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4.7. Ocean chlorophyll trends in times of global change

Francesc Peters

Chlorophyll is a necessary pigment for photosynthesis, and it serves as a proxy measurement for the biomass of primary producers (mainly phytoplankton) in the ocean. All ecosystems depend totally or partially on the organic carbon produced through photosynthesis, that is, the use of CO_2 and H_2O to synthesize sugars with the energy from solar radiation. In addition, phytoplankton, like terrestrial plants, need inorganic nutrients to grow, and here is where global change comes into the picture.

Concern about the effects of climate change has pervaded society in recent years as scientists now have a high certainty about the human cause of climate change (IPPC 2013). The increase in average global air temperature is without question and is also translating into an increase in surface seawater temperature. The amount of heat per unit volume needed to raise the temperature of seawater is roughly 4500 times larger than that for air and gives an idea of the magnitude of global warming. Surface ocean water masses of tropical, subtropical and temperate regions tend to be relatively depleted of inorganic nutrients, limiting phytoplankton growth, while deeper waters are rich in such nutrients but have no light. Nutrients slowly diffuse upward. One of the consequences of surface seawater warming is that the vertical diffusion of nutrients from bottom waters is further hindered, so phytoplankton growth is expected to decrease.

The Mediterranean Sea is an oligotrophic sea with low inorganic nutrient concentrations naturally occurring in surface waters and low chlorophyll biomass, mainly because of the depth of the basin and the anti-estuarine circulation with respect to the Atlantic Ocean. Oligotrophy increases towards the eastern Mediterranean, which is considered one of the ultraoligotrophic areas of the world. The Mediterranean is also a region where climate change is exacerbated, with a potential to further impoverish surface waters. I hypothesize that this trend should be present in the satellite-derived chlorophyll signal. Thus, in this study I analyse a 20-year time series of satellite-derived chlorophyll in the Mediterranean Sea.

Problem-solving approach using satellite data

I used the surface chlorophyll concentration of the Mediterranean Sea from multi-satellite and Sentinel-3 OLCI observations (Volpe *et al.* 2019). The data were spatially averaged in 179 cells of 1×1 degrees. In order to remove the seasonal (annual cycle) trend in the data, for each cell I adjusted a cubic spline to yearly ensembled data and worked with the residuals from this adjustment. Then, I fitted a linear trend to these residuals. Statistical significance was set at $\alpha=0.05$. Finally, in order to visualize and compare these long-term trends, a Q_{10} parameter, which provides the multiplying factor of chlorophyll after 10 years, was calculated as $Q_{10} = 10^{b*10}$, where b is the slope of the fitted trend. Q_{10} values were averaged over the entire Mediterranean ocean or by subregions. Average values were t-tested (two-tails) against a null hypothesis of $Q_{10}=1$.

