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Effects of resuspended sediments on the environmental changes in the inner part of Ariake Bay, Japan

Katsuhisa TANAKA [*1] and Masashi KODAMA [*2]

Abstract: Turbidity, *in situ* fluorescence of phytoplankton pigments and dissolved oxygen concentration were monitored and their relationships to tidal variations investigated in the inner part of Ariake Bay. Turbidity during spring tides showed large short-term variations due to the tidal resuspension of bottom sediments. The phytoplankton biomass increased from neap tides to before spring tides, because of the higher nutrient availability in the surface low salinity water caused by the stratification and the higher transparency due to the low turbidity. While during the spring tides, the increase of phytoplankton biomass was restricted by the low light availability due to the turbid water caused by the resuspended sediments, strong mixing with offshore water and possibly flocculation of phytoplankton with the resuspended sediments. During the neap tides in summer, large scale hypoxia was also observed in the offshore area of tidal flats, where resuspended sediments accumulate on the surface sediments. These observations indicate that the recent reduction of tidal currents is one of the contributing factors to the decrease of resuspension of the bottom sediments and increase in hypoxic areas within the bay.

Key words: Ariake Bay, resuspended sediments, phytoplankton, turbidity, tidal flats, hypoxia

Introduction

Ariake Bay (1,700km^2), located in the western part of Kyushu Island, is a shallow semi-enclosed estuary with maximum tidal range over 5 m in the inner part. The strong tidal current and large tidal flats areas are produced by the large tidal range. Bottom sediments are resuspended by the strong tidal current and high turbidity zone (up to 4,000 mg·L^{-1}) is formed around the tidal flats (Shirota and Kondo, 1985). Dynamics of resuspended sediments strongly influences on phytoplankton productivity through light availability (Cloern, 1987). Besides, mutual flocculation of phytoplankton and resuspended sediments leads to the removal of phytoplankton from the water columns (Avnimelech *et al.*, 1982), by which large scale red tide was scarce in Ariake Bay (Shirota and Kondo, 1985).

However, red tides are frequently observed in recent years, especially in the winter season of 2000 to 2001 when the extensive bloom of diatom seriously damaged Nori (*Porphyra*; Rhodophyta) farming production (Watanabe *et al.*, 2004). In Ariake Bay, increase of transparency from 1980s is reported, which seems to be caused by the reduction of bottom sediments resuspension (Tanaka *et al.*, 2004). From 1980s, the gradual reduction of tidal amplitude and mean sea level rising are also pointed out (Takigawa and Tabuchi, 2002; Unoki, 2003), which was attributed to the topographic changes due to the reclamation projects and the effects of decrease of tidal amplitude in the outer sea. Those may reduce the bottom sediments resuspension. Moreover, hypoxia is formed in the bottom water in the inner part of the bay from summer to fall and the concentration of dissolved oxygen falls drastically especially during neap tides (Tanaka and

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[*1] Seikai National Fisheries Research Institute, Fisheries Research Agency, Taira-machi, Nagasaki, 851-2213, Japan
[*2] National Research Institute of Fisheries Science, Fisheries Research Agency, Yokohama, Kanagawa, 236-8648, Japan

Kodama, 2004).

In this paper, the results of continuous monitoring of turbidity, *in situ* chlorophyll fluorescence and dissolved oxygen in the inner part of Ariake Bay during the Nori farming season of 2002 to 2003 (Tanaka *et al.*, 2004) and summer 2003 (Tanaka and Kodama, 2004) were summarized and their relationships to tidal variations were discussed.

Materials and Methods

Data were collected using the towers constructed for observation of temperature and salinity for Nori farming (Fig. 1: T1-T4).

Light penetration was measured with an under water quantum sensor (ALEC MDS-MkV/L) at T4 (Fig. 1) in the north-eastern part of inner Ariake Bay (Chikugo River Estuary) on 25 Nov. 2003. At the station, measurements were taken every 10 min. at 0, 0.5, 1.0, and 1.5m depths to obtain data to calculate the attenuation coefficient (k). At the same time, turbidity was measured with a sensor (ALEC COMPACT CL/W) calibrated with suspended sediments concentration (SS: mg・L^{-1}).

