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Distribution and Fluxes of Dissolved Nutrients in the Strait of Gibraltar and its Relationships to Microphytoplankton Biomass

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This study presents the distribution and fluxes of dissolved nutrients in the Strait of Gibraltar, as well as their relationship to the microphytoplankton biomass distribution in the zone. In June and September 1997, the upper Atlantic inflowing waters west of the sill showed low nutrient concentrations. A significant increase was observed at the east of the sill. This increase can be attributed to mixing events at the sill between nutrient-rich Mediterranean Outflowing Waters (MOW) and the impoverished upper Atlantic Inflowing Waters (AW). Physical phenomena induced by tides at the sill act like an intermittent upwelling system and a part of the MOW nutrients re-circulate to the euphotic zone. Another factor is the injection of nutrient-rich North Atlantic Central Water (NACW) into the upper layer induced by the tides at the sill. These features along with the shallower position of the Atlantic-Mediterranean Interface (AMI) towards the north-east contribute to support high microphytoplankton biomass on the eastern side of the Strait. In the north-east, the injected nutrients are consumed by a high microphytoplankton standing stock. An accumulation of biomass is possible because the Atlantic-Mediterranean Interface (AMI) is shallower and the advection of cells is lower. In the south-east, AMI is deeper and the advection is higher. Nutrients are exported into the Alborán Sea with low consumption by phytoplankton.

Nitrate, phosphate and silicate fluxes between the Mediterranean Sea and Atlantic Ocean showed that Atlantic nitrate, phosphate and silicate concentrations compensate for about 21, 39 and 17% respectively of the outflowing losses. The results, extrapolated on an annual basis, show a net loss budget of nitrate, phosphate and silicate from the Mediterranean Sea of 3·00, 0·24 and $4{\cdot}82 \times 10^6$ tons year^{-1}, respectively. The evaluation of the flux of nutrients in the upper Atlantic current shows high variability due to biological and vertical mixing processes.

Keywords: nutrient fluxes; microphytoplankton; Atlantic inflow; Mediterranean Outflow; Gibraltar Strait

Introduction

The general oligotrophic regime of the Mediterranean Sea is explained by the circulation through the Strait of Gibraltar characterized by a surface inflow of relatively nutrient-depleted Atlantic water and a deep outflow of nutrient-rich Mediterranean Sea water, that generates a negative budget where nutrient export in the deeper layers exceeds the import (Thomsen, 1931; Schink, 1967; McGill, 1969; Coste, 1969; Béthoux, 1981; Coste *et al.*, 1988). The net loss is compensated by natural and anthropogenic sources such as atmospheric inputs, land and river discharge and nitrogen fixation (Béthoux & Copin-Montégut, 1986). In the Mediterranean Sea, the increase in nutrient load is starting to cause problems of eutrophication to coastal areas (UNESCO, 1988; Turley, 1999). Biological variables respond immediately to these phenomena, whereas the increase in deep nutrient concentrations has a lag of several decades (Béthoux, 1989).

The Strait of Gibraltar could be regarded as the place where deep Mediterranean nutrients are lost, although it has been shown to be a place of intensive mixing as part of the outflowing nutrients recover by physical processes induced by tides which contribute to supply nutrients to the euphotic zone (Minas *et al.*, 1991). However, it is uncertain what amount of nutrients are recovered by vertical mixing through the interface between in- and outflowing waters and the Atlantic inflow (Minas & Minas, 1993).

This study proposes new nutrients budgets between the Mediterranean Sea and the Atlantic Ocean based on the nutrient data set collected together with recent water transports calculated within a subproject entitled ' Fluxes and outflow from the Mediterranean '. These estimations may provide more realistic values for models on oceanic nutrient circulation.

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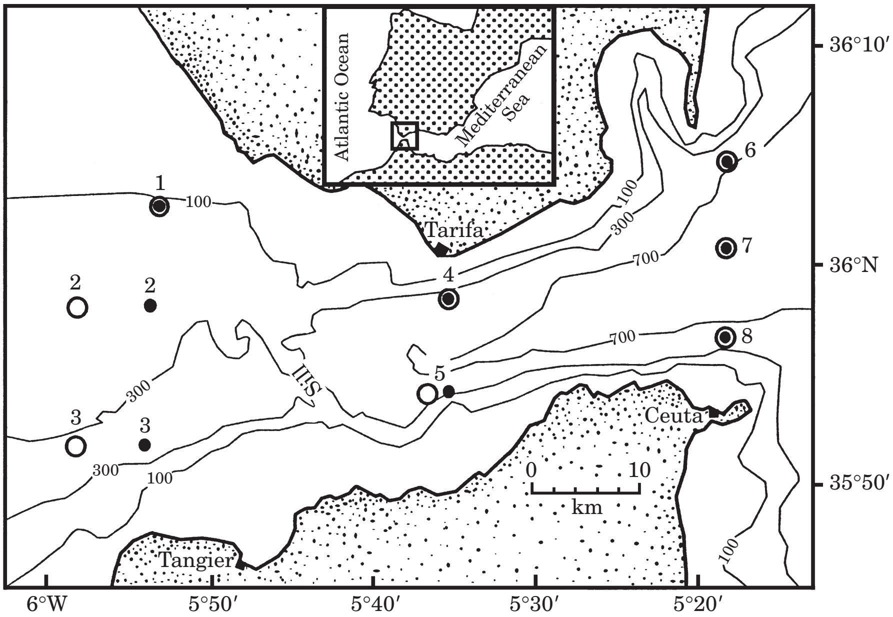

FIGURE 1. Map of the Strait of Gibraltar including sampling stations. ○: June; ●: September; ◉: June/September.

Materials and methods

During two cruises on board the RV *Cornide de Saavedra* (18–25 June, 1997) and the RV *Thalassa* (2–9 September, 1997), we sampled in eight stations arranged in three transects at the Atlantic, central and Mediterranean sections of the Strait (Figure 1). A CTD-rosette system equipped with 20-l Niskin bottles was used to collect samples at 11 depths. In September, several casts were performed at each station through the day.

From each sampled depth (June: 90 samples, September: 250 samples), water for dissolved inorganic nutrients (5 ml) was frozen (− 20 °C). After thawing, the concentration of nitrate, phosphate and silicate was measured with an automatic Technicon AA-II analyser following the method described by Grasshoff *et al.* (1983). Nitrite or ammonium (about 0·1 μM are not taken into account for flux estimations, due to the negligible values compared to nitrate.

