Rep. Fac. Sci. Engrg.
Saga Univ.
36-1 (2007)

Reports of the Faculty of Science and Engineering,
Saga University, Vol. 36, No.1, 2007

Study on Water Quality and *Chattonella* in the Ariake Sea Using Water Quality Model

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Abstract: The Ariake Sea is a semi-closed sea located in the west of Kyushu Island. It is not yet clear exactly what has caused red tide and poor water qualities in the Ariake Sea. During winter of 2000, red tide of *Rhizosolenia* occurred in wide area of the Ariake Sea and damaged seaweed production. This paper aimed to investigate water quality and occurring of *Chattonella* in the Ariake Sea. From this study, it has been revealed that bottom sediment resuspension influences the behavior of *Chattonella* red tide in the Ariake Sea. Furthermore, the simulation results reveal that one of the regular blooms of red tides in the Ariake Sea is caused by *Chattonella* with resuspension process.

Key words: Ariake Sea, *Chattonella*, finite volume model, water quality model

1. Introduction

The semi-closed Ariake Sea is located in the west of Kyushu Island. Total area of the Ariake Sea is about 1,700 km^2 with the length of 100 km, average width of 15 km and average water depth of 20 m. The Ariake Sea has a unique feature. During the ebb tide, the tidal flat with the length of 6-10 km appears. The tidal flat area of the Ariake Sea is about 40 percent of total tidal flat in Japan. Total watershed area of the Ariake Sea is about 8,400 km^2 composed of 5 prefectures: Fukuoka; Saga; Kumamoto; Oita and Nagasaki. As shown in Fig. 1, there are eight class A rivers located in the catchment of the Ariake Sea namely, Chikugo River, Midori River, Shira River, Kukuchi River, Yabe River, Kase River Rokkaku River and Honmyo River. Total basin area of these rivers is 6,852 km^2.

The Ariake Sea is famous growing region of "Nori", seaweed, accounting for nearly 40 percent of total production in Japan. However, during winter 2000, *Rhizosolenia* occurred in wide area of the Ariake Sea and damaged seaweed production. The Ariake Sea suffered a poor harvest and with decreased output by 50 percent of other years [(1)]. It is not yet clear exactly what has caused red tide and poor water quality in the Ariake Sea. Water quality in the Ariake Sea not only has an economic impact because of the economic activities it supports but also a social and environmental impact because it contributes to the quality of people's lives. Therefore, the management of water quality in the Ariake Sea is necessary. As the result, the present paper aimed to investigate water quality, algal production and red tide especially *Chattonella* in the Ariake Sea in order to support the decision making for water quality management in further study.

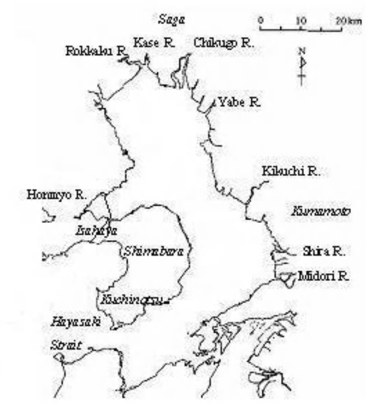

Fig. 1 The Ariake Sea and the rivers flowing into the Ariake sea

Received May 9, 2007
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2. Red tide and *Chattonella* life cycle

Okaichi [2] stated that, the expression "red tides" became common in Japan during the later half of 1960s, irrespective of whether or not there was damage to fisheries and aquacultures. The description "red tide" is visual and not scientific, and the phenomenon referred to by Okamura [3] is known as "water bloom" in Europe, the U.S. and other countries, but in Japan the meaning of the term translated into Japanese is not so clear, so "red tides" seems to be more popular in spite of some scientific report published in Japan with the title of "*Akashio ni tsuite*" (in English, "On red tides") was by Nishikawa [4] and in some old overseas reports, "red tides" were also used to express seawater color changes.

