Control of the phytoplankton distribution in the Strait of Gibraltar by wind and fortnightly tides

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Abstract

CTD–fluorescence–turbidity profiles from two surveys conducted in June and September 1997 were examined in order to evaluate the influence of the predictable fortnightly (spring/neap) tidal cycle and the less predictable wind on the phytoplankton distribution in the Strait of Gibraltar. The injection of the nutrient-rich North Atlantic Water (NACW) in the Atlantic inflowing current is associated with initial phytoplankton blooming conditions (high fluorescence, low turbidity). In September, a thick layer of NACW was recorded in the euphotic zone of the Atlantic side of the Strait, but biological variables showed post-bloom conditions. This is interpreted as the previous development of a phytoplankton bloom favoured by the ascent of NACW into the euphotic zone during the neap tide period. The passage of NACW through the Strait into the Mediterranean Sea was initially hindered by easterly winds and later by the spring tide. The neap tide period favoured the injection and passage of nutrient-rich North Atlantic Water (NACW) into the Atlantic inflowing current, enhanced during the westerly winds regime. During the spring tides, the injection and passage of NACW is hindered, especially when the easterlies blow. The contribution of the NACW to the primary production was estimated as 100–150 kg carbon s^{-1} (enhanced during the neap tides). The influence of the wind-driven upwelling along the NW Alborán Sea on the northeastern side of the Strait is discussed.
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1. Introduction

The Strait of Gibraltar, with an eastward fresher Atlantic inflow and saltier westward Mediterranean outflow, controls the exchange between the Mediterranean Sea and Atlantic Ocean. This mean flow is subject to hydraulic controls at the shallowest sill (Camarinal Sill) and the narrowest constriction (Tarifa Narrows). The exchange is strongly modulated by tides as well as by barometric and wind effects (Candela et al., 1989, 1990; Bryden et al., 1994). On each semidiurnal tide cycle, when the inflowing tide is maximum, the interface is deeper and the Atlantic layer is thicker and inversely so during the outflowing tide. At the sill, the interface achieves its shallowest depth about 1 h before High Water (Candela et al., 1990). Around this time, a strong internal bore (moving hydraulic jump) is released accompanied by interfacial waves of amplitude 100 m or more (Izquierdo et al., 2001). The Atlantic–Mediterranean interface, characterised by a well-developed halocline, is shallower eastwards showing a transition from a three-layer system (surface-shallow thermocline and a deep halocline) in the western entrance, to a two-layer system in the northeastern side of the Strait where both pycnoclines merge producing a single shallow pycnocline (Bray et al., 1995).

The Strait of Gibraltar is a unique natural laboratory for the study of the biological response to extreme

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physical processes, however, these studies have not run in parallel to the physical inputs and most of them have been focused on the budgets of the trace elements or pollutants in the western Mediterranean Sea (Gómez, 2003). From the biological point of view, the Strait reveals a strong heterogeneity, where the Atlantic inflowing current is fertilised by the mixing at sill with the Mediterranean Outflowing Water (Wesson and Gregg, 1994; Gómez et al., 2000b), by the eastward shoaling of the interface (Bray et al., 1995; Gómez et al., 2000a; Echevarría et al., 2002) and the injection of nutrient-rich NACW in the upper current (Gascard and Richez, 1985; Gómez et al., 2001).

Despite these achievements on the comprehension of the Strait's functioning, the low temporal and vertical resolution based on conventional methods (e.g., discrete water samples) that requires high time-consuming analysis limits the available data set. The methodology based on continuous and repeatable acquisition of information such as fluorescence and nephelometry is especially useful for the study of different time and space scales in strongly dynamic environments as the Strait of Gibraltar. It must be stressed that both measurements deal only with bulk properties, and qualitative aspects of the particulate material nature are not directly accessible. However, the available data set from discrete variables (nutrients, chlorophyll, phytoplankton, carbon, lipids, etc.) obtained simultaneously during the surveys (Echevarría et al., 2002) facilitates the interpretation and evaluation of the potential origins of the fluorescence and turbidity.

The aim of this study is to assess the influence of the strong and variable winds and fortnightly tidal variability on the phytoplankton distribution (estimated as fluorescence) in the Atlantic water entering into the Mediterranean Sea. Here, each physical forcing and the combination of both are analysed based on the results from two cruises.

2. Material and methods

2.1. Field sampling and instruments

Data were collected during the CANIGO cruises carried out on June 18th–25th 1997 (Full moon on June 20th) aboard the R/V *Cornide* and September 2nd–9th 1997 (New moon on September 1st) aboard the R/V *Thalassa* in the Strait of Gibraltar (Table 1). During both cruises the sampling in the Atlantic stations was carried out under the influence of the spring tides. The sampling in the Mediterranean stations was carried out under during the spring and neap tide periods in June and September, respectively. At each cruise seven stations were sampled spending a day in each station from the west (Atlantic) to east (Mediterranean) (Fig. 1).

Table 1
Date, position, water depth, wind speed module (m s^{-1}) and angle (°) (relative to north direction) recorded by the research vessels during the midday in June and September 1997

Station	Date	Lat. N	Long. W	Water depth (m)	Wind module	Wind angle
June 1997						
2	19/06/97	35°56.5	5°59.9	268	5	220°
3	20/06/97	35°52.2	6°00.0	420	6	220°
4	22/06/97	35°58.6	5°36.0	521	10	220°
5	21/06/97	35°54.4	5°38.4	568	13	210°
6	24/06/97	36°05.0	5°17.9	547	1.5	50°
7	25/06/97	36°01.0	5°18.0	844	0	–
8	23/06/97	35°57.7	5°17.9	563	14	210°
September 1997						
2	03/09/97	35°57.9	5°55.0	250	20.2	83°
3	04/09/97	35°52.8	5°55.1	415	17.9	78°
4	05/09/97	35°58.4	5°35.9	517	19	69°
5	06/09/97	35°54.7	5°36.1	543	14.3	74°
6	07/09/97	36°04.9	5°18.2	696	10.7	65°
7	08/09/97	36°02.0	5°18.0	831	10.7	63°
8	09/09/97	35°57.7	5°18.0	575	8.7	71°

In June stations 2 and 3 were sampled westward due to diplomatic clearance difficulties.

Conductivity–temperature–depth (CTD) profiles were performed by using a Seabird Seacat-19 probe equipped with fluorescence and nephelometry sensors. The fluorometer (Chelsea Instruments) measures the stimulated fluorescence emission by chlorophyll *a* (units are expressed as relative units, r.u.). Nephelometry was measured as the light scattering (635 nm) of suspended particles recorded with a nephelometer (Chelsea Instruments) (units are expressed as FTU: Formazin Turbidity Unit).

Data acquisition comprised 32 and 33 profiles from the June and September surveys, respectively. For representation, values were subsequently binned over 5 m intervals applying a 5-m running average to each profile in order to smooth out very high frequency variability (e.g., due to pitch and roll of the ship during profiling).

