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Enhanced particle fluxes and heterotrophic bacterial activities in Gulf of Mexico bottom waters following storm-induced sediment resuspension

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ABSTRACT

Bottom nepheloid layers (BNLs) in the deep sea transport and remobilize considerable amounts of particulate matter, enhancing microbial cycling of organic matter in cold, deep water environments. We measured bacterial abundance, bacterial protein production, and activities of hydrolytic enzymes within and above a BNL that formed in the deep Mississippi Canyon, northern Gulf of Mexico, shortly after Hurricane Isaac had passed over the study area in late August 2012. The BNL was detected via beam attenuation in CTD casts over an area of at least 3.5 km^2, extending up to 200 m above the seafloor at a water depth of ~1500 m. A large fraction of the suspended matter in the BNL consisted of resuspended sediments, as indicated by high levels of lithogenic material collected in near-bottom sediment traps shortly before the start of our sampling campaign. Observations of suspended particle abundance and sizes throughout the water column, using a combined camera-CTD system (marine snow camera, MSC), revealed the presence of macroaggregates (> 1 mm in diameter) within the BNL, indicating resuspension of canyon sediments. A distinct bacterial response to enhanced particle concentrations within the BNL was evident from the observation that the highest enzymatic activities (peptidase, β-glucosidase) and protein production (^{3}H-leucine incorporation) were found within the most particle rich sections of the BNL. To investigate the effects of enhanced particle concentrations on bacterial activities in deep BNLs more directly, we conducted laboratory experiments with roller bottles filled with bottom water and amended with experimentally resuspended sediments from the study area. Macroaggregates formed within 1 day from resuspended sediments; by day 4 of the incubation bacterial cell numbers in treatments with resuspended sediments were more than twice as high as in those lacking sediment suspensions. Cell-specific enzymatic activities were also generally higher in the sediment-amended compared to the unamended treatments. The broader range and higher activities of polysaccharide hydrolases in the presence of resuspended sediments compared to the unamended water reflected enzymatic capabilities typical for benthic bacteria. Our data suggest that the formation of BNLs in the deep Gulf of Mexico can lead to transport of sedimentary organic matter into bottom waters, stimulating bacterial food web interactions. Such storm-induced resuspension may represent a possible mechanism for the redistribution of sedimented oil-fallout from the Deepwater Horizon spill in 2010.

1. Introduction

Particulate organic matter derived from the photic zone provides nutrients and energy for deep ocean microbial food webs and higher trophic levels (Aristegui et al., 2009). Major pathways for organic matter export to the deep sea include downward flux

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of marine snow and feces, as well as near-bed lateral transport of particulate matter along continental slopes (Thomsen, 1999). Particle advection above the seafloor is driven by bottom flow and seafloor topography, affecting particle and elemental fluxes on spatial scales from a few centimeters to meters above the deep seafloor (Graf and Rosenberg, 1997). Larger scale transport of particulate matter along continental slopes is triggered by gravity flow of fine-grained shelf sediment suspensions, forming deep-sea turbidity currents or by storm activity (Hollister and McCave, 1984). Hydrodynamic forces resulting from storms affecting the surface ocean propagates to the deep ocean, leading to resuspension of deep-sea sediments and formation of bottom water turbidity layers, also known as bottom nepheloid layers (BNLs; McCave, 1986).

Deep-sea BNLs can form on a seasonal basis, as seen in the deep northwestern Mediterranean Sea during winter, when particle-rich shelf waters trigger downslope turbidity currents and resuspension of slope sediments (Puig et al., 2013). Storm-induced perturbations of the surface ocean can also result in resuspension of the seabed, as periodically observed in the Eel River submarine canyon of the northern California margin (Puig et al., 2004). The Mississippi Canyon, an undersea canyon in the northern Gulf of Mexico south of Louisiana, is also frequently affected by high flow events of down-canyon turbidity currents and sediment resuspension in the aftermath of passing storms (Ross et al., 2009).

