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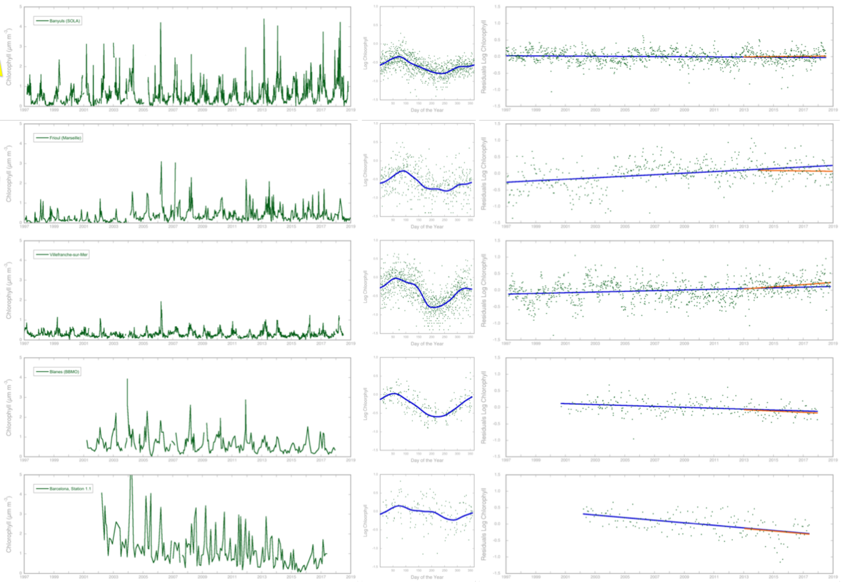
Coastal phytoplankton in a global changing world, oceanic and terrestrial factors

Francesc Peters, Ginebra Domènech, Laura Carrillo, Pau Fornós, Laura Arin, Estela Romero*
Institut de Ciències del Mar (CSIC), Barcelona, Catalunya, Spain and *CREAF, Campus de Bellaterra (UAB) Edifici C, 08193 Cerdanyola del Vallès, Catalunya, Spain. E-mail: cesc@icm.csic.es

Phytoplankton production is majorly a function of the availability of nutrients. In the open ocean, nutrient availability is largely determined by the mechanical energy needed to mix nutrient-rich deep water with upper ocean surface water, marking a clear seasonal cycle, at least in temperate and subtropical seas. In the coastal ocean, terrestrial sources of nutrients, with their own dynamics, blur the seasonal cycle to varying degrees (Fig. 1) depending on the importance of these sources. Riverine sources, with discharge dynamics often heavily modified by anthropogenic water use, especially around large urban areas, may alter the plankton community composition in coastal waters. Our objective is to study the long term dynamics of chlorophyll in the coastal and open ocean Mediterranean, and infer underlying drivers. In the northwestern Mediterranean, long term chlorophyll dynamics show increasing trends at coastal stations heavily influenced by the Rhône discharge (although trend changes are hinted in recent years) and decreasing trends further south (Fig. 1 and Table 1).

Although the influence of the Rhône river, through a hypothetical increase in nutrient discharge, seems to be behind the increase in chlorophyll in southwestern France coasts, chlorophyll decrease in Catalan coasts could be related to a decrease in phosphorus, probably as a consequence of phosphorus reduction policies and better waste water treatment (Table 2). Nevertheless, chlorophyll decreases seem to be stronger and more consistent for chlorophyll than for phosphorus (Table 2, spring decrease). Nitrate and silicate show no significant trends in Barcelona.



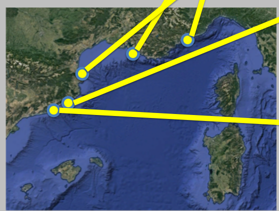


Figure 1. Analytically determined chlorophyll at different locations of the NW Mediterranean coast. Left panels: time series. Middle panels: cubic spline adjustment to yearly ensembled data using log transformed chlorophyll and the day of the year (1 to 365). Right panels: Long term chlorophyll trends of the residuals resulting from the spline adjustment (seasonality removal); the blue line uses all data and the orange line only data from 2013 and onwards.