2.2. Satellite observations

In order to evaluate the favourable conditions for phytoplankton blooms in the area before and during each cruise, the following satellite observations were used: daily Sea Surface Temperature (SST) distributions from the NOAA/NASA AVHRR Pathfinder project (June and September 1997, 9 km), weekly wind fields measured by the second European Remote Sensing satellite, ERS-2 (June and September 1997, 1 degree), and Ocean Colour and Temperature Scanner (OCTS) (June 1997). OCTS operational life aboard the ADEOS I satellite spanned from November 1996 to end of June 1997, when the ADEOS I platform had a general operational malfunctioning.
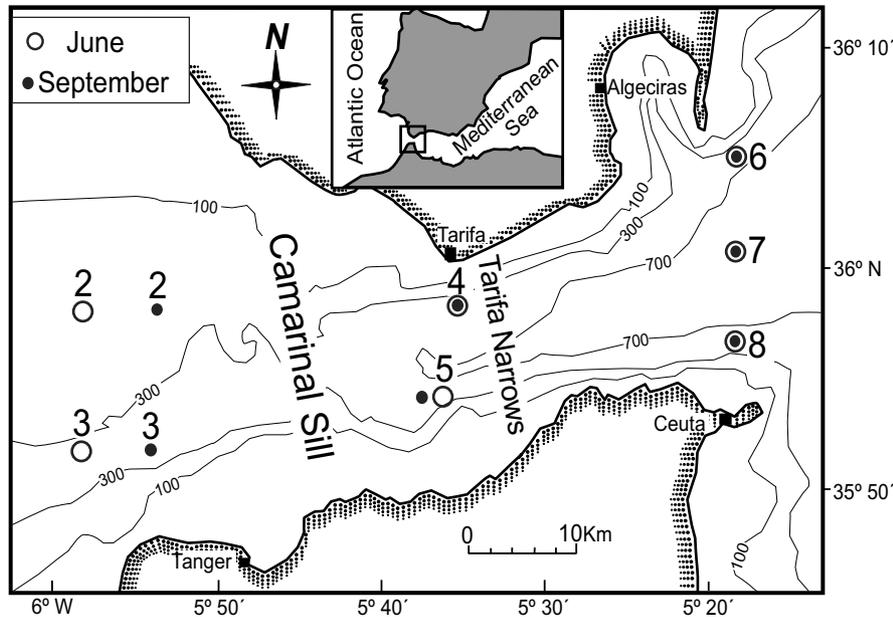
Fig. 1. Map of the Strait of Gibraltar and the stations during the CANIGO cruises in June and September 1997. Isobaths are in meters (m).

2.3. Physical approaches

The description and interpretation of the results requires establishing criteria in order to facilitate the comparative analysis among the stations. These assumptions are focused on the definition of the Atlantic–Mediterranean Interface (AMI hereafter), the definition of the water masses from the salinity vertical profiles and a "normalised" tide among the stations.

The AMI denotes the limit between the deeper nutrient-rich Mediterranean undercurrent (~ 9 μM NO_3^-) and the relative nutrient-depleted upper Atlantic current (~ 2 μM NO_3^-) (see Gómez et al., 2000b). It acts as a strong pycnocline, trapping and accumulating biological matter and as a layer of null advection increasing the residence time of matter in the Strait (Gómez et al., 2000a). The AMI definition varies among the depth of the maximum backscatter, the depth of zero velocity or the depth of maximum shear (Tsimplis and Bryden, 2000). Usually the interface is defined in terms of a single value of salinity, typically 37 (Bryden et al., 1994) or 37.5 (Candela et al., 1989, 1990). This particular isohaline that defines the interface, increases eastward along the Strait from values ~ 37.2 at the sill area (e.g., Bryden et al., 1994; Tsimplis and Bryden, 2000) to 37.85 on the eastern Mediterranean entrance (García Lafuente et al., 2000). For the purposes of this study, the AMI region will be defined as the layer ranging between the 37–38 isohalines (mean value 37.5).

The Atlantic inflow is formed by the mixing of the Surface Atlantic Water (SAW) and North Atlantic Central Water (NACW). In order to compare the biological characteristics of each layer among the stations, it is convenient to define the regions or layers based on the salinity profile: the SAW layer is defined from the surface (salinity ~ 36.4) to the shallower 36.2 isohaline. Usually eastwards the salinity did not reach values lower than 36.2, being considered the minimum of salinity in the Atlantic layer. The NACW layer was defined between the upper and deeper 36.2-isohalines according to the approach by Gascard and Richez (1985). Below the NACW (or SAW) layer, it was defined as a transition layer between the Atlantic waters and the interface (AW–AMI, hereafter), this region is from the deeper limit of the NACW (or from the salinity minimum if salinity > 36.2) to the 37-isohaline, where the AMI region begins (37–38 isohalines) (see inset, Fig. 2).

The tidal status was obtained from Anuario de Mareas (1997). All sampling times were referred to High Water at Tarifa (HW hereafter) in order to normalise the tide position of each coast.

3. Results

3.1. Physical background

The description of the physical structure during the surveys is focused on aspects more relevant for the biological signatures. The variability of the fluorescence and turbidity distributions is related to the AMI depth and the presence of NACW in the euphotic zone (< 100 m depth) (Fig. 2). The Atlantic layer is thinner parallel to the shoaling of the AMI towards the northeast. In the Atlantic side of the Strait (stations 2 and 3), the interface was located most of the tidal cycle below 150–200 m depth. The east sill in the Tarifa Narrows (stations 4 and
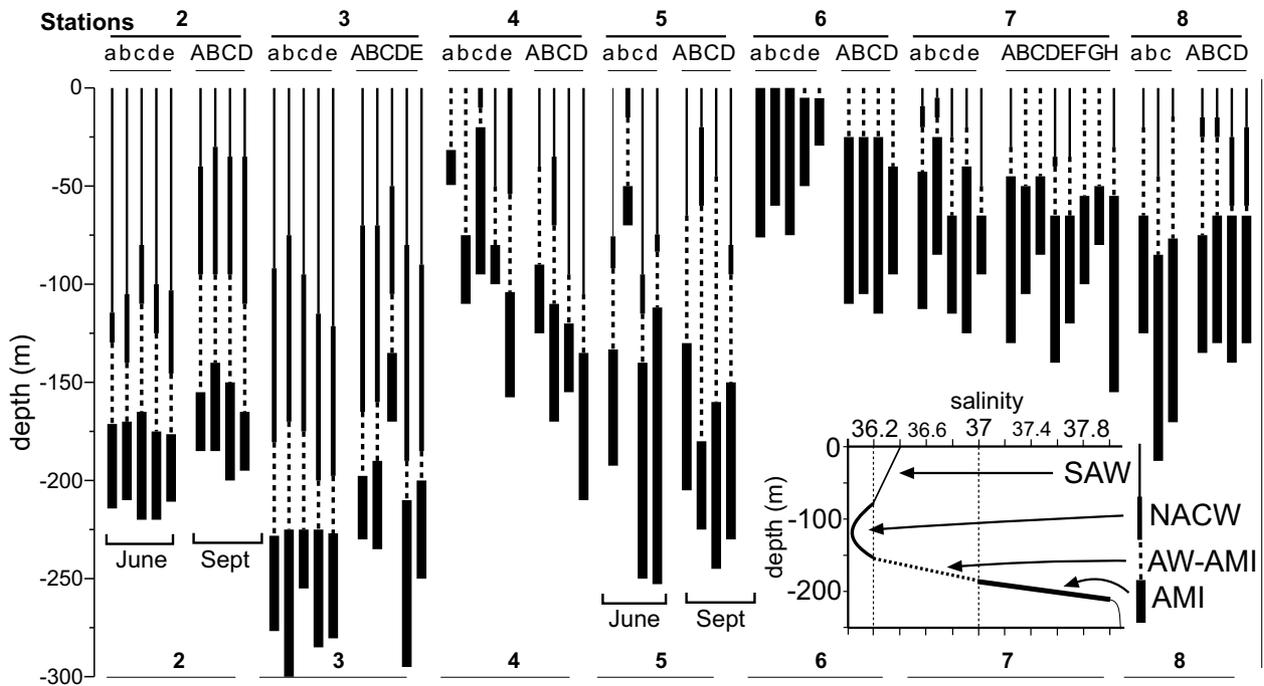
Fig. 2. Vertical distribution of the defined layers: Surface Atlantic Water (SAW), North Atlantic Central Water (NACW), Atlantic–AMI transition (AW–AMI) and AMI region (Atlantic–Mediterranean Interface) for both cruises (see Material and methods for details). Small and capital letters correspond to the June and September cruises, respectively.