Chattonella first appeared in Hiroshima Bay in 1969. *Chattonella* is classified in division of Heterokontophyta division and Raphidophyceae class [5]. *Chattonella* is form of red tide in coastal eutrophicated waters; associated with mass mortality of fish and some species product cysts [6]. It is well known that *Chattonella* has a cyst stage for overwintering, and the cysts play a major role in the total ecology of the *Chattonella* by serving several important functions [7]. Cysts settle to bottom sediments to overwinter. When resuspension process of SS by tide and wind occurs, *Chattonella* cysts lying in the bottom sediments are resuspended to water column. Similar to other phytoplankton, the appropriate conditions for growth are sunlight, nutrients, water temperature and other limiting factors. When these environmental conditions reach the optimum for photosynthesis, *Chattonella* is blooming. *Chattonella* actively absorbs the nutrients and usually floats at surface water in day time. At night, *Chattonella* sinks down from the water surface to the lower layer and absorbs the nutrients needed [8]. However, time step of this model is one day; all of parameters including *Chattonella* concentration are the average within one day.

It seemed to be not easy to develop simulation model on *Chattonella* red tide outbreak, which is controlled by complex factors, using the rather limited amount of information available. This study, parameters concern in the model is temperature, major nutrients as nitrogen and phosphorus and suspension process for *Chattonella* productivity. Okaichi [2] found that phosphorus is the limiting factor for growth of *Chattonella antiqua* and the second is soluble iron. As the solubility of iron in natural seawater is 0.0034 ppm [9] and iron data are not available; therefore to simplify water quality model, iron limiting factor for *Chattonella* is neglected.

3. Water quality model

In this study, Isahaya water quality model [10] is combined with the Ariake Sea model.

Two-dimensional water quality model in the Ariake Sea is modified based on the finite volume model [11] as shown in Fig. 2. In this model, the Ariake Sea is divided into 11 elements; each divided element is considered to be in complete mixing state.

Water quality parameters in this model are chemical oxygen demand (COD), suspended solids (SS), dissolved inorganic nitrogen (DIN), orthophosphate phosphorus (PO_4), chloride ion (Cl^-) and chlorophyll-a (Chl-a). In this study, there are 4 kinds of algae concerned, namely, diatom, green algae, blue green algae, and *Chattonella*. With given boundary conditions, a net flow rate between two adjacent elements can be obtained from the continuity equation in Eq. (1) [11]. Basic equation in each element of the finite volume model [12] is described in Eq. (2). The reaction terms of DIN and PO_4 of element n are described as S_N and S_P in Eqs. (3) and (4). The substantial biomass change of algae (AG) is shown in Eq. (5). The reaction term of suspended solids (S_S) in element n is expressed in Eq. (7). The reaction term of particulate COD (S_{CP}) and dissolved COD (S_{CD}) are described in Eqs. (10) and (12), respectively. The simulation period is from 1997 to 2000 and time step of model is one day.

According to salinity level, the Ariake Sea is divided into three parts, namely, innermost part, central part and gulf mouth as shown in Fig. 2. In this study, element 1, 4 and 9 which represent the gulf mouth zone, the central part and the innermost part are discussed. The description for each parameter in Eq. 1 to 12 and parameters of the developed finite volume model obtained from the calibration are listed in Table 2 and 3 respectively. Fig. 3 demonstrates the optimal temperature for algal productivity in the Ariake Sea obtained from the developed model.

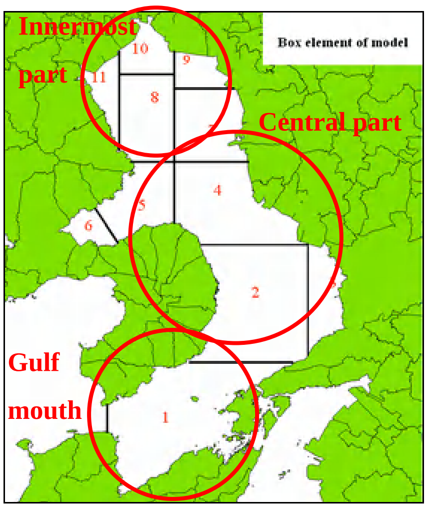

Fig. 2 The Ariake Sea and divided elements

$$\frac{dV_n}{dt} = \sum Q_{nm} + Q_{B(n)} \quad (1)$$

$$\frac{dc_{(n)} \cdot V_{(n)}}{dt} = \sum \{ Q_{nm} [\delta_{nm \cdot c(m)} + (1-\delta_{nm}) c_{(n)}] + E'_{nm} (c_{(m)} - c_{(n)}) \} \pm S_{(n)} \quad (2)$$

