



**HAL**  
open science

## Dust deposition in an oligotrophic marine environment: impact on the carbon budget

Cécile Guieu, Céline Ridame, Elvira Pulido-Villena, Matthieu Bressac, Karine Desboeufs, François Dulac

### ► To cite this version:

Cécile Guieu, Céline Ridame, Elvira Pulido-Villena, Matthieu Bressac, Karine Desboeufs, et al.. Dust deposition in an oligotrophic marine environment: impact on the carbon budget. 2015. hal-00952669

**HAL Id: hal-00952669**

**<https://hal.science/hal-00952669>**

Preprint submitted on 9 Dec 2015

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



Dust deposition in an oligotrophic marine environment

C. Guieu et al.

This discussion paper is/has been under review for the journal Biogeosciences (BG). Please refer to the corresponding final paper in BG if available.

# Dust deposition in an oligotrophic marine environment: impact on the carbon budget

C. Guieu<sup>1,2</sup>, C. Ridame<sup>3,4</sup>, E. Pulido-Villena<sup>5</sup>, M. Bressac<sup>1,2</sup>, K. Desboeufs<sup>6</sup>, and F. Dulac<sup>7</sup>

<sup>1</sup>INSU-CNRS, UMR7093, LOV, Observatoire océanologique, 06230, Villefranche/mer, France

<sup>2</sup>Sorbonne Universités, UPMC Univ Paris 06, UMR7093, LOV, Observatoire océanologique, 06230, Villefranche/mer, France

<sup>3</sup>CNRS-INSU/IRD/MNH/UPMC, UMR7159, LOCEAN, Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques, 75252, Paris, France

<sup>4</sup>Sorbonne Universités, UPMC Univ Paris 06, UMR7159, LOCEAN, 75252 Paris, France

<sup>5</sup>Aix Marseille Université CNRS/INSU, IRD, Mediterranean Institute of Oceanography (MIO), UM110, 13288 Marseille (France)

<sup>6</sup>Université Paris Diderot, Sorbonne Paris Cité Université Paris Est Créteil, CNRS UMR7583, Laboratoire Interuniversitaire des Systèmes Atmosphériques (LISA), 61 av. Gal de Gaulle, 94010 C France

<sup>7</sup>Laboratoire des Sciences du Climat et de l'Environnement (LSCE), UMR8212 CEA-CNRS-UVSQ, 91191 Gif-Sur-Yvette, France

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Received: 7 January 2014 – Accepted: 10 January 2014 – Published: 29 January 2014

Correspondence to: C. Guieu (guieu@vifr.fr)

Published by Copernicus Publications on behalf of the European Geosciences Union.

**BGD**

11, 1707–1738, 2014

---

**Dust deposition in an  
oligotrophic marine  
environment**

C. Guieu et al.

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

By bringing new nutrients and particles to the surface ocean, atmospheric deposition impacts biogeochemical cycles. The extent to which those changes are modifying the carbon balance in oligotrophic environments such as the Mediterranean Sea that receives important Saharan dust fluxes is unknown. DUNE project provides the first attempt to evaluate the changes induced in the carbon budget of an oligotrophic system after simulated Saharan dust wet and dry deposition events. Here we report the results for the 3 distinct artificial dust seeding experiments in large mesocosms that were conducted in the oligotrophic waters of the Mediterranean Sea in summer 2008 and 2010. Simultaneous measurements of the metabolic rates (C fixation, C respiration) in the water column have shown that the dust deposition did not change drastically the metabolic balance as the tested waters remained net heterotroph (i.e. net primary production to bacteria respiration ratio  $< 1$ ) and in some cases the net heterotrophy was even enhanced by the dust deposition. Considering the different terms of the carbon budget, we estimate that it was balanced with a dissolved organic carbon (DOC) consumption of at least 10% of the initial stock. This corresponds to a fraction of the DOC stock of the surface mixed layer that consequently will not be exported during the winter mixing. Although heterotrophic bacteria were found to be the key players in the response to dust deposition, net primary production increased about twice in case of simulated wet deposition (that includes anthropogenic nitrogen) and a small fraction of particulate organic carbon was still exported. Our estimated carbon budgets are an important step forward in the way we understand dust deposition and associated impacts on the oceanic cycles. They are providing knowledge about the key processes (i.e. bacteria respiration, aggregation) that need to be considered for an integration of atmospheric deposition in marine biogeochemical modeling.

BGD

11, 1707–1738, 2014

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 1 Introduction

Atmospheric deposition provides new nutrients to the marine environment and, in a number of oligotrophic environments submitted to significant deposition, those new nutrients are likely able to relieve on going (co)limitations by providing available nitrogen, phosphorus, iron and other micronutrients (de Leeuw et al., 2013). The response of the biota to such input (natural, polluted or mixed aerosols) has been explored in a number of experimental artificial aerosols addition and in situ observations. In a recent paper, Guieu et al. (2014a) have synthesized the results from 26 of those studies showing that biota in Low-Nutrients and Low-Chlorophyll (LNLC) areas positively responds to aerosol addition, with bacterial production and N<sub>2</sub> fixation showing the strongest responses. Increases in chlorophyll *a* (Chl *a*) have also been seen but to a lesser extent. In fact, this synthesis shows that changes in biological standing stocks tend to be smaller than changes in metabolic rates (i.e. chlorophyll *a* vs. primary production, and bacterial abundance vs. bacterial respiration and/or production). Indeed, this could be due to the effect of grazing by zooplankton on phytoplankton and bacteria, (i.e. Bonnet et al., 2005; Herut et al., 2005; Marañón et al., 2010) which may increase turnover at the expense of stocks and rapidly propagate responses through the whole food web. This may result in an experimental artifact in that Chl *a* concentration may increase in experiments where grazers are filtered, but remains unchanged in natural waters, possibly explaining the variable and low response of satellite-derived chlorophyll signals to dust events (Volpe et al., 2009). This indicates that the use of metabolic rates instead of stocks seems more appropriate in tackling the response of biota to atmospheric deposition. Unfortunately, only a couple of studies have so far considered together the changes in metabolic rates induced by atmospheric deposition for both autotrophic and heterotrophic communities: for example, Herut et al. (2005) show that both communities were highly stimulated after fresh dust addition to surface seawater in microcosm experiments with bacterial production (BP) stimulated twice as much as primary production (PP) in the ultra-oligotrophic eastern Mediterranean Sea (increase

BGD

11, 1707–1738, 2014

### Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of 770 % and 450 %, respectively). Marañon et al. (2010) conducted eight bioassay experiments, over the basin-wide geographical range in the tropical Atlantic and have shown that the effect of Saharan dust deposition on the biological activity of the surface ocean may vary with the degree of oligotrophy of the tested waters. For four out of the eight addition experiments, the relative change in response to dust exceeded a value of 200 % for BP and community respiration (CR), whereas PP never increased by more than 100 % (Marañon et al., 2010). In the western Mediterranean Sea, Pulido-Villena et al. (2008) also show a strong stimulation of bacterial respiration (BR) after dust deposition either in microcosms (125 % average increase in BR) or in situ (100 % increase), the stimulation being proportional to the intensity of the dust flux. Unfortunately no autotrophic metabolic rate was measured during that study. Depending on the balance between the heterotrophic vs. autotrophic community, the stimulation by atmospheric deposition may thus either result in a CO<sub>2</sub> input or a CO<sub>2</sub> output in oligotrophic environments. Such opposite effects in terms of carbon (C) fate deserve to be explored if we want to understand the role of atmospheric deposition in marine ecosystem functioning, C cycling and feedbacks on climate.