5), the AMI and the transitional layer to Atlantic waters (AW–AMI) showed high vertical oscillations and higher thickness, especially close to the Low Tide (deeper interface). In the Mediterranean side of the Strait, the Atlantic inflowing layer was thinner northwards and station 6 showed salinity values >37.5 at the surface during the cruise in June (Fig. 2: 6a–e).

Concerning the NACW, in the Atlantic side of the Strait a thick layer appeared below the euphotic zone. However, station 2 in September constituted an exception with a thick layer of NACW in the euphotic zone (salinity minima ∼35.94–36.02). At the eastward sill, in the Tarifa Narrows (stations 4 and 5) when the interface was shallower, the Atlantic layer was composed of a thin layer of NACW in June (Fig. 2: 4c, 5b). For example at station 4 in June, the early night profile (ebbing tide) was associated with diluted SAW that was 1 h later replaced by a thick layer (0–60 m) of NACW with a salinity of 36.0 at 35 m depth (Fig. 2: 4c). Station 5 (just east of the sill) showed more fluctuations on the interface depth and water masses. In the Mediterranean side, the NACW signature did not appear in the north (station 6) in both cruises. Southwards, at station 8 in June the NACW signature (sampled during the spring tide period) did not appear whereas in September the NACW signature (neap tide period) was evident (Fig. 2: 8C, D). In this case the sunrise and sunset profiles were different despite the casts being performed at the same time of the tidal cycle. In the morning a thin NACW layer and a thicker AW–AMI layer appeared and

inversely during the night profiles, probably associated with a diurnal tide component, especially during the neap tide periods.

3.2. Fluorescence and turbidity vertical distributions

In the Atlantic side as a general trend the fluorescence was characterised by low values and deep fluorescence maxima (70–80 m depth). The fluorescence maxima were not associated with a significant increase of the turbidity values (except station 2: 2A–D). Turbidity showed a minima coinciding with the NACW layer and an increase just above the interface, sometimes with a maximum at the halocline (station 3: 3E). The turbidity profiles of station 2 during the September cruise (located eastward than in June) showed extraordinary high values (only comparable with the Mediterranean stations) reaching values of 0.16–0.19 FTU. The fluorescence showed a subsurface maxima of ∼0.39–0.42 r.u. at 50–55 m (at 10–15 m above the turbidity maxima) (Fig. 3: 2A–D).

At the Tarifa Narrows (eastward Sill) profiles showed the higher variability and faster changes associated with large excursions of the AMI (Fig. 2). At station 4, the ascent of the interface appeared associated with a sharp surface fluorescence maximum. In June as a general trend, the deeper interface (Low Water) was associated with a surface maximum and a secondary maximum at the halocline (Fig. 3: 4d–e). The ascent of the interface during the High Water implied that both maxima
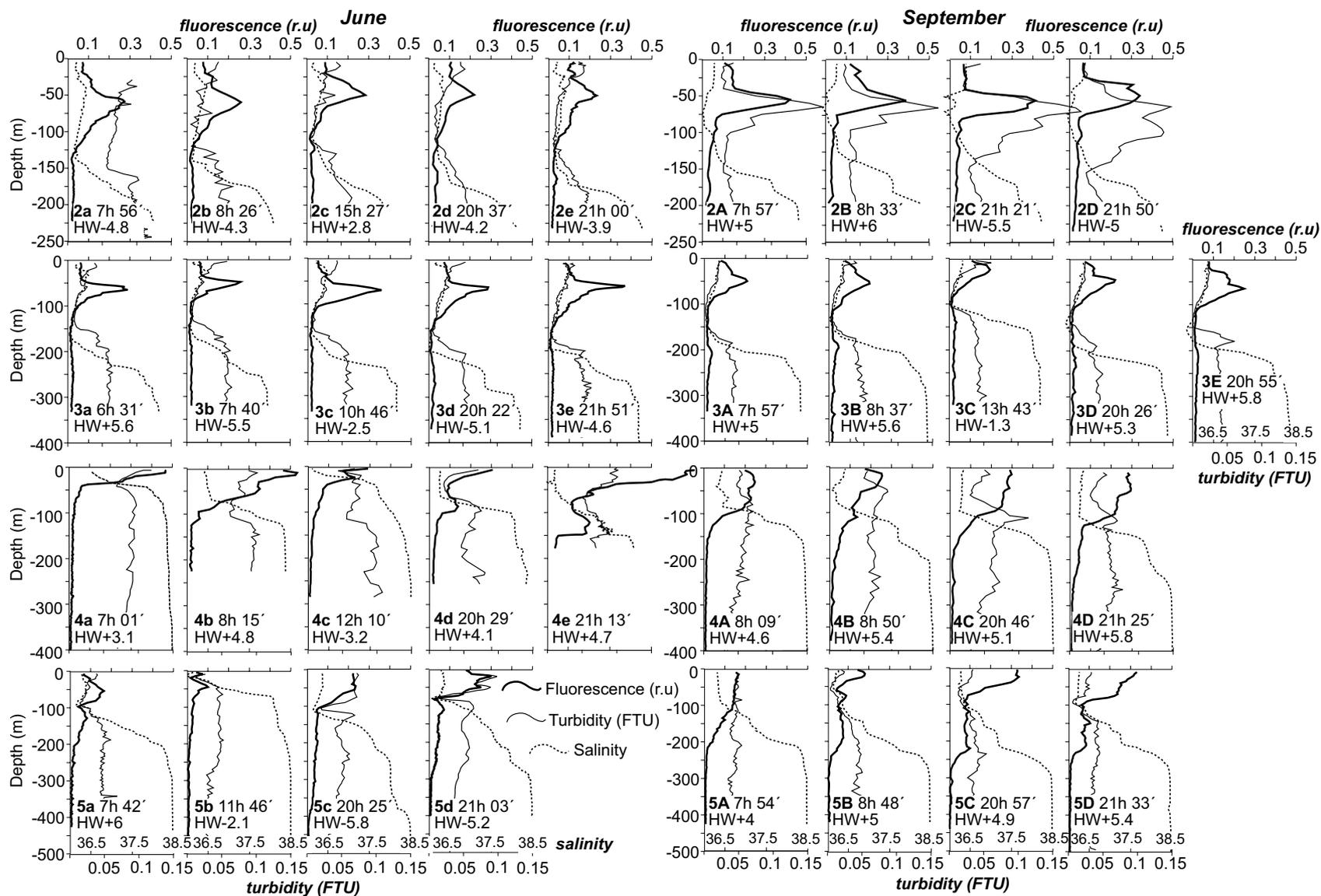
Fig. 3. Vertical distributions of fluorescence (scale from 0 to 0.5 r.u.), salinity (scale from 36 to 38.5) and turbidity (scale from 0 to 0.15 FTU) in the Atlantic side and Tarifa Narrows (stations 2–5). Sampling time and tide relative to HW at Tarifa are expressed at each profile. Note the change of depth scale among stations.

