14.70%).

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

2.2.3. Remote sensing

Daily Sea Surface Temperature (SST) images from the Advanced Very High-Resolution Radiometer (AVHRR) installed on NOAA satellites were obtained from the Intelligent Satellite Data Information System (ISIS) of the Deutschen Zentrum für Luft- und Raumfahrt (DLR). We used these images to determine the surface circulation. Daily chlorophyll-a concentration images recorded by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) from September 1997 onwards, obtained through the website of the Marine Environment Unit of the Space Applications Institute (Joint Research Centre, European Comission) (Melin, 2000), were used to evaluate chlorophyll-a concentrations in surface waters and their relationship with hydrological structures.

2.3. RESULTS

2.3.1. Particle fluxes

Time-weighted mean total mass fluxes (TWF) and fluxes of main constituents (organic carbon, opal, calcium carbonate, and lithogenics), and maximum and minimum fluxes and relative contributions are shown in Table 2.1. TWF decreased from 483 mg $m^{-2}d^{-1}$ in the upper trap to 338 mg $m^{-2}d^{-1}$ in the middle trap and to 300 mg $m^{-2}d^{-1}$ in the near-bottom trap. TWF reduction with depth was 31% between the two upper traps and 11% between middle and the near-bottom trap, which represents a 38% overall reduction. These data point to a dominance of vertical particle settling in the area under the influence of the AOF.

Total mass flux time series for the three levels are shown in Figure 2.2, where rather similar patterns could be observed during summer 1997 and spring 1998. Two strong peaks were recorded synchronously in the upper and the middle traps in mid July 1997 and beginning of May 1998. While there is no record from the near-bottom trap from July 1997, the mass flux peak was recorded with a 9 day delay in May 1998. Total mass flux peaks were also recorded in autumn and winter, although the correspondence between peaks at various depths is less obvious or lacking. A noticeable peak occurred in December 1997 and was transferred from the upper to the middle and finally to the near-bottom level within a few weeks. Peaks were also noted at the end of January 1998 in the upper trap only and at the beginning of March 1998 in the middle trap only. The March 1998 peak represents the highest total mass flux recorded during the whole experiment. The general tendency of larger fluxes at the upper trap was thus broken occasionally as in December 1997, when the largest fluxes were recorded by the deeper trap, and in March 1998 as already explained (Fig. 2.2).

Table 2.1. Descriptive statistics of total mass and main constituents fluxes (mg $m^{-2}d^{-1}$) and percentages (%) for the three trap depths of the monitoring site ALB4 in the Eastern Alboran Sea.

Depth	Statistics	Total mass	Organic carbon	Opal	Carbonate	Lithogenics
645 m	TWF (mg $m^{-2}d^{-1}$)	**482.86**	**26.43**	**31.12**	**108.53**	**290.34**
	(%)		**5.47**	**6.44**	**22.48**	**60.13**
	Max (mg $m^{-2}d^{-1}$)	1136.98	98.43	155.98	245.31	672.60
	(%)		11.04	17.49	30.51	69.19
	Min (mg $m^{-2}d^{-1}$)	121.26	7.41	4.08	29.36	59.93
	(%)		3.26	1.97	12.65	41.66
1170 m	TWF (mg $m^{-2}d^{-1}$)	**337.80**	**16.61**	**22.39**	**78.91**	**206.18**
	(%)		**4.92**	**6.56**	**23.14**	**60.46**
	Max (mg $m^{-2}d^{-1}$)	1340.93	70.39	106.21	278.46	977.81
	(%)		11.48	15.74	35.15	74.46
	Min (mg $m^{-2}d^{-1}$)	38.57	1.72	0.41	8.21	25.37
	(%)		2.07	0.87	10.70	42.90
2210 m	TWF (mg $m^{-2}d^{-1}$)	**299.60**	**10.54**	**12.35**	**85.79**	**188.86**
	(%)		**3.52**	**4.12**	**27.76**	**61.11**
	Max (mg $m^{-2}d^{-1}$)	1053.01	33.05	42.28	281.21	670.06
	(%)		6.48	11.83	36.83	66.95
	Min (mg $m^{-2}d^{-1}$)	65.18	2.19	1.50	21.42	37.87
	(%)		2.89	1.81	23.86	44.26

Time-weighted fluxes of total mass and main constituents (TWF) are highlighted in bold. Organic matter is used instead of organic carbon when calculating %lithogenics.

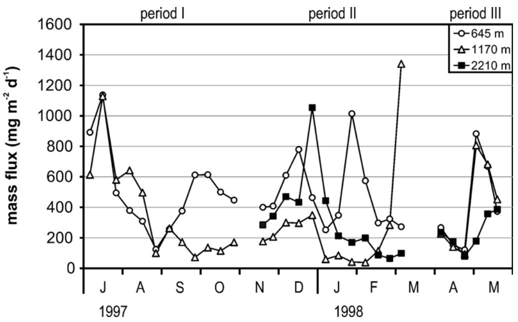

Figure 2.2. Time-series plot of total mass flux as measured in the ALB4 site sediment traps deployed at 645 m, 1170 m and 2210 m of water depth.

The fluxes of the main constituents and their relative contributions time series (organic carbon, opal, calcium carbonate and lithogenics) are shown in Figure 2.3. In percentages, the abundances measured in the trapped material showed the following ranges of variation: organic carbon 2-11%, opal 1-17%, calcium carbonate 11-37%, and lithogenics 42-74% (Fig. 2.3). Organic carbon and opal followed a rough seasonal pattern, with their relative abundances increasing dramatically at all depths, up to the highest recorded values during the summer 1997 (July) and spring 1998 (May) peaks. Both the organic carbon and opal fluxes reached top values of 98 mg $m^{-2}d^{-1}$ and 156 mg $m^{-2}d^{-1}$ in July 1997 at the 645 m depth trap, respectively. The delay between the organic carbon and opal peaks in upper, middle and near-bottom traps was estimated to be up to 9 days as observed in July 1997 for both constituents and in May 1998 for the opal flux only (Fig. 2.3a, b). Organic carbon and opal fluxes decreased continuously from the July 1997 peak until the end of August when a prolonged period of comparatively low fluxes punctuated by minor variations preceded the May 1998 peak. During these intervening periods, the most pronounced highs were observed in December 1997 and January-February 1998 for the upper trap, in early March 1998 for the middle trap, and at the end of December 1997 for the near-bottom trap (Fig. 2.3a, b).

