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Minimum Wind Stress for the Occurrence of Blue Tide on the Southeast Shore of Tokyo Bay

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Abstract

In Tokyo Bay, blue tide is a phenomenon that seawater presents to be milky blue due to reflection of sunshine off surface water in which a large number of sulfur particles suspend. Its occurrence is because of coastal upwelling of the oxygen-depleted water at the bottom of the bay induced by the blowing of a northeasterly wind, consequently leading to many deaths of shellfish and some aquatic animals in the bay. In this study, an analytical solution of minimum wind stress for the occurrence of blue tide on the southeast shore of the bay is presented based on a two-layered model, and comparison with observation data of blue tide from 2003 to 2010 shows the validity of this solution. The results of sensitivity analysis to all of parameters involved in this solution were also found to agree with qualitative understandings of blue tide phenomenon.

Keywords

Minimum Wind Stress, Blue Tide, Tokyo Bay

1. Introduction

Tokyo Bay was subject to the consequences caused by a rapid urbanization and an intensive industrial development. Large quantities of untreated domestic sewage and municipal sewage as well as industrial sewage, which contained large nitrogen and phosphorus loads, were discharged into Tokyo Bay, consequently influencing seriously the development of the ecosystem in the bay. The input of these nutrient loads, with available sunlight in the surface and suitable temperature in spring or summer, promoted the excessive growth of phytoplankton. As a result, a phenomenon known as red tide (or algal bloom) took place, where the concentration of phytoplankton was so high that the color of seawater presented to be red. Red tide occurred frequently in Tokyo Bay, and its occurrence led to decreased biodiversity, toxin production and dissolved oxygen depletion in the bay. When phytoplankton died and fell into the bottom water due to gravity, some of them were largely decomposed by bacteria at the bottom. During this process, a large concentration of dissolved oxygen at the bottom was consumed, and consequently the bottom water became oxygen-depleted or even anoxic. On the other hand, fresh water discharge into the bay from several rivers and intermittent precipitation particularly from summer to au-

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tumn, along with seasonal temperature variation caused by surface heating and cooling, resulted in a well-mixed upper water with high temperature and low salinity and a lower water with low temperature and high salinity in the bay. As a result, a stable stratification developed, where the lighter upper water covered on the surface of the heavier lower water. This stable structure prevented a vertical circulation to bring dissolved oxygen from the surface to the bottom, thus enhancing the oxygen-depleted state of the lower water. Under anaerobic conditions, sulfate contained in the bottom water will be reduced into hydrogen sulfide. When a northeasterly wind as frequently observed blew on the surface, the well-mixed upper water will follow the wind in the downwind direction, and the oxygen-depleted lower water will flow in the opposite direction to compensate, finally resulting in coastal upwelling of the bottom water from the bottom to the surface. During this process, a large amount of hydrogen sulfide present in the lower water was oxidized to colloidal sulfur substances when they meet the oxygen in the atmosphere. When sunshine reflected off the surface water containing these sulfur substances, the color of seawater presented quickly to be blue–green, and this phenomenon has been termed as blue tide. Coastal upwelling of the oxygen-depleted bottom water accompanying the outbreak of blue tide phenomenon caused a large number of mortalities of fish and shellfish in the upper warm water, consequently resulting in a substantial economical loss to coastal fisheries in Tokyo Bay.

Plenty of researches concerning blue tide have been carried out in the past from different perspectives (Gomyo et al., 1998; Ichioka et al., 2009; Kakino et al., 1987; Kataoka et al., 1989; Koibuchi & Isobe, 2007; Matsuyama et al., 1990; Nakatsuji et al., 1991; Nakatsuji et al., 1995; Otsubo et al., 1991; Sasaki et al., 1993; Sasaki et al., 1996). These research results are helpful to understand the mechanism of outbreak of blue tide phenomenon, and, based on them, this study presents the minimum wind stress for the occurrence of blue tide on the southeast shore of the bay by using an analytical solution in the context of a two-layered model. The layout of this paper is as follows. Section 2 introduces briefly the engineering background and derivation of the analytical solution. Comparison with observation data from 2003 to 2010 is provided in section 3, and section 4 presents the sensitivity analysis of the solution to all of the chosen parameters. As a summary, section 5 shows the concluding remarks.