Chlorophyll over time covering the whole Mediterranean basin (Fig. 2), and thus not influenced by coastal processes, also shows decreasing trends, especially since ca. 2013 (Fig. 3 and Table 3). Trends are very small, albeit significant, when the 1998-2017 time span is analyzed. Only the Aegean Sea region shows a slight increase, that strongly reverses for the 2013-2017 period. As the surface waters increase their temperature with climate change, stratification becomes stronger and mixing is reduced, decreasing in consequence nutrient availability to phytoplankton and chlorophyll production. Other sources of nutrients, such as atmospheric deposition, are increasingly being recognized as important, especially in the desertification scenario of the Mediterranean area (Sahara dust), but also owing to anthropogenic aerosols in an increasingly industrialized area (Fig. 4). We have computed the trends over time in atmospheric deposition of mineral origin from the MENA (Middle East and North Africa) region in the Mediterranean Sea. There are clear increasing trends in atmospheric deposition over all subregions of the Mediterranean Sea (Table 4).

	Time series	whole	2013 onwards
Barcelona	2002-2017	0.401 ***	0.408 ns
Blanes	2000-2017	0.726 ***	0.647 ns
Banyuls	1997-2018	1.275 ***	2.124 ***
Frioul	1997-2018	1.706 ***	0.508 *
Villefranche	1997-2018	0.945 ***	1.079 ns

Table 1. Q_{10} values of chlorophyll change for the different locations and taking into account the whole time series or from 2013 onwards as in Fig. 1. Statistical significance is p≤0.001 (***), p≤0.01 (**), p≤0.05 (*) and p>0.05 (ns). Q_{10} values are the rates of change of chlorophyll over a period of 10 years as derived from the linear fits to log chlorophyll data; values above 1 show increases and values below 1 decreases over time.

	Chlorophyll	Nitrate	Phosphate	Silicate
All data	***	ns	***	ns
WIN	**	ns	ns	ns
SPR	***	ns	**	ns
SUM	**	ns	ns	ns
AUT	**	ns	ns	ns

Table 2. Statistical significance of trends along time for chlorophyll and some phytoplankton nutrients for Station 1.1 in Barcelona. All trends are negative (decreasing) over time. The analyses have been done for all data and for different seasons separately. WIN (DJF), SPR (MAM), SUM (JJA) and AUT (SON). Statistical significance is p≤0.001 (***), p≤0.01 (**), p≤0.05 (*) and p>0.05 (ns

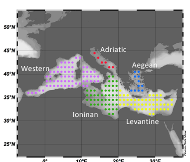


Figure 2. Mediterranean 1°x1° cells used for analysis of satellite chlorophyll data (EU Copernicus Marine Service Mediterranean Sea reprocessed chlorophyll from multi satellite observations) and for dust deposition data (Barcelona Supercomputing Center models). Cells are color grouped by regions of particular ocean characteristics.

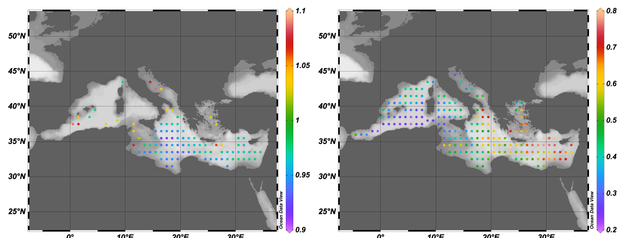


Figure 3. Q_{10} values derived from long term daily satellite chlorophyll trends (same methodology as in Fig. 1 and Table 1). Only cells with statistically significant tendencies (p≤0.05) are shown. Upper panel: the whole time series (1998 to 2017) was used. Lower panel: only recent years (2013-2017) were used. Note the different color scales and especially that in the lower panel all values are below 1.

