Volume 23/1991/EMECS '90

# Field Survey and Hydraulic Study of "Aoshio" in Tokyo Bay

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**We have studied the so-called "Aoshio" phenomenon for years. In Japanese, "ao" means blue and "shio" means tide. The color of the sea surface changes to milky-blue and lots of shells and fish are killed when the "Aoshio" water covers them. This phenomenon has appeared only in a particular eutrophic coastal area of Tokyo Bay in Japan in summer time. The "Aoshio" phenomenon has been explained as follows: The origin is believed to be an anoxic bottom water mass in the offshore area, which develops in summer time and contains much $H_2S$. This water mass arises in the coastal area when an offshore-ward wind blows several days in a row. When the anoxic water mass meets oxygen under the sea, the dissolved $H_2S$ turns into colloidal sulfur particles. The milky-blue color is attributed to the random reflection of sunshine in the water with these particles. To explain such water mass ascent, we considered two simple hydraulic mechanisms and conducted numerical simulations using two dimensional equations for stratified flow. We also conducted field surveys on the sea and from the sky, to assess the "Aoshio" physico-chemically and biologically and to develop a "Aoshio" monitoring procedure by remote sensing.**

## Introduction and Procedures of Field Survey

Many field surveys have been conducted on Aoshio phenomena in the past, and they provided important information. However, they were rather limited to a particular speciality. The research work on Aoshio has been reviewed by the Japan Environment Agency (1988). We have thought that interdisciplinary knowledge, such as eutrophication, marine chemistry and biology, hydraulics, remote sensing technology, and so on, is necessary to solve the Aoshio problems. Therefore, we conducted an interdisciplinary field survey of Aoshio. We organized three parties for the survey, group I for remote sensing from the sky, group II for collecting sea truth data on ship, and group III for bacteria study on ship. A helicopter was used for the survey by group I. No satellite image data were available because thick clouds had covered the area whenever the Aoshio had appeared. The most perplexing problem for the Aoshio survey project was that one could not project when and where the Aoshio would take place. We were forced to stand by for the survey from the latter part of August till the middle of September. A preliminary survey was made by group II on September 5th, 1988, while the main survey was launched on September 8th, 1988. In 1989, the Aoshio failed to appear during the standby period.

The reflectance spectra of water surface in Aoshio and non-Aoshio zones were measured from the helicopter. The path radiance data were taken at both zones as well as at the height of 50 m, 100 m, 200 m, and 400 m. We also recorded both zones on videotape during the survey and took pictures there by multi-band and ordinary cameras. The videotape was very useful to know the scale of the Aoshio and its time change. Corresponding to the remote sensing from the helicopter, group II collected sea truth data on board. The reflectance spectra of water surface were measured on board as well at two points in each zone. The transparency and water temperature, salinity, dissolved oxygen (DO), oxygen reduction potential (ORP) levels were measured at 1 m interval at each point. The surface and bottom waters were sampled at each point to determine the concentrations of Chl-a, suspended solid (SS), particulate carbon, phosphorus and nitrogen, and chemical forms of sulfur. Group III collected water samples to determine the numbers of particular species of bacteria at intervals of 3 m at each point.

## Results of Field Survey

The main field results obtained on September 8th, 1988 have been shown here. The meteorological and tidal data during the survey were given by the Chiba meteorological observatory and the Chiba Port point. Northeast or east northeast wind kept blowing at the speed of 5 - 6 m/s on September 8th. The high tide time was 16:34 at Chiba Port on that day. Figure 1 shows the field site and the zone where the Aoshio was observed. The Aoshio zones are the shaded areas in Fig. 1. One small-scale Aoshio was observed at the end of the Funabashi channel and harbor and another in the Honda harbor. The Funabashi channel has a rectangular cross section 500 m wide

*Marine Pollution Bulletin*, Vol. 23, pp. 51–55, 1991.
Printed in Great Britain
0025-326X/91 $3.00+0.00

and about 7 m deeper than other area in this port. Figure 2 is a photo of the Aoshio observed in Honda harbor. The one-sixth right-hand side area of the harbor is the Aoshio. The windward side is to the right in the photo. There must be an anoxic water mass at the middle or bottom layer around this survey area because a very vivid milky-blue color wake appeared behind each ship. The Aoshio at the Funabashi harbor was confirmed early on the morning of September 8th and remained until the next afternoon. The Aoshio appearance time at the Honda harbor could not be known; however, we captured its disappearing process on videotape from 14:00 till 15:40. The Aoshio almost disappeared at around 15:00 there. Even after 15:40, the Aoshio was still observed at a small tideland which was connected to the harbor by a small channel. Figure 3 shows an example of reflectance spectrum data of water surface at Aoshio and non Aoshio zones obtained on board. Similar results were obtained by spectrum measurement from the helicopter. The reflectance of Aoshio zone was stronger at 400 - 700 nm than that of non Aoshio zone with the peak around 550 nm. This result shows us that the two zones can be categorized by reflectance spectrum data.

