Vol. 314: 61–75, 2006 | MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser | Published May 22

Role of Saharan dust on phytoplankton dynamics in the northeastern Mediterranean

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ABSTRACT: Effects of atmospheric deposition and other environmental factors on phytoplankton dynamics were evaluated from an open (having offshore characteristics) and a coastal station in the northeastern Mediterranean between December 2000 and December 2001. Data on phytoplankton, chlorophyll *a*, nutrients, temperature and salinity were obtained at bi-weekly or more intense intervals during 1 yr, whilst transport of Saharan dust towards the sampling region was monitored daily by SeaWiFS (sea-viewing wide field-of-view sensor) images. Diatoms were the group of highest average biomass during the entire investigation period. Although coccolithophores (mainly *Emiliania huxleyi*) numerically dominated at the open station during the study period, their maximum abundance was as low as 50×10^3 cells l^{-1}. The intensity of dust transport was observed to be highest in spring. Less intense transports were observed in summer and autumn. Several intense episodic dry and wet dust deposition events during the spring season observed by SeaWiFS images caused little or no increase in phytoplankton abundance and biomass in the following days and weeks. Nevertheless, it appears that less intense dust transport events increased phytoplankton abundance and biomass in August, September and October 2001, when water column stratification was at its peak. However, these increases were much weaker than the major winter-early spring bloom (in February and March), which was caused by upwelling, mixing the water column. We suggest that the impact of atmospheric nutrient input on phytoplankton in the Mediterranean is rather low on a yearly basis.

KEY WORDS: Phytoplankton abundance · Biomass · Composition · Chlorophyll *a* · Saharan dust · Winter mixing

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INTRODUCTION

There have been numerous investigations indicating the importance of atmospheric deposition of nutrients and trace metals for surface waters of several oligotrophic marine regions, including the Mediterranean Sea (Rodhe et al. 1980, Duce 1986, Prospero & Savoie 1989, Loÿe-Pilot et al. 1990, Donaghay et al. 1991, Bergametti et al. 1992, Zhang & Liu 1994, Herut & Krom 1996, Guerzoni et al. 1999, Guieu et al. 2002a, Markaki et al. 2003). Effects of atmospheric nutrient input on primary production or pigment composition of phytoplankton have also been investigated (e.g. Martin et al. 1989, Loÿe-Pilot et al. 1990, DiTullio & Laws 1991, Young et al. 1991, Bergametti et al. 1992, Guerzoni et al. 1999, Herut et al. 2002). There have been a limited number of investigations on the effects of atmospheric deposition on phytoplankton abundance, biomass and species composition of the world's oceans (Paerl & Whitall 1999, Seitzinger & Sanders 1999, Walsh & Steidinger 2001). Among them, only Walsh & Steidinger (2001) studied the impact of Saharan dust on phytoplankton abundance. They suggested that cyanobacterial abundance increased as a result of Saharan dust input, and consequently, the nitrogen, fixed by cyanobacteria, caused dinoflagellate blooms in coastal waters off western Florida, Gulf of Mexico.

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A hypothesis has been formulated in several publications (Saydam 1996, Guerzoni et al. 1999, Kapur et al. 2000) suggesting that 'Saharan dust has the potential to induce phytoplankton (especially *Emiliania huxleyi*) blooms in the Mediterranean. At present, however, no phytoplankton data exists from the field to substantiate this hypothesis. 'Significant relationships between Saharan dust transport events and local oceanic production of methane sulfonic acid (MSA) through occasional fertilization of the eastern Mediterranean during wet deposition events' were pointed out by Kubilay et al. (2002, p. 1). MSA is the oxidized form of dimethylsulfide (DMS), the principal and most abundant biogenic organic sulfur compound entering the atmosphere. DMS is excreted by phytoplankton (mainly dinoflagellates, prymnesiophytes, including coccolithophores, and other chromophyte algae, including chrysophytes and diatoms; Keller et. al. 1989, Malin et al. 1993) through several processes, such as cell lyses under physical or chemical stress, zooplankton grazing (Wolf & Steinke 1996) and viral activity (Bratbak et al. 1995). Thus, if Saharan dust (which is dispersed over very large oceanic areas) is causing phytoplankton blooms, the implication of this process would be significant, not only for increased primary production (which may lead to enriched fisheries), but also for global climate dynamics. Phytoplankton may play a role in the global climate changes by producing dimethyl-sulfoniopropionate (DMSP) the oxidized form of which is DMS, a cloud condensation nuclei in the atmosphere. Increased cloudiness increases the Earth's albedo (Charlson et al. 1987, Falkowski et al. 1992, Ciglenecki & Cosovic 1996). Furthermore, phytoplankton production is important in the CO_2 pressure equilibrium of the atmosphere due to CO_2 drawdown (Geider et al. 2001).

In Saydam's (1996) hypothesis dissolved iron was identified as the major element causing phytoplankton blooms. Previously, Visser et al. (2003) had reported that iron from Saharan dust increased the growth rate of 2 Antarctic diatom species, which were grown in the laboratory in seawater from the high nutrient, low chlorophyll (HNLC) region. However, both particulate and dissolved iron have been reported to be abundant in the Mediterranean (Guerzoni et al. 1999, Guieu et al. 2002b), whilst inorganic phosphorus for both the eastern and western Mediterranean (Woodward & Owens 1989, Raimbault & Coste 1990, Dolan et al. 1995, Thingstad & Rassoulzadegan 1995, Zavatarelli et al. 1998) or nitrogen for the western region (Krom et al. 1991, 2004, Yilmaz & Tugrul 1998) has frequently been identified as the limiting nutrient, depending on time of year. Thus, atmospheric input of either phosphorus or nitrogen has often been reported to be significant in the Mediterranean, particularly during stratification periods. However, there is only 1 study suggesting the negligible effect of an atmospheric nutrient (i.e. dissolved inorganic phosphate, DIP) on the total annual primary production of the western Mediterranean (Ridame & Guieu 2002). Krom et al. (2004) state that the dominant term in the nutrient budget of the eastern Mediterranean is the atmospheric flux, as atmospheric nitrogen and phosphorus constitute 62 and 28%, respectively, of total nutrient input to the basin.

Since there are opposing views relating to the importance of atmospheric dust on phytoplankton, it is clear that there is a need for further studies. This could be achieved by taking into account, not only Saharan dust deposition (its route, etc.), but also simultaneous phytoplankton levels (abundance, biomass and composition), particularly *Emiliania huxleyi*, in the surface waters. Until now, no such study has been published. In the present work, we have investigated the role of Saharan dust deposition (irrespective of its composition at this stage) along with other major factors (e.g. winter mixing and other water dynamics, riverine input and rain) on phytoplankton dynamics. If Saharan dust is found to be important in causing phytoplankton blooms, then the agents in the dust responsible should be investigated in detail in follow-up studies.

MATERIALS AND METHODS

In order to observe any possible effects of dust on phytoplankton, Saharan dust transport events were regularly observed via satellite. In addition, frequent field sampling (generally biweekly) of phytoplankton (Table 1) and of the conventional physical and chemical parameters of seawater was carried out. Extra samples, out of the normal sampling intervals, were obtained following dust transport events observed by SeaWiFS (sea-viewing wide field-of-view sensor) images (Table 1). Rainfall data for the same period for a nearby region (10 km distance from the coastal station) were provided by Erdemli Meteorological Station (36° 38′ N, 34° 20′ E).

