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## Research paper

## Living and thanatocoenosis coccolithophore communities in a neritic area of the central Tyrrhenian Sea

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## ABSTRACT

The analyses of water and sediment samples, collected at 24 marine stations in a coastal area (Gulf of Gaeta, central Tyrrhenian Sea) during a three year survey (2012–2014), have improved our knowledge of coccolithophore ecology in the Mediterranean neritic domain. A comparison between the results and the oceanographic data has highlighted the ecology of the considered groups, and quantified the relationship between the community structures and the environmental parameters. The coccosphere concentration measured in the Gulf of Gaeta is extremely variable over the sampling periods (min:  $64 \text{ l}^{-1}$ ; max:  $2.4 \times 10^5 \text{ l}^{-1}$ ), and comparable with data from other Mediterranean sites. Placolith-bearing taxa are the dominant group of the living communities. The concentration and distribution of *Emiliana huxleyi* is controlled by the distance from the coast and the Volturno River runoff. The K-strategist taxa are an important component of the summer nanoplankton in the upper 15 m and in the sediment samples. These taxa are also related to summer oligotrophic warm waters and low turbidity as well. The opportunistic behaviour of *Helicosphaera carteri* is confirmed and is related to moderately elevated nutrient levels and also tolerance to low salinity and terrigenous input. Nevertheless, our findings raise some questions on the reliability of *H. carteri* as a low salinity proxy. Overall, the sediment assemblages reflect the composition and the temporal distribution of the living communities. The occurrence and distribution of abundant reworked coccoliths, both in water and sediments, provides useful information about coastal dynamics and confirm their use as a reliable runoff proxy.

## 1. Introduction

Knowledge of living coccolithophore ecology is key to reconstructing palaeoenvironmental changes. Coccolithophores are ubiquitous, calcareous scale-bearing marine microalgae, and are primary producers in the photic zone and directly dependent on changing gradients in surface waters (Henriksson, 2000). In general, coccolithophores prefer oligotrophic conditions in warm and stratified waters from low to middle latitude regions (McIntyre and Bé, 1967; Honjo and Okada, 1974; Cortés et al., 2001). Widespread throughout the oceans, coccolithophores are important markers of oceanographic changes, as they are sensitive indicators of photic zone (0–200 m) conditions. Each coccolithophore species has specific spatial and temporal distributions (e.g., Oviedo et al., 2015; and references therein). Environmental parameters such as temperature, salinity, dissolved nutrients, turbidity and light intensity are important controlling factors of the seasonal dynamics of the coccolithophores (e.g., Oviedo et al., 2015; and

references therein). Thus, knowledge of living coccolithophore ecology can be used to monitor present day environmental/oceanographic changes as well as past climate changes (Andruleit, 1997; Andruleit et al., 2003; Beaufort and Heussner, 2001; Bonomo et al., 2012, 2014; Broerse et al., 2000a, 2000b; De Bernardi et al., 2005; Gogou et al., 2016; Kleijne, 1990; Mitchell-Innes and Winter, 1987; Oviedo et al., 2015; Rogalla and Andruleit, 2005; Sprengel et al., 2000; Triantaphyllou et al., 2009a, 2009b; Winter et al., 1994; Ziveri et al., 1995a; Ziveri and Thunell, 2000). *Exempli gratia*, recently an innovative proxy, based on fossil coccolithophore assemblages, has been proposed by Bonomo et al. (2016), which found a direct relationship between the reworked coccoliths relative abundance and the hydrological regime of the past 400 yr in the Volturno estuary area (Tyrrhenian Sea).