Finally, it has been shown recently that aggregation and sorption processes between atmospheric lithogenic particles and in situ (dissolved and particulate) organic matter and subsequent ballasting can induce a strong and rapid particulate organic carbon (POC) export independently of a fertilization effect (Ternon et al., 2010; Bressac and Guieu, 2013; Bressac et al., 2014; Desboeufs et al., 2014). So far, the balance between the different main processes involved in the C cycle after a dust deposition has never been explored. As shown in Guieu et al. (2014b), the 52 m<sup>3</sup> mesocosm strategy developed during the DUNE (a DUst experiment in a low Nutrient, low chlorophyll Ecosystem, <http://www.obs-vlfr.fr/LOV/DUNE/index.html>) project allows us to consider a number of stocks and fluxes after a representative simulation of atmospheric deposition performed in situ at the surface of a large body of water. In particular considering the vertical transport of particles within the 12.5 m depth of the mesocosms over a rep-

## BGD

11, 1707–1738, 2014

### Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



representative length of time (7 days after the deposition) is an important improvement compared to the microcosm strategy.

Here we first explore how the balance between bacterial respiration and net primary production evolve after the dust deposition. We then attempt to use the numbers obtained (stocks and fluxes), along with estimates, to quantify how the carbon budget modified by the introduction of dust simulating wet and dry deposition events can be balanced. We report the results for the 3 distinct artificial seeding experiments that were conducted in the frame of the DUNE project in the oligotrophic waters of the Mediterranean Sea in summer 2008 and 2010.

## 2 Methods

### 2.1 Three seeding experiments during oligotrophic period in the oligotrophic waters of the Mediterranean Sea

The methodology concerning the “large clean mesocosms” (diameter: 2.3 m, surface area: 4.15 m<sup>2</sup>, and volume: 52 m<sup>3</sup>) setup is fully described in Guieu et al. (2010) and the 2 field campaigns main features are described in a companion paper (Guieu et al., 2014b). In this paper we will report on primary production (PP), bacterial respiration (BR) and particulate organic carbon export (POC<sub>export</sub>) data acquired during the campaigns DUNE-1 in June 2008 and DUNE-2 in June–July 2010. DUNE-1 consisted in two distinct 8 day experiments: a first simulation of a Saharan wet deposition event (hereafter named “DUNE-P”) and a second simulation of a Saharan dry deposition event (hereafter named “DUNE-Q”). DUNE-2 consisted of a single 16 day experiment (hereafter named “DUNE-R”) with 2 successive dust wet deposition simulations with 7 days between each seeding (respectively named “R1” and “R2”). Mineral dust deposition was mimicked using the finest fraction (< 20 μm) of alluvial soils collected in a desert soil source area in south Tunisia known to export Aeolian dust to the western Mediterranean (Guieu et al., 2010). Dry deposition was mimicked using the raw

**BGD**

11, 1707–1738, 2014

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



soil dispersed in surface seawater whereas wet deposition was mimicked using the same sieved soils after a chemical treatment reproducing cloud water processing by condensation-evaporation. This “evapo-condensed” dust is named hereafter “EC-dust”. The methodology to produce those proxies of wet and dry dust deposition is fully described in Guieu et al. (2010). Both dust types had similar chemical composition for nutrients i.e. P, Fe and C, but not for N because of the addition of HNO<sub>3</sub> in the simulated cloud water used to process dust for wet deposition simulation (Guieu et al., 2010). Their respective detailed composition is reported in Desboeufs et al. (2014). For each experiment, 3 mesocosms “CONTROL” without dust addition and 3 mesocosms “DUST” seeded each with a dust flux of 10 gm<sup>-2</sup> were deployed. In addition for DUNE-R, a fourth mesocosm was seeded with EC-dust and was devoted to optical measurements (see details in Bressac et al., 2012). The ways the dust was seeded and the mesocosms sampling strategy are fully described in Guieu et al. (2010, 2014). Sampling is summarized hereafter.

## 2.2 Methodology for sampling and measuring bacteria respiration (BR), net primary productivity (NPP) and particulate organic carbon flux (POC<sub>export</sub>)

The methods are described in companion papers of this special issue (see for bacteria respiration: Pulido-Villena et al., 2014, net primary productivity: Ridame et al., 2014 and POC<sub>export</sub>: Bressac et al., 2014, and Desboeufs et al., 2014). The main points are summarized here. The sampling was done every day at the same hours.

*BR* – Briefly, BR was determined on 5 m depth samples from each mesocosm gently filtered through a 0.8 μm polycarbonate filter under low vacuum pressure and siphoned into a set of six BOD (biological oxygen demand) bottles. Three BOD bottles from each mesocosm were immediately fixed with Winkler reagents. The other 3 were incubated during 24 h in the dark in a tap water bath to minimize temperature variations and were then fixed with Winkler reagents. Oxygen concentration was measured through a spectrophotometric approach based on measuring the absorbance at 466 nm of the colored I<sub>2</sub> and I<sub>3</sub><sup>-</sup> (Labasque et al., 2004, Reinthaler et al., 2006). There is growing evidence

BDG

11, 1707–1738, 2014

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



that the used technique, involving pre-filtration and long incubation time, can lead to an overestimation of the BR rates (see for example, Aranguren-Gassis et al., 2012). This potential overestimation should not be a big problem as far as results are compared with literature data (mostly obtained with the same method) and/or relative changes after dust addition are concerned. We are aware, however, that absolute values of BR or net CO<sub>2</sub> fluxes must be taken with caution.

*NPP* – One sample per depth was collected at both 0.1 and 5 m depth during DUNE-P and -Q and at 5 m depth only during DUNE R, for the determination of NPP using the <sup>13</sup>C uptake determination method. Immediately after sampling, <sup>13</sup>C tracer was added to obtain a final enrichment of about 9 atom% excess. Then, the <sup>13</sup>C-amended bottles were incubated under in situ conditions on a mooring line for 24 h at the corresponding sampling depths. Incubations were ended by filtration onto pre-combusted 25 mm glass fiber filters. Sample filters were stored at –20 °C and dried at 40 °C for 48 h before analysis. Concentration of carbon in particulate matter and <sup>13</sup>C-enrichment were quantified using a ThermoFisher Scientific™ (Bremen, Germany) isotope ratio mass spectrometer (IRMS) Delta plus, coupled with a C/N analyzer Flash EA via a type III-interface. This net primary productivity corresponds to the net particulate primary productivity.

*POC<sub>export</sub>* – Samples from sediment traps were preserved using a 5% buffered solution of formaldehyde. Swimmers were carefully handpicked and the remaining sample was desalted using ultrapure water and freeze-dried. Mass flux was determined by weighing the entire freeze-dried sample. The total concentration of carbon (TC) was measured using a CHN analyzer (Perkin Elmer 2400). HNO<sub>3</sub>/HF acid-digestion was performed in 7-mL Teflon flasks at 150 °C. Following complete evaporation, samples were diluted in 0.1 M HNO<sub>3</sub> and analyzed for their calcium (Ca), and sulfur (S) concentrations by ICP-AES (Desboeufs et al., 2014). In dust analogs Ca is present both as calcium carbonate and calcium sulfate (Guieu et al., 2010; Desboeufs et al., 2014). The part of Ca associated with sulfate (%Ca<sub>CaSO<sub>4</sub></sub>) was estimated from the particulate S concentration. Therefore, the particulate Ca concentration as carbonate (%Ca<sub>CaCO<sub>3</sub></sub>) corresponded to the difference between total Ca (%Ca)



## 2.4 Statistical tests

The mean relative changes (RC, in %) after the P, Q, R1 and R2 seedings were calculated as  $(X_{\text{Dust}} - X_{\text{Control}}) \times 100 / (X_{\text{Dust}})$  for each parameter ( $X = \text{NPP, BR and POC}_{\text{export}}$ ), where  $X_{\text{Control}}$  is the mean for the 3 mesocosms CONTROL. In order to compare the results between experiments), means were compared using a one-way ANOVA and a Fisher Least Significant Difference (LSD) means comparison test ( $\alpha = 0.05$ ). When assumptions for ANOVA were not respected, means were compared using a Kruskal-Wallis test and a post hoc Dunn's test. The statistical tests and the box plots were performed using the Addinsoft™ XLstat software (<http://www.xlstat.com>).

