Numerical Simulation and Remote Sensing for the Analysis of Blue Tide Distribution in Tokyo Bay in September 2012

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Abstract. To determine the factors contributing to large-scale blue tide occurrences, blue tide distributions captured from satellite images were estimated using the estimation model for blue tides. This model was developed based on the observation results of the optical properties of Tokyo Bay and numerical simulation by a three-dimensional hydrodynamics and ecological model. By complementing the information from the results of both satellite image analysis to estimate the blue tide reflectance and the numerical simulation to calculate the dissolved oxygen (DO) concentration, the upwelling areas of sulfide-containing anoxic water were distinguished from those of non-sulfide-containing anoxic water.

Keywords: Blue tide, GOCI, three-dimensional hydrodynamics, ecological model

1. Introduction

Anoxic water is generated at the bottom layers of eutrophic areas at the beginning of summer and at the end of fall in Tokyo Bay, Japan. Such generation begins when oxygen is consumed by aerobic microorganisms during the decomposition of organic matter settled at the sea bottom and accumulated due to the death of phytoplankton during spring to summer under the stratification condition of the bay. Under anoxic conditions, the number of anaerobic microorganisms increases and, due to their respiration, generate nitrogen gas and sulfide using nitric acid and nitrate instead of oxygen. Therefore, blue tides occur when anoxic water containing generated sulfide rises to the surface due to external forces such as continuous north
wind. Such conditions result in harmful ecological effects at the sea bottom and shallow sea areas and often result in fish and shellfish mass mortality. In particular, massive blue tide occurrences result in severe losses to fisheries and are regarded as one of the crucial environmental problems.

The dynamics of anoxic water and the mechanism of blue tide occurrences have been previously studied through field observation and numerical simulation (Furota, 1987; Tanaka et al., 1997; Gomyou et al., 1998; Koibuchi and Isobe, 2005). It has been reported that blue tides usually occur under the following conditions: (1) existence of sulfide-containing anoxic water at the bottom, (2) continuous north wind persisting for at least 2 days, and (3) decrease of more than 4°C from the daily average temperature (Watanabe and Kohata, 1995).

It is also important to determine the spatial behavior or the blue tide distribution because shellfish mass mortality occurs when blue tides encroach on shallow sea areas. Therefore, the factors causing varying magnitudes of blue tides have also been studied. Large-scale blue tides occur not only as a result of anoxic water upwelling from dredged trenches or navigation channels where sulfide is readily generated but also due to the effect of upwelling originating from the flat bottom of the bay (Sasaki et al., 1997). However, because the horizontal scale of blue tide distribution originating from a dredged trench is small, the upwelling from a dredged trench is not a proximate cause for the large-scale occurrence of blue tides (Sasaki et al., 1997).

In addition, Ichioka et al. (2009) simulated the upwelling of sulfide in dredged trenches, a navigation channel, and the flat bottom of a bay using a three-dimensional hydrodynamics model and attempted to determine the contribution of each area to the occurrence of blue tides. As a result, it was found that the dredged trench and navigation channel contributed to the occurrence of blue tides but the contribution from the flat bottom bay was negligible. This was because sulfide disappeared at the last minute of blue tide occurrence because the temporal and spatial variation of sulfide is extremely large in the flat bottom of a bay (Sasaki et al., 2007). This acts as an obstacle in the numerical simulation of large-scale blue tides because sulfide monitoring is difficult at the flat bottom of a bay.

Although numerical simulation can capture the horizontal scale of blue tides for understanding the tide behavior, satellite remote sensing, which has a beneficial effect on spatial observation, is a more effective approach for accurately capturing blue tide distribution. In previous studies, patterns and processes occurring in the upwelling areas were clarified using satellite images of sea surface temperature. The areas with low temperature were assumed to be upwelling areas (Ueno et al., 1992). However, it is difficult to completely conclude that the upwelling water with low temperature is related to blue tide occurrences, because it is impossible to determine whether sulfide is present in the upwelling water.
Although blue tide distribution can be captured and estimated using optical sensors for satellites because ocean color changes significantly during blue tide occurrences, it is difficult to capture images of blue tide distribution because of bad weather conditions during blue tide occurrences. However, the large-scale blue tide that occurred from September 23 to October 1, 2012, was successfully captured using the Geostationary Ocean Color Imager (GOCI), which can capture images of ocean color near Tokyo Bay 8 times a day through a geostationary satellite.

