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Thin–layer Bloom of Diatoms Around the Mouth of the Arakawa River in Tokyo Bay

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A thin–layer diatom bloom was examined during four surveys in July and August 2005 around the mouth of the Arakawa River, Japan. During two surveys, a thin layer of concentrated chlorophyll a (thickness 1–3 m), was found under a layer of salinity 10–15 over 5 km offshore. The dominant taxa in the thin layer were *Skeletonema costatum, Thalassiosira binata*, and Cryptomonadales. When the thin layer was found, an estuarine circulation pattern occurred around the mouth of the river. The direction of flow was seaward in the upper layer and landward in the lower layer. The seaward flux of chlorophyll a in the upper layer was nearly the same as the landward flux of chlorophyll a in the lower layer. In addition, a surface layer was found over 5 km offshore. The surface layer (first upper layer) was formed above the halocline, which was at about 0.5–m depth. In the first upper layer, salinity was low, chlorophyll a concentration was low, and nutrient concentrations were high. Therefore, the thin layer of concentrated chlorophyll a was formed and maintained by phytoplankton remaining around the mouth of the river in response to the estuarine circulation pattern and the supply of nutrients from the first upper layer.

INTRODUCTION

In recent years, we have investigated the restoration of ecological systems at the mouths of rivers in urban areas. In their original states, river mouths have characteristics that provide unique habitats for plants and animals. The health of these biological systems may have widespread and significant impacts beyond the river mouth, for instance, extending to adjoining bays. Water pollution and habitat degradation in urban areas can have negative effects on the environments of river mouths. One characteristic of river mouths in urban areas is exceedingly rich nutrient flows, which frequently cause eutrophic conditions that lead to phytoplankton blooms. The phytoplankton blooms settle and accumulate on the river floor around the mouth, causing sludge and anoxic water conditions in the bottom layer, resulting in habitat loss for the plants and animals at the river mouth.

In this study, we examined the Arakawa River, which flows into Tokyo Bay. Approximately 25 million people live in the bay catchment area, and the river catchment area has a population of about 9.2 million. Although 98% of domestic waste is treated, the nutrient load is still high because of the large population. Our estimation indicated that the nutrient load into Tokyo Bay (represented by chemical oxygen demand) was 23×10^{4} kg d^{-1} in 2000, and about 30% of this nutrient load flows into the bay via the Arakawa River.

Diatom blooms often occur at the mouth of the Arakawa River. A thin layer (~1 m) of highly concentrated chlorophyll *a* (*Skeletonema costatum*), extending about 10 km along the axis of the river, has been reported to occur at the 1– to 2–m depth layer around the mouth of the river (Okada and Nakayama, 2004). A thin layer of highly concentrated chlorophyll *a* that is not at the surface may be overlooked, resulting in underestimation of the primary production at the river mouth. Many studies have investigated phytoplankton, chlorophyll *a*, and primary production at river mouths. Some have focused on the differences between rainy and dry seasons (Fisher *et al*., 1988; Muylaert and Raine, 1990; Legovic *et al*., 1994; Eyre and Twigg, 1997; Sin *et al*., 1999), and others have focused on the plane distribution of chlorophyll *a* (Lohrenz *et al*., 1990; Turner *et al*., 1990; Schuchardt and Schirmer, 1991; De Seve, 1993; Robertson *et al*., 1993; Ayukai and Wolanski, 1997). However, none of these studies have examined the mechanisms underlying the presence of a thin layer of highly concentrated chlorophyll *a* around river mouths.

Studies of harmful blooms of dinoflagellates, however, have revealed such thin layers of highly concentrated chlorophyll *a* and cell density in coastal waters and estuaries (Delmas, 1933; Honjo *et al*., 1990; Figueiras and Rios, 1993; Moita, 1993). For example, a thin layer (10–20 m) of highly concentrated chlorophyll *a* (*Gymnodinium catenatum*) occurred in the 20– to 50–m depth layer in the Ria de Vigo (Figueiras *et al*., 1995). Upwelling of nutrient–rich water from the lower layer and the existence of a pycnocline played important roles in the formation of the thin layer. The upwelling nutrient–rich water flowed landward along the bottom. Then, after it reached the pycnocline, the upwelling water flowed offshore along the pycnocline. If the pycnocline existed within a eutrophic zone, the thin layer of highly concentrated chlorophyll *a* was found along the pycnocline.

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These studies suggest that circulation patterns and the existence of a pycnocline also may play important roles in the formation of a thin layer in a river mouth. Small and Prahl (2004) likened the circulation in a river mouth to a conveyor belt and indicated a relationship between the circulation of particulate organic carbon and phytoplankton populations. By accounting for circulation patterns and a pycnocline, we investigated the process of formation of, and the support system for, the thin layer of diatoms around the mouth of the Arakawa River.

