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ORIGINAL RESEARCH ARTICLE

Spatio-temporal variability of the phytoplankton biomass in the Levantine basin between 2002 and 2015 using MODIS products

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Summary The Levantine basin in the Eastern Mediterranean Sea is subject to spatial and seasonal variations in primary production and physical-chemical properties both on a short and long-term basis. In this study, the monthly means of daily MODIS product images were averaged between 2002 and 2015, and used to characterize the phytoplankton blooms in different bioregions of the Levantine basin. The selected products were the sea surface temperature (SST), the chlorophyll-*a* concentration (Chl-*a*), the diffuse attenuation coefficient for downwelling irradiance at 490 nm (Kd_490) and the colored dissolved organic matter index (CDOM_index). Our results showed that phytoplankton blooms were spatially and temporally variable. They occurred in late autumn at the Nile Delta, in early spring and late summer at the eastern coastline, and in spring at the northeastern coastline. The northern coastline and the open water had a common bloom occurring in winter. The Nile Delta was found to be the most productive area of the Levantine basin showing high Chl-*a*. Kd_490 and Chl-*a* present a parallel co-variation indicating a dominance of Case 1 waters in the Levantine basin. The CDOM_index shows a phase shift with the Chl-*a* fluctuation. A strong inverse correlation was observed between both Chl-*a* and CDOM_index with SST, connoting an indirect relation represented by a depression of CDOM in summer by photobleaching, and a suppression of the chlorophyll-*a* concentration due to water

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stratification, together with nutrient stress. An overestimation of the Chl-*a* values had been signaled by the use of the CDOM_index, suggesting a correction plan in a latter study.

1. Introduction

The Mediterranean Sea is a semi-enclosed basin, covering approximately 0.8% of the world's ocean surface area. Although it has limited geographical dimensions, it is considered one of the most complex marine environments where little is known with regard to circulation dynamics, biogeochemistry and biological activity (Tanhua et al., 2013). The Mediterranean Sea presents a deficit in hydrological balance, as evaporation exceeds the supply of fresh water from streams and precipitation. This deficit is partially compensated by the inflow of Atlantic waters through the Strait of Gibraltar. This results in fresh, nutrient-poor surface flow into the basin with saltier, nutrient-richer deeper water outflow through the Strait of Gibraltar (Bethoux et al., 1992). Hydrological differences along the basin cause the presence of an increasing oligotrophic gradient from west to east.

The Eastern Mediterranean behaves in a similar manner, with surface inflow and deeper water outflow through the Straits of Sicily. This results in a west to east gradient of decreasing surface chlorophyll-*a* concentration (Chl-*a*) (Turley et al., 2000) that was observed from space (Antoine et al., 1995), with the Eastern Mediterranean Levantine waters exhibiting highly oligotrophic conditions. As a result, surface Chl-*a* in the Levantine basin normally don't exceed 0.4 mg m^{-3} (Abdel-Moati, 1990; Dowidar, 1984; Krom et al., 1991; Yacobi et al., 1995) except near the Nile Delta coast and other adjacent coasts where it can reach up to 80 mg m^{-3} (EIMP-CWMP, 2007).

The Levantine basin regroups the Egyptian northern coast where the Nile River discharges on its delta, the Sinai Peninsula's northern coast, the Israeli coast, the Lebanese coast, the Syrian coast, the southern Turkish coast and the coast of Cyprus. This region is nourished by small water streams, and the Nile River.

The knowledge of the space and time heterogeneity of phytoplankton growth in oligotrophic to ultra-oligotrophic conditions is essential to understand the marine ecosystem dynamics (Mann and Lazier, 2006). In the last decade, remote sensing of surface optical properties has provided synoptic views of the abundance and distribution of sea surface constituents, such as the concentration of Chl-*a* pigments (Su et al., 2015). Nowadays, many studies showed that time series of remotely sensed data can provide information on phytoplankton growth patterns, and related environmental conditions, to serve *in situ* assessments of ecosystem dynamics over wide space and time scales (Brando et al., 2012; Devlin et al., 2012; Kennedy et al., 2012; Schroeder et al., 2012).

The aim of the present work is to assess recurrent algal blooms in the Levantine basin, by using optical remote sensing data. To this end, a time series of data collected by the MODIS Terra and Aqua missions was selected to explore the large-scale, long-term features of the Chl-*a* fields in the Levantine basin, between 2002 and 2015. In the following the MODIS-derived multi-annual database, used here to examine the variability of the Chl-*a* field at a monthly and climatological scale, will be introduced, together with a statistical application. Finally, the spatiotemporal patterns emerging from this analysis will be discussed, simultaneously with other MODIS remotely sensed parameters; sea surface temperature (SST), colored dissolved organic matter index (CDOM_index), and the diffuse attenuation coefficient for downwelling irradiance at 490 nm (Kd_490) and compared to previous studies results.

2. Material and methods

The MODIS Terra and aqua daily Level 2 products of SST, Chl-*a*, CDOM_index and Kd_490 computed with sensor standard algorithms from 2002 till 2015 were provided by the oceancolor.gsfc.nasa.gov portal.

The standard OC3 algorithm returns the near-surface Chl-*a* in mg m^{-3} at a spatial resolution of 1 km, calculated using an empirical relationship derived from *in situ* measurements of Chl-*a* and blue-to-green band ratios of water-leaving remote sensing reflectances (Rrs) developed by O'Reilly et al. (1998) and can be expressed as the following:

$$\log_{10}(\text{Chl-}a) = 0.2424 - 2.7423R + 1.8017R^2 + 0.0015R^3 - 0.1228R^4 \quad (1)$$

with

$$R = \log_{10}\left(\frac{\text{Max}(\text{Rrs}_{443}, \text{Rrs}_{488})}{\text{Rrs}_{547}}\right). \quad (2)$$

The empirical algorithm OC3M is an adapted form for MODIS, developed from SeaWiFS OC2 and OC4 algorithms.

Level 2 satellite-to-*in situ* match-up validation results are available for MODIS from the validation tool of the SeaWiFS Bio-Optical Archive and Storage System (SeaBASS), showing a global correlation coefficient above 0.75 with a RMSE = 0.3 mg m^{-3}. For this study, the same standard sensor algorithm was used for waters differing in the degree of eutrophication.

For the SST estimation, the satellite measurement is made by sensing the ocean radiation in two or more wavelengths within the infrared part of the electromagnetic spectrum which can then be empirically related to SST. In this case, the MODIS SST product provides sea surface temperature [°C] at a spatial resolution of 1 km.

The Kd_490 (in m^{-1}, 1-km spatial resolution) is calculated using an empirical relationship derived from *in situ* spectroradiometric data from oceanographic stations of Kd_490 and blue-to-green band ratios of remote sensing reflectances (Rrs) belonging to a wide variety of water types (Austin and Petzold, 1981).