Applied Mechanics and Materials
ISSN: 1662-7482, Vols. 641-642, pp 1040-1045
doi:10.4028/www.scientific.net/AMM.641-642.1040

Submitted: 2014-07-09
Accepted: 2014-07-12

Qualitative discussion of influences of some factors on the occurrence of wind-driven coastal upwelling associated with "Aoshio" on the northeast Shore of Tokyo Bay using the developed analytical model

Zhongfan Zhu

College of Water Sciences, Beijing Normal University, Xinjiekouwai Street 19, 100875 Beijing, China

zhuzhongfan1985@gmail.com

Keywords: Qualitative discussion; Coastal upwelling; Aoshio; Analytical model; Tokyo Bay

Abstract. An analytical model based on some solutions in the context of a two-layered fluid was developed to estimate the occurrence of northeasterly wind-driven coastal upwelling associated with "Aoshio" on the northeast shore of Tokyo Bay, and its validity was verified by comparing with observation data[1]. In this study, influences of all of the factors incorporated into this analytical model (including densities and thicknesses of the upper and lower layers, the parameter expressing the influences of interfacial friction and bottom friction) on the model are analyzed. The analytical model is found to express the competition between the wind-shear effect and the stratification effect: when the former dominates over the latter, Aoshio will occur on the northeast shore of the bay. The parameter that can be used to characterize the stratification effect can be simply expressed in terms of the product of density contrast and the square of thickness of the upper layer. Using different values of this parameter corresponding to different months in the model can simply estimate in which months it is easy for Aoshio phenomenon to happen on the northeast shore of the bay, and the result is roughly consistent with an observation phenomenon that Aoshio was frequently observed on the northeast shore of the bay in September and May and relatively less observed in June and July during 1978-2010.

Introduction

As shown in Fig. 1(a), Tokyo bay is located in the southeastern part of Honshu island of Japan with main axis length of 60 km, mean width of 20 km and average water depth of 15 m, respectively.

Tokyo Bay, a typical semi-enclosed bay, is subject to eutrophication, consequently resulting in a excessive growth of phytoplankton on the surface of the bay. When phytoplankton died and fell into the bottom of the bay, some of them were largely decomposed by bacteria at the bottom, as a result leading to dissolved oxygen-depleted state of the bottom water. Moreover, fresh water discharge from serveral rivers to the bay, as well as precipitaton during summer to autumn, 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 density stratification develops, which prevents a vertical circulation to bring dissolved oxygen from the surface to the bottom and thus enhances the oxygen-depleted state of the lower water. Under anaerobic conditions, sulfate in the bottom water will be reduced into hydrogen sulfide. When a northeasterly wind begins to blow 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 leading to coastal upwelling of the bottom water from the bottom to the surface. During this dynamic process, a large amount of hydrogen sulfide in the lower water will be oxidized to colloidal sulfur substances when they meet the oxygen in the atmosphere. When sunshine reflected off the surface water in which these sulfur substances suspend, the color of seawater presented to be blue–green, and this phenomenon has been termed as blue tide. Coastal upwelling of the oxygen-depleted bottom water accompanying the occurrence of blue tide caused a large number of mortalities of fish and shellfish in the upper warm water around the bay, as a consequence causing a substantial economical loss to coastal fisheries in Tokyo Bay. As an addition, Fig. 2 shows the frequency of Aoshio observed in Tokyo Bay during 1978-2010.