$$S_N = -\sum_{x=1}^{4} Y_{N(x)} \cdot AG_{(x)} + K_{RN} \cdot DIN_B \cdot R_M \cdot A \quad (3)$$

$$S_P = -\sum_{x=1}^{4} Y_{P(x)} \cdot AG_{(x)} + K_{RP} \cdot PO4_B \cdot R_M \cdot A \quad (4)$$

$$AG_{(x)} = \left(\mu_{(x)} - K_{D(x)} \cdot \theta_{(x)}^{(T - T_D(x))} \right) CH_{(x)} \cdot V \quad (5)$$

$$\mu_{(x)} = \mu_{MAX(x)} \cdot T_{G(x)} \frac{DIN}{\left(K_{N(x)} + DIN\right)} \frac{PO4}{\left(K_{P(x)} + PO4\right)} \quad (6)$$

$$S_S = SS_{RS} - K_{SS} \cdot B_S \cdot SS \cdot A \quad (7)$$

$$SS_{RS} = (R_T \cdot K_{RT} + K_{RW}) \frac{R_M \cdot A}{D} \quad (8)$$

For $v_w > v_w^*$ $K_{RW} = \phi \cdot K_W [(\frac{v_w}{v_w^*})^2 - 1]$

In which $\phi = 1 - \frac{\phi_w}{2} [1 - \cos(\varpi^* - \varpi)]$

For $v_w \le v_w^*$ $K_{RW} = 0$ (9)

$$S_{CP} = Y_{SC} \cdot SS_{RS} - \left(K_{SC} \cdot PCOD + SCOD_{ALGAE} \right) A + \sum_{x=1}^{4} Y_{C(x)} \cdot AG_{(x)} \quad (10)$$

$$SCOD_{ALGAE} = \sum_{x=1}^{4} Y_{C(x)} \cdot K_{SA(x)} \cdot CH_{(x)} \quad (11)$$

$$S_{CD} = K_{RC} \cdot DCOD_B \cdot R_M \cdot A \quad (12)$$

Table 2 Description for each parameter used in Model of the Ariake Sea

	parameter	unit
V	Water volume of element	m^3
Q_{nm}	Net flow rate between element n and m	m^3/s
Q_B	Boundary condition of flow rate of the element	m^3/s
c	Average concentration in the element	g/m^3
δ_{nm}	Net advection factor between element n and m	-
E'_{nm}	Mixing coefficient between element n and m	m^3/s
S	Reaction term	g/s
Y_N	DIN: Chl-a	mg DIN/µg Chl-a
Y_P	DIP: Chl-a	mg DIP/µg Chl-a
K_{RN}	Release rate of DIN	g/m^2-d
K_{RP}	Release rate of DIP	g/m^2-d
DIN_B	DIN in mud bed	g/m^3
DIP_B	DIP in mud bed	g/m^3
R_M	Ration of mud bed area in the element	-
A	Element area	m^2
K_D	Specific decay rate	1/d
θ	Temperature coefficient for decay	-
T_D	Critical temperature for decay	^oC
T	Water temperature	^oC
$\mu_{\max}$	Maximum specific growth rate	1/d
T_G	Temperature coefficient for algae growth	-
K_N	Saturation constant of DIN	g/m^3
K_P	Saturation constant of DIP	g/m^3
CH	Chlorophyll-a	mg/m^3
DIN	Dissolved inorganic nitrogen	g/m^3
$PO4$	Orthophosphate phosphorus	g/m^3
SS_{RS}	Resuspension suspended solids	m/d
K_{SS}	Settling velocity of SS	m/d
B_S	Settling coefficient	-
SS	Suspended solids	g/m^3
Y_{SC}	PCOD content of particulate materials in mud bed	mg COD/ mg SS
K_{SC}	Settling velocity of PCOD Particulate COD	m/d

PCOD	Particulate COD	g/m^3
Y_C	PCOD: Chl-a	mg COD / µg Chl-a
K_{SA}	Settling velocity of algae	m/d
K_{RC}	Release rate of DCOD	g/m^2-d
$DCOD_B$	DCOD in mud bed	g/m^3
R_T	Resuspension coefficient due to tidal movement	-
K_{RT}	Resuspension rate due to tidal movement	g/m-d
K_{RW}	Resuspension rate due to wind	g/m-d
D	Water depth of the element	m
v_w	Maximum wind speed	m/d
v_w^*	Critical wind speed	m/d
ϕ_w	Wind direction factor	-
ϖ^*	Critical wind direction for resuspension	m/d
ϖ	Direction of maximum wind speed	radian

Note: Subscripts *n* and *m* denote the considered element and the adjacent element, respectively.