MATERIALS AND METHODS

The study site was the mouth of the Arakawa River (35°35'N, 139°50'E), which flows into Tokyo Bay (Fig. 1). Its hydrological catchment area covers about 2940 km^2. A dam is located 35 km upstream from the river mouth to provide water for Tokyo residents and to prevent seawater intrusion upstream. The tidal motion reaches the dam, and the riverbed is nearly flat (zero slope) over this 35–km stretch. The average downstream flow rate at the dam is 50 m^3 s^{-1}. As the river enters the bay, the river mouth is 1 km wide and 5 m deep.

In 2005, four surveys were conducted: 20 July (survey 1), 29 July (survey 2), 5 August (survey 3), and 15 August (survey 4). These days were chosen to provide a wide range of global solar radiation and tidal flow.

A combination of moving shipboard and anchored shipboard sampling was used for spatial and temporal resolution of salinity and chlorophyll *a*. During each survey, 10 moving shipboard samples were gathered along a transect following the river axis from 5 km upstream from the river mouth (station 10) to 5 km offshore (station 1) to the south (Fig. 1). Stations were 1 km apart. The anchored sampling was conducted at 1 km offshore (station 5) after the shipboard sample was collected.

For the moving shipboard sampling, at each station an Alec Electronics Co., Ltd. (Kobe, Japan) Chlorotech (ACL1183–PDK), which measures conductivity, temperature, chlorophyll *a*, turbidity, dissolved oxygen, and depth, was lowered from the surface to the bottom. It sampled data at depth intervals of 10 cm. For the anchored shipboard sampling at station 5, an Alec Electronics Co., Ltd. TurboMAP turbulence ocean microstructure acquisition profiler, which measures DU/Dz (U: velocity), conductivity, temperature, chlorophyll *a*, turbidity, and depth, was floated from the bottom to the surface. The TurboMAP sampling was carried out 10 times per hour, and data were sampled at depth intervals of about 1 mm (sampled rate: 512 Hz; floating speed: ~50 cm s^{-1}). TurboMAP was originally developed to measure dissipation rate, so it can measure hydrographic conditions without disturbing the halocline and the thin layer of chlorophyll *a*.

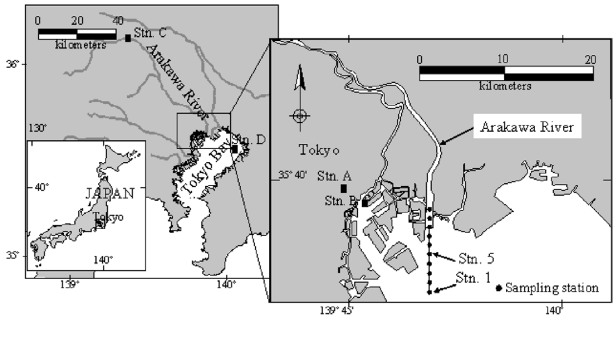


Fig. 1. Location of the Arakawa River, Japan, and sampling stations around the mouth of the river.

Velocity was measured using a WorkHorse acoustic Doppler current profiler (1200 kHz; Teledyne RD Instruments (CA, USA) from stations 1 to 8 for the moving shipboard sampling during survey 4 and at station 5 for the anchored shipboard sampling during all surveys. The instrument sampled data at depth intervals of 20 cm at stations 1 to 4 and intervals of 10 cm at stations 5 to 8. For the anchored shipboard sampling, data was collected once every 5 min.

Water column samples were taken using a hose–pumping system with a depth sensor. The sensor transmitted depth information to the ship, enabling us to accurately position the hose in the water column during sampling. During each survey, water samples were collected from 8 or 9 layers. We decided which layers to sample and time of day on the basis of the chlorophyll *a* concentration and halocline conditions that were measured using TurboMAP.

Pumped samples from each layer were immediately mixed well and then aliquotted for biological or chemical analyses. Samples for chlorophyll *a*, salinity, and nutrient analyses were preserved in a cooler, and phytoplankton samples for species counts were preserved in a formalin solution (5%). Analyses of all samples were performed in the onshore laboratory.

Samples for chlorophyll *a* analyses were filtered using 47–mm GF/F filters and determined following the fluorometric analysis method of Parsons and Strickland (1963) and Jeffrey and Humphrey (1975). Samples for nutrient measurement (NO_2^-, NO_3^-, NH_4^+ and PO_4^{2-}) were filtered in–line through a Gelman Sciences Japan Ltd., (Japan) 10–mm polypropylene membrane and analyzed using a Technicon autoanalyzer. A quantitative estimation of in situ chlorophyll *a* was performed by computing the relationship between in situ fluorescence and laboratory chlorophyll *a* values. The calculated relationship was applied to all fluorometric data.

