Remote Sensing of Environment 152 (2014) 557–575

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Identification of dominant phytoplankton functional types in the Mediterranean Sea based on a regionalized remote sensing approach

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ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form 23 May 2014
Accepted 23 June 2014
Available online xxxx

Keywords:
Ocean color
Phytoplankton functional types
PHYSAT
Mediterranean Sea

ABSTRACT

During the last decade, the analysis of the ocean color satellite imagery has allowed determining the dominant phytoplankton groups in surface waters through the development of bio-optical models aimed at identifying the main phytoplankton functional types (PFTs) or size classes from space. One of these bio-optical model is PHYSAT, which is a global method applied for oceanic Case I water and used to identify in satellite pixels specific dominant phytoplankton groups, such as nanoeukaryotes, *Prochlorococcus*, *Synechococcus*, diatoms, *Phaeocystis*-like and coccolithophores. Here, we present a regionalized version of the PHYSAT method that has been specifically developed for the Mediterranean Sea due to the peculiarities of phytoplankton assemblages and succession than can be found in the basin and its particular optical properties. The updated version of the method, the so called PHYSAT-Med, has been validated successfully with large in situ datasets available for this oceanic region, mainly for nanoeukaryotes, *Prochlorococcus*, *Synechococcus* and diatoms. PHYSAT-Med allows to include a much higher number of pixels for the Mediterranean than PHYSAT does, through the use of a new Look-Up-Table created specifically for this oceanic region. Results provided by PHYSAT-Med showed the dominance of *Synechococcus* versus prochlorophytes throughout the year at the basin level, although nanoeukaryotes were more abundant during winter months. In addition, PHYSAT-Med data identified a rise in the eukaryote biomass (mainly diatoms) during the spring period (March to April), especially in the Ligurian and Adriatic seas. PHYSAT-Med represents a useful tool for the spatio-temporal monitoring of different dominant phytoplankton functional types in Mediterranean surface waters at a high resolution.

1. Introduction

The Mediterranean Sea is the largest semi-enclosed sea on Earth and is considered one of the most complex marine environments where much remains to be known with regard to circulation dynamics, biogeochemistry and biological activity (Tanhua et al., 2013). The Mediterranean Sea presents a deficit 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, which penetrates into the basin as a surface current that is less salty and less dense than the deeper counter current of the Mediterranean outflow. This export of intermediate depth water to the Atlantic directly influences the oceanographic conditions in the North Atlantic (Peliz et al., 2009) and its biogeochemical inventories (Flecha et al., 2012; Huertas et al., 2012). The Mediterranean is sensitive to climatic changes and hence monitoring the evolution of its dynamics and biogeochemistry is essential not only for the basin itself but also for the Atlantic Ocean.

Hydrological differences along the basin cause the presence of an increasing oligotrophy gradient from west to east in the Mediterranean, which can be evidenced by both satellite data and in situ measurements. A decreasing chlorophyll-*a* (Chl*a*) gradient from north to south has been also described, with the exception of a high Chl*a* region detected along the Algerian coast (see review by Siokou-Frangou et al., 2010). Overall, low chlorophyll concentrations are present over large areas in the Mediterranean although local phytoplankton blooms that can be regularly found in the Liguro-Provencal region, Alborán Sea and the Catalan–North Balearic front (Ignatiades, Gotsis-Skretas, Pagou, & Krasakopoulou, 2009). The nutrients and chlorophyll-*a* pools rank the basin as oligotrophic to ultraoligotrophic (Antoine, Morel, & Andre, 1995; Krom, Kress, Brenner, & Gordon, 1991).