The calcium carbonate flux displayed half a dozen peaks (July, September-October, and December 1997, and January, March and May 1998) whose impact on the various monitored depth levels was highly variable (Fig. 2.3c). Extreme flux values ranged from near zero to almost 300 mg $m^{-2}d^{-1}$. The highly variable calcium carbonate flux was smoothed when converted into a percentage curve with values ranging from 10% to about 38%. While an overall rise could be interpreted from December 1997 to April 1998 in the percentage curve, the flux record showed that from the end of December 1997 to mid March 1998 the behaviour was just the opposite, with the calcium carbonate flux decreasing continuously from 250-300 mg $m^{-2}d^{-1}$ to 0-50 mg $m^{-2}d^{-1}$.

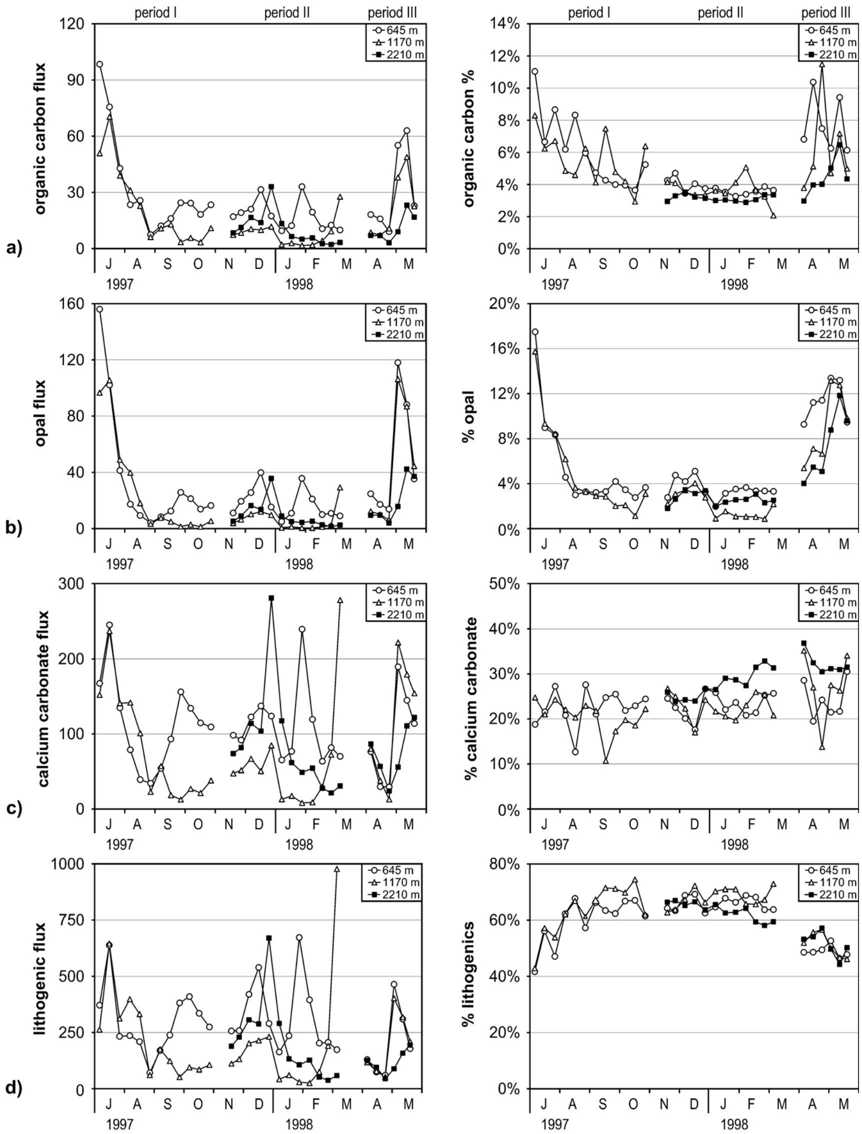

Figure 2.3. Time-series plots of (a) organic carbon, (b) opal, (c) calcium carbonate and (d) lithogenic fluxes (mg $m^{-2}d^{-1}$, left) and relative contributions (%, right) as measured in the ALB4 site sediment traps deployed at 645 m, 1170 m and 2210 m of water depth.

Lithogenics were, followed by calcium carbonate, the most abundant constituent. Because of their overall significance both constituents showed a similar pattern and essentially matched total mass fluxes at the three trap levels (Figs. 2.2 and 2.3c, d). Lithogenics never fell below 40% of the total mass flux and exceeded 60% most of the time (Fig. 2.3d). The highest flux (978 mg $m^{-2}d^{-1}$) was recorded in the middle trap during the March 1998 peak.

The lithogenic percentage record roughly mirrors the organic carbon and opal percentage records, with lower percentages of lithogenics corresponding to higher percentages of organic carbon and opal, and vice versa (Fig. 2.3a, b and d). The lowest percentages of lithogenics could be observed at both ends of the time series (July 1997 and April-May 1998), coinciding with the highest percentages of organic carbon and opal. The opposite occurred in autumn and winter, when lowest percentages of organic carbon and opal corresponded to highest percentages of lithogenics. The calcium carbonate time series showed a poorly defined character (Fig. 2.3c), perhaps indicating a mixed origin from biogenic and terrigenous sources. Overall, the above observations could indicate that the lithogenic flux fluctuates around a rather constant value year-round. Peaks at the beginning and at the end of the time series (Fig. 2.3d) were not essentially different from those throughout the rest of the year. Nevertheless, the fluxes of organic carbon and opal were higher at spring and summer, with the flux of lithogenic constituents representing a lower percentage, while in winter the organic carbon and opal fluxes were lower, and the lithogenic component represented a higher percentage. This would therefore imply that the seasonal cycle was associated to the biogenic constituents and not lithogenics and calcium carbonate.