Wind speed and direction, precipitation, and solar radiation were monitored hourly at station A (Fig. 1), which is maintained by the Japan Meteorological Agency. Water level of Tokyo Bay was monitored hourly at station B (Fig. 1), which is maintained by the Japan Coastal Guard. Water level of the Arakawa River was monitored hourly at station C (Fig. 1, left), which is maintained by the Ministry of Land, Infrastructure, and Transport.

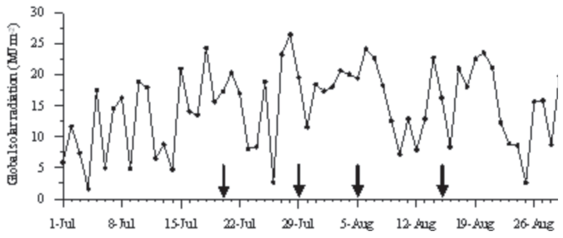
RESULTS

General conditions

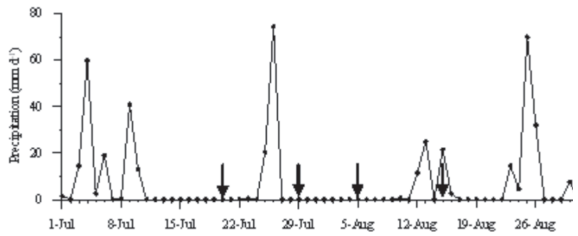
Global solar radiation during July and August 2004 was cyclical, and the four surveys were carried out on days when the global solar radiation was relatively high. The global solar radiation was 17.3, 19.6, 19.5, and 16.3 MJ m^{-2}, respectively, during the four surveys (Fig. 2a). We considered that the chlorophyll *a* concentration of blooms would be affected by the global radiation on previous days, as well as by that on the survey day. For survey 1, the global solar radiation values during the five previous days were above 10 MJ m^{-2}. For survey 2, the global solar radiation values during the two previous days were above 20 MJ m^{-2}, although the values on the three days before were below 10 MJ m^{-2}. For survey 3, the global solar radiation values during the five previous days were above 15 MJ m^{-2}. For survey 4, the global solar radiation values during the two previous days were above 10 MJ m^{-2}, but values were less than 10 MJ m^{-2} on the three days before.

Heavy rains fell on 25 and 26 July (i.e. between surveys 1 and 2), and precipitation was 20.5 and 74.5 mm d^{-1}, respectively (Fig. 2b). The water level of the Arakawa River rose owing to these precipitation events. Although there were no discharge data available, we expected that the river discharge would be roughly correlated with the water level. These precipitation events increased the water level to 13 times the prior water level (Fig. 2c), and the water level during survey 3 was five times higher than that before the precipitation. Lighter rains fell on 12 August (i.e. between surveys 3 and 4), and precipitation was 11.5 mm d^{-1}. The increase in water level due to the rainfall on 12 August was 0.25 times the increase due to the precipitation events on 25 and 26 July.

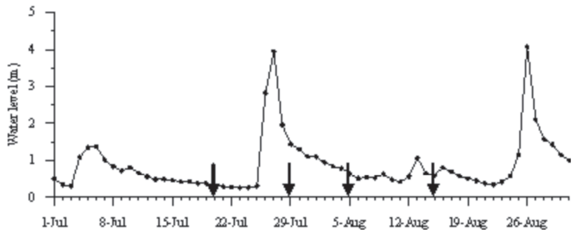
The tidal ranges of surveys 1 and 3, during spring tides, were 203 and 171 cm, respectively (Fig. 2d), and those of surveys 2 and 4, during neap tides, were 109 and 100 cm, respectively.



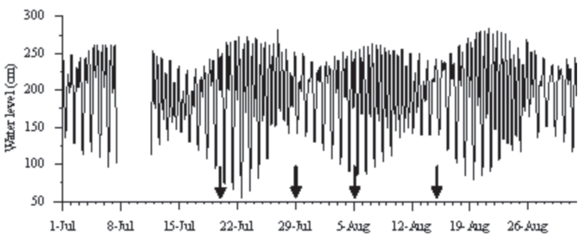
(a)



(b)



(c)



(d)

Fig. 2. (a) Global solar radiation, (b) precipitation, (c) water level in the Arakawa River, and (d) water level at station B during July and August 2005. Arrows indicate survey days.

Vertical distribution of salinity

The vertical profiles of salinity and mixing regime differed with the tidal range and discharge. During surveys 1 and 3, fresh water (salinity <10) did not reach station 5 (Figs. 3a, c). During surveys 2 and 4, during the neap tide, fresh water was recovered on the surface from stations 2 to 10 (Figs. 3b, d) and a salt wedge structure (salinity ≥15) intruded to station 10 upstream.