merged in a surface maximum (Fig. 3: 4a). The occurrence of NACW was associated with an increase of fluorescence (Fig. 3: 4e). In September, the Atlantic layer appeared fresher with higher NACW presence and the surface and interface maxima formed a thick core of fluorescence (Fig. 3: 4A–D). At station 5 fluorescence presented relatively high values below the euphotic zone (Fig. 3: 5A–D).

In the Mediterranean side, station 6 presented very high values of fluorescence and turbidity in both cruises, especially in June when the Atlantic layer was replaced by saltier waters (Fig. 4: 6a–e). The profile of turbidity resulted in three maxima. The two deeper ones appeared where the salinity gradient was lower (Fig 4: 6a–e). Station 7 in June also presented high turbidity values just below the interface but not also associated with a fluorescence increase (Fig. 4: 7c–e). Station 8 in June (spring tide) showed low values of fluorescence and turbidity. In September (neap tide) the fluorescence reached the highest values among the stations during the last profile associated with "pure" NACW (Fig. 4: 8C–D).

3.3. Comparative analysis among the stations

3.3.1. Fluorescence

The Deep Fluorescence Maxima (DFM) appeared in the stations with the lower values of fluorescence (Fig. 5A). In the Atlantic side, stations 2 and 3 showed the deeper fluorescence maximum between 50 and 70 m depth, typical subsurface maximum in summer oligotrophic waters, with deeper values in station 3. One exception was the profile 3C that coincided with the rise of the interface near the HW (September; HW-1.3). The DFM is often considered to be a consequence of phytoplankton photoadaptation to dim light and does not reflect a proportional abundance increase. As a general trend it was observed that the deep fluorescence maximum was not associated with an increase of the turbidity values (Fig. 3). This situation changed, however, when the NACW was found in the euphotic zone (station 2 in September). In the Tarifa Narrows (station 5) despite the general variability some trends appeared. The high vertical oscillation of the interface was associated with a surface maximum during the HW (rise of the interface) and the other LW (deepening interface). As a consequence at the central stations, the higher values of fluorescence at subphotic layers were observed (Fig. 5B). In the Mediterranean side, the fluorescence at station 6 achieved its maxima values due to the coincidence of the superficial and interface fluorescence maxima. Southwards at station 8, the interface was too deep to maintain a phytoplankton peak at the interface levels (aphotic zone) (Figs. 4, 5B).

High values of fluorescence were recorded in the apparently nutrient-depleted Surface Atlantic Water

(SAW). For example, the salinity profile at station 8 suggested that SAW was mixed with NACW during the night transit along the Strait in the inflowing current (Fig. 4: 8). The northeastward shoaling of the interface determine that stations 6, 7, 4, and 8 showed the highest values of fluorescence (Fig. 5C). The stations located at the Atlantic side (deeper AMI) showed the lower values especially at station 3 in June when the sampling was performed westwards than in September. As a general trend the tidal ascent of interface tended to reduce the integrated values of fluorescence due to the intrusion of Mediterranean water during the High Water (Fig. 5C, D). Station 6 in September presented similar values of integrated fluorescence along the day without a clear influence of the tide (Fig. 5D). In June the physical structure was anomalous with different values of integrated fluorescence along the day (Fig. 5C). This anomalous situation also seemed to influence station 7 in June sampled some hours before (Fig. 5C).

3.3.2. Turbidity

The turbidity layers are associated with density gradients or discontinuities such as Atlantic Mediterranean Interface. Here, phytoplankton cells and detritus are not so rapidly advected as observed in the upper and lower layers, leading to an increased residence time of particulate organic matter of photosynthetic origin (Gómez et al., 2000a). In the Strait, the turbidity showed an inverse relation to the interface depth as also the fluorescence (except station 2A–D) (Fig. 5E). The ratio of fluorescence/turbidity used as an indirect estimator of the proportion of living phytoplankton in the particulate matter showed high values in stations 3 and 5 (higher proportion of photosynthetic-active matter), whereas the lower values appeared in station 2 in September and stations 6 and 7 that indicated the lower proportion of particles with fluorescence (living matter) versus the bulk of particulate matter (Fig. 5F).

