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An initial carbon export assessment in the Mediterranean Sea based on drifting sediment traps and the Underwater Vision Profiler data sets

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A R T I C L E I N F O

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A B S T R A C T

During the SESAME EU FP6 project, all available particulate organic carbon (POC) data collected from drifting sediment trap and Underwater Vision Profiler deployments (INSU PROOF database, 1991–2011) were gathered in order to assess carbon export at the scale of the Mediterranean Sea. In this study, we observed that particle size, POC export, and the contribution of microphytoplankton to the phytoplankton community structure, all decreased following the west to east net primary production gradient. One the other hand, no clear longitudinal gradient was found regarding particle composition (C/N ratio or lipid content). The above longitudinal patterns were also observed at the seasonal scale from spring to summer in the northwestern sub-basin. These observations suggest that particle size rather than organic matter composition controls fluxes of POC in the Mediterranean Sea. The comparison between POC and dissolved organic carbon (DOC) fluxes highlights the different time-scale of physicals vertical mechanisms and suggests that DOC flux can play an underestimated role in the supply of fresh carbon to the deep waters Mediterranean Sea. Indeed, DOC supply to deeper layers can be one order of magnitude larger than particle carbon flux but occurs in pulses when stratification breaks due to (i) deep-water formation, or (ii) winter mixing. In contrast, the vertical export of POC occurs throughout the year bringing weak, but almost continuous, energy to meso- and bathypelagic organisms.

1. Introduction

Quantifying and understanding mechanisms that export carbon from surface layers to the deep ocean (here export is defined as the flux leaving the euphotic layer) is fundamental for modeling the carbon cycle and its response to future climate changes (Gehlen et al., 2006; Le Quéré et al., 2005). However, this is challenging as multiple biological and physical processes mediate its variability (Buesseler et al., 2007; Burd et al., 2010; Stemmann et al., 2004). Among these, the biological carbon pump, converting atmospheric CO_2 into organic matter *via* photosynthesis, plays a key role in regulating the ocean's efficiency for carbon sequestering. During this process, particulate, and dissolved organic carbon (POC and DOC, respectively) are released at all levels of the food web through extracellular release, grazing, egestion, excretion, production of fecal pellets, cellular death and viral lysis (Carlson, 2002). Carbon can be exported from the surface to the deep waters by the sinking of large and fast particles (Volk and Hoffert, 1985) as well as by deep-water formation and winter mixing (Carlson et al., 2010; Santinelli et al., 2013). This vertically-transferred POC and DOC that escape mineralization in the upper layers lead to long-term carbon sequestration in the deep waters.

In that context, the semi-enclosed Mediterranean Sea appears to be a good model to study the biological carbon pump variations in a constrained environment. Indeed, the Mediterranean pelagic ecosystem is mainly limited by inorganic nitrogen and phosphorus available for bacteria and planktonic growth (Berland et al., 1980; Krom et al., 1991; Thingstad and Rassoulzadegan, 1995). This limitation results in an overall trophic status similar to the open oceans varying from oligotrophic to ultra-oligotrophic from the western to the eastern basins (Krom et al., 1991; Moutin and Prieur, 2012). Biogenic particle fluxes calculated from a POC to mass ratio (Moutin and Raimbault, 2002) or derived from POC/^{234}Th ratios (Speicher et al., 2006) are

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higher in the western basin compared to the eastern basin, representing on average 10% and 1%, of primary production, respectively. In addition to this spatial pattern, seasonal variations of particle fluxes have been observed. For example, a recent study conducted at the DYFAMED (DYnamique des Flux de mAtière en MEDiterranée; 43°25'N, 7°52'E) station over a 17 years' time period, showed that organic carbon fluxes were on average higher during spring than summer by a factor of 8 (Miquel et al., 2011). Finally, seasons are not only affecting the amount of sinking material but also its quality. Sediment trap material showed a higher contribution from carbohydrates in the eastern Mediterranean during spring (Kerhervé et al., 1999) and higher lipid to protein ratio at the DYFAMED station as the system shifted from spring mesotrophy to summer oligotrophy (Goutx et al., 2000).

Here, within the framework of the SESAME (Southern European Seas: Assessing and Modeling Ecosystem changes) project, we combined all available historical POC data from drifting sediment traps and particle profiles from the Underwater Vision Profiler (UVP) to present a Mediterranean Sea carbon export synthesis and compare these data with DOC fluxes in order to discuss the potential processes leading to carbon export and sequestration in the Mediterranean Sea.

2. Material and methods

2.1. Drifting trap-measured carbon export

During the last decades, drifting sediment traps have been used intensively in the Mediterranean Sea to monitor short-term vertical carbon flux in a coherent water mass. The data presented in this synthesis have been collected in the framework of the PROOF, PCRD, and JGOFS programs and gathered through the SESAME project (Fig. 1 and Table 1). Overall, 187 individual drifting sediment trap (of type PPS3, PPS4 and PPS5) flux measurements were acquired between 1994 and 2004, from sediment traps deployed between 50 and 300 m with sampling intervals between 4 and 36 h. Sediment trap deployments, material recovery, and swimmers treatment before sample splitting was performed by the "Cellules Pièges" service (Coppola et al., 2015) according to the JGOFS protocol described in Miquel et al. (1994). Herein "basin" refers to the Mediterranean Scale estimates while "sub-basin" is used for regional estimates to allow comparisons of fluxes using different methods.

