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Reprint of: Carbon flux to the deep in three open sites of the Southern European Seas (SES)☆

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ABSTRACT

In this study, we investigate the strength and efficiency of carbon sequestration in the Southern European Seas (SES), by analyzing the export of POC at three deep sites located in the Western Mediterranean Sea (WMED), the Eastern Mediterranean Sea (EMED) and the Black Sea (BS). We combine estimations of satellite and algorithm-generated primary production data, calculated POC fluxes out of the euphotic layer and POC fluxes measured by sediment traps at the mesopelagic and bathypelagic layers during a one year period, with an ultimate goal to obtain a better understanding of the functioning of the biological pump in the SES. Annual particulate primary production based on satellite estimations (SeaWiFS) at the three sites, averages 205, 145 and 225 gC m^{-2} y^{-1} at the WMED, EMED and BS, respectively. According to our findings, the fraction of primary production that is exported out of the euphotic zone in the SES ranges between 4.2% and 11.4%, while the fraction reaching the mesopelagic layer (1000–1400 m depth) ranges between 0.6% and 1.8%. Finally, the fraction of primary production exported at the bathypelagic layer (2000–2800 m depth) is found to be 0.6%, 0.3% and 1.4% in the WMED, EMED and BS, respectively. The role of various processes responsible for the replenishment of surface waters with nutrients, giving rise to productivity episodes and organic carbon export to depth at the three SES sites is considered.

1. Introduction

Primary production at the ocean's surface captures carbon dioxide (CO_2) from the atmosphere. Particulate organic carbon (POC) produced here through photosynthesis is subjected to extended remineralisation. Sinking particulate matter is the major vehicle for exporting carbon from the sea surface to the ocean interior. A large fraction of the POC produced in the upper layer is generally remineralized before reaching the base of the euphotic zone. The attenuation of POC in the upper meters of the water column is controlled by the phytoplankton community composition, trophic relationships, aggregation–coagulation processes, scavenging of phytoplankton exudates, grazing and repackaging through fecal pellet production, and the loading of ballast particles ($CaCO_3$, opal, lithogenics) (De La Rocha and Passow, 2007; Dehairs et al., 2008; Gogou and Repeta, 2010; Honjo et al., 2008; and references therein). During its transport towards the sea floor, most POC is returned to inorganic form and redistributed in the water column. This redistribution determines the surface concentration of DIC, and hence the rate at which the ocean can absorb CO_2 from the atmosphere. This process is known as the biological pump (Honjo, 1980, 1996; McCave, 1975), and its magnitude and efficiency is controlled by physical and biogeochemical processes in surface, mesopelagic and bathypelagic layers, varying at daily, weekly, seasonal and inter-annual timescales.

The international multi-disciplinary program JGOFS (Joint Global Ocean Flux Study) improved significantly our understanding of CO_2 air–sea fluxes, as well as the spatial and temporal variability of POC and other key element vertical export fluxes in many oceanic sites (Fasham, 2003 and references therein). The deployment of sediment trap moorings in many parts of the world ocean, helped to develop an integrated picture of the ocean carbon cycle and POC export to the mesopelagic and bathypelagic depths (*e.g.*, Antia et al., 2001; Boyd and Trull, 2007; Buesseler and Boyd, 2009; Buesseler et al., 2007a; Honda et al., 2002; Honjo et al., 2008; Lampitt et al., 2010; Lutz et al., 2002,

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2007, among others). However, there are still several oceanic regions with limited or even lack of data, restricting our knowledge on the mechanisms and magnitudes of marine carbon cycling on a global scale.

In this study, we focus on three deep sites of the Southern European Seas (SES), located in the Western Mediterranean Sea (WMED), the Eastern Mediterranean Sea (EMED), and the SW Black Sea (BS), during an annual cycle from September 2007 to September 2008. The locations of the three mooring sites have been chosen to characterize specific hydrological and biological regimes of the Mediterranean and Black Seas, which were seldom or never considered. The WMED site is thus located in a convective and mesotrophic region, where the WMED Deep Water is formed, and which presents a significant spring phytoplankton bloom. The EMED site is located in an oligotrophic region, characterized by a weak seasonality of the phytoplanktonic biomass. The BS site is located in a mesotrophic region marked by a deep anoxic environment. Although these sites are located in basins, the proximity of continental margins and boundary currents in these semi-enclosed seas imposes taking into consideration potential lateral inputs. These sites complement the open sea areas already covered in previous studies conducted in the Alboran Sea (Sanchez-vidal et al., 2005), the Algero-Balearic Basin (Zúñiga et al., 2007), the Ligurian Basin (Miquel et al., 2011), the South Adriatic basin (Miserocchi et al., 1999), the Cretan Sea (Stavrakakis et al., 2000) and the 'NESTOR' site in the Ionian Sea (Stavrakakis et al., 2013) among others.

Our aim is to determine the fraction of POC produced in the euphotic zone which is exported to the mesopelagic and bathypelagic layers in the SES, by means of parametrization of POC flux attenuation with depth (Martin et al., 1987). In order to achieve this goal, we use estimates of net primary production derived from satellite data, along with calculated export fluxes out of the euphotic layer, and measured mid-depth and near-bottom POC fluxes collected concomitantly at the three sites. Imbalances in the vertical export (measured *vs.* calculated) are basically regarded as lateral POC inputs at the different depth layers.