Vertical distribution of chlorophyll *a*

There were differences in the vertical distribution of chlorophyll *a* among the four surveys. Enhanced chlorophyll *a* concentrations (>40 μg L^{-1}) were not recorded during surveys 1 and 2 (Figs. 3e, f). During surveys 3, however, a thin layer of enhanced chlorophyll *a* was found under a layer of salinity 15, ranging from stations 1 to 6 (Fig. 3g). The layer of enhanced chlorophyll *a* concentration measured about 1 m at stations 3 to 5 and about 3 m at stations 1 and 2. During survey 4, chlorophyll *a* concentrations >40 μg L^{-1} were found only at stations 1 and 2, although concentrations >30 μg L^{-1} were found from stations 1 to 7 under a layer of salinity 10 (Fig. 3h).

Vertical profiles of salinity, chlorophyll *a*, and nutrients

By comparing the salinity of water samples and salinity measured by TurboMAP, we were able to note the difference between the depths of the sampled and target layers. Errors of about plus or minus 10 cm seem to be unavoidable when pumping water samples onboard. Good agreement between the salinity measurements, however, indicated that waves did not have much influence on the sampling (Figs. 4a, g, m, s). During survey 2, however, the salinity of the water sample from 50–cm depth was larger than that measured by TurboMAP and near the salinity of TurboMAP at 80–cm depth (Fig. 4g). Therefore, the data from the water sample taken from 50–cm depth during survey 2 should be regarded as data for 80–cm depth. In addition, data from 50–cm depth in survey 3 should be regarded as representing the layer under the halocline (Fig. 4m).

During survey 1, the salinity of the surface layer was about 24 and a clear halocline was not found (Fig. 4a). During surveys 2, 3, and 4, however, salinity in the surface layer was below 15, and clear haloclines were observed (Figs. 4 g, m, s). Compared with those in survey 2, the haloclines observed during surveys 3 and 4 were sharper and were found in the 0.5– to 1.0–m layer.

During surveys 1 and 2, the maximum concentrations of chlorophyll *a* were about 40 μg L^{-1}, and clear peaks were not found (Figs. 4b, h). In contrast, during surveys 3 and 4, the maximum concentrations of chlorophyll *a* were above 100 μg L^{-1}, and peaks of chlorophyll *a* occurred near the haloclines (Figs. 4n, t). During surveys 3 and 4, the concentrations of chlorophyll *a* decreased markedly with depth and were less than 40 μg L^{-1} below 3–m depth. During survey 3, the dominant species in the thin layer of concentrated chlorophyll *a* were *S. costatum* and *Thalassiosira binata*, diatoms typically found in Tokyo Bay; the population densities of these phytoplankton were 11,808 and 13,537 cells mL^{-1} at 1–m depth, respectively. During survey 4, the dominant species in the thin layer were Cryptomonadales and *T. binata*; the population densi-