The shallow water environment and in particular the marine areas in front of the river mouths represent key sites to study the interaction between freshwater and open sea. The mixing of sea and fresh waters provides high levels of nutrients in the water column and in the bottom

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sediment, making the marine areas in front of the river mouths the most productive natural habitats in the world (McLusky and Elliott, 2004). Consequently, the flow regime strongly controls the coastal marine ecosystem evolution (Boesch et al., 2001; Cloern, 2001; Rabalais et al., 2001; Humborg et al., 2008; Paerl et al., 2014). Most coccolithophore studies have been carried out using sediment trap and surface sediment assemblages (e.g., Incarbona et al., 2008; Ziveri et al., 2000; and references therein). Although these studies provide similar information concerning the taxonomic composition of living communities (Haidar et al., 2000), the coccoliths can be affected by processes of dissolution (Eynaud et al., 1999; Sprengel et al., 2000). Thus, due to high spatial and temporal changes in plankton communities, a comparison between living and thanatocoenosis floras could provide useful information on short time and spatial scale variability (Andruleit, 1997; Andruleit et al., 2004).

Along the Italian coast, very few studies have been conducted on water column samples (Balestra et al., 2008; Bonomo et al., 2012, 2014, 2017a,; Borsetti and Cati, 1972, 1976, 1979; Cerino et al., 2017; Damiani et al., 1988; Knappertsbusch, 1993; Šupraha et al., 2016). The present work aims to describe the ecological dynamics of the coccolithophore community in a neritic area in front of the Volturno estuary (central Tyrrhenian Sea) based on 3-year monitoring project of seawater and surface sediment samples. The distribution patterns of three ecological groups, their relationships with the reworked coccolith (RC) signal and the environmental parameters (temperature, salinity and beam transmission) will be discussed to improve the reliability of coccolithophores as palaeoproxies.

## 2. Study area

### 2.1. The Tyrrhenian Sea and Gulf of Gaeta

Among all the Mediterranean sub-basins the Tyrrhenian Sea is peculiar as its dynamics show a pronounced barotropic component. The Tyrrhenian Sea is connected to the other Mediterranean sub-basins through the Corsica channel in the north and the Sardinia channel in the south, and is the deepest major basin in the western Mediterranean Sea (Astraldi and Gasparini, 1994). The general circulation is organised into a series of gyres, the most important is the cyclonic gyre East of the Mouths of Bonifacio (the Corsica–Sardinia Strait). The circulation of the Tyrrhenian Sea is overall cyclonic triggered by the Modified Atlantic Water (MAW) entering from the northern Sicilian coast and establishing a northward current along the western Italian coasts (Fig. 1a) (Artale et al., 1994; Krivosheya and Ovchinnikov, 1973; Millot, 1987; Pierini and Simioli, 1998). Recently, Poulain and Zambianchi (2007) and Rinaldi et al. (2010) have revealed the presence of some changing mesoscale sub-basin structures, which are either transient or semi-permanent, whose effects on the circulation largely overcome those of the mean flow, particularly in the southern portion of the basin and along its southern coasts.

The circulation in the Gulf of Gaeta (GoG) (Fig. 1a) is related to the circulation of the southern and middle Tyrrhenian Sea (Iermano et al., 2012). However, the GoG circulation is also strongly affected by a local forcing factor driven by wind stress, which produces currents up to one order of magnitude larger than the mean basin circulation (Moretti et al., 1976). The winds blow mainly from the NE and SW quadrants in winter and summer, respectively (Iermano et al., 2012). During spring and fall, the main directions are the NE–SW axes (Menna et al., 2007). The study area is characterised by the presence of two major rivers, the Garigliano and Volturno (Fig. 1b–c). This study focuses on the coccolithophore community in front of the Volturno river mouth (Fig. 1c), the longest river in southern Italy (175 km) with an estimated mean discharge of  $40 \text{ m}^3 \text{ s}^{-1}$ , and has a  $\sim 6000 \text{ km}^2$  catchment basin (Iermano et al., 2012). The Volturno catchment basin contains mainly Cretaceous, Paleogene and Neogene sedimentary rocks and an alternation of recent volcanic and alluvial deposits (Bonardi et al., 1988).