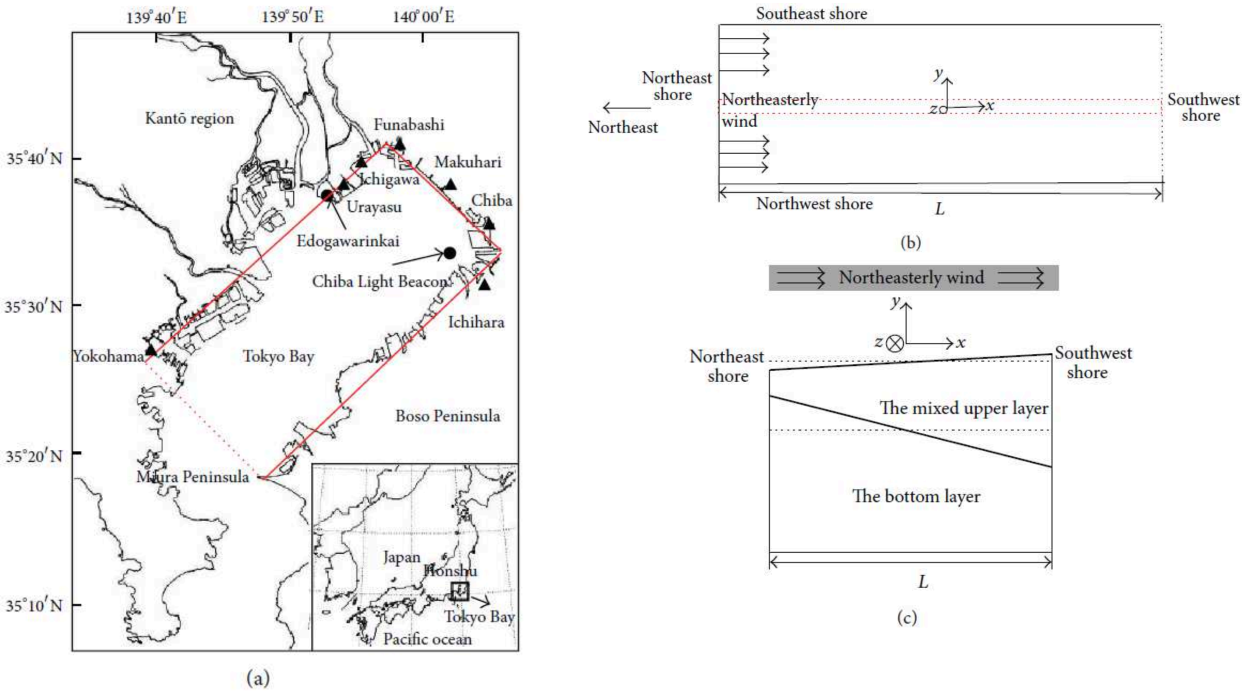

Fig. 1. (a) Map of Tokyo Bay including the chosen research domain; (b) Dimensions of the domain (L is the length of the bay); (c) Schematic diagram of coastal upwelling on the northeast shore, caused by the blowing of a northeasterly wind [1].

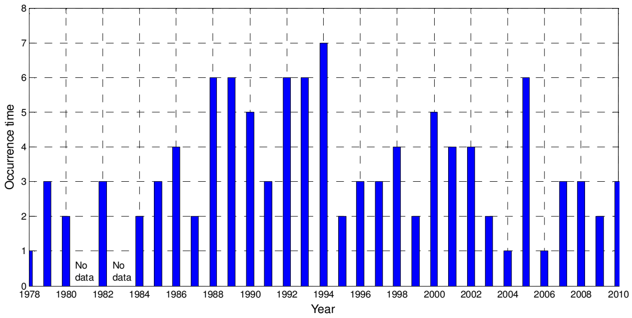

Fig. 2. Frequency of Aoshio observed in Tokyo Bay during 1978-2010.

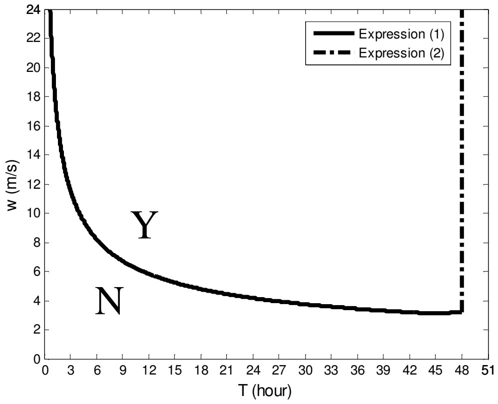

Fig.3. Presentation of the analytical model using typical parameter values in Table 1[1].

There have been a large number of studies concerning coastal upwelling associated with Aoshio phenomenon in Tokyo Bay[2, 3, 4, 5]. These results were helpful to help us gain the understanding of Aoshio phenomenon, and, based on them, an analytical model for estimating the occurrence of Aoshio on the northeast shore of the bay using some solutions in the context of a two-layered fluid was proposed in Zhu and Yu's study[1]. Following their study, this study focuses on qualitative analysis of this analytical model.