2. Engineering Background and Derivation of the Solution

As shown in **Figure 1**, Tokyo Bay is located in the central part of main islands of Japan. Its main axis, mean width and average water depth are 50 km, 20 km and 15 m, respectively. When a northeasterly-oriented wind begins to blow on the surface of the bay, blue tide is frequently observed along the coastline from off Funabashi to off Ichihara.

As described in Zhu and Isobe (2012), although the real coastline of the bay is complicated, we just consider the research domain to be a rectangular one with the length of 50 km, the width of 20 km and water depth of 15 m, respectively, as shown by real lines and one dashed red line just indicating the imaginary southwest shore in **Figure 1**. **Figure 2(a)** illustrates the dimensions of this domain (b is the width, and a right-handed Cartesian coordinate system is defined as follows: the origin is in the center of domain, the x axis follows the northeasterly wind, the y axis is perpendicular to the length direction of the domain, and the z axis is positive upward above the still surface level.).

Considering that a northeasterly wind is imposed suddenly and uniformly over the surface of the whole water body, Zhu and Isobe (2012) analyzed the occurrence process of blue tide using a two-layered model which is consisted of the upper, well-mixed layer and the lower anoxic layer, separated by a density interface. Since the wind begins to blow on the surface, within a short time, the initial oscillation arising from the Coriolis force due to the rotation of the Earth does not influence the water body, so that a wind-driven current in the water body can be simply viewed as being in $x-z$ longitudinal section. The wind generates some surface waves and then these surface waves are reflected by two boundaries of the bay, which forms a standing wave group. Motion of this standing wave group causes the surface tilt with the southwest boundary up and the northeast shore down, further causing the surface to oscillate about an equilibrium tilt. Such an equilibrium tilt will be reached when all wave energy is completely dissipated and, at this point, barotropic pressure on the whole water body caused by this equilibrium tilt is in balance with surface wind stress. The imposed wind stress also causes the vertical motions of the water body. Specifically, since the onset of wind stress, the thin layer water beneath the surface will follow instantly the wind downwind and, as the compensation, the rest layer water between it and density interface will flow upwind, as also schematically shown in **Figure 2(b)**. This opposite motion makes the interface up

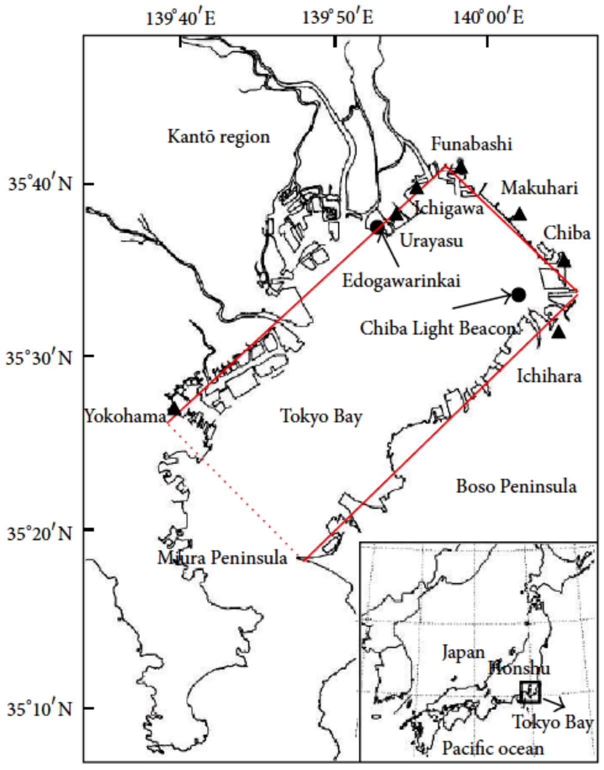

Figure 1. Map of Tokyo Bay and the chosen research domain for the study of blue tide (Zhu & Yu, 2014).