Daily true color SeaWiFS images were downloaded from internet sites (SeaWiFS.gsfc.nasa.gov/cgi/SeaWiFS_browse.pl and SeaWiFS.gsfc.nasa.gov/cgi/SeaWiFS_subreg.pl) in order to observe dust transport to the sampling region. In addition, raw data taken from the internet (daac.gsfc.nasa.gov/data/dataset/SEAWIFS/01_Data_Products/02_LAC/01_L1A_HRPT/) were also processed by the SeaDAS computer program, to obtain better resolution of images for the days when high dust loads were seen over the sampling region. Daily dust concentrations over the sampling region (Fig. 1, ~30 × 30 km^2 Erdemli–Mersin), observed in SeaWiFS images, were graded in a graphic program (PaintShop-

Table1. Dates of the most intense dust transport events (wet or dry; *: rain was also reported) to the sampling area and their intensity (strong or minor) along with sampling dates (**: samples taken along the Aegean Sea coast), hydrographic conditions (M: mixed; S: stratified), nutrient and phytoplankton biomass change in surface waters at the open station between December 2000 and December 2001

	2000	2001											
	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Major dust events	30*		26, 27, 28	20, 27	1, 18*–23, 30	1, 13*, 20, 26, 27		12,13, 19	6, 9	24–25	12, 22	4*, 5*	
Precipitation	Wet	Wet	Dry	Dry	Wet, Dry	Wet, Dry	Dry	Dry	Dry	Dry	Dry	Wet	Wet
Intensity of dust	Strong	Minor	Strong	Strong	Strong	Strong	Minor	Strong	Strong	Strong	Strong	Minor	Minor
Sampling dates	7, 20	4, 24	8	3, 8, 16, 19, 22, 27	12, 20**, 22**, 23** 24**, 27**	2**, 3, 15,18, 22, 25	8, 21, 29	13, 25	16	6, 28	4, 23	7, 14	11
Hydrographic conditions	M	M	M	M	M	M	M/S	S	S	S		S	M
Nutrient increase	None	None	None	Strong	None	Mild	None	None	Strong	Strong	Strong	None	None
Phyto. biomass increase	None	Mild	None	Strong	None	Mild	None	None	mild	Strong	None	Strong	None

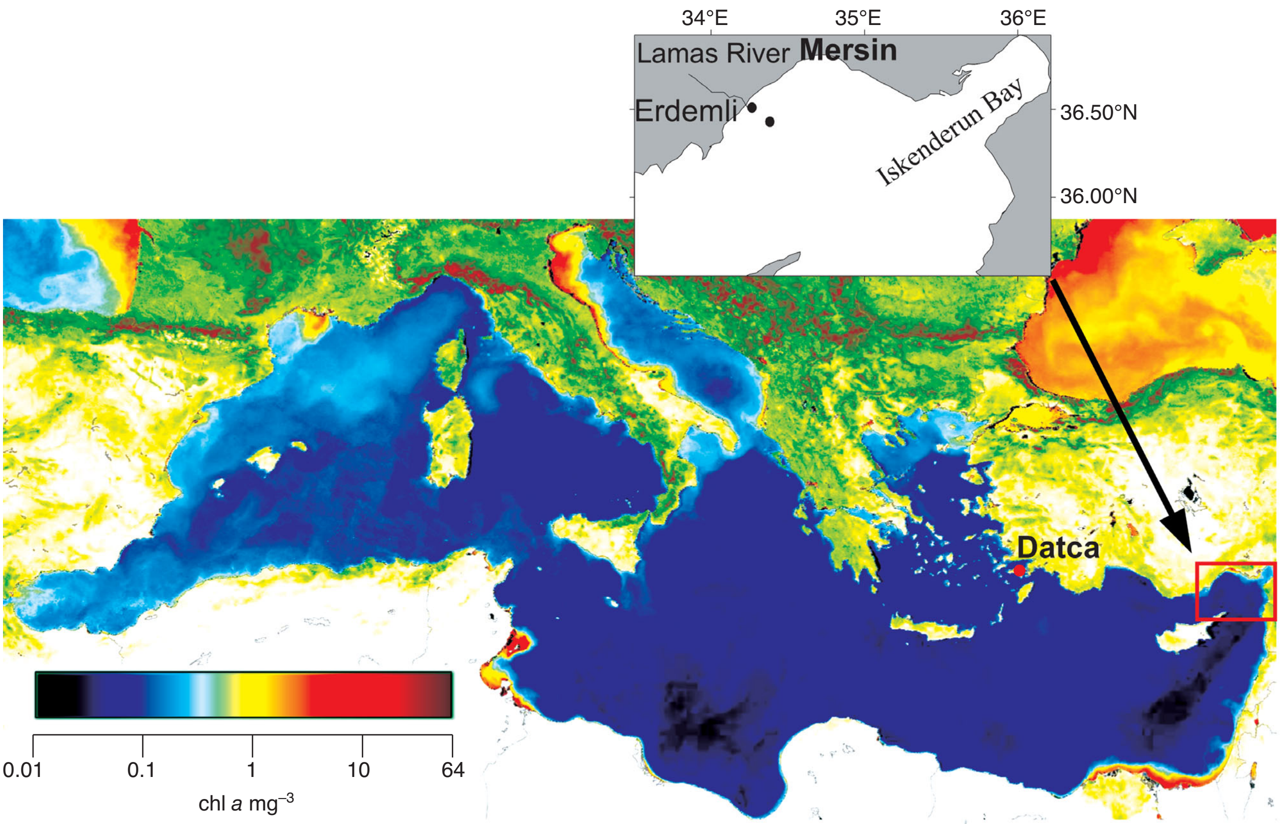

Fig. 1. Composite chl *a* concentrations from SeaWiFS in June 2001 in the Mediterranean (from http://marine.jrc.cec.eu.int/frames/OceanColourPortal.htm and the 2 sampling stations off Erdemli)

Pro), in order to determine relative dust loads. Using the toggle histogram window the mean value of the number of pixels in the red channel for the selected area was recorded for each day. The histogram is a graph of the distribution of red, green, blue, grayscale, hue, saturation and/or lightness values in an image. The horizontal axis represents the lightness values of the image, from black to white (0 to 255). The vertical axis indicates the number of pixels at each value. The red channel was chosen since it showed dust concentrations better than the blue or green channels, similar to the dust enhancement study of Miller (2003). We also used the daily Aerosol Robotic Network-Atmospheric Optical Thickness (AERONET-AOT, direct ground-based sun radiance measurements of AOT by a sun photometer/sky radiometer) values at 870 and 440 nm wavelengths over the sampling region (IMS-METU-ERDEMLI, obtained from http://aeronet.gsfc.nasa.gov). However, these data only included part of our sampling period (from January to June 2001). In order to confirm the validity of our SeaWiFS quantification, we compared relative dust concentrations obtained from daily SeaWiFS images with AERONET-AOT values for the period mentioned (Fig. 2). Spearman rank correlation confirmed that results from these 2 methods were significantly positively correlated ($r = 0.7$, $p < 0.05$). Similar to the relationship between AERONET-AOT and SeaWiFS relative dust load, Kubilay et al. (2005) found that from January 2000 to June 2001 AERONET-AOT values co-varied linearly with total ozone mapping spectrometer (TOMS)–derived AOT at the Erdemli site (linear regression coefficient 0.86, $p < 0.05$). This result shows that the quantity of atmospheric dust was proportional to the amount of deposition on the sea surface during the period from January 2000 to June 2001. In addition, we used aluminum (Al, an indicator of Saharan dust; Kubilay & Saydam 1995) concentrations measured by Koçak et al. (2004) in the dust collected from a sampling tower at the same location right on the coast (which could be assumed to reflect the actual dust deposition on surface waters (see Fig. 4). Aluminum results also confirmed that, generally, the higher the dust load in the atmosphere, the higher the deposition. Indeed, the Spearman rank analysis showed that total monthly relative dust concentrations obtained from SeaWiFS images were well correlated (Spearman rank correlation $r = 0.8$, $p < 0.05$) with monthly average aluminum data (Fig. 3). Thus, such highly significant statistical analysis permitted us to compare phytoplankton abundance and biomass values with relative dust load data from SeaWiFS images.

In the field, sampling was carried out from an open (bottom depth ~150 m, ~6.4 nautical miles offshore, 36° 30′ N, 34° 22′ E) and a coastal station (bottom depth ~15 m, <0.5 nautical miles offshore, 36° 33′ N, 34° 15′ E, Fig. 1) during the study period (December 2000 to December 2001). Although both stations were in nearshore waters, the station called 'open' did not show nearshore characteristics (see 'Discussion'). At the open station, phytoplankton and nutrient samples were taken from 5 distinct depths (1, 25, 50, 75 and 100 m), while chl *a* samples were obtained from 0, 25 and 50 m depths. Only surface samples were taken from the coastal station, and from the open station in December 2001. In addition, surface phytoplankton and nutrient samples were collected from Datca (36° 41′ N, 27° 23′ E; Fig. 1) on the Aegean coast of Turkey on 20, 22, 23, 24, 27 April and 2 May 2001, following a very intense dust transport period to this region.