The vast majority of studies on deep ocean BNLs have focused on measuring and modeling associated hydrodynamic conditions (Fohrmann et al., 1998). Information on bacterial transformation of organic matter within BNLs are comparatively rare and limited to a few oceanic regions, despite their important role in processing and transforming organic matter associated with suspended particles near the deep seafloor (Turley, 2000). In the deep Arabian Sea, elevated heterotrophic bacterial abundance, protein production, and organic matter degradation have been reported in particle-rich bottom waters (Boetius et al., 2000). Investigations in bottom waters of the Mid-Atlantic Ridge revealed substantial bacterial activities and organic matter degradation rates associated with suspended particles (Baltar et al., 2010). Substantial bacterial biomass associated with (re-) suspended sediments was also found above continental slope sediments of the Norwegian Sea (Thomsen and Graf, 1994) and the northeastern shelf of Greenland (Ritzrau et al., 1997). Ritzrau et al. (1997) also reported high levels of bacterial activities, as indicated by elevated rates of amino acid uptake in aggregates of resuspended sediments in these high latitude systems. In shallow coastal environments, sediment resuspension enhances the upward flux of sediment-associated benthic bacteria (Stevens et al., 2005), often resulting in increased rates and activities of bacterial hydrolytic enzymes in the overlying water (Chrost and Rieman, 1994; Ritzrau and Graf, 1992; Ziervogel and Arnosti, 2009).

To investigate the effects of enhanced particle fluxes on rates and activities of deep ocean heterotrophic bacteria, we measured bacterial abundance, protein production and hydrolytic enzyme activities within a BNL that formed in the deep Mississippi Canyon shortly after Hurricane Isaac made landfall on the Louisiana coast in late August 2012. We also measured bottom water bacterial dynamics during a laboratory experiment, mimicking particle interactions and transport of resuspended sediments from the study area.

2. Material and methods

2.1. Study site

Our study site is located in the Mississippi Canyon, northern Gulf of Mexico, approximately 80 km to the southeast of the Mississippi River mouth (Fig. 1). The water column survey (CTD profiles, in situ aggregate profiles, water column samples; see Sections 2.2 and 2.3) near Oceanus site 26 (OC26; 28° 44.20'N, 88° 23.23'W; water depth: 1500 m) was conducted from September 05 2012 to September 13, 2012, onboard the R/V *Endeavor*. OC26 is located 3.5 km to the south of the sunken Deepwater Horizon (DWH) oil rig and the Macondo wellhead (Fig. 1) that exploded in April 2010, causing the largest oil spill of the offshore oil and gas industry to date (Atlas and Hazen, 2011). Our water sampling campaign at OC26 started one week after Hurricane Isaac made landfall on the Louisiana coast near the Mississippi River mouth on August 28, 2012. The slow moving hurricane produced sustained tropical force winds for up to 45 h in coastal areas and heavy rainfall. A vast amount of water was pushed westward against the southeastern shoreline of Louisiana, causing the Mississippi River to flow upstream for 24 h, with the storm surge advancing > 300 river miles (Berg, 2013).

Sediment cores for the roller bottle experiments with resuspended sediments (see Section 2.5) were collected onboard the R/V *Falkor* in November 2012 at OC26 as well as 5 km to the

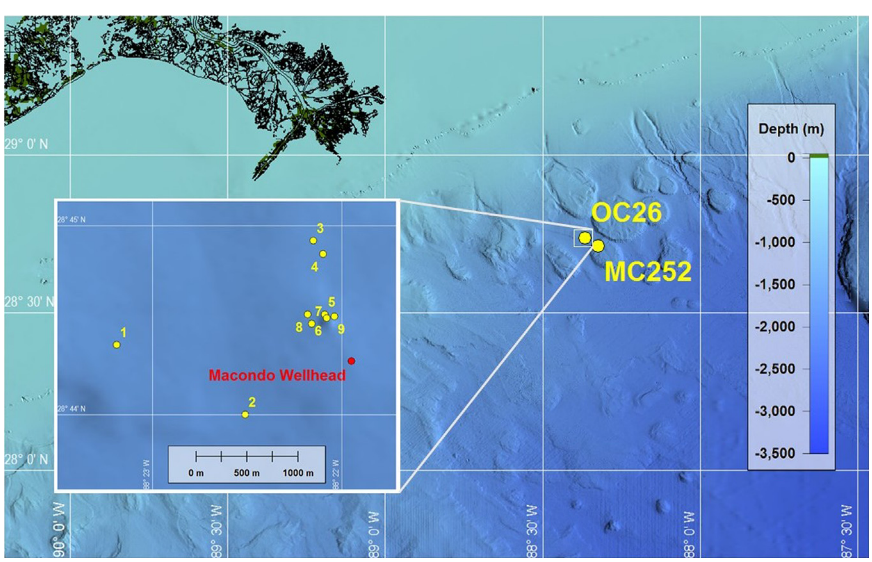

Fig. 1. Map of the sampling sites in the Oceanus Site 26 (OC26) area. Numbers in the insert correspond to cast numbers from Table 1.