For microplankton biomass, 21 were filtered through 5 μm-pore sized mesh to a final volume of 120 ml and immediately preserved with acid Lugol's solution. As a consequence of the low pH of acid Lugol, some calcareous structures such as that of cocolithophorids are presumably lost. Bottles were kept in cold dark conditions until further analysis in the laboratory. Subsamples (10–50 ml) were allowed to settle for 24 h on Utermöhl chambers. Cells or colonies were measured using an inverted microscope connected with a semiautomatic image analysis system (Analytical Measuring Systems, model VIDS V). The biovolume of each individual planktonic organism was calculated by approximation to regular figures (cylinder, ellipsoid, etc.) using length and width measurements. A minimum of 400, but more typically 500 to 1000 cells were counted and measured in each sample in order to keep the counting error within ± 10% (Lund *et al.*, 1958).

The transports used for the nutrient fluxes have been recently reported by García Lafuente *et al.* (2000) from three mooring lines of Aanderaa current meters deployed in the eastern side of the Strait during 1995–1996. These authors calculated an average annual Atlantic water inflow of 0·92 Sv and a Mediterranean water outflow of − 0·87 Sv (1 Sverdrup = 10^6 m^3 s^{-1}).

Results

Physical structure

The Strait of Gibraltar shows a transition from a 3-layer system, with a surface-shallow thermocline and a deep halocline in the western entrance, to a 2-layer system in the north-east of the Mediterranean entrance, where both pycnoclines merge, producing a single pycnocline. The Atlantic-Mediterranean Interface (AMI hereafter) is defined in terms of a particular isohaline. This isohaline was calculated at each station according to the considerations reported by Bryden *et al.* (1994), Bray *et al.* (1995) and García Lafuente *et al.* (2000).

TABLE 1. Date, GMT hour, hour relative to high water at Tarifa and interface depth (m) at each station during the sampling period in both cruises. Ship observations at the different stations are non-synoptic, therefore it will be convenient to refer all times to high water (HW) at Tarifa

	June				September			
Station	Date	Hour	H/tide	AMI	Date	Hour	H/tide	AMI
1	18/06/97	19:30	HW − 5	130	2/09/97	15:30	HW + 1·5	140
2	19/06/97	11:45	HW − 1	160	3/09/97	9:15	HW − 5·5	160
3	20/06/97	12:15	HW − 1	220	4/09/97	9:20	LW	210
4	22/06/97	13:20	HW − 1·5	45	5/09/97	9:35	LW	130
5	21/06/97	13:30	HW − 1	50	6/09/97	10:30	HW − 5·5	190
6	24/06/97	14:45	HW − 1·5	50	7/09/97	9:30	LW	65
7	25/06/97	14:10	HW − 3	100	8/09/97	7:15	HW + 2	90
8	23/06/97	12:20	HW − 3	135	9/09/97	9:30	HW + 4·5	100

The M_2 tide is the dominant contributor to the variability in the Strait (García Lafuente *et al.*, 1990), inducing the semidiurnal fluctuations of the interface depth, with vertical oscillations higher than 100 m in 15 min (Lacombe & Richez, 1982). On each M_2 semidiurnal cycle, when the inflowing tide is maximum, the interface is deeper than the average value and the AW layer is thicker, whereas during the outflowing tide, the interface is shallower than the average and the MOW layer is thicker. On the sill, the interface achieves its shallowest depth about one hour before high water (HW) (Candela *et al.*, 1990). The highest differences in interface position in both sampling periods appear at central stations (just east of the sill), with the interface near the surface in June and deeper in September (Table 1). In June at station 6, samples were taken at HW when the interface is near surface, whereas in September, we sampled at low water when AMI is deeper.

Also, the fortnightly tidal cycle strongly modulated the semidiurnal cycle, thus resulting in a deeper interface just after neap tides (Bryden *et al.*, 1994). In general, most of the sampling effort in this study was performed during neap tides.

The thickness of the Atlantic layer (AW) decreases progressively towards the Mediterranean Sea. In the Gulf of Cádiz, there are two water masses entering the Strait: a deeper layer of North Atlantic Central Water (NACW) and a layer of Surface Atlantic Water (SAW) above (Gascard & Richez, 1985). Along the Strait, these waters lose their salinity signature, although NACW is identified by minimum salinity at the south-western entrance of the Strait. There is a transitional layer of water which results from mixing of MOW and AW and this coincides with the maximum salinity gradient above AMI. This transitional layer is thicker and the halocline is weaker when the interface is deeper (frequently observed at southern Atlantic and central stations) as previously reported by Wesson and Gregg (1994).

Distribution and nutrient fluxes

The vertical distribution of dissolved nutrients at all the stations follows the expected pattern of increase according to depth in the upper layer, with concentration values much more constant in deep waters. The average values of nitrate concentration in the upper 50 m in both cruises are given in Table 2. Atlantic stations (1, 2 and 3) showed low nitrate values ($<0{\cdot}7\ \mu mol\ l^{-1}$) in both cruises, except at station 1 in September, with higher nitrate concentration ($2{\cdot}8\ \mu mol\ l^{-1}$). The shallowness of this coastal station ($\sim$150 m depth) favours a higher frequency of episodic mixing events that leads to enhanced production (Establier & Margalef, 1964). This station might be less related to the specific hydrodynamic processes of the Strait, because the MOW is not usually detected.

TABLE 2. Average values of nitrate, phosphate and silicate ($\mu mol\ l^{-1}$) in the upper 50 m depth

	June			September		
Station	NO_3	PO_4	Si	NO_3	PO_4	Si
1	0·44	0·30	0·26	2·90	0·26	5·5
2	0·12	0·13	0·34	0·15	0·09	0·91
3	0·14	0·13	0·79	0·67	0·09	1·05
4	2·68	0·28	1·72	1·26	0·17	1·77
5	3·45	0·25	2·78	3·42	0·24	0·97
6	2·92	0·20	1·99	0·43	0·12	0·65
7	1·27	0·18	1·74	0·38	0·11	1·13
8	3·76	0·28	2·32	5·01	0·31	1·61

Table 3. Average nutrient concentrations (μM) in the inflowing and outflowing waters in June. —, Low data number, in- and outflowing water layers because they are too thin

Station	Inflow			Outflow		
	$[NO_3]$	$[PO_4]$	$[SiO_2]$	$[NO_3]$	$[PO_4]$	$[SiO_2]$
1	1·55	0·29	0·57	—	—	—
2	1·82	0·22	0·92	—	—	—
3	2·40	0·25	1·4	8·05	0·47	6·03
4	2·33	0·30	1·6	7·92	0·42	6·51
5	2·45	0·23	2·05	9·20	0·44	8·79
6	—	—	—	10·09	0·44	7·07
7	1·46	0·20	1·74	10·88	0·49	7·28
8	3·77	0·29	2·29	10·25	0·45	8·47

Table 4. Average nutrient concentrations (μM) in the inflowing and outflowing waters in September, including several casts along the day at each station