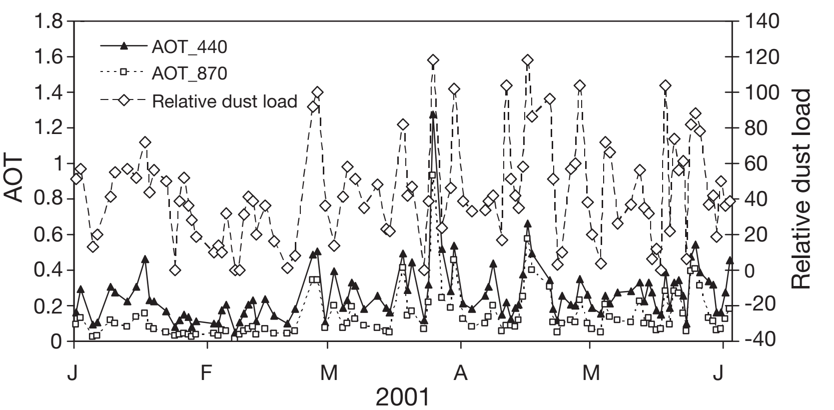

Fig. 2. AERONET-AOT and SeaWiFS relative dust load values from Januar to June 2001. AOT: Atmosphere Optical Thickness

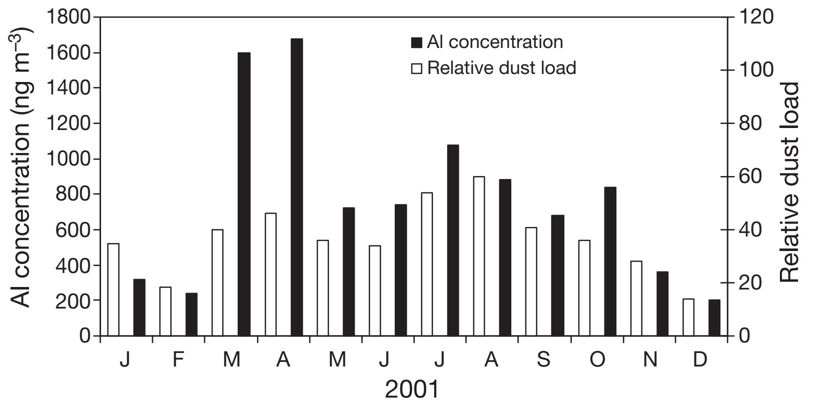

Fig. 3. Monthly average concentrations of aluminum and relative dust load in 2001

Nutrient (PO_4-P, NO_3-N and Si) samples were placed in acid-cleaned polyethylene bottles and kept frozen for a few weeks until their analysis using a Technicon model 3-channel auto-analyzer (Strickland & Parsons 1972). Detection limits for nitrate, phosphate and reactive silicate are 0.05, 0.02 and 0.3 µM, respectively. Chl *a* samples were filtered through GF/F filters and extracted using 90% acetone solution. The fluorescence intensity of clear extracts were then measured (Strickland & Parsons 1972, Holm-Hansen & Riemann 1978), using a Hitachi F-3000 model spectrofluorometer. The detection limit for chl *a* was 0.01 µg l^{-1}.

The temperature, salinity and density of the water column were measured with a SeaBird CTD probe. Secchi disk depth was also measured for both stations. Euphotic zone depth was calculated as 2.7 times Secchi disk depth.

Phytoplankton samples (including micro- [>20 µm] and nano- [2 to 20 µm] fractions) were put into 1 l dark bottles and preserved by buffered formaldehyde to obtain a final concentration of 2.5%. In the preparation of samples for microscopic analysis, the sedimentation method was used. After the samples remained immobile for at least 2 wk, thin pipettes were gently lowered into the bottles and water was evacuated down to a layer of 100 ml. The remaining liquid was agitated and poured into smaller bottles. After further immobilization for 1 to 2 wk, the supernatant was discarded with a thinner and curved tube (in order not to miss sunken cells by convection currents) until ~20 ml water remained in the bottles. The micro- and nanophytoplankton were counted using a Sedgewick–Rafter counting cell and a Palmer Maloney counting chamber under a phase contrast binocular microscope. The volume of each cell was calculated by measuring its appropriate morphometric characteristics (i.e. diameter, length and width) (Kovala & Larrance 1966, Senichkina 1986, Hillebrand et al. 1999). Volume values were converted to biomass assuming 1 µm^3 equals 1 pg (Velikova 1998).

RESULTS

Dust transport towards the sampling region

Atmospheric Al concentrations are often used as indicators of the atmospheric dust load (Prospero & Nees 1987). If >30 µg m^{-3} dust load is considered to be an intense dust outbreak and assuming 8.2% of the desert dust was made up of Al (Kubilay et al. 2000), an Al concentration of 2500 ng m^{-3} (Fig. 4 and Table 1) can be considered as a threshold value for intense dust transport events. Corresponding relative dust loads from SeaWiFS would be 80, based on major peaks in dust transport events.

According to the SeaWiFS images, the intensity of dust transport was observed to be highest in spring (Table 1, Figs. 4 & 5). The wet dust events of 18 April in Datca and 13 May in Erdemli were so heavy that the regions were covered with a thick layer of red

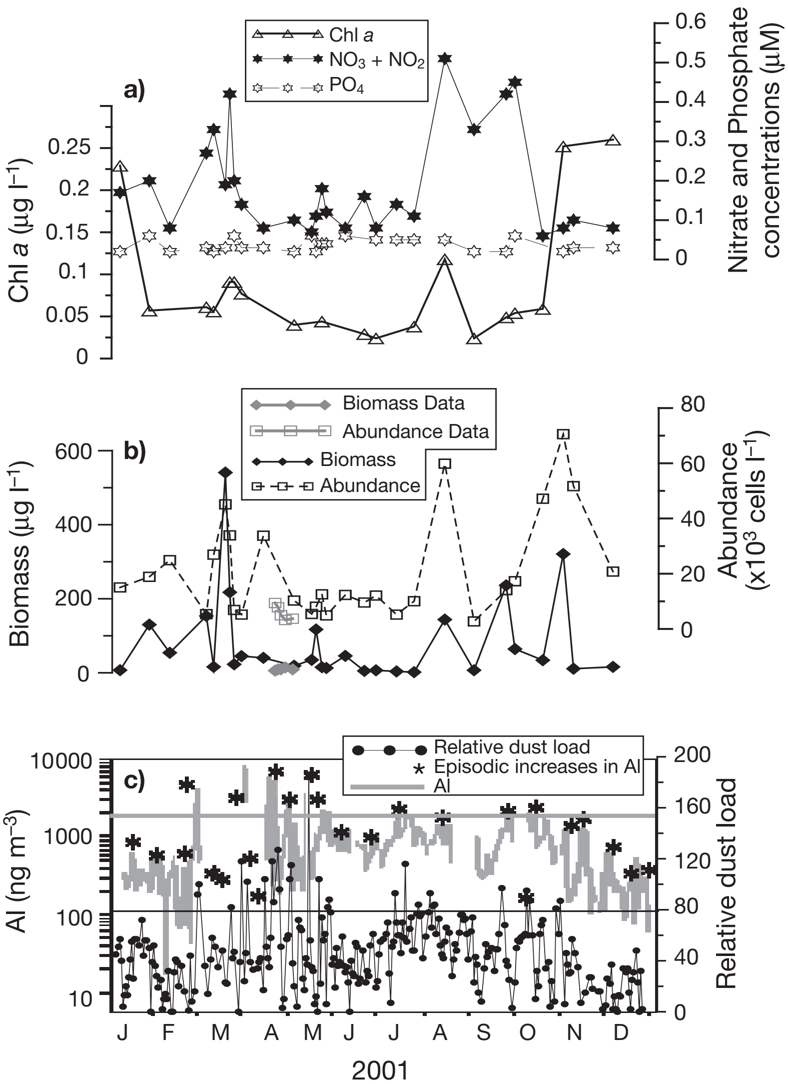

Fig. 4. (a) Chl *a* (µg l^{-1}) and nutrient (µM) concentrations in the surface waters of the open station. (b) Phytoplankton levels in the surface waters of the open station. (c) Time series of daily aerosol aluminum (Al) concentrations (from Koçak et al. 2004; stars show episodic increases in Al concentrations) and relative dust load from SeaWiFS, off Erdemli during 2001. Upper grey line, belonging to Al axis, was assumed as the threshold for episodic dust events and corresponds to the lower black line, belonging to the relative dust load axis

powder, astonishing the local population. The dust appeared to have been transported to the northeastern Mediterranean generally from the Saharan desert and Arabian peninsula. For instance, the source region seemed to be the northwestern and central Sahara on 28 February 2001, mainly the central and eastern Sahara between 18 and 23 April 2001, the eastern Sahara and (possibly) the Arabian peninsula on 1 May 2001 and the Arabian peninsula or northeastern Anatolia on 13 May 2001 (Fig. 5). However, sometimes aerosols from the urban-industrial regions of Europe and the Balkan peninsula might have contributed to intrusions towards the sampling region.

