Deep-Sea Research I 57 (2010) 284–296

Contents lists available at ScienceDirect

Deep-Sea Research I

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

The diffusive component of particulate organic carbon export in the North Atlantic estimated from SeaWiFS ocean color

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ARTICLE INFO

Article history:
Received 18 August 2009
Received in revised form
13 November 2009
Accepted 18 November 2009
Available online 26 November 2009

Keywords:
Ocean color
Particulate organic carbon
Particulate organic carbon export
SeaWiFS

ABSTRACT

The diffusive component of the particulate organic carbon (POC) export from the ocean's surface layer has been estimated using a combination of the mixed layer model and SeaWiFS ocean color data. The calculations were carried out for several example sites located in the North Atlantic over a 10-year time period (1998–2007). Satellite estimates of surface POC derived from ocean color were applied as an input to the model driven by local surface heat and momentum fluxes. For each year of the examined period, the diffusive POC flux was estimated at a 200 m depth. The highest flux is generally observed in the spring and fall seasons, when surface waters are weakly stratified. In addition, the model results demonstrate significant interannual and geographical variability of the flux. The highest diffusive POC flux occurs in the northern North Atlantic and the lowest in the subtropical region. The interannual variability of the diffusive POC flux is associated with mixed layer dynamics and underscores the importance of atmospheric forcing for POC export from the surface layer to the ocean's interior.

1. Introduction

The fixation of inorganic carbon into organic matter in the photic zone, its transformation by food web processes, and subsequent vertical transport by physical mixing and gravitational settling of particles are commonly called the biological pump (e.g., Ducklow et al., 2001). Determining the efficiency of the biological pump, including the magnitude of the fraction of primary production (PP) that is removed from the euphotic zone (export production, e.g., Dugdale and Goering, 1967; Eppley and Peterson, 1979; Eppley, 1989) has been a high priority research objective in oceanography, because of its potential significance for the atmospheric CO_2 budget and global climate.

Over the years a number of methods have been used to estimate particulate organic carbon (POC) export from surface waters to greater depths. The experimental techniques include direct measurements of vertical particulate fluxes with moored or drifting sediment traps (e.g., Martin et al., 1993; see also reviews by Antia et al., 2001; Berelson, 2001; Lutz et al., 2002; Honjo et al., 2008) and the application of naturally occurring radionuclides, for example thorium-234 (^{234}Th), as tracers for sinking particles (e.g., Buesseler et al., 1992, 1995). The modeling approaches for estimating the strength of the biological pump include food web and particle transformation models (e.g., Legendre and Rivkin, 2002; Boyd and Stevens, 2002), ecosystem models (e.g., Patsch et al., 2002; Lima and Doney, 2004), and inverse models of biogeochemical processes based on distributions of oxygen, dissolved nutrients, and carbon in the ocean (Anderson et al., 2000; Schlitzer, 2004; Schlitzer et al., 2003; Usbeck et al., 2003). Approaches in which primary and export production are estimated from chlorophyll distributions obtained from ocean color satellite data have also been developed (e.g., Antoine et al., 1996; Behrenfeld and Falkowski, 1997; Behrenfeld et al., 2005; Laws et al., 2000; Dunne et al., 2007). In comparison to in situ measurements, which are usually limited geographically and temporally, satellite and modeling methods have the advantage of providing export estimates for extended periods of time for large regional, basin, and global scales. Unfortunately, all current POC flux estimates involve substantial uncertainties for a variety of reasons. For example, satellite estimates of export production rely on assumed conversion of chlorophyll *a* concentration (Chl) to productivity rates, phytoplankton Chl/POC ratios, and export production ratios (*f*), which are hard to quantify accurately and validate with a limited number of in situ calibration sites. A number of issues relating to sediment trap efficiency remain unresolved (e.g., Siegel and Deuser, 1997; Siegel et al., 2008). Inverse model calculations suggest higher estimates of POC fluxes from surface to mid-water depths than sediment trap and satellite-based methods (Schlitzer, 2004; Usbeck et al., 2003). The uncertainties inherent in the current POC flux estimates indicate a need for further development of alternative ways for studying POC dynamics and fluxes in the ocean.

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doi:10.1016/j.dsr.2009.11.007

In this paper, satellite ocean color data and a mixed layer model are used to derive estimates of the diffusive component of the POC export flux (PE_d) at seven sites in the North Atlantic. This diffusive component accounts for that fraction of the total POC export (PE), which is transported by vertical turbulent mixing out of the oceanic surface waters. One of the goals of this paper is to demonstrate that PE_d contributes significantly to total POC export. In addition we would like to develop a basic understanding of the geographical and temporal (seasonal and interannual) variability of PE_d in the North Atlantic and its responses to atmospheric forcing. Note that, traditionally, transport by the zooplankton (particularly by the diel migrators) and gravitational settling of biogenic aggregates ballasted by heavy biomineral and lithogenic particles have been considered as the two basic processes influencing PE (e.g., Honjo et al., 2008). The role of POC export by the vertical mixing has not received much attention, while our calculations indicate that PE_d is significant for the initial transport of particles from surface waters to below the mixed layer.

2. Study sites

The geographical locations of the seven sites discussed in this paper are displayed in Fig. 1. These sites are meant to represent different biogeochemical provinces in the North Atlantic (Longhurst, 1998). Each site corresponds to an open ocean region where historical oceanographic data sets provide a context for our results. The sites are briefly presented below.