Station	Inflow			Outflow		
	$[NO_3]$	$[PO_4]$	[Si]	$[NO_3]$	$[PO_4]$	[Si]
1	5·30	0·40	2·20	—	—	—
2	4·02	0·30	1·96	—	—	—
2	1·38	0·15	1·25	—	—	—
3	3·53	0·24	1·78	9·74	0·48	8·32
3	3·78	0·28	1·94	9·59	0·47	7·84
4	2·68	0·23	2·18	10·19	0·48	8·35
4	3·74	0·26	1·33	9·94	0·48	6·26
4	—	—	—	10·13	0·50	7·30
5	4·72	0·30	1·26	9·28	0·45	7·89
5	6·82	0·34	1·45	9·25	0·44	7·68
6	0·28	0·12	0·57	9·90	0·48	7·34
6	0·23	0·11	0·86	9·89	0·48	6·97
6	0·73	0·12	0·95	10·00	0·49	5·09
7	1·06	0·14	0·73	9·13[a]	0·55[a]	6·38[a]
7	0·53	0·12	1·22	8·94	0·50	8·90
7	0·77	0·13	1·50	9·23	0·49	8·51
7	0·79	0·10	1·13	9·11	0·46	8·65
7	0·90	0·18	1·89	8·62	0·53	8·10
7	1·94	0·11	0·42	7·99	0·49	7·90
8	2·39	0·14	0·71	10·82	0·55	7·30
8	4·80	0·31	1·61	9·82	0·51	7·80
8	4·60	0·31	1·33	9·85	0·50	8·14

[a] Not considered for nutrient fluxes, statistically not representative.

There was a clear increase in upper layer nitrate concentration in both central stations, 4 and especially 5, with values up to 3 μmol l^{-1}. This relatively high nutrient concentration in comparison with the Atlantic side in the upper layer during the June cruise could be explained by the shallower AMI, although in September AMI is deeper and displayed higher nutrient concentrations. As can be seen in Figure 1 the sill region of the Strait is situated between the Atlantic and central stations, so the upper water coming from the Atlantic crosses the sill region before reaching the central transect.

In the Mediterranean sector (stations 6, 7 and 8), the situation was different for both cruises: in September there was a new clear decrease in nitrate concentrations in the north (stations 6 and 7), which could be related to the uptake by the very abundant phytoplankton community (Figure 3). This effect was not apparent at station 6 in June in spite of similar biomass values, because the AMI is so shallow that it probably increases the rate of mixing with deeper waters. Station 8, at the south-eastern side showed the highest concentration of nitrate on both cruises.

For the evaluation of nutrient fluxes, the average nutrient concentration at each layer was calculated after a trapezoidal integration of discrete data (Tables 3, 4). However, we have selected the sampling stations nearest to the current meter mooring lines (stations 6, 7 and 8) for the evaluation of nutrient fluxes. The average interface value between these opposite currents was estimated to be around the isohaline of 37·85 (García Lafuente *et al.*, 2000). We adopted the isohaline of 37·6 as the limit for upper layer, whereas the lower layer extended from the bottom to the 38·3 isohaline. The interface region in the eastern entrance is considered to range from 37·6–38·3, where the halocline is stronger. The nutrients from the interface region waters are not considered in these estimations due to the horizontal velocities being close to zero.

For a better approach, this eastern cross-section for Mediterranean outflow (stations 6, 7 and 8) has been divided into three areas. Northern and southern areas represent about 30% of the total cross-section area (for stations 6 and 8; an outflow of − 0·87 × 0·3 = − 0·261 Sv), whereas for station 7, we considered nutrient fluxes to be 40% of the total outflow (− 0·348 Sv) (Figure 2). The inflowing waters should converge to the south by the action of the Coriolis force (e.g. Bray *et al.*, 1990), so in the north section the interface is shallower. Based on the differences at the interface average depths between stations 6, 7 and 8, the above mentioned averaged transport of 0·92 Sv has also been divided into three sections. On the northern side (station 6) the average interface depth is around 80 m depth, whereas in the southern side (station 8) is around 120 m depth (Bray *et al.*, 1990, 1995). The cross-section for inflowing waters in the north has been considered to be about 20% lower than the mean inflow value and a 20% higher value has been adopted in the south (Figure 2; Table 5, 6).

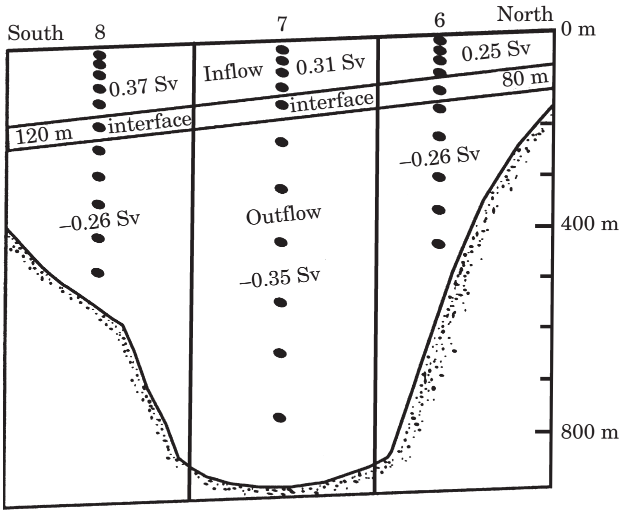

FIGURE 2. Cross section of the eastern side of the Strait used for the estimation of the nutrient fluxes.

The results show that the average inflowing nitrate, phosphate and silicate fluxes from the two cruises may compensate for 21, 39 and 17% of the outflowing nutrient concentrations, respectively.

Discussion

Return of a fraction of the Mediterranean outflowing nutrients and microphytoplankton biomass

The results show a progressive increase of nutrients from west to east in the upper layer. The largest interface oscillations are found at the sill, especially in the south (Bray *et al.*, 1990, 1995), where nutrients in the upper layer were higher (Table 2). The internal hydraulic jump at the sill (Armi & Farmer, 1988) creates a thick interface between Atlantic and Mediterranean waters by mixing with a turbulent layer of approximately 100 m thick (Wesson & Gregg, 1989). The average shear values are of 0·035 s^{-1} during neap tides and 0·025 s^{-1} during the spring tides (Pettigrew & Needell, 1989). Therefore, a part of the MOW nutrients are upwelled by vertical turbulence through the AMI. High mixing rates at the sill with high nutrient values near the surface, together with the upwelling events in the Spanish coast of Alborán (Sarhan *et al.*, 2000) are consistent with the nitrate maximum in the surface layer of the western Alborán Sea, the highest being in the Mediterranean Sea, described in the inverse model of Denis-Karafistan *et al.* (1998).