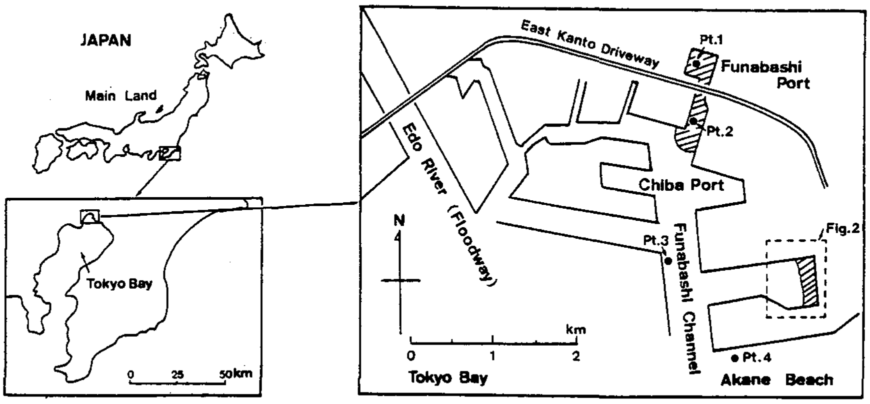


Fig. 1 Field site and Aoshio Zones (shaded areas)

Fig. 2 Aoshio in Honda harbor

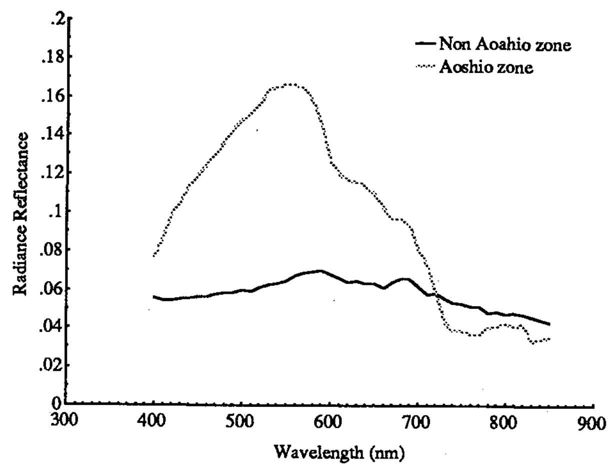


Fig. 3 Reflectance spectra at the site

The sea truth data were taken at four points, shown as Pt. 1, Pt. 2, Pt. 3 and Pt. 4 in Fig. 1. Points 1 and 2 were in the Aoshio zones and points 3 and 4 in the non-Aoshio zones. Points 1, 2 and 3 were in the Funabashi channel and point 4 at Akane beach. The distributions of vertical profiles on water temperature, salinity, DO and ORP suggested that the lower layer water with low temperature and DO and high salinity ascended to the surface at the end of the Funabashi channel (Muraoka *et al.*, 1988). Table 1 shows the results of water quality and nutrients at the four points. The transparency at the Aoshio zones was lower than that of non Aoshio zones. The values of Chl-a were high at the non Aoshio zones, especially on the surface at Pt. 4. In the Aoshio zones, dissolved nutrients were more evident than in the non-Aoshio zone, especially $NH_4$-N. Nevertheless, the values of Chl-a were very low at the Aoshio zones because of very few living things. Large-scale red tides were often observed at Aoshio zones several days after its disappearance. This was attributed to the rich nutrients of the upwelling water and sufficient supply of oxygen and sunshine.