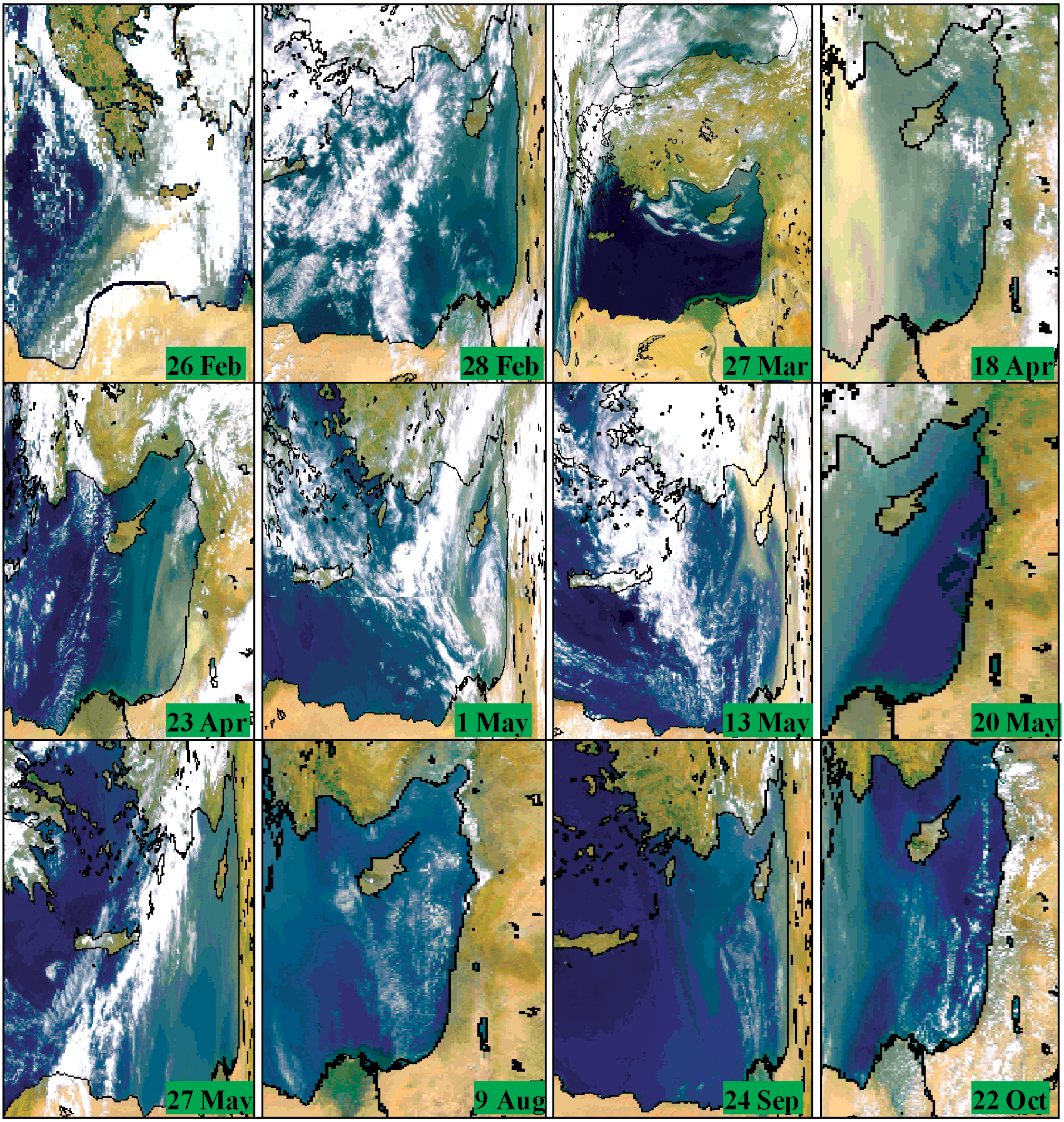

Fig. 5. Most intense dust transport to the present sampling region in 2001, as observed by SeaWiFS

Hydrography and precipitation

The lowest surface seawater temperatures (~17.5°C), both at the open and the coastal stations, were measured between February and March 2001, when the water column was well mixed (Figs. 6 & 7). The maximum temperature (29.8°C) was recorded in August 2001 at the open station and in September at the coastal station, during periods associated with stratified conditions. Temperature and salinity stratification became visible by the end of May 2001 (Fig. 7). In September, the stratification was sharpest (the salinity changed from 39.44 to 38.8 psu and temperature from 28.73 to 23.78°C between 20 and 35 m). The deepest thermocline depth was 70 m in November 2001 (Fig. 7). The minimum salinity in the surface waters was 38.6 psu on 22 March 2001, during a rainy period, while the maximum was 39.4 psu in September 2001 at the open station. At the coastal station, maximum salinity was 39.4 psu in November 2001, while the minimum was 38 psu in December 2001 (Fig. 4). Surface advection might have affected the open station only in March 2001.

Euphotic zone depth changed from 21 m (8 February 2001) to 76 m (22 May 2001) at the open station (average 50 m) and from 5 m (11 December 2001) to 45 m (20 December 2000) at the coastal station.

Highest precipitation was recorded in winter (Fig. 8). Less intense, but frequent precipitation occurred in spring.

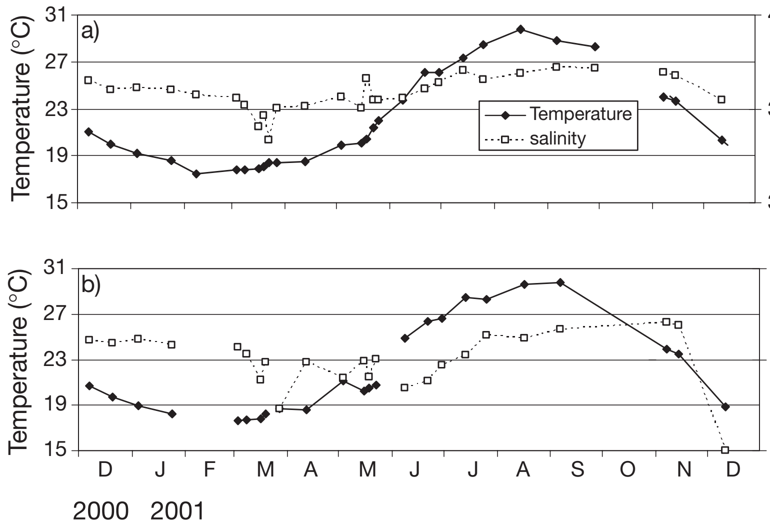

Fig. 6. Surface temperature and salinity variations during the sampling period at the (a) open and (b) coastal station

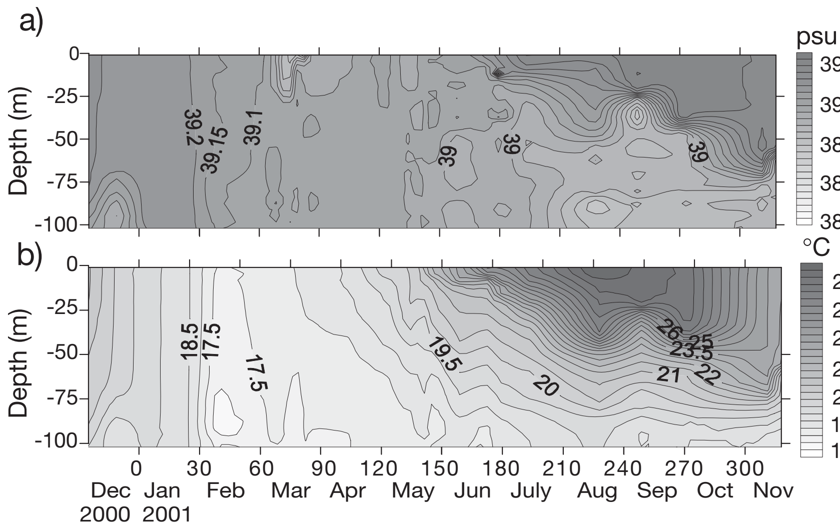

Fig. 7. Vertical (a) salinity and (b) temperature and profiles at the open station between December 2000 and November 2001

Nutrients

Nutrient concentrations were much higher at the coastal station than at the open station in the surface waters between December 2000 and December 2001 (Fig. 9). Nitrate + nitrite and silicate concentrations showed an extreme increase (~20-fold above the annual average) at the coastal station in December 2001, after heavy rains, and remained high during the following months. Statistical analysis showed that nitrate and silicate (but not phosphate) concentrations were significantly different within the 2 regions (single-factor ANOVA, $p < 0.05$).