Wesson and Gregg (1994) estimated the rate of formation of new transitional water between AW and MOW during neap tide as 0·08–0·12 Sv. According to Pettigrew and Hyde (1990), at least during neap tides, most of the water in the transition layer is being advected eastwards into the Mediterranean. As an approximation to the effect on the plankton biomass in the Strait, it can be supposed that (a) this water (about 0·1 Sv) is moving into the Mediterranean Sea in the euphotic zone and (b) the limiting nutrient is nitrate with an initial average concentration in this incoming water of 5 $\mu mol\ l^{-1}$. Therefore, approximately 500 mol $NO_3^-\ s^{-1}$ could be upwelled. According to Takahashi *et al.* (1986), we can use the constant 1·59 to convert mmol nitrate to mg chlorophyll *a*. If we also assume a carbon to chlorophyll ratio of 50 (Harris, 1986) or the classical Redfield ratio (C:N=6·6), we can propose a preliminary estimation of the contribution of the nutrients upwelled by these mixing events to the plankton biomass as a potential value of about 40 kg C s^{-1}.

On the northern side of the eastern sill, the average interface depth along the tidal cycle is shallower than at the southern side, due to the fact that the interface shows a rising pattern following the south–north axis with a tilt downwards to the south to accommodate the geostrophycally balanced buoyancy-driven exchange through the Strait (Bray *et al.*, 1990). Thus, on the north-eastern side, the seasonal thermocline and AMI depths coincide, generating a strong pycnocline in the euphotic zone which leads to high accumulation of microphytoplankton in this layer of velocity near zero. The coincidence between thermocline and AMI is related to high phytoplankton biomass (Gómez *et al.*, 2000). Thus, microphytoplankton biomass shows a tendency to increase from the south-west towards the north-east. This increase of biomass, expressed as integrated microphytoplankton biovolume in the upper 100 m, towards the north-eastern sector is parallel to an ascent of the AMI in the same direction (Bray *et al.*, 1995; Gómez *et al.*, 2000) (Figure 3). Stations 6 and 7 in both cruises showed the highest biomass values in assemblages dominated by diatoms (>90% total biomass), mainly of the genera *Chaetoceros, Guinardia* and *Rhizosolenia*.

The periodical contributions of high nutrient waters from mixing between inflowing and outflowing waters at the sill due to internal tidal bores generated by breaking internal waves, also detected on the Spanish coast near the eastern end of the Strait (García Lafuente & Cano, 1994), is a phenomenon that also has an influence on the primary productivity of the eastern region of the Strait.

The passage of the internal bore has its most pronounced effect in the south-eastern side (Pettigrew & Hyde, 1990). At the station 8, despite periodical enrichments with high-nutrients of the AW from

TABLE 5. Average nutrient concentrations (µM) and nutrient fluxes (mole s^{-1}) in the eastern entrance of the Strait of Gibraltar in June. Water fluxes expressed as Sverdrup (1 Sv=1 × 10^{6} m^{3} s^{-1})

June	Water	[NO_3]	N flux	[PO_4]	P flux	[SiO_2]	Si flux
Inflow							
6	0·25	0[a]	0	0[a]	0	0[a]	0
7	0·31	1·46	447·6	0·20	60·3	1·74	532
8	0·37	3·77	1386	0·29	105·3	2·29	842
Total	0·92	1·99	1833·6	0·18	166·5	1·49	1375
Outflow							
6	− 0·26	10·09	− 2634	0·44	− 114·3	7·07	− 1845
7	− 0·35	10·88	− 3787·2	0·49	− 168·3	7·28	− 2533
8	− 0·26	10·25	− 2673·6	0·45	− 117	8·47	− 2210
Total	− 0·87	10·45	− 9096	0·46	− 401·4	7·57	− 6589
Budget			− 7261·2		− 234·9		− 5214

[a] Interface near surface during sampling.

TABLE 6. Average nutrient concentrations (µM) and nutrient fluxes (mole s^{-1}) in the eastern entrance of the Strait of Gibraltar in September. Water fluxes expressed as Sverdrup (1 Sv=1 × 10^{6} m^{3} s^{-1})

September	Water	[NO_3]	N flux	[PO_4]	P flux	[SiO_2]	Si flux
Inflow							
6	0·25	0·41	100·8	0·12	27·9	0·79	194
7	0·31	1·20	366	0·13	39·6	1·09	332
8	0·37	3·92	1444·8	0·25	92·7	1·22	447
Total	0·92	2·08	1911·6	0·17	160·2	1·06	974
Outflow							
6	− 0·26	9·92	− 2590·8	0·48	− 125·1	6·47	− 1687
7	− 0·35	8·82	− 3067·2	0·49	− 168·3	8·49	− 2954
8	− 0·26	10·16	− 2652	0·52	− 135	7·75	− 2021
Total	− 0·87	9·55	− 8311·2	0·50	− 428·4	7·66	− 6664
Budget							
		− 6399·6		− 268·2		− 5689	

mixing at the sill, the AMI depth is deeper below the euphotic zone, and the current velocity higher (Send *et al.*, 1999) below the euphotic zone, and does not coincide with thermocline (Figure 4). Therefore, these facts cannot lead to high phytoplankton accumulation in a low velocity layer. Presumably this low phytoplankton biomass does not have a high nutrient consumption effect and this could explain the high nutrient value found in this station 8 (Table 2). Fraga and Establier (1975) measured the nitrate concentrations at both sides of the southern half of the Strait and they reported very high values in the surface waters (2 µM) in a station near Ceuta compared to the rest of the stations of the Gulf of Cádiz and Alborán Sea.

The hydrodynamic structure of the eastern side of the Strait determines that the nutrients on the northern side are depleted by the standing stock of diatoms, whereas on the southern side the nutrients are exported and diluted in the Alborán Sea and probably consumed by other phytoplankton (presumably non-diatoms, small cells with low nutrient requirements).

All these mixing processes contribute to provide nutrients from deep waters to the euphotic zone in the AW, as in an upwelling system, leading to an increase of phytoplankton biomass, while the upper waters move into the Mediterranean Sea. This return of nitrogen by mixing at the sill is associated with a plankton biomass increase. This plankton patch moves into the western Alborán Sea and the nutrients contained in the particles are being continuously removed from the surface in the Alborán Sea by downward sinking and regeneration in the deep waters

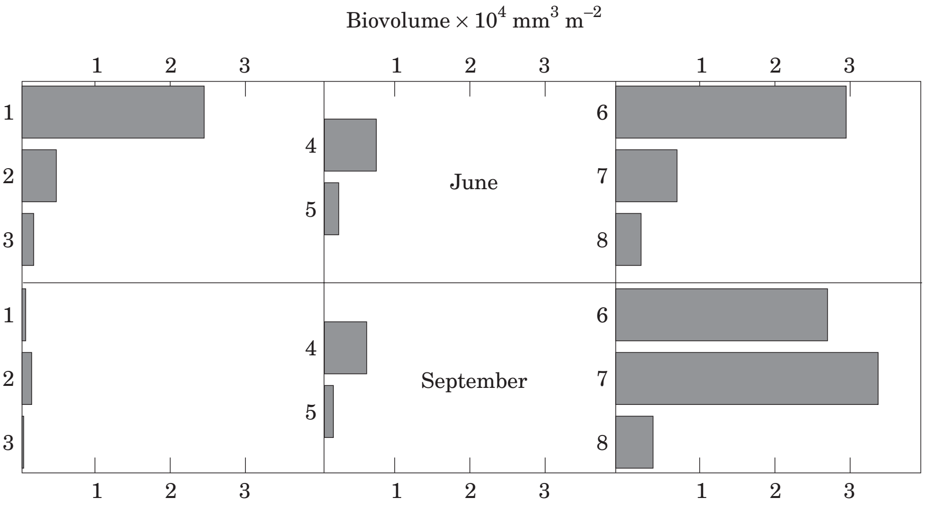

FIGURE 3. Microphytoplankton biovolume per m^2 in the upper 100 m in both cruises.

