EVALUATION OF HYDRODYNAMIC EFFECTS ON BLUE CARBON DYNAMICS IN THE YATSUSHIRO SEA

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ABSTRACT

In this study, we conducted the first field measurement of blue carbon dynamics in the Yatsushiro Sea, which is a semi-enclosed bay in Japan, in order to analyze water quality parameters such as Dissolved Inorganic Carbon (DIC) and Total Alkalinity (TA) that have the greatest influence on the partial pressure of carbon dioxide (pCO_2) in seawater. In addition, we tried a hydrodynamic numerical simulation by a 3D model that can evaluate hydrodynamic effects, such as the effects of freshwater inflow from rivers and seawater inflow from the Ariake Sea, on the dynamics of DIC and TA in the bay. As a result of this study, we find out the followings: i) the value of ΔTA is extremely low comparing to the past study in another coastal region (Tada *et al*., 2015); ii) the largest effects of the inflow of seawater from the Ariake Sea can be evaluated as about 2%; and iii) the inflow effects of the small rivers are totally accounted for about 3.54% of the value of the Kuma River.

Keywords: blue carbon, global warming, field measurement, 3D numerical model, Yatsushiro Sea

1. INTRODUCTION

With the rapid development of the industry, carbon dioxide CO2, one of the main causes of global warming, is rapidly increasing in the atmosphere due to anthropogenic emissions. It is predicted that the anthropogenic continuous increase in atmospheric carbon dioxide concentration will lead to significant changes in climate (Houghton *et al*., 1995). In order to prevent various adverse effects caused by climate change, effective mitigation measures such as reducing greenhouse gas emissions are necessary.

In 2009, a report (Nellemann *et al*., 2009) clarifies that carbon segregated and stored by photosynthesis in marine ecosystems corresponds to approximately 55% of the carbon stored in global photosynthesis (including land area). The report is "*Blue Carbon. A rapid response assessment*", co-published by the United Nations organizations such as UNEP (United Nations Environment Program), FAO (United Nations Food and Agriculture Organization), and IOC/UNESCO (Intergovernmental Oceanography Committee/United Nations Educational, Scientific and Cultural Organization). The ocean plays a major role in the global carbon cycle. Approximately 90% (about 40 Tt) of the CO2 on the earth is present in the ocean, as well as its role as the largest sink for the long-term preservation of carbon. The carbon that is separated and stored in the marine ecosystem is called "*blue carbon*".

In addition, as a sink of carbon sequestration and storage, coastal waters are considered to be particularly important (Mcleod *et al*., 2011; Watanabe and Kuwae, 2015). It is clear that about 45 to 71% of blue carbon is absorbed by the shallow coastal waters (seas from coast to continental shelf (< depth of 200 m)). In mangrove forests, salty wetlands, and seagrass beds located in shallow coastal waters, only 0.05% of the plants are present compared to the existing amount of all land plants, but their annual carbon stock is comparable to the amount of carbon stored in all the terrestrial plants on the earth. Some studies have estimated that the rate of carbon accumulation is higher in coastal sediments (238 Tg C yr^{-1}) than that in open ocean sediments (6 Tg C yr^{-1}) (Nellemann *et al*., 2009). Therefore, coastal waters with vegetation such as algae are considered to be important sinks for carbon sequestration and storage.

However, researches on coastal waters are far less than researches on open ocean. Recently, Europe and the United States began to focus on the study on the dynamics of carbon dioxide in coastal waters (Chen and Bortges, 2009). While, as the country with the sixth-longest coastline in the world, Japan has extremely rich coastal resources which is very important for storing and sequestrating carbon. But data on the dynamics of carbon dioxide in coastal waters around Japan are very scarce. In order to predict more accurately and prevent the negative effects of global warming, it's quite necessary to understand the dynamics of partial pressure of CO_2 (pCO2) in seawater in a variety of coastal oceans around Japan.

