Continental Shelf Research 77 (2014) 61–68

Contents lists available at ScienceDirect

Continental Shelf Research

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

Research papers

Chlorophyll distribution and variability in the Sicily Channel (Mediterranean Sea) as seen by remote sensing data

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ARTICLE INFO

Article history:
Received 27 June 2013
Received in revised form
8 November 2013
Accepted 8 January 2014
Available online 28 January 2014

Keywords:
Empirical orthogonal function
Channel Sicily
Chlorophyll
Kinetic Energy
Sea Surface Temperature

ABSTRACT

Remotely sensed ocean chlorophyll concentration is related to the presence of phytoplankton in the upper ocean layers. Its spatial and temporal variability significantly differs from region to region, originating from both purely ecological factors and local environmental conditions (e.g. species involved, grazing, light and nutrient availability, temperature, etc.). As a result, various physical processes are known to significantly affect chlorophyll distribution especially in coastal areas. Among these, wind-driven upwelling, river discharge, cross-shelf exchanges related to local dynamics and horizontal advection due to larger scale dynamics are often invoked as dominant mechanisms. In this work, we investigate which physical process mostly contributes to the phytoplankton variability in the Channel of Sicily (Mediterranean Sea), based on satellite estimates of surface chlorophyll (CHL) concentration, kinetic energy (KE) and sea surface temperature (SST). An empirical orthogonal function (EOF) analysis is applied to the three time series, spanning the 1998–2006 period. The main patterns of variability of each parameter and the physical processes associated with KE and SST modes are identified. The successive cross-correlation analysis shows that most of the CHL variability (explained variance 78%) is induced by the seasonal advection of the Atlantic Waters ($r=0.7$), while wind-driven upwelling, generally considered the main process modulating phytoplankton growth in the area, only explains 1.4% of the total CHL variance.

1. Introduction

Phytoplankton is one of the key components of the marine ecosystem, representing the base of the marine food web. The growth-limiting factor of phytoplankton and its biogeographical distribution, as well as its community structure and population dynamics are directly influenced by several specific biological, chemical and physical factors, as the availability of light and nutrients and the presence of predators, both on global and regional scales. Nutrient availability depends in turn on both physical and biogeochemical processes (Behrenfeld et al., 2006), such as horizontal/vertical advection and mixing at the ocean surface (e.g. driven by mixed-layer dynamics, by mesoscale/submesoscale processes, and/or by deep water formation events in the open ocean and wind-driven upwelling in the coastal areas), the solar cycle and light absorption by the atmosphere, remineralization processes, atmospheric deposition and local sources (such as river discharge and other anthropogenic sources). To characterize and understand the distribution and temporal evolution of phytoplankton in regional areas, it is therefore of crucial importance to investigate which process mostly influences phytoplankton presence and growth.

In this work, we aim to determine which physical process has the strongest impact on the phytoplankton distribution and variability in a key area of the Mediterranean Sea: the Channel of Sicily. The hypothesis is that the chlorophyll concentration is modulated by the phytoplankton abundance and by the availability of nutrients in the surface layers, which can be modified either by local or remote sources, through vertical transport and horizontal advection, respectively. In fact, local nutrient replenishment can be driven by both the mesoscale features and by the recurrent wind-driven coastal upwelling events commonly observed inside the Channel (e.g. Buongiorno Nardelli et al. (1999, 2001, 2006) and references therein). Actually, coastal upwelling has been often considered the dominant mechanism sustaining phytoplankton growth in the area (Garcia Lafuente et al., 2002; Beranger et al., 2004; Patti et al., 2004, 2010). Conversely, little attention has been paid to the possible role played by horizontal advection associated with the large scale inflow of Atlantic water along the North African coasts in contributing to the phytoplankton distribution inside the Channel.

The role of these physical processes in modulating the phytoplankton variability in the Channel of Sicily is here investigated comparing

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0278-4343/$ - see front matter
http://dx.doi.org/10.1016/j.csr.2014.01.010

satellite estimates of surface chlorophyll (CHL) concentration, kinetic energy (KE) and sea surface temperature (SST). In fact, phytoplankton biomass is usually approximated by surface chlorophyll (CHL) concentration data (Jeffrey and Vesk, 1997; Boyce et al.,2010; Volpe et al., 2012). On the other hand, local sea surface temperature (SST) cooling can represent a proxy of the surface water nutrient enrichment process driven by the vertical transport from the deeper colder layers in coastal upwelling systems (Traganza et al. 1983; Bignami et al., 2008; Silio´-Calzada et al., 2008). Finally, the surface kinetic energy (KE), calculated from satellite altimeter sea level slope data, provides a reliable estimate of the sub-basin scale circulation patterns that may influence and modulate the CHL distribution.

The approach chosen here consists in the identification of the spatial and temporal patterns of variability of CHL, SST, and KE and in their comparison through a cross-correlation analysis. To identify the dominant physical processes and their potential impact over CHL distribution, the modes of variability of both physical and biological variables were determined through an empirical orthogonal function (EOF) decomposition. The purpose of the EOF decomposition is to find the signals (called functions and/or modes or patterns) that explain the maximum variance within a time series (Lorenz, 1956). The original data can thus be interpreted as a linear combination of empirical modes, also known as principal components, which often reflect the variability associated with specific physical (or biological) processes, or to their interaction. EOF analysis represents an efficient tool to describe the ocean physical and biological variability, as demonstrated by the growing number of studies that have used it (e.g. Gallaudet and Simpson (1994), Marullo et al. (1999a,b), Buongiorno Nardelli and Santoleri (2004, 2005), Buongiorno Nardelli et al. (2003, 2010), Iida and Saitoh (2007), Katara et al. (2008), Garcia and Garcia (2008), Primpas et al. (2010), Volpe et al. (2012)).

