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Estimation of spatial distribution of coastal ocean primary production in Hiroshima Bay, Japan, with a geostationary ocean color satellite

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Abstract

Ocean primary production measured by conventional methods using carbon isotope are mostly calculated from point sampling, which is not appropriate for estimating the temporal and spatial variations involved in marine ecosystems. Ocean color remote sensing can estimate spatial variation of ocean primary production at the global scale. However, the spatial resolution of the ocean color remote sensing is not adequate for estimating coastal ocean primary production. This study sought to establish a novel methodology for estimating coastal ocean primary production in Hiroshima Bay, Japan using high-resolution ocean color data (~500 m) and higher temporal resolution (hourly during the day) obtained by a geostationary ocean color satellite, GOCI-COMS. Estimated values of primary production derived from the ocean color satellite based on the Kameda & Ishizaka model did not correlate with observed primary production. We estimated primary production in Hiroshima Bay with a modified Kameda & Ishizaka model. The coefficient of determination between observed and estimated primary production by the ocean color satellite was 0.750. The slope of the linear regression was 1.00, and root mean square error was 165 mg-C m^2 d^{-1}. Our proposed method was thus sufficient for discussions of the changes in spatial distribution of primary production in Hiroshima Bay. Finally, spatial distribution of primary production in Hiroshima Bay was

estimated using our proposed method. In January, the primary production of the Hiroshima Bay ranged <50-1000 mg-C m^{-2} d^{-1}, and increased to 1000-1600< mg-C m^{-2} d^{-1} during seasonal blooms in spring and autumn. The primary production was relatively high at the innermost and western parts of the bay which affected by terrigeneous loads compared to other parts of the bay. In July 2016, highest primary production was observed at the innermost of the bay, ranging from 1200–1600< mg-C m^{-2} d^{-1}. The high primary production was considered to be due to the supply of nutrients from terrigeneous load. Hence, our proposed method based on the high-resolution (approx. 500 m) ocean-color product has been enabled us to estimate primary production in coastal seas including complicated topographic areas such as enclosed seas or channels of less than 1 km wide.

Key Words

Carbon fixation, Coastal sea, Chlorophyll, Food chain, GOCI/COMS, Remote sensing

Highlights

Coastal primary production was estimated using a geostationary ocean color satellite.

GOCI-COMS was used to estimate primary production in Hiroshima Bay, Japan.

The root mean square error of estimated primary production was 165 mg-C m^2 d^{-1}.

The proposed algorithm is adequate for the monitoring of coastal primary production.

1. Introduction

Primary production (PP) is the synthesis of organic matter from inorganic substances such as carbon dioxide through photosynthesis or chemosynthesis. In aquatic ecosystems, algae are mainly responsible for PP, and thus support the base of the food chain. Therefore, PP is what is called the starting point of the material cycle in ecosystems. Approximately 45 gigatons of organic carbon is formed by marine phytoplankton each year, 16 gigatons of which are exported to the ocean interior (Falkowski et al., 1998). Therefore, PP by marine phytoplankton plays an important role in the global carbon cycle (Bauer et al., 2013; Siegel et al., 2016). PP is also important in the field of marine ecosystems. The biological productivity of lower trophic levels supports the production of higher trophic levels in food webs. Estimation of PP is therefore an essential step for understanding upper trophic level yields (Friedland et al., 2012). Hence, it is very important to quantify PP to understand the global carbon cycle and marine ecosystems in coastal seas, in addition to open oceans.

PP has conventionally been measured by the ^{14}C method, ^{13}C method, and oxygen light and dark bottle method (Steeman Nielsen, 1952; Hama et al., 1983; Gaarder and Gran, 1927). The ^{14}C and ^{13}C methods measure uptake rate of ^{13}C or ^{14}C labeled bicarbonate by photosynthesis of phytoplankton (Steeman Nielsen, 1952). The ^{14}C method is sensitive

because it measures ^{14}C labeled bicarbonate, which is phytoplankton uptake by photosynthesis, with a scintillation counter. Therefore, the ^{14}C method has been widely used to determine PP in, for example, arctic plankton PP (Engel et al., 2013), deep PP (Lyngsgaard et al., 2014) and Antarctic spring bloom PP (Johanna et al., 2015). However, it is difficult to apply the ^{14}C method in places such as Japan, where use of radioactive isotopes in the field is strictly controlled.

To measure PP in these areas, the ^{13}C method is usually applied. The ^{13}C method measures the isotopic balance of ^{13}C and ^{12}C before and after incubation, and estimates ^{13}C uptake by phytoplankton (Hama et al., 1983). The ^{13}C method takes a 4-h incubation to enrich ^{13}C into phytoplankton, because it is less sensitive than the ^{14}C method. In addition, an isotope ratio mass spectrometer is needed to determine the isotope ratio of ^{12}C and ^{13}C. The ^{13}C method has also been widely used (Kluijver et al., 2013; Shiozaki et al., 2013; Tsuchiya et al., 2013).

In the light and dark bottle method, PP is estimated from the difference of dissolved oxygen concentration in light and dark bottles after incubation (Gaarder and Gran, 1927). However, this method has low sensitivity. In addition, these methods all involve time-consuming incubation to measure PP in the ocean or laboratory. For those reason, most PP is calculated from spot sampling, which is not appropriate for estimating temporal and

spatial variations of ocean PP involved in marine ecosystems. In order to estimate temporal and spatial variations, ocean color remote sensing has been proposed (Feldman et al., 1989; Platt and Sathyendranath, 1988; Saino, 1993; Behrenfeld et al., 2006). Ocean color remote sensing enables estimations of temporal and spatial variation in ocean PP on a global scale. However, these studies have been chiefly based on coastal zone color scanner (CZCS) data, in which accuracy of phytoplankton pigment (chlorophyll-a; Chl a) is not sufficient and also data amount is not enough for estimating coastal ocean PP (1-20 km; Feldman et al., 1989). Presently, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and MODIS were used to estimate oceanic PP, and improved accuracy of Chl a concentration and time resolution of estimating oceanic PP (Bosc et al., 2004; Arrigo and Dijken, 2011). Although, these ocean color remote sensing enabled us to estimate spatial variations of ocean PP on a global scale, spatial resolution was not enough to estimate coastal ocean primary production. The high resolution, less than 1 km mesh was required for estimating coastal ocean PP because coastal ocean includes topographically complicated area such as enclosed seas or channels.