Qualitative analysis of the model

In Zhu and Yu's study [1], research domain for the study of coastal upwelling in Tokyo Bay was simplified to be a rectangular box with the main length of 50 km, the width of 20 km and the water depth of 15 m respectively, as shown in Fig. 1(b) also including the defined Cartesian coordinate system (the origin is in the center of the domain, the x axis follows the northeasterly wind with the y axis perpendicular to it, and the z axis is positive in the upward direction with respect to the still surface level). As shown in Fig. 1(c), a two-layered fluid model, which consists of a well-mixed upper water layer and an oxygen-depleted lower water layer with a density interface between them, was adopted to describe the occurrence of upwelling on the northeast shore of the domain. Sudden blowing of a northeasterly wind finally leads to respective movements of the surface and the interface. If some wind conditions are satisfied, the interface will intersect with the surface on the northeast shore of the bay, and at this point upwelling associated with Aoshio will occur on this shore.

After some mathematical derivations, wind conditions which are necessary for coastal upwelling to happen on the northeast shore of the bay can be expressed as follows [1]:

$$\frac{\tau_w}{\rho_0} \ge \frac{g\varepsilon h^2\pi^2}{4L\left[\frac{\pi^2}{8} - e^{-\frac{k_1}{2}T}\sum_{n=1}^{+\infty}\frac{1}{(2n-1)^2}\frac{\left(\frac{k_1}{2}\sinh\sigma_n T + \sigma_n\cosh\sigma_n T\right)}{\sigma_n}\right]} \tag{1}$$

$$T \le 2 \text{ days} \tag{2}$$

where τ_w, T are stress and duration of a northeasterly wind, respectively ($\tau_w = \rho_a\gamma_a^2 w^2$, where ρ_a is the air density, γ_a^2 is the surface drag coefficient, and w is average wind speed which is measured 10 m above the still surface), ρ_0 is reference density of water, g and ε are gravitational acceleration and density contrast between two layers ($\varepsilon = \left(\rho^{'} - \rho\right)/\rho^{'}$, where $\rho, \rho^{'}$ are densities of the upper layer and the lower one, respectively), respectively, $h, h^{'}$ are thicknesses of the upper layer and the lower one, respectively, k_1 is a parameter expressing the influences of interfacial friction and bottom friction ($k_1 = C_I/h + C_I^{'}/h^{'} + C_B h/\left[h^{'}\left(h + h^{'}\right)\right]$], where $C_I, C_I^{'}$ are interfacial friction coefficients of the upper layer and the lower one, respectively, and C_B is bottom friction coefficient), σ_n is a parameter related to oscillations of surface displacement and interfacial displacement, $\sigma_n = \sqrt{k_1^2 - 4g\varepsilon hh^{'}/\left(h + h^{'}\right)(2n-1)^2\pi^2/L^2}\Big/2$, $n = 1,2,3,\cdots$.

Typical values of all of parameters in the mathematical expression (1) for Tokyo Bay are provided in Table 1[1], where values for densities and thicknesses of the upper layer and the lower one are only adopted as an example. Using parameter values in this table, Fig. 3 presents expressions (1)-(2). In this figure, the region Y is the region in which upwelling associated with Aoshio can occur on the northeast shore of the bay, and the region N is a non-Aoshio region on this shore.

Tabe1. Typical parameter values for Tokyo Bay.

The parameter	Value	The parameter	Value
Thickness of the upper layer h	5 m	Air density ρ_a	1.23 kg/m^3
Thickness of the lower layer $h^{'}$	10 m	Surface drag coefficient γ_a^2	1.30×10^{-3}
Density of the upper layer ρ	1020 kg/m^3	Interfacial friction coefficient of the upper layer C_I	0.50×10^{-5} m/s
Density of the lower layer $\rho^{'}$	1023 kg/m^3	Interfacial friction coefficient of the lower layer $C_I^{'}$	0.50×10^{-5} m/s
Density contrast ε	2.93×10^{-3}	Bottom friction coefficient C_B	0.50×10^{-5} m/s
Length of the bay L	50 km	The parameter expressing the influences of interfacial friction and bottom friction k_1	1.67×10^{-6} s^{-1}
Reference density ρ_0	1000 kg/m^3		

It can be observed that the second term in the denominator term of the right-handed side of the expression (1) approaches zero when a northeasterly wind lasts for an infinitely long time ($T \to \infty$). In this case, the expression (1) can be transformed to be: $\frac{\tau_w}{\rho_0}L\Big/2g\varepsilon h^2 \ge 1$, where the numerator term can be simply regarded to express the wind-shear effect and the denominator term the stratification effect. Thus, the expression (1) can be simply regarded to express the competition between the wind-shear effect and the stratification effect: Aoshio can happen if the former dominates over the latter. In addition, it seems to be applicable to use the parameter εh^2 to represent the stratification effect, which will be used in the following discussion.