The POC fluxes at the three sites are compared to assess the efficiency of the biological carbon pump in these contrasted environments. The three sites differ in terms of hydrography and nutrient availability and thus productivity and oxygen content. The detailed investigations of underlying physical and biogeochemical processes affecting the particle flux variability and export rates of associated biogenic and anthropogenic constituents in the three areas are addressed in specific independent papers (Bouloubassi et al., in preparation; Parinos et al., 2013; Stabholz et al., 2013; Theodosi et al., 2013).

2. Oceanographic settings

The intense evaporation over the Mediterranean exceeds precipitation and river runoff (Durrieu de Madron et al., 2010). This water deficit is compensated by the inflow of Atlantic water through the Strait of Gibraltar in the WMED, and the BS outflow in the northeastern Mediterranean (Fig. 1). The warmer and fresher Atlantic water (AW) entering the Mediterranean Sea describes a counter-clockwise circuit along the continental slopes through both WMEDand EMED sub-basins (see Millot and Taupier-Letage, 2005). Intense episodes of cold and dry northerly winds in winter cause dense water formation in the NW Mediterranean, the Adriatic and the Aegean Seas, increasing the density of AW, which sinks to intermediate or deep layers forming the Levantine Intermediate Water and the Mediterranean Deep Waters (see review in 'The MerMex Group', 2011; Fig. 1).

The Mediterranean Sea is one of the most oligotrophic regions in the world ocean, due to limited supply of nutrients to the surface waters (McGill, 1963), especially inorganic phosphorus (Krom et al., 1991; Thingstad and Rassoulzadegan, 1995). Nutrient distribution in the Mediterranean Sea is characterized by a decreasing trend in nutrient concentrations from the oligotrophic western basin to the ultra-oligotrophic eastern basin caused by physical dynamics and water transport. The large loss of inorganic nutrients, through the inflow of relatively nutrient-depleted Atlantic water at surface layers and the outflow of the underlying nutrient-rich Mediterranean waters through the Strait of Gibraltar (Béthoux et al., 1998 and references therein), prevents nutrient accumulation in deep waters and explains the oligotrophic character of the basin. It is also characterized by anomalous values in nutrient ratios that differ from Redfield values, with a decreasing west to east gradient (N:P > 25, Si:N > 1.3 and N:P ~ 20, Si:N ≤ 1.0 in the EMED and WMED mesopelagic and deep waters, respectively) (Ribera d'Alcala et al., 2003, and references therein). These skewed N/P ratios are essentially explained by the excess N over P in all nutrient sources arriving to the basin *via* atmospheric deposition (Mara et al., 2009; Markaki et al., 2010) and river discharge (Krom et al., 2010; Ludwig et al., 2010 and references therein).

Recently, the biogeography of the Mediterranean Sea and the seasonal cycle of the surface biomass were characterized in different areas of the basin by analyzing ten years of satellite surface Chl-*a* concentrations data (D'Ortenzio and Ribera d'Alcala, 2009), indicating that the Mediterranean sub-regions have asymmetric physical, chemical and biological forcing factors. In their study, they clearly show

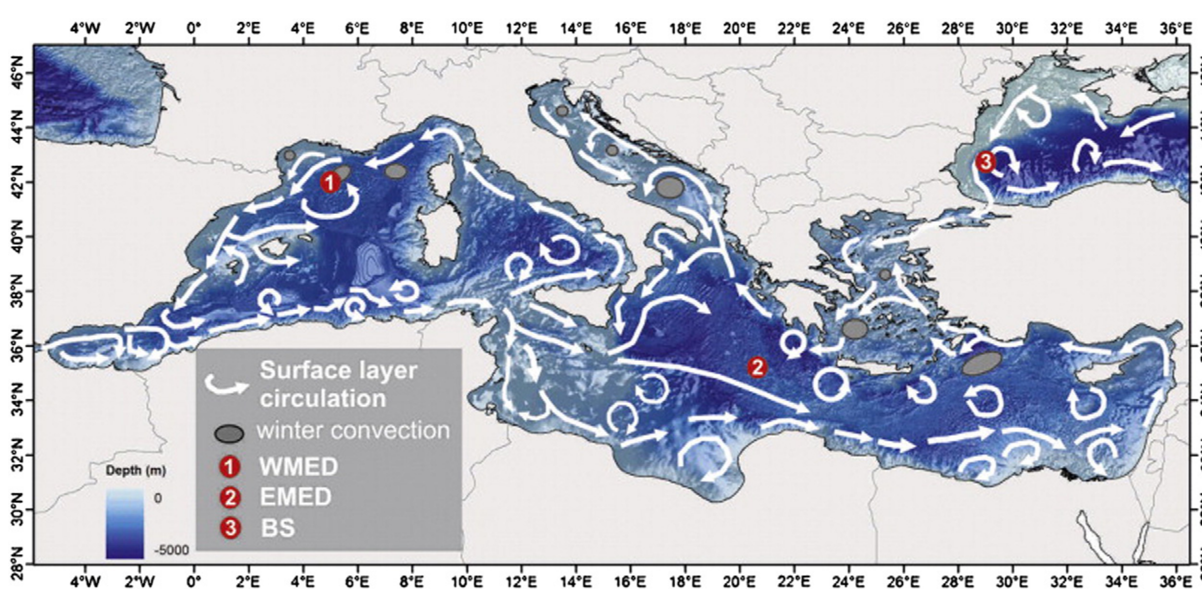

Fig. 1. Location of the three study sites in the Western and Eastern Mediterranean Sea and the Black Sea. Major surface circulation patterns (white arrows) and dense water formation sites (gray cycles) are also indicated.