In this study, field observations were conducted to elucidate the optical properties of blue tides for the remote sensing of satellites equipped with ocean color sensors. On the basis of these optical properties, an estimation model of blue tides was developed to determine the behavior of large-scale blue tide distributions generated from September 23 to October 1, 2012, in Tokyo Bay. Furthermore, to determine the factors contributing to the occurrence of the large-scale blue tides, numerical simulation was conducted to compute the dynamics of anoxic water using a three-dimensional hydrodynamics and ecological model to complement the information of the vertical profile of the bay and the time series variation, which are weak points of satellite remote sensing.

2. Method

2.1. Field observation
Field observation was conducted in Funabashi Port during a blue tide occurrence on August 30, 2011. For comparison, observation was also conducted in nearby areas not affected by the blue tide. Observations for the unaffected areas were conducted at Stn.98 located near the estuary areas of Sumidagawa and Arakawa rivers on August 30, 2011, and at Stn. 13 located at a distance from the estuary on October 24, 2011 (Fig. 1). At Stn.98, turbidity was relatively
higher because precipitation occurred the day before observation. In contrast, low turbidity was observed at Stn.13 because of good weather conditions during the observation period.

At all stations, various water parameters such as turbidity, chlorophyll-a (Chl-a), salinity, temperature, and dissolved oxygen (DO) concentration of the vertical profile of the bay were measured using multiple water quality sensors (Biosherical Instruments Inc. 04. QSP200A). At the same time, the vertical profile of the backscattering coefficient ($b_b$) inside the water was measured using Hydroscat-6P. In addition, the spectral upward radiance and downward irradiance at the blue tide area and at each station were measured with submersible radiometers (TriOS Optical Sensors; RAMSES ACC/ARC). Remote sensing reflectance $R_s$ was calculated from the radiometer measurements (Higa et al., 2012). Furthermore, the absorption coefficients of the total suspended solids, colored dissolved organic matter (CDOM), detritus, and phytoplankton from the sampled surface water from each station were measured immediately in the laboratory.

### 2.2. Outline of numerical simulation by a three-dimensional hydrodynamics and ecological model

#### 2.2.1. Numerical simulation by a three-dimensional hydrodynamics and ecological model

In this study, DO was calculated using a three-dimensional model that employed hydrodynamics, circulating nutrients, and low-order ecological model. The fundamental equations were composed by the Navier–Stokes equation, which is a continuous equation to calculate hydrostatic and boussinesq approximation, and equations for the states of temperature, salinity, and density. In addition, the correlation of growth rate of some phytoplankton species, light intensity, nutrients, and DO in the water were simulated using three models: (1) an ecological model, (2) a bottom sediment model, and (3) a hydrodynamics model. This was sup-

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**Table 1: Input conditions for numerical simulation**

| Items                        | Contents                                                                 |
|------------------------------|-------------------------------------------------------------------------|
| Computation period           | From 1, April to 30, September                                           |
| Computational domain         | Whole length of Tokyo Bay, North-South: 65 km, East-West: 43 km         |
| Computational grid           | Horizontal direction (Cartesian coordinates):1000 m                     |
|                              | Vertical direction (σ coordinates): 20 layers                           |
| Boundary condition           | Temperature and Salinity: Assimilation of field observation results at each layer |
| Meteorological condition     | Sea-level pressure, Air temperature, Stream pressure, Humidity, Wind, Cloud amount, Solar radiation, Precipitation amount |
| Entered rivers for discharge | Edogawa river, Arakawa river, Sumida river, Tama river, Tsurumi river |
ported by data from the detailed results of field observation conducted in 1999 (Koibuchi et al., 2007). In this study, the accuracy of simulation results have already been verified because the same model parameters were used by Saya et al. (2012).

2.2.2. Computational condition

The input condition of the numerical simulation is shown in Table 1. The computational period was from April 1 to September 30, 2012 including summer, in which anoxic water generation is more substantial. The input conditions used from the meteorological data included sea-level pressure, air temperature, stream pressure, humidity, wind, cloud amount, solar radiation, and precipitation amount. In addition, wind input with 16 azimuth directions as well as the hourly averaged data of velocity and tidal level were used. River discharges were also used as an input, which included the daily-averaged data estimating the H–Q curve of the Edogawa river discharge. Discharges from the other rivers were calculated from the fraction of the Edogawa river discharge.

