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A mesocosm experiment of suspended particulate matter dynamics in nutrient- and biomass-affected waters

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ABSTRACT

An experimental study was conducted to test the hypothesis that the biomass growing after an increase in available nutrient in an aquatic ecosystem affects the flocculation dynamics of suspended particulate matter (SPM). The experiment was carried out in a settling column equipped with a turbulence generating system, a water quality monitoring system, and an automated μPIV system to acquire micro photographs of SPM. Three SPM types were tested combinatorially at five turbulence shear rates, three nutrient concentrations, and three mineral concentrations. Analyses of experimental data showed that nutrient availability together with the presence of biomass increased the SPM size by about 60% at low shear as compared to nutrient- and biomass-free conditions; a lower increase was observed at higher shears. In contrast, only 2% lower fractal (capacity) dimension and nearly invariant settling velocity were observed than in nutrient- and biomass-free conditions. Likewise, SPM size and capacity dimension were found to be insensitive to the SPM concentration. Although limited to nearly homogeneous mineral mixes (kaolinite), these experimental findings not only reject the hypothesis that SPM in natural waters can be dealt with as purely mineral systems in all instances, but also anticipate that SPM dynamics in natural waters increasingly exposed to the threat of anthropogenic nutrient discharge would lead to an increased advective flow of adsorbed chemicals and organic carbon.

1. Introduction

With increasing anthropogenic stresses posed onto natural waters (e.g., temperature rise, chemical and nutrient pollution, eutrophication, altered hydrometeorological forcing, Anderson et al., 2002; Heisler et al., 2008; Paerl and Huisman, 2009; O'neil et al., 2012), the frequency and intensity of algal blooms have been observed to increase globally in both fresh and marine waters since the past two decades (e.g., Parsons et al., 2002; Verschuren et al., 2002; Glibert and Burkholder, 2006; Heisler et al., 2008; Leliaert et al., 2009). While wide attention has been paid to understand and mitigate detrimental impacts on water quality, oxygen depletion and loss of aquatic biodiversity (e.g., Turner and Chislock, 2010; Arend et al., 2011), the effect of algal blooms in altering flocculation processes and dynamics of mineral suspended particulate matter (SPM) has been in the public and scientific interest to a lesser extent.

SPM is a micro-ecosystem that sustains multiple processes, such as, chemicals sorption (e.g., Hedges, 1977; Ongley et al., 1981), microbial colonization (e.g., Kirchman, 2002; Grossart et al., 2006) and particle–particle interactions (e.g., Wolanski et al., 1992; Maggi, 2005). One of the key aspects of fine SPM clay minerals is that they have selective sorption characteristics, with a higher affinity for polar than non-polar molecules (e.g., Ensminger and Gieseking, 1939; Hedges and Hare, 1987). An increased concentration of ionic and polar nutrients (e.g., NH_4^+, NO_3^-, glutamic acid, lysine) in natural waters could therefore lead to desorption of neutral molecules (e.g., monosaccharides, alanine) so to offset the aqueous nutrient balance and the biological processes at the mineral interface. Adsorbed nutrient creates a protected, nutrient-rich habitat that makes SPM an optimal site for microbial colonization (e.g., Kirchman, 2002; Grossart et al., 2006).

In the presence of an increased nutrient availability, a higher microbial activity may increase secretion of extracellular polymeric substances (EPS) and transparent exopolymer particles (TEP) that act as biological glue and affect particle–particle interactions (e.g., Kiorboe et al., 1990; Logan and Kilps, 1995). The microbial activity was observed to facilitate SPM flocculation with biomass-affected

