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Seasonal to interannual phytoplankton response to physical processes in the Mediterranean Sea from satellite observations

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ABSTRACT

The relation between physical and biological processes affecting the Mediterranean Sea surface layer was investigated through univariate Empirical Orthogonal Function (EOF) decompositions of remotely sensed chlorophyll-a (CHL), sea surface temperature (SST) and Mediterranean Absolute Dynamic Topography (MADT) weekly time series (1998–2006). As part of the analysis, the Data INterpolating Empirical Orthogonal Functions (DINEOF) technique was successfully applied to CHL images. Results from the single EOFs, along with a cross-correlation analysis, identified physical–biological interactions at both short (weeks to months) and long (years) temporal scales, and from meso- to basin-scales. Phytoplankton biomass abundance and the sea surface thermal stratification show a strong inverse relationship at seasonal and sub-basin scales. At a regional scale, the spring bloom space–time variability is related to the intensity and spatial extent of the deep water formation process and especially to its pre-conditioning phase. At interannual and sub-basin scales, a gradual decline of the phytoplankton biomass in the whole central Mediterranean occurs with a delay of one year relative to the decrease of the cyclonic circulation in the eastern basin, and the northward displacement of the Algerian current. Regionally, the phytoplankton biomass and the surface heat content anomalies associated with extreme atmospheric anomalies (such as the cold 1998–1999 winter and the summer 2003 heat wave) show a significant correlation with a ~5-month time lag.

1. Introduction

The ocean, covering more than 70% of the Earth's surface, can modulate the atmospheric CO_2 concentration by means of the so-called biological pump. This mechanism refers to the sinking of organic matter from the surface productive layers to deep waters in the ocean (Lalli & Parsons, 1997). As the ocean overturning period involves millennial temporal scales (Rahmstorf, 2006), the organic matter leaving the productive layers could take centuries to re-enter the surface layer, therefore enhancing the ocean's capability for absorbing atmospheric CO_2. Quantifying the carbon flux into the ocean through the marine primary productivity, and understanding the mechanisms that might control it, are of crucial importance for defining the planet's carbon budget. The major player of the oceanic primary production is phytoplankton through photosynthesis. Phytoplankton distribution in the ocean is mainly driven by the availability of light and nutrients (Parsons et al., 1983). These growth-limiting factors depend in turn on physical processes at different space and time scales: general ocean circulation, deep water formation, mixed-layer dynamics, upwelling, atmospheric dust deposition, and the solar cycle. The control of the biological activity by these physical processes results in a well-defined zonation of the world oceans: the so-called bio-provinces (Longhurst, 1998).

Satellite data provide an opportunity for quantifying oceanic phytoplankton biomass and production at fine space–time resolution. Remote sensing techniques give a synoptic view of some of the environmental variables capable of influencing phytoplankton production. Remotely sensed data were used to investigate the link between upper ocean stratification and phytoplankton productivity (Behrenfeld et al., 2006). Behrenfeld et al. (2006) found an inverse relationship between monthly NPP and sea surface temperature (SST) anomalies over about 74% of ocean surfaces, giving a solid explanation of the mechanisms linking NPP response to SST variations, in terms of enhanced/reduced nutrient availability as a consequence of decreased/increased stratification (Doney, 2006). Although pigment distribution analyses, alone, cannot take into account phenomena such as photoacclimation, this work relies on an assumption commonly made in ocean color remote sensing, i.e. that the pigment distribution is, indeed, a proxy of phytoplankton biomass.

Wilson and Coles (2005) analyzed the global scale relationships between SST, sea level and chlorophyll (CHL) monthly climatologies, and sub-surface physical observations such as the mixed layer depth (MLD), the thermocline depth (TD) and the depth of the nutricline (ND).

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They found that in nutrient-limited systems, such as in subtropical and mid-latitude regions, surface satellite chlorophyll and TD or MLD variations can be either positively or negatively correlated, depending on whether the surface mixed layer reaches the nutricline. The relationship between surface and sub-surface observations resulted in a high spatial correlation between SST and both TD and MLD, especially at mid-latitudes including the Mediterranean Sea. Wilson and Coles (2005) identified three different scenarios: 1) the dynamic uplift, through which both nutricline and thermocline shoal toward the surface or deepen, results in a negative correlation between CHL and TD/MLD (see Fig. 6a in Wilson & Coles, 2005); 2) the nutrient entrainment scenario results in a positive correlation (typical of the tropics), where the thermocline and the nutricline variations are uncoupled: i.e., a phytoplankton increase occurs only when the mixed layer deepens below the nutricline (see Fig. 6b in Wilson & Coles, 2005), and 3) the seasonal control of nutrients and light at mid- and high-latitudes (negative correlation, e.g. Fig. 6c in Wilson and Coles (2005)). A characterization of the Mediterranean Sea seasonal trophic regime, through cluster analysis of ocean color data, was carried out by D'Ortenzio and Ribera d'Alcala (2009). These schemes refer to climatological patterns, and whether they may apply to other timescales (e.g., interannual), which can involve different physical processes (e.g., mesoscale instabilities, dense water formation, etc.) has not yet been proven. A method to capture the variability at all time scales, including the long-term variability, of the physical–biological coupling, is through the Empirical Orthogonal Functions (EOF) analysis. This method is based on the use of statistical techniques for the identification of principal patterns of variability and will be here applied to SST, sea level and surface CHL time series. Although the EOFs do not always (and not necessarily) identify physical or biological processes, in some cases they can be related to distinct physical or biological processes. Looking at their spatial and temporal cross-correlations may then shed light on the link between the biological response and the physical forcing.