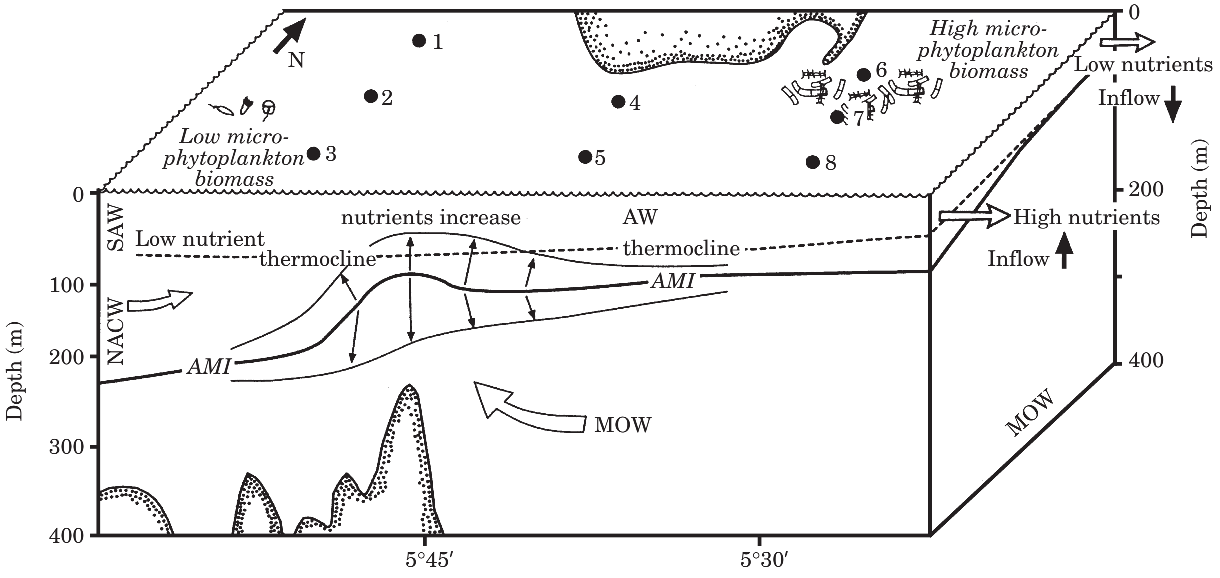

FIGURE 4. Conceptual scheme of the physical structure and the distribution of nutrients in the Strait of Gibraltar. Abbreviators: NACW, North Atlantic Central Water; SAW, Surface Atlantic Water; AW, Atlantic inflowing Water; MOW, Mediterranean Outflowing Water; AMI, Atlantic-Mediterranean Interface.

(MOW). In the north-western Alborán Sea, this mechanism can contribute to the most intense oxygen minimum zone in the Mediterranean Sea (Packard *et al.*, 1988).

Nutrient fluxes

The water fluxes used were particularly important for estimating nutrient fluxes. Water exchange values estimated since the ‘ Gibraltar Experiment ’ were significantly smaller than most of the previously reported values (Bryden *et al.*, 1989). During October–November 1985, Bryden *et al.* (1994) estimated a time-averaged Mediterranean outflow of − 0·68 Sv at the Camarinal sill region. In the upper Atlantic layer, due to lack of current meters, these authors estimated an indirect value of 0·72 Sv based on the net evaporation in the Mediterranean Sea. The transport values on the eastern side adopted in this study (0·92 Sv, − 0·87 Sv) are similar to the in–outflow of 0·92 and − 0·88 Sv of the maximal exchange predicted by Bryden and Kinder (1991). The differences between the values calculated by Bryden *et al.* (1994) at the sill region and those from García Lafuente *et al.* (2000) at