At the open station, the highest nitrate concentrations were measured during March 2001 at 50 to 75 m depth, with a maximum value of 2.11 µM (Fig. 10). This high nutrient level might have been advected from another region to these depths. August and September followed March 2001 in highest nitrate concentrations. When the nutrients in the water column were considered, it was seen that phosphate concentrations were relatively high during warm months (May to August 2001), while nitrate and silicate concentrations were low. Nevertheless, towards the end of this warm period, in September, phosphate concentrations decreased to very low levels, while nitrate and silicate concentrations increased. In October, phosphate (up to 0.23 µM at 50 m) and silicate concentrations increased, while nitrate was low.

Phosphate concentrations were near detection limits (0.02 µM) in more than half of the samples at both stations. Thus, N:P ratios and the effects of Saharan dust on phosphate were not evaluated.

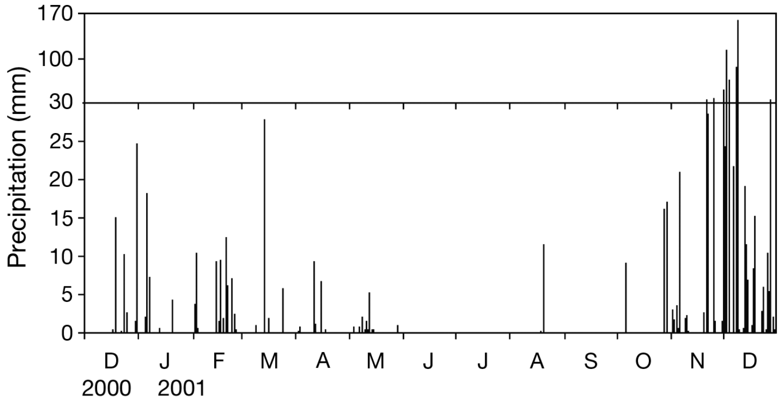

Fig. 8. Total precipitation variations during the sampling period. Note scale change at 30 mm

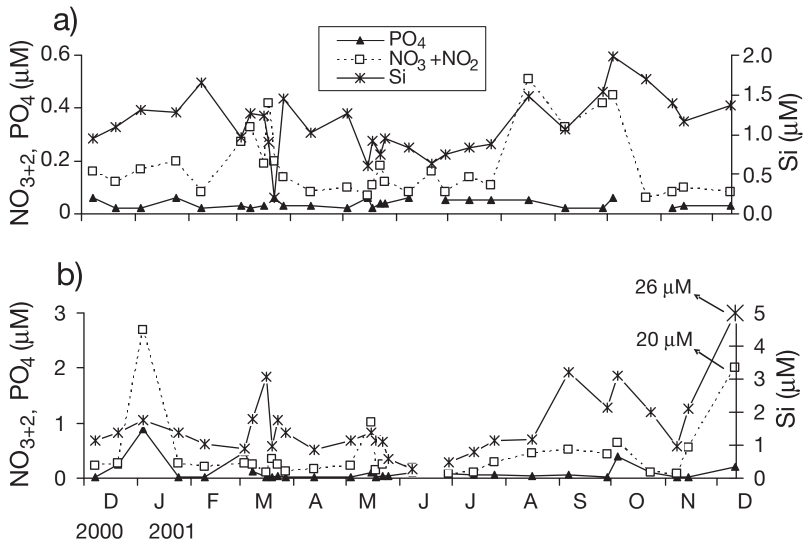

Fig. 9. Nutrient concentrations ($NO_3 + NO_2$, PO_4-P, Si) at the surface (1.5 m) during the sampling period at the (a) open and (b) coastal station

Chlorophyll *a*

Chl *a* concentrations were significantly different between the open and coastal stations (single-factor ANOVA test, $p < 0.05$). Higher values, even in summer, were observed at the coastal station.

At the open station, the bulk of chl *a* concentration was observed in the winter to spring period. Whilst vertically homogeneous chl *a* profiles were observed in December 2000, January 2001 and November 2001 (Fig. 11), much higher values were observed below 25 m in February and March 2001. High chl *a* concentrations did not always coincide with high phytoplankton biomass values. There was no correlation between 1 wk average dust concentrations and chl *a* concentrations ($p > 0.05$).

Phytoplankton abundance, biomass and composition

A total of 212 phytoplankton species were identified in the water column at both stations during the study period. The number of dinoflagellate species (94) was higher than that of diatoms (82).

During 2001, the nanophytoplankton group (2 to 20 µm) formed 80% of the total phytoplankton abundance (micro- + nanophytoplankton) at the open station, but at the coastal station this group formed 44% of the total abundance (data not shown).

Similar to chl *a* concentrations, total abundance and biomass values were higher in the surface waters at the coastal station than at the open station (Figs. 12 & 13). Phytoplankton abundance and biomass were high even in summer months at the coastal station. However, at the open station, except for August, low values were conspicuous in summer (Figs. 12 & 13).

Generally, diatoms were the most important group in terms of biomass in both open and coastal waters, while coccolithophores (mainly *Emiliania huxleyi*) were the most abundant group in open waters during the sampling period (Figs. 12 & 13). In contrast to the open station, diatom abundance was high during summer at the coastal station. *E. huxleyi* abundance was high in March and even higher in August, October and November 2001 in the surface waters of the open station. At the coastal station, highest *E. huxleyi* abundances were observed in autumn (Fig. 13).

With the exception of February and March, phytoplankton abundance and biomass were generally higher in the surface waters than at the deeper depths during the study period (Fig. 14). The vertical distribution of diatoms was very similar to that of total biomass, since diatoms formed 88% of the total biomass in the water column. Diatom abundance in May, June and July was low. Coccolithophores and dinoflagellates comprised the bulk of surface phytoplankton in terms of abundance in these months. The species reaching the highest abundance and biomass during blooms are shown in Tables 2 & 3 (Species with an abundance >250 cells l^{-1} and a biomass >3 µg l^{-1} are given).

When the entire sampling period was taken into account, there was no correlation between phytoplankton (abundance or biomass) at the open station and relative dust loads (Spearman rank correlation, $p > 0.2$; Fig. 4). Regression analysis between 1 wk average relative dust load and phytoplankton abundance or biomass change did not show any relation between these parameters (Fig. 15). However, the total abundance and biomass of phytoplankton positively correlated with the sum of weekly precipitation values at the open station over the sampling period.

For the entire water column at the open station, the major bloom period was in the winter months (Fig. 14). The water column was well mixed during this period (Fig. 7). In surface waters, the highest phytoplankton peak appeared in early spring (i.e. 16 March).

Phytoplankton abundance and biomass in Datca, the Aegean Sea coast of Turkey, were very low (<10 000 cells l^{-1} and 15 µg l^{-1}) from 20 April to 2 May 2001, following very intense wet dust deposition on 18 April 2001 (Figs. 4 & 5). Dust load was also visible in the satellite images over the following days, but phytoplankton abundance and biomass did not increase.

Phytoplankton biomass at the open station increased slightly (on 18 May), following very high wet dust deposition on 13 to 14 May 2001 (Figs. 4 & 5).