2.3.2. Current meter data

Table 2.2 displays the basic statistics for current speed and direction recorded by the current meters moored jointly with the sediment traps (see section 2.1.). Data show a prevailing southeastward current down at all depths, with residual directions oriented SSE at the upper level, and ESE at the middle and near-bottom levels. Average speeds from the various levels ranged from 2.5 ±1.6 cm s^{-1} at the middle level to 3.2 ±1.9 cm s^{-1} at the near-bottom level. The recorded speeds were all well below 12 cm s^{-1}, the threshold value above which currents significantly affect the collection of settling particles by sediment traps (Gardner et al., 1997), therefore trapping of settling particles during our experiment was not biased because of current activity.

Table 2.2. ALB4 site current meter data statistics.

Depth (m)	Recording periods	Average speed ± S.D. (cm s^{-1})	Max. absolute speed (cm s^{-1})	Max. W-E speed (cm s^{-1})	Max. S-N speed (cm s^{-1})	Residual direction (º from N)
645 m	I, III	2.78 ± 1.99	8.95	8.93	-8.44	150
1170 m	I	2.54 ± 1.58	10.40	10.20	-5.76	134
2210 m	I, III	3.19 ± 1.91	11.85	11.60	8.28	136

Average speed, maximum absolute speed, maximum W-E and S-N speeds and residual directions are shown.

Average 24h current stick plots are shown in Figure 2.4. The average SE direction of the flow indicates that the prevailing circulation in the Eastern Alboran Sea is anticylonic, as depicted in Fig. 2.1. According to this circulation scheme and the position of the mooring line within it, the expected direction of the flow in the upper layer is SE. The consistency of our current meter records at 645 m, 1170 m and 2210 m proves that the influence of the anticyclonic circulation reaches the bottom layer.

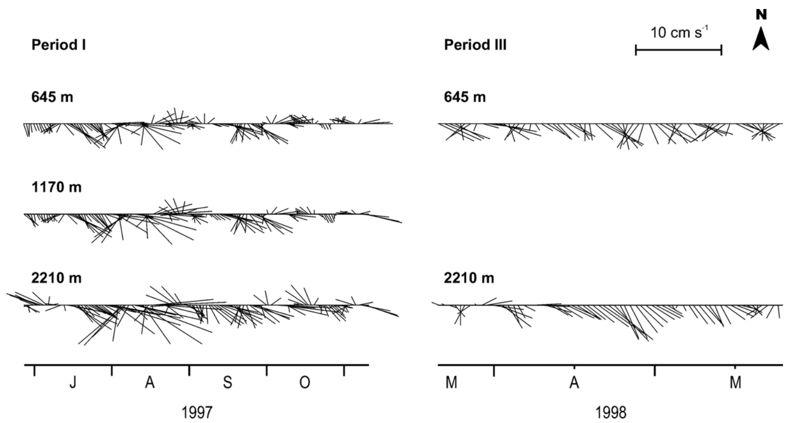

Figure 2.4. Average 24 hour current stick plots as measured in the ALB4 current meters deployed at 645 m, 1170 m and 2210 m depth. No data is available from 11/11/1997 to 22/3/1998 (monitoring period II, see section 2.1.).

Signals of eddy-like activity were recorded simultaneously at the three depths during the entire monitoring period I and, to a much lesser extent, during period III. These results are in agreement with those obtained by Millot et al. (1997) and Ruiz et al. (2002), who recorded an eastward flow of all water masses between 0º and 5ºE off Algeria and suggested that mesoscale eddies can reach deep layers while propagating eastward along the Algerian continental slope. The eddies we have interpreted could be, however, also associated to intermediate waters since we do not have evidence that they were also present at the surface.

2.3.3. Sea surface events from satellite data

The qualitative analysis of AVHRR-SST and SeaWiFS images allows for tracking the evolution of oceanographic structures and associated biological processes. AVHRR-SST images are particularly useful in locating and tracking sea surface gyres, and thus the path of the Atlantic jet and the position of the AOF. SeaWiFS images, available since September 1997, are particularly helpful in monitoring phytoplankton dynamics as related to hydrological structures. Joint analysis of both types of images allowed for identification of four main productive events during the monitoring period corresponding to specific hydrological conditions. These events occurred in June 1997, November 1997, December 1997-January 1998, and April 1998.

The June 1997 event (Fig. 2.5a) started at the beginning of the month and was characterised by the upwelling of cold waters from 5º to 3º W along the southern Spanish coast. An intrusion of cold waters to the Eastern Alboran Sea could be also seen on the AVHRR-SST image of Figure 2.5a. Garcia-Gorriz and Carr (1999, 2001) identified an associated highly productive event based on phytoplankton pigment concentrations observed by means of the Ocean Color and Temperature Scanner (OCTS). The WAG was well developed and shifted northward while the EAG was compressed southward. According to Vargas-Yañez et al. (2002) this would be a typical summer situation when, because of the presence of the EAG, the current flows south of the Alboran Island in a NE direction, then it turns to the coast and finally to the southeast at ALB4 mooring site, as shown in Figure 2.1.

The November 1997 event started at the beginning of the month and lasted until the first days of December 1997. The main feature was the upwelling of cold waters from 4.5º to 2º W along the Spanish coast that were later advected into the Algerian Basin (Baldacci et al., 2001). Both the WAG and the EAG were well developed and centred around their mean positions, with a robust AOF from Almeria to Oran. The advection of nutrient-rich waters led to an increase in chlorophyll-a between the Spanish coast and the boundaries of the gyres from November 10th onwards. Two patches particularly rich in chlorophyll-a coincided with the areas where advection of upwelled waters was more intense (Fig. 2.5b).

The third event took place in late December 1997 and January 1998. It consisted of a rather uniform bloom generating moderate pigment concentration over the entire area (Garcia-Gorriz and Carr, 2001). Vargas-Yañez et al. (2002) pointed out southward drifts of the Atlantic current, that gave birth to three gyres compressed against the eastward flowing jet and the North African coast (Fig. 2.5c).

The fourth event began in mid-April 1998 coinciding with the upwelling of cold waters along the southern Spanish coast from the Strait of Gibraltar to Cape Gata. AVHRR-SST imagery shows an advected filament south of Almeria (Fig. 2.5d). WAG was shifted westward and EAG was replaced by a set of eddies formed by the eastward flowing Atlantic current to the east of Cape Tres Forcas. SeaWiFS imagery shows two high productive areas, a northern one at the upwelling off the Spanish coast, and a southern one following the path of the eastward jet and associated gyres (Fig. 2.5d).