## 3 Results

### 3.1 Orders of magnitude of the background fluxes

The orders of magnitude of all the POC export, NPP and BR fluxes measured in the CONTROL-mesocosms and the DUST-mesocosms before seeding for the three experiments are reported in Table 1. Among the 3 parameters, NPP was the more stable flux in the tested waters over the 3 experiments (variation coefficient of 24 %).  $\text{POC}_{\text{export}}$  and BR were more variable but with variation coefficients below 100 % (82 and 68 % respectively).

For  $\text{POC}_{\text{export}}$ , no data are reported at such a depth as sediment traps are usually placed below 100 m depth (see synthesis data for the Mediterranean Sea in Ternon et al., 2010). Comparing POC export in surface waters (15 m in the DUNE experiments) and at 150–200 m is difficult as a high remineralization occurs reducing rapidly the amount of POC as a function of water depth, but at least our numbers can indicate orders of magnitude of the POC export from the surface mixed layer (SML) during summer in the western Mediterranean Sea (mixed layer depth from 10 to 15 m; D'Ortenzio et al., 2005). Ternon et al. (2010) measured an average POC flux at 200 m over 4 yr

BGD

11, 1707–1738, 2014

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of  $11 \pm 12 \text{ mgCm}^{-2} \text{ d}^{-1}$  at the DYFAMED (DYnamique des Flux Atmosphériques en MEDiterranée) site located in the northwestern Mediterranean Sea, with the lowest values from July to December. Our values at 15 m are in the lower range of values reported for the Ligurian Sea at 200 m at the same period of the year, indicating that the POC export flux was extremely low in the tested waters during DUNE.

*Net primary production* measured over 7 yr at the DYFAMED site in the Ligurian Sea in the surface mixed layer after the spring period ranged from 2 to  $10 \mu\text{gCL}^{-1} \text{ d}^{-1}$  (Marty and Chiaverini, 2002), which is in good agreement with the NPP rates measured in the tested waters during the DUNE experiments. Such values are typical of non-productive waters of the open ocean (del Giorgio et al., 1997).

*Bacterial Respiration* – A recent review on heterotrophic bacteria in the Mediterranean Sea (Pulido-Villena et al., 2012) indicates the scarcity of data on bacterial respiration compared to abundance and production, with only few studies focusing on the western basin, all showing high seasonal variability of BR for both coastal and open waters. BR values of the tested waters during the DUNE experiments were in the upper range of the most recent data obtained at the open sea DYFAMED site (Pulido-Villena et al., 2008) in the Ligurian Sea with values in May being  $14.4 \pm 7.2 \mu\text{gCL}^{-1} \text{ d}^{-1}$ . In particular, during DUNE-P, BR was higher than previously reported for the open Mediterranean Sea, with values more similar to coastal data as those reported by Navarro et al. (2004). As pointed out by these authors, the production of dissolved organic carbon (DOC) by seagrass meadows, highly abundant in the DUNE study site, may be responsible for such high BR rates.

All those comparisons indicate that our study site is a low productive oceanic system with low POC export.

*Order of magnitude of induced changes* – In order to evaluate the overall impact of the dust deposition on POC export, NPP and BR, the parameters were integrated (POC) or averaged (NPP, BR) over the same duration (7 days) after the artificial seedings. The relative changes (RC in %) compared to CONTROL-Meso are represented in Fig. 1.

Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Average increases relative to CONTROL-meso over 7 days higher than 500 % were observed only for  $\text{POC}_{\text{export}}$ . NPP did not increase after seeding during the Q experiment (dry deposition) and for the other experiments it increased in the range 75–144 %. BR increased in the range 137–156 % in P, Q and R2; a factor 2 higher increase of BR was observed after the R1 seeding (291 %).

*Heterotrophic character of the tested waters* – In the literature, the NPP/BR ratio is commonly used to quantify the metabolic status of aquatic systems (see for ex. Del Giorgio et al., 1997; Duarte and Augusti, 1998). If  $\text{NPP} > \text{BR}$ , then the considered system would be a  $\text{CO}_2$  sink and on the contrary, if  $\text{NPP} < \text{BR}$ , the ecosystem would be a  $\text{CO}_2$  source. During DUNE, the average NPP/BR ratio was always  $\leq 0.5$  in the CONTROL-meso (Fig. 2) indicating that the total carbon processed by bacteria exceeds by far the carbon fixed by phytoplankton: all the tested waters during DUNE before dust addition would thus be a source of dissolved  $\text{CO}_2$ . This is in good agreement with recent findings that unproductive aquatic systems are net heterotrophic (del Giorgio et al., 1997). This is reported for the whole Mediterranean sea (Duarte et al., 2013) and in the NW Mediterranean Sea (i.e. Lemee et al., 2002).

There are extremely large ranges of the gross primary production (GPP)/Community respiration (CR) ratio reported in the literature; for example, in open ocean, GPP/CR mean is 1.71 with values ranging from 0.05 to 45.7 (Duarte and Agustí, 1998). As a simplistic first approach, if we consider that the phytoplankton respiration accounts for about 20–40 % of GPP (Marra and Barber, 2004) and represents 10–20 % of total primary production, and that BR represents on average 50 % of CR in the western Mediterranean Sea (see for ex. Navarro et al., 2004; Obernosterer et al., 2010), our min-max GPP/CR would be 0.11–0.16 during DUNE-P, 0.3–0.45 during DUNE-Q, 0.22–0.33 during DUNE-R1, and 0.16–0.24 during DUNE-R2. This is lower than the ratio given for the Mediterranean Sea by Duarte et al. (2013):  $\text{GPP}/\text{CR} = 0.74 \pm 0.22$ . DUNE data are also in the lower range of the data compiled in Giorgio et al. (1997).

## BGD

11, 1707–1738, 2014

### Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 4 Discussion

### 4.1 A strong heterotrophic character remains after seeding

Although there are some variations in between the triplicate mesocosms as one may expect in natural systems responding to external forcing such as atmospheric deposition, the DUNE data show an increase in both BR and NPP fluxes after seeding (except for NPP for DUNE-Q). The first important point is to note that NPP/BR are below 1 with the average value for the whole data set being  $0.32 \pm 0.25$ . As seen on Fig. 3, NPP/BR tends to be significantly lower in DUST-Meso compared to CONTROL-Meso for P and Q indicating that the dust deposition induced an increase in the net heterotrophic character of the tested waters in these experiments.

Indeed, when normalizing to CONTROL values (Fig. 4), there is evidence that the net heterotrophic character of the waters is increasing after seeding for P and Q experiments. Normalized ratio are also on average below 1 after the first seeding of R, but after the second seeding, the ratio is found slightly above 1, signifying that the evolution of the NPP/BR ratio was roughly comparable in both seeded and non-seeded mesocosms. So except for the second seeding of DUNE-R experiment, the dust input did increase the net heterotrophic character of the tested waters.