During the stratification period in warm months, phytoplankton abundance and biomass were high in the surface waters at the open station and decreased with depth (e.g. on 16 August 2001). There was slight dust transport during the previous days. On this sampling day, phytoplankton abundance and biomass decreased towards the deeper waters concurrent with nutrient concentrations (Fig. 16). Similarly, the abundance of surface phytoplankton (mainly due to *Emiliania huxleyi* abundance) was high on 23 October 2001, again decreasing with depth. In spite of low nutrient concentrations in the surface waters on 23 October, increase in abundance of *E. huxleyi* (a nanoplankton) could be related with possible atmospheric input of a nutrient other than nitrogen or phosphorus.

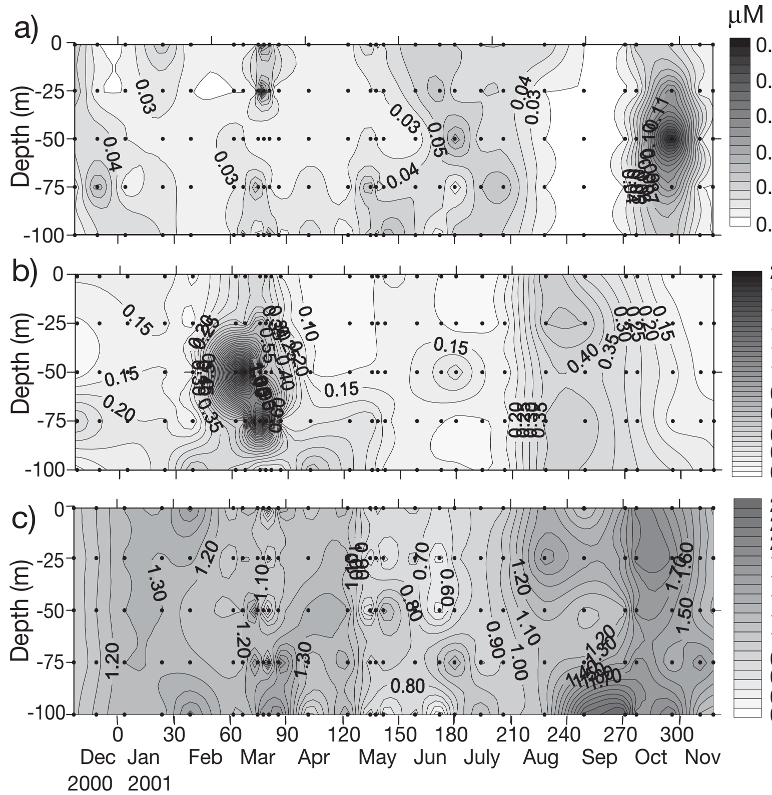

Fig. 10. Vertical (a) phosphate, (b) nitrate + nitrite and (c) silicate profiles at the deep station between December 2000 and November 2001

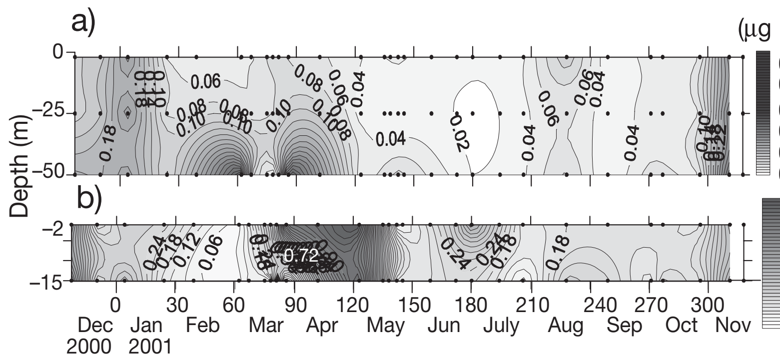

Fig. 11. Vertical chl *a* distribution between December 2000 and November 2001: (a) for the open station and (b) for the coastal station. Dots are the sample locations

DISCUSSION

Although our open station is only 6.4 nautical miles (12 km) offshore, it was found to be influenced very little by coastal effects, thus being suitable to investigate the effects of atmospheric input between December 2000 and December 2001. Chl *a* concentrations found during this period at this station were far below 1 µg l^{-1} (average 0.09 ± 0.07 µg l^{-1}), exhibiting oligotrophic open-water characteristics. Monthly SeaWiFS images during these dates also showed low chl *a* values around the open station (http://marine.jrc.cec.eu.int/me-website/contents/shared_utilities/frames/archive_seawifs.htm; Fig. 1). Small phytoplankton are generally associated with nutrient-depleted oligotrophic waters, while large phytoplankton predominate in nutrient-rich and productive systems (Vidussi et al. 2001).

The contribution of nanoplankton (2 to 20 µm) to the total micro- and nanophytoplankton (>2 µm) was much higher at the open station (80%) than at the coastal station (44%) in the present study. In addition, Köksalan (2000) also reported that the abundance of *Synecoccocus* spp. (cyanobacteria) was also much higher (39×10^6 cells l^{-1}) at the same open station during 1998 than at the same coastal station (18×10^6 cells l^{-1}). During our sampling period, riverine input, as revealed from decreased salinity values, did not influence the open station (except perhaps once in mid-March 2001; Fig. 6). On the contrary, the coastal station was affected by terrestrial inputs (i.e. phytoplankton production was high even during the oligotrophic summer period and simultaneously surface water salinity was low). Since the coastal station was under the effects of riverine input, only the open station was taken into account for evaluating the actual influence of dust on phytoplankton dynamics, whilst the coastal station, which was not affected by dust, was used for comparative purposes.

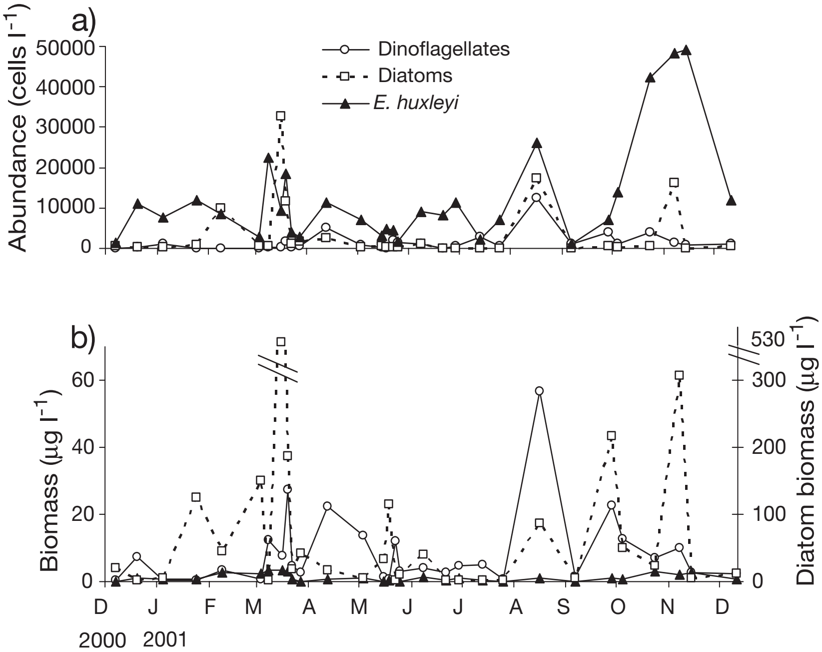

Fig. 12. (a) Abundance and (b) biomass of different phytoplankton groups during the sampling period in surface waters at the open station. Note *y*-scale break for diatom biomass is on the right axis

Here, we have shown that the intense dust transport events observed by SeaWiFS images (Figs. 4 & 5) usually corresponded to the high Al concentrations (an indication of Saharan dust transport and deposition) above the sea surface as measured in the same sampling region by Koçak et al. (2004) in the Levantine basin. Monthly average Al concentrations were significantly positively correlated with monthly averaged relative dust load observed by SeaWiFS (Spearman rank correlation $r = 0.8$, $p < 0.05$; Fig. 3). According to the SeaWiFS images, the intensity of dust transport was observed to be highest in spring. This is similar to the 4 yr mean TOMS aerosol index observations of Israelevich et al. (2002) for aerosol dust distribution from August 1996 to April 2000, and to the mineral dust deposition study of Kubilay et al. (2000). According to 33 yr climatological data along the Israeli coast, maximum Saharan dust transport events occurred in spring (Ganor 1994). Moulin et al. (1998) reported that the source region of dust transported to the eastern Mediterranean during spring was generally the western and eastern part of North Africa, due to the so-called Sharav cycle. Less intense transports were observed in summer and autumn (Table 1, Figs. 4 & 5), as reported in the study by Kubilay et al. (2002).