It must be noted that both the WAG and the EAG disappeared between the two later events reported, from February to March 1998. During that period the Atlantic jet flowed in a coastal mode close to the North African shores (Vargas-Yañez et al., 2002).

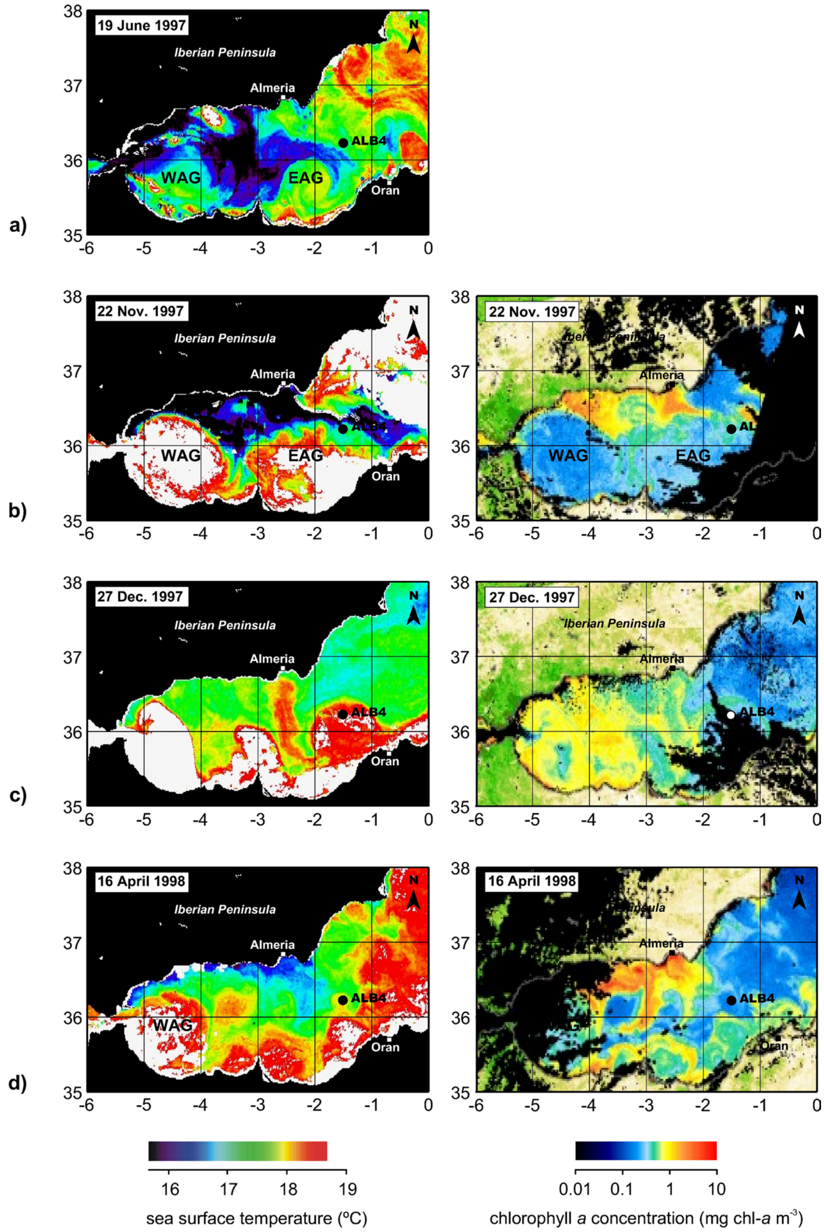

Figure 2.5. Sea Surface Temperature (AVHRR, left) and chlorophyll-a concentration (SeaWiFS, right) images illustrating the main upwelling and productivity events that occurred during the particle flux monitoring experiment in the Alboran Sea: a) June 1997, b) November 1997, c) December 1997 and d) April 1998. SeaWiFS was not in operation yet in June 1997.

2.4. DISCUSSION

Total mass and biogenic fluxes indicate that vertical particle settling is coupled to the phytoplankton concentration in surface waters. In order to know how this coupling occurs, the variability and complexity of the Alboran Sea hydrological structures have to be taken into account. The following sections constitute an effort to unveil the variety of processes and their interactions affecting downward particle fluxes in the vicinity of the AOF.

2.4.1. Biological and physical control on particle fluxes

Several authors (La Violette, 1984; Minas and Coste, 1991; Baldacci et al., 2001; Ruiz et al., 2001) have reported an eastward mass transfer in the Alboran Sea having a fertilization effect over large parts of the basin. We found, in addition, a north to south transfer that combined with the former results in a net southeastward advection of water, nutrients and chlorophyll. During our study, from June 1997 to May 1998, four advection events of this type were observed (see section 3.3 and Fig. 2.5). The biomass transfer from the northern side to the southern side of the Alboran Sea has been lately a matter of debate within the scientific community. Such an oceanographic connection between the northern and southern riparian of the Alboran Sea, first outlined by Garcia-Gorriz and Carr (1999), could have important consequences, for example on fish stock management.

The enhancement of phytoplankton populations in frontal areas of the Alboran Sea due to vertical supply of nutrients is well known after the studies of Lohrenz et al. (1988), Claustre et al. (1994), Fiala et al. (1994), Peinert and Miquel, (1994), Videau et al. (1994), Zakardjian and Prieur (1998), Moran and Estrada (2001), Youssara and Raymond (2001), and Arin et al. (2002). Garcia-Gorriz and Carr (2001) demonstrated that in the periphery of the WAG eddy-induced vertical supply of nutrients could account for 20-60% of the amount advected from coastal upwelling sites.