To provide a novel methodology for estimation of coastal ocean PP to overcome defects in conventional method, we use a high-resolution ocean color data (~500 m) with modifications which obtained by an ocean color satellite, GOCI-COMS. The Korean

geostationary satellite Communication, Ocean and Meteorological Satellite (COMS) equipped with a geostationary ocean color sensor, the Geostationary Ocean Color Imager (GOCI), was launched in June 2010. The GOCI is the world's first geostationary ocean color sensor that can measure radiance from the ocean surface in the visible and near-infrared bands for application to ocean remote sensing (Ryu et al., 2012; Choi et al., 2012). Observations from the GOCI-COMS enabled us to access high-resolution (~500 m) ocean color data, as well as higher temporal resolution (hourly during the day). These specifications are advantageous for estimating the temporal and spatial distribution of coastal ocean production compared to other sensors. The goals of this study were: (1) to establish a novel methodology for estimating coastal ocean PP from high-resolution ocean color data obtained by GOCI-COMS; and (2) to discuss the accuracy of our proposed method by comparison with field observation data; and ultimately (3) to reveal spatial distribution coastal ocean PP in Hiroshima Bay, Japan, using our proposed method.

2. Experimental

2.1 Study area of field observation

We measured the seasonal net PP (four times per year) at 7 sampling stations in Hiroshima Bay, Seto Inland Sea, Japan, between November 2014 and August 2015 (**Fig.**

1) in order to compare PP obtained by field observations with estimated values from the ocean color satellite (OCS).

Hiroshima Bay is a semi-enclosed bay located in the middle west part of the Seto Inland Sea, and measures about 30 km from east to west and 50 km north to south for a total area of 1043 km^2, with an average depth of 26 m. Hiroshima Bay is significantly affected by intensive oyster culture (annual production approximately 19,000 tons as meat weight) and terrigeneous loads from the Ohta River (catchment area: 1710 km^2). The yearly averaged discharge of the Ohta River is approximately 78.81 m^{-3} s^{-1} (Japan River Association). The terrigenous loads from the Ohta River form halocline in the northern part of the bay every summer. Ohta River input accounts for 90% of total freshwater input to the northern area of Hiroshima Bay. Entrained seawater from the southern area by the estuary circulation is 7-14 times larger than riverine fresh water input in the northern area of the bay (Yamamoto et al., 2000). Anthropogenic activities such as industrialization and urbanization have resulted in frequent summertime red tide since 1970s (Yanagi, 2008). In recent years, red tide occurrence in the bay decreased to only one or two times a year due to intensive reduction of nutrients load. However, the bottom sediments in the northern part of the bay are affected by high organic flux (Asaoka et al., 2018).

2.2 Sampling procedures of field observation

Training and research vessels, Hikari (National Institute of Technology, Hiroshima College) was used for the observations. Vertical profiles of temperature, salinity, fluorescence and photon flux density were measured using a multi electrode (AAQ176, JFE Advantec, Kobe, Japan).

To measure chlorophyll *a* (Chl a) and PP, 4 L of seawater was collected at depths of 100%, 50%, and 10% surface irradiance with a Van Dorn water sampler. The collected water samples were kept in cool and dark conditions, and transferred to a laboratory.

2.3 Sample treatment and analysis

To determine the Chl a concentration in the laboratory, 300 ml of seawater was filtered through glass-fiber filters (GF/F, Whatman, Maidstone, UK), and filter residues were extracted with 10 mL of 90% acetone under dark conditions at -20 °C for 16–24 hours. The extracts were sonicated for 20 min, and Chl *a* concentrations were determined fluorometrically (10-AU-5, Turner Designs, Sunnyvale, CA, USA), according to the Welschmeyer method (Welschmeyer, 1994).

To measure PP, seawater samples were filtered through a 220-µm mesh screen to remove large zooplankton, and then transferred into 500-mL polycarbonate bottles, which

regulated light intensity (50% and 10%) using cheesecloth. After the addition of $NaH^{13}CO_3$ (Cambridge Isotope Laboratories, Inc.), bottles were immediately incubated in a water bath at in situ temperature with light intensity of ca. 200 µmol-photons m^{-2} sec^{-1} using fluorescent lamps for 4 h. After incubation, the samples were filtered through precombusted (450 ºC, 4 h) GF/F filters, treated with 1 mol L^{-1} HCl for removal of inorganic carbon, and stored at -20 °C until isotope analysis. Particulate organic carbon (POC) and atom% of ^{13}C of the residuals on the dried filters (60 °C, 48 h) were analyzed by elemental analyzer-isotope ratio mass spectrometer (FlashA EA1112-DELTA V Advantage, Thermo Fisher Scientific, MA, USA). The photosynthetic rate was calculated according to Hama et al., (1983).

2.4 Estimation of primary production from field observation

Primary production was estimated by following Umehara et al., 2018. Chl a specific productivity was estimated as

$$PB = PR / CHL \quad \cdot \cdot \cdot (1)$$

where *PB*, *PR* and *CHL* are Chl a specific productivity (mgC mgChl.a^{-1} h^{-1}), photosynthetic rate (mgC m^{-3} h^{-1}), and Chl a concentration (mgChl.a m^{-3}), respectively.

PP in the euphotic zone (surface to depth of 1% surface irradiance) of the each station were obtained using the following equations:

$$PP_{STN} = 12 \times \int (PB_Z \times CHL_Z) dz \cdot \cdot \cdot (2)$$

$$PB_Z = a \times \left(\frac{I_Z}{I_0}\right) \times 100 \cdot \cdot \cdot (3)$$

where PP_{STN}, PB_Z and $CHLz$ are PP in the euphotic zone at each station (mgC m^{-2} d^{-1}), Chl *a* specific productivity at a depth of Z m (mgC mgChl.a^{-1} h^{-1}) and Chl a concentration (mgChl.*a* m^{-3}) at a depth of Z, respectively. In equation (3), a is a regression coefficient between relative irradiance (%) and Chl a specific productivity in the bay at each seasonal investigation. I_z and I_0 indicate photon flux density (μmol-photons m^{-2} sec^{-1}) at depth Z, and at the surface, respectively.