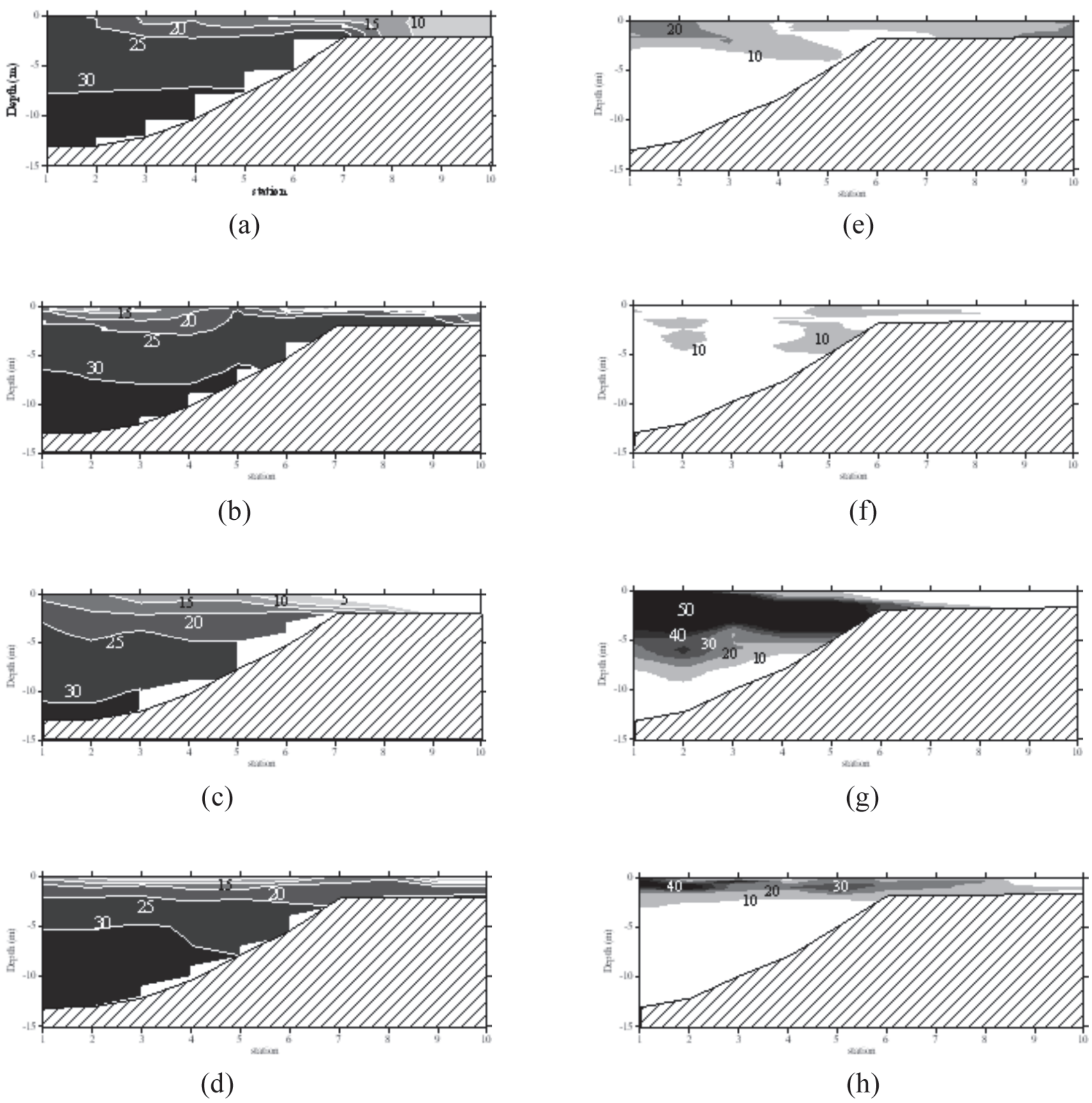


Fig. 3. Vertical cross–section of salinity during (a) survey 1, (b) survey 2, (c) survey 3, and (d) survey 4 and chlorophyll *a* (μg L^{-1}) during (e) survey 1, (f) survey 2, (g) survey 3, and (h) survey 4.