Table 3 Parameters used in the two-dimensional finite volume model of the Ariake Sea

	parameter	unit
μ_{max}	0.34/ 0.3/ 0.32/ 0.75	1/d
K_N	0.07/ 0.05/ 0.05/ 0.03	mg/l
K_P	0.01/ 0.01/ 0.02/ 0.006	mg/l
K_D	0.01/ 0.005/ 0.005/ 0.003	mg/l
θ	0.014/ 0.014/ 0.016/0.014	-
T_D	19/ 24/ 30/ 27.3	^oC
K_{SS}	0.1	m/d
K_{SC}	0.1	m/d
K_{SA}	0.1/ 0.1/ 0.1/ 0.1	m/d
K_{RC}	0.05	g/m^2-d
K_{RN}	0.05	g/m^2-d
K_{RP}	0.02	g/m^2-d
Y_N	0.02/ 0.02/ 0.02/ 0.035	mg DIN/µg Chl-a
Y_P	0.0012	mg DIP/µg Chl-a
Y_C	0.035	mg COD/µg Chl-a
Y_{SC}	0.1/ 0.1/ 0.1/ 0.1	mg COD/ mg SS

Note: Diatom/ Green algae/ Blue green algae/ *Chattonella*

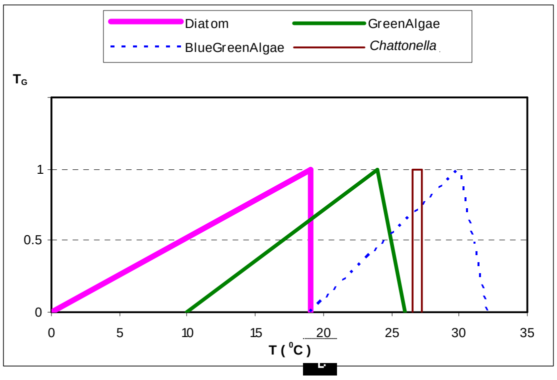

Fig. 3 Coefficients of temperature for each algae growth

4. Result and Discussion

4.1 Salinity

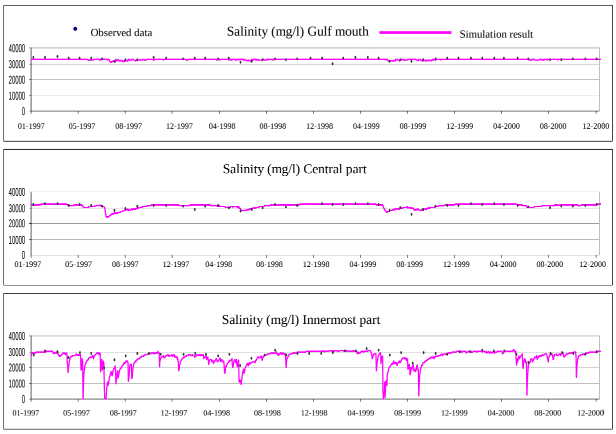

Fig. 4 Salinity concentration in gulf mouth, central part and innermost part of the Ariake Sea

The simulation of salinity in Fig. 4 has good agreement with the observed data which means the given advection coefficients and dispersion coefficients in momentum equation are satisfied. Beside this, the momentum equation can be used to simulate other water quality parameters as well. Approximated chloride concentrations of element 1, gulf mouth, which connected to the open sea, is 33,000 mg/l and higher than in the central part and the innermost part. Between element 4 and 9, central part and innermost part, lower concentrations occurred during high rainfall periods. Moreover, fluctuated salinity concentration can often be seen at element 9, indicating that the influence of Chikugo River is often greater than the discharge flow from other watersheds.