Table 1 Water qualities at Aoshio and Non-Aoshio zones

| Point | S.D. (m) | T.S. (m) | W.T. (℃) | Sal. (%) | DO ppm | ORP (v) | Chl.a μg/l | S.S (mg/l) | NH4-N (ppb) | DTN (ppb) | PO4-P (ppb) | DTP (ppb) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pt.1 s | 0 | 0.7 | 22.6 | 29.7 | 0.54 | 0.07 | 1.29 | 7.31 | 828.5 | 1938.0 | 51.0 | 213.2 |
| Pt.1 b | 7 | | 22.2 | 33.5 | 0.13 | -0.15 | 1.15 | 4.87 | 275.8 | 794.5 | 72.2 | 135.0 |
| Pt.2 s | 0 | 0.7 | 23.0 | 31.0 | 1.08 | 0.22 | 2.41 | 5.70 | 568.3 | 692.5 | 98.4 | 197.2 |
| Pt.2 b | 7 | | 21.7 | 33.5 | 0.15 | -0.08 | 0.79 | 4.42 | 289.5 | 916.0 | 79.5 | 130.0 |
| Pt.3 s | 0 | 1.0 | 22.4 | 32.1 | 1.35 | 0.25 | 1.21 | 5.15 | 325.0 | 914.5 | 79.1 | 156.9 |
| Pt.3 b | 10 | | 21.3 | 34.0 | 0.11 | 0.01 | 0.36 | 4.14 | 340.3 | 515.5 | 97.4 | 85.6 |
| Pt.4 s | 0 | 2.2 | 22.3 | 32.1 | 5.63 | 0.28 | 19.60 | 8.08 | 72.1 | 582.5 | 32.1 | 82.1 |
| Pt.4 b | 6 | | 21.3 | 34.0 | 1.19 | 0.27 | 16.10 | 5.91 | 93.4 | 562.5 | 42.5 | 120.0 |

s: surface; b: bottom; S.D.: sampling depth; T.S.: transparency; W.T.: water temperature; Sal.: salinity; DTN: dissolved total nytrogen; and DTP: dissolved total phosphrous.

Table 2 Chemical forms of sulfur at Aoshio and Non-Aoshio zones

| | | Concentration (μg/ml) | | | | Percentage in suspensed solid (%) | | | |
|---|---|---|---|---|---|---|---|---|---|
| point | date | T-S | $SO_4$-S | $S^0$-S | ΔS | T-S | $SO_4$-S | $S^0$-S | ΔS |
| 1s | 88/9/5 | 0.392 | ND* | 0.273 | 0.119 | 2.35 | ND**(0) | 1.64(70) | 0.71(30) |
| b | | 0.417 | ND* | 0.484 | 0 | 9.46 | ND**(0) | 11.0(100) | 0(0) |
| 2s | | 0.168 | 0.010 | 0.110 | 0.048 | 2.84 | 0.17(6) | 1.86(66) | 0.81(28) |
| b | | 0.248 | ND* | 0.143 | 0.105 | 3.56 | ND**(0) | 2.06(58) | 1.50(42) |
| 4s | | 0.120 | 0.025 | 0.018 | 0.077 | 1.54 | 0.33(22) | 0.22(14) | 0.99(64) |
| b | | 0.135 | 0.024 | 0.007 | 0.104 | 1.94 | 0.35(18) | 0.11(6) | 1.48(76) |
| 1s | 88/9/8 | 0.320 | 0.088 | 0.108 | 0.124 | 2.16 | 0.60(28) | 0.74(34) | 0.82(38) |
| b | | 0.344 | 0.021 | 0.282 | 0.041 | 4.10 | 0.25(6) | 3.35(82) | 0.50(12 |
| 2s | | 0.666 | 0.153 | 0.067 | 0.446 | 13.2 | 3.05(23) | 1.32(10) | 8.87(67) |
| b | | 0.353 | 0.073 | 0.149 | 0.131 | 2.59 | 0.54(21) | 1.10(42) | 0.95(37) |
| 3s | | 0.066 | 0.029 | 0.033 | 0.004 | 0.78 | 0.35(45) | 0.40(51) | 0.03(4) |
| b | | 0.084 | 0.007 | 0.053 | 0.024 | 2.20 | 0.18(8) | 1.40(64) | 0.62(28) |
| 4s | | 0.025 | ND* | ND* | 0.025 | 0.39 | ND**(0) | ND**(0) | 0.39(100) |
| b | | 0.047 | ND* | ND* | 0.047 | 0.82 | ND**(0) | ND**(0) | 0.82(100) |

s: surface; b: bottom; ND*: < 0.005μg/ml; ND**: <0.05%; ΔS = T-S - ($SO_4$-S + $S^0$-S); and ( ): percentage to T-S. All values were determined by Dr.Takamatsu.