In oligotrophic waters, phytoplankton community is mainly composed by picoplankton and ultraplankton (Brunet, Casotti, Vantrepotte, Corato, & Conversano, 2006; Dandonneau, Montel, Blanchot, Giraudeau, & Neveux, 2006; Li et al., 1983; The MerMex Group, 2011). In the Mediterranean, on the other hand, phytoplankton community reveals a considerable diversity variability over spatial and temporal scales

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http://dx.doi.org/10.1016/j.rse.2014.06.029
0034-4257/

(Siokou-Frangou et al., 2010) and large dissimilarities in phytoplankton species composition and other microorganisms across the basins have been highlighted. The picture emerging from many studies shows the dominance of the picoplankton as the fingerprint of the Mediterranean Sea and its overriding oligotrophy but local physical structures that allow the formation of phytoplankton blooms cause the coexistence of more microalgal groups (Siokou-Frangou et al., 2010). An extensive amount of information on the phytoplankton community structure along the Mediterranean coastline is available. On the contrary, longitudinal data based on large-scale investigations in open ocean waters are scarce in the literature (Ignatiades et al., 2009).

This lack of measurements can be partly overcome by using new tools, such as remote sensing techniques. During the last decade and based on different approaches, several algorithms are now able to detect phytoplankton functional types (PFTs) or size classes from space (Aiken et al., 2009; Alvain, Moulin, & Dandonneau, 2008; Alvain, Moulin, Dandonneau, & Breon, 2005; Brewin et al., 2010; Ciotti & Bricaud, 2006; Hirata et al., 2009; Raitsos et al., 2008; Sathyendranath et al., 2004; Uitz, Claustre, Morel, & Hooker, 2006). Platt, Sathyendranath, and Stuart (2006) concluded that the detection of different phytoplankton groups from remote sensing images was a major challenge in ocean optics.

The PFTs are groups of species that play specific roles in the marine biogeochemical cycles and trophic flows (see Le Quéré et al., 2005; Nair et al., 2008; Rudorff & Kampel, 2011). One of the methods that enables to detect PFTs from space is the so called PHYSAT (Alvain et al., 2005, 2008), which was specifically developed to identify the dominant phytoplankton groups from ocean color measurements. Briefly, PHYSAT is a global model applied for oceanic Case I water and is designed to detect satellite pixels in which the dominant groups are nanoeukaryotes (and separately *Phaeocystis*-like and coccolithophores), two types of picoplankton (*Prochlorococcus* and *Synechococcus*-like cyanobacteria) and diatoms (Alvain et al., 2008). PHYSAT is based on the analysis of normalized water-leaving radiance (nLw, Table 1) measurements anomalies, computed after removal the impact chlorophyll *a* variations. Specific nLw spectra anomalies (in terms of shapes and amplitudes) have been empirically associated to the presence of dominant phytoplankton groups, based on in situ biomarkers pigments observations. (Alvain et al., 2005, 2008, 2012; Ben Mustapha, Alvain, Jamet, Loisel, & Dessailly, 2014). Alternative methods have been also applied to detect distinct phytoplankton groups, for instance, diatoms (Sathyendranath et al., 2004), the cyanobacteria *Synechococcus* (Morel, 1997), the N_2-fixing cyanobacteria *Trichodesmium* (Subramaniam, Brown, Hood, Carpenter, & Capone, 1999, 2001; Subramaniam, Carpenter, & Falkowski, 1999), *Phaeocystis globosa* (Astoreca et al., 2009; Lubac et al., 2008) and coccolithophores (Ackleson, Balch, & Holligan, 1994; Brown & Podestá, 1997; Brown & Yoder, 1994; Cokacar, Kubilay, & Oguz, 2001; Gordon et al., 2001; Iglesias-Rodríguez et al., 2002; Kopelevich et al., 2013; Moore, Dowell, & Franz, 2012; Smyth, Moore, Groom, Land, & Tyrell, 2002; Tyrell, Holligan, & Mobley, 1999). Nevertheless, the PHYSAT method allows to distinguish several groups of phytoplankton simultaneously and identifies the dominant PFT at each particular pixel and at each point in time. This method has been successfully validated and used in recent years (Alvain et al., 2005, 2006, 2008, 2012, 2013; Arnold et al., 2010; Belviso et al., 2012; Ben Mustapha et al., 2014; Bopp, Aumont, Cadule, Alvain, & Gehlen, 2005; D'Ovidio, De Monte, Alvain, Dandonneau, & Levy, 2010; De Monte, Soccodato, Alvain, & d'Ovidio, 2013; Demarcq, Reygondeau, Alvain, & Vantrepotte, 2012; Gorgues et al., 2010; Hashioka et al., 2013; Masotti et al., 2010, 2011). Results were satisfactory for nanoeukaryotes (82%) and a decrease in the percentage of successful retrieval was observed for diatoms (73%), *Synechococcus* (57%) and *Prochlorococcus* (61%) (Alvain et al., 2012).