2.5 Estimation of primary production from the ocean color satellite

GOCI-COMS obtains eight hourly images during the day, and covers approximately 2,500 × 2,500 km^2 around the Japanese Islands and Korean Peninsula, centered at 36°N and 130°E with a spatial resolution of ca. 500 m and a very high signal-to-noise ratio (>1000) (Amin et al., 2013). GOCI has six visible bands, centered at 412, 443, 490, 555, 660, and 680 nm, and two near-infrared bands, centered at 745 nm and 865 nm. Level-1

products eight hourly images (9:00AM to 4:00PM) were downloaded from the website of the Korea Ocean Satellite Center (KOSC, http://kosc.kiost.ac/eng/p20/kosc_p21.html). Well-calibrated Level-2 products can be derived from Level-1 data converted with the GOCI Data Processing System (GDPS) developed by the Korea Institute of Ocean Science and Technology (Ryu et al., 2012). Products at 412, 443 and 572 nm were extracted in the study area from 34.40° to 33.90°N and 132.1° to 132.6° E. The acquisition period for GOCI products was from January 2015 to December 2017.

We used the vertically generalized production model (VGPM) established by Behrenfeld and Falkowski (1997) to estimate depth-integrated PP (*IPP*: mg C m^{-2} d^{-1}). In the VGPM, *IPP* was calculated as follows:

$$IPP = 0.66125 \; P_{opt}^{B} \; \frac{E_0}{E_0 + 4.1} \; Z_{eu} \; Chl_{opt} \; D_{irr} \quad \cdot\cdot\cdot (4)$$

$$E_{\%}(z) \cong 1 = \exp\{2.3(\kappa sat)z\} \quad \cdot\cdot\cdot (5)$$

$$P_{opt}^{B} = \frac{0.071T - 3.2 \times 10^{-3}T^2 + 3.0 \times 10^{-5}T^3}{Chl_{total}}$$
$$+(1.0 + 0.17T - 2.5 \times 10^{-3}T^2 - 8.0 \times 10^{-5}T^3) \quad \cdot\cdot\cdot (6)$$

where E_0 is daily photosynthetically active radiation (PAR) above the sea surface (E m^{-2} d^{-1}) obtained by MODIS/AQUA, Z_{eu} (m) is euphotic depth, defined as physical depth at 1% of E_0 (m) calculated by equation (5), and *ksat* is the extinction coefficient derived from Level-2 products with GDPS (m^{-1}). Photoperiod (D_{irr}) is set at 12 h, corresponding to estimation of PP used in field observations (Umehara et al., 2018). Chl a concentration at the sea surface (SSC) is used as daily mean Chl_{opt} (mg m^{-3}), which was calculated from hourly Chl *a* concentration obtained by GOCI. The optimal assimilation efficiency of the productivity (P^B_{opt} : mg m^{-3}) was defined as equation (6) established by Kameda and Ishizaka (2005), where Chl_{total} (mg m^{-3}) is Chl *a* concentration obtained from Level-2 products, Chl*a*. Daily surface temperature (SST) was obtained by MODIS/AQUA.

Chromophoric dissolved organic matter (CDOM: m^{-1}) was obtained by Level-2 products from GDPS (Nakada et al., 2018).

CDOM (λ=400 nm) was calculated using the remote sensing reflectance ratio of bands 1 (R_{rs} 412 nm) to 4 (R_{rs} 555 nm) with equation (7).

$$CDOM(400)=0.2355R^{-1.3423}\ m^{-1} \quad \cdots (7)$$

where $R=R_{rs}(412)/R_{rs}(555)$

The observed chlorophyll-specific photosynthetic rate as a function of PAR (P_{obs}) was

calculated from following equation (8).

$$P_{obs}=0.0109I+0.388 \quad \cdot\cdot\cdot \quad (8)$$

where P_{obs} is the observed chlorophyll-specific photosynthetic rate (μgC μgChla^{-1} h^{-1}), and I is PAR (μE m^{-2} s^{-1}).

3. Results and discussion

3.1 Accuracy of primary production estimated from the ocean color satellite

PP in Hiroshima Bay estimated from the ocean color satellite (OCS), based on Kameda & Ishizaka (2005) shown in equations (4) – (6), did not correlate with observed PP (coefficient of determination; r^2=0.109) indicating that the chlorophyll-specific photosynthetic rate proposed by Kameda & Ishizaka (2005) in equation 6 was not appropriate in Hiroshima Bay. In response to this result, we used an observed chlorophyll-specific photosynthetic rate to estimate PP using the OCS in equation (8), because the Seto Inland Sea is enclosed and affected by significant terrigenous nutrients load, resulting in a chlorophyll-specific photosynthetic rate that is different from the open ocean.

The observed chlorophyll-specific photosynthetic rate used in equation (8) was observed from Hiroshima Bay in autumn when nutrients were not a limiting factor in PP

292 because the concentration of DIN and DIP in the bay ranged from 3.1-25.3 and 0.4-1.5
293 μmol L^{-1}, respectively. Therefore, in autumn, the chlorophyll-specific photosynthetic rate
294 is controlled by PAR rather than by nutrients. The slope in equation (8) was almost the
295 same as in winter (0.0104) when nutrients were not a limiting factor in PP either.

296 The water temperature ranged from 20.5 to 21.5 ºC in autumn, and from 9.6 to 11.9 ºC
297 in winter. Because the slope of the chlorophyll-specific photosynthetic rate was almost
298 the same despite the water temperature in Hiroshima Bay, we did not take water
299 temperature into account when calculating the chlorophyll-specific photosynthetic rate
300 used in our proposed model (equation (8)).

301 When the observed chlorophyll-specific photosynthetic rate calculated by equation 8
302 was used to estimate PP obtained by equation 4, the coefficient of determination between
303 observed and estimated PP by the OCS improved to r^2=0.750 (**Fig. 2**). However, the slope
304 of the linear regression was 0.713, indicating that the PP estimated by OCS was
305 approximately a 28.7% overestimation compared to observed PP.

306 Other parameters for PP estimation in equation (4) were euphotic depth (Z_{eu}),
307 chlorophyll concentration (Chl_{opt}), $E_0/(E_0+4.1)$ and photoperiod (D_{irr}). Because
308 photoperiod corresponded to the estimation of PP in field observations, we did not take
309 photoperiod into account. Therefore, we compared other parameters from satellite-

derived euphotic depth (Z_{eu}), chlorophyll concentration (Chl_{opt}) , $E_0/(E_0+4.1)$, and observations of in situ. The relationship between the observed euphotic depth and the satellite-derived euphotic depth calculated by equation 5 is shown in **Fig. 3**. The euphotic depth value derived from OCS at Sts. 3 and 4, which are shallow areas (water depth 11~15 m) in winter, was estimated to be 27~29 m, high compared to observed water depth. This overestimation might be due to high transparency, which causes underestimation of the extinction coefficient by OCS resulting in the overestimation of euphotic depth. When the euphotic depth derived from OCS at these two stations in winter was excluded from the analysis, the slope of the linear regression was 0.971 (r^2=0.658; **Fig. 3**). The accuracy and precision of estimated euphotic depth from the OCS was evaluated by root mean square error (RMSE) (Sasaki et al., 2008). The RMSE and bias of the estimated euphotic depth was 3.2 and -0.19, respectively. Therefore, the euphotic depth derived from OCS was in good agreement with observed euphotic depth.