In order to discuss the influences of all of factor on the model, all of parameters are kept the same as presented in Table 1, except for the mentioned one. For that mentioned parameter, three different values are adopted, as shown in Fig. 4(a)-(e). A simple method that can be used to evaluate this effect is to compare the area of the region in which upwelling takes place (that is region Y). The larger the area is, the easier it is for upwelling to occur.

During the transition of a two-layered fluid system from the initial state to the upwelling state, the center of gravity of the upper layer will decrease and in contrast that of the lower layer will increase. Because the lower layer is heavier than the upper layer, the total potential energy of the two-layered system should increase. In this case, the energy input to the system due to surface wind shear is finally transformed into: production of kinetic energy of the two-layered fluid system, increase of potential energy of this system and production of heat due to friction (this term is simply characterized by the parameter k_1 in this study). Increasing the density of the upper layer (Fig. 4(a)) or decreasing the density of the lower layer (Fig. 4(b)) means decreasing the variation of potential energy of the two-layered system required for upwelling to happen, thus implying the occurrence of upwelling will become easier. This conclusion is consistent with the result of numerical simulation of [3] that coastal upwelling was prone to happen in early autumn because the density difference between the upper layer and the lower one became weaker during this period. From the initial state to the upwelling state, interfacial displacement on the northeast shore of the bay is almost equal to thickness of the upper layer (surface displacement can be negligible compared with interfacial displacement, as discussed in [1]). Thus, increasing the thickness of the upper layer actually means lengthening the spatial distance of upwelling, consequently making upwelling become more difficult to take place (Fig. 4(c)). Since upwelling of the interface is only in the upper layer, the analytical model should be insensitive to thickness of the lower layer (Fig. 4(d)). The two-layered system with a large friction parameter k_1 corresponds to a large production of heat, further implying that a stronger wind is needed for upwelling to happen (Fig. 4(e)). These conclusions are consistent with our known understandings of coastal upwelling.

As already mentioned, the analytical model actually reflects the competition between the wind-shear effect and the stratification effect, and the parameter to characterize the stratification effect can be regarded to be εh^2. Thus it can be simply inferred that coastal upwelling is prone to occur in the case of a two-layered fluid system with small values of εh^2. In order to verify this deduction, we attempt to compare it with statistical data of Aoshio observed on the northeast shore of Tokyo Bay during 1978-2010. The stratification parameter εh^2 should vary temporally and spatially. At present, due to a lack of spatially averaged stratification data in Tokyo Bay, we only use a series of data sets (including temperature, salinity and thickness of the well-mixed upper layer) measured in real time at the Chiba Light Beacon, which is also shown in Fig. 1(a). However, these data sets only start from 2003. In order to carry out qualitative analysis, we simply consider the algebraically averaged density values of the upper and lower layers and thickness value of the upper layer for each month from 2003 to 2010 to be representative of all of real cases from 1978 to 2010. The month that we consider is from May to October, because stratification generally forms in May, flourishes in September, and starts to decay at the end of October. Algebraically averaged density values of the upper and lower layers and thickness value of the upper layer for each month from 2003 to 2010 can be found in [6] and [1], respectively. Here Table 2 presents the calculated algebraically averaged values of the parameter εh^2 for each month.

The analytical model using different parameter values in Table 2 is presented in Fig. 5, where it can be observed that during the mentioned months the degree of easiness for upwelling associated with Aoshio to occur on the northeast shoe of the bay is: September, October > May > July, August > June. This sequence is in accordance with the sequence of values of the parameter εh^2 among these months: September, October > May > July, August > June. Fig. 6 shows the statistical data concerning frequency of occurrence of Aoshio observed on the northeast shore of the bay for each month during 1978-2010 (only medium-scale Aoshio and large-scale Aoshio are considered here). Comparing Fig. 5 and Fig. 6 can find that the results inferred from the model are consistent with observation results in both cases of September and May in which Aoshio was frequently observed on the northeast shore of the bay and both cases of June and July in which Aoshio was relatively less observed, but both cases of August and October are two exceptions. Considering that some simplifications were contained into this qualitative analysis, we can conclude that it may be valid to use the parameter εh^2 to estimate the degree of easiness for Aoshio phenomenon to occur on the northeast shore of Tokyo Bay.