4. Discussion

4.1. North Atlantic Central Water

The NACW has an important role in the biogeochemistry of the Atlantic inflowing current due to the high amount of nutrient provided by this water mass that is initially located at the subphotic zone of the Gulf of Cádiz (Gascard and Richez, 1985). The values reported in the literature concerning the proportion of NACW injected in the Atlantic current vary according to the methodology. Bray et al. (1995) based on a triangulation method reported a contribution of 30–40% of NACW in the upper layer, decreasing eastwards. Elbaz-Poulichet et al. (2001) based on chemical trace metals reported an average value of 3%
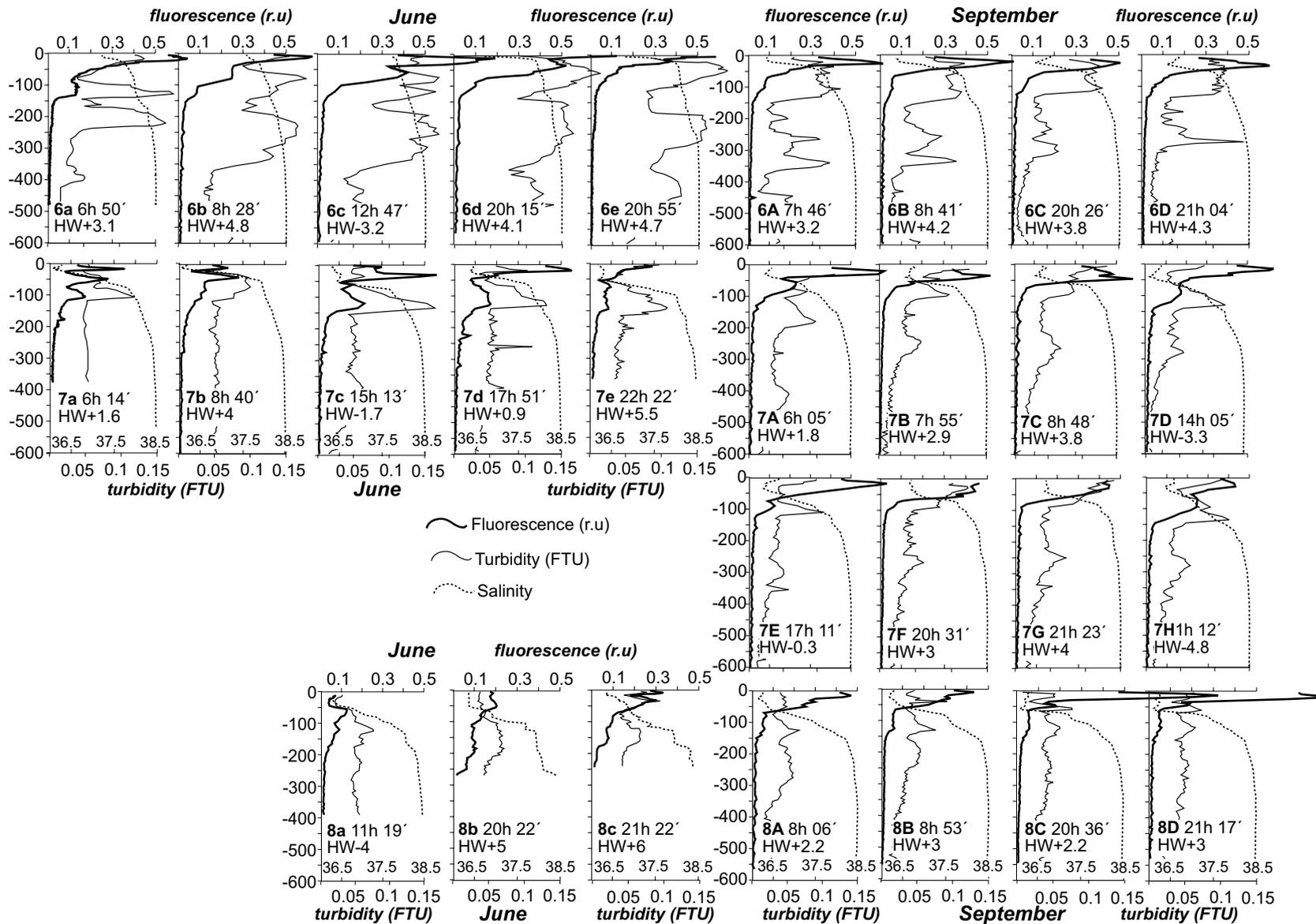
Fig. 4. Vertical distributions of fluorescence (scale from 0 to 0.5 r.u.), salinity (scale from 36 to 38.5) and turbidity (scale from 0 to 0.15 FTU) in the Mediterranean side of the Strait (stations 6–8). Sampling time and tide relative to HW at Tarifa are expressed at each profile.
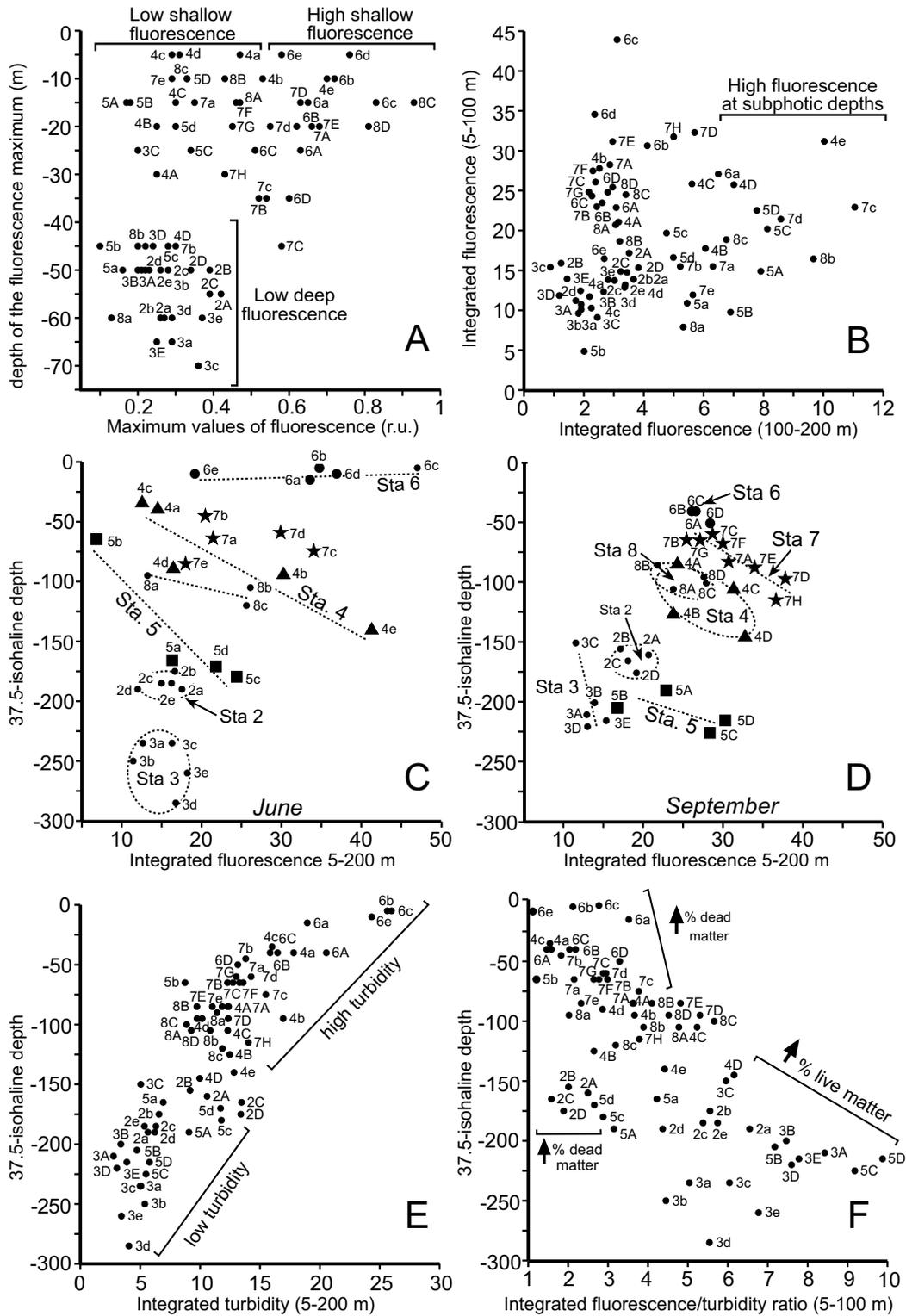
Fig. 5. (A) Scatter plot of the depth of the fluorescence maxima and the maximum values of fluorescence. (B) Scatter plot of the integrated fluorescence in the upper 5–100 m and the 100–200 m layers in June and September, respectively. (C, D) Scatter plot of the integrated fluorescence values in the 5–200 m depth in relation to the interface depth. (E) Scatter plot of nephelometry values integrated in the 5–200 m layer in relation to the depth of the interface. (F) Scatter plot of the fluorescence/nephelometry ratio in the upper 5–100 m depth in relation to the depth of the interface.