Chlorophyll a concentration (Chl_{opt}) is also significant factor in estimating PP. The relationship between observed Chl_{opt} and Chl_{opt} derived from the OCS in Hiroshima Bay is shown in **Fig. 4**. Although a linear relationship was observed between observed Chl a (average concentration of 0-5 m depth) and OCS-derived Chl a (r^2=0.835), the slope of the linear regression was 3.46. Therefore, the value derived from the OCS underestimated

chlorophyll a concentration (by approximately 1/3) compared to the observed value. The error here was might be attributed to atmospheric correction (Gordon, 1997; Cota et al, 2003; Hayashi et al., 2015).

When the corrected chlorophyll *a* concentration (3.46 times OCS-derived Chl *a*) was used to estimate PP calculated by equation 4, the slope of the linear regression was 0.206. The PP estimated by OCS was approximately 79% overestimation compared to observed PP.

The satellite-derived PAR used in this study ranged from 26.1–54.9 E m^{-2} d^{-1}, corresponding to 0.86–0.93 in $E_0/(E_0+4.1)$. Therefore, $E_0/(E_0+4.1)$ was not a significant parameter for estimating PP in equation 4.

Hence, the overestimation of PP by the OCS could not be explained by the errors attributed to euphotic depth (Z_{eu}), Chlorophyll a concentration (Chl_{opt}), or $E_0/(E_0+4.1)$. Therefore, the coefficient (0.66125) in equation (4) was tuned to 0.1362 to be consistent with observed PP. The coefficient used in Kameda & Ishizaka (2005), which was optimized to estimate PP in the open ocean, might not be appropriate for coastal and enclosed waters like Hiroshima Bay. Finally, we estimated PP based on equation (9) modified the equation (4).

$$IPP = 0.1362P_{obs} \quad \frac{E_0}{E_0 + 4.1} \quad Z_{eu} \;\; Chl_{cor} \quad D_{irr} \quad \cdot\cdot\cdot (9)$$

Chl_{cor} is used as 3.46 times (in the case of Hiroshima Bay) daily mean Chl a concentration calculated from hourly Chl a concentration obtained by GOCI.

Relationship between observed and corrected PP in Hiroshima Bay estimated from the OCS was shown in **Fig. 5**. The coefficient of determination between observed and corrected PP estimated by the OCS was r^2=0.750. The slope of the linear regression was 1.00. The RMSE, normalized RMSE (%), and bias were 165 mg-C m^{-2} d^{-1}, 31.2%, and 10.8, respectively. The RMSE of PP was less than the standard deviation (SD: 250) and relative standard deviations (RSD 57%) of observed PP at all stations, indicating that the error of estimated PP by the OCS was smaller than the temporal and spatial distribution of PP in Hiroshima Bay. Therefore, our proposed method is sufficiently accurate for discussions of changes in temporal and spatial distribution of PP in Hiroshima Bay.

PP obtained by our proposed model was compared to the previous VGPM developed by Behrenfeld & Falkowski, 1997 and Kameda & Ishizaka, 2005. The RMSE, bias, slope and the coefficient of determination between observed and PP estimated by this study were improved compared to the previous VGPM (**Table 1**). Our proposed model was modified both the chlorophyll a concentration and the chlorophyll-specific photosynthetic

rate (P^B_{opt}). As mentioned above, the chlorophyll a concentration was corrected to 3.46 times GOCI-derived chlorophyll a concentration to compensate for the error of atmospheric correction. The chlorophyll-specific photosynthetic rate in the VGPM proposed by Behrenfeld and Falkowski (1997) was defined as a function of SST. However, the observed chlorophyll-specific photosynthetic rate in Hiroshima Bay was almost the same despite the water temperature. In the case of modified VGPM developed by Kameda and Ishizaka 2005, the chlorophyll-specific photosynthetic rate was a function of SST and chlorophyll concentration at the sea surface considering the phytoplankton community; one was small-sized phytoplankton with high P^B_{opt} and the other was large-sized phytoplankton. The observed phytoplankton community in Hiroshima Bay was mainly composed of *Skeletonema costatum* and *Chaetoceros spp*. which accounted for 47-98% of the total cells (16-23,740 cells mL^{-1}) in November, February and August except at Sts. 6 and 7 in August. In contrast, 35-87% of phytoplankton was composed of *Leptocylindrus danicus* and *Cerataulina sp.* in May (Umehara et al., 2018). Because the dominant species of phytoplankton were only a few diatom species in Hiroshima Bay affected by terrigeneous load, we did not take phytoplankton community into account when calculating the chlorophyll-specific photosynthetic rate. Therefore, the chlorophyll-specific photosynthetic rate calculated by the previous VGPM developed by Behrenfeld

& Falkowski, 1997 and Kameda & Ishizaka, 2005 was not appropriate for estimating the chlorophyll-specific photosynthetic rate in Hiroshima Bay. Therefore, we modified the chlorophyll a concentration and the chlorophyll-specific photosynthetic rate to calculate PP. Ultimately, the coefficient (0.66125) in equation (4) was also adjusted to 0.1362 to be consistent with observed PP.

We also succeeded in estimating PP at St. 5 which was narrow area (1-3 km) surrounded by islands (**Fig. 1**). The error between observed and estimated PP was 1.3-23%. The high-resolution (~500 m) ocean color data obtained by the GOCI-COMS was advantageous for estimating the spatial distribution of PP.

3.2 Monthly variations of primary production in Seto Inland Sea estimated from the OCS

We estimated PP in Hiroshima Bay, Japan using a modified Kameda & Ishizaka model proposed in this study.

3.2.1 Primary production in 2015 (Fig. 6)

In January, PP at the innermost and western parts of the Hiroshima Bay ranged < 50-400mg-C m^{-2} d^{-1}. The PP at the center and southern parts of the bay was 500-1000mg-C

m^{-2} d^{-1}. This is because, Chl a concentration at the center and southern parts of the bay was 4-8 μg L^{-1}, which was higher than that of other areas (0.2-3 μg L^{-1}; **Fig. S1**). The SST at the center and southern parts of the bay was also higher than that of other areas (**Fig. S2**). Hence, it is considered that the PP at the center and southern parts of the bay was enhanced by the high SST.