4.2 Suspended solid

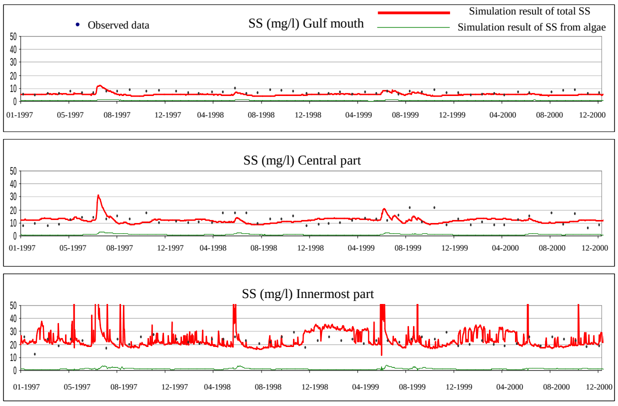

Fig. 5 SS concentration in gulf mouth, central part and innermost part of the Ariake Sea

High SS concentration occurs because of high discharged loading during high rainfall periods. Simulation results of SS in the innermost part are fluctuated and higher than gulf mouth zone and central part. It means SS loading from land area which contributed from Chikugo River watershed is higher than other watersheds. Furthermore, it agrees that high flow rate from Chikugo River is also discharged into the Ariake Sea. The resuspension of bottom deposits in the Ariake Sea has been studied and shown that resuspension from mud bed plays an important role on SS and PO_4 in the innermost part [11]. In this model, resuspension process can be generated by tidal currents and wind.

4.3 Nutrients

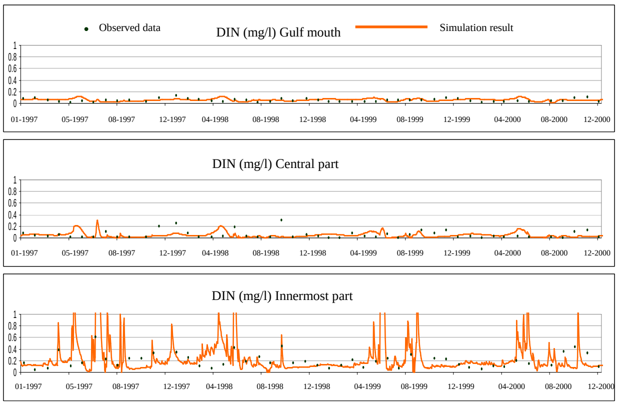

Fig. 6 DIN concentration in gulf mouth, central part and innermost part of the Ariake Sea

DIN and PO_4 concentrations of gulf mouth, central part and innermost part are shown in Figs. 6 and 7. Both of DIN and PO_4 are lower in gulf mouth zone because nutrients in this area are diluted by sea water from the open sea. Simulation results of DIN in the innermost part are higher than central part because of high discharged loading from Chikugo River watershed. Lower DIN simulation results in the central part mean the discharged loading from the surround watersheds has small effect to DIN in the Ariake Sea. For PO_4, simulation results in central part and innermost part are high in irrigation period because of discharge loading from watershed. However, during summer and period of low discharge loading from land area, PO_4 is still high. It occurs from the release process from the mud bed. It can be said that, orthophosphate for algae production is in excess. As the result, it is found that inorganic nitrogen is the growth-limiting factor for algae in the Ariake Sea.

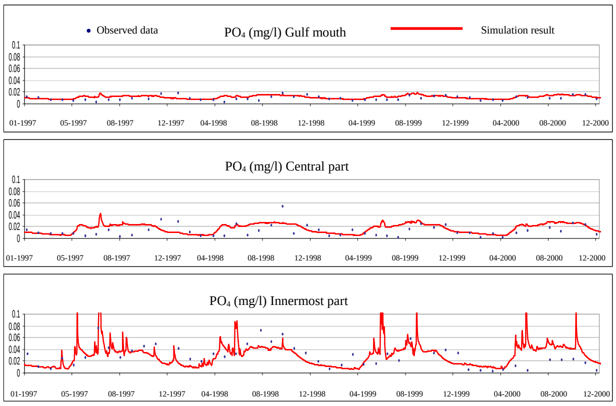

Fig. 7 PO_4 concentration in gulf mouth, central part and innermost part of the Ariake Sea