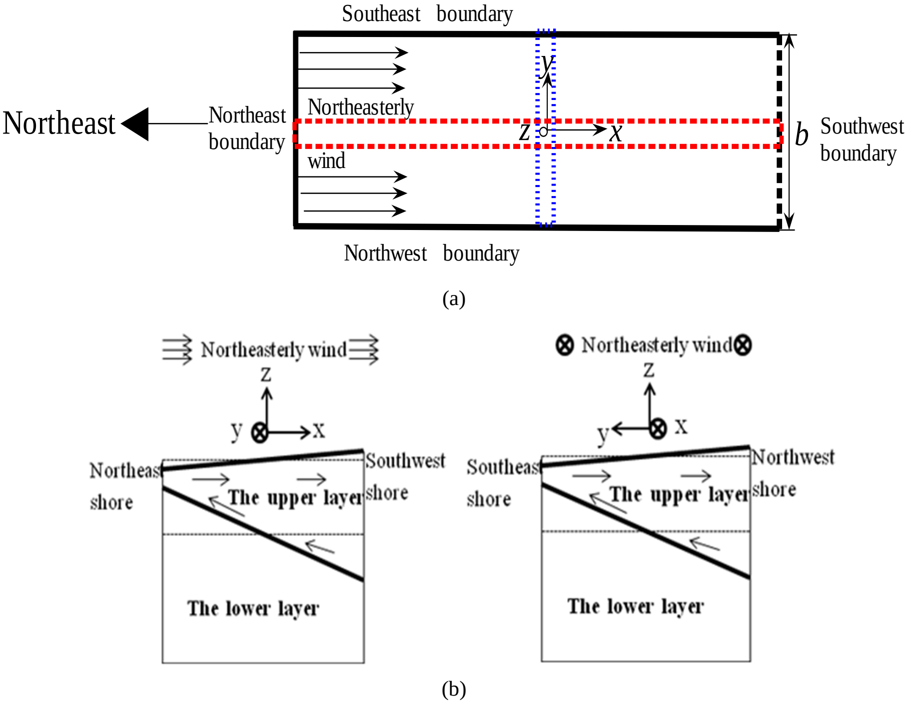

Figure 2. Dimensions of the chosen research domain (a) and schematic diagrams of coastal upwelling (b) and (c), caused by the continual blowing of a northeasterly wind. (b) (The wind direction is from the left to the right); (c) (The wind direction is perpendicular to the surface of this paper and inward).

at the northeast shore and down at the southwest shore of the bay, which is opposite to that of the surface. Similarly, this interface tilt is created by the motion of another standing wave group formed by some internal waves, thus also oscillating around an equilibrium position at which buoyancy force balances barotropic pressure caused by the surface set-up. If wind condition is enough, the interface will intersect the surface at the northeast shore of the bay, and the lower anoxic water begins to touch and interact with dissolved oxygen at the surface, at this point, blue tide takes place. When the northeasterly wind continuously blows on the surface, the effect of the Earth's rotation must be taken into account, and thus velocity direction of the upper layer water in the research domain is gradually deflected to the right of wind direction. In this case, the thin layer water beneath the surface will flow towards the northwest shore of the bay while the rest layer water between it and the density interface will flow in an opposite direction towards the southeast shore. Similarly, this opposite motion causes the corresponding tilt of the interface. If wind conditions are satisfied, the interface will also reach the surface and hence blue tide will occur on the southeast shore of the bay.

Occurrence of blue tide on the southeast shore is just discussed in this study. In order to simplify the theoretical method for calculating this case, all of parameters are simply assumed to be uniform along the x axis (Zhu & Isobe, 2012), and we simply analyze the vertical motion in the transverse section of the bay as shown in **Figure 2(c)**.

Governing equations for the upper layer water and the lower one can be expressed as follows:

$$\frac{\partial \bar{u}}{\partial t} - f\bar{\upsilon} = \frac{\tau_{sx}}{\rho_0\left(h+\zeta-\zeta'\right)} - \frac{\tau_{Ix}}{\rho\left(h+\zeta-\zeta'\right)}, \quad (1)$$

$$\frac{\partial \bar{\upsilon}}{\partial t} + f\bar{u} = -g\frac{\partial \zeta}{\partial y} - \frac{\tau_{Iy}}{\rho\left(h+\zeta-\zeta'\right)}, \quad (2)$$

$$\frac{\partial\left[\bar{\upsilon}\left(h+\zeta-\zeta'\right)\right]}{\partial y} = -\frac{\partial\left(\zeta-\zeta'\right)}{\partial t}; \quad (3)$$

$$\frac{\partial \bar{u'}}{\partial t} - f\bar{\upsilon'} = \frac{\tau_{Ix}-\tau_{Bx}}{\rho'\left(h'+\zeta'\right)}, \quad (4)$$

$$\frac{\partial \bar{\upsilon'}}{\partial t} + f\bar{u'} = -g\frac{\partial \zeta}{\partial y} - g\varepsilon\frac{\partial\left(\zeta'-\zeta\right)}{\partial y} + \frac{\tau_{Iy}-\tau_{By}}{\rho'\left(h'+\zeta'\right)}, \quad (5)$$

$$\frac{\partial\left[\bar{\upsilon'}\left(h'+\zeta'\right)\right]}{\partial y} = -\frac{\partial \zeta'}{\partial t} \quad (6)$$

