Progress in Oceanography 154 (2017) 1–24

Contents lists available at ScienceDirect

Progress in Oceanography

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

Can neap-spring tidal cycles modulate biogeochemical fluxes in the abyssal near-seafloor water column?

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ARTICLE INFO

Article history:
Received 11 September 2016
Received in revised form 9 March 2017
Accepted 5 April 2017
Available online 21 April 2017

Keywords:
Neap-spring tide
Sediment trap
Biogeochemical flux
Boundary layer
Abyssal ocean

ABSTRACT

Before particulate matter that settles as 'primary flux' from the interior ocean is deposited into deep-sea sediments it has to traverse the benthic boundary layer (BBL) that is likely to cover almost all parts of the seafloor in the deep seas. Fluid dynamics in the BBL differ vastly from fluid dynamics in the overlying water column and, consequently, have the potential to lead to quantitative and compositional changes between primary and depositional fluxes. Despite this potential and the likely global relevance very little is known about mechanistic and quantitative aspects of the controlling processes. Here, results are presented for a sediment-trap time-series study that was conducted on the Porcupine Abyssal Plain in the abyssal Northeast Atlantic, with traps deployed at 2, 40 and 569 m above bottom (mab). The two bottom-most traps were situated within the BBL-affected part of the water column. The time series captured 3 neap and 4 spring tides and the arrival of fresh settling material originating from a surface-ocean bloom. In the trap-collected material, total particulate matter (TPM), particulate inorganic carbon (PIC), biogenic silica (BSi), particulate organic carbon (POC), particulate nitrogen (PN), total hydrolysable amino acids (AA), hexosamines (HA) and lithogenic material (LM) were determined. The biogeochemical results are presented within the context of time series of measured currents (at 15 mab) and turbidity (at 1 mab). The main outcome is evidence for an effect of neap/spring tidal oscillations on particulate-matter dynamics in BBL-affected waters in the deep sea. Based on the frequency-decomposed current measurements and numerical modelling of BBL fluid dynamics, it is concluded that the neap/spring tidal oscillations of particulate-matter dynamics are less likely due to temporally varying total free-stream current speeds and more likely due to temporally and vertically varying turbulence intensities that result from the temporally varying interplay of different rotational flow components (residual, tidal, near-inertial) within the BBL. Using information from previously published empirical and theoretical relations between fluid and biogeochemical dynamics at the scale of individual particle aggregates, a conceptual and semi-quantitative picture of a mechanism was derived that explains how the neap/spring fluid-dynamic oscillations may translate through particle dynamics into neap/spring oscillations of biogeochemical aggregate decomposition (microbially driven organic-matter breakdown, biomineral dissolution). It is predicted that, during transitions from neap into spring tides, increased aggregation in near-seafloor waters and/or reduced deposition of aggregates at the seafloor coincides with reduced biogeochemical particulate-matter decomposition in near-seafloor waters. By contrast, during transitions from spring into neap tides, enhanced biogeochemical particulate-matter decomposition in near-seafloor waters is predicted to coincide with increased deposition of particulate matter at the seafloor. This study suggests that, in addition to current speed, the specifics and subtleties of the interplay of different rotational flow components can be an important control on how the primary flux from the interior ocean is translated into the depositional flux, with potential implications for sedimentary carbon deposition, benthic food supply and possibly even the sedimentary records of environmental change.

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http://dx.doi.org/10.1016/j.pocean.2017.04.006
0079-6611/

1. Introduction

Deep-sea sediments constitute one of the main biogeochemical compartments of the Earth system and are a net carbon sink for ocean and atmosphere (Berner, 2004; Kump et al., 2004). Moreover, they provide food supply to almost all organisms living in the seafloor (Gage and Tyler, 1991) and are a crucial recorder of environmental change. Consequently, an in-depth understanding of the processes involved in the formation of deep-sea sediments is essential.

Quantitatively important vehicles for the transport of particulate material from the surface into the deep interior ocean, and from the interior ocean into the near-seafloor waters (the 'primary flux'), are phytodetrital particle aggregates and zooplankton faecal pellets (e.g., Rowe and Staresinic, 1979; Turner, 2002, 2015). Before settling particulate material from the surface and interior ocean is finally deposited in sediments, it has to traverse the "benthic transition zone" (Honjo et al., 1982), i.e., the lower part of the oceanic water column in which the presence of the seafloor has a detectable direct or indirect influence on physical, chemical, biological and/or sedimentological aspects (Fig. 1) (Boudreau and Jørgensen, 2001). Lampitt et al. (2000) pointed out that the "role of the benthopelagic layer [which can be viewed as another term for the 'benthic transition zone'] relative to that of the sediment/water interface (SWI) and sediment mixed layer has been largely neglected". This is despite the fact that there is "no a priori reason why this layer might not be a region of high biogeochemical activity" (Rutgers van der Loeff and Boudreau, 1997). Moreover, the specifics and subtleties of boundary-layer fluid dynamics can control aspects of early diagenesis of organic matter in surface sediments ("breathing sediments": Lorke et al., 2003).