ranging from 1 to 5% of the Atlantic inflow. According to Bray et al. (1995) the contribution of the NACW to the Atlantic current showed a seasonal variability that comprises in spring twice the fraction than it does in autumn. During the September survey (two days before the crescent moon) based on the Bray et al.'s (1995) methodology, the NACW contribution [NACW/ (SAW + NACW)] in the Atlantic layer ranged from 26% when the interface was deeper to <1% when the AMI was shallower (Gómez et al., 2001).

At the Camarinal sill, Tsimplis and Bryden (2000) reported NACW lenses that appeared around 130–140 m depth with higher signatures on each of the two tidal cycles associated with the deeper interface values. García Lafuente et al. (2000) reported that tidal currents are diurnal in the middle of the eastern side of the Strait (near station 7) during the neap tides and semidiurnal during the spring tides. The diurnal inequality in the injection of NACW could explain the differences between the morning and night profiles of salinity which appeared at station 8 (Fig. 4: 8A–D). The fluorescence associated with the NACW also varies according to the light/dark cycle. For example at station 5, the cast performed in the first hours of the morning (8–9 h GMT) corresponded to uplifted water during the night and the increase of the fluorescence was not evident (Fig. 3: 5B).

Another factor that should be taken into account is the influence of the fortnightly variability on the exchange through the Strait. The maximum inflow occurs just after neap tide (deeper interface) and the maximum outflow occurs during the spring tides period (shallower interface) with an oscillation of the average interface depth at the sill of ∼20 m (Bryden et al., 1994; Tsimplis and Bryden, 2000). Semidiurnal currents and vertical shear reach their maximum after the full/new moon (García Lafuente et al., 2000). Gascard and Richez (1985) concluded that only during neap tides was relatively "pure" NACW observed in the Mediterranean side of the Strait, whereas during the spring tide it did not appear in the Mediterranean entrance due to a strong mixing (internal waves) that occurs at the levels where the NACW was presented. Station 8 in June was sampled two days after the full moon (spring tide) (Table 1). In September, one day before the growing quarter moon (neap tide), the layer of NACW was thicker and its appearance in the night profiles implies that the passage of this water mass in the euphotic zone through the Strait occurred during the illumined period with the consequent highest values of fluorescence recorded (up to 0.93 r.u., Fig. 4: 8C).

Wind constitutes a factor that reaches extreme values in the Strait of Gibraltar. The different atmospheric pressure between the Eastern Atlantic and Western Mediterranean basin is associated with strong winds (sometimes >30 m s^{-1}) through the Strait (Dorman et al., 1995). The surface currents in the Strait are pushed in the wind direction (Candela et al., 1989). Winds, mainly westerlies or easterlies (called "Poniente" or "Levante", respectively, in the local terminology) enhanced an eastward and westward flow, respectively (Pistek and La Violette, 1999; García Lafuente et al., 2002b). Several studies reported a strong cool signature in the southern half of the Strait due to the upwelling caused by Levantes that are enhanced by the strong orographic constraints in the Strait (see Vargas-Yáñez et al., 2002; Vargas et al., 2003 for winds in the Gulf of Cádiz). Tsimplis and Bryden (2000) quantified the effect of the winds on the Atlantic inflowing current. They reported an Atlantic inflow of 0.78 Sv (1 Sv = 1×10^6 m^3 s^{-1}), being the contribution of the wind to the inflow ±0.13 Sv. They concluded that winds to the west (easterlies) could reverse the flow of the upper layer.

4.2. Retention of NACW in the Atlantic entrance of the Strait

Station 2 in September presented a thick core of NACW in the euphotic zone in all profiles obtained along the day (Figs. 2A–D, 3: 2A–D), showing unusual high turbidity values for the NACW in the Atlantic side of the Strait and low values of fluorescence (Fig. 5). This station presented low nutrient concentrations with an average nitrate concentration in the upper 50 m depth of ca. 0.15 µM (Gómez et al., 2000b). From water samples collected during the same survey, Dafner et al. (2001) reported values of organic carbon <85 µm in all the stations. Station 2, however, constituted an exception, reaching the highest values (132 µM TOC; 60 m depth). The most general explanation for the high values of organic carbon is that after the bloom, primary production induces the release of extracellular substances that together with the decomposition of the organic matter increases the organic carbon content in the water column (Cauwet et al., 1997). Biological variables show that the NACW remained in the euphotic zone for several days before the sampling. Subsequently, the nutrients that were initially in the water mass were transformed into phytoplankton biomass. After the depletion of the nutrients high turbidity and low fluorescence values (low proportion of photosynthetic-active plankton biomass) were recorded as typical in senescent phytoplankton populations (post-bloom) (Fig. 5F). At the moment of the sampling the thick layer of NACW in the euphotic zone (<100 m depth) was observed (Fig. 2A–D). Available Sea Surface Temperature (SST) images before the September cruise corroborate the presence of a patch of cold water in the Atlantic side of the Strait of Gibraltar (Fig. 8). This phenomenon is here considered a retention of the NACW in the euphotic zone, with a scarce renewal of the water mass that cannot cross eastwards the Strait.
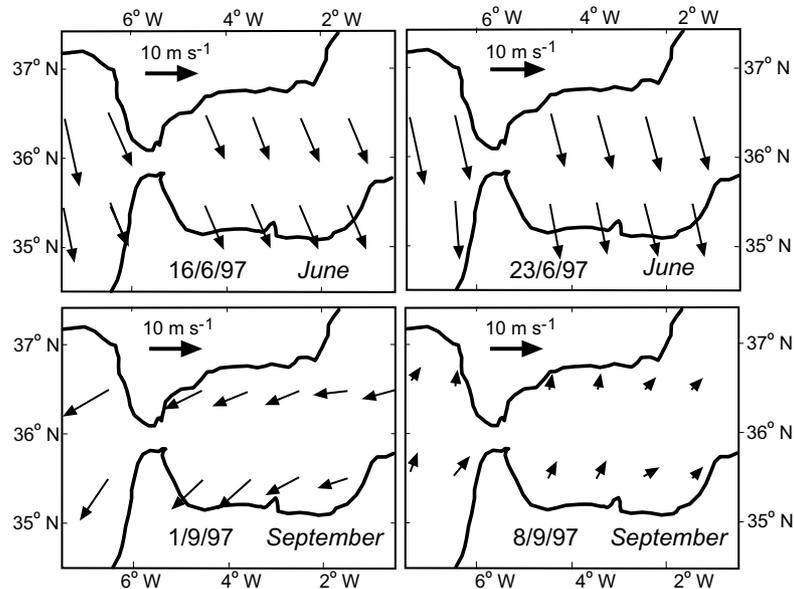
Fig. 6. Weekly wind fields in the vicinity of the Strait of Gibraltar measured by the second European Remote Sensing satellite (ERS-2) in June and September 1997 (1 degree).