Where $\left(\bar{u},\bar{\upsilon}\right),\left(\bar{u'},\bar{\upsilon'}\right)$ are vertically-averaged horizontal velocity components in x, y directions of the upper and the lower layers, respectively, h, h' are thicknesses of the upper layer and the lowe-r one, respectively, ρ, ρ' are densities of the upper layer and the lower one, respectively, ρ_0 is the reference of wa-ter, ζ, ζ' are surface displacement and interfacial displacements, respectively, g and ε are gravitational accele-ration and density contrast between two layers ($\varepsilon = \left(\rho'-\rho\right)/\rho'$), τ_{sx} is surface wind stress, $\left(\tau_{Ix},\tau_{Iy}\right),\left(\tau_{Bx},\tau_{By}\right)$ are components of interfacial and bottom shear stresses in x, y directions, respectively, f is the Coriolis coefficient, and t is the time.

Considering a specific steady state at which the surface and the interface just intersects on the southeast shore when the northeasterly wind lasts for a infinitely long time, there should be a vertical circulation in each layer as shown by **Figure 2(c)**, so $\bar{\upsilon} = \bar{\upsilon'} = 0$. If the interfacial shear stress is simply assumed to be expressed in terms of the velocity difference between the upper layer and the lower one as, $\left(\tau_{Ix},\tau_{Iy}\right) \approx \rho C_I$, $*\left(\bar{u}-\bar{u'},\bar{\upsilon}-\bar{\upsilon'}\right) = \rho C_I'\left(\bar{u}-\bar{u'},\bar{\upsilon}-\bar{\upsilon'}\right)$, where C_I, C_I' are coefficients of interfacial shear stress of the upper layer and the lower one, respectively, similarly, bottom shear stress being expressed in terms of velocity of the lower layer as $\left(\tau_{Bx},\tau_{By}\right) \approx \rho' C_B\left(\bar{u'},\bar{\upsilon'}\right)$, where C_B is the coefficient of bottom shear stress, it can be found readily that $\tau_{Iy} = \tau_{By} = 0$, $\tau_{Ix} \approx \rho C_I\left(\bar{u}-\bar{u'}\right)$ and $\tau_{Bx} \approx \rho' C_B \bar{u'}$. At this point, for the upper layer, the force balance along x

direction is between wind stress τ_{sx} and interfacial shear stress τ_{Ix}, and the balance of forces along *y* direction is among the Coriolis force $f\bar{u}$, pressure gradient due to the surface displacement $\partial\zeta/\partial y$, as schematically shown by **Figure 3(a)**; for the lower layer, interfacial shear stress τ_{Ix} simply balances bottom shear stress τ_{Bx} along *x* direction, and the force balance along *y* direction is among the Coriolis force $f\bar{u}'$, pressure gradient due to surface displacement $\partial\zeta/\partial y$ and that due to interfacial displacement $\partial\zeta'/\partial y$ as also schematically shown in **Figure 3(b)**.

Substituting these expressions in Equation (1)-Equation (6) and considering all parameters at the steady state can yield

$$\bar{u} = \frac{\tau_{sx}}{\rho_0}\frac{C_B + C_I'}{C_I C_B}, \quad \bar{u}' = \frac{\tau_{sx}}{\rho_0}\frac{C_I'}{C_I C_B}; \tag{7}$$

$$\zeta(y) = -\frac{f}{g}\frac{\tau_{sx}}{\rho_0}\frac{C_B + C_I'}{C_I C_B}y, \quad \zeta'(y) = \frac{f}{g\varepsilon}\frac{\tau_{sx}}{\rho_0}\frac{1}{C_I C_B}\left[\frac{\rho}{\rho'}\left(C_B + C_I'\right) - C_I'\right]y. \tag{8}$$