The paper is organized as follows: after the brief characterization of the Sicily Channel in Section 2, a description of the dataset and methods is presented in Section 3. In Section 4 the EOF and correlation analysis results are discussed. Finally, conclusions are given in Section 5.

2. Study area

The Sicily Channel divides the Mediterranean Sea into two sub-basins: the eastern and the western. These sub-basins display a significant difference in the average surface CHL concentration (Santoleri et al., 2008; Volpe et al., 2012) along with different characteristic seasonal cycles: the eastern basin presents a seasonal cycle similar to that of the sub-tropical gyres, whereas the western basin is similar to that of the north Atlantic, with a pronounced spring bloom (D'Ortenzio and Ribera d'Alcalà, 2009). From the biogeochemical point of view, the entire Sicily Channel is characterized by chlorophyll concentration values ranging between 0.04 (summer) and 0.5 (winter) mg m^{-3}. The entire area can be considered as a mesotrophic area, with a CHL spatial variability encompassing 3 orders of magnitude: roughly between 0.01 and 10 mg m^{-3} on a daily basis (estimated from SeaWiFS data). In general, maximum (minimum) values recur during winter-spring (summer) in correspondence to periods of low (high) water column stratification. From the visualization of daily SeaWiFS data, higher and nearly constant values are found throughout the year in coastal areas, whereas offshore regions exhibit a more pronounced variability. However, specific oceanographic features, such as wind-induced coastal upwelling, frontal meanders and instabilities significantly modulate the local distribution of phytoplankton biomass. In fact, the wind-induced coastal upwelling along the Southern coasts of Sicily is presently considered the main driver for CHL variations inside the Channel (Garcia Lafuente et al., 2002; Mazzola et al., 2000).

It is worth noting that important fishery activities are carried out by the countries bordering the Channel, and that the whole area represents an important region for the spawning and growth of sardines and anchovies (Agostini and Bakun, 2002; Cuttitta et al., 2003). CHL concentration and its seasonal and interannual variations were shown to influence the anchovy growth and spawning in the Channel, even if there is not a definitive view on the main factors driving the observed variability (Agostini and Bakun, 2002; Garcia Lafuente et al., 2002; Cuttitta et al., 2003; Garofalo et al., 2003; Patti et al., 2004; Bonanno et al. 2006, 2007).

From a dynamical point of view, the Sicily Channel can be schematically considered as a two-layer system: a surface (top 200 m layer) and fresher water mass (relative to the Mediterranean resident water mass) of Atlantic origin (Atlantic Water, AW) flowing eastwards, and the saltier Levantine Intermediate Water (LIW) travelling westwards at depth. Once the AW enters the Channel near Cap Bon (Fig. 1), it splits into two veins: the Atlantic Tunisian Current (ATC), that flows close to the Tunisian coasts (Beranger et al., 2004; Pierini and Rubino, 2001) and the Atlantic Ionian Stream (AIS, Robinson et al., 1999), that occupies the central and northern region of the Channel (Poulain and Zambianchi, 2007), resulting in an average cyclonic circulation around the Adventure Bank (sometimes referred to as Adventure Bank Vortex, ABV, Robinson et al., 1999). South of Pantelleria Island, the AIS often bifurcates: a principal vein flows north-north-eastward generating the Maltese front with the warm water present in the channel (Marullo et al., 1999a,b), while a weaker stream directly flows along the Tunisian shelf (Lermusiaux and Robinson, 2001). In summer, the principal vein is found in the center of the channel, while recurrent wind-driven upwelling events create intense thermal fronts offshore the southern coasts of Sicily (Buongiorno Nardelli et al., 1999; Marullo et al., 1999a,b; Le Vourch et al., 1992; Kostianoy, 1996; Piccioni et al., 1988; Sorgente et al., 2003; Beranger et al., 2004). These upwelling fronts often evolve as mesoscale jets and filaments detaching from Mazara del Vallo and Cape Passero (e.g. Buongiorno Nardelli et al. (1999), Bignami et al. (2008)). On the contrary, downwelling processes can occur along the eastern coast of Tunisia (Agostini and Bakun, 2002). During winter, the AIS extends over a wider region inside the Channel.

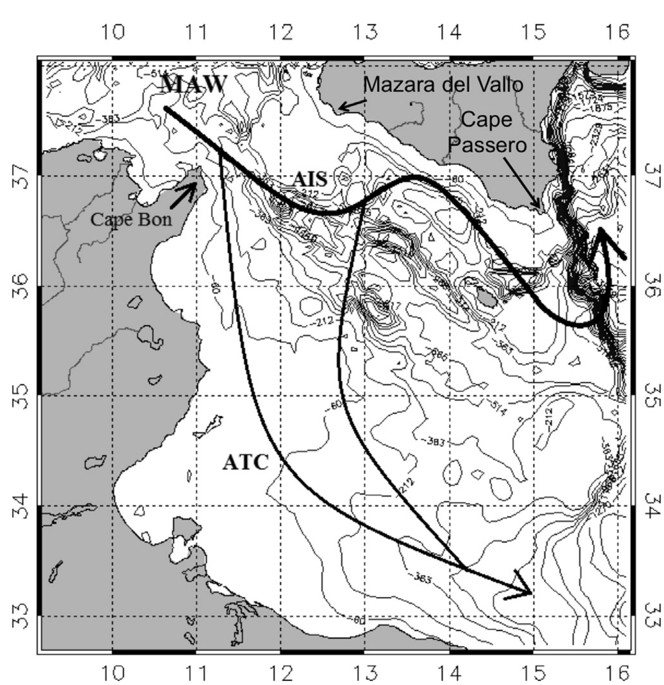

Fig. 1. Sketch of the Sicily Channel surface circulation.