Two factors should be taken into account in an analysis of the physical origin of the phenomenon: (1) the sampling was carried out on September 3rd (New moon on September 1st), but the biological data showed that the ascent of NACW occurred several days before and consequently under the influence of the neap tide period; and (2) the easterlies (Levante) were blowing several days before sampling (Fig. 6). As previously reported, during the neap tide period the injection of NACW in the inflowing Atlantic waters is favoured (Gascard and Richez, 1985). On the other hand, recently García Lafuente et al. (2003) also presented evidence of the interruption of the Atlantic inflow by easterlies in the Strait of Gibraltar. The combination of the fortnightly tidal cycle that favoured the intrusion of NACW and the easterlies interrupting the inflow into the Mediterranean Sea are considered here as the pheno-

mena responsible for the retention of NACW in the euphotic zone of the Atlantic side of the Strait (Fig. 7).

4.3. Influence from the upwelling along the NW Alborán coast

Upwelling is an almost permanent feature along the NW Alborán coast (García-Górriz and Carr, 1999, 2001). Sarhan et al. (2000) reported two mechanisms responsible for the upwelling dynamics in the NW Alborán Sea: the southward drifting of the Atlantic Jet (gyre induced) and the wind-driven upwelling. Both upwelling mechanisms are associated with different types of water mass taking place in different locations. Wind-driven upwelling dominates in coastal zones moving up colder and saltier water on the continental shelf, whereas the other upwelling mechanism (gyre
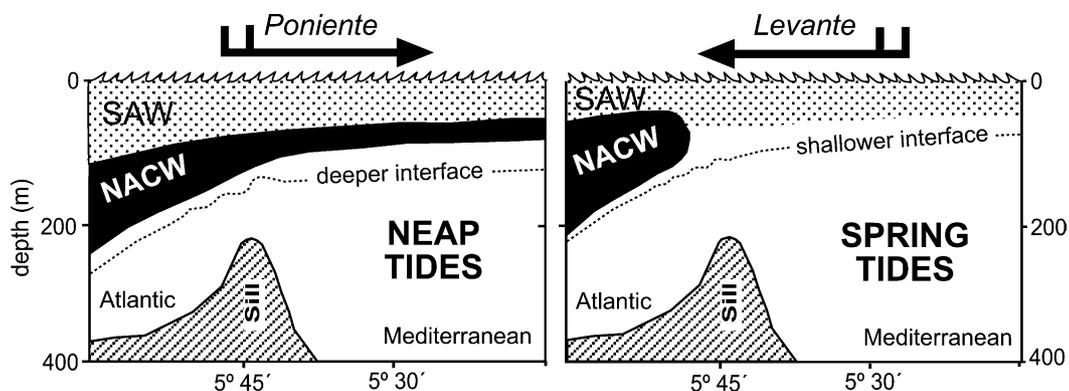

Fig. 7. Schematic representation of the NACW distribution during the neap and spring tide periods based partially on Gascard and Richez (1985). The easterlies (Levante) favoured the passage of the NACW through the Strait, whereas the westerlies (Poniente) could disfavour and/or retain the NACW in the Atlantic side of the Strait.
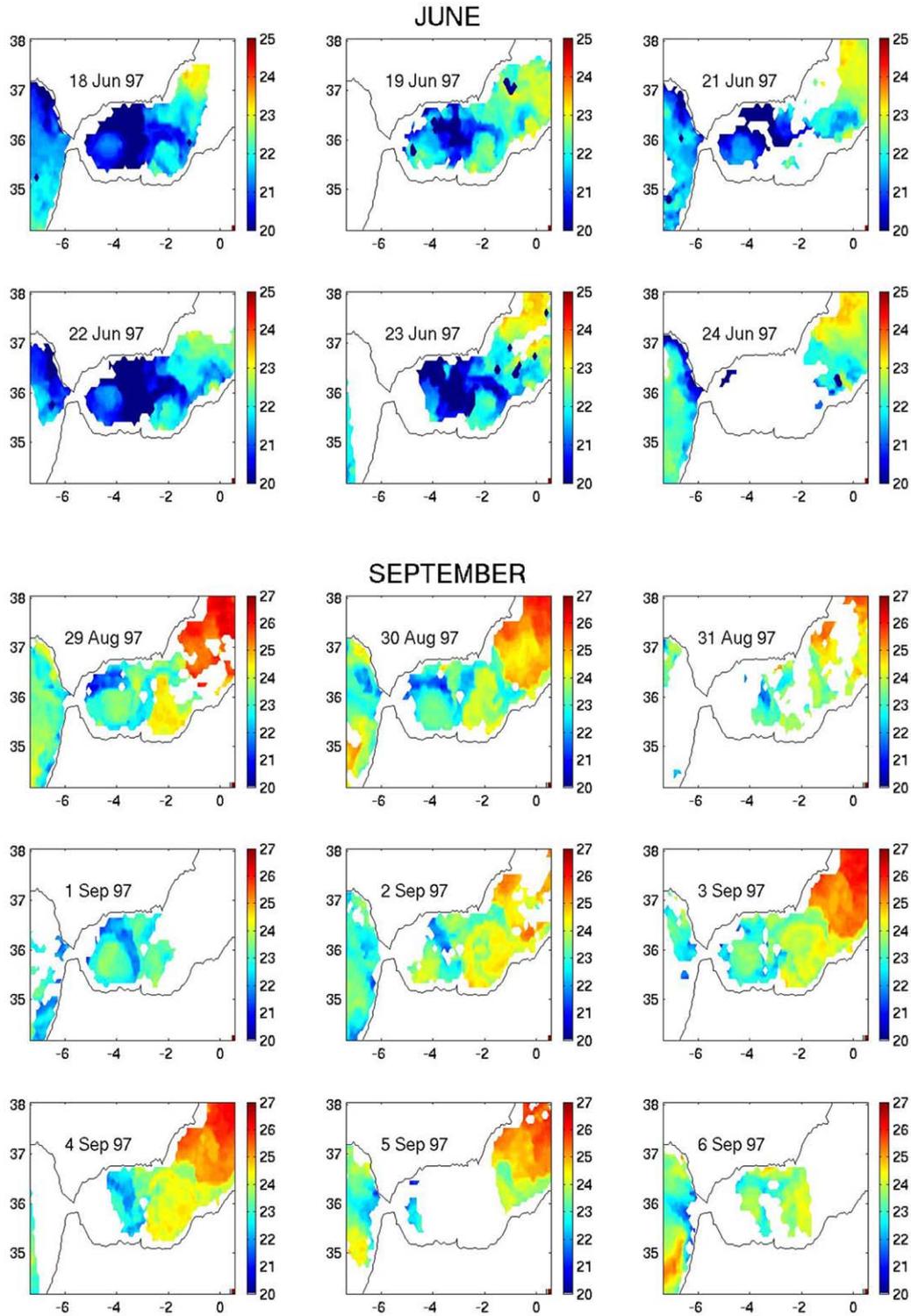
Fig. 8. Daily Sea Surface Temperature (SST) images in the vicinity of the Strait of Gibraltar in June and September 1997 (9 km). Temperature units as °C.