DUNE setup offers the opportunity to quantify how the carbon budget is perturbed after a simulation by an intense dust deposition onto an oligotrophic system. As discussed in the introduction, until recently most of the studies on impact of dust deposition on the surface ocean have focused on the stimulation of phytoplankton. But a first comprehensive study has been published recently indicating how the bacteria community can be stimulated preferentially to autotroph community in the oligotrophic ocean, this stimulation being likely a function of the degree of oligotrophy status where and when the dust deposition does occur (Maranon et al., 2010). Our data are in very good agreement with this previous study as we show that both bacteria activity and primary production have been stimulated by the wet dust input, the stimulation of the bacterial respiration being either higher than that of net  $\text{CO}_2$  fixation after the dust event (R1 ex-

BGD

11, 1707–1738, 2014

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



periment) or equivalent (P and R2). The dust deposition did not thus change drastically the metabolic balance as the tested waters remained net heterotroph. In the 2 cases of DUNE-1 (P, Q), the net heterotrophy was even enhanced by the dust deposition. But this simplistic picture is of course incomplete if other processes that alter the carbon balance are not taken into account.

## 4.2 Carbon balance

As argued in Guieu et al. (2014b), our large clean mesocosms are closed systems with no lateral advection, enclosing a body of water large enough to be representative of the water outside and where stocks and fluxes can be measured after a perturbation such as a simulated dust deposition. Here, we will attempt to use the numbers obtained along with estimates of unmeasured parameters in order to quantify how the carbon budget is affected after dust deposition.

The mass balance equation for organic carbon from the mesocosm approach can be written as follows:

$$(\delta C_{\text{org}}/\delta t) = (\delta \text{POC}/\delta t) + (\delta \text{DOC}/\delta t) = \text{NCP} - \text{POC}_{\text{export}} + \text{At}_{\text{input}} \quad (1)$$

with NCP, the net community production,  $\text{POC}_{\text{export}}$ , the particulate organic carbon exported downward as measured in the sediment traps, and  $\text{At}_{\text{input}}$ , the amount of organic carbon added by the top to the DUST-meso by seeding (0.31 % of the total dust as determined by Desboeufs et al., 2014).

NCP is the difference between gross community production (GCP) and community respiration (CR):  $\text{NCP} = \text{GCP} - \text{CR}$ . The gross community production can also be expressed by the sum of the net primary production (NPP) that corresponds to the particle primary production in stratified conditions, and of the dissolved primary production (DPP):  $\text{GCP} = \text{NPP} + \text{DPP}$ . The community respiration comprises the bacterial respiration, the phytoplankton respiration and the zooplankton respiration. Considering that bacterial respiration represents on average 50 % of the community respiration in the western Mediterranean Sea (see for ex. Navarro et al., 2004, Obernosterer et al., 2010,

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





although a fraction of the BR can be missed as it was measured on the fraction  $< 0.8 \mu\text{m}$  that does not take into account the attached bacteria),  $\text{CR} \approx 2 \text{BR}$  and Eq. (1) can be rewritten as:

$$(\delta C_{\text{org}}/\delta t) = (\delta \text{POC}/\delta t) + (\delta \text{DOC}/\delta t) = \text{NPP} + \text{DPP} - 2\text{BR} - \text{POC}_{\text{export}} + \text{At}_{\text{input}} \quad (2)$$

Photosynthetic production of dissolved organic carbon (DPP) has been found to be a non-negligible fraction of the total primary production (dissolved and particulate) (see for ex. Baines and Pace, 1991). A similar range of its contribution to total primary production has been found in situ for open ocean oligotrophic systems (i.e 22 % Maranon et al., 2005;  $14\% \pm 7$  for 9 studies in marine systems reported in Baines and Pace, 1991) and, from a mesocosm study in a coastal productive ecosystem, (19 % Lopez-Sandoval et al., 2010). According to recent work in the western Mediterranean Sea in summer (Lagaria et al., 2011), DPP was found to represent  $\sim 10\%$  of the total photosynthetic production. The term DPP in Eq. (2) can thus be replaced by  $\text{DPP} = (0.1 \cdot \text{NPP})$ .

The calculation of  $(\delta C_{\text{org}}/\delta t)$  is given in Table 2a. Results indicate that the organic carbon sinks, especially respiration, strongly dominate the organic carbon sources, demonstrating that the dust deposition induced a loss of organic carbon of the system in all the experiments, particularly marked after the 3 simulated wet deposition events (P, R). In an attempt to quantify dissolved and particulate partitioning of this organic carbon sink, we have first calculated the changes induced by the seeding inside the mesocosm in the particulate pool  $(\delta \text{POC}/\delta t)$ .  $(\delta \text{POC}/\delta t)$  is the sum of (1) the changes in the organic carbon pools of phytoplankton, micro- and meso-zooplankton, and bacteria plus (2) a fraction of POC associated to added lithogenic material ( $\text{POC}_{\text{dust}}$ ) (Bressac et al., 2012, 2013) and still in suspension inside the mesocosm at the end of the experiment (Desboeufs et al., 2014). Details on the quantification of  $(\delta \text{POC}/\delta t)$  are given in Tables 2b and S2. Results show that changes in biomass are mostly due to an increase in phytoplankton biomass but that  $\text{POC}_{\text{dust}}$  dominates the particulate organic pool inside the DUST-meso at the end of the experiments ( $\sim 55\text{--}65\%$  for the 3 wet deposition

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





simulations P and R, and 100% for Q following the non-stimulation of autotrophs by the dry deposition; Ridame et al., 2014).

The remaining term of this carbon budget is the change in the dissolved carbon pool. As emphasized in the methodology section, unfortunately, the non-validated DOC data cannot be used to close this budget. Assuming that the budget is balanced, we deduced the loss in the DOC pool induced by the dust deposition from the available data (Table 2c): we found that the DOC loss was 43 g of C when considering the whole mesocosm, i.e.  $10 \mu\text{molCL}^{-1} \text{d}^{-1}$  for P experiment,  $6 \text{gCmesocosm}^{-1}$  or  $1.4 \mu\text{molCL}^{-1} \text{d}^{-1}$  for Q experiment, and  $17 \text{gCmesocosm}^{-1}$  or  $4 \mu\text{molCL}^{-1} \text{d}^{-1}$  for R experiment. The same order of magnitude for DOC consumption has been measured during heterotrophic phases at oligotrophic coastal Mediterranean site (Navarro et al., 2004), with a net DOC consumption as high as  $18 \mu\text{molCL}^{-1} \text{d}^{-1}$  and an average consumption during heterotrophic phases of  $3.24 \pm 3.55 \mu\text{molCL}^{-1} \text{d}^{-1}$ ). The authors of this last study indicate that such a consumption implies that the system has to import DOC, either derived from land (storm runoff) or released by benthic communities. In our case, as our system does not allow allochthonous inputs, it means that our dissolved organic stock should have decreased during the course of the experiment. The question is raised whether the numbers are realistic. Our DOC consumption over the whole mesocosm during 7 days following the seeding would have been of 70, 10, and  $27 \mu\text{molCL}^{-1}$  for P, Q, and R1 experiment, respectively, compared to an initial DOC concentration of  $87 \pm 9 \mu\text{molCL}^{-1}$  (see Sect. 2). For Q and R, our DOC consumption would indicate a decrease of 10% (Q) and 30% (R) of the DOC stock leading to plausible in situ final DOC concentrations (respectively 78 and  $60 \mu\text{molCL}^{-1}$ ). However, the DOC consumption for P experiment appears unlikely as it would indicate that most of the DOC stock was consumed. This could well be explained by an overestimation of the BR whose value for the whole mesocosm was extrapolated from the rate measured at the depth of 5 m, meaning that BR was not homogeneous contrary to what was hypothesized in Sect. 2. This speaks for possible BR variations with depth in stratified waters.