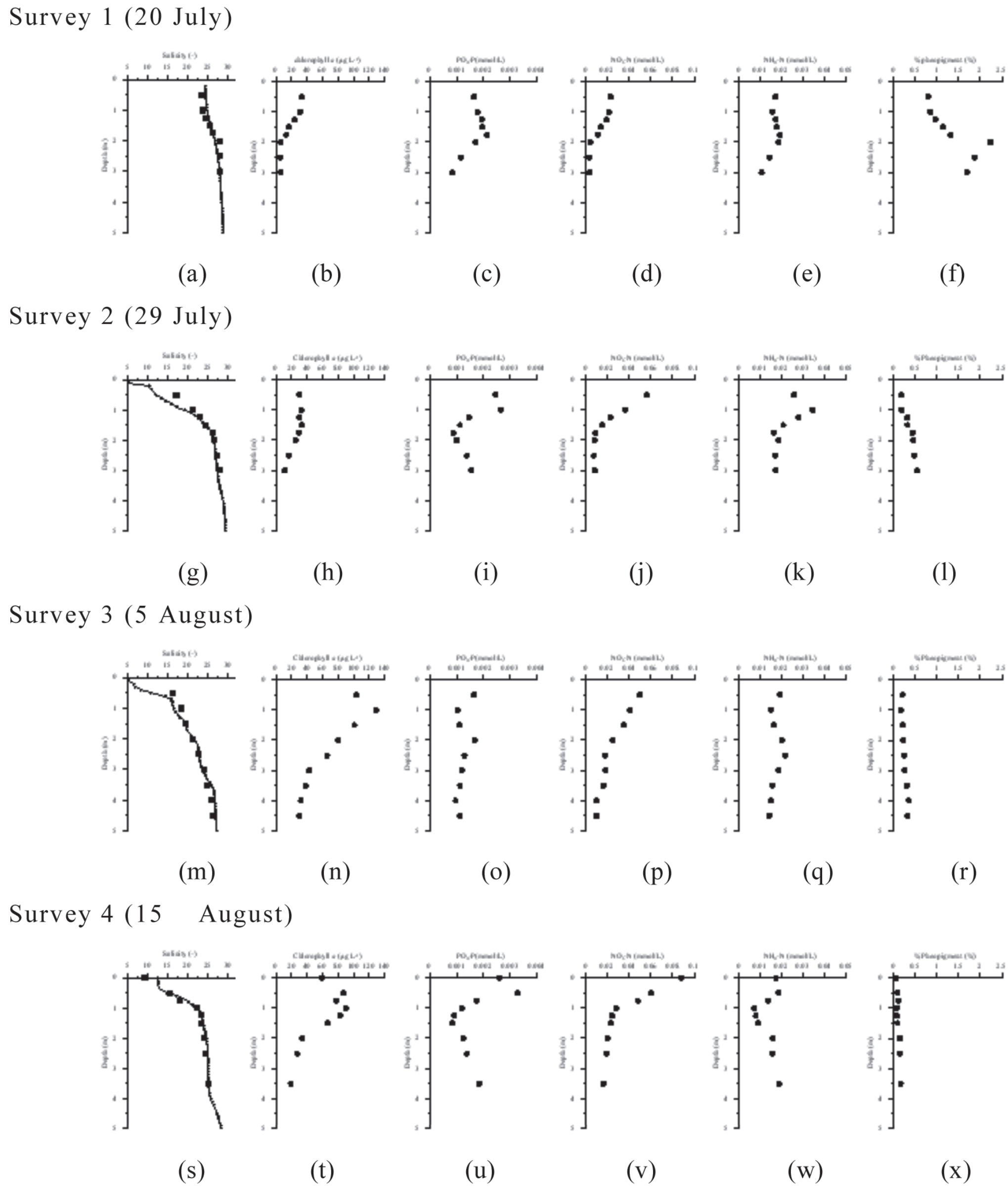


Fig. 4. Vertical profiles of (a, g, m, s) salinity; (b, h, n, t) chlorophyll a (μg L^{-1}); (c, i, o, u) PO_4^{2-} (mmol L^{-1}); (d, j, p, v) NO_2^- (mmol L^{-1}); (e, k, q, w) NH_4^+ (mmol L^{-1}); and (f, l, r, x) percentages of pheopigment (pheophytin) measured during surveys 1–4.

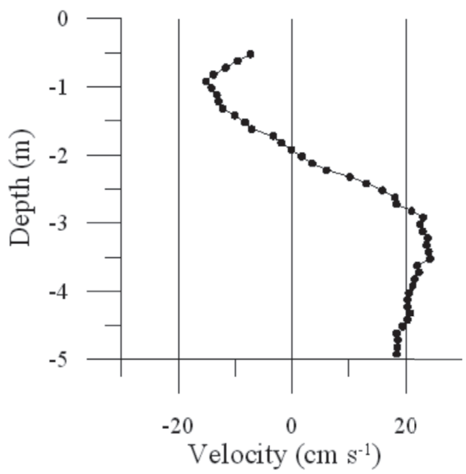


Fig. 5. Vertical distribution of water velocity at 14:00 h during survey 3.

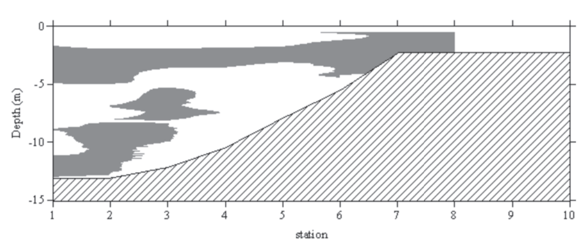


Fig. 6. Vertical distribution of the velocity from stations 1 to 8 during survey 4. Landward direction (gray area); seaward direction (white area).

ties were 2,876 and 3,888 cells mL^{-1} at 1–m depth, respectively.

During surveys 2, 3 and 4, concentrations of PO_4^{2-}, NO_3^-, and NH_4^+ in the layer above the halocline were higher than those in the layer below the halocline (Fig. 4). During surveys 3 and 4, the minimum concentrations of PO_4^{2-} and NH_4^+ were recorded in the layer in which highly concentrated chlorophyll *a* was found, which highlights the uptake of PO_4^{2-} and NH_4^+ in this layer. In all surveys, NO_3^- concentration decreased with increasing depth. Only during survey 1 was the percentages of pheophytin (% pheophytin) relative to chlorophyll *a* above 1%; during the other surveys, it was less than 0.5% (Figs. 4f, l, r, x).

Vertical distribution of velocity

The direction of velocity was seaward above 2–m depth and landward below 2–m depth at 14:00 h during survey 3 (Fig. 5). The minimum velocity was –18 cm s^{-1} at 1–m depth, and the maximum velocity was 22 cm s^{-1} at 3–m depth. These velocity conditions were maintained from 13:00 h (start of observation) to 15:30 h (end of observation). During survey 4, the direction of velocity above 2–m depth was seaward, ranging from station 1 to 6 (Fig. 6), whereas the direction of velocity between 2– and 5–m depth was landward. The velocity below 5–m depth was nearly 0 cm s^{-1}.

DISCUSSION

Enhanced chlorophyll *a* concentrations were not found during surveys 1 and 2, although they were found during surveys 3 and 4. These results indicate that enhanced chlorophyll *a* concentrations occurred under some conditions but not others.