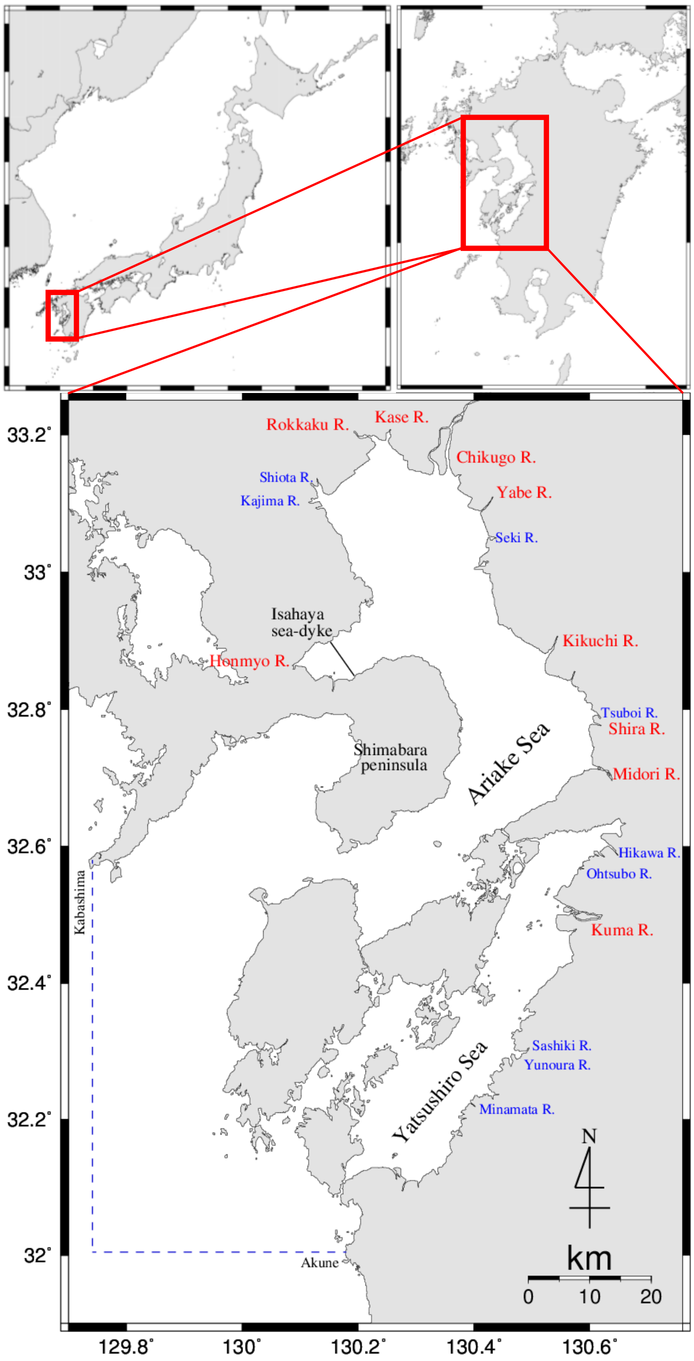


Figure 1. The location of the Yatsushiro Sea and related rivers, and computational domain for numerical model.

According to the chemical equilibrium relationship, pCO_2 in seawater is mainly calculated from the dissolved inorganic carbon concentration (DIC) and the total alkalinity (TA) (Zeebe and Wolf-Gladrow, 2001). Water quality parameters affecting pCO2 in water include water temperature, salt content (salinity), DIC, and TA. These variables can fluctuate complicatedly on a short time scale. In addition, pCO2 in seawater varies greatly in time and space due to various factors, such as physical processes like flows of seawater, and mixing of seawater and riverine freshwater, and biological processes like photosynthesis, and respiration of aquatic plants calcification caused by corals.

In this study, we selected the Yatsushiro Sea, Japan as a research target region, which is a shallow semi-enclosed inland sea located in the western part of Kyushu island. The bay has a characteristic that it is extremely closable as compared with other inland bays in Japan (see Fig.1), has a high river influx loading rate, a large tidal range, and extensive tidal flats and brackish water area. We conducted the first field measurement of blue carbon dynamics in the Yatsushiro Sea, in order to analyze water quality parameters such as DIC and TA that have the greatest influence on pCO2 in seawater. In addition, we tried to develop a 3D numerical model that can evaluate hydrodynamic effects, such as the effects of inflow from rivers and the Ariake Sea, which is connected to the Yatsushiro Sea by three very narrow channels, on the dynamics of DIC and TA in the bay.

The DELFT3D model (Deltares, 2011) is used to evaluate the hydrodynamic effects on blue carbon dynamics in the Yatsushiro Sea. The specific method is to use the WAQ-PART module of DELFT3D to develop a particle tracking numerical model to simulate the amount of the inflow that flowing into the measurement points from the Ariake Sea and rivers. DELFT3D PART module can simulate the transportation and simple water quality processes by using particle tracking methods from the FLOW module's (2D or 3D) flow data. The three-dimensional trajectory is tracked over time, whereby the dynamic concentration distribution is obtained by calculating the mass of the particles in the grid cell.