when the surface only intersect the surface on the southeast shore, the following mathematical relation should be satisfied: $\zeta'(y = b/2) + \left|\zeta(y = b/2)\right| = h$. Thus a wind stress can be gotten:

$$\frac{\tau_{sx}}{\rho_0} = 2C_I\frac{g\varepsilon h}{fb} \tag{9}$$

It can be found from Equation (8) that the large parameter τ_{sx}/ρ_0 results in the larger parameters ζ' and $|\zeta|$ at the steady state, indicating that Equation (9) actually represents the minimum wind stress for the occurrence of blue tide on the southeast shore of the bay.

3. Comparison with Observation Data

As presented in Zhu and Yu (2014), surface wind stress in Equation (9) is generally expressed to be a quadratic function of surface wind speed (Matsuyama et al., 1990; Wilson, 1960): $\tau_{sx} = \rho_a\gamma_a^2 w^2$, where ρ_a is air density (ρ_a = 1.23 kg/m^3), γ_a^2 is surface drag coefficient (here γ_a^2 = 1.30 × 10^{-3} is adopted, as presented in Matsuyama et al. (1990) and Wilson (1960), and w is the average wind speed measured 10 m above the still surface. Some typical parameter values in Equation (9) in case of Tokyo Bay are as follows: $b = 20$ km, $f = 8.47 \times 10^{-5}\cdot\text{s}^{-1}$, $\rho_0 = 1000$ kg/m^3. Especially, a simple estimate regarding C_I shows that it should be of the order of 10^{-4}, so we simply chose the empirical value 10^{-4} in this preliminary study.

Observation data sets of blue tide at the head of Tokyo Bay from 2003 to 2010 are available (Zhu and Isobe, 2012), and, among these data sets, those data sets of blue tide observed on the southeast shore of the bay are only chosen. Wind data set measured at Edogawarinkai shown in **Figure 1(a)** is simply adopted to represent wind condition across the whole bay (Zhu and Yu, 2014). By using this raw data set, the average speed of the northeasterly-oriented wind w and the total duration are calculated. The starting point for calculating the wind duration across which the average wind speed is calculated corresponds to the first appearance of the northeasterly-oriented wind that can directly contribute to outbreak of blue tide, the ending point corresponds to the timing at which blue tide just happens, as shown in **Figure 4** as a typical example.

As introduced in Zhu and Isobe (2012) in detail, for each real case of blue tide, value of minimum wind speed in Equation (9) should be different, because the density contrast ε and thickness of the well-mixed upper layer h are closely related to stratification degree and they should differ one case by another case. In order to calculate them, a series of real-time measurement data from Chiba Light Beacon (CLB) also indicated in **Figure 1(a)** are used. Densities of the upper and lower layers can be calculated based on the temperature and salinity, and thickness of the well-mixed upper layer can be estimated from vertical distribution contours of temperature, salinity and dissolved oxygen. Here it needs to be mentioned that this study did not use spatially-averaged wind data and stratification data across the whole bay because of a lack of a long-term and real-time data measured at different locations of the bay beyond CLB.

Table 1 summarizes the comparison result of the analytical solution with real cases from 2003 to 2010. The first big column shows date of the occurrence of blue tide on the southeast shore of Tokyo Bay from 2003 to 2010; the second column presents the calculated average wind speed along the northeast-southwest direction and

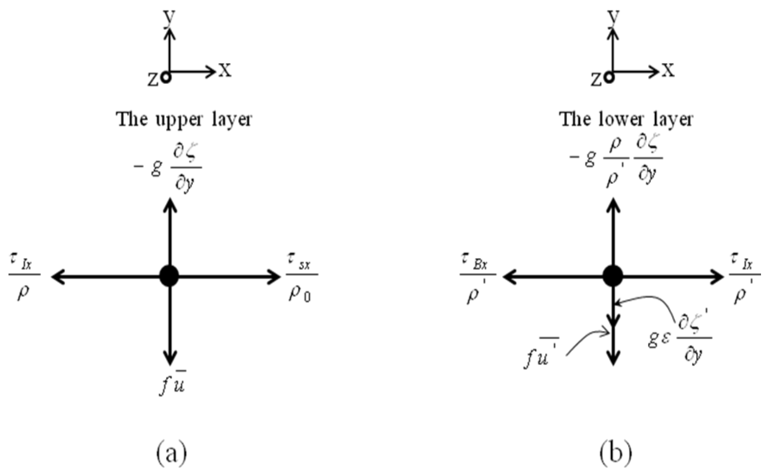

Figure 3. Schematic diagram of the force balance for the upper layer (a), and that for the lower layer (b) when the two-layered fluid is in the steady state in the case of blue tide on the southeast shore of Tokyo Bay.