Table 2 shows the concentrations of different chemical forms of sulfur at the four sampling points. The amounts of total sulfur(T-S) at the Aoshio zones were ten to twenty times more than those at non Aoshio zones. A larger part of the T-S was occupied with elemental sulfur($S^0$-S) at Aoshio zones. On the other hand, the percentage of sulfur defined here by ΔS = T-S - $S^0$-S - $SO_4$-S in T-S was high in the non-Aoshio zones, especially at Pt. 4 at 100%. All sulfur there was considered to be organic. Similar results were obtained in the preliminary survey of sulfur in water. The difference between the two surveys was that the amount of sulfate ion ($SO_4^{--}$) and its ratio to T-S in the Aoshio zone were higher on September 8th than on September 5th. This suggested that the Aoshio of September 8th contained more Iron sulfate (FeS) and Pyrite ($FeS_n$) and was more anoxic than that of September 5th. However, the chemical forms of sulfur in water should be fixed immediately at sampling sites to confirm this. The results of bacteria at the Aoshio period will be reported by a member of Group III at another opportunity.

## Hydraulic Study on Aoshio Phenomena

First, we discuss the hydraulic mechanism of Aoshio appearance, considering the simple two-dimensional basin topography shown in Fig. 4(a). This discussion is available for a large-scale Aoshio. The Aoshios observed at coastal areas have been attributed to an upwelling of anoxic bottom water which develops offshore. Two simple models are discussed here for the upwelling of stratified flow at the coastal area under the offshore-ward wind condition; one is circulation with the water depth vertical scale shown in Fig. 4(b), the other is ascent of the interface of the stratified water to the surface shown in Fig. 4(c). Although a three-dimensional secondary flow due to a complicated basin topography may cause the upwelling, we will not discuss it here. Large-scale Aoshio phenomena have usually been explained by the first model, Fig. 4(b). However, there is a problem with this model. If the water depth scale circulation is developed, the interface will be fully mixed and the anoxic bottom water in the offshore will be dispersed and diluted fully during its journey to the coastal zone. In this situation, no Aoshio will appear even if the offshore water reaches the shore. We have calculated that the interface under the typical stratified state at Tokyo Bay would be stable and rise 5 to 10 m at the shore when the offshore-ward wind at 4 to 6 m/s has kept blowing for two days (Otsubo & Muraoka, 1988). In that calculation, the effect of a turbulent dispersion on the interface mixing was neglected. The interface may be mixed to some extent and the ascent of the interface may be smaller in the field. Nevertheless, the calculated result suggests that the ascent of the interface may play an important rule in the appearance of large-scale Aoshio as well as the circulation.