4.4 COD

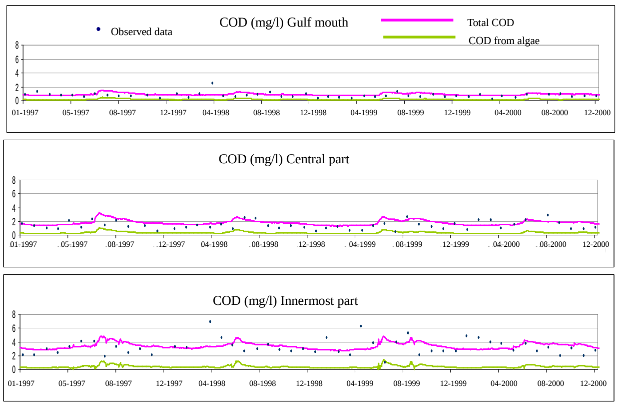

Fig. 8 COD concentration in gulf mouth, central part and innermost part of the Ariake Sea

COD simulation results are shown in Fig. 8. COD concentrations in gulf mouth zone and central part are lower than the innermost part. However, COD simulation results in the innermost part have fairly good agreement with observed data only in some period. Simulation results are lower than observed data during spring. In the future study, to provide better agreement of COD simulation results with observed data, Chlorophyll-a simulation results should be concerned more in detail. Nevertheless, these simulation results suggest that high COD occurs during high algal productivity. Mud bed also plays an important role for the release process of COD especially during summer.

4.5 Chlorophyll-a concentration

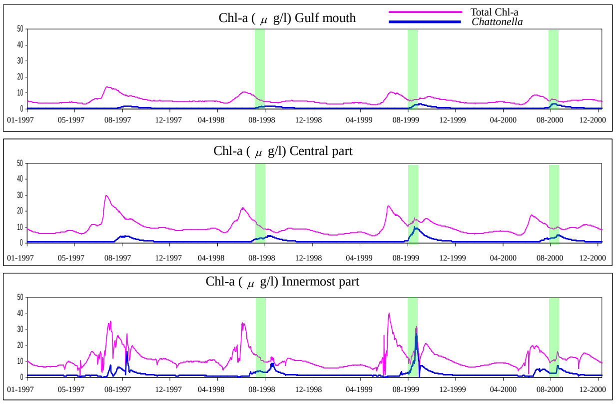

Fig. 9 Chl-a concentration in gulf mouth, central part and innermost part of the Ariake Sea

Chlorophyll-a concentration for gulf mouth, central part and innermost part are shown in Fig. 9. From Chlorophyll-a simulation results, higher concentration occurs in the innermost part of the Ariake Sea, element 9, due to high nutrient discharge from Chikugo River watershed. Results of Chlorophyll-a simulation reveal that high *Chattonella* occurs at the same time when high SS concentration occurs which shown in Fig. 5. That is, occurrences of *Chattonella* can be affected by high SS concentration after high resuspended period. Furthermore, the simulation results are almost happened in the same time with observed data, occurring periods of *Chattonella* bloom, as shown in the shade columns in Fig. 9. From this agreement, it can be verified that this water quality model can simulate the periods of *Chattonella* bloom in the Ariake Sea. In addition, it is clearly shown that *Chattonella* is resuspended from the bottom.

5. Conclusions

From simulation results of three parts in the Ariake Sea, the most important area which should be strongly concerned is the innermost part. The influence of Chikugo River watershed to nutrients and SS loading greater than the discharge flow from other watersheds, such as in the gulf mouth zone and central part. The contributions from mud bed such as release of dissolved matters and resuspension of particle also play an important role on water quality in the Ariake Sea, especially SS. From this study, it can be said that blooming of *Chattonella* phenomenon in the Ariake Sea is the effect of the bottom resuspension process. In the other words, without this resuspension process *Chattonella* will not be occurred. Poor water quality in the Ariake Sea is caused by rapid growth of algae during high nutrients discharge loading period. It means, *Chattonella* productivity can be caused by high resuspension rate which represented by high SS concentration under the other optimum conditions such as nutrient, temperature and etc. In order to control *Chattonella* blooms in the Ariake Sea, management of water quality especially SS is very important issue. Form this study, it can be concluded that the *Chattonella* is one of significant red tide species in the Ariake Sea and the behavior of *Chattonella* should be concerned in the water quality model of the Ariake Sea.

6. Acknowledgement

The authors gratefully thank Kyushu Regional Development Bureau, Ministry of Land, Infrastructure and Transportation for offering useful information of the Ariake Sea.

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