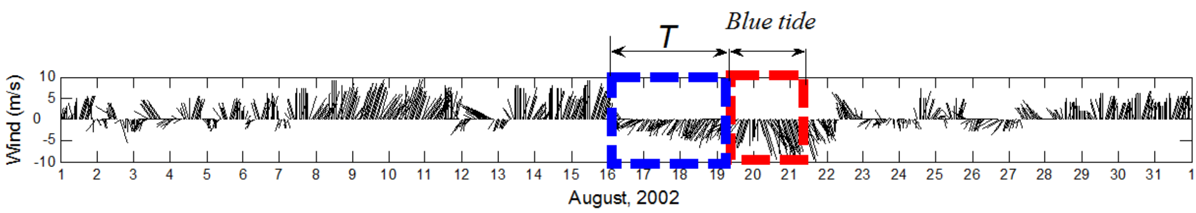

Figure 4. Vector diagrams of surface wind measured at Edogawarinkai in Tokyo Bay in August, 2002. The orientation is as follows: the up points to the north, the down the south, the left the west and the right the east. The red dashed rectangle denotes the duration of an observed blue tide: the left dashed line shows the timing of the occurrence of blue tide, and the right shows the timing of its disappearance. The blue dashed rectangle denotes the duration of the northeasterly-oriented wind: the left dashed line shows the first timing of the occurrence of the northeasterly-oriented wind, and the right corresponds to the timing of the appearance of blue tide.

wind duration; the third column shows the stratification degree for each case using measurement data sets from CLB (including densities of the upper and lower layers, thicknesses of the upper and lower layers). Using these values, the fourth column presents the calculated minimum wind speed from Equation (9). Whether the wind speed of each real case exceeds the calculated minimum wind speed is shown in the fifth column, which shows a good agreement between real cases and the solution. It can be concluded that the analytical solution shows a certain degree of validity.

4. Sensitivity Analysis

Sensitivity of the analytical solution to all of parameters incorporated into it can be carried out by qualitatively analyzing Equation (9), and some results can be obtained as follows:

1) When density of the lower layer water with a fixed density for the upper layer water is increased, minimum wind stress will increase accordingly. This is because a heavy lower water layer has a large gravity against surface wind effect, thereby making coastal upwelling become difficult. This conclusion is consistent with the results of numerical simulation of Matsuyama et al. (1990), which showed that coastal upwelling is prone to happen in early autumn because during this period stratification becomes weak. This conclusion is also applicable to the case in which density of the upper layer water is decreased and density of the lower layer water is fixed.

2) When thickness of the upper layer water is increased, minimum wind stress needed for the occurrence of coastal upwelling will increase accordingly. This is because increasing thickness of the upper layer is equivalent to lengthening the spatial distance of coastal upwelling, thus making coastal upwelling get more difficult.

3) The wider the research domain is, the easier the occurrence of blue tide gets. This may be interpreted by virtue of geometry of the research domain: under the circumstance in which all of parameters keep the fixed

Table 1. Comparison of the analytical solution with real cases of blue tide observed on the southeast shore of Tokyo Bay from 2003 to 2010 (based on measured data from Chiba Light Beacon).