The area in front of the river mouth consists of a wide shallow continental platform, made mainly of coarse-medium silt and subordinate sand in the area close to the coast ( $< 50 \text{ m}$  depth) (De Pippo et al., 2003–2004). Therein the sediment distribution is under fluvial control close to the mouth, whereas waves and currents regulate the adjacent portions (De Pippo et al., 2003–2004).

## 3. Materials and methods

The oceanographic measurements, the living coccolithophores and the surface sediment coccolith sampling were carried out during six I-AMICA oceanographic cruises from June 2012 to October 2014 (e.g., June 2012, October 2012, February 2013, June 2013, February 2014; October 2014) using the R/V Urania (National Research Council - CNR) and R/V Astrea (Italian National Institute for Environmental Protection and Research - ISPRA) at 24 hydrographic stations located in the GoG ( $40.91\text{--}41.10^\circ\text{N}$ ,  $13.76\text{--}14^\circ\text{E}$ , Table 1). Sampling could not be performed in October 2013 and June 2014 due to vessel unavailability. We also have used data of June 2012, already published in Bonomo et al. (2014), to compare and discuss the data provided from all the cruises. In order to fully cover the Volturno river mouth, the hydrographic stations were distributed along five transects normal to the coast (Fig. 1c). Hydrographic profiles covered the region from the very shallow water (9 m) along the coast to about 50 m water depth on the continental shelf. To show the very large amount of data (see Supplementary Materials) we use surface maps (5 m depth) and the vertical sections along 3 transects perpendicular to the coast (Fig. 1c), located north (transect A), in front (transect C), and south (transect E) of the Volturno river mouth. For the data of February 2014 we have used transect D in place of transect E, because of an instrument failure during the oceanic survey. All data were plotted using ODV software (Schlitzer, 2017).

Monthly surface runoff and precipitation data were extracted from ERA-Interim reanalysis (Dee et al., 2011) with a resolution of  $10 \times 13$  square kilometres (Fig. 1b). (All raw data are in Supplementary Material).

### 3.1. Oceanographic measurements (CTD)

At all the hydrological stations (Fig. 1c), continuous depth profiles of salinity, temperature and beam transmission were obtained by means of a CTD SBE 911-plus mounted on a General Oceanics rosette equipped with 12 Niskin bottles. All sensors were calibrated before every cruise. The physical and chemical oceanographic data are presented in Figs. 2–7.

### 3.2. Living coccolithophores

During the first explorative cruise (June 2012; Bonomo et al., 2014), the 5, 20 and 40 m depths were sampled, but in the next cruises the 5, 15 and 30 m depth intervals were selected, thus avoiding the extremely turbid bottom water. A total of 250 water samples were collected with Niskin bottles: two to five litres ( $\pm 0.1 \text{ l}$ ) of sea water were immediately filtered, using a vacuum pump, onto cellulose nitrate filters ( $0.45 \mu\text{m}$  pore size, 47 mm diameter). Each filter membrane was rinsed with distilled water immediately after filtration in order to remove sea-salt, oven-dried at  $40^\circ\text{--}60^\circ$  and stored in plastic Petri dishes (Bollmann et al., 2002).

For light microscope analysis, a wedge of filter membrane was mounted onto a glass slide using Norland Optical Adhesive and fixed beneath a cover slip. Coccospere counts were carried out with a polarising light microscope ( $1250\times$ ; 1 field of view =  $0.047 \text{ mm}^2$ ).

Generally, at least 200 coccospere per sample were counted in an area of approximately  $10 \text{ mm}^2$ . The coccospere abundance was calculated using the following equation:  $\text{CD} = (\text{A} \times \text{N}) / (\text{a} \times \text{V})$ , where  $\text{CD}$  = coccospere density ( $\text{l}^{-1}$ );  $\text{A}$  = filtration area ( $\text{mm}^2$ );  $\text{N}$  = total

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