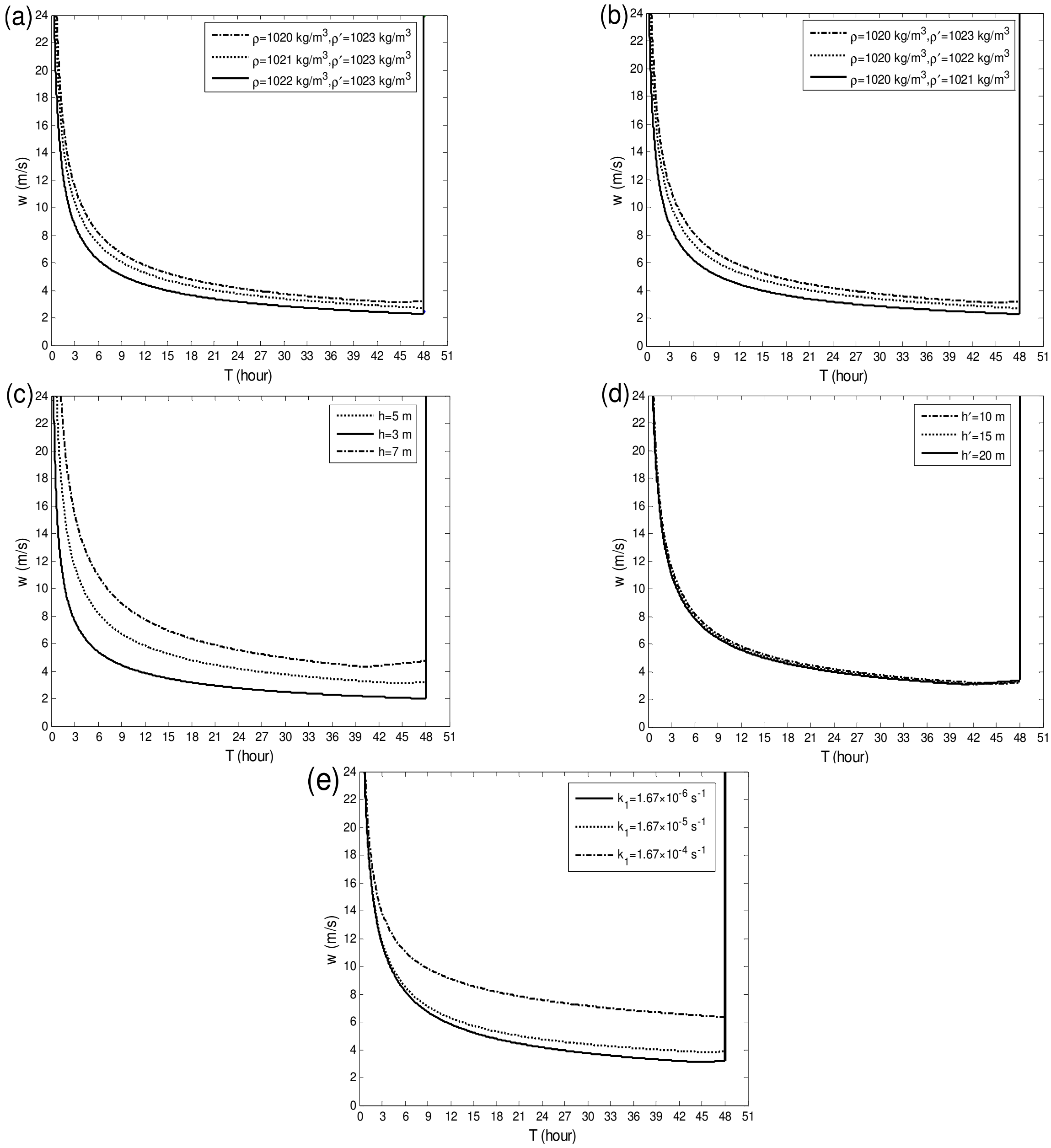

Fig.4. Influences of factors incorporated into the model on the model, and these factors including: (a) the density of the upper layer (with a fixed density for the lower layer); (b) the density of the lower layer (with a fixed density for the upper layer); (c) thickness of the upper layer; (d) thickness of the lower layer; (e) the parameter expressing the influences of interfacial friction and bottom friction; In each figure, all of the parameters are taken as constants (as presented in Table 1) except for the mentioned parameter, for which three parameter values are adopted.