In February, PP was almost uniformly distributed around the bay, ranging from 300–500 mg-C m^{-2} d^{-1}. In March, both PP and CDOM increased to 700–1300 mg-C m^{-2} d^{-1} and was 0.12–0.24 m^{-1} at the innermost and western parts of the bay (**Fig. S3**). Because CDOM showed significant negative correlations among observed sea surface salinity (SSS), CDOM is considered one of the powerful indicators of riverine plumes (Nakada et al., 2018). Hence, the innermost and western parts of the bay were substantially affected by terrigeneous load from the Ohta, Oze and Nishiki rivers compared to other areas. At the same time, Chl a concentration at the innermost and western parts of the bay increased by 4–15 μg L^{-1} (**Fig. S4**). Therefore, the increase of PP at the innermost part of the bay was attributed to spring bloom. In contrast, PP at the southeastern part of the bay was 400–700 mg-C m^{-2} d^{-1}. CDOM in the southeast was 0.06–0.12 m^{-1} and low compared to other areas, indicating that this part of the bay was affected by the intrusion of open-ocean water derived from Kuroshio (**Fig. S3**). Since the open-ocean water was low in nutrients,

the PP in the southeast bay was considered to be low. In April, the spring bloom expanded to the southeastern part of the bay and the PP ranged from 400–1400 mg-C m^{-2} d^{-1}. Such high productivity continued into September. In August-September, the highest PP was observed at the bay (500–1600 < mg-C m^{-2} d^{-1}) due to terriegeneous load, which agreed well with the high CDOM (**Figs. S5 and S6**). In October, PP of the bay decreased to 400–1200 mg-C m^{-2} d^{-1}. From November to December, PP at the bay decreased further to 250–700 mg-C m^{-2} d^{-1} except for blooming areas.

3.2.2 Primary production in 2016 (Fig. 7)

The low PP continued from November 2015 through January 2016. In February, spring bloom (Chl a concentration 15–50< μg L^{-1} **: Fig. S7**) was significantly observed at the southwest coast of the bay. The spring bloom might have been triggered by terrigeneous loads from the Oze and Nishiki rivers. Therefore, this bloom increased the PP to 800–1600 mg-C m^{-2} d^{-1} at the southwest coast. The increase of PP attributed to the spring bloom spread throughout the bay in March. The PP then decreased to 600–700 mg-C m^{-2} d^{-1} in April-May. However, the PP of the innermost and western parts of the bay kept 800-1600 mg-C m^{-2} d^{-1} due to terrigeneous nutrients load from the Ohta, Oze and Nishiki rivers. In June, PP at the innermost part of the bay increased again to 1600< mg-C m^{-2} d^{-1}. This

increase was considered to be a result of rainfall increasing the terrigeneous load, and was in good accord with high CDOM (0.20–0.24 m^{-1}; **Fig. S8**). This high productivity at the innermost part of the bay continued into August. In September, the PP decreased due to the depletion of nutrients at the center and southern parts of the bay (400–700 mg-C m^{-2} d^{-1}). It is clear that the depletion of nutrients decreased the Chl a concentration to 1.8–5 μg L^{-1} at the center and southern parts of the bay (**Fig. S9**).

In October, PP of the bay increased again to 600-1600 mg-C m^{-2} d^{-1}. The high PP was observed due to spring bloom at the innermost and center parts of the bay (1100-1600< mg-C m^{-2} d^{-1}). From November-December, PP of the bay decreased to 400–700 mg-C m^{-2} d^{-1} except for the innermost and center parts of the bay. The high PP due to autumn boom partially continued at the innermost and center parts of the bay (700–1600 mg-C m^{-2} d^{-1}).

3.2.3 Primary production in 2017 (Fig. 8)

In January-March, low-PP was observed throughout the bay, ranging from 150–800 mg-C m^{-2} d^{-1}. In April, PP at the innermost and western cost of the bay increased to 400–1400 mg-C m^{-2} d^{-1} due to spring bloom. In May, PP at innermost of the bay reached to 700-1600 mg-C m^{-2} d^{-1}. In July-August, high PP was observed throughout the bay, 900–1600< mg-C m^{-2} d^{-1} and 600–1000 mg-C m^{-2} d^{-1} for the innermost area and central to

southern areas, respectively. The high PP was considered to be due to the supply of nutrients from terrigeneous and vertical mixing caused by a typhoon. The high PP slightly decreased in September-October, which might have been due to nutrient depletion after the bloom. In November-December, the low-PP area (150–400 mg-C m^{-2} d^{-1}) expanded throughout the bay.

3.2.4 Summary of the PP in Hiroshima Bay

In January, the PP in Hiroshima Bay ranged <50-1000 mg-C m^{-1} d^{-1} (**Figs. 6, 7 and 8**). In spring, increases in seasonal irradiance create favorable conditions for phytoplankton growth (Dugdale et al., 2007). Just like, Solent, estuary system on the south coast of the UK (Iriarte and Purdie, 2004) and San Francisco Bay, USA (Dugdale, 2007), spring bloom was observed at the innermost and western parts of the Hiroshima Bay. In February to March 2015 and February 2016, high chlorophyll concentration (10-50< μg L^{-1}) observed at the innermost and western parts of the bay (ex. **Figs. S4 and S7**) and the PP increased to 700-1600 mg-C m^{-1} d^{-1} at the innermost and western parts of the bay (**Fig. 6 and 7**) substantially affected by terrigeneous load from the Ohta (2.82 x 106 m^3 d^{-1}), Oze (7.99 x 105 m^3 d^{-1}) and Nishiki (1.06 x 106 m^3 d^{-1}) rivers (Lee and Hoshika, 2000). The observed concentrations of DIN, DIP and DSi at surface seawater ranged 2.5-18.1 μmol