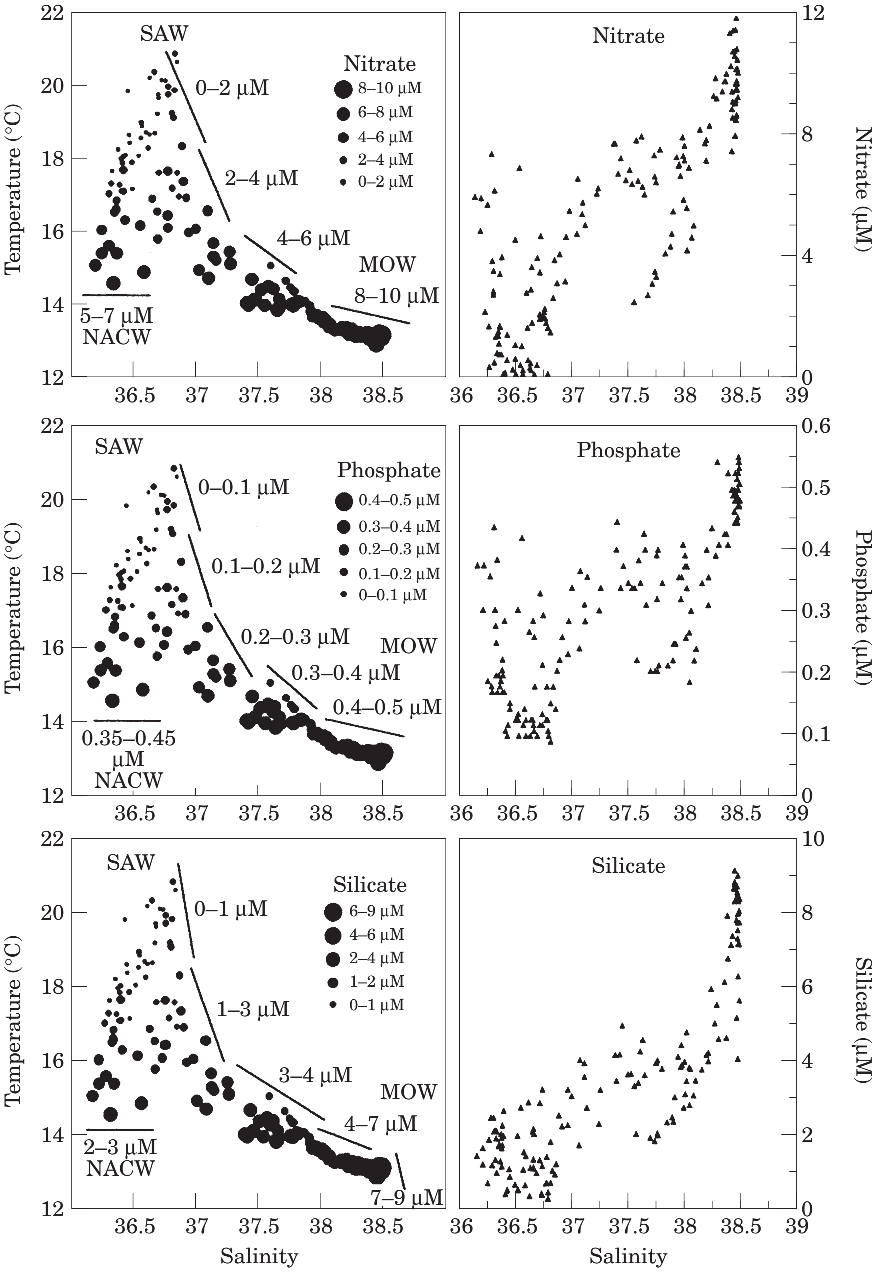

FIGURE 5. Temperature-salinity diagrams including the concentrations of nitrate, phosphate and silicate and relation between the salinity and nutrient concentrations.

the eastern side are compatible if we consider the return by mixing of part of the Mediterranean water to the Atlantic inflow that takes place at the sill region (Wesson & Gregg, 1994; Bray *et al.*, 1995; García Lafuente *et al.*, 2000).

Another important factor for the nutrient flux estimations is the position of the interface between the Mediterranean and Atlantic layers. According to Bryden *et al.* (1994), it is not possible to define the interface based on a depth of zero velocity between inflow and outflow at each instant of time. In fact, at the sill, sometimes all the flux is eastwards or westwards and, hence, there is no defined zero-velocity depth. Bryden *et al.* (1994) reported that, at the sill, the salinity of zero velocity ranged from 36·6 to 37·4, the isohaline of 37 being used to define the interface more precisely. García Lafuente *et al.* (2000) have considered 37·85 as the characteristic interface value for the eastern side.

TABLE 7. Summary of average concentration of nitrate, phosphate and silicate (μM) and annual estimation of nutrient fluxes ($\times 10^{10}$mole yr^{-1}) and some previous estimations

$[NO_3]$	N flux	$[PO_4]$	P flux	$[SiO_2]$	Si flux	Reference	Water flux	Reference
Inflow								
—	—	—	—	1·2	2·7	Schink (1967)	0·73	Carter (1956)
4	9·2	0·2	0·46	—	—	McGill (1969)	0·73	Carter (1956)
1	5·3	0·05	0·26	—	—	Béthoux (1981)	1·68	Béthoux (1979)
—	—	0·24	0·52	—	—	Sarmiento *et al.* (1988)	0·69	[a]
4	21·2	0·23	1·21	2·4	12·7	Coste *et al.* (1988)	1·68	Béthoux (1979)
	15·4		0·88		9·2		1·22	Lacombe (1971)
1·99	5·77	0·18	0·52	1·49	4·33	June	0·92	García Lafuente *et al.* (2000)
2·07	6·02	0·17	0·50	1·06	3·07	September	0·92	
2·03	5·89	0·17	0·51	1·27	3·70	Av. June/September	0·92	
Outflow								
—	—	—	—	6·5	−14·1	Schink (1967)	−0·69	Carter (1956)
6	−13·05	0·3	−0·65	—	—	McGill (1969)	−0·69	Carter (1956)
6	−30·3	0·27	−1·41	—	—	Béthoux (1981)	−1·60	Béthoux (1979)
		0·40	−0·82			Sarmiento *et al.* (1988)	−0·65	[a]
8·6	−43·4	0·43	−2·17	8·4	−42·3	Coste *et al.* (1988)	−1·60	Béthoux (1979)
	−31		−1·54		−30·2		−1·14	Lacombe (1971)
7	−35	0·32	−1·62	6·7	−34	Béthoux *et al.* (1998)	−1·60	Béthoux (1979)
10·45	−28·68	0·45	−1·26	7·57	−21·01	June	−0·87	García Lafuente *et al.* (2000)
9·55	−26·20	0·49	−1·35	7·66	−20·78	September	−0·87	
9·99	−27·4	0·47	−1·3	7·61	−20·89	Av. June/September	−0·87	

[a]Transports based on the preliminary results from the ‘ Gibraltar Experiment ’ and data by Van Geen *et al.* (1988). Béthoux *et al.* (1998) only reported outflow estimations.

TABLE 8. Summary of annual nitrate, phosphate and silicate budgets in the Strait of Gilbratar ($\times 10^{10}$mole yr^{-1}) and previous estimations

Nitrate	Phosphate	Silicate	Reference
—	—	−11·4	Schink (1967)
−3·85	−0·19	—	McGill (1969)
−25	−1·15	—	Béthoux (1981)
−22·2	−0·96	−29·6	Coste *et al.* (1988)
−15·6	−0·66	−21	
—	−0·30	—	Sarmiento *et al.* (1988)
−17·8	—	—	Crise *et al.* (1998)
−22·89	−0·73	−16·44	June
−20·17	−0·83	−17·94	September
−21·54	−0·78	−17·19	Av. June/September

Mediterranean outflow loses its salinity signature along the Strait to the Gulf of Cádiz due to mixing with Atlantic water (Price *et al.*, 1993). This mixing process also affects nutrient concentrations that would typically increase in the inflowing Atlantic waters from the sill to the Mediterranean Sea. Similarly, there would be a dilution of the outflowing nutrient concentrations westwards. In the Gulf of Cádiz, the MOW can also be detected by a minimum in the nutrient concentrations (Howe, 1982). In the Atlantic side (stations 1, 2, 3), the upper Atlantic layer was composed of the nutrient impoverished Surface Atlantic Water (<0·5 μM NO_3^-) and was below the characteristic salinity minimum (36–36·2) of the North Atlantic Central Water that has a high nutrient concentration (5–7 μM NO_3^- or 0·35–0·45 μM PO_4^-). The lower salinity and high nutrient concentration of the NACW versus the SAW make it difficult to form a linear relationship between the salinity and the nutrients in the upper layer (Figure 5). A consideration of this last water mass could overestimate the calculated upper layer average nutrient concentrations, because this water is not always injected into the upper layer that crosses the Strait (Lacombe & Richez, 1982; Gascard & Richez, 1985). Thus it is preferable to evaluate flux through the Strait on the eastern side than on the western side.