Table 2. Algebraically averaged values of the parameter εh^2 for each month from 2003 to 2010.

	May	Jun	Jul	Aug	Sep	Oct
The value of the parameter εh^2 (m^2)	3.83×10^{-2}	7.14×10^{-2}	6.74×10^{-2}	6.95×10^{-2}	2.57×10^{-2}	2.08×10^{-2}

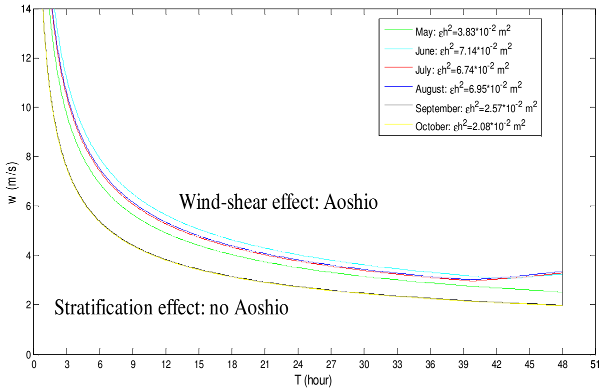

Fig.5. Presentation of the analytical model using different values of the parameter εh^2 for each month.

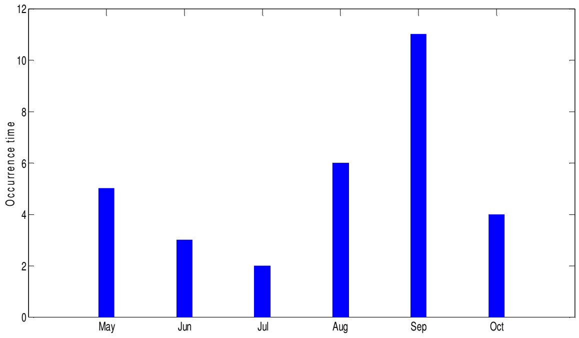

Fig.6. Frequency of occurrence of Aoshio observed on the northeast shore of the bay for each month during 1978-2010.

Concluding remarks

Following Zhu and Yu's study[1], this study has discussed influences of all of factors incorporated into the analytical model on the model, and all of conclusions obtained were found to agree with known understandings of Aoshio phenomenon. The analytical model was found to express the competition between the wind-shear effect and the stratification effect. The parameter that can be used to characterize the stratification effect can be simply expressed in terms of the product of density contrast and the square of thickness of the upper layer. Using different values of this parameter corresponding to different months in the model can simply reflect in which months it is easy for Aoshio phenomenon to occur on the northeast shore of the bay, and the analysis result was roughly in accordance with an observation result of Aoshio during 1978-2010.

Acknowledgment

This research is supported by National Key Technology Research and Development Program of the Ministry of Science and Technology of China (Number: 2013BAB05B04), and “the Fundamental Research Funds for the Central Universities” in China (Number: 2013NT50).

References

[1] Z. Zhu and J. Yu, The Scientific World Journal, vol. 2014, Article ID 769823, 11 pages, doi: 10. 1155/2014/769823.

[2] K .Otsubo, A. Harashima, T. Miyazaki, Y. Yasuoka, and K. Muraoka, Marine Pollution Bulletin , vol. 23, 1991, pp. 51-55.

[3] M. Matsuyama, K. Touma, and A. Ohwaki, Bulletin on Coastal Oceanography, vol. 28, 1990, pp. 63-74(in Japanese) .

[4] J.S. Yoon, K. Nakatsuji and K. Muraoka, Proceedings of Hydraulic Engineering (Japan Society of Civil Engineers)37, 1993, pp. 285-292(in Japanese).

[5] Z. Zhu, Journal of Geoscience and Environment Protection, vol.2, 2014, pp.126-134.

[6] Z. Zhu and M. Isobe, Journal of Oceanography, vol. 68, 2012,pp. 561-574.