The strong correlation (r^2=0.89) between organic carbon and opal flux at the three trap depths (Fig. 2.3a, b) suggests a close relationship between organic carbon fluxes and siliceous phytoplankton blooming. The concurrent increases of organic carbon and opal both in absolute value and in relative composition (percentages) indicate the growth of diatoms under favourable upwelling / frontal conditions. However, the lack of information on other species prevents us from certifying that the upwelling is diatom-dominated. Notwithstanding, high abundances of diatoms have been previously documented north of the WAG by Moran and Estrada (2001) and Arin et al. (2002), and at the AOF by Lohrenz et al. (1988), Claustre et al. (1994), Fiala et al. (1994) and Videau et al. (1994). High opal fluxes were recorded in both areas by moored and drifting sediment traps (Fabres et al., 2002, 2003;

Peinert and Miquel, 1994). In addition, Barcena et al. (2001) confirmed the presence of diatom-rich phytoplanktonic communities north of the WAG in July 1997 and May 1998, which was within our monitoring period. Thus, the fact that waters enriched by the upwelling events off the Spanish coast were advected southeastwards along with the similarity of the opal fluxes time series recorded during the same period at the northern part of the WAG by Fabres et al. (2002), give the highest likelihood that our opal peaks represent diatom-rich, if not diatom-dominated, phytoplankton communities. This finding indicates an efficient connection between the Western and the Eastern Alboran seas also in terms of downward transfer of biogenic material. Observations by Baldacci et al. (2001) and Garcia-Gorriz and Carr (2001) on physical and optical features during the same monitoring period further support our interpretation.

The position and development of the WAG and the EAG are crucial in controlling the spreading of the fertilised waters to the east and the south, as observed during the June 1997, November 1997, December 1997-January 1998, and April 1998 sea surface events (Fig. 2.5).

The SST image of June 1997 shows a well-developed WAG and an EAG which was shifted southwards. The cold upwelled waters were advected southeastwards as controlled by the gyres until reaching the position of the mooring station ALB4. The large biogenic peak recorded at the start of the experiment (July 1st, 1997) resulted from a nutrient-rich advection event which was already ongoing by mid-June, as illustrated by the SST image of the 19th of June (Fig. 2.5a), also identified by Garcia-Gorriz and Carr (1999) by means of the Ocean Color and Temperature Scanner (OCTS). The arrival of nutrient and phytoplankton-rich waters above the mooring site would correspond to the remarkable enhancement of the organic carbon and opal fluxes (Fig. 2.3a, b).

In November 1997, an upwelling event triggered a phytoplankton bloom offshore the Spanish coast. The WAG and the EAG occupied central positions in each subbasins and were well developed (Fig. 2.5b), with an advection of nutrient-rich waters into the Eastern Alboran Sea extending from Almeria to Oran. Opal and organic carbon flux peaks of medium magnitude were recorded at the upper and near-bottom traps ca. 20 and 30 days later, respectively (Fig. 2.3a, b). Although at first sight this event was very weakly or not recorded by the middle trap, some evidence has been found to support a down transfer of the biogenic signal through the water column. A valuable source of information about the characteristics of the trapped material is the ratio between major constituents. The biogenic silica to inorganic carbon ratio (Si/IC) reflects the silica-dominance/carbonate-dominance of the phytoplankton community. Si/IC atomic ratio evolution throughout the sampling period (Fig. 2.6) shows a vertical transfer (from 645 m down to 1170 m, and then to 2210 m) of the biogenic signal of the particulate matter during the November-December 1997 period.

Furthermore, opal relative contributions record a weak increase at the three depths. These data suggest not only a decrease in the amount of settling material between the upper and the near-bottom traps but also a vertical transfer of the biogenic character, as reported in the Western Basin by Fabres et al. (2003). Note that the calcium carbonate and lithogenic fluxes roughly parallel those from the biogenic constituents, with the middle trap being the less responsive to the flux increase (Fig. 2.3c, d). The fact that the highest fluxes corresponded to the near-bottom trap could indicate a near-bottom advective input of particulate material that would add to the amount derived from vertical settling. However, the lack of current meter data during that period (period II, see section 2.1.) prevents elucidating any eventual influence of the current regime that could account for the observed peculiar behaviour of the particulate material fluxes.

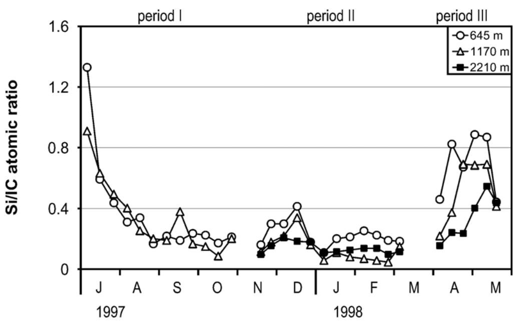

Figure 2.6. Time-series plot of Si/IC atomic ratio as obtained from the ALB4 site sediment trap samples at 645 m, 1170 m and 2210 m of water depth.

The late December 1997-January 1998 event increased chlorophyll-a concentration to intermediate levels (< 1 mg chl-a m^{-3}) over most of the basin (Fig. 2.5c). During this event, three surface gyres developed, as could be observed on the SST image of December 27^{th}. Approximately one month later, by the end of January 1998, large calcium carbonate and lithogenic fluxes and moderate organic carbon and opal fluxes were recorded at the upper trap only (Fig. 2.3). Following Lohrenz et al. (1988), it could be hypothesised that the extensive bloom observed was caused by destratification of the water column affecting large parts of the Alboran Basin. This could lead to a situation less favourable to the development of opal-rich phytoplankton communities than upwelling events. Therefore, calcareous phytoplankton could become dominant and the settling of lithogenic particles at least down to several hundreds of meters would be favoured because of vertical mixing. A noticeable difference between this winter event and the preceding one is that the increase was much larger at the upper trap than in the intermediate and the near-bottom ones, which showed no increase at all and a minor increase of the calcium carbonate and lithogenic fluxes at the beginning of February 1998, respectively (Fig. 2.3). This apparent lack of depth transfer of the peaks of the various components remains difficult to explain. It might be related to a combination of advection, trapping by deep turbulence, and degradation and dilution during settling, but none of these is convincing enough. Autumn 1997 was warmer than usual, which produced a late destratification and fertilization of the basin (Garcia-Gorriz and Carr, 2001). Pigment concentrations in autumn and winter 1997-1998 were lower than those recorded in summer 1997 and spring 1998 (Garcia-Gorriz and Carr, 1999), which suggests a relation between processes affecting the vertical transfer of particles either to intermediate and/or near-bottom levels and processes associated to surface pigment concentration. Another difference with respect to the spring and summer blooms, represented by the April 1998 (see section 3.3 and further down) and June 1997 events, is that since the four constituents were augmented in the upper trap, the relative composition of the settling material remained essentially stable. In spring-summer, the organic carbon and opal magnification was more powerful than the increase in calcium carbonate and lithogenics, and this produced a change in the relative composition of the particle fluxes with respect to the autumn-winter blooms.