A comparison with previous nutrients concentrations for outflowing estimations, shows smaller values than the results presented here (Table 7, 8). Differences in nutrient concentration could be partially explained by the current nutrient analysis versus previous methodologies used. Real changes on the measured concentrations should also be expected though. Thus, Béthoux *et al.* (1992, 1998) concluded that nitrate and phosphate undergo a constant increase in the Mediterranean Sea, due to cultural eutrophication. Historically, nitrate and phosphate values show a tendency to increase in the Mediterranean outflowing waters, whereas silicate concentrations are not significantly different from the previously reported measurements (Table 7).

According to Béthoux *et al.* (1992) the surface concentrations used by Coste *et al.* (1988) cannot correspond to the assumed impoverished Atlantic inflowing waters. The north-south cross section on the eastern side reveals higher differences for nutrient concentrations, showing higher values on the southern side where the phytoplankton standing stock is lower and the water flux is higher. The evaluation of nutrient flux in the upper layer presents higher variability (not only for frequent mixing events). There is also a high variability induced by the consumption of the phytoplankton.

Two cruises are insufficient to evaluate the seasonal variability on nutrient concentrations. Also, the annual variability of water transports may be considered. Bryden *et al.* (1994) reported an amplitude of 0·12 Sv peaking in September for the inflow and 0·03 Sv peaking in January for the outflow based on less than 1 year of measurements. Recently, García Lafuente *et al.* (2000) based on continuous measurements from 1995 to 1998 reported an annual cycle water for the inflow peaking in late summer produced by the seasonal warming of the Atlantic Ocean. The local wind-stress and the atmospheric pressure differences between the Atlantic Ocean and the western Mediterranean Sea forced a semi-annual signal, more important for the outflow and the depth of the interface.

We have considered low variability on our nutrient outflow estimations, where the nutrient concentrations are relatively homogeneous. However, the nutrient inflow estimations will present a higher variability associated with the biological and physical phenomena mentioned above. It will be necessary to carry out further studies to reveal the spatial and temporal variability in the nutrients exchanged between the Mediterranean Sea and the Atlantic Ocean.

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References

Armi, L. & Farmer, D. M. 1988 The flow of Mediterranean water through the Strait of Gibraltar (also entitled: Farmer, D. M. & Armi, L. The flow of Atlantic water through the Strait of Gibraltar). *Progress in Oceanography* **21,** 1–105.

Béthoux, J. P. 1979 Budgets of the Mediterranean Sea. Their dependence on the local climate and on the characteristics of the Atlantic waters. *Oceanologica Acta* **2,** 157–163.

Béthoux, J.P. 1981 Le phosphore et l'azote en mer Méditerranée, bilans et fertilité potentielle. *Marine Chemistry* **10,** 141–158.

Béthoux, J. P. 1989 Oxygen consumption, new production, vertical advection and environmental evolution in the Mediterranean Sea. *Deep Sea Research* **36,** 769–781.

Béthoux, J. P. & Copin-Montégut, G. 1986 Biological fixation of atmospheric nitrogen in the Mediterranean Sea. *Limnology and Oceanography* **31,** 1353–1358.

Béthoux, J. P., Morin, P., Madec, C. & Gentili, B. 1992 Phosphorus and nitrogen behaviour in the Mediterranean Sea. *Deep Sea Research* **39,** 1641–1654.

Béthoux, J. P., Chaumery, P. C., Connan, O., Gentili, B. & Ruiz-Pino, D. 1998 Nutrients in the Mediterranean Sea, mass balance and statistical analysis of concentrations with respect to environmental change. *Marine Chemistry* **63,** 155–169.

Bray, N. A., Winant, C. D., Kinder, T. H. & Candela, J. 1990 Generation and kinematics of the internal tide in the Strait of Gibraltar. In *The Physical Oceanography of Sea Straits.* (Pratt, L. J., ed.). Kluwer, Boston, pp. 477–491.

Bray, N. A., Ochoa, J. & Kinder, T. H. 1995 The role of the interface in exchange through the Strait of Gibraltar. *Journal of Geophysical Research* **100,** 10775–10776.

Bryden, H. L., Brady, E. & Pillsbury, R. 1989 Flow through the Strait of Gibraltar. In *Seminario sobre la Oceanografía Física del Estrecho de Gibraltar* (Almazán, J. L., Bryden, H. L., Kinder, T. H. & Parrilla, G., eds). SEGEC, Madrid. pp. 166–194.

Bryden, H. L. & Kinder, T. H. 1991 Steady two-layer exchange through the Strait of Gibraltar. *Deep Sea Research* **38,** S445–S463.

Bryden, H. L., Candela, J. & Kinder, T. H. 1994 Exchange through the Strait of Gibraltar. *Progress in Oceanography* **33,** 201–248.

Candela, J., Winant, C. D. & Ruiz, A. 1990 Tides in the Strait of Gibraltar. *Journal of Geophysical Research* **95,** 7313–7335.

Carter, D. B. 1956 The water balance of the Mediterranean and Black Seas. *Publications in Climatology* **9,** 123–175.

Coste, B. 1969 Echanges de sels nutritifs dissous entre la mer Méditerranée et l'océan Atlantique. *Cahiers Océanographiques* **21,** 943–963.

Coste, B., Le Corre, P. & Minas, H. J. 1988 Re-evaluation of the nutrient exchanges in the Strait of Gibraltar. *Deep Sea Research* **35,** 767–775.

Crise, A., Crispi, G. & Mauri, E. 1998 A seasonal three-dimensional study of the nitrogen cycle in the Mediterranean Sea: Part I. Model implementation and numerical results. *Journal of Marine Systems* **18,** 287–312.

Crispi, G., Crise, A. & Mauri, E. 1999 A seasonal three-dimensional study of the nitrogen cycle in the Mediterranean Sea: Part II. Verification of the energy constrained trophic model. *Journal of Marine Systems* **20,** 357–379.

Denis-Karafistan, A., Martin, J. M., Minas, H., Nihoul, J. & Denis, C. 1998 Space and seasonal distributions of nitrates in the Mediterranean Sea derived from a variational inverse model. *Deep Sea Research* **45,** 387–408.

Establier, R. & Margalef, R. 1964 Fitoplancton e hidrografía de las costas de Cádiz (Barbate), de junio de 1961 a agosto de 1962. *Investigaciones Pesqueras* **25,** 5–31.

Fraga, F. & Establier, A. 1975 Hidrografía de la zona del Estrecho de Gibraltar. Datos básicos de la campaña Maroc-Iberia I del Cornide de Saavedra. *Resultados de Expediciones Científicas del B/O Cornide de Saavedra* **3,** 53–66.

García Lafuente, J. M., Almazán, J. L., Castillejo, F., Khribeche, A. & Hakimi, A. 1990 Niveau de la Mer dans le Détroit de Gibraltar: Marées. *Revue Hydrographique International Monaco* **67,** 113–132.