472 L^{-1}, 0.5-1.0 μmol L^{-1} and 11.8-41.5 μmol L^{-1}, respectively at the innermost and western
473 parts of the bay in February 2015. Therefore, the primary nutrients supplied from
474 terrigeneous load and estuary circulation were sufficient for growth of phytoplankton.
475 The beginning of PP increase due to spring bloom was April in 2017, and it was 1-2 month
476 later compared to that in 2015 and 2016 (**Figs. 6, 7 and 8**). The SST is also one of factors
477 in controlling spring bloom. When a wind velocity (especially north wind) exceeds 10 m
478 s^{-1}, wind energy produces turbulence in the surface water and tends to deform the
479 stratification in northern Hiroshima Bay (Hashimoto et al., 2000). Most of daily
480 maximum wind velocity (north–south component) was less than 10 m s^{-1} at the innermost
481 Hiroshima Bay (Yamamoto et al., 2002). Therefore, surface mixing layer might become
482 shallow and SST increase to favorable conditions for phytoplankton growth in March.
483 The SST at spring bloom observed area in March 2015, 2016 and 2017 increased to 11-
484 14 ºC, 11-14 ºC, and 9-12 ºC, respectively (**Fig. S10, S11 and S12**). The SST in March
485 2017 was low compared to that in 2015 and 2016. Hence, the delay of spring bloom in
486 2017 attributed to low sea surface water temperature.
487 After the spring bloom, the highest PP was observed in June- July 2016 (1600<. mg-C
488 m^{-2} d^{-1}). Monthly rainfall in June 2015, 2016 and 2017 at Hiroshima Prefecture were
489 237.5 mm, 509.5 mm and 261.0 mm, respectively (Japan Metrological Agency). The

rainfall in June 2016 was twice of that in 2015 and 2017, suggesting that high terrigeneous loads which could be supposed by the fact that the CDOM (0.22-0.24 m^{-1}) was high at the innermost of the bay in June 2016 compared to 2015 and 2017 (**Figs. S8, S13 and S14**). Yamamoto et al, 2011 reported that estuary circulation increased when the increasing flow rate of Ohta river. Therefore, both terrigeneous load and upwelling of nutrients due to increasing in estuary circulation kept PP high at the innermost of the bay in June 2016 (**Fig. 7**). The high productivity continued into September at the innermost of the bay. In summer, hypoxic water mass is observed at the innermost of the bay every year (Yamamoto et al, 2011; Asaoka et al., 2018). Under such anoxic condition, nutrients especially phosphate adsorbed on organically enriched sediments desorbe in water column. Hence, nutrients dissolution from sediments as well as terrigeneous load might increase PP at the innermost of the bay.

In autumn, although haloclines were slightly observed due to fresh water inflow from the Ota River at the innermost of the bay, the vertical mixing of seawater resulted in the disappearance of haloclines (Asaoka et al., 2018). Autumn bloom was partially observed at the innermost and center parts of the bay. The PP in November to December ranged 150-600 mg-C m^{-2} d^{-1} except for blooming areas (**Figs. 6,7 and 8**).

4. Conclusions

We estimated the PP in Hiroshima Bay, Japan with a modified Kameda & Ishizaka model using an OCS, GOCI-COMS. Our proposed method is superior to previous methods for estimating PP in coastal seas due to its higher temporal and spatial resolution. The coefficient of determination between observed and estimated PP by the OCS was r^2=0.750. The slope of the linear regression was 1.00. The RMSE was 165 mg-C m^2 d^{-1}, which is sufficient for discussions of changes in spatial distribution of Hiroshima Bay. We underscore line that our proposed method based on the high-resolution (approx. 500 m) ocean-color product can estimate ocean primary production in coastal seas including complicated topographic areas such as enclosed seas or channels less than 1 km wide where the conventional method cannot be employed applied.

Acknowledgements

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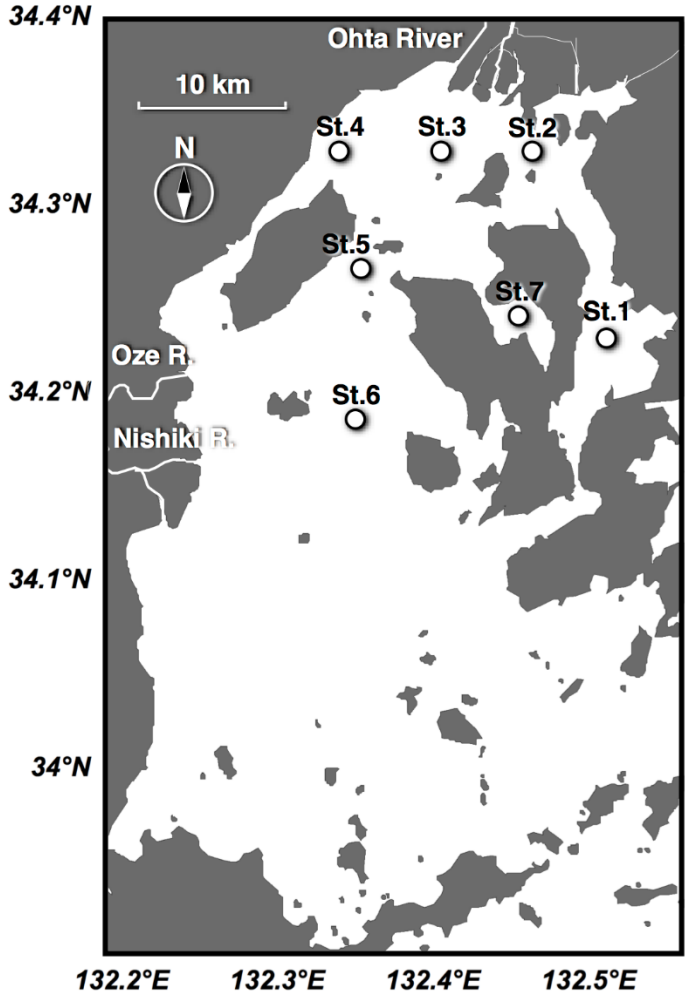
Figures



Map of sampling stations were drawn using software for the analysis and visualization of oceanographic and meteorological data sets, Ocean Data View ver. 4.7.10.

Fig. 1Hiroshima Bay and its 7 sampling stations.