Blue tide on the southeast shore of Tokyo Bay		Northeasterly wind	Degree of stratification						The analytical solution Equation (9)	Does the average wind speed exceed the calculated minimum wind speed?
Date of appearance		Average wind speed/Wind duration (m/s)/(h)	Surface temperature/ Surface salinity (˚C)/(psu)	Bottom temperature/ Bottom salinity (˚C)/(psu)	Density of the upper layer (kg/m^3)	Density of the lower layer (kg/m^3)	The initial thickness of the upper layer (m)	The initial thickness of the lower layer (m)		
2003	May 16-May 19	3.64/45	18/29.8	15.6/33	1021.48	1024.24	5.00	10.00	$w \geq 3.1224$ m/s	Yes
	Sep 22-Sep 24	5.52/47	22.8/31	20.4/33	1020.99	1023.27	5.00	10.00	$w \geq 2.8393$ m/s	Yes
2004	Jul 28-Jul 31	6.06/48	26.4/29.8	20.4/33	1019.17	1023.27	5.00	10.00	$w \geq 3.8074$ m/s	Yes
2005	May 31-Jun 1	5.10/61	18/30.6	16.2/33.40	1022.24	1024.55	5.00	10.00	$w \geq 2.8561$ m/s	Yes
	Jun 15-Jun 17	4.57/68	19.2/32.2	16.8/33.60	1022.71	1024.47	5.00	10.00	$w \geq 2.4931$ m/s	Yes
	Sep 6-Sep 7	4.27/37	25.2/27	21.6/33.0	1017.28	1022.73	2.50	12.50	$w \geq 3.1048$ m/s	Yes
	Sep 26-Sep 30	4.24/138	21.6/31.8	20.4/33.0	1022.08	1023.27	3.00	12.00	$w \geq 1.5889$ m/s	Yes
	Oct 12-Oct 17	3.89/72	21.6/31.8	21.6/33.20	1022.08	1022.88	5.00	10.00	$w \geq 1.6822$ m/s	Yes
2006	Sep 13-Sep 18	4.15/69	24/31	22.8/32.80	1020.65	1022.29	4.00	11.00	$w \geq 2.1548$ m/s	Yes
2007	Sep 2-Sep 4	4.08/84	25.8/29.4	21.6/33.00	1018.60	1022.73	4.50	10.50	$w \geq 3.6262$ m/s	Yes
	Oct 16-Oct 18	4.06/48	21/31.8	21/33.00	1022.24	1023.00	4.00	11.00	$w \geq 1.4664$ m/s	Yes
2008	Aug 22-Aug 28	5.40/40	26.4/29	21.6/32.60	1018.42	1022.42	4.00	11.00	$w \geq 3.3651$ m/s	Yes
	Oct 9-Oct 10	3.33/55	22.2/31	21/33.00	1021.16	1023.00	3.00	12.00	$w \geq 1.9760$ m/s	Yes
2009	May 29-May 31	2.85/39	18/31	16.8/33.00	1022.24	1024.01	4.00	11.00	$w \geq 2.2367$ m/s	Yes
	Aug 31-Sept 1	4.84/46	24/29	21.6/32.20	1019.14	1022.12	5.00	10.00	$w \geq 3.2478$ m/s	Yes
2010	Sep 9-Sep 10	3.87/43	27.6/27	25.2/32.20	1016.55	1021.26	5.00	10.00	$w \geq 4.0848$ m/s	No
	Sep 15-Sep 21	3.68/44	26.4/29.8	22.8/33.00	1019.17	1022.45	3.00	12.00	$w \geq 2.6389$ m/s	Yes
	Sep 24	4.36/48	24/31	22.8/33.20	1020.65	1022.60	5.00	10.00	$w \geq 2.6266$ m/s	Yes

constants except the width of the domain, a wide bay should mean a larger displacement of the interface on the boundary of domain between the upper and lower layers, consequently making coastal upwelling become easier.

4) It is apparent that upwelling can happen more easily in the research domain with a high latitude (that is a large Coriolis coefficient). This is simply because a high latitude means the larger Coriolis force, which intensifies the vertical motion of the upper layer water and subsequently accelerates the interface tilt on the boundary of the domain.

5) It can be found that it is difficult for coastal upwelling to happen in the domain with a large coefficient of interfacial shear stress of the upper layer. This is because the two-layered fluid system with a large coefficient of

interfacial shear stress corresponds to a large production of heat, further implying that a stronger wind is needed for the occurrence of coastal upwelling on the boundary of the domain.

5. Concluding Remarks

In this study, an analytical solution of minimum wind stress for the occurrence of blue tide on the southeast shore of Tokyo Bay based on a two-layered model has been derived. Comparison with observation data of blue tide from 2003 to 2010 showed certain the validity of this analytical solution. The results of sensitivity analysis to all parameters involved in it were also found to agree with qualitative understandings of blue tide phenomenon.

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