3. Results

3.1. Optical properties of blue tide

3.1.1. Observed $b_b$

Figure 2: Vertical profiles of backscattering coefficient, turbidity, chlorophyll-a, and salinity in a blue tide
The vertical profiles of $b_0$, turbidity, Chl-a, and salinity in the bay’s blue tide area are shown in Fig. 2. Figure 2(a) shows the extent of increase of $b_0$ at various wavelengths. The level was highest at wavelength 442 nm and lowest at 676 nm. Turbidity significantly increased with increase in $b_0$ at depths around 1 m (Fig. 2(b)) because, during blue tide events, hydrogen sulfide upwelled from the bottom layer of the bay is oxidized to sulfide, which causes changes in ocean color. Figure 2(c) shows that the vertical concentration of Chl-a was low due to the upwelling of the water mass from the bottom. Furthermore, Figure 2(d) shows that the salinity was vertically uniform in the blue tide region.

Figure 3 shows the detailed increment of $b_0$ at each wavelength in the surface water of the sampling stations. $b_0$ was higher at the estuary area (Stn.98) with relatively high turbidity than at Stn.13, which was at a distance far from the estuary. However, the region directly affected by blue tide showed significantly higher $b_0$ than these 2 areas. Thus, blue tides exhibit unique $b_0$ properties.

3.1.2. Light absorption coefficient and remote sensing reflectance

The results of light absorption coefficient and remote sensing reflectance at each station are shown in Fig. 4. The light absorption coefficients of CDOM ($a_{\text{CDOM}}$), detritus ($a_d$), and phytoplankton ($a_{\text{ph}}$) in the areas affected by blue tide were significantly higher than those at Stn.98 and Stn.13. In addition, the light absorption coefficient at Stn.98 was higher than that at Stn.13.

$R_s$ showed a trend similar to that of the absorption coefficient. Theoretically, the higher the adsorption coefficient, the lower the $R_s$. However, in this case, the spectral analysis results showed that despite the increase in the adsorption coefficient in CDOM and phyto-

![Figure 3: Backscattering coefficient at the surface](image)

plankton, the $R_s$ of the blue tide was markedly high. This was because backscattering was too large and more prevalent than the light absorption. Furthermore, the colloidal particles of sulfur may not have been totally eliminated in the water filtration stage during the laboratory experiment to measure the light absorption coefficient of the blue tide.

As shown in the $R_s$ spectrum of the blue tide in Fig. 4, $R_s$ markedly increased from 350 nm to 720 nm. In particular, an apparent reflectance peak occurred at approximately 550 nm (Sakuno et al., 2011), which may be attributed to the high $b_b$ in the blue tide area. However, the $R_s$ at Stn.98 was higher than that at Stn.13. Because Stn.98 is located around the river mouth of the bay, the backscattering of the detritus was larger because of the discharge of highly turbid water from the river. It was also observed that the $R_s$ for both stations showed consistency at short wavelengths ranging from 350 nm to 450 nm because phytoplankton and CDOM absorb light at such wavelengths. These results are clearly shown in Fig. 4.

3.2. Estimation model of blue tides for a satellite

The optical properties of the blue tide were analyzed on the basis of the field observation results. It was found that the $R_s$ significantly increased with an increase in $b_b$ in the spectrum’s entire visible region. In this section, $R_s$ spectrum analysis results obtained from the field ob-

![Figure 4: Variabilities of each absorption coefficient and remote sensing reflectance](image-url)
The use of GO-CI's high temporal and spatial resolution satellite images enabled us to clearly capture the blue tide distributions. Figure 5 shows the result of Rs spectral analysis of the GO-CI satellite image in areas affected by the blue tide on September 24, 2012. The Rs of the satellite image showed different optical properties at each station at the blue tide area, the boundary between the blue tide, the unaffected inner part of Tokyo Bay, the central part of the bay, and the estuary area near Stn.98. The negative value obtained at wavelength 412 nm was because of a calibration problem with the GO-CI's optical sensor. This, however, is not considered an issue because the trend of the Rs spectrum was captured clearly.

The absolute value of the Rs in the blue tide-affected areas peaked at 555 nm, which was significantly higher than the reflectance in the other areas. The Rs at the boundary between the blue tide area and the unaffected area was also relatively high because the water masses mixed at that point.