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)



deposition as it was previously shown by Pulido-Villena et al. (2008) and Marañón et al. (2010) using microcosm approaches.

DUNE is an important step forward in the way we understand dust deposition to the ocean in particular because the term “fertilization” is often associated with the a priori belief that dust deposition should increase chlorophyll biomass (despite some evidences of the contrary from satellite data; Dulac et al., 2004; Volpe et al., 2009) and carbon fixation (and thus increase atmospheric CO<sub>2</sub> drawdown). Instead, DUNE results have shown that by fertilizing predominantly heterotrophic bacteria, dust deposition induces the remineralization of DOC, thereby reducing atmospheric CO<sub>2</sub> drawdown (Rivkin and Anderson, 1997). As emphasized by Pulido-Villena et al., 2008 and this issue, this may reduce substantially the fraction of the dissolved organic carbon stock in the surface ocean that can be exported to deep waters at the time of the winter mixing. Nevertheless, according to the “microbial carbon pump hypothesis” (Jiao et al., 2010), information on the lability of the remaining DOC pool after the enhanced bacterial respiration would be needed to better assess the net effect of dust deposition on DOC export. Other interesting development of this study would be to predict possible scenarios for the future using global biogeochemical models where dust pulses such as the ones simulated during DUNE are represented (Guieu et al., 2014a). Indeed on going environmental changes (i.e. increasing temperature and stratification, expansion of the oligotrophic ocean, changes in atmospheric deposition) could modify the role of atmospheric deposition on biogeochemistry of Low-Nutrient-Low-Chlorophyll ocean such as the Mediterranean Sea and an adequate representation of the input of atmospheric new nutrients and particles in those models is timely (Guieu et al., 2014a). In particular, biogeochemical models should consider the important processes highlighted by the DUNE results such as bacterial respiration and (organic matter-Dust) aggregation, a process that allows particulate organic carbon export even in heterotrophic systems.

**BGD**

11, 1707–1738, 2014

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Supplementary material related to this article is available online at  
[http://www.biogeosciences-discuss.net/11/1707/2014/  
bgd-11-1707-2014-supplement.pdf](http://www.biogeosciences-discuss.net/11/1707/2014/bgd-11-1707-2014-supplement.pdf).

5 *Acknowledgements.* The DUNE project, a DUst experiment in a low Nutrient, low chloro-  
phyll Ecosystem, is a fundamental research project funded by the ANR under the contract  
“ANR-07-BLAN-0126-01”. It was conducted in partnership with the laboratory of LISA (Créteil),  
LEMAR (Brest), LOCEAN (Paris), and in collaboration with the laboratories LSCE (Gif-sur-  
10 Yvette), LOMIC (Banyuls), IRD/LOBP/COM (Marseille), CEFREM (Perpignan), CERES/ERTI,  
ENS (Paris) and the Regional Parc of Corsica, Preservation Area of Scandola. DUNE was  
also conducted in strong collaboration with foreign research institute including the Institut des  
Régions Arides (IRA), Médenine (Tunisie), IFM-GEOMAR, Kiel (Germany), Stazione Zoolog-  
ica Anton Dohrn, Napoli (Italy) and Alfred Wegener Institute, Bremerhaven (Germany). This  
work would not have been possible without the huge involvement of engineers F. Louis, J.M.  
15 Grisoni, and divers J.M. Grisoni, D. Luquet, M.C. Rouvières, and L. Gilleta from the Obser-  
vatoire Océanologique de Villefranche-sur-Mer. We finally thank the service RADEZOO for  
the zooplankton analysis using the Zooscan system at the Observatoire Océanographique  
de Villefranche-sur-Mer (OOV). DUNE was endorsed by the international SOLAS (Surface  
Ocean – Lower Atmosphere) program in February 2009, ([http://www.solas-int.org/activities/  
project-endorsement.html](http://www.solas-int.org/activities/project-endorsement.html)). The authors wish to thank Stephane Blain for his helpful comments  
20 of an earlier version of the paper.

## References

- Aranguren-Gassis, M., Teira, E., Serret, P., Martínez-García, S., and Fernández, E.: Potential  
overestimation of bacterial respiration rates in oligotrophic plankton communities, *Mar. Ecol.-  
Prog. Ser.*, 453,1–10, 2012.
- 25 Baines, S. B. and Pace, M. L.: The production of dissolved organic matter by phytoplankton  
and its importance to bacteria: patterns across marine and freshwater systems, *Limnol.  
Oceanogr.*, 36, 1078–1090, 1991.

BGD

11, 1707–1738, 2014

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Benner, R. and Herndl, G. J.: Bacterially derived dissolved organic matter in the microbial carbon pump, in: *Microbial Carbon Pump in the Ocean*, edited by: Jiao, N., Azam, F., and Sanders, S., Science/AAAS, Washington DC, 46–48, 2011.
- Bonnet, S., Guieu, C., Chiaverini, J., Ras, J., and Stock, A.: Effect of atmospheric nutrients on the autotrophic communities in a low nutrient, low chlorophyll system, *Limnol. Oceanogr.*, 50, 1810–1819, 2005.
- Bressac, M., Guieu, C., Doxaran, D., Bourrin, F., Obolensky, G., and Grisoni, J. M.: A mesocosm experiment coupled with optical measurements to observe the fate and sinking of atmospheric particles in clear oligotrophic waters, *Geo-Mar. Lett.*, 32, 153–164, 2012.
- Bressac, M. and Guieu, C.: Post-depositional processes: What really happens to new atmospheric iron in the ocean surface?, *Global Biogeochem. Cy.*, 27, 859–870, 2013.
- Bressac, M., Guieu, C., Doxaran, D., Bourrin, F., Desboeufs, K., Leblond, N., and Ridame, C.: Quantification of the lithogenic carbon pump following a dust deposition event, *Biogeosciences*, in press, 2014.
- Cole, J. J.: Aquatic microbiology for ecosystem scientists: new and recycled paradigms in ecological microbiology, *Ecosystems*, 2, 215–225, 1999.
- Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., and Middelburg, J. J.: Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget, *Ecosystems*, 10, 172–185, 2007.
- de Leeuw, G., Guieu, C., Arneth, A., Bellouin, N., Bopp, L., Boyd, P., Denier van der Gon, H., Desboeufs, K., Dulac, F., Facchini, C., Gantt, B., Langmann, B., Mahowald, N., Maranon, E., O'Dowd, C., Olgun, N., Pulido-Villena, E., Rinaldi, M., Stephanou, E., and Wagener, T.: Ocean-atmosphere interactions of particles, in: *Ocean-Atmosphere Interactions of Gases and Particles*, edited by: Liss, P. and Johnson, M., Publisher, Springer, Springer Berlin Heidelberg, 171–246, 2014.
- Del Giorgio, P. A. and Duarte, C. M.: Respiration in the open ocean, *Nature*, 420, 379–384, 2002.
- Del Giorgio, P. A., Cole, J. J., and Cimleris, A.: Respiration rates in bacteria exceed phytoplankton production in unproductive aquatic systems, *Nature*, 385, 148–151, 1997.
- Desboeufs, K. V., Leblond, N., Wagener, T., Bon Nguyen, E., and Guieu, C.: Chemical fate and settling of dust after atmospheric deposition: Study Case of dust seeding in large mesocosms, *Biogeosciences*, submitted, 2014.