At the very beginning of March 1998, the intermediate trap detected a sudden increase, unrelated to any noticeable surface or near-bottom event that affected all constituents, especially calcium carbonate and lithogenics (Fig. 2.3). Unfortunately, the decreasing branch of this peak was not recorded because of a temporal interruption to monitoring due to maintenance works. The fluxes of the biogenic constituents were about the same as recorded at the upper and near-bottom traps in the late autumn-winter preceding events. While the lithogenic flux was the highest recorded at all levels during the whole experiment, the calcium carbonate flux also reached maximum values comparable to those recorded by the near-bottom trap following the November 1997 surface event. The origin of these isolated intermediate level peaks is unknown, although we can speculate about a more than two month delayed transfer of the December 1997-January 1998 surface event initially recorded by the upper trap only and also about a significant advective contribution at about 1200 m of water depth. In any case, the record of enhanced fluxes distinctly affecting shallow, intermediate and deep levels illustrates the complexity of downward particle transfer in the area of the AOF.

In April 1998, the Atlantic jet flowed in an eastward direction forming several eddies along the North African coast, the WAG was compressed to the south, and coastal upwelling occurred along most of the southern Spanish coast (Fig. 2.5d). High chlorophyll-a concentrations (up to 10 mg chlorophyll-a m^{-3}) were detected along the jet and at the northern part of the basin, with fertilization extending to most of the basin. According to Sarhan et al. (2000), the southward shift of the Atlantic jet could enhance productivity on the northern part of the basin. This mechanism implies that the jet was flowing to the northeast in previous days, and then it migrated to the south, leaving room for subsurface waters and enhancing productivity to the north. The actual situation was probably more complex than hypothesised by Sarhan et al. (2000) since the Atlantic jet was flowing close to the North African coast (Vargas-Yañez et al., 2002) and the WAG was absent before spring 1998. Organic carbon and opal fluxes increased dramatically at the very end of April 1998, accompanied by parallel increases of the calcium carbonate and lithogenic fluxes (Fig. 2.3). Peak flux values were higher in the upper and middle traps and lower in the near-bottom trap. There is no loss of material between the various depths, and the high biogenic fluxes recorded synchronously at the three depths strengthen the hypothesis that the processes affecting the vertical transfer of particles are linked to the processes governing pigment concentration in surface waters, at least under the hydrological conditions existing in spring-summer as observed during our experiment. The upwelling off the Spanish coast, and the establishment of strong frontal situations linked to the reactivation of the WAG, which had disappeared during the two previous months (Garcia-Gorriz and Carr, 1999; Vargas-Yañez et al., 2002), led to a net biogenic flux enhancement. Flux augmentation was likely related to the growth of phytoplankton populations due to front-induced vertical injection of nutrients resulting in higher chlorophyll contents and production as previously reported by Lohrenz et al. (1988), Fiala et al. (1994), Videau et al. (1994), Claustre et al. (1994), Peinert and Miquel (1994), Zakardjian and Prieur (1998), and Youssara and Raymond (2001).

Therefore, both coastal and front-induced upwelling controlled pigment distribution in the study area as could be observed after combining SST and SeaWiFS images (Fig. 2.5). The soundness of using SeaWiFS images as indicators of the distribution of potential biogenic particle fluxes at the scale of the basin is reinforced by the good estimations achieved by Moran and Estrada (2001) on the regional primary production from superficial chlorophyll-a data in the Western Alboran Sea. The subduction of surface waters by across-front ageostrophic motion may be a significant process to be taken into account when trying to correlate surface chlorophyll concentrations and hydrology with particle fluxes into the water column. Fielding et al. (2001) observed this type of motion resulting in phytoplankton patchiness in the subsurface.

2.4.2. Vertical transfer of a spring bloom

Concurrent opal and organic carbon flux peaks at various depths provide an excellent opportunity to calculate the vertical settling speeds of biogenic particles. The opal flux peak of spring 1998 was recorded synchronously at the upper and the middle traps in the cups that sampled from April 29th to May 7th and with a delay of 9 days at the near-bottom trap, in the cup that sampled from May 8th to May 16th. Accordingly, (2210m – 645m) / 18 days = 87 m d^{-1}, which is the minimum settling velocity for opal particles.

The organic carbon flux peak was in turn registered synchronously at the three traps in the cup that sampled from May 8th to May 16th. Following the same procedure as above, it yields a minimum settling velocity of 117 m d^{-1} for organic carbon particles.

These values give a range of settling velocities that fit with that of diatom blooms (up to 117±56 m d^{-1}) as predicted by Alldregde and Gotschalk (1989). The rapid sinking of diatom blooms is well known not only in the Alboran Sea (Fabres et al., 2002) but also in other Mediterranean areas, such as the Adriatic Sea (Miserocchi et al., 1999). According to the authors cited in section 4.1, diatoms are responsible for most of the primary production in the AOF. Water subduction processes, as those reported at the end of the former section, could further favour fast diatom sinking in frontal settings (Allen et al., 2001; Fielding et al., 2001). Moreover, Claustre et al. (1994) highlighted the significant contribution to organic matter exportation in such a situation by the production of fast sinking faecal material associated with siliceous aggregates.

Data from period III (see section 2.1) perfectly illustrate that flux data and relative contributions of the various constituents do not necessarily match. The left column in Figure 2.3 shows that the flux of organic carbon and opal decreased continuously from the beginning of the period to April 27th. This evidences that the amount of biogenic settling material before the bloom was lessened each day. Such a decrease was common in the four constituents and so it was reflected in the total mass flux (Fig. 2.2). Until April 28th the decrease in the calcium carbonate and lithogenic fractions was even higher than the decrease in organic carbon and opal, and that is why the percentages of the biogenic constituents increased.