Continuous monitoring of turbidity, *in situ* chlorophyll fluorescence, salinity and temperature at 1m depth were carried out from 20 Sept. 2002 to 10 April 2003 at T4 located in the middle of the Nori farming ground in the Chikugo River Estuary (Fig. 1). Continuous monitoring of turbidity and dissolved oxygen in bottom water (0.5m above the bottom) in the inner part of Ariake Bay were made at 4 stations (T1-T4) from 9 July to 3 Sept. 2003.

Turbidity, *in situ* chlorophyll fluorescence and dissolved oxygen concentration (DO) were measured with Chlorophyll/Turbidity sensors (ALEC COMPACT CL/W) and DO sensors (ALEC COMPACT DO/W). They were set 1m depth using buoys or 0.5m above the bottom by attaching to the towers. Time series data were collected at 10 min intervals. Salinity and temperature data were collected by using a telemetry system and time series data of 1-hour intervals were obtained. Maintenance of instruments was carried out once or twice a month to clean up attached organisms on the instruments together with water sampling for

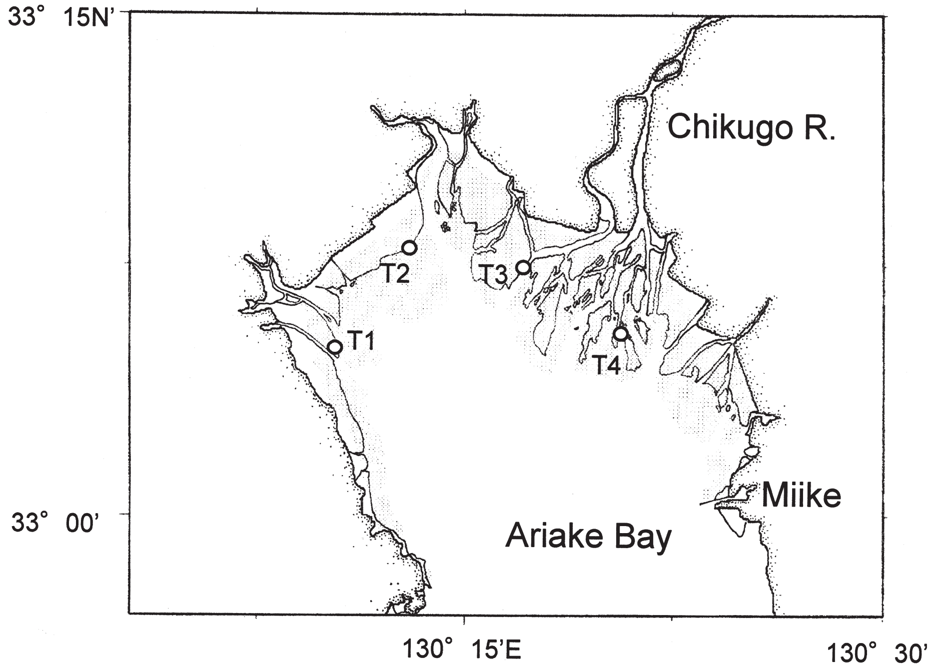

Fig. 1. Distribution of tidal flats areas and environmental monitoring towers for Nori farming in the inner Ariake Bay (T1-T4). Each station is located in the middle of the Nori farming grounds and outer edges of tidal flats.

calibration.

Water samples for calibration of instruments were filtered with Whattman GF/F filters and concentration of suspended sediments (SS) and chlorophyll pigments (chlorophyll a+ phaeo-pigments) were determined. Relationships between SS and turbidity(NTU), and between chlorophyll pigments and in situ fluorescence were both linearly related as follows. [SS = 2.16 × NTU + 2.74, r = 0.99, n = 62], [Chl. a + phaeo. = 2.99 × (fluorescence) + 1.97, r = 0.92, n = 62]. These relationship curves were used to convert turbidity and fluorescence data to SS ($mg \cdot L^{-1}$) and chlorophyll pigments ($\mu g \cdot L^{-1}$), respectively.

Results and Discussion

Light limitation by the resuspended sediments

Fig. 2 shows linear regression of Light extinction coefficient against SS measured at T4. We obtained strong correlation (k = 0.062 × SS + 0.28 r = 0.98), which imply that light attenuation is primarily a function of suspended sediment concentration. Using this equation, we calculated the compensation depth (depth of 1% surface irradiance) from SS, assuming the vertically uniform SS distribution, which was commonly observed in the shallow well-mixed type estuary, such as the Chikugo River Estuary (Shirota and Tanaka, 1981). Fig. 3 shows variations in the tidal level at Miike (A), daily mean salinity and water temperature (B), in situ chlorophyll fluorescence (C), SS (D), daily average compensation depth (E), and chlorophyll pigments at high water (F) at T4(1m). The data of chlorophyll fluorescence and turbidity from 18 Oct. to 2 Dec. 2002 could not be obtained by the instrument trouble.

SS was higher during spring tides and lower during neap tides (Fig. 3(D)). During spring tides, higher SS was observed at low water while lower SS was observed at high water. These results indicate high turbidity water formed by the resuspension of bottom sediments in the upper reaches of the estuary was tidally transported to the offshore area of the tidal flats. In this manner, SS exhibited semi-diurnal variations during spring tides, however it was not clear during neap tides. During spring tides, variations of *in situ* chlorophyll fluorescence exhibited similar pattern to SS, due to the tidal resuspension of bottom sediments which contained large amounts of chlorophyll pigments (Tanaka *et al.*, 1982). Over 100mg・L^{-1} of SS was commonly

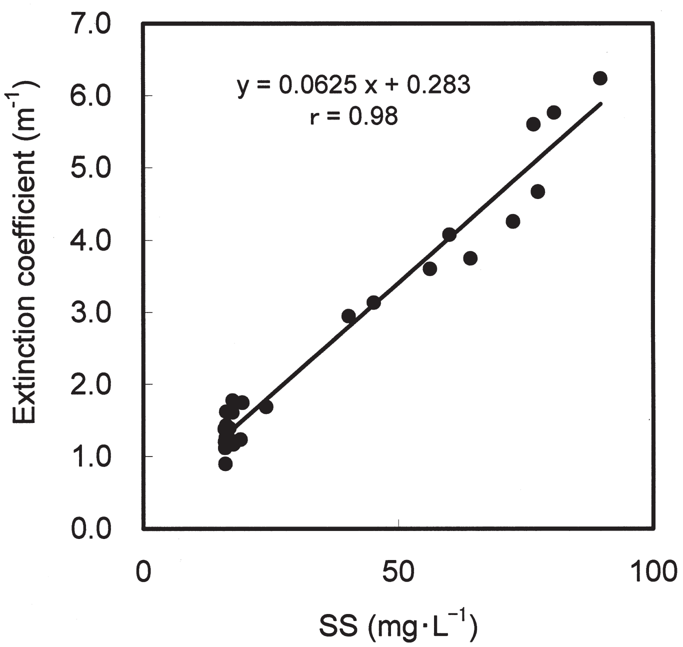

Fig. 2. Linear regression of extinction coefficient (k) against SS concentration, for measurements made at T4 on Nov. 25, 2003.

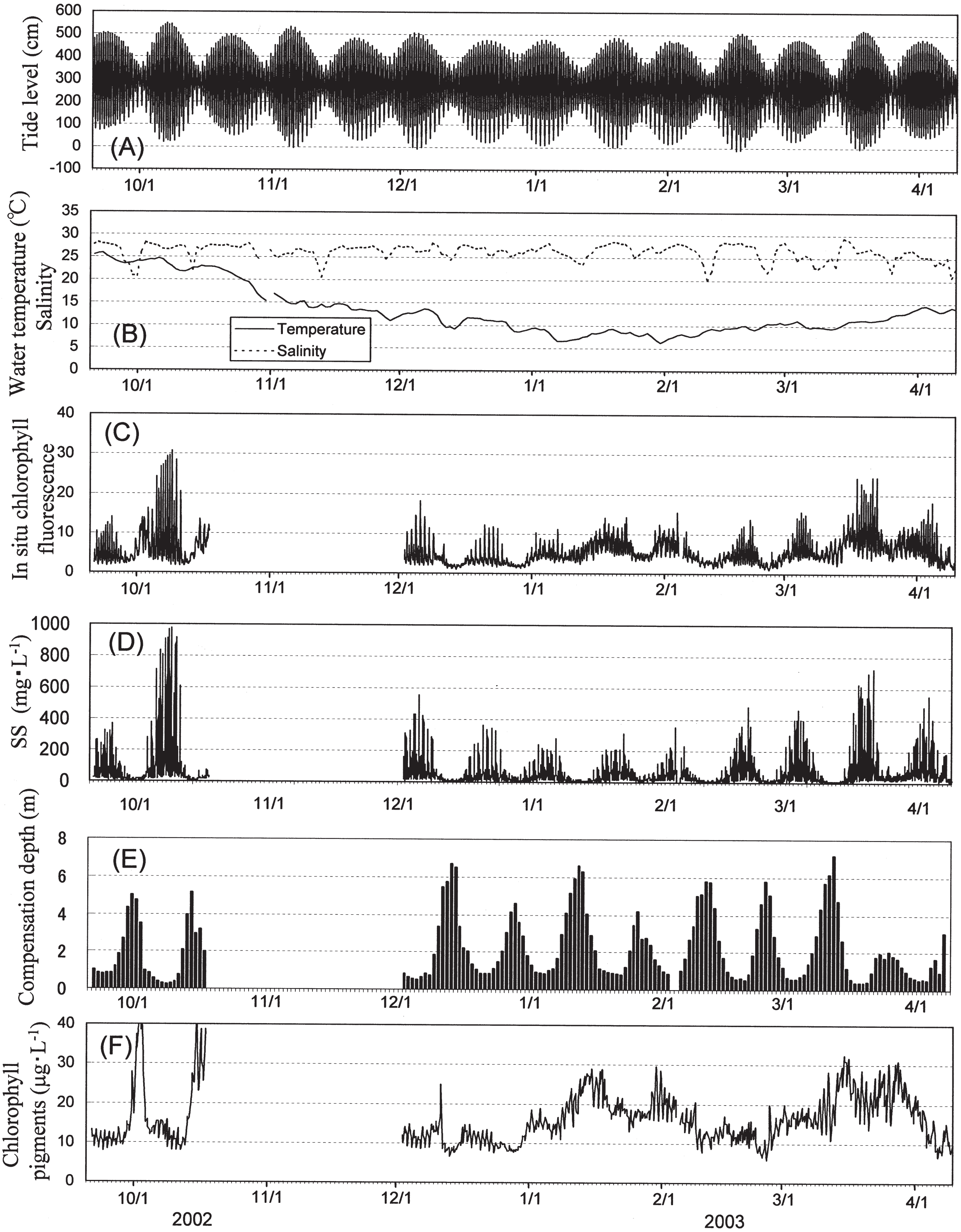

Fig. 3. Variations in tidal level at Miike (A), daily mean salinity and temperature (B), *in situ* fluorescence (C), SS (D), daily average compensation depth (E) and chlorophyll pigments at high water (F) at T4 (1m). SS, chlorophyll pigments and compensation depth were estimated from turbidity and *in situ* fluorescence.

observed in the inner Ariake Bay during spring tide which is equivalent to compensation depth lower than 0.7m. On the other hand, compensation depth was higher during neap tides, and occasionally reached to 6 m during the high season of Nori farming (late October to March).

As variations of in situ chlorophyll fluorescence include the influence of chlorophyll pigments in the resuspended sediments, especially at low water during spring tides, it is difficult to identify variation of phytoplankton biomass itself from Fig. 3(C). Therefore, in order to minimize the influence of chlorophyll pigments in the resuspended sediments, chlorophyll pigments data only at high water were plotted in Fig. 3(F). Phytoplankton biomass increased from neap tides to before spring tides, and decreased or stable during spring tides. During neap tides, lower salinity was observed (Fig. 3 (B)). These results indicate that the phytoplankton biomass increase from neap to before spring tides was caused by the higher nutrient availability in the surface low salinity water by the stratification and higher light availability with low turbidity. Significant increase of chlorophyll pigments (up to $30\mu g \cdot L^{-1}$) were observed in the middle of January and March, when compensation depth reached to 6m. Blooms of diatom species (*Skeletonema costatum*, *Chaetoceros* spp., *Thalassiosira* spp. in Jan., *Rhizosolenia setigera* in Mar., respectively) were recorded in those periods. While, during spring tides, phytoplankton bloom may be suppressed by low light availability with turbid water, strong mixing with offshore water and possibly mutual flocculation of phytoplankton together with resuspended sediments (Avnimelech *et al*., 1982).

During high season of Nori farming (from middle of December to March), SS was lower compared with other periods (from October to November and from end of March). Fig. 4 shows the relationship between tidal range at Miike and daily average SS at T4. Daily average SS increases exponentially with the tidal range, however, increasing rate during high season of Nori farming was lower in comparison with other periods. These results suggest that tidal current was reduced and resuspension of sediments was suppressed by the Nori farming gears.

The gradual reduction of tidal amplitude in recent years is reported to approximately 4% (Takigawa and Tabuchi, 2002; Unoki, 2003), which is equivalent to the SS decrease of 11% on average and 17% on maximum, using the equations of Fig. 4. These observations indicate that the recent reduction of tidal currents is one of the contributing factors to the decrease of resuspension of the bottom sediments. Therefore, the resuspended sediment is considered to have key roles linking currents and phytoplankton production through light availability.

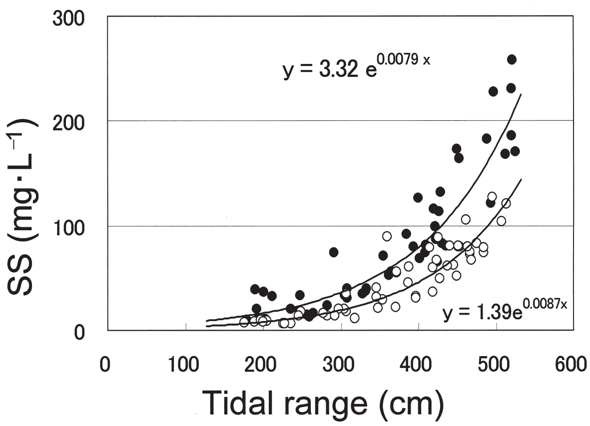

Fig. 4. Relationship between tidal range at Miike and daily average SS at T4.
○ : during high season of the Nori farming,
● : before and after the season of the Nori farming.

Hypoxia and resuspended sediments

Fig. 5 shows variations in the tidal level at T3, DO and SS at T1-T4 in the bottom water (0.5m above the bottom) during summer (9, July-3 Sept., 2003). The data of 6-10, Aug. and DO data at T4 (25, July-10, Aug.) could not be obtained by the instrument trouble or typhoon. At all stations, the high SS concentrations in spring tides decreased to below $10mg \cdot L^{-1}$ during neap tide. As the SS concentrations decreased during the neap tides, DO also decreased. At the north-western part of inner Ariake Bay, T1 and T2, DO decreased drastically to almost $0mg \cdot L^{-1}$ in late August. Mutual flocculation of phytoplankton and resuspended sediments leads to the removal of phytoplankton cells from the water column and their accumulation at the bottom (Avnimelech *et al*., 1982). The coincidence of drastic decrease of DO and SS during the neap tides indicates that the rapid decomposition

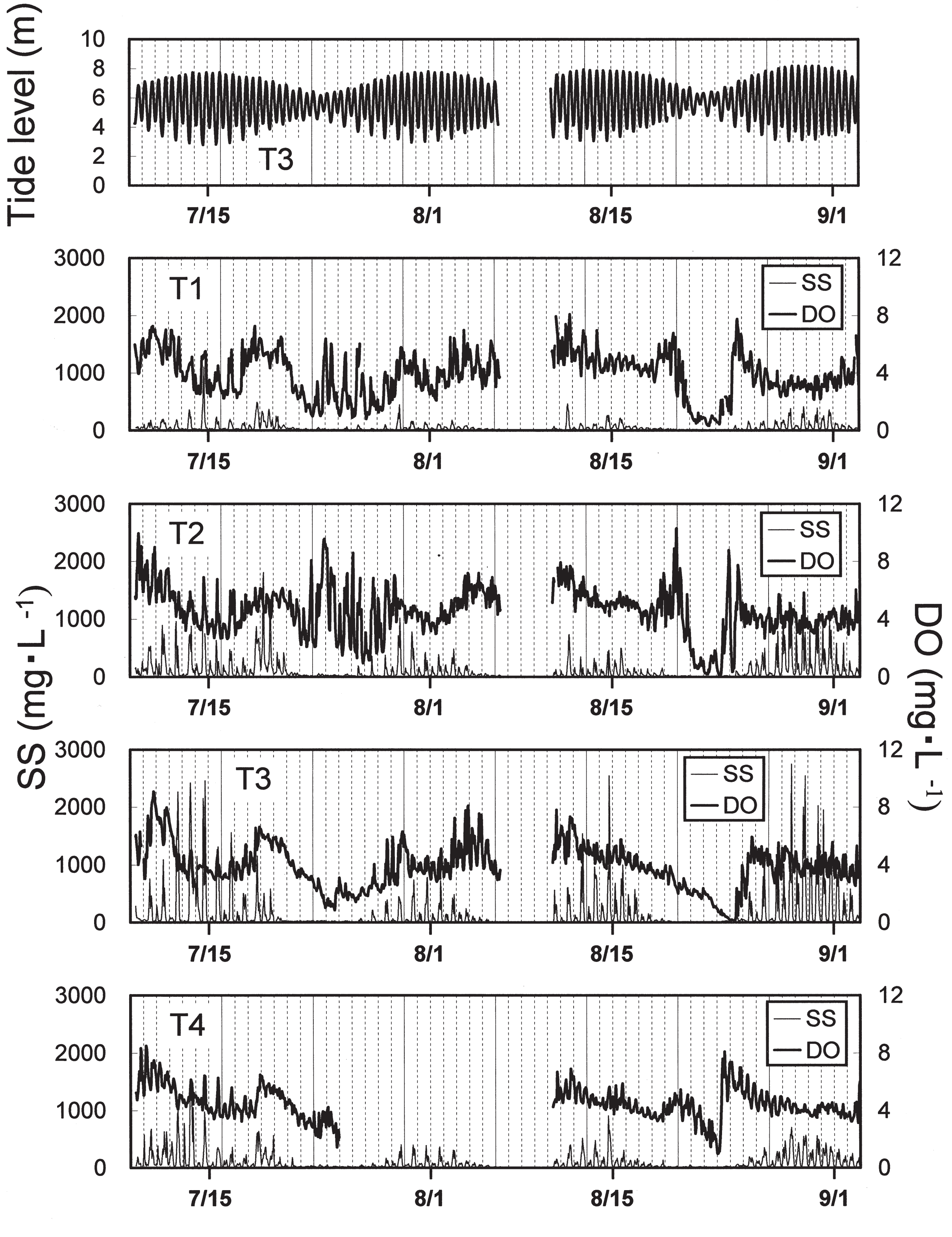

Fig. 5. Variations in SS, DO (B-0.5m) at T1-T4 and tide level at T3 during summer 2003.

of phytoplankton cells is taking place after the sedimentation.

Conclusion

The phytoplankton biomass increase from neap to before spring tides was caused by the higher nutrient availability in the surface low salinity water by the stratification and the higher transparency with low turbidity. While, during the spring tides, the increase of phytoplankton biomass was restricted by the low light availability with turbid water by the resuspended sediments, strong mixing with offshore water and possibly mutual flocculation of phytoplankton with resuspended sediments. In the Inner Part of Ariake Bay, tidal currents have become slower resulted from gradual reduction of tidal range and mean sea level rising, which weakened resuspension of bottom sediments and increased transparency and light availability for phytoplankton. Red tide phytoplankton cells and resuspended sediments accumulate on the bottom by the mutual flocculation during neap tides. Therefore, the drastic decrease of DO during the neap tides indicates the rapid decomposition of phytoplankton cells is taking place after the sedimentation. These observations indicate that reduction of tidal currents is one of the contributing factors to the changes of ecosystem in Ariake Bay, such as the frequent occurrence of red tide and hypoxia.

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