induced) is located offshore. When winds from the north or west (Poniente) blow, high values of fluorescence are found near the NW Alborán coasts associated with salty and cold waters (Sarhan et al., 2000). Westerlies intensify the eastward Atlantic inflow (Tsimplis and Bryden, 2000) and these salty and productive waters from the coastal wind-driven upwelling are supposed to be pushed eastwards by the Atlantic current, preventing these salty waters from being observed on the eastern side of the Strait (stations 6 and 7). Strong winds from
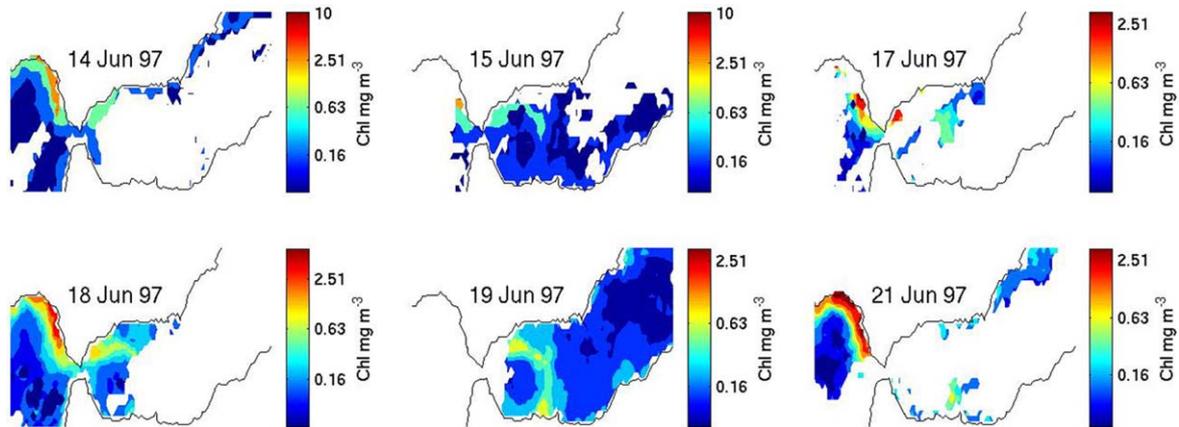
Fig. 9. Ocean Colour and Temperature Scanner (OCTS) images in the vicinity of the Strait of Gibraltar during the cruise June 1997.

the north that favoured the coastal upwelling were recorded the week before the cruise in June 1997 (Fig. 6). During this period, cold upwelled waters in the NW Alborán Sea (Fig. 8) associated with high pigment values were observed by remote sensing (Fig. 9).

During the survey carried out in June, north-westerlies blew from 18th to 23th June (5–13 m s^{-1}; $\sim$220°). Station 6 was sampled on June 24th when the wind dropped to 1.5 m s^{-1} and turned to the East $\sim$50° (Table 1). As a general trend, at the position of station 6 the average interface is located around $\sim$80 m depth (Bray et al., 1995) with usually a layer of Atlantic Water flowing eastwards. In June, however, the salinity showed values higher than 37.5 at the surface (Fig. 2). The layer of Atlantic water has been replaced by salty Mediterranean waters upwelled the previous week along the NW Alborán coast forced by the upwelling favourable winds (Fig. 6). Sampling at station 6 was performed three days after the full moon (spring tide) that implies a weak Atlantic current (Tsimplis and Bryden, 2000).

The biological production is exported southward from the NW Alborán coast to the Mediterranean Outflowing current that enters the Strait (Send et al., 1999). In June 1997, Fabres et al. (2002) reported a very high flux of the biogenic particles in the NW Alborán Sea. Gorsky et al. (2002) also reported a high concentration of particles on the northeastern side of the Strait of Gibraltar in the same period. This could explain the deep turbidity maxima observed at the station 6 (Fig. 4: 6a–e).

5. Final remarks and biological budgets through the Strait

The biological production in the NE side of the Strait seems to be more constant, whereas the wind-induced upwelling provides more intense primary production but more sporadic and unpredictable. In this fluctuation environment, diatoms are mainly responsible for the biological production as was revealed by their high

abundance (Gómez et al., 2000a). Morán and Estrada (2001) based on photosynthetic parameters reported that phytoplankton in this area is adapted to continuous changes, reflecting the strong variability of the physical environment in the NW Alborán Sea. The induced physical changes determine that the biological variability in the Strait of Gibraltar and NW Alborán Sea is more related to hydrodynamic events, overlaying and hiding the typical phytoplankton seasonality in the western Mediterranean Sea (see examples in Gómez and Gorsky, 2003). Thus, in the western Alborán Sea the higher chlorophyll maximum appeared in winter (García-Górriz and Carr, 2001) when the wind favours coastal upwelling (Bakun and Agostini, 2001).

Gómez et al. (2000b) estimated a potential production of 40 kg carbon s^{-1} from the mixing of a transitional layer of the Mediterranean Outflowing Water at the sill of the Strait. To this value, should be added the contribution of the NACW. As an approach, an Atlantic of current $\sim$0.8 Sv [0.78 Sv at the sill by Tsimplis and Bryden (2000) and 0.82 Sv in the Mediterranean side by García Lafuente et al. (2000)] can be considered. The contribution of the NACW to Atlantic inflow is between 30 and 40% (Bray et al., 1995). This implies the injection of 0.25–0.3 Sv of NACW. Considering that the NACW initially contains $\geq$ 7 μM nitrate in the Atlantic side of the Strait (Gómez et al., 2000b), it implies the injection of 2000 moles NO$_3^-$ s^{-1} in the euphotic zone that potentially corresponds to 100–150 kg carbon s^{-1} based on the Redfield ratio (C : N = 6.6). Both mechanisms (mixing of MOW and injection of NACW) generated a primary production from different origins. The biomass from MOW is originated by "recovered Mediterranean nutrients", whereas the NACW production is generated by "Atlantic nutrients". A permanent monitoring of the exchanges of substances at the Strait (Gómez, 2003) as already existing for water fluxes (García Lafuente et al., 2002a,b) would be convenient in order to evaluate the variability of the biogeochemical exchanges.

Acknowledgements

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