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Spatio-temporal variability of phytoplankton (Chlorophyll-a) in relation to salinity, suspended sediment concentration, and light intensity in a macrotidal estuary

Gubash Azhikodan, Katsuhide Yokoyama *

Department of Civil and Environmental Engineering, Tokyo Metropolitan University, 1-1, Minami-Osawa, Hachioji, Tokyo 192-0397, Japan

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ABSTRACT

The influences of environmental gradients on the spatio-temporal variability of phytoplankton (Chlorophyll-a) in the macrotidal Chikugo River Estuary were studied during a two-week period of September 2010. Vertical profiles of salinity, turbidity, and light intensity were measured at 18 stations separated by a 1-km interval. Water samples for the determination of suspended sediment concentration (SSC), concentration of Chlorophyll-a (Chl-a) and Pheophytin-a (Pheo-a) were collected from the surface layer at all stations. The estuarine water column was vertically well mixed with high SSC (100–2000 mg L^{-1}) during spring tide and the photic depth (z_p) was less than 0.2 m. The mixing depth (z_m) was more than 10 times the photic depth for the major part of the estuary. The estuary gradually changed to partially mixed with decrease in SSC ($\leq$ 400 mg L^{-1}) during the intermediate tide. The estuary became stratified with low SSC (20–50 mg L^{-1}) during neap tide and the z_p reached 4 m. The z_m was less than 0.5 times the z_p for the whole estuary. Light attenuation was dominated by SSC and the z_p varied according to semidiurnal and semilunar tidal cycle. The z_p: z_m ratio did not show any relationship with Chl-a in the Chikugo river estuary. This is because the Chl-a concentration reached maximum two to three days after the neap tide. The peak concentration of Chl-a was located near the low salinity region and that of Pheo-a was located in the Estuarine Turbidity Maximum (ETM) zone. The Pheo-a concentration reached maximum during the spring tide. A good relation between z_p: z_m ratio and Pheo-a indicates that the increase in Pheo-a was caused by the light limitation due to suspended sediment and the responses of the Pheo-a on the light condition was instantaneous. These phenomena were remarkably found in the interface between freshwater and saltwater. Light availability driven by mixing and ETM process during semidiurnal and semilunar tidal cycle is the controlling factor of the phytoplankton dynamics in the Chikugo River Estuary.

1. Introduction

Estuaries, which form a transition zone between ocean and land, experience various environmental gradients (such as salinity, temperature, and turbidity) in spatial or temporal scales. The most important estuarine gradient is based on salinity. The spatial salinity gradient is mainly horizontal, but a vertical gradient may also exist due to the mixing of seawater and river water. Temporal salinity gradients can occur fortnightly or seasonally because of tides and changes in freshwater discharge (Uncles, 2002; Patchineelam and Kjerfve, 2004; Azhikodan and Yokoyama, 2015).

Estuarine ecosystems are highly productive and play a major role in supporting the commercial fisheries of coastal areas with varieties of fish communities that can be seen only in the estuarine environment. The abundant productions of fish and shellfish communities in estuaries are supported by the phytoplankton as a dominant primary producer (Paerl et al., 1998). Phytoplankton dynamics in estuaries are inevitably affected by these environmental gradients. Additionally, phytoplankton growth is influenced by both nutrients and light availability (Bruno et al., 1980; Pennock, 1987; Domingues et al., 2005; De Swart et al., 2009) and zooplankton can also influence the estuarine phytoplankton by grazing (Ensign et al., 2014). Hence the diversity of phytoplankton dynamics can affect the food web and other ecological functions of the estuarine ecosystem (Cloern et al., 2014; Zhu et al., 2009).

Phytoplankton production in the turbid Westerschelde Estuary, Netherlands, is driven mainly by light as compared with nutrients (Van Spaendonk et al., 1993). The Chlorophyll-a (Chl-a) concentration in the highly turbid Chikugo River Estuary did not have any relationship with nutrients (Yokoyama et al., 2011; Yokoyama et al., 2012). Furthermore, zooplankton (i.e., the copepods) in the

* Corresponding author.

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Chikugo River Estuary was mainly supported by the plant detritus (Suzuki et al., 2013). Therefore, nutrient concentration and zooplankton grazing may not be the dominant factors for primary production in a river estuary where turbidity is high due to mixing.

A well-defined zone of locally elevated suspended sediments in an estuary where the suspended sediment concentration (SSC) of the water column is higher than that observed in both seaward and landward is known as Estuarine Turbidity Maximum (ETM) zone. The ETM occurs due to erosion, mixing, and transport of bottom sediment when saltwater moves into an estuary (Azhikodan et al., 2014). This process is also a constituent of the environmental gradient and controls the growth of phytoplankton. Light for photosynthesis is limited by the SSC, especially in highly turbid estuaries (May et al., 2003). Light limitation by the suspended particulate matter in the water column strongly influenced the phytoplankton bloom in the well mixed Bahia Blanca estuary, Argentina (Guinder et al., 2009). In those turbid estuarine environments, underwater light attenuation due to turbidity can become the most important bottom-up factor controlling phytoplankton growth (Domingues et al., 2011).