2.1. Site #1 (31°40′N 64°10′W)

This site is located near Bermuda, in the western North Atlantic subtropical gyre province (NAST-W, Longhurst, 1998). Multiyear in situ oceanographic and biogeochemical data sets are available from Hydrostation S, the Bermuda Atlantic Time-series Study (BATS; Michaels and Knap, 1996; Steinberg et al., 2001; Lomas and Bates, 2004), as well as the Ocean Flux Program (OFP, e.g., Deuser, 1986; Conte et al., 2001, 2003). Primary productivity (PP) at the BATS site displays high seasonal variability with maximum daily rates observed during the winter/spring convective mixing period. During this time, the mixed layer depth (MLD) is 200 m deep and elevated nutrients are available in the euphotic zone. In the summer, PP is limited by nutrients (e.g., Steinberg et al., 2001). Annual net PP at this site has been estimated at about 360 mg C m^{-2} day^{-1} (Michaels et al., 1994). Particulate flux is characterized by a strong seasonal cycle. There is significant interannual variability in the timing, duration, and magnitude of the seasonal peak flux. In addition, abrupt short-lived peaks in mass flux in December–January have been reported (Conte et al., 2001).

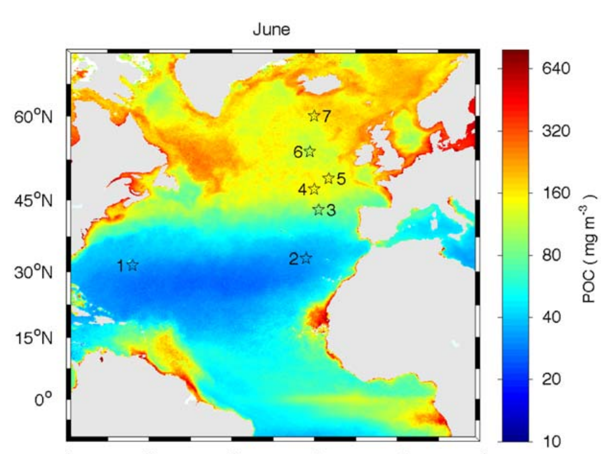

Fig. 1. Map of the 10-year averaged (1998–2007) monthly mean surface POC concentration derived from SeaWiFS for the month July, showing the location of the study sites used in this paper.

2.2. Site #2 (33°N 22°W)

This site is located west of Madeira in the eastern part of the North Atlantic Subtropical Gyral Province (NAST-E, Longhurst, 1998). Long-term observations of carbon fluxes and other oceanographic parameters at this site have been part of the German Joint Global Ocean Flux Study (JGOFS) program (station L1/K276, e.g., Waniek et al., 2005a,b). Other data sets from NAST-E province include data from the European Union Canary Islands Azores Gibraltar Observations Project (CANIGO) and from the European Station for Time Series in the Ocean, Canary Islands (ESTOC), located at 29°10′N, 15°30′W (e.g., Neuer et al., 2002, 2007).

This region is influenced by the Azores Current, which is an extension of the Gulf Stream. The winter mixing of the waters is relatively weak (100–200 m). The MLD stratification to 20–40 m occurs in March (Waniek et al., 2005a). PP is estimated at about 370 mg C m^{-2} day^{-1} (Dunne et al., 2007), and is limited by nutrients. For example, nitrate is only available in surface waters when the mixed layer is at its deepest, with concentrations of less than 1.0 μM, (Glover and Brewer, 1988; Waniek et al., 2005a). Surface chlorophyll *a* concentrations are about 0.5 mg m^{-3} during February and smaller than 0.2 mg m^{-3} during summer. The maximum particulate flux in deep-water moored sediment traps was documented in February, while a minimum flux occurred between April and August (Waniek et al., 2005b). Interestingly, particulate flux measured at ESTOC (NAST-E province) has been lower by a factor of up to four than the flux documented at BATS (NAST-W province), despite similar annual primary production at both sites (Neuer et al., 2007).

2.3. Site #3 (43°N 19°W)

This site represents a transition zone between productive regions in the north, associated with deep winter mixed layers (500 m and more), and oligotrophic regions in the south, associated with shallower (100–200 m) winter mixed layers (de Boyer Montégut et al., 2004). The site at 43°N 19°W is characterized by a pronounced seasonal cycle, and significant year-to-year variability. Data collected during the Programme Ocean Multidisciplinaire Meso Echelle (POMME) research project (Memery et al., 2005) indicate that MLD during late winter is highly variable due to day-to-day changes in the air–sea heat fluxes. The onset of the spring bloom is coincident with the rapid shallowing of the MLD, which takes place from mid-March through early May. The maximum Chl observed during POMME was about 1 mg m^{-3}. Interannual variability over the POMME area, including bloom timing and intensity, is caused by the variable position of the geographical frontier between subpolar, midlatitude and subtropical regimes (Levy et al., 2005). Primary productivity, estimated at 677 mg C m^{-2} day^{-1} (Dunne et al., 2007), is in summer limited by nutrients. Sediment trap data from the POMME region documented a clear seasonal cycle and significant interannual variability of particulate flux. Seasonal peak flux was observed in March–April in 2001, while in 2002 it was documented in April–May. This peak flux was significantly higher in 2001 (Guieu et al., 2005).