2. FIELD MEASUREMENT

2.1 Measurement point and date

The measurement point is set near the mouth of Kuma River, which is the largest class-A river in the bay, in the northern Yatsushiro Sea is shown in Fig.2.

The measurement dates were August 26, 2018, in the summer stratified season, and December 7, the same year in the winter well-mixed season, and both periods were during the spring tide. The measurement period was set from the high tide in the morning around 9 AM to the low tide around 3 PM in the both measurements.

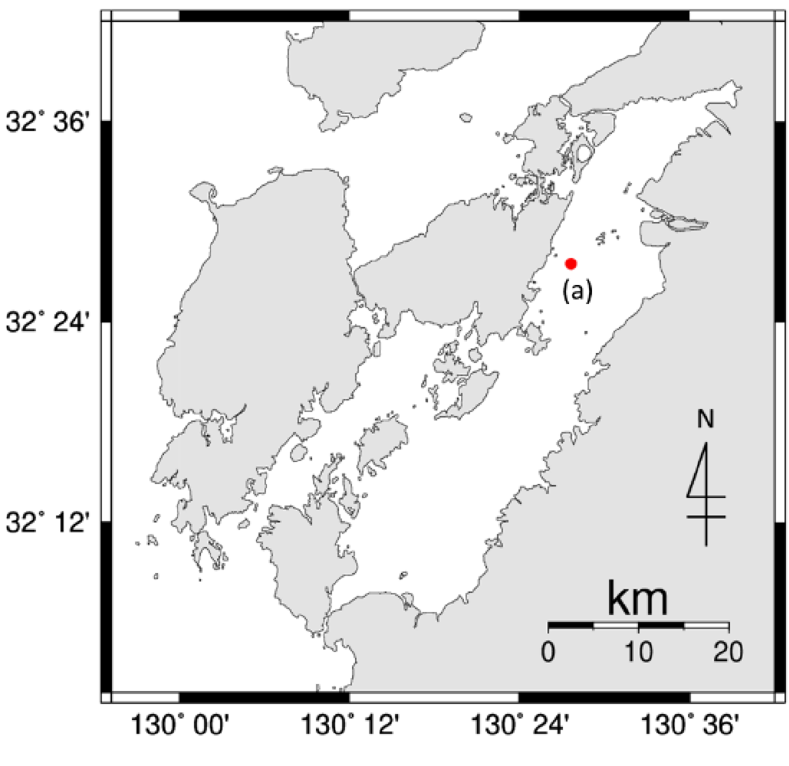


Figure 2. Measurement point location.

2.2 Methodology of field measurement

Vertical profiles of water temperature, salinity, *etc*. were measured every 20 minutes using CTD (ProDSS, YSI Co. Ltd, USA). Measurements of DIC and TA were conducted by collecting water samples in total of 6 layers of water depths (0 m, 3 m, 6 m, 9 m, 12 m, and 15 m under sea surface) five times (at high tide, 1.5 hours after high tide, maximum tide of ebbing, 1.5 hours before low tide, and low tide). Thus, 30 samples were totally taken. The deviation ΔDIC and ΔTA due to biological processes were calculated as the difference between the value of DIC and TA estimated from the mixing ratio (from the endmembers in the Kuma River freshwater and outer sea area) and the measured values.

2.3 Results and discussion

The comparison between ΔDIC and ΔTA obtained from this measurement and ones from the previous study (Tata *et al*., 2015) is shown in Table 1. As we can see, compared to seagrass meadow, ΔDIC shows similar values, but ΔTA is extremely low. Therefore, we can consider that DIC and TA measured at the measurement point are affected by both the photosynthesis of plants and the calcification of corals. However, although ΔDIC and ΔTA are calculated by considering the influence of the A-class river Kuma River that accounts for 60% of the whole catchment area inflow into the Yatsushiro Sea, we still need to evaluate whether other smaller rivers have obvious effects on DIC and TA measured in this study. In addition, because the measurement point is located near the strait between the Ariake Sea and the Yatsushiro Sea, the effects of the inflow of seawater from the Ariake Sea on the measured data must be considered as well. Thus, we can consider that the factors affecting DIC and TA at the point are both of hydrodynamic factors such as the seawater inflow from the Ariake Sea and the freshwater inflow from other small rivers, and biological factors such as the photosynthesis of seaweeds and phytoplankton and the calcification of corals. Next, we tried to develop a numerical model to evaluate the hydrodynamic factor’s effects.