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Abbreviations

β	Coefficient for l, [-]
δ	Primary particle capacity dimension, [-]
ℓ	Image resolution, [-]
γ	Characteristic rate of change in d_0, [-]
$\gamma_{1,O}$	Skewness of variable O, [-]
$\gamma_{2,O}$	Excess kurtosis of variable O, [-]
ν	Kinetic viscosity, [L^2 T^{-1}]
σ_O	Standard deviation of variable O, [L]
ε	Energy dissipation rate, [L^2 T^{-3}]
ε_{eff}	Effective energy dissipation rate, [L^2 T^{-3}]
$a(\ell)$,$b(\ell)$	Coefficients for d_0, [-]
d	Grid bar size, [L]
d_0	Capacity dimension, [-]
$\mathring{d}_P$	Optimal perimeter-based fractal dimension, [-]
$d_P(I,\ell)$	Perimeter-based fractal dimension spectrum, [-]
$f(\ell)$	Optimal intensity function, [-]
f_g	Grid frequency, [T^{-1}]
$k(\ell)$	Coefficient for d_0, [-]
l	Integral time scale, [L]
m	Coefficient for u_{rms}, [-]
n_A	Number of aggregates, [-]
n_O	Number of observations, [-]
p	Significance, [-]
t	time, [T]
u_{rms}	Root mean square velocity, [LT^{-1}]
v	Settling velocity, [LT^{-1}]
x, y	Horizontal and vertical position, [L]
$z(\ell)$	Coefficient for d_0, [-]
A	Area, [L^2]
B	Coefficient for ε, [-]
C	Coefficient for u_{rms}, [-]
C_K	Kaolinite mineral concentration, [ML^{-3}]
D	Travelled distance, [L]
F	Focus level, [-]
F_{thres}	Focus level threshold, [-]
G	Turbulence shear rate, [T^{-1}]
H	Spacing between grid elements, [L]
I	Grayscale image intensity, [-]
L	Aggregate size, [L]
L_p	Primary particle size, [L]
M	Grid mesh size, [L]
R^2	Correlation coefficient, [-]
S	Grid stroke, [L]
Z	Orthogonal distance from the grid, [L]
ANOVA	Analysis of variance
FFT	Fast Fourier Transform
NABA	Nutrient- and biomass-affected
NABF	Nutrient-affected and biomass-free
NFBF	Nutrient- and biomass-free
SPM	Suspended particle matter

SPM generally developing extensive web-like networks with larger size commonly associated with lower density and settling velocity as compared to biomass-free SPM (e.g., Paerl, 1975; Azetsu-Scott and Passow, 2004; Tan et al., 2012). EPS and TEP were found to promote not only the binding of SPM but also chemicals and contaminants (e.g., Headley et al., 1998; Bhaskar and Bhosle, 2006), thus further promoting chemical and biological processes within the SPM and, hence, increasing process interconnectedness.

Although it may be straightforward to infer that an increased stress on our natural waters could alter SPM dynamics, all processes described above are interconnected and their outcome is unlikely to be predictable to its entirety because the complexity of all possible interactions within the SPM has not yet been formulated and integrated into a theoretical or computational framework. For example, evidence exists on increased aggregation rate following algal blooming (e.g., Silver et al., 1978; Asper, 1987; Alldredge and Silver, 1988; Riebesell, 1991; Simon et al., 2002); yet, a comprehensive analysis of experimental data from a number of ecosystems has shown that the average quantities describing SPM in biomass-free and biomass-affected conditions combine in a way (nonlinear) that the resulting settling velocity is a nearly invariant quantity even when the size and fractal dimension change substantially (Maggi and Tang, 2015).

While recognizing the wideness of above aspects, this communication aims to a narrower topic and, in particular, it focuses on the response of SPM dynamics (e.g., size, settling and fractal characteristics) against increased dissolved NH_4^+ and NO_3^- concentrations, and physical conditions including turbulence shear rate and sediment concentration. The investigation was conducted in a fully controlled laboratory-based experiment by using a settling column equipped with a turbulence generating system, a water quality measuring system, and a μPIV imaging system to measure the characteristics of settling SPM. Five turbulence shear rates, three nutrient, and three mineral concentrations were tested for SPM in nutrient- and biomass-free (NFBF), nutrient-affected and biomass-free (NABF), and nutrient- and biomass-affected (NABA) conditions. The design of the experimental facility, the experimental procedures, and the results are presented in the following sections.

2. Methods

2.1. Experimental facility

To capture and preserve most, if not all, characteristics of settling SPM, a non-invasive method was adopted by using the settling column largely detailed in Tang and Maggi (2015a) and shown in Fig. 1.

The settling column, made of Perspex, consists of: a flocculation section (210 mm × 140 mm × 600 mm), which is the control volume where SPM was tested; a measuring section (210 mm × 140 mm × 270 mm); and a diaphragm between the flocculation and the measuring sections. The flocculation section is divided into a compartment equipped with a turbulence generating system (140 mm × 140 mm cross-section), and a compartment that hosts a water quality meter (70 mm × 140 mm cross-section). SPM in the flocculation section was allowed to flow into the measuring section through a 5 mm sediment sampling hole located on the diaphragm, which was kept closed by a slider and was opened with an external mechanism when measurements were to be taken.

Photographs of SPM were acquired using a digital CCD camera (Prosilica GC2450) and a high magnification lens (Navitar 12X Body Tube). The CCD camera has a size of 2448 × 2050 pixel, 8-bit grayscale depth, and a frame rate of 15 Hz at full size. The magnification lens corresponded to a field of view of 1.82 μm × 1.84 μm size. Settling SPM was illuminated by a 3.7 W, 400 lumens, Cree LED (cool white colour). Light from the LED was transported through optical fibres inserted into the measuring section and shined