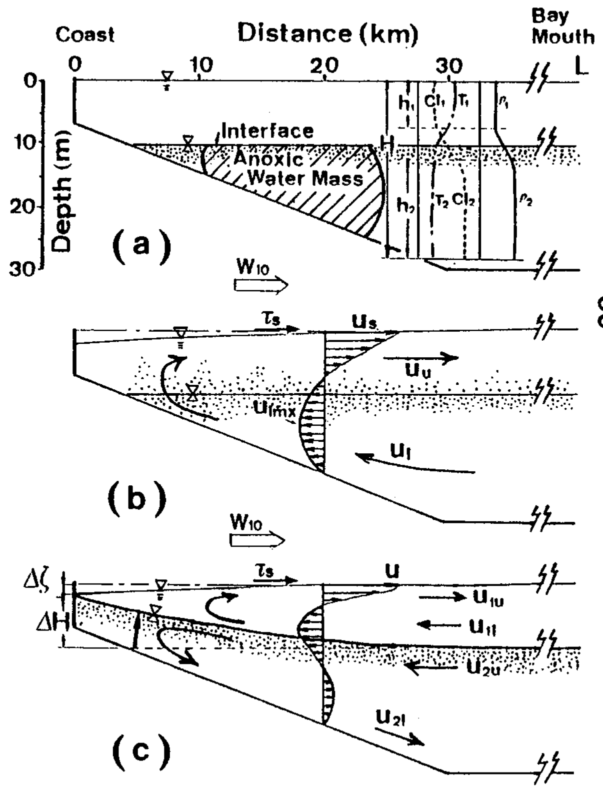


Fig. 4 Simplified upwelling models

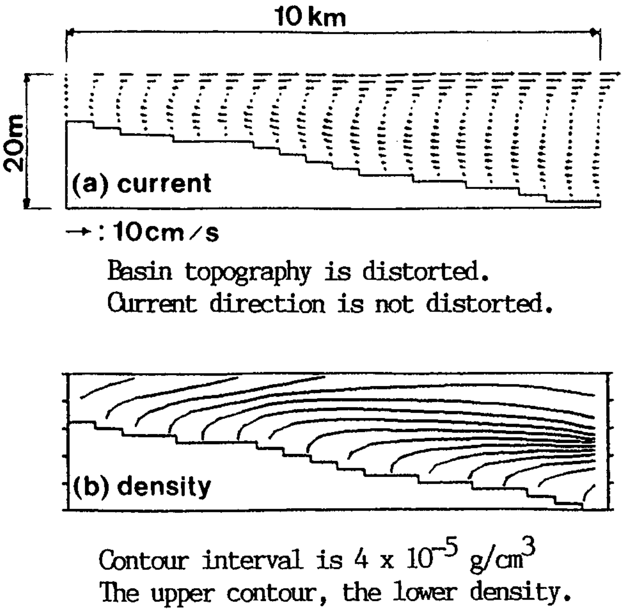


Fig. 5 Simulation results of stratified flow

For further discussion, we have conducted a numerical simulation of two-dimensional stratified flow at simplified Tokyo Bay basin (Harashima & Watanabe, 1988). The initial vertical profiles of temperature and salinity were assumed to be step-like with a interface at 10 m deep. The differences of temperature and salinity across the interface were assumed to be 5 °C and 3 ‰, respectively. Figure 5 gives the simulation results of the current (Fig. 5(a)) and density distribution(Fig. 5(b)) 2 days later, driven by an offshore-ward wind. The following values were adopted for the simulation: wind velocity, 5 m/s; horizontal and vertical turbulent diffusion coefficients, $10^4$ $cm^2/s$ and 2 $cm^2/s$ for temperature and salinity; horizontal and vertical turbulent viscosity, $10^4 cm^2/s$ and 10 $cm^2/s$, respectively; and wind drag coefficient, $10^{-3}$. The onshore-ward current is strongest in the middle layer. The high density water rises at the shore. The uniform vertical turbulent viscosity was assumed here; however, it must have a distribution decreasing with depth and density in the field. Therefore, the bottom current might be much weaker in the field. Although the behavior of an interface is not sufficiently clear, the simulation result suggests that the middle layer water with low temperature and high salinity may cause the Aoshio.

Secondly, let us discuss the disappearing process at the Honda harbor from a hydraulic viewpoint. Most of the Aoshio shown in Fig. 2 disappeared rapidly within one hour. Four causes may be considered for its disappearance. First, the flow direction had reversed. Secondly, colloidal sulfur particles had deposited during that time. Thirdly, an interface had descended to some extent. And, lastly, the high tide might somehow have reduced the upwelling there. The first and second causes are unlikely because the northeast or east-northeast wind had kept blowing and the other Aoshio zones had remained throughout the survey. The fourth one is also unlikely because a high tide pressure affects both upper and lower layers and does not change the current pattern there. As to the third possible cause, the descent of the interface at the shoreline due to the internal seiche might leave the Aoshio water back in the middle or lower layers, thereby reducing the upwelling. The question is whether the descending time scale is reasonable.

Here, the internal seiche characterized by the local basin topography is discussed. The period of the first mode of the local internal seiche, $T_{1s}$, is calculated by 4L/c, where L is length of the harbor and c is wave velocity of the seiche given by $\{(\rho_2 - \rho_1)/\rho_1\}gh_1h_2/(h_1+h_2)$ for perfect flow. The letters $\rho_1$, $\rho_2$ indicate densities of upper and lower layers, and $h_1$ and $h_2$ are their depths, respectively. Assuming that $h_1 = h_2 = 5$ m, $\rho_1 = 1.021$ $t/m^3$, and $\rho_2 = 1.025$ $t/m^3$, $T_{1s} = 17$ hrs. This result shows that the interface will descend from the top to the level within about 4 hours. This time scale seems acceptable to correlate the descent of the interface with the disappearance of the Aoshio.