Enhanced chlorophyll *a* concentrations were likely not found during survey 1 (20 July) for the following reasons. The water column around the river mouth had the characteristics of seawater. Compared with that in other surveys, the water column during survey 1 was characterized by weak stratification and high salinity in the surface layer. In addition, the phytoplankton bloom had become senescent. Concentrations of chlorophyll *a* on the surface layer in the head of the bay decreased from 18 July (Fig. 7), despite the global radiation remaining above 10 MJ m^{-2} from 15 to 22 July (data from Japan Coastal Guard). Moreover, % pheophytin around the river mouth were above 1% (Fig. 4f).

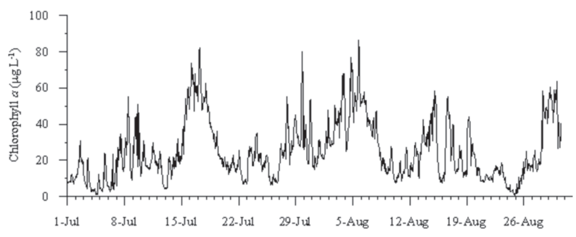


Fig. 7. Concentration of chlorophyll a in the surface layer in the middle of the bay (station D, Fig. 1, left) during July and August 2005.

Therefore, we assume that a water column with a senescent phytoplankton bloom reached the river mouth from the head of the bay during survey 1.

The lack of enhanced chlorophyll *a* concentrations during survey 2 (29 July) would have been affected by the increased river discharge on 26, 27, and 28 July. We assumed that the high volume of discharge on these dates had flushed phytoplankton away from the river mouth. Because the growth rate of *S. costatum* is 3.3 d^{-1} at a water temperature of 25 °C (Sakshaug, 1977), after chlorophyll *a* concentrations had decreased to about 1 μg L^{-1} because of the increased discharge it would take about 3 d for *S. costatum* to form a bloom (chlorophyll *a* >40 μg L^{-1}). That is, phytoplankton would have to remain around the mouth of the river for at least 3 d in order to form enhanced chlorophyll *a* concentrations there.

An estuarine circulation pattern is formed in a river mouth where a halocline is formed. The upper layer flows seaward, whereas the lower layer flows landward

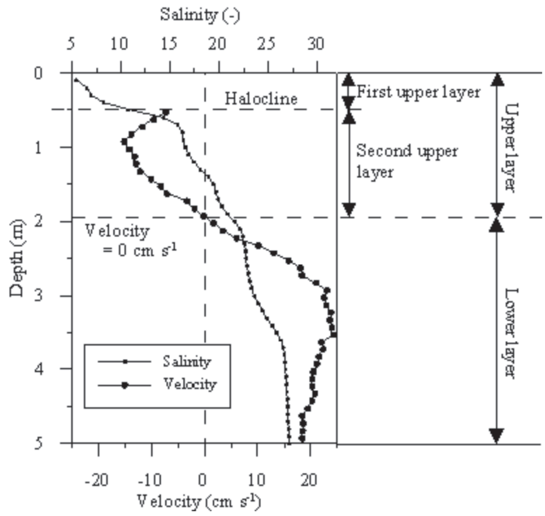


Fig. 8. Delineation of upper, lower, first upper, and second upper layers, and water velocities.

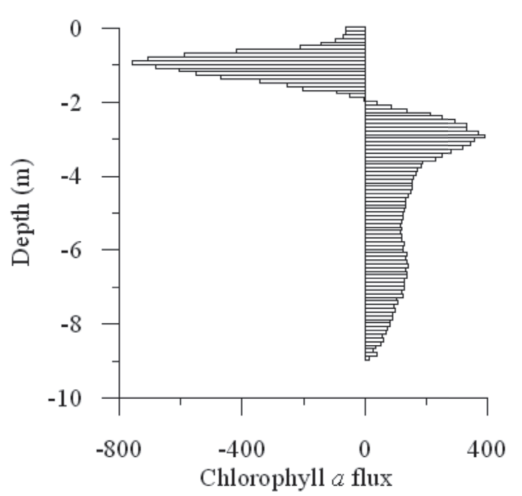


Fig. 9. Vertical profile of chlorophyll a flux (cm^2 s^{-1} μg L^{-1}) during survey 3.