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[◀](#)

[▶](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



- Duarte, C. M. and Agusti, S.: The CO<sub>2</sub> balance of unproductive aquatic ecosystems, *Science*, 281, 234–236, 1998.
- Duarte C. M., Regaudie-de-Gioux, A., Arrieta, J. M., Delgado-Huertas, A., and Agusti, S.: The oligotrophic ocean is heterotrophic, *Annu. Rev. Mar. Sci.*, 5, 551–69, 2013.
- 5 Ducklow, H. W. and Doney, S. C.: What is the metabolic state of the oligotrophic ocean? A debate, *Annu. Rev. Mar. Sci.*, 5, 525–33, 2013.
- Dulac, F., Moulin, C., Planquette, H., Schulz, M., and Tartar, M.: African dust deposition and ocean colour in the eastern Mediterranean, in: Proc. 37th CIESM Congress, Barcelona, 7–11 June 2004, CIESM (Commission Internationale pour l'Exploration Scientifique de la Méditerranée), Monaco, 190 pp., 2004.
- 10 Engel, A., Borchard, C., Piontek, J., Schulz, K. G., Riebesell, U., and Bellerby, R.: CO<sub>2</sub> increases <sup>14</sup>C primary production in an Arctic plankton community, *Biogeosciences*, 10, 1291–1308, doi:10.5194/bg-10-1291-2013, 2013.
- Estrada, M.: Primary production in the northwestern Mediterranean, *Sci. Mar.*, 60, 55–64, 15 1996.
- Fukuda, R., Ogawa, H., Nagata, T., and Koike, I.: Direct determination of carbon and nitrogen contents of natural bacterial assemblages in marine environments, *Appl. Environ. Microb.*, 64, 3352–3358, 1998.
- Guieu, C., Dulac, F., Desboeufs, K., Wagener, T., Pulido-Villena, E., Grisoni, J.-M., Louis, F., Ridame, C., Blain, S., Brunet, C., Bon Nguyen, E., Tran, S., Labiadh, M., and Dominici, J.-M.: Large clean mesocosms and simulated dust deposition: a new methodology to investigate responses of marine oligotrophic ecosystems to atmospheric inputs, *Biogeosciences*, 7, 2765–2784, doi:10.5194/bg-7-2765-2010, 2010.
- 20 Guieu, C., Aumont, O., Paytan, A., Bopp, L., Law, C. S., Mahowald, N., Achterberg, E. P., Marañón, E., Salihoglu, B., Crise, A., Wagener, T., Herut, B., Desboeufs, K., Kanakidou, M., Olgun, N., Peters, F., Pulido-Villena, E., Tovar-Sanchez, A., and Völker, C.: The significance of episodicity in atmospheric deposition to Low Nutrient Low Chlorophyll regions, *Global Biogeochem. Cy.*, submitted, 2014a.
- Guieu, C., Dulac, F., Ridame, C., and Pondaven, P.: Introduction to the project DUNE, a DUST experiment in a low Nutrient, low chlorophyll Ecosystem, *Biogeosciences*, in press, 2014b.
- 30 Herut, B., Zohary, T., Krom, M. D., Mantoura, R. F. C., Pitta, P., Psarra, S., Rassoulzadegan, F., Tanaka, T., and Thingstad, T. F.: Response of East Mediterranean surface water to Saha-

ran dust: on-board microcosm experiment and field observations, *Deep-Sea Res. Pt. II*, 52, 3024–3040, 2005.

Jiao, N., Herndl, G. J., Hansell, D. A., Benner, R., Kattner, G., Wilhelm, S. W., Kirchman, D. L., Weinbauer, M. G., Luo, T., Chen, F., and Azam, F.: Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean, *Nat. Rev. Microbiol.*, 8, 593–599, doi:10.1038/nrmicro2386, 2010.

Labasque, T., Chaumery, C., Aminot, A., and Kergoat, G.: Spectrophotometric Winkler determination of dissolved oxygen: re-examination of critical factors and reliability, *Mar. Chem.*, 88, 53–60, 2004.

Lagaria, A., Psarra, S., Lefèvre, D., Van Wambeke, F., Courties, C., Pujo-Pay, M., Oriol, L., Tanaka, T., and Christaki, U.: The effects of nutrient additions on particulate and dissolved primary production and metabolic state in surface waters of three Mediterranean eddies, *Biogeosciences*, 8, 2595–2607, doi:10.5194/bg-8-2595-2011, 2011.

Lemée, R., Rochelle-Newall, E., Van Wambeke, F., Pizay, M.-D., Rinaldi, P., and Gattuso, J.-P.: Seasonal variation of bacterial production, respiration and growth efficiency in the open NW Mediterranean Sea, *Aquatic Microb. Ecol.*, 29, 227–237, 2002.

López-Sandova, D. C., Marañón, E., Fernández, A., González, J., Gasol, J. M., Lekunberri, I., Varela, M., Calvo-Díaz, A., Morán, X. A. G., Álvarez-Salgado, X. A., and Francisco, G., and Figueiras, F. G.: Particulate and dissolved primary production by contrasting phytoplankton assemblages during mesocosm experiments in the Ría de Vigo (NW Spain), *J. Plankton Res.* 32, 1231–1240 doi:10.1093/plankt/fbq045, 2010.

Marañón, E., Cermeño, P., and Pérez, V.: Continuity in the photosynthetic production of dissolved organic carbon from eutrophic to oligotrophic waters, *Mar. Ecol.-Prog. Ser.*, 299, 7–17, 2005.

Marañón, E., Fernández, A., Mouriño-Carballido, B., Martínez-García, S., Teira, E., Cermeño, P., Chouciño, P., Huete-Ortega, M., Fernández, E., Calvo-Díaz, A., Morán, X. A. G., Bode, A., Moreno-Ostos, E., Varela, M. M., Patey, D., M. D., and Achterberg, E. P.: Degree of oligotrophy controls the response of microbial plankton to Saharan dust, *Limnol. Oceanogr.*, 55, 2339–2352, 2010.

Marty, J. C. and Chiaverini, J.: Seasonal and interannual variations in phytoplankton production at DYFAMED time-series station, north-western Mediterranean sea, *Deep-Sea Res. II*, 49, 2017–2030, 2002.

# BGD

11, 1707–1738, 2014

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Dust deposition in an oligotrophic marine environment**

C. Guieu et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

- Navarro, N., Agustí S., and Duarte, C. M.: Plankton metabolism and dissolved organic carbon use in the Bay of Palma, NW Mediterranean Sea, *Aquat. Microbial Ecol.*, 37, 47–54, 2004.
- Obernosterer, I., Lami, R., Larcher, M., Batailler, N., Catala, P., and Lebaron, P.: Linkage between bacterial carbon processing and the structure of the active bacterial community at a coastal site in the NW Mediterranean Sea, *Microb. Ecol.*, 59, 428–435, 2010.
- Pérez, V., Fernández, E., Marañón, E., Morán, X. A. G., and Zubkov, M. V.: Vertical distribution of phytoplankton biomass, production and growth in the Atlantic subtropical gyres, *Deep-Sea Res. Pt. I*, 53, 1616–1634, 2006.
- Pulido-Villena, E., Wagener, T., and Guieu, C.: Bacterial response to dust pulses in the western Mediterranean: implications for carbon cycling in the oligotrophic ocean, *Global Biogeochem. Cy.*, 22, GB1020, doi:10.1029/2007GB003091, 2008.
- Pulido-Villena, E., Ghiglione, J.-F., Ortega-Retuerta, E., van Wambeke, F., and Zohary, T.: Heterotrophic bacterian in the pelagic realm of the Mediterranean Sea, in: *Life in the Mediterranean Sea: a Look at Habitat Changes*, edited by: Stambler, N., Nova Science Publishers, Inc, 2012.
- Pulido-Villena, E., Baudoux, A.-C., Obernosterer, I., Landa, M., Caparros, J., Catala, P., Georges, C., Harmand, J., and Guieu, C.: Microbial food web dynamics in response to a Saharan dust event: results from a mesocosm study in the oligotrophic Mediterranean Sea, *Biogeosciences Discuss.*, 11, 337–371, doi:10.5194/bgd-11-337-2014, 2014.
- Reinthal, T., Bakker, K., Manuels, R., Van Ooijen, J., and Herndl, G. J.: Fully automated spectrophotometric approach to determine oxygen concentrations in seawater via continuous-flow analysis, *Limnol. Oceanogr.*, 4, 358–366, 2006.
- Ridame, C., Dekaezemacker, J., Guieu, C., Bonnet, S., L'Helguen, S., and Malien, F.: Phytoplanktonic response to contrasted Saharan dust deposition events during mesocosm experiments in LNL environment, *Biogeosciences Discuss.*, 11, 753–796, doi:10.5194/bgd-11-753-2014, 2014.
- Rivkin, R. B. and Anderson, M. R.: Inorganic nutrient limitation of oceanic bacterioplankton, *Limnol. Oceanogr.*, 730–740, 1997.
- Ternon, E., Guieu, C., Loÿe-Pilot, M.-D., Leblond, N., Bosc, E., Gasser, B., Miquel, J.-C., and Martín, J.: The impact of Saharan dust on the particulate export in the water column of the North Western Mediterranean Sea, *Biogeosciences*, 7, 809–826, doi:10.5194/bg-7-809-2010, 2010.