2.4.3. Allochtonous inputs and the role of advection

As formerly stated, the two dominant constituents in terms of percent contribution to the total mass flux in ALB4 were the lithogenic and calcium carbonate fractions (Fig. 2.3). While peaks of biogenic constituents could be explained as related to coastal upwellings, fronts and biological production in surface waters, peaks of lithogenics and calcium carbonate must have a different explanation. To a large extent, the flux of biogenic constituents in the AOF responds in a way that is typical of open ocean environments dominated by inputs from the sea surface. The flux of lithogenics and calcium carbonate respond differently, in a way that is more typical of continental margin settings.

During the entire monitoring period, and in particular in autumn and winter, calcium carbonate and lithogenic flux peaks accompanying organic carbon and opal peaks were of considerable magnitude (Fig. 2.3). Several mass pulses at different depths were poorly related or unrelated to vertical entries of matter but were signals of lateral inputs. This applies to three marked lithogenic and calcium carbonate peaks by the end of January 1998 at 645 m, the beginning of March 1998 at 1170 m, and the end of December 1997 at 2210 m. A clear indication of advection is provided by the fluxes at relatively deeper traps exceeding those from shallower traps. Within these three events, the intermediate and near-bottom calcium carbonate peaks were higher than the one corresponding to the upper trap, and the intermediate lithogenic peak was higher than the ones corresponding to the upper and bottom traps, which were almost equal. The perfectly synchronous character of these three peaks points to a common origin of the calcium carbonate and the lithogenics.

Lithogenic input to the Alboran Sea is closely linked to fluvial sediment transport and airborne dust. Riverine material could include substantial calcium carbonate contributions. That the temporal evolution of mid-water (400-500 m of water depth) lithogenic fluxes in the Western Alboran Sea is mainly controlled by intermittent local fluvial discharge in autumn and winter, mostly from the Iberian Peninsula, has been convincingly shown by Fabres et al. (2002). The southeastward dominating circulation and the progressive sinking of riverine particles while travelling, favoured by biological scavenging, would extend this riverine signal to the east of the Alboran Sea and to deeper water levels.

An aeolian lithogenic deposition of 23 g $m^{-2}y^{-1}$ of windblown Saharan dust on the southeastern Iberian Peninsula has been reported by Diaz-Hernandez and Miranda-Hernandez (1997). This amount is in the upper range of those cited by Guerzoni et al. (1997) and represents 22% of the annual lithogenic flux collected by the upper sediment trap at the ALB4 station. As for riverine inputs, biological scavenging of aeolian dust in the upper ocean layers would result in their transfer through the water column down to the seafloor, as illustrated by the near-bottom trap lithogenic peaks.

An additional source of advected material might be the escape of resuspended particles, likely calcium carbonate-rich, from the continental shelf (Masque et al., 2003). The injection of supplementary amounts of settling particles from the shelf to the Western Alboran Basin intermediate and deep water levels was found by Fabres et al. (2002). Because of their nature, the middle and near-bottom trap peaks of December 1997 and March 1998 candidate to lateral particle transport from the northern continental shelf of the Alboran Sea. The lack of particle flux data from the 10th of March to the 31st of March because of mooring maintenance work could have prevented the near-bottom trap recording the lithogenic peak seen just before at 1170 m depth (Fig. 2.3c, d).

2.4.4. Export of organic carbon production and seasonality

The export ratio is the carbon flux measured at a given site as a proportion of the original primary production integrated through the euphotic zone (Honjo et al., 1995), i.e. the proportion of primary production exported from the surface layer as sinking organic carbon. According to May 1986 data from Lohrenz et al. (1988), primary production integrated over the upper 100 m was higher (880 mg carbon $m^{-2}d^{-1}$) in the MAW and the Algerian Current frontal region, which forms a continuum with the AOF (Fig. 2.1), than in Mediterranean Water north of the current (470 mg carbon $m^{-2}d^{-1}$). These values are of about the same order of magnitude as May 1991 estimates by Videau et al. (1994) in the AOF (800-1800 mg carbon $m^{-2}d^{-1}$) and in Mediterranean Water (500-700 mg carbon $m^{-2}d^{-1}$). Moran and Estrada (2001) also found similar results. Nevertheless, the primary production data of the study area we have used is that of Antoine et al. (1995) (548 mg carbon $m^{-2}d^{-1}$) since it is an annual estimate. Using Antoine's et al. (1995) primary production value an export ratio of 1.92% at 2210 m of water depth is obtained. This value is very similar to the 1.89% found from an empirical relationship that predicts the organic carbon flux at any depth as a function of the primary production rate and depth-dependent consumption described by Suess (1980). In addition, we have calculated the expected vertical distribution of particulate organic carbon using Martin's et al. (1987) algorithm. The flux at the upper trap has been taken as the primary flux. Organic carbon data from ALB4 fits almost perfectly with Martin's et al. (1987) curve. Measured values were 16.61 and 10.54 mg carbon $m^{-2}d^{-1}$ while calculated values of 15.86 and 9.19 mg carbon $m^{-2}d^{-1}$ have been obtained at 1170 m and 2210 m of water depth, respectively. This demonstrates, therefore, that pelagic settling governs organic carbon fluxes in the AOF region, which contrasts with the noticeable role of lateral inputs over lithogenic and calcium carbonate fluxes as described in the previous subchapters.

Few authors have published estimations on organic carbon export in the Mediterranean Sea. Miserocchi et al. (1999) and Boldrin et al. (2002) estimated a 2.4-2.7% export through 1000 m of water in the Adriatic Sea, and a 0.8% export through 2250 m in the Ionian Sea. At the ALB4 site, the exported carbon production during our experiment was 4.82% and 3.03% through 645 m and 1170 m of water depth, respectively. This moderately higher organic carbon export in the Eastern Alboran Sea to depths in excess of 500 m in comparison with other Mediterranean sites suggests that the hydrodynamic structures in the Alboran Sea behave as efficient conveyor belts of organic carbon down to deep ocean layers and to the sea floor. The impact of this mechanism on the carbon cycle of the area is certainly noteworthy.