However, due to the specific character of phytoplankton assemblages in the Mediterranean Sea and their associated bio-optical relationships that can be affected by continental inputs such as rivers discharge and desert dust events (Alvain et al., 2006; Bricaud, Bosc, & Antoine, 2002; Claustre et al., 2002; Loisel et al., 2011), it is necessary to adapt the PHYSAT method and evaluate its derived results in this specific ocean region. In fact, Santoleri, Volpe, Marullo, and Nardelli (2008) pointed out that the difference in bio-optical characteristics at the regional scale in Mediterranean Sea is due to ecological reason such as the presence of specific phytoplankton groups. Moreover, the presence of the aerosols due to anthropogenic atmospheric emissions from continental Europe and Saharan dust makes it difficult to apply standard remote sensing procedures for the atmospheric correction (Moulin et al., 1997). In fact, the presence and abundance of aerosols is one of the factors determining the different optical properties of the Mediterranean with respect to the global ocean (Claustre et al., 2002). Therefore, during the last years, many regional algorithms have been developed for the Mediterranean Sea, such as DORMA-SeaWiFS (D'Ortenzio, Marullo, Ragni, d'Alcala, & Santoleri, 2002), BRIC-SeaWiFS (Bricaud et al., 2002), MedOC4-SeaWiFS (Volpe et al., 2007), MedOC3-MODIS (Santoleri et al., 2008) and MedOC4ME-MERIS (Santoleri et al., 2008) since standard algorithms overestimate low Chl*a* and conversely, underestimate high concentrations.

In this work, the previous version of PHYSAT (Alvain et al., 2005, 2008) has been modified in order to estimate the most frequent phytoplankton groups in the Mediterranean Sea. The updated version (hereafter PHYSAT-Med) has been validated using in situ measurements collected in different cruises conducted throughout the entire basin. Therefore, the main objectives of this study were: (i) to adapt

Table 1
Acronyms information.

Acronym	Name	Units	Explanation
Chl *a*	Chlorophyll *a* concentration	mg m^{-3}	Chlorophyll *a* concentration
OC3M-Chl*a*	Chlorophyll *a* concentration	mg m^{-3}	Chl*a* estimated by standard OC3M algorithm for MODIS images
MedOC3-Chl*a*	Chlorophyll *a* concentration	mg m^{-3}	Chl*a* concentration estimated by regional MedOC3 algorithm for MODIS images
K490	Diffuse attenuation coefficient at 490 nm	m^{-1}	The diffuse attenuation coefficient in water indicates how strongly light intensity at a specified wavelength is attenuated within the water column.
nLw	Normalized water-leaving radiance	mW cm^{-2} μm^{-1}	The upwelling radiance just above the sea surface, in the absence of an atmosphere, and with the sun directly overhead
nLw^{ref}	Specific water-leaving radiance	mW cm^{-2} μm^{-1}	Represents the average nLw spectrum for a given value of Chl*a*. This reference is used to remove the first order effect of Chl*a* on nLw(λ) measurements.
LUT	Look-Up-Table		Look-Up-Table of nLw^{ref} for a given λ and Chl*a* concentration
Rrs	Remote sensing reflectance	Adimensional	Upwelling radiance emerging from the ocean divided by the downwelling irradiance reaching the water surface
F_0	Mean solar irradiance	mW cm^{-2} μm^{-1}	Mean solar irradiance to convert nLw into Rrs
Ra	Radiance anomalies	Adimensional	Represents the second order variation of the nLw after removal the first order effect of the Chl*a* variation. Ra is independent of the Chl*a* levels and represents the second order variation of nLw(λ)