Table 1. Comparison between ΔDIC and ΔTA obtained from the measurement and ones from the previous study (Tata *et al*., 2015)

	Measurement area	Ecosystem type	ΔDIC [μmol/kg]	ΔTA [μmol/kg
This study	Yatsushiro sea (2018/8/26)	unknown	-118.1±15.0	-57.3±13.3
	Yatsushiro sea (2018/12/7)	unknown	-70.2±2.7	-58.8±2.4
Previous study (Tata et al.,)	Furen lagoon	seagrass meadow	-62.0±18.7	-29.1±22.6
	Komuke lagoon	seagrass meadow	-230.3±85.2	16.7±119.3
	Hashirimizu coast	seagrass meadow	-36.5±9.0	9.5±4.9
	Nojima coast	seagrass meadow	-311.7±206.2	-1.1±21.9
	Matsuwa mudflat	mudflat	8.9±101.0	44.9±48.8
	Banzu mudflat	mudflat	27.6±15.6	50.3±88.8
	Futtsu mudflat	mudflat	-85.6±108.7	-45.9±27.5
	Fukidogawa estuary	coral reef	17.5±14.9	-111.3±21.9
	Shiraho coast	coral reef	-48.4±177.7	-132.1±113.2

3. NUMERICAL MODEL

3.1 Methodology of the numerical model

In this study, the generalized hydrodynamics numerical model DELFT3D in a coastal region and an estuary is applied to evaluate the hydrodynamic effects on the blue carbon dynamics in the Yatsushiro Sea.

3.1.1 Hydrodynamic model

The hydrodynamic model was basically built by Yano *et al*. (2010). They developed a 3D numerical model that can calculate unsteady flow and transportation of salinity and heat from tidal and climatic conditions by applying the DELFT3D-FLOW module. The computational domain includes both the Yatsushiro Sea and the Ariake Sea.

3.1.2 Particle tracking model

In this study, a particle tracking model to calculate the amount of seawater inflow from the Ariake Sea and freshwater one from small rivers was developed by applying the D-WAQ PART module in DELFT3D. The hydrodynamic results such as velocity are coupled into the module first. In this model, the effects of vertical and horizontal dispersion are not to be considered (Deltares, 2011).

We can instantaneously release particles in two areas with an optional radius near the strait connects two bays. The radius of 4,250m for one area and 5,000m for the other are shown in Fig.3. The initial concentration of particles was 1 kg/m^3 in both areas. In this way, we can evaluate the inflow rate of the seawater originated in the Ariake Sea into the Yatsushiro Sea comparing the concentration with the initial one. Here, we conducted four calculation cases with different release timing for the four tide periods in July 2018 at high tide and at low tide in both spring and neap tides.

Next, we evaluated the effects of small rivers. Continuous releases from four small rivers in the bay (B-class rivers: the Minamata River, the Ohtsubo River, the Hi River, and the Sashiki River) and the Kuma River were set. The release rate was set from linear interpolation data of the hourly river flow rate data by MLIT with a time interval of 2 hours. The particle concentration was 1 kg/m^3. River discharge of the B-class river was estimated by the specific discharge method using the nearest A-class river's data.

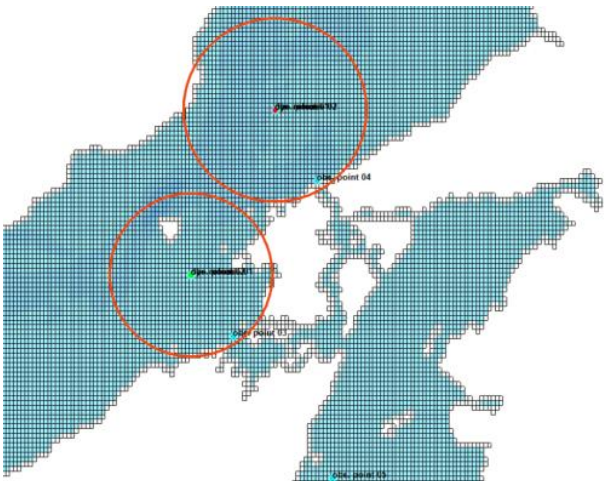


Figure 3. Instantaneous particle release areas near straits in the Ariake Sea

3.2 Results and discussion of numerical simulation

We choose the measurement point as an observation point in the present simulations. In the calculation of the inflow effects of the Ariake Sea, the temporal variations in the particle concentration of seawater at the observation point for each release timing case were calculated, and we compared these results as shown in Fig.4. We can see that the maximum peak of concentration is about 0.021 kg/m^3 at 8:00 on July 18, 2018, in case of the release at the low tide of spring tide. That means the largest effects of the inflow of seawater from the Ariake Sea can be evaluated as about 2%.