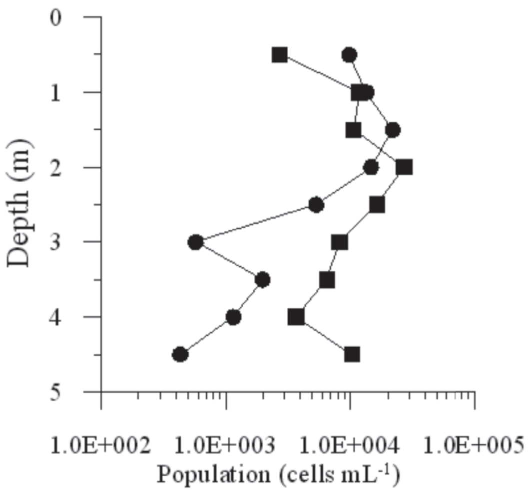


Fig. 10. Vertical profiles of *Skeletonema costatum* (■) and *Thalassiosira binata* (●) during survey 3.

as a compensatory flow for discharge from the river (Fig. 8). An estuarine circulation pattern was found during surveys 3 and 4. The seaward flux of chlorophyll *a* in the upper layer was nearly the same as the landward flux of chlorophyll *a* in the lower layer. The chlorophyll *a* fluxes integrate each 10–cm flux into the upper layer and the lower layer; each 10–cm flux is the product of velocity and chlorophyll *a* concentration in each 10–cm layer (Fig. 9). The seaward flux was 600 $cm^2\ s^{-1} \mu g\ L^{-1}$, and the landward flux was 1000 $cm^2\ s^{-1} \mu g\ L^{-1}$. Because the vertical profiles of *S. costatum* and *T. binata* decreased smoothly from the upper layer to the lower layer (Fig. 10), the phytoplankton in the lower layer with the landward flux would be the phytoplankton settling from the upper layer.

Therefore, part of the phytoplankton in the upper layer settled to the lower layer, and the rest was carried to sea because of the seaward flow. In addition, because of the estuarine circulation pattern, part of the settling phytoplankton in the lower layer was carried to the river mouth and then to the upper layer again. On the basis of the circulation of about 5–km length and 5–m depth in the region, we assumed that phytoplankton could stay around the river mouth. The velocities in both layers were about 20 $cm\ s^{-1}$ (17 $km\ d^{-1}$) at the mouth of the river, so phytoplankton circulate around the region about once per day.

As mentioned above, the conditions necessary for enhanced chlorophyll *a* concentrations include high global radiation and phytoplankton remaining around the river mouth for at least 3 d. However, these two conditions are not sufficient for the enhanced chlorophyll *a* concentrations that were recorded over the 5–km length between stations. A mechanism for supplying nutrients in this 5–km range also would be necessary.

From the viewpoint of salinity, the upper layer can be divided into two layers: one is a layer above the halocline, and the other is a layer below the halocline. We refer to the layer above the halocline as the "first upper layer" and the layer below the halocline as the "second upper layer" (Fig. 8). During survey 3 (5 August), the halocline was found at 0.5–m depth and salinity at the halocline was 10–15 (Fig. 4m). The first upper layer ranged from stations 2 to 6 (Fig. 3c). During survey 4 (15 August), the halocline was found at 0.8–m depth and salinity at the halocline was 15–22 (Fig. 4s). The depth of the first upper layer ranged from stations 1 to 10 (Fig. 3d). As shown in Fig. 4, PO_4^{2-}, NO_3^-, and NH_4^+ concentrations in the first upper layer were higher than in the second upper layer, whereas the chlorophyll *a* concentration in the first upper layer was lower than in the second upper layer. It is likely that chlorophyll *a* concentrations were relatively low in the first upper layer because of lower phytoplankton growth rates at low salinity (<27) (Yamaguchi, unpublished). Another reason would be that phytoplankton could not remain for three days in the first upper layer because salinity was far lower than the lower layer, a condition that allows less intrusion of the circulation flow into the first upper layer. Instead, the circulation flow would mainly intrude into the second upper layer, because the maximum seaward velocity was found in the second upper layer and there was not a large difference between salinity values in the second upper layer and the lower layer. In addition, because the dominant species were diatoms that are not phototaxic, phytoplankton could not move to the first upper layer from the second upper layer. Therefore, nutrients in the first upper layer remained at high concentrations with less phytoplankton intake.

This first upper layer, with high nutrient concentration, flows as an extension of the river flow around the river mouth, covering the area. During surveys 3 and 4, the first upper layer extended over 5 km offshore. This extended layer would sustain the 5–km–long enhanced chlorophyll *a* concentrations in the second upper layer. However, the existence of the first upper layer was affected by wind stress. During survey 4, the first upper layer was mixed with the second upper layer in the river mouth by wind with a velocity of 10 $m\ s^{-1}$.

CONCLUSIONS

Around the mouth of the Arakawa River, a thin layer of enhanced chlorophyll *a* concentrations (>40 $\mu g\ L^{-1}$) occurred in the region from the river mouth to 5 km offshore. The enhanced chlorophyll *a* concentrations were formed and maintained by phytoplankton remaining around the mouth of the river in response to the estuarine circulation pattern and the supply of nutrients from the first upper layer. However, it was unclear how much of the chlorophyll *a* flux reintruded into the upper layer because of the circulation process. Thus, to precisely estimate the primary production around the mouth of the Arakawa River, this process of reintrusion must be clarified.

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