Volpe, G., Banzon, V. F., Evans, R. H., Santoleri, R., Mariano, A. J., and Sciarra, R.: Satellite observations of the impact of dust in a low-nutrient, low chlorophyll region: Fertilization or artifact?, *Global Biogeochem. Cy.*, 23, GB3007, doi:10.1029/2008GB003216, 2009.

Williams, P. J. le B., Quay, P. D., Westberry, T. K., and Behrenfeld, M. J.: The oligotrophic ocean is autotrophic, *Annu. Rev. Mar. Sci.*, 5, 535–49, 2013.

5

## BGD

11, 1707–1738, 2014

### Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

**Table 1.** Average, standard deviation and coefficient of variation of all the measurements of  $\text{POC}_{\text{export}}$ , NPP and BR performed in both DUST-mesocosms before seedings and the CONTROL- during the DUNE experiments.

	$\text{mgCm}^{-2} \text{d}^{-1}$			$\mu\text{gCL}^{-1} \text{d}^{-1}$	
	$\text{POC}_{\text{export}}$	NPP	BR	NPP	BR
mean	4.4	57	241	4.6	19.3
standard deviation	3.6	13	163	1.1	13.0
variation coeff.	82 %	24 %	68 %	24 %	68 %

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

⏪

⏩

◀

▶

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**Table 2a.** Carbon mass budget. Data result from the integrated carbon fluxes over 7 days for DUST-Meso corrected from the integrated carbon fluxes over 7 days for the CONTROL-Meso. All data are in g C in the whole mesocosm. Budget of Organic Carbon according to Eq. (2).

Experiment	$\delta C_{\text{org}}/\delta t =$	(+)1.1·NPP	(-) 2 BR	(-) POC <sub>export</sub>	(+)At <sub>input</sub>
P	-41	1.9	-42.4	-0.48	0.128
Q	-4	0.1	-4.4	-0.05	0.128
R (1st seeding)	-17	1.8	-18.2	-0.24	0.128
R (2nd seeding)	-16	2.5	-18.8	-0.2	0.128

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**Table 2b.** Induced changes in the organic particulate pool inside the DUST-meso.

Experiment	$\delta\text{POC}/\delta t =$	+Chl <i>a</i> C term	+Zooplankton C term		+Bacteria C term	+POC <sub>dust</sub>
			meso- (2)	micro- (3)		
P	2.6	(1) 0.7	0.04	0	(4) 0.2	(5) 1.7
Q	1.6	0	0	0	0	1.6
R (1st seeding)	0.9	0.35	0	0	0	0.5
R (2nd seeding)	1.3	0.55	0	0	0	0.7

(1) From [Chl *a*] (Guieu et al., 2013) with a conversion factor  $C/\text{Chl } a = 103$  for cells  $< 2 \mu\text{m}$  and  $C/\text{Chl } a = 247$  for cells  $> 2 \mu\text{m}$  (from Perez et al., 2006 in the Atlantic subtropical gyre, an oligotrophic environment dominated by picoplankton, which is similar to the conditions during DUNE; Ridame et al., 2014). Discrimination between size cells relies on Vasco et al. (2013) who report that Chl *a* in the  $< 3 \mu\text{m}$  fraction represents 70 % of the total Chl *a*.

(2) Biovolume of mesozooplankton with size  $> 200 \mu\text{m}$  was analyzed using a zooscan system (L. Stemann, personal communication, 2013 and Service RADEZOO, OOV Villefranche-sur-Mer) from net sampling performed at the beginning of experiments outside the mesocosms and both inside and outside after the last sampling of the experiment. When significant difference was found between DUST-meso and CONTROL-meso, a ratio of biovolume to zooplankton carbon equal to  $0.03 \text{ mg C mm}^{-3}$  (Estrada, 1996) was taken to calculate the increase in zooplankton biomass.

(3) The abundance of heterotrophic nanoflagellates (HNFA) was determined at 5 m depth during the R experiment: as no significant difference between CONTROL- and DUST-meso at any of the seeding period was reported by Pulido-Villena et al. (2013), we conclude that the HNFA did not contribute to any significant change in the particulate organic carbon pool after the seeding. This conclusion was extrapolated to P and Q as no data were available for HNFA for those experiments.

(4) The abundance of heterotrophic bacteria (BA) was measured from samples collected at 0, 5 and 10 m (P, Q: Pulido-Villena, personal communication, 2013; R: Pulido-Villena et al., 2014). When a significant difference in BA was found between DUST-meso and CONTROL-meso, a factor of  $12.4 \text{ fg C cell}^{-1}$  (Fukuda et al., 1998) was applied to determine the corresponding increase in biomass.

(5) The strong correlation between lithogenic and POC fluxes found in the sediment traps of the DUST-meso over the course of all the experiments after the seeding (Bressac et al., 2014; Desboeufs et al., 2014) was used to estimate the POC fraction associated to the remaining lithogenic pool (POC<sub>dust</sub>) and still in suspension in the mesocosm at the end of the experiment (details of the calculation in Table S2).

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

⏪

⏩

◀

▶

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

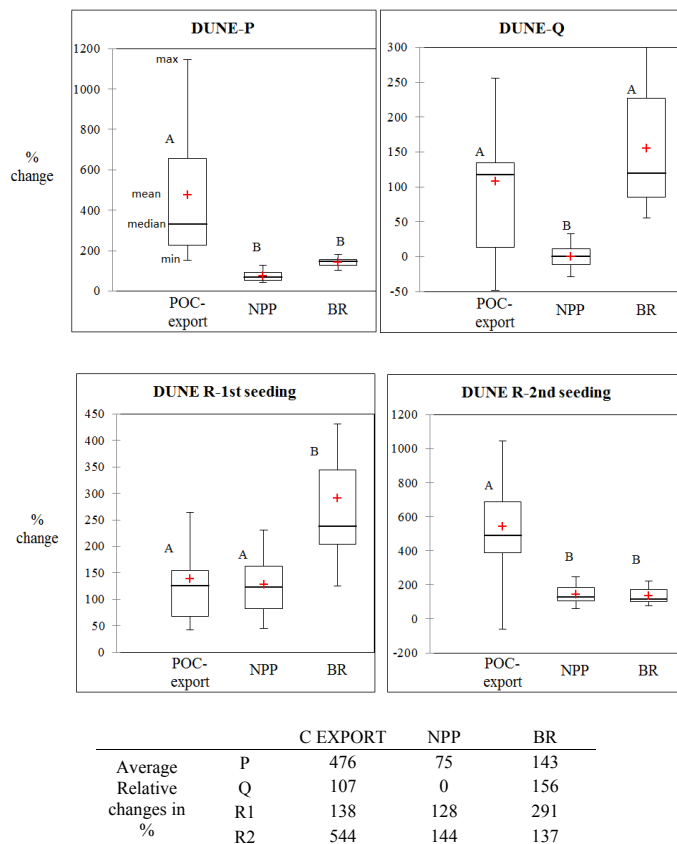


**Table 2c.** Estimation of the partitioning between dissolved and particulate carbon pool.

In g of C in the whole mesocosm	$\delta C_{\text{org}}/\delta t$	$(+)\delta \text{POC}/\delta t$	$(\delta \text{DOC}/\delta t)$
P	-41	2.6	-43
Q	-4	1.6	-6
R (1st seeding)	-17	0.9	-17
R (2nd seeding)	-16	1.3	-18

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.