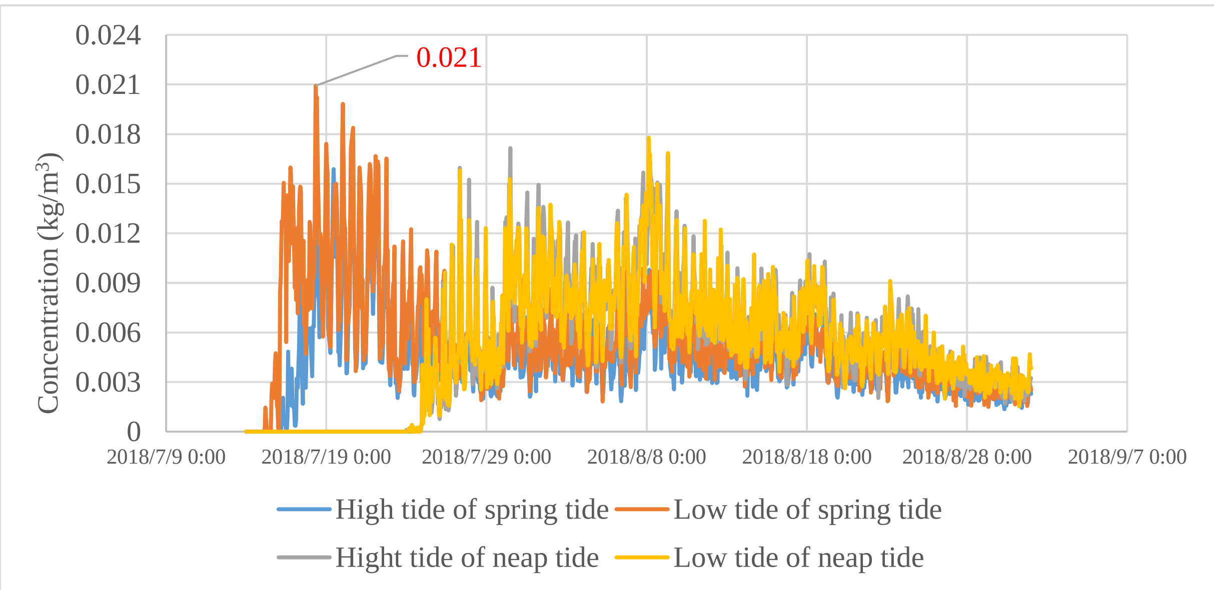
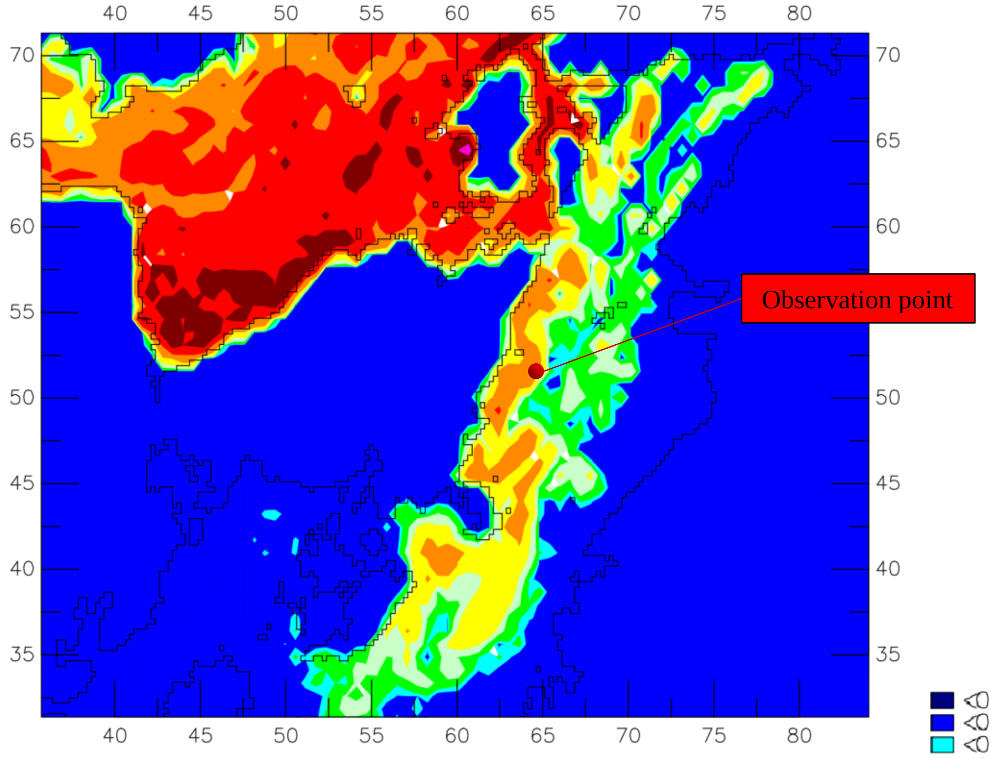
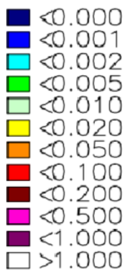