○：seasonal sampling stations

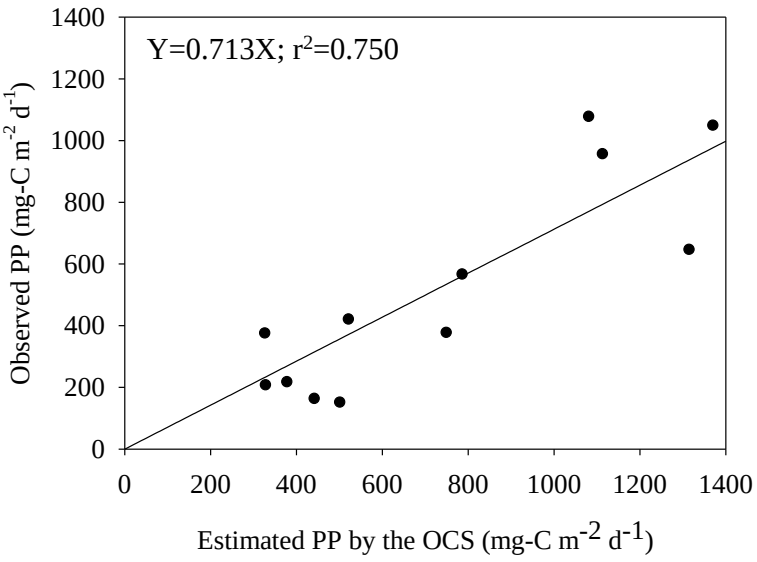


Fig. 2 Relationship between observed and estimated PP by the OCS

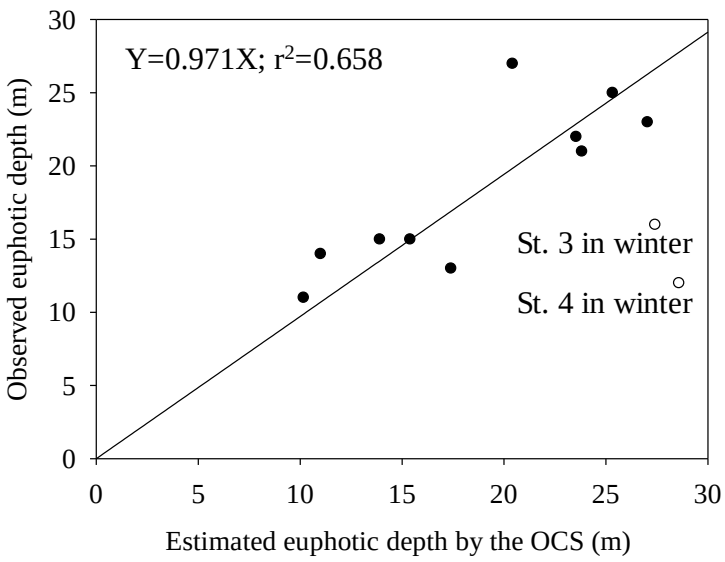


Fig. 3 Relationship between observed and estimated euphotic depth by the OCS

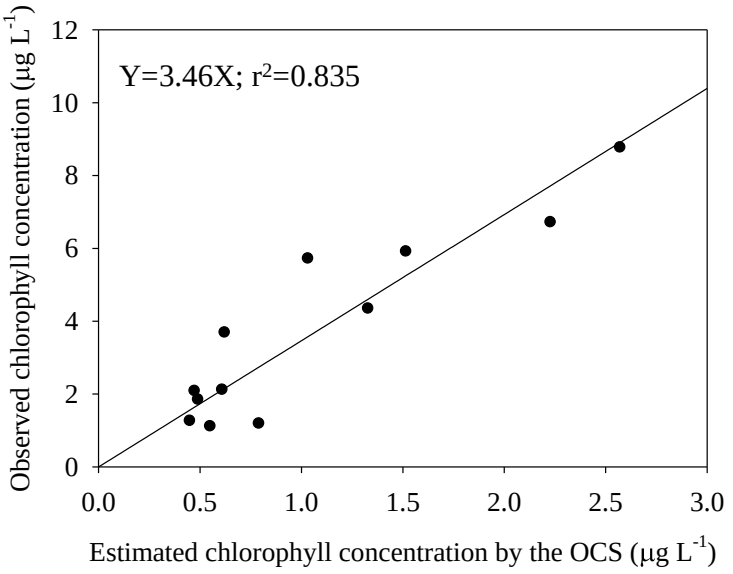


Fig. 4 Relationship between observed and estimated chlorophyll concentration by the OCS

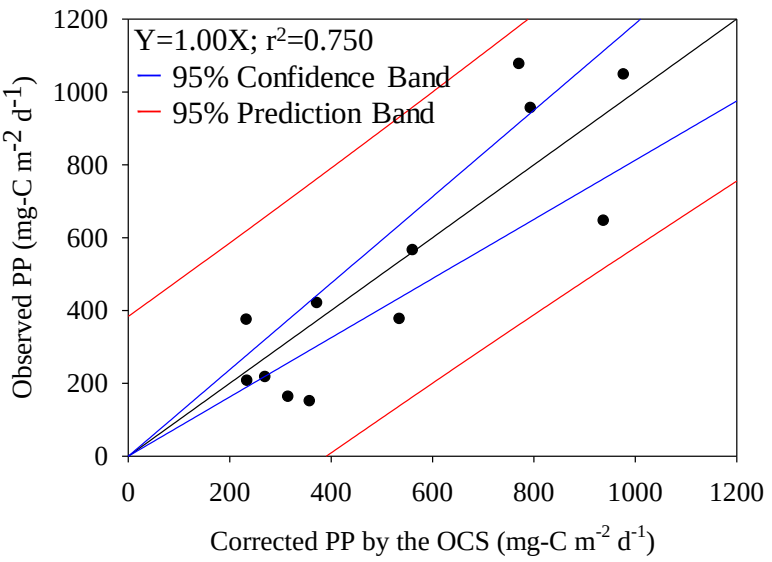


Fig. 5 Relationship between observed and corrected PP in Hiroshima Bay estimated from the OCS