**Fig. 1.** Box plots of the net fluxes expressed in Relative Change (%) and table with the average relative changes in percentage. The letters indicate the results of the statistical test in between the % change for the 3 parameters: means that were not significantly different between the different parameters ( $p > 0.05$ ) were labeled with the same letter.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

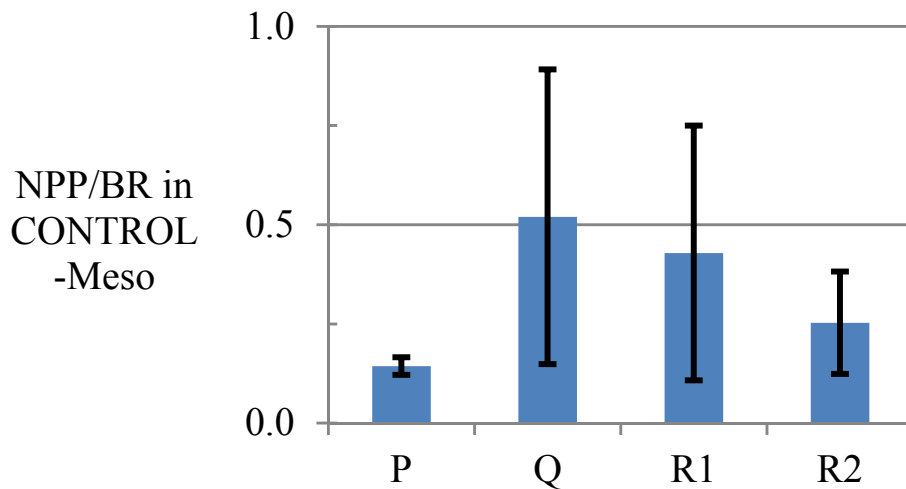
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Fig. 2.** Net primary production (NPP) to bacteria respiration ratio in the CONTROL-mesocosms averaged during the whole 7-d course of each experiment (bars indicate standard deviation).

Dust deposition in an oligotrophic marine environment

C. Guieu et al.

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

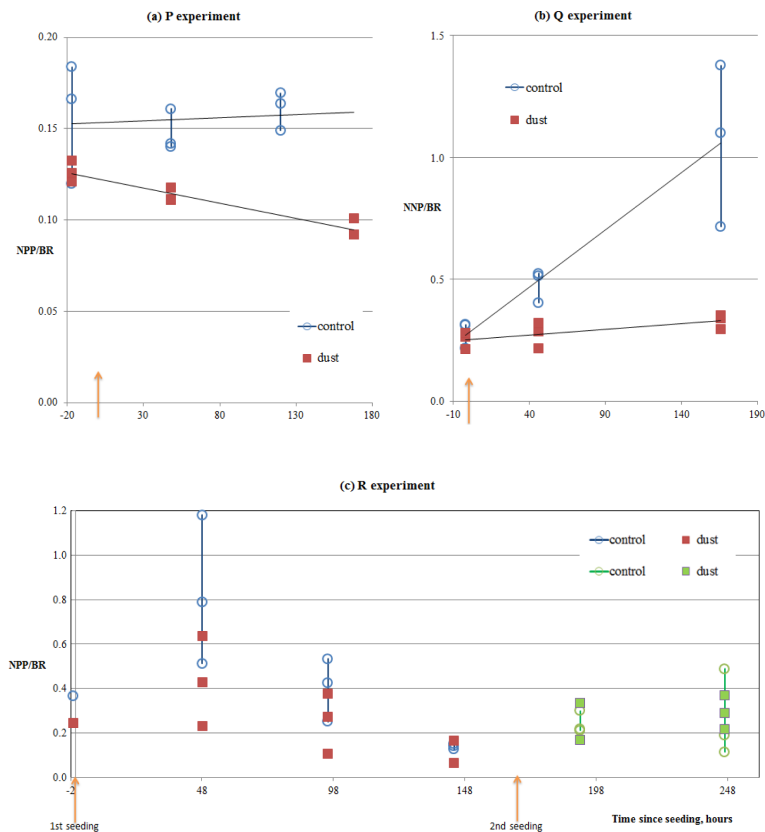
Printer-friendly Version

Interactive Discussion



Dust deposition in an oligotrophic marine environment

C. Guieu et al.



**Fig. 3.** Evolution of the ratio NPP/BR in CONTROL-meso and after seeding in DUST-Meso **(a)** during DUNE-P experiment, **(b)** during Q experiment and **(c)** during R experiment. Vertical arrows indicate seeding time (time origin for DUNE-P, -Q, and -R1, 172 h for DUNE-R2).

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



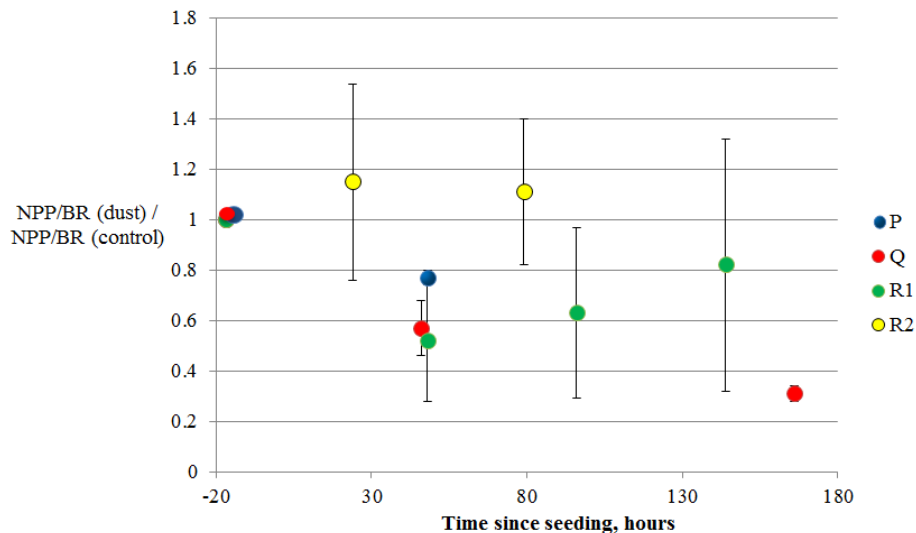


## BGD

11, 1707–1738, 2014

## Dust deposition in an oligotrophic marine environment

C. Guieu et al.



**Fig. 4.** Same ratio as in the previous figure but here the NPP/BR DUST-meso is normalized to the NPP/BR ratio in the CONTROL-Meso.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)