## New Hypothesis of Aoshio

We first thought that most colloidal sulfur particles were produced during the upwelling process; however, $H_2S$ cannot turn into $S^0$-S within such a short upwelling process, and even if possible, the concentration of the dissolved $H_2S$ is unlikely to be high enough to color the water milkey-blue. There must be some chemical mechanism which makes the upwelling water contain so many $S^0$-S particles. Here, we introduce a new hypothesis proposed by Dr. Takamatsu. Most $S^0$-S particles have already been produced and accumulated around the interface in the stratified offshore before the upwelling shown in Fig. 6(a). According to the chemical characteristics of sulfur forms, only $S^0$-S can accumulate very densely around the interface. This hypothesis leads to the idea that the water in the middle layer mainly causes the Aoshio through the chemical and physical process shown in Fig. 6(b). This idea agrees with the above simulation results in Fig. 5. Considering this agreement and the case of the Honda harbor, the following hydraulics is the most likely for the Aoshio at simple topography basins: The origin of Aoshio is the very rich colloidal sulfur water around an interface in the offshore area and this water is transported toward the coast and then upwards by the circular current driven by the offshore-ward wind. The interface becomes unclear with time, ascending at the coastal area but rarely reaches the surface; however, its ascent surely enhances the upwelling of the middle layer water, and its descent suppresses the upwelling water downwards.

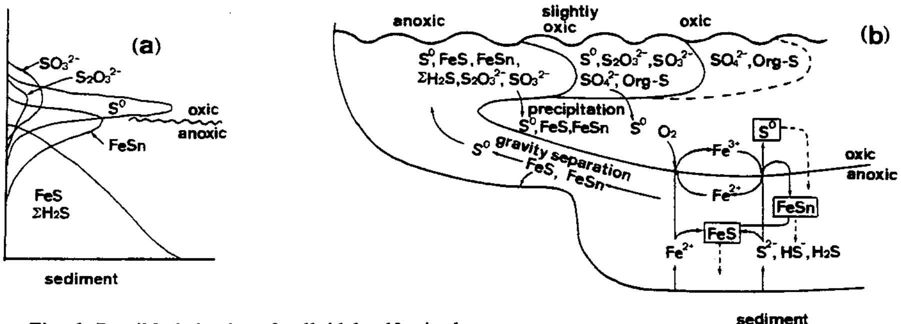


Fig. 6 Possible behavior of colloidal sulfur in the sea
(Takamatsu, private communication)

In closing, we mention some future problems for Aoshio study. First of all, the relation between tide and Aoshio should be investigated. Although, tidal motion has been considered not to cause the Aoshio directly, the low tide might trigger an Aoshio appearance rather than the high tide. As far as we studied, the Aoshio appearance time which had been confirmed by us or others (Kakino *et al.*, 1987) coincided well with the low tide time except for a few cases. We should keep checking the tide height and the Aoshio appearance time in future field study. Secondly, the vertical distributions of different chemical forms of sulfur in the stratified offshore water should be investigated in summer time, especially just before the Aoshio appearance. The process by which the colloidal sulfur particles accumulate around the interface and their physical and chemical properties (e.g., diameter, specific gravity, falling velocity, color in water, chemical stability) should be studied in the laboratory. Thirdly, the effects of local coastal topography, such as channel, river mouth, depth and profile of beach, on the behavior of anoxic bottom water should be studied as well. These may yield important rules for the appearance of a small-scale Aoshio and might explain why the Aoshio has been rarely observed in the Kanagawa coast area, in the northwest part of Tokyo Bay.


## Acknowledgment

We would like to thank the Japan Environment Agency, Tokyo Kyuei Co., Ltd. and the Funabashi Fishermen's Union for providing information on Aoshio appearance during our standby period.



### References

Japan Environment Agency (1988). Study on the mechanism of Aoshio formation, Report from the Japan Environment Agency, p.260 (in Japanese).

Muraoka, K., Harashima, A., Watanabe, M., Otsubo, K., Yasuoka Y., and Miyazaki, T. (1988). Study on remote sensing of coastal marine environment, Progressive report of research and development of ocean remote sensing from the Japan Science and Technology Agency, 65-72 (in Japanese).

Otsubo, K., and Muraoka, K. (1988). Study on hydraulic mechanism of Aoshio appearance, Proc. of the 22nd Annual Conf. of Japan Society of Water Pollution Research, 193-194 (in Japanese).

Harashima, A., and Watanabe, M. (1988). Physical modelling of the anoxic water behavior in coastal seas, Proc. of TECHNO-OCEAN '88, International. Symp. at Kobe, Vol. 2, 60-65.

Kakino, J., Matsumura, S., Sato, Y., and Kase, N. (1987). Relationship between Aoshio, blue-green turbid water, and wind-driven current, Nippon Suisan Gakkai, 53(8), 1475-1481 (in Japanese).