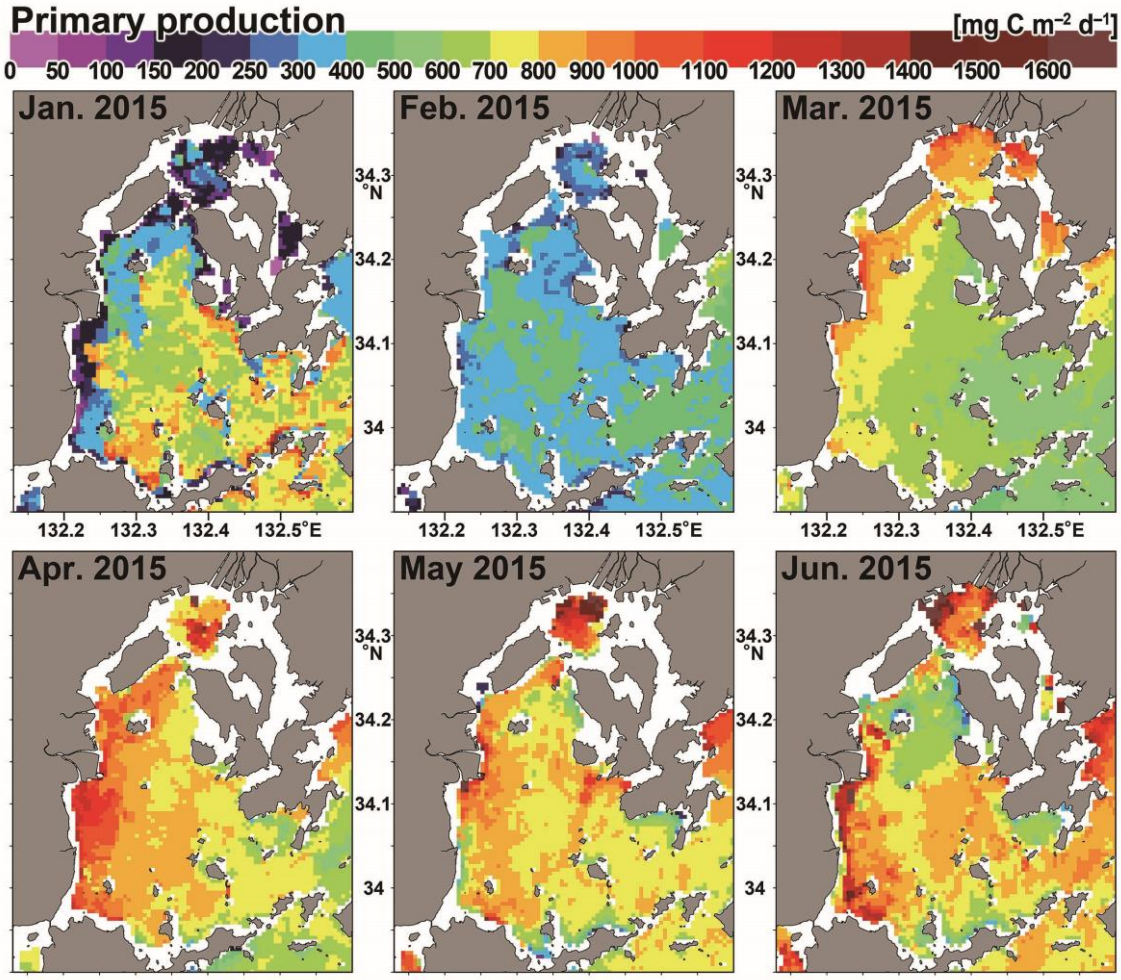


Fig. 6 PP in Hiroshima Bay in 2015

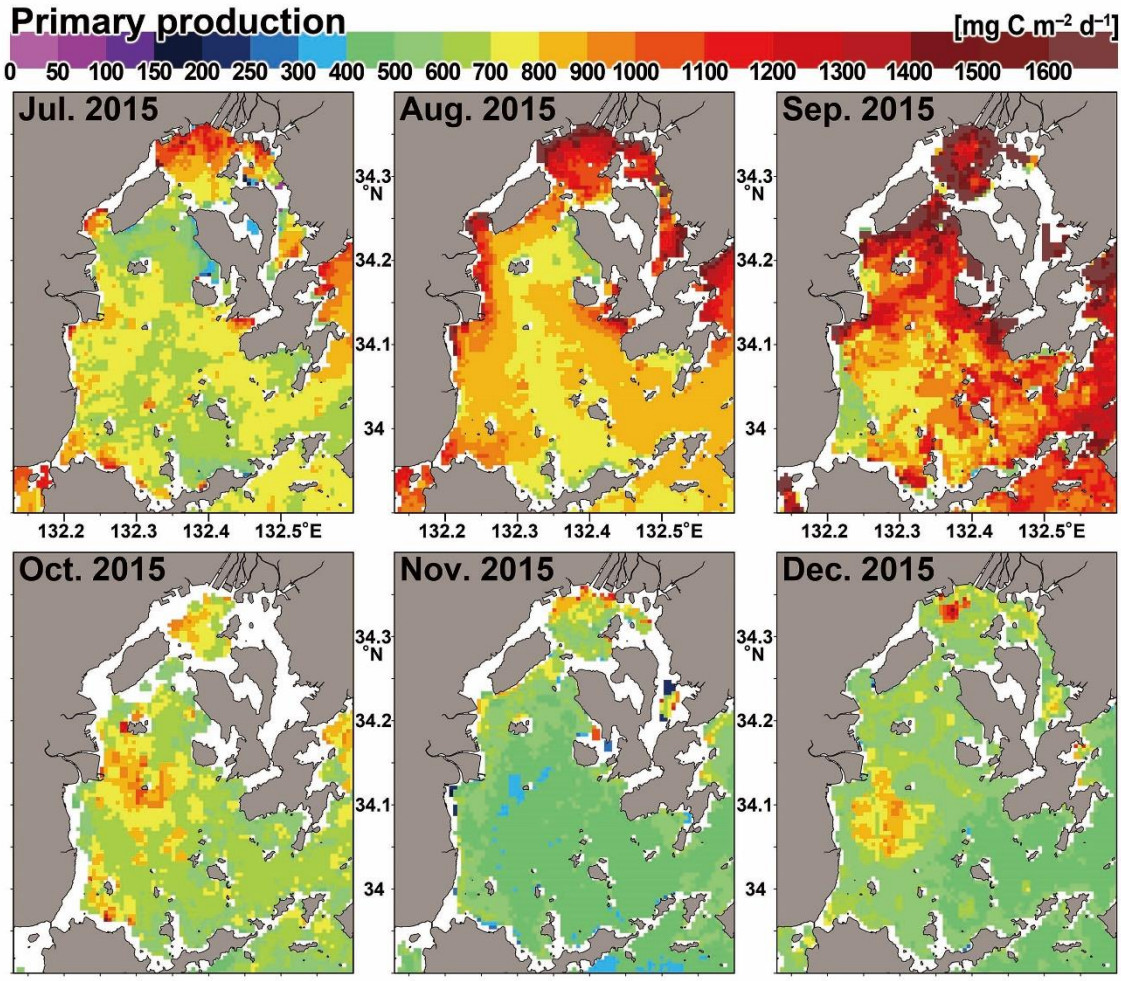


Fig. 6 PP in Hiroshima Bay in 2015 (Continued)