Area	1998-2017	2013-2017
Mediterranean	0.977 ± 0.002 ***	0.414 ± 0.010 ***
Western Mediterranean	0.992 ± 0.003 **	0.305 ± 0.009 ***
Adriatic Sea	1.032 ± 0.011 *	0.379 ± 0.032 ***
Ionian Sea	0.958 ± 0.005 ***	0.407 ± 0.014 ***
Aegean Sea	0.996 ± 0.006 ns	0.553 ± 0.033 ***
Levantine Basin	0.964 ± 0.003 ***	0.541 ± 0.017 ***

Table 3. Q_{10} values of chlorophyll change for the Mediterranean and the different subregions defined in Fig. 2. Values are averages of the cells in the corresponding region ± 1 SE. The columns are the computations for the whole time series or from 2013 to 2017. Statistical significance is p≤0.001 (***), p≤0.01 (**), p≤0.05 (*) and p>0.05 (ns).

Figure 4. Examples of important sources of aerosols in the Mediterranean. Upper panel: mineral aerosols form the Sahara desert. Lower panel: anthropogenic emissions, especially from high-temperature combustion.

Area	2000-2014
Mediterranean	1.505 ***
Western Mediterranean	1.402 **
Adriatic Sea	1.581 **
Ionian Sea	1.379 *
Aegean Sea	2.373 ***
Levantine Basin	1.623 ***

Table 4. Q_{10} values of total (dry and wet) atmospheric deposition of Saharan and Middle East origin for the Mediterranean and the different subregions defined in Fig. 2. Statistical significance is p≤0.001 (***), p≤0.01 (**), p≤0.05 (*) and p>0.05 (ns).

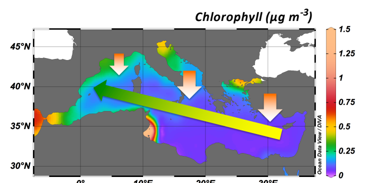


Figure 5. The effect of large deposition events on chlorophyll in the Mediterranean diminishes eastward (arrows), despite the fact that the eastern Mediterranean is ultraoligotrophic and receives much larger dust loads than the western Mediterranean (background map of average chlorophyll concentration just for illustrative purposes). This is interpreted on the basis of a bacterial competition with phytoplankton for nutrients and a consequently prevalent heterotrophic bacterial response to aerosols the larger the nutrient limitation.

It seems clear that a general trend related to global warming is affecting the amount of chlorophyll in Mediterranean surface waters. We know that seawater temperature is increasing in the Mediterranean reducing the entrance of nutrients from deep waters. This decreasing trend in chlorophyll has been especially strong in the 2013-2017 period. We do not know whether this strong recent decrease is part of a cycle or a consequence of a system tipping point. A reduction of phytoplankton production has extremely far-reaching consequences, as these organisms are at the base of the marine food web, regulate the global carbon cycle and sustain fisheries. We see similar trends in some coastal areas, although here the human footprint of water discharges interfere and may counterbalance negative trends in some areas. As global warming keeps melting glaciers, annual discharges from large rivers will also keep increasing the nutrient load in coastal areas.

In a Mediterranean scenario of exacerbate ocean nutrient limitation, nutrients from atmospheric deposition may become even more important than nowadays. Although nutrients from atmospheric deposition can not be equated to winter water mixing, they will become more important to fuel production peaks in the warmer months. This is more so, as aridity increases in the Mediterranean region, and the atmospheric dust load will be larger. Also, the industrialization of northern Africa, emitting anthropogenic aerosols into the atmosphere, may well counterbalance emission reduction policies in Europe. However, it is possible that bacteria and not phytoplankton will mostly take advantage of the nutrients added through atmospheric deposition (Fig. 5).

ANIMA (Spanish MINECO/FEDER CTM2015-65720-R). We thank Dr. Sara Basart from the BSC for dust deposition model output data. http://anima.icm.csic.es