Furthermore, the Rs in the estuary area was relatively high due to a rainfall event that occurred on September 23, 2012, a day before the field observation. A precipitation of 45.0

Figure 5: Remote sensing reflectance observed by Geostationary Ocean Color Imager (GOCI)
mm/day was observed at the Edogawa Rinkai observation point near Arakawa River, which caused the discharge of highly turbid waters to Tokyo Bay, which in turn, caused the increase in $R_{m}$. However, the extent of light scattering due to turbidity was still relatively less compared with that at the blue tide area because a blue tide exhibits unique optical properties. The results of the $R_{m}$ analysis from the GOCI satellite images are consistent with the trends of the results of field observations.

3.3. Development of the estimation model of the blue tide through satellite

The estimation model of blue tides was developed on the basis of the satellite images and the optical properties determined during field observation.

Blue Tide Reflectance = Band (555 nm) – 0.006 * |(Band (680 nm)/Band (660 nm))| (1)

The model explains that the reflectance in bands over the regions without blue tides should be less than zero. To calculate the blue tide reflectance, the band ratio at 680 nm/660 nm should be subtracted from that at 555 nm, which has the highest reflectance in the bay. These 2 bands at 660 nm and 680 nm indicate the light absorption by chlorophyll in the spectral region and the chlorophyll fluorescence spectra, respectively. Because the model can show blue tide occurrences based on color strength, it is helpful in the monitoring of the extent of distribution of blue tides and in the identification of areas of blue tide upwelling.

Figures 6(a) and (b) show the satellite images captured on September 24, 2012, at approximately 9:00 a.m. and 11:00 a.m. The model developed for estimating the blue tide distributions was applied to these images. In Fig. 6(a), the estimated blue tide distribution dispersed near the offing of Makuhari at approximately 9:00 a.m. However, many values were

Figure 6: GOCI images showing blue tides
missing in this image because of the effect of clouds during this period. Although the area of blue tide occurrence can be identified in the image to a certain extent, it is difficult to determine the distribution itself. Figure 6(b) is the subsequent image captured at 11:00 am, which shows the estimated blue tide distribution spanning across the offing of Makuhi to that of Urayasu. During this period, the entire blue tide distribution was captured because the image was less affected by clouds. Because the blue tide light reflectance was high in this region, this result confirmed the upwelling of the anoxic water occurred at both areas.

To evaluate the consistency in the upwelling areas in the offing of Urayasu, wind velocity and direction, DO, and the stream regimes of the upper and lower layers were investigated during September 22–26, 2012 (Fig. 7). During this period, a continuous north wind was persistent with a velocity of 6 m/s to 8 m/s. The DO level dropped at all layers when the wind velocity increased after September 2012 at 12:00 p.m. During this period, each wind direction was roughly opposite to that of the stream regime at the upper and lower layers. The upwelling occurred near the offing of Urayasu during this period because the surface water flowed to the central part of the inner bay and the bottom water flowed to the side of the land around Urayasu.

Figure 7: Wind speed, DO, and stream regimes at the surface and bottom at the offing of Urayasu
4. Discussion

4.1. Spatial distributions of the upwelling area of the anoxic water

Figure 8 shows a time series of the spatial distribution of DO from September 22 to 25. It was found that the upwelling of the anoxic water from the offing of Makuhari occurred on September 22, which corresponds with the period in which the DO in the offing of Urayasu did not decrease, as shown in Fig. 7. Thereafter, the upwelling area increased and expanded in the area north of the inner bay on September 23. Although no decrease in DO was observed at 12:00 p.m. on September 23, as shown in Fig. 7, the DO decreased at all layers after 6 h. However, the result of the numerical simulation showed a time lag because upwelling had already began at 12:00 p.m. on September 23. Furthermore, after September 23, the upwelling area became smaller. During this period, for 15 h, beginning on September 24 3:00 a.m., the wind velocity weakened, as shown in Fig. 7. Furthermore, the upwelling of the anoxic water in the offing of Urayasu stopped after September 25, and thereafter, the upwelling in the offing of Makuhari became dominant. During that period, the increase and decrease in DO in

Figure 8: Time series of surface DO by numerical simulation during the upwelling period
the offing of Urayasu was evident in the time series (Fig. 7). After several days, the extent of the blue tide gradually decreased possibly due to changes in wind conditions.

Thus, the upwelling of the anoxic water at the offing of Makuhari occurred mainly due to the continuous north wind with a 5 m/s velocity, beginning on September 22. Driven by an increasing continuous north wind of 8 m/s to 10 m/s, the upwelling continued to extend until it reached the entire head of the inner bay, including the offing of Urayasu, by September 23. In this regard, it was found that the expanse of upwelling intensified with increasing continuous wind velocity and vice versa.