The aim of this work is to find the link between biotic and abiotic factors acting in the Mediterranean Sea and to improve the understanding of the ecosystem functioning at different space and time scales. This objective will be pursued by 1) identifying the main modes of variability within single satellite datasets (CHL, SST and sea level), and 2) looking for correlations among them. The analysis of the covariability of SST, sea level and CHL (1) is carried out by estimating EOFs for each variable separately. In theory this approach enables the isolation of different physical and biological processes. A spatial and temporal correlation analysis is then used to define the timing of the covariability between physical and biological processes (2), as far as the EOF analysis can identify them.

2. Study area

In spite of its limited size (~0.6% of the global ocean surface, ~0.3% of the volume), the Mediterranean Sea (MED) is considered one of the most complex marine environments on Earth, because of the variety of physical processes characterizing its circulation (Williams, 1998). These processes span from the mesoscale to the basin-scale, and include deep-water formation. MED is an almost completely closed basin, and it is divided into two main sub-basins by the shallow Sicily Channel (500 m, Fig. 1a): the eastern (EMED) and the western basins (WMED). MED has often been considered as a “miniature ocean” or a “laboratory basin” (Lacombe et al., 1981; Robinson & Golnaraghi, 1995) because most of the processes controlling the global ocean general circulation are present at reduced temporal and spatial scales. The MED is thus expected to respond more quickly than the global ocean to climate changes. In this respect, it represents an excellent site to investigate the coupling between physical and biological processes, and to examine whether global warming reduces phytoplankton growth by enhancing the upper ocean stratification thus limiting the nutrient entrainment to the euphotic layer, as observed by Behrenfeld et al. (2006) at global scale.

The MED oceanic circulation is defined by the complex topography of the basin and can be schematically pictured as a three-layer system: surface, intermediate and deep circulation. An overall cyclonic circulation characterizes the basin scale surface dynamics. The surface Atlantic water (AW) enters at the Gibraltar Strait occupying approximately the top 200 m. During its eastward flow, the AW progressively mixes with the saltier MED waters. The AW flow is characterized by intense mesoscale activity and creates a series of meanders and gyres such as those associated with the Algerian Current, in the WMED, or with the Atlantic–Ionian Stream or Mid-Mediterranean Jet in the Ionian and Levantine basins, respectively (Malanotte Rizzoli et al., 1997). Dense water formation (DWF) processes take place in both sub-basins. These phenomena are initially favored by the lifting of deep isopycnals related to the presence of intense and quasi-permanent cyclonic gyres, induced by a particular wind pattern and/or by topographic effects. This implies weak stratification at the center of the gyres, which is easily homogenized and made unstable by the winter severe buoyancy loss due to strong air–sea interactions in these specific areas. These areas are the Gulf of Lion–Ligurian Sea, in the WMED, and, in the EMED, the south Adriatic for deep mixing processes and the Rhodes Gyre for the formation of Levantine Intermediate Water (LIW).

Biogeochemically, the MED is considered one of the most oligotrophic seas on Earth (Crise et al., 1999), with an average chlorophyll value of 0.19 mg m^{-3}; 0.05 and 0.3 mg m^{-3} in the eastern and western basins, respectively (Santoleri et al., 2008). The oligotrophic character of the basin can be mainly explained in terms of the water mass exchange at the Gibraltar Strait; the MED exports nutrient-rich intermediate waters and imports surface water from the Atlantic Ocean, relatively nutrient-depleted (as compared to the LIW, but richer than the older MED surface waters). The order of magnitude difference between the two sub-basins' average chlorophyll (0.05 versus 0.3 mg m^{-3}) has been attributed to the combination of the biological pump and the anti-estuarine circulation (Crise et al., 1999); that is, the importance of the nutrient-richer AW in stimulating phytoplankton production decreases eastward, as AW mixes with the resident nutrient-depleted MED surface waters. D'Ortenzio et al. (2005) estimated a deeper average MLD in the EMED with respect to the WMED. Similarly, nutrient estimates in both winter (Siokou-Frangou et al., 2010) and summer (Moutin & Raimbault, 2002) show an eastward increasing nutricline depth (ranging from ~30 m in the WMED to ~270 m in the EMED in summer), which further contributes to explain the EMED lower amount of biomass. This oligotrophy pattern can be also seen from the 1° resolution climatologies of the ND and MLD difference (see Fig. 4 in Wilson & Coles, 2005), in which the entire EMED is characterized by ND much deeper of the MLD, whereas the WMED shows similar depths.

The cluster analysis performed by D'Ortenzio and Ribera d'Alcala (2009) identified four dominant trophic regimes: coastal, blooming, intermittent and non-blooming. The coastal regime is limited to the Northern and Western Adriatic boundaries, and to other few spots in coastal areas (i.e., the Gulf of Gabes and part of the Alboran Sea). These areas display a phytoplankton biomass maximum in late summer–early autumn. Blooming areas are located in the northwestern MED (Gulf of Lion–Ligurian Sea), and exhibit a North-Atlantic-like dynamic spring bloom, though with reduced latitudinal (or temporal, depending on the perspective) range of variability, with a seasonal peak in late winter–early spring. Intermittently blooming regions are located in correspondence of the South Adriatic, Calabrian, Rhodes and Bonifacio Gyres, and in a region encircling the blooming cluster. These areas are characterized by a strong interannual variability in both the spatial shape and the timing of the bloom, resulting in a seasonal cycle similar to the blooming regions, with highs during spring. The rest of the basin (i.e., the entire EMED, the Tyrrhenian Sea and the southern WMED) belongs to the non-blooming regions, which exhibit