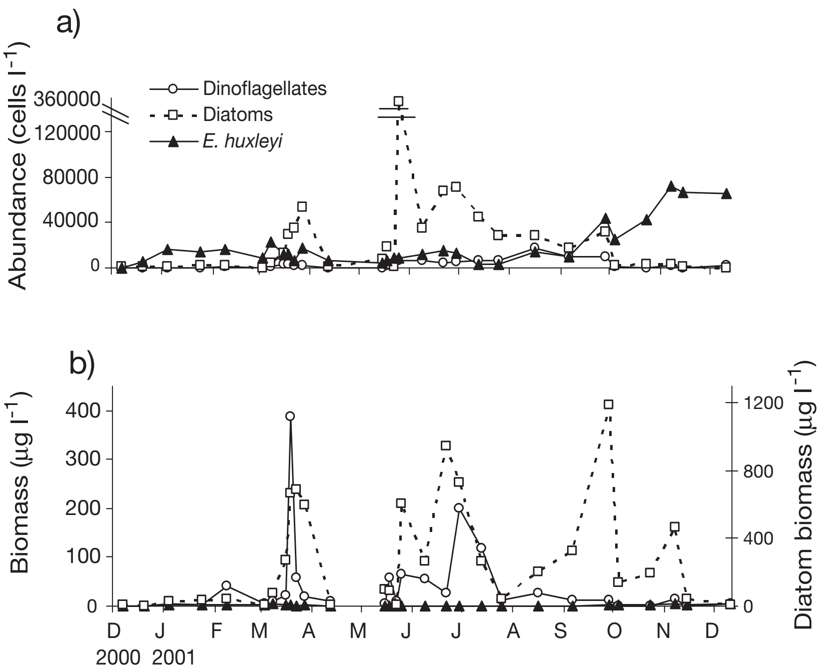

Fig. 13. (a) Abundance and (b) biomass of different phytoplankton groups during the sampling period in surface waters at the coastal station. Note *y*-scale break in (a)

At the open station, the highest phytoplankton abundance and biomass values in the water column occurred in December 2000 and February 2001 (Fig. 14), during a period with no noticeable dust deposition events. Thus, the major phytoplankton blooms in this period resulted from winter mixing, as revealed in the vertical temperature–salinity profiles (Fig. 7). However, high phytoplankton abundance and biomass in the surface waters on 16 and 19 March 2001 might also have been favored by rain (as salinity was slightly lower, Fig. 6). It is noteworthy that there was no appreciable dust transport to the sampling region until March.

The spectacular wet dust deposition event of 18 April 2001 in Datca, on the Aegean coast of Turkey (Figs. 4 & 5), did not seem to have an effect on phytoplankton abundance or biomass in this region. Unfortunately, we had no data on the grazing pressure on phytoplankton, which might have obscured the effect of dust on phytoplankton in our study. Phytoplankton abundance and biomass values were consistently very low (<10 000 cells l^{-1} and 15 µg l^{-1}) on 20, 22, 23, 24, 27 April and 2 May 2001 (Table 1). Back-trajectory analysis also showed that the source region was indeed the Sahara during this period (Koçak et al. 2004). Yet, the considerable dry dust transport from the central Sahara on 20 May 2001 (Fig. 5) towards the Erdemli region did not seem to increase phytoplankton abundance and biomass on 22 and 25 May (Fig. 4). Although Saharan dust has been suggested

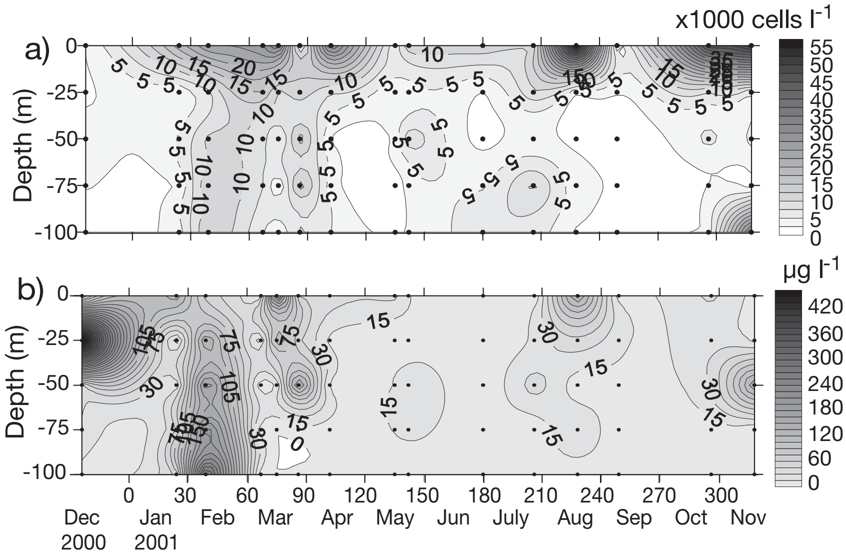

Fig. 14. Vertical phytoplankton (a) abundance and (b) biomass distribution at the open station. Dots indicate sample locations

Table 2. Dominant phytoplankton species in terms of abundance (>250 cells l^{-1}) during bloom periods at the open station

Dates	Species
7 Dec 2000	*Emiliania huxleyi*, *Glenodinium paululum*, *Amphidinium* spp. *Rhizosolenia stolterfothii*, *Leptocylindrus danicus*
8 Feb 2001	*Emiliania huxleyi*, *Chaetoceros affinis*, *Nitzschia* sp., *Thalassiothrix mediterranea*, *T. fraunfeldii*, *Asterionella japonica*, *Pseudo-nitzschia pseudodelicatula*, *Syracosphaera* sp., *Detonula confervacea*
16 Mar 2001	*Proboscia alata*, *Emiliania huxleyi*, *Detonula confervacea*, *Chaetoceros constrictus*, *Skeletonema costatum*, *Chaetoceros lauderi*, *Thalassiothrix mediterranea*, *Thalassiothrix frauenfeldii*
16 Aug 2001	*Emiliania huxleyi*, *Prorocentrum cordatum*, *Pseudonitzschia* cf. *fraudulenta*, *Cerataulina bergoni*, *Pseudonitzschia pseudodelicatula*, *Glenodinium paululum*, *Leptocylindrus danicus*, *Chaetoceros affinis*
7 Nov 2001	*Emiliania huxleyi*, *Prorocentrum cordatum*, *Proboscia alata*, *Rhizosolenia stoltherfothi*, *Leptocylindrus danicus*, *Chaetoceros affinis*, *Chaetoceros wighamii*, *Chaetoceros laciniosus*

Table 3. Dominant phytoplankton species in terms of biomass (>3 µg l^{-1}) during bloom periods at the open station

Dates	Species
7 Dec 2000	*Rhizosolenia castracanei*, *Pseudosolenia calcar-avis*, *Rhizosolenia stolterfothii*, *Rhizosolenia robusta*, *Guinardia flaccida*
8 Feb 2001	*Pseudosolenia calcar-avis*, *Thalassiothrix mediterranea*, *Guinardia flaccida*, *Chaetoceros affinis*, *Detonula confervacea*, *Cerataulina bergonii*, *Pleurosigma elongatum*, *Rhizosolenia stolterfothii*
16 Mar 2001	*Proboscia alata*, *Detonula confervacea*, *Pseudosolenia calcar-avis*, *Chaetoceros constrictus*, *Guinardia flaccida*, *Thalassiothrix mediterranea*, *Ceratium hexacanthum*, *Chaetoceros lauderi*
16 Aug 2001	*Gymnodinium fuscum*, *Cerataulina bergonii*, *Eucampia cornuta*, *Rhizosolenia castracanei*, *Pseudosolenia calcar-avis*
7 Nov 2001	*Pseudosolenia calcar-avis*, *Proboscia alata*, *Rhizosolenia stolterfothii*, *Guinardia flaccida*, *Eucampia cornuta*, *Prorocentrum compressum*, *Cerataulina bergonii*

