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Exploring temporal trend of morphological variability of a dominant diatom in response to environmental factors in a large subtropical river

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ABSTRACT

The temporal trend of morphological variability of *Aulacoseira granulata* (Ehrenberg) Simonsen and its response to environments was studied within the downstream region of a large subtropical river, the Pearl River (China), through time-series sampling during 2009. Both wavelet analysis and redundancy analysis (RDA) were used to demonstrate not only the correlations between morphological parameters but also the correlations between morphology and environments. High coherence between morphological parameters, especially cell size, was confirmed; but the coherence, especially that between cell and filament, could easily be impacted by water turbulence which was associated with discharge, this might reflect the interaction between life cycle and size selectivity. Moreover, phase angles in wavelet figures illustrated that cell diameter was the most sensitive parameter to environmental variations, and changes in cell diameter triggered the size change in both cell and filament; thus through this way cell and filament size variations could be related.

Based on the annual variation pattern of morphological parameters, the morphology of *A. granulata* exhibited an integrated cycle; during which morphological parameters might have different responses to physicochemical factors. Water temperature was closely associated with algal occurrence rates and size values during the spring–winter period. Algal life cycle could be affected by discharge, as well as filament length by allowing for selection of chains with optimum buoyancy. The responses of algal sizes to nutrients, especially silicate, phosphate, and total nitrogen, were associated with the start and end of a life cycle. These correlations between size and nutrients were supported by both wavelet analysis and RDA. Moreover, the extremely high values at the end of the year were explained as algal recruitment from benthos.

1. Introduction

Diatoms are known as the most important group of phytoplankton assemblages in lotic river ecosystems (Reynolds, 2006). The genus *Aulacoseira* contains a group of centric diatoms with chain colonies composed of cylindrical frustules united by shortened linking spines (Tremarin et al., 2012). Population dynamics and new species records of this genus were often reported in various aquatic ecosystems (Horn et al., 2011; Hötzel and Croome, 1996; Poister et al., 2012; Usoltseva and Tsoy, 2010; Wang et al., 2009) due to its high taxonomic compositions and obvious high density. Moreover, morphological studies of this genus always generated interests because changes in cell size and hence in filament dimension were often observed and reported in natural waters (Babanazarova et al., 1996; Davey, 1987; Manoylov et al., 2009; O'Farrell et al., 2001; Poister et al., 2012; Turkia and Lepistö, 1999), and these morphological features could potentially be used as indicators when their correlations with environments were built up, as the response of morphological changes was more rapid than possible observations of changes in population dynamics (Gibson et al., 2003). In addition, the rigid silica cell wall of members of this genus permits only two main possibilities for adaptation: varying either length or diameter; thus the process of morphological changes could be observed (Jewson et al., 2010).

Aulacoseira granulata, a cosmopolitan species of this genus, has an international distribution due to its adaptive capacity and tolerance of a wide range of environmental conditions. Generally, *A. granulata* is regarded as a good indicator species to eutrophic water conditions (Kamenir et al., 2004; Lepistö et al., 2006; Nogueira, 2000), since it can easily form predominant populations and even become blooms (Miyajima et al., 1994; Nakano et al., 1996) in eutrophic waters under suitable conditions (e.g. high temperature). The author has also reported that *A. granulata* is predominant in the downstream of the Pearl River (Wang et al., 2009, 2012, 2013), which is known as a hyper-eutrophic

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river system. Except for population abundance, morphological variability of *A. granulata* was also found closely related to environmental variations, especially sensitive to nutrient concentrations (Davey, 1987; Gómez et al., 1995; Stoermer et al., 1981; Turkia and Lepistö, 1999). Relevant studies on the correlations between its morphology and environments have been carried out more in lentic water bodies such as lakes (Davey, 1987; Manoylov et al., 2009; Stoermer et al., 1981; Turkia and Lepistö, 1999) and reservoirs (Gómez et al., 1995; Reynolds et al., 1986), in which strong stratification occurred. Generally, the eutrophic status and specific nutrient availability of the studied water system explained a significant proportion of the observed morphological results (Gómez et al., 1995; O'Farrell et al., 2001; Turkia and Lepistö, 1999). In rivers, conditions are different: the lotic flows and oligotrophic status may enhance the importance of physical and hydrological factors in impacting morphological changes, especially in filament size selectivity. In such lotic systems, exploring temporal trend of morphological variability of *A. granulata*, based on frequent sampling, might help finding more elaborate and accurate correlations between this diatom species and environments.