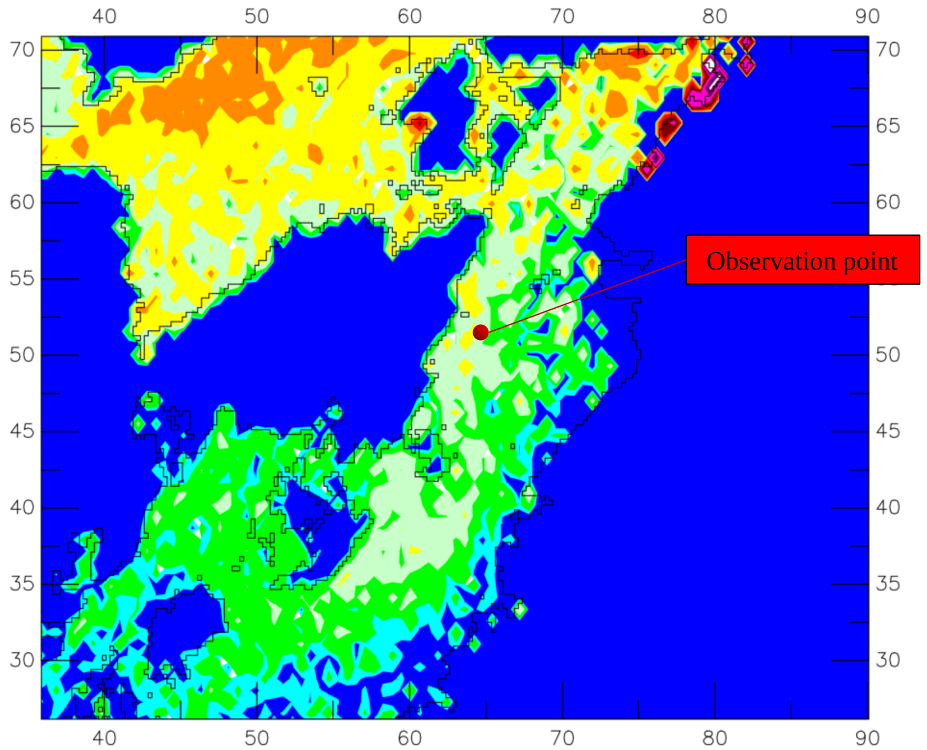
Figure 4. Comparison of the results from four cases of release timings.

Figure 5 shows the calculated particle concentration distribution in the case with release at the low tide of spring tide. The upper figure shows the result with the maximum concentration at the observation point at 8:00 on July 18, 2018, while the lower one shows after one month (8:00 on August 18, 2018,). We can see that once the effect of the Ariake Sea seawater in the area around the observation point reaches the maximum value of about 0.021, then it drops to less than one-fifth of the maximum (<0.005) and then is stable.