García Lafuente, J. M. & Cano, N. 1994 Tidal dynamics and associated features of the northwestern shelf of the Alborán Sea. *Continental Shelf Research* **14,** 1–21.

García Lafuente, J., Vargas, J. M., Plaza, F., Sarhan, T., Candela, J. & Bascheck, B. 2000 The tide at the eastern section of the Strait of Gibraltar. *Journal of Geophysical Research* **105,** 14197–14214.

García Lafuente, J., Delgado, J., Vargas, J. M., Vargas, M., Plaza, F. & Sarhan, T. Low frequency variability of the exchanged flow through the Strait of Gibraltar during CANIGO. Submitted to *Deep Sea Research*, CANIGO especial issue.

Gascard, J. C. & Richez, C 1985 Water masses and circulation in the Western Alborán Sea and in the Straits of Gibraltar. *Progress in Oceanography* **15,** 157–216.

Gómez, F., Echevarría, F., García, C. M., Prieto, L., Ruiz, J., Reul, A., Jiménez-Gómez, F. & Varela, M. 2000 Microplankton distribution in the Strait of Gibraltar: coupling between organisms and hydrodynamic structures. *Journal of Plankton Research* **22,** 603–617.

Grasshoff, K., Erhardt, M. & Kremling, K. 1983 *Methods of Seawater Analysis*, 2nd edn., Verlag Chemie, Weinheim, 419 pp.

Harris, G. P. 1986 *Phytoplankton Ecology: Structure, Function and Fluctuation*. Chapman and Hall, New York, 384 pp.

Howe, M. R. 1982 The Mediterranean water outflow in the gulf of Cádiz. *Oceanography Marine Biology Annual Review* **20,** 37–64.

Lacombe, H. 1971 Le détroit de Gibraltar, océanographie physique. *Notes et Mémoires du Service Géologique de Marocco* **222 bis,** 111–146.

Lacombe, H. & Richez, C. 1982 The regime of the Strait of Gibraltar. In *Hydrodynamics of Semi-enclosed Seas* (Nihoul, J. C. J., ed.), Elsevier, Amsterdam, pp. 13–73.

Lund, J. W. G., Kipling, C. & Le Cren, E. D. 1958 The inverted microscope method of estimating algal numbers, and the statistical basis of estimation by counting. *Hydrobiologia* **11,** 143–170.

McGill, D. A. 1969 A budget for dissolved nutrient salts in the Mediterranean Sea. *Cahiers Océanographiques* **21,** 543–554.

Minas, H. J. & Minas, M. 1993 Influence du Détroit de Gibraltar sur la biogéochime de la Méditerranée et du proche Atlantique. *Annales de L'Institute Océanographique, Paris* **69,** 203–214.

Minas, H. J., Coste, B., Le Corre, P., Minas, M. & Raimbault, P. 1991 Biological and geochemical signatures associated with the water circulation through the Strait of Gibraltar and in the western Alborán Sea. *Journal of Geophysical Research* **96,** 8755–8771.

Packard, T. T., Minas, H. J., Coste, B., Martínez, R., Bonin, M. C., Gostan, J., Garfield, P., Christensen, J., Dorth, Q., Minas, M., Copin-Montégut, G. & Copin-Montégut, C. 1988 Formation of the Alborán oxygen minimum zone. *Deep Sea Research* **35,** 1111–1118.

Pettigrew, N. R. & Needell, G. J. 1989 Flow structure and variability in the Tarifa Narrows section of the Strait of Gibraltar. In *Seminario Sobre la Oceanografia Física del Estrecho de Gibraltar* (Almazán, J. L. Bryden, H. L., Kinder, T. H. & Parrilla, G., eds). SECEG, Madrid, pp. 207–230.

Pettigrew, N. R. & Hyde, R. A. 1990 The structure of the internal bore in the Strait of Gibraltar and its influence on the Atlantic inflow. In *The Physical Oceanography of Sea Straits* (Pratt, L. J., ed.). Kluwer, Boston, pp. 493–508.

Price, J. F., O'Neil-Baringer, M., Lueck, R. G., Johnson, G. C., Ambar, I., Parrilla, G, Cantos, A., Kennelly, M. A. & Sandford, T. B. 1993 Mediterranean outflow mixing and dynamics. *Science* **259,** 1277–1282.

Sarhan, T., García Lafuente, J., Vargas, M., Vargas, J. M. & Plaza, F. 2000 Upwelling mechanisms in the northwestern Alborán Sea. *Journal of Marine Systems* **23,** 317–331.

Sarmiento, J. L., Herbert, T. & Toggweiler, J. R. 1988 Mediterranean nutrient balance and episodes of anoxia. *Global Biogeochemical Cycles* **2,** 427–444.

Schink, D. R. 1967 Budget for dissolved silica in the Mediterranean Sea. *Geochimica Cosmochimica Acta* **31,** 987–999.

Send, U., Font, J., Krahmann, G., Millot, C., Rhein, M. & Tintoré, J. 1999 Recent advances in observing the physical oceanography of the western Mediterranean Sea. *Progress in Oceanography* **44,** 37–64.

Takahashi, M., Ishizaka, J., Ishimaru, T., Atkinson, L. P., Lee, T. N., Yamaguchi, Y., Fujita, Y. & Ichimura, S. 1986 Temporal change in nutrient concentrations and phytoplankton biomass in short time scale local upwelling around the Izu Peninsula, Japan. *Journal of Plankton Research* **8,** 1039–1049.

Thomsen, H. 1931 Nitrate and phosphate contents of Mediterranean water. *Reports Danish Oceanographic Expedition 1908–1910 to the Mediterranean and adjacent seas* **no. 3(6),** pp. 1–14.

Turley, C. M. 1999 The changing Mediterranean Sea—a sensitive ecosystem. *Progress in Oceanography* **44,** 387–400.

UNESCO 1988 Eutrophication in the Mediterranean Sea: receiving capacity and monitoring of long term effects. *UNESCO Reports in Marine Science* **49,** 195 p.

Van Geen, A., Rosener, P. & Boyle, E. 1988 Entrainment of trace-metal-enriched Atlantic-shelf water in the inflow to the Mediterranean Sea. *Nature* **331,** 423–426.

Wesson, J. C. & Gregg, M. C. 1989 Dissipation measurements in the Gibraltar experiment. In *Seminario Sobre la Oceanografía Física del Estrecho de Gibraltar* (Almazán, J. L., Bryden, H. L., Kinder, T.H. & Parrilla, G., eds). SECEG, Madrid, pp. 401–411.

Wesson, J. C. & Gregg, M. C. 1994 Mixing at Camarinal Sill in the strait of Gibraltar. *Journal of Geophysical Research* **99,** 9847–9878.