2.2. Particle size-based carbon flux

Four different generations of UVP instruments (UVPs 2a, 2c, 4a and 5; Fig. 1 and Table 1; Guidi et al., 2009; Picheral et al., 2010) were deployed from 1991 to 2011 providing a total of 834 profiles of particle size distribution. Previous inter-calibration studies of UVPs showed that only the common size range of the different instruments could be used to compare particle profiles (Guidi et al., 2008; Picheral et al., 2010). Therefore only particle size distributions from 250 to 1500 µm were used to estimate particle size-based carbon fluxes (using Eqs. (2) and (3)) using the relationship described by Guidi et al. (2008).

Particle-size-distribution (PSD) follows a decreasing power law over the µm to mm size range (Guidi et al., 2009; McCave, 1984; Sheldon et al., 1972). This distribution, known as the *Junge-type* distribution, is retrieved from the Underwater Vision Profiler (UVP) images (Picheral et al., 2010) and translates into the following equation :

$$n(d) = \propto d^{\beta} \quad (1)$$

where d is particles diameter and $n(d)$ is the particle size spectrum. The exponent (β) is defined as the slope of number spectrum when Eq. (1) is log transformed. This slope is commonly used as a descriptor of the shape of the aggregate size distribution (Brun-Cottan, 1971; McCave, 1984; Sheldon et al., 1972).

The particle size-based carbon approach relies on the assumption that the total carbon flux of particles (F) corresponds to the flux spectrum integrated over all particle sizes from the smallest ($dmin$) to

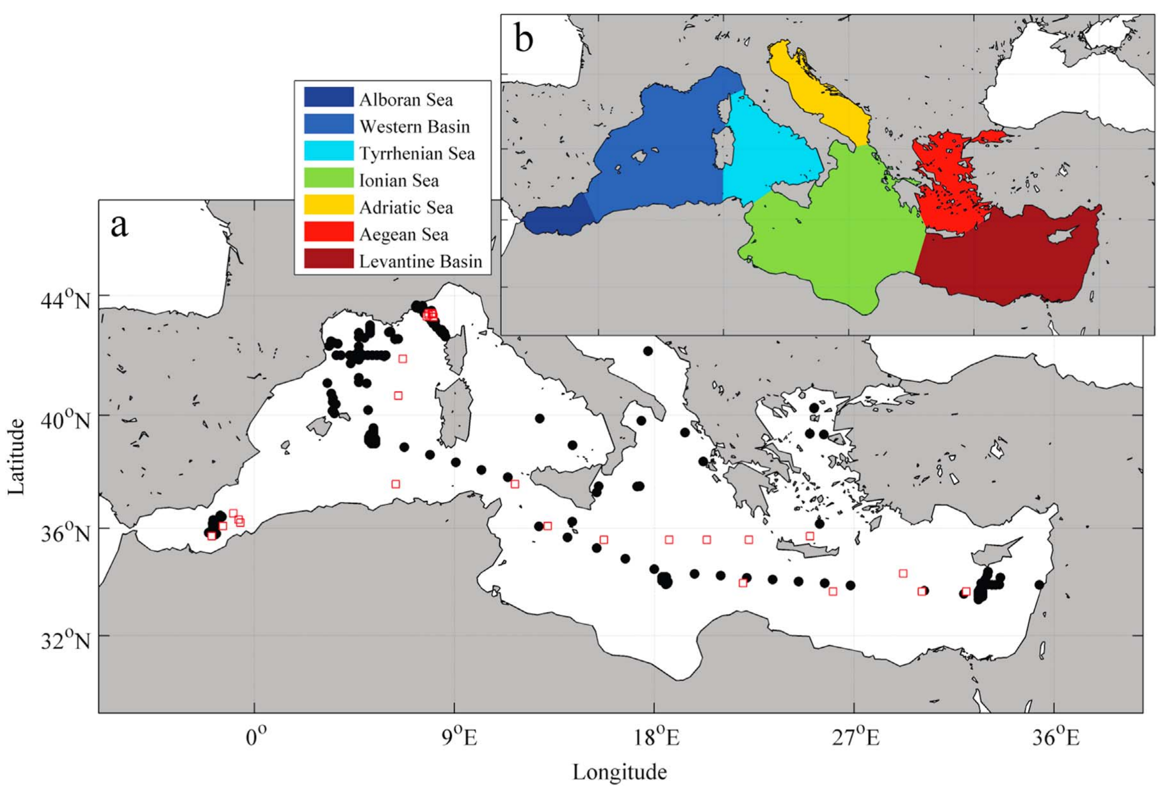

Fig. 1. (a) Location of particle size distribution profiles (black dots) and sediment traps deployments (red open squares) in the Mediterranean Sea. (b) Segmentation of the Mediterranean Sea in sub-basins used for further analysis and discussions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).