4.2. Comparison between the upwelling area of the anoxic water by numerical simulation and the blue tide distribution by GOCI

On the basis of the identification upwelling area near the offing of Urayasu and the west side of the offing of Makuhari, as illustrated in Fig. 6(b), it was found that the satellite image showing the higher light reflectance by the blue tide is consistent with the estimation results of the numerical simulation (Fig. 9). However, the results showed that the blue tide distribution on the east side of the offing of Makuhari differed from that on the northeast side of the inner bay because blue tides occur only if sulfide is generated by anaerobic microorganisms in upwelling water. However, upwelling of anoxic waters do not always generate sulfide.

To verify the reason for the upwelling around the offing of Urayasu, the DO concentration of the area’s vertical cross-section was calculated, as shown in Fig. 10. From the result, it was found that the anoxic water from the dredged trench of the offing of Urayasu was rising to the surface water due to the continuous wind of 8 m/s to 10 m/s velocity that began on
Thus, the blue tide occurrence at the offing of Urayasu may be attributed to the huge amount of sulfide-containing anoxic water originating from the dredged trench of Urayasu, which upwelled from an early stage on September 23. The upwelling at the offing of Makuhari and the east side of the inner bay may not be directly connected with the blue tide occurrence because, as previously stated, upwelled anoxic water does not always contain sulfide.

These results indicate that the blue tide captured by GOCI on September 24 may have remained on the west side of the offing of Makuhari and the offing of Urayasu because the surface water movement was almost negligible due to the weakening of the wind velocity. It is indicated that although the blue tide at the offing of Makuhari existed in the morning of September 24, as shown in Fig. 6(a), its expanse was limited only to the northwest part of Makuhari as time progressed.

Thus, although it was impossible to capture blue tide distributions using temperature distribution estimated by previous satellite images, the calculation of accurate blue tide distributions and the elucidation of reasons for its distribution became possible through use of GOCI images, which were applied in our estimation model for blue tides. Furthermore, the determination of whether the upwelled anoxic water contained sulfide became possible by analyzing the information from blue tide distributions estimated by satellite images and the calculations from numerical simulation.

Figure 10: DO determined in the cross section of a–a’ by numerical simulation.
5. Conclusion

In this study, we developed the estimation model for blue tides by determining their optical properties for satellite remote sensing. In previous studies, it was inaccurate to estimate blue tide distributions since the previous studies used low-temperature distribution estimated by satellite. However, with the use of GOCI images, identification of blue tide occurrences in the upwelling areas is possible. Furthermore, the model can identify blue tide occurrences. Therefore it be useful for monitoring the extent of blue tide distributions and identifying the upwelling areas.

In our study, we used the data from a large-scale blue tide occurrence in September 2012 to simulate anoxic water using a three-dimensional model for hydrodynamics, bottom sediment, and an ecosystem. It was found that the expanse of upwelling intensified with an increase in continuous wind velocity and vice versa. On the basis of the estimated blue tide distribution together with continuous observation of the DO concentration as well as calculation results of the numerical simulation, it was found that the sulfide-containing anoxic water originated from the dredged trench of Urayasu that swelled to the surface water on September 24, 2012, due to a continuous north wind of 8 m/s to 10 m/s velocity.

Furthermore, although the upwelled anoxic water at the dredged trench of Urayasu contained sulfide, the upwelled anoxic water on the east side of the bay did not. It is indicated that although the anoxic water existed at the bottom of the bay, the upwelling may not have been related to the occurrence of the blue tide if sulfide was not generated by anaerobic microorganisms. Although a continuous north wind persisted, a time lag may have occurred, depending on the location of the blue tide occurrence, which may in turn depend on the behavior of the water mass at the bottom, which may have contained sulfide. By complementing the results of the numerical simulation with the information from the vertical profile of the bay and temporal data resolution, which are the weak points of satellite remote sensing, it is now possible to distinguish anoxic water containing sulfide from that not containing sulfide in the upwelling area.

In this regard, acquiring and analyzing numerous images capturing blue tide occurrences, complemented with the results of numerical simulation of anoxic water and sulfide, are essential in understanding the detailed condition of blue tide occurrence as well as the dynamics of anoxic water in relation to detailed climatic conditions.

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