As an estuary with highly turbid zone and strong mixing condition, the dominant factor is the tidal force which can vary semi diurnally, fortnightly or seasonally. Therefore, it is necessary to study the spatio-temporal dynamics of the primary producer based on the environmental factors in the area. Some studies have investigated the effects of physical dynamics such as mixing, movement of saltwater, and ETM on the state of phytoplankton in macrotidal/mesotidal estuaries (Pennock and Sharp, 1986; Muylaert et al., 2000; Gameiro et al., 2007). However, most of the studies were focused in long term with sampling conducted in a monthly basis. Studies on short term dynamics of phytoplankton with spring-neap transition in estuaries were limited.

The objective of the present study is to assess the influence of estuarine mixing and ETM process on the phytoplankton in the Chikugo River estuary where ETM developed well. The Chikugo River Estuary and offshore tidal flats are strongly affected by the intrusion of freshwater from the Chikugo River and the high tidal range (5 m) of the bay (Islam et al., 2006a; Islam and Tanaka, 2007). A few studies have been undertaken to assess the ETM and the ecosystems of the highly turbid macrotidal Chikugo River Estuary and Ariake Sea (Suzuki et al., 2008, 2009, 2012a, 2013). However, the relationships between environmental gradients and phytoplankton growth were not fully explained because the data were collected only during high water at spring tide. We investigated the spatial and temporal variation of phytoplankton (Chlorophyll-a) dynamics over a short period in the macrotidal Chikugo River Estuary based on the relationship between various environmental gradients, such as salinity, turbidity, temperature and river discharge.

2. Materials and methods

2.1. Study site

The inner part the Ariake Sea is one of the most productive estuarine systems in Japan and many harvestable communities are only found in this area (Suzuki et al., 2012a). The Chikugo River (Fig. 1), the largest river draining into the western part of the Ariake Sea, is located in the Kyushu district in southwestern Japan (Islam et al., 2006a). The total length of the river is nearly 143 km. It ranks as the 22nd largest river in Japan, with a drainage basin of 2,860 km^2, a mean discharge of 54 $m^3 s^{-1}$ (during the dry season), and a mean annual storm discharge of 2,800 $m^3 s^{-1}$ (Azhikodan et al., 2014).

The Chikugo River Estuary varies in width from 1,000 m at the estuary mouth to 250 m at 23 km upstream. The main estuarine channel has a branch at 10 km upstream, which joins the main channel at 6.8 km (Fig. 1). Another branch forms at 6.1 km and discharges into the Ariake Sea. The bottom sediments in the tidal flat consist mainly of mud, whereas the section between the estuary mouth and 10 km consists mainly of fine sand. The section between 10 km and 20 km consists mainly of silt and clay, and the region upstream of 20 km consists mainly of sand. The estuary experiences semidiurnal tidal conditions with a tidal amplitude of 5 m at spring tide and 1.5 m at neap tide. In terms of tidal range, the estuary is classified as a mesotidal/macrotidal estuary (Davies, 1964). The tidal currents in the estuary increase by more than 1 $m s^{-1}$ during spring tide. The considerable tidal influence in the Chikugo River reaches up to the barrage, which is located 23 km upstream from the estuary mouth (Suzuki et al., 2009). The dominant phytoplankton species (60–90% of the total cell) in the Chikugo River Estuary was Skeletonema costatum (Ikenoya, 2011).

2.2. In situ observation

A field survey was conducted in the Chikugo River Estuary from September 11 to September 25, 2010. Vertical profiles of salinity and turbidity were measured in the mid channel at 1 km intervals from the estuary mouth (0 km) to 17 km upstream at a total of 18 measurement stations using a conductivity, temperature, depth (CTD) probe with an optical backscatter sensor (AAQ-1183, JFE Advantech, Japan). Vertical profiles of photo-synthetically active radiation (PAR) intensity were measured using ultra-miniature light intensity recorder (MDS-Mk *V*/L, JFE Advantech, Japan) in synchrony with the acquisition of CTD data. The vertical profiles of these parameters were recorded at depth intervals of 0.1 m.

A high-speed boat equipped with a differential global positioning system (DGPS) was used to undertake the field survey. Data were collected at each station within a period of 2 min, and the travel time between stations was an additional 2 min at a boat speed of approximately 25 $km h^{-1}$. This allowed data collection with one boat for all 18 stations within 75 min. An additional 45 min were used for the return trip from the last station to the starting point; thus, each sampling period could completed in 2 h, and it was possible to complete seven sampling cruise within the semidiurnal tidal cycle for spring and neap tides. Water samples for the determination of SSC and Chlorophyll pigments (chlorophyll-a and pheophytin-a) were collected from the surface layer at all 18 measurement stations. For intermediate tides, measurements were taken three times, during low tide, flood tide, and high tide.

Water level data were collected in every 10 min at 14.6 km using a HOBO U20 water level logger with a resolution of 2.1 mm (Onset, USA). A gauge station was located in the freshwater region (25 km from the estuary mouth), which is just upstream of the Chikugo River barrage. River discharge monitored at the gauge station and rainfall data of the area were collected from the Japanese Ministry of Land, Infrastructure, Transport and Tourism. Daily solar radiation and mean wind speed were collected from the Japan Meteorological Agency.

2.3. Lab analysis

Chl-a concentrations were used as an indicator of phytoplankton in coastal areas and estuaries (Madhu et al., 2006; Jendyk et al., 2014). Water samples for sediment and Chlorophyll analyses were filtered through a glass-fiber filter with a pore size of 0.7 μm and then sent to the laboratory. The dry weight of the sediment in the water sample was measured and SSC was determined gravimetrically. SSC was plotted against the in situ turbidity value (TB)