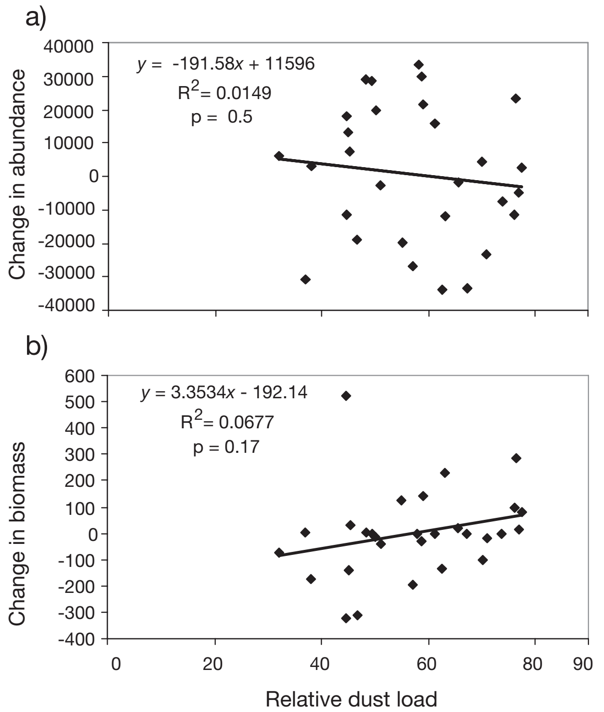

Fig. 15. Regression of change in phytoplankton (a) abundance (b) biomass and 1 wk average relative dust load

to have the potential to induce phytoplankton blooms in the Mediterranean (especially *Emiliania huxleyi*) (Saydam 1996, Guerzoni et al. 1999, Kapur et al. 2000), these 2 clear deposition events did not result in a phytoplankton (or *E. huxleyi*) increase.

However, in some cases, wet dust deposition might cause a slight increase in phytoplankton abundance and biomass. Phytoplankton biomass at the open station increased slightly (on 18 May) following very high wet dust deposition on 13 to 14 May 2001 (Figs. 4 & 5). The source region for this date seemed to be either the Arabian peninsula or northeastern Anatolia.

Dry dust transport events, particularly during the stratification period, may also occasionally increase phytoplankton abundance or biomass, but at other times they do not. The highest dust loads during the summer to autumn months were observed on 12, 13 and 19 July, 6 and 9 August, 25 September and 12 and 22 October 2001, as indicated by both SeaWiFS images and Al concentrations (Table 1, Fig. 4). Phytoplankton abundance and biomass were low during July 2001, but high in August, September and October 2001, following dust transport events (Fig. 4). Nutrient concentrations were also low in July 2001 (Figs. 4, 9 & 10), despite considerable dust transport (which might have had a low nutrient content). Whereas, nutrient concentrations on 16 August 2001 (following dust transport events) indicate a clear input in surface waters, resulting in high abundance and biomass values for all phytoplankton groups (including *E. huxleyi*) at the open sampling station (Fig. 12). High surface salinity on this date suggests that rivers were not the source of these nutrients (Figs. 6 & 16). Low nutrient and phytoplankton abundance and biomass values at deeper depths, down to 100 m, and strong stratification at 40 to 50 m indicate that deep waters were likewise not the source. Thus, atmospheric deposition may be the reason for high production and nutrients on this date.

There was no clear effect of atmospheric deposition on phytoplankton species composition during our study period. Spearman rank correlation did not show any relation between 1 wk average dust concentrations and Shannon-Weaver diversity index or species richness or evenness.

Species reaching high abundances and biomasses (Tables 2 & 3) were phytoplankton species commonly found in the sampling region (Eker & Kideys 2000). Diatom abundance and biomass increases were generally related to winter mixing (e.g. February) at the open station. Following the dust deposition in May

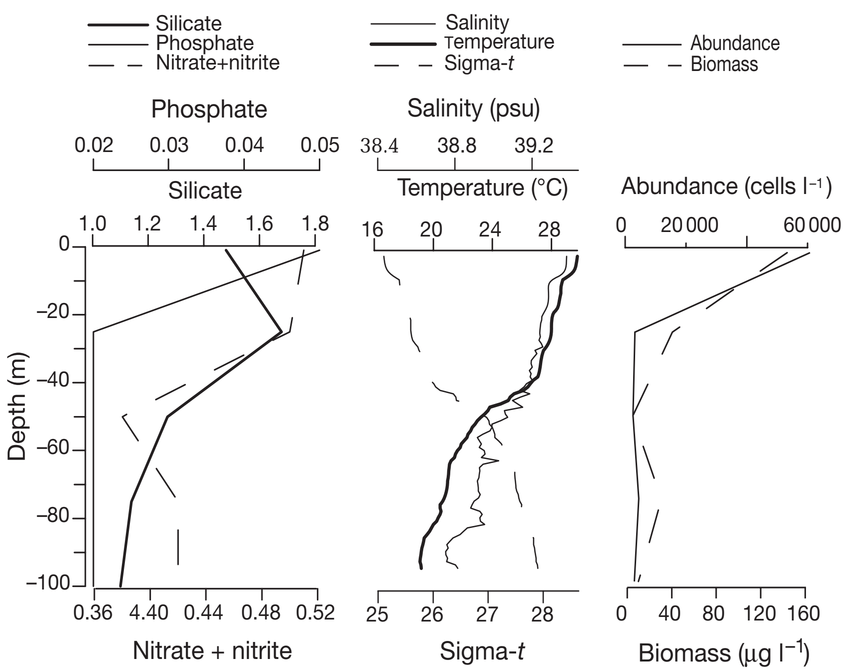

Fig. 16. Nutrient, temperature, salinity, density, phytoplankton abundance and biomass profiles on 16 August 2001 at the open station

2001, there was a slight increase in diatom biomass. Dinoflagellates rarely exceeded diatoms in terms of abundance and biomass in the April to June period, which is one of the most oligotrophic periods during the entire study period (Fig. 12). However, the highest *Emiliania huxleyi* (coccolithophore) abundances were observed during August, October and November 2001. Atmospheric input may have contributed to these peaks in this well-stratified period. It is worth noting that during August (when there was no rain), all phytoplankton groups increased in abundance. Rain in November 2001 might also have contributed to the increase of *E. huxleyi* abundance (as well as of diatoms). The next highest *E. huxleyi* abundance value was in March. Interestingly, in this period, as well as in August and October, high *E. huxleyi* abundances corresponded to high nitrate concentrations in the seawater. Eker-Develi et al. (2006) reported that nitrate was more favorable for this species under laboratory conditions. In many investigations it has been reported that *E. huxleyi* is a good competitor at low phosphate concentrations (Egg & Heimdal 1994, Townsend et al. 1994, Vanbleijswijk et al. 1994, Marañón et al. 1996).

In the present investigation, the study area was generally arid during the stratification period. No rain was reported between 28 May and 5 October 2001 (except on 18 and 19 August 2001, which occurred after our phytoplankton sampling). However, the contribution of the possible dust effect during the stratified period on the total integrated phytoplankton biomass would be low if considered on a yearly basis, similar to the findings of Ridame & Guieu (2002). For example, 72 % of the total depth-integrated annual biomass was formed during the December 2000–March 2001 period, when phytoplankton production was found to be mainly due to winter mixing. Conversely, only 16 % of the total depth-integrated annual biomass was formed during-stratified June–October 2001 period, when the major nutrient input to the euphotic layers was through the atmosphere.

The main conclusion from this study is that the overall importance of the input of atmospheric dust on phytoplankton is limited for our study region. However, in the summer months, atmospheric deposition caused an increase in both nutrients and phytoplankton biomass.

Acknowledgements. This investigation was supported by TUBITAK Project No. YDABAG 100Y017. We acknowledge S. Cebe and E. Kakac for nutrient and chlorophyll *a* analyses, D. Ediger and D. Yilmaz for allowing us to use their phytoplankton data from December 2001 and the crew of the RV 'Erdemli'. The authors are indebted to the SeaWiFS Project for the production and distribution of the SeaWiFS data acquired, and to NASA, for providing the SeaDAS software. We thank Brent Holben (NASA-GSFC) for his effort in establishing and maintaining related AERONET sites.

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Editorial responsibility: Otto Kinne (Editor-in-Chief), Oldendorf/Luhe, Germany

Submitted: March 3, 2005; Accepted: October 27, 2005
Proofs received from author(s): April 26, 2006