It has been argued that the potential biogeochemical importance of boundary-layer processes results from an increase of the residence time of particulate matter in the near-seafloor waters as compared to the residence time in a corresponding layer of water of the same thickness in the interior ocean. This increase leaves more time for microbially driven breakdown of organic matter and dissolution of biogenic minerals such as calcite and biogenic silica to act upon the particles before final deposition in the underlying sediments. [In this paper, the term 'biogeochemical decomposition' is used to describe microbially driven decay of organic matter, leaching and dissolution of biogenic minerals, but not physical disaggregation.] The increased residence times of the particulate matter are thought to be due to increased turbulence intensities near the seafloor (Fig. 1a) (e.g., Wimbush and Munk, 1970; Gust and Weatherly, 1985; Gross et al., 1986; Taylor and Sarkar, 2007; Sakamoto and Akitomo, 2009). This is because turbulent overturns might have a direct 'suspending' effect on the particle aggregates and/or an indirect effect through gradual breakdown of larger faster settling aggregates into smaller more slowly settling aggregates or even primary particles, thereby reducing net settling speeds. In addition, it has been argued that increased turbulence intensities might also directly affect rates of biogeochemical reactions in near-seafloor waters (Karp-Boss et al., 1996; Rutgers van der Loeff and Boudreau, 1997).

Main parts of the benthic transition zone or benthopelagic layer are illustrated in Fig. 1. The part of the near-seafloor water column where the presence of the seafloor has a detectable influence on fluid dynamics is the benthic or bottom boundary layer (BBL). The BBL typically overlaps with a near-seafloor layer in which seawater turbidity is increased; this latter layer is called benthic or bottom nepheloid layer (BNL). Maintenance of the BNL is thought to require repeated "recirculation" of particulate matter in near-seafloor waters. Some of this recirculating material will have been in transient contact with the seafloor. In this context, the term 're-suspension' is used for particles that were already deposited at the seafloor for some time and may have become part of the more consolidated surface sediment, whereas the term 'rebounding' is used for particles that were recently and transiently in contact with the seafloor but had not yet become part of the more consolidated sur-

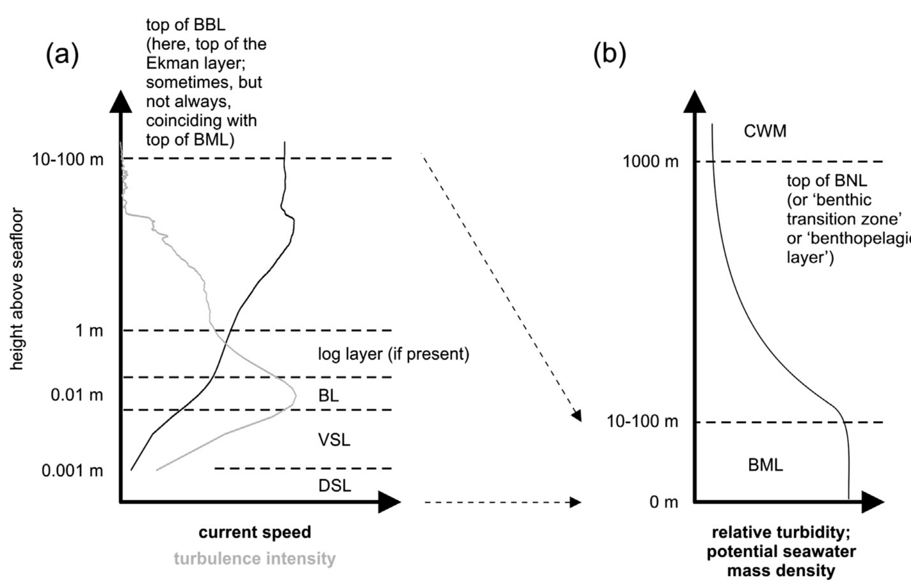

Fig. 1. Different ways of describing the vertical structure of the near-seafloor water column above a flat seafloor in the deep sea. (a) Structure of the near-seafloor water column according to the shapes of the profiles of current speed and turbulence intensity. BBL: bottom or benthic boundary layer (the part of the water column whose fluid dynamics are influenced by the ocean currents interacting with the seafloor). VSL: viscous sublayer (VSL). BL: buffer layer (transition between the log layer and the VSL). DSL: diffusive sublayer. All heights above the seafloor are only given as order-of-magnitude values. (b) Structure of the near-seafloor water column according to the vertical distribution of turbidity and/or potential mass density of seawater. CWM: clear water minimum (region within the interior ocean where turbidity reaches minimum values). BNL: bottom or benthic nepheloid layer (region above the seafloor where turbidity values are in excess of the CWM value). BML: bottom or benthic mixed layer (region above the seafloor where turbidity and mass-density values reach their maxima and where the values of these parameters are vertically largely invariable). The BNL is probably mechanistically and conceptually identical with what some researchers call the 'benthic transition zone' or 'benthopelagic layer' (mainly from a biological and/or biogeochemical perspective).