A good indicator of the importance of fertilization events on the annual export fluxes of organic carbon and opal is the Flux Stability Index (FSI), which has been defined as the number of days required to reach 50% of the total organic carbon and opal flux (Lampitt and Antia, 1997). The FSI is usually obtained from graphs of the accumulated organic carbon and opal fluxes expressed as percentages of the total annual flux versus the accumulated time expressed in days (Fig. 2.7). Time series data are ranked according to the magnitude of the fluxes. FSI is measured as the time to reach half the annual flux. Low FSIs indicate highly variable sedimentation regimes, while high FSI values correspond to steadier sedimentation regimes. FSI can thus be used to assess seasonal signals on particle fluxes.

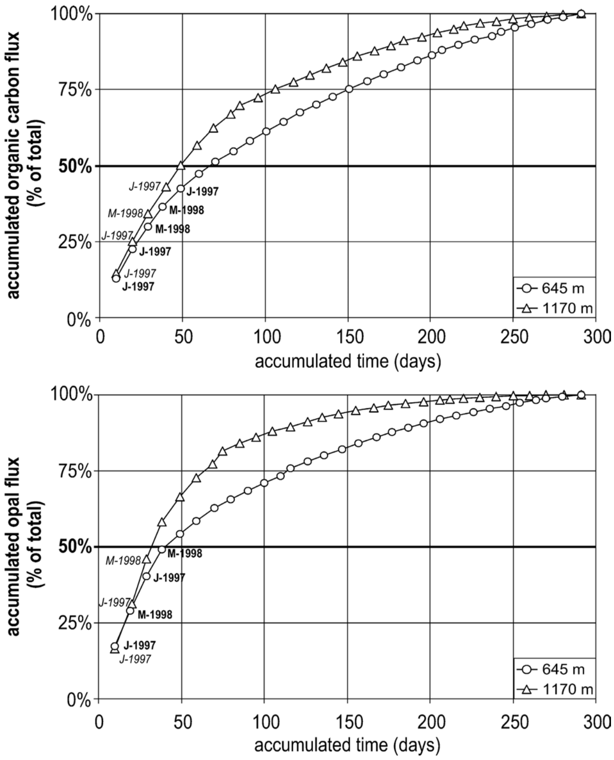

Figure 2.7. Accumulated organic carbon and opal flux curves versus accumulated time (days) calculated following Lampitt and Antia (1997). Time-series data is ranked according to the magnitude of the organic carbon and opal fluxes, and each value is expressed as the percentage of the annual flux. The Flux Stability Index (FSI) is calculated as the time to reach half the annual flux. Date labels of the cups contributing to FSI are also indicated in the figure (bold labels, 645 m depth; cursive labels, 1170 m depth).

The FSI values we have obtained for ALB4 are 70 and 38 days for carbon and opal in the upper trap, and 49 and 32 days in the middle trap (Fig. 2.7). Since the opal content range is wider (1-17%) than the organic carbon range (2-11%), opal FSIs are therefore smaller than the organic carbon ones. Following Berger and Wefer (1990), shape differences between curves, and hence FSI, as observed in Figure 2.7, would indicate a seasonal-influenced regime at 645 m and an episodic regime at 1170 m, with sharper pulses with increasing of water depth. Even though FSI has not been calculated for the near-bottom trap since monitoring period I data were lacking (Figs. 2.2 and 2.3), the near-bottom sedimentation regime is likely episodic too. Close examination of data reveals that samples accounting for half of the organic carbon and opal fluxes are those previously interpreted as representative of the arrival of phytoplankton-rich waters above the mooring site, i.e. those of July 1997 and May 1998. The relatively small FSI values found fit with a high export ratio through 1170 m of water thickness, with episodes of high export efficiency alternating with periods of relative quietness. This view strengthens the concept that seasonality of vertical fluxes in the Eastern Alboran Sea is closely related to the path of the Atlantic jet, and that unstable environments with variable hydrological structures export a higher proportion of their primary production than more stable areas, as suggested by Lampitt and Antia (1997).

2.5. CONCLUSIONS

The results from the first year-round sediment trap-current meter experiment in the Eastern Alboran Sea show that the downward particle flux is closely related to the spatial and temporal variability of the hydrological structures in surface waters. Sea-surface temperature and chlorophyll-a satellite images provide evidence of a southeastward transfer of phytoplankton-rich water from the upwelling off the Spanish coast by the Atlantic jet that directly influences downward particle flux in the AOF region. The spreading to the east and to the south of the fertilized waters enhancing phytoplankton development is controlled by the position and development of the WAG and the EAG, and is clearly noticed in the organic carbon and opal fluxes down the water column. There is, however, a noticeable lithogenic and calcium carbonate supply linked to autumn-winter fluvial sediment and airborne dust inputs and to lateral particle transport of resuspended material from the shelf. The largest biogenic flux peaks originate from sea surface production in spring and summer. Autumn and especially winter are marked by large calcium carbonate and lithogenic flux peaks distinctly affecting the various depth levels, a situation that is interpreted as largely due to advection. An important conclusion of our study is that matter and energy are transferred to intermediate and near-bottom levels following episodes of several weeks in length dominated by pelagic settling, in the case of biogenic components, and by a combination of vertical settling and advection for the calcium carbonate and the lithogenics.

While transfer of biogenic components from the sea surface to the upper trap at 645 m usually took a few weeks, transfer from this depth to the sea floor at >2000 m depth was only slightly delayed to practically instantaneous. In other words, transfer of the biogenic signal from the sea surface to the sea floor seems to occur in two steps with different speeds, slower in the uppermost water layer where water subduction and across-front movements play a crucial role, and faster over the rest of the water column. The intense hydrological dynamics and the associated turbulence in the uppermost layers could account for the delayed transfer, while the steadier condition prevailing at the depths where our traps were deployed may favour a quicker sinking.

A marked seasonal imprint on biogenic fluxes, closely connected to the annual hydrological variability, and a moderate to high export of organic carbon compared to other Mediterranean sites provide additional evidence on the fundamental control exerted by biophysical processes along frontal areas such as the AOF over the organic carbon cycle in the Alboran Sea.

Following a successful integration of satellite imagery data and particle flux monitoring over approximately one year, this study offers an unprecedented picture of the functioning of the Eastern Alboran Sea from various viewpoints. Because of this, its results and implications could be of interest to a large community of marine scientists, including physical oceanographers, biologists, paleoceanographers, sedimentologists and fisheries managers.

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