Modern statistical methods provide different ways to analyze and explore a large and complex data set. Wavelet analysis is a multi-resolution analytical approach by which to analyze signal timescales (Yan et al., 2013). Wavelet coherency reveals dependencies between two signals and accounts for non-stationarity within ecological time series (Zhang et al., 2014). This method has now been well applied to examine time-scale specific correlations between two variables in phytoplankton (Blauw et al., 2012; Recknagel et al., 2013) and algal dynamics (Zhang et al., 2014). Redundancy analysis (RDA) is similar to canonical correlation analysis but allows users to derive a specified number of synthetic variables from one set of (independent) variables that explain as much variance as possible in another (independent) set. This innovative multivariate canonical analysis can detect the above wavelet analysis and improve the rigor for linking morphology to environmental conditions through comparing one of our quantitative response variables (morphometrics), with one or more categorical explanatory variables (environmental conditions).

The purpose of this study was to explore the temporal trend of morphological variability of *A. granulata* within the downstream region of the Pearl River based on consecutive and frequent sampling throughout a whole year. Wavelet analysis was used to demonstrate the possible coherence between the selected two variables, and RDA was used to test the validation of the one dimensional cross wavelet analysis. To this end, we aimed to demonstrate the basic annual variations of morphological size and their response to environmental factors. We also postulate that cell size, closely associated with life cycle, correlated more with nutritional factors, i.e. nitrogen and phosphate; while filament morphology, generally representing results of size selectivity, correlated more with physical factors, i.e. water temperature and discharge (Poister et al., 2012).

2. Materials and methods

2.1. Study area

The Pearl River, with a length of 2,320 km, a catchment area of 450,000 km^2, and annual discharge of 10,000 $m^3 s^{-1}$, is the third longest river in China. The river consists of three major tributaries: the West River, the North River and the East River, merging at the Pearl River Delta and ultimately flowing into the South China Sea. The West River, running through Guangdong and Guangxi province, is the largest tributary of the Pearl River. A seasonal flow regime is evident, with high flows during spring and summer, and low flows during autumn and winter.

The Zhaoqing section of the West River, with an average width of 1100 m and a peak flow of 30,000 $m^3 s^{-1}$, is the primary passage for river flow entering into the downstream river web of the Pearl River Delta. Our long term sampling site (23° 2′ 40″ N,112° 27′ 5″ E) is located in this section, near the wharf of the Zhaoqing Fishery Administration, which is about 160 km upper from the Pearl River Estuary (Fig. 1). The largest difference between the minimum and maximum water level at the site does not exceed 15 m, and the depth of sampling site ranges from 3 to 5 m. In order to understand the temporal variations of primary production and their correlation with environmental factors, we collected phytoplankton samples and undertaken environmental measurements at this fixed site in 2009.

2.2. Sampling and data collection

Qualitative subsurface phytoplankton samples were collected at 8:00 am every 5 days each month. For each qualitative sample, 9–10 L of water was collected from subsurface and passed through a 20 μm nylon mesh. The retained particles were then washed into a preweighed glass bottle using 100–200 mL of water. Aliquots of the qualitative samples were cleaned by conventional methods (Patrick and Reimer, 1966) and subsequently used to prepare permanent slides. The valve diameter and mantle height were measured for a minimum of 100 cells per sample, and the results represented cell diameter and cell length respectively. Moreover, the cell volume was calculated from diameter and mantle height by applying geometric formulae. In each sample, the number of cells per colony was recorded for a

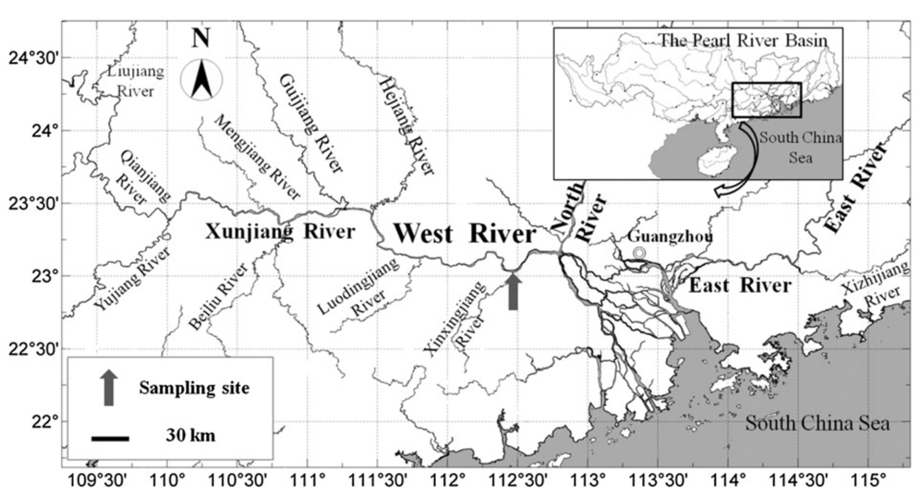

Fig. 1. The downstream river network of the Pearl River, including its location in the Pearl River Basin, river tributaries and sampling site.