Particle concentration distribution at maximum time (8:00 on July 18, 2018)





1 month after maximum time (8:00 on Aug 18, 2018)

Figure 5. Particle concentration distributions at 8:00 on July 18, 2018, and at 8:00 on 18 Aug. 2018, in the case of release at the low tide of spring tide

In the calculation of the inflow effects of the smaller rivers, the particle concentration variation of the riverine freshwater flowing at the observation point was calculated. We compared these results in cases of five rivers including the Kuma River case as shown in Fig.6. We can see that the measurement point area was significantly affected by the freshwater from the Kuma River, and its maximum concentration of inflow reaches about 0.728 kg/m^3. Also, we calculated the effects of the inflow from the other four smaller rivers as shown in Table 2. We found that the inflow effects of the small rivers are totally accounted for about 3.54% of the value of the Kuma River. Therefore, it can be ignored. From these considerations, we can conclude that the hydrodynamic effect, namely, the inflows of the Ariake Sea seawater and freshwater of small rivers, on the pCO_2 dynamics is not significant in the area.

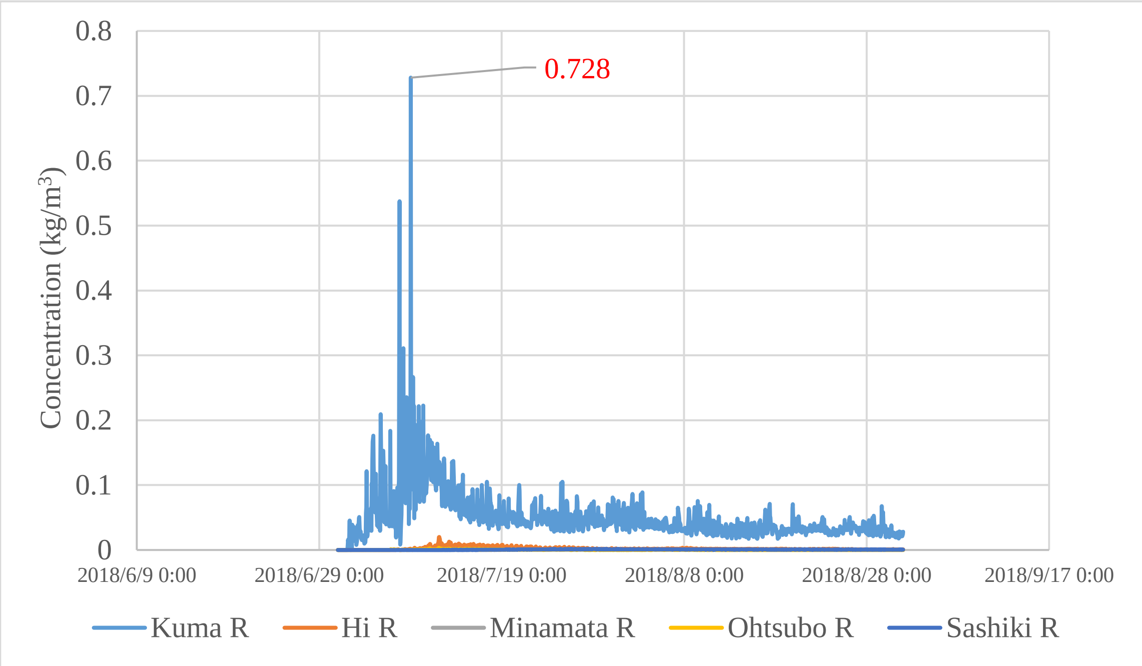


Figure 6. Comparison of the results in cases that release from five rivers

Table 2. Maximum concentration of the freshwater of five rivers flowing into the Observation point

River name	Maximum of concentration (kg/m^3)	Ratio to Kuma R
Kuma R	0.728	100.00%
Hi R	0.020	2.75%
Minamata R	0.001	0.14%
Ohtsubo R	0.003	0.45%
Sashiki R	0.001	0.20%

4. CONCLUSIONS

We conducted field measurement of the blue carbon dynamics and hydrodynamic numerical simulation to investigate the physical effects in the Yatsushiro Sea. As a result of this study, we found out the followings:

i) the value of ΔTA is extremely low comparing to the past study (Tata *et al.*, 2015);

ii) the largest effects of the inflow of seawater in the Ariake Sea can be evaluated as about 2%; and

iii) the inflow effects of the small rivers are totally accounted for about 3.5% of the Kuma River.

We can conclude that biological effects by photosynthesis of both seaweed and phytoplankton, and calcification of corals can be considered as a significant factor affecting the blue carbon dynamics in the bay.

ACKNOWLEDGMENTS

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