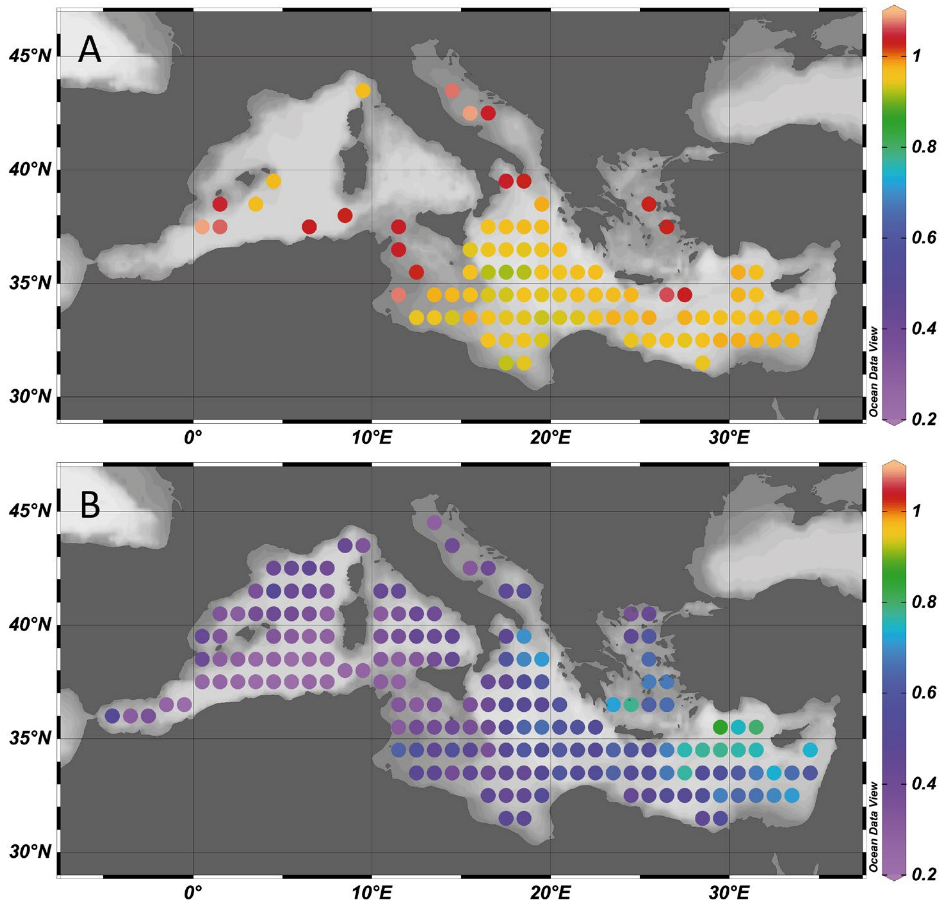

Figure 1. Q_{10} values derived from satellite chlorophyll time series. Only cells with statistically significant trends ($p \leq 0.05$) are shown. A, trends for the whole time series (1998 to 2017). B, trends derived from recent years (2013–2017).

Mediterranean chlorophyll trends

From the 1998–2017 times series, there is a slight but statistically significant tendency for chlorophyll to decrease in the Mediterranean, with a Q_{10} of 0.98 (Figure 1A). However, there are regional differences (Table 1). No significant tendency is observed for the western Mediterranean or the Aegean Sea. A tendency for chlorophyll to increase over time is observed in the Adriatic, while decreasing chlorophyll is observed for the Ionian Sea and the eastern Mediterranean (Levantine) Sea. However, the time series of the residuals from the seasonal adjustments do not tend to be monotonically increasing or decreasing. In general, the trends showed increases in chlorophyll over the first half of the series and decreases afterwards. In a second analysis, I focus on the last five years of the series (2013 to 2017). When this is done (Figure 1B), a strong and consistently decreasing trend in chlorophyll is observed with a Mediterranean average Q_{10} of 0.47 (Table 1). The highest decreases are found in the western Mediterranean, in the Adriatic and in the Ionian Sea, while somewhat lower decreases are observed in the Aegean and Levantine seas.

Take-home message

There seems to be a system tipping point between 2007 and 2017, depending on the specific cell considered, for chlorophyll to clearly decrease in the Mediterranean. One could spec-

Table 1. Summary of chlorophyll concentration Q_{10} values (average, se: standard error, and n: number of cells) for the Mediterranean Sea and subregions[†]. T-test significance against a $Q_{10} = 1$ is $p < 0.05$ (*), $p < 0.01$ (**) or $p < 0.001$ (***).

	Mediterranean	estern Mediterranean	Adriatic	Ionian	Aegean	Levantine
n	179	65	6	49	11	48
Years 1998–2017						
Average (se)	0.985*** (0.003)	1.002 (0.003)	1.041* (0.013)	0.966*** (0.005)	1.004 (0.005)	0.970*** (0.003)
Years 2013–2017						
Average (se)	0.474*** (0.012)	0.336*** (0.010)	0.400*** (0.036)	0.483*** (0.015)	0.601*** (0.039)	0.633*** (0.016)

[†] Western Mediterranean, from the strait of Gibraltar to the strait of Sicily; Adriatic Sea, down to 40°N; Ionian Sea, from 40°N down to Africa and from the strait of Sicily to 20°E; Aegean Sea, from Crete to the north and framed by Greece in the west and Turkey in the east; and Levantine basin, from 20°E to the east, excluding the Aegean Sea.

ulate that the decline in the terrestrial inputs of phosphorus driven by legislation in the northern Mediterranean partly explains the consequent decrease in chlorophyll. However, when such a Mediterranean-wide synoptic trend is observed, a large-scale effect related to nutrient availability is expected more than local or coastal nutrient depletion trends. It seems that this trend fits the hypothesis of a stronger separation of surface and deep water masses owing to increasing water temperatures. Trends in the decrease of ocean chlorophyll have been reported elsewhere (Gregg and Rousseaux 2019), providing confidence for these results. Nevertheless, absolute values of the decrease remain uncertain.

Chlorophyll reflects phytoplankton biomass, and we know that biomass is related to biodiversity (Irigoien *et al.* 2004). For low phytoplankton biomass, there is a direct relationship with species richness, so we should expect a reduction in biomass to be accompanied by a reduction in phytoplankton biodiversity, a worrisome issue if we take into account that the Mediterranean can be considered a hotspot of marine biodiversity (Coll *et al.* 2010). Also, if current high extinction rates observed for land-dwelling organisms are mirrored in the plankton, an additional stress related to biomass could strongly disrupt marine ecosystems. In addition to ecosystem stability issues, there would be important consequences for the fisheries that depend directly or indirectly on phytoplankton biomass. This study also highlights the importance of having long time series when addressing climate change issues. Trends are often small over short periods of time, and longer time series are crucial for proving significance out of the inherent noise.

If the decreasing trends observed for the years 2013–2017 hold and can be extrapolated, chlorophyll levels in the Mediterranean will in ten years be roughly half the current values across the basin, somewhat more in the east and increasingly less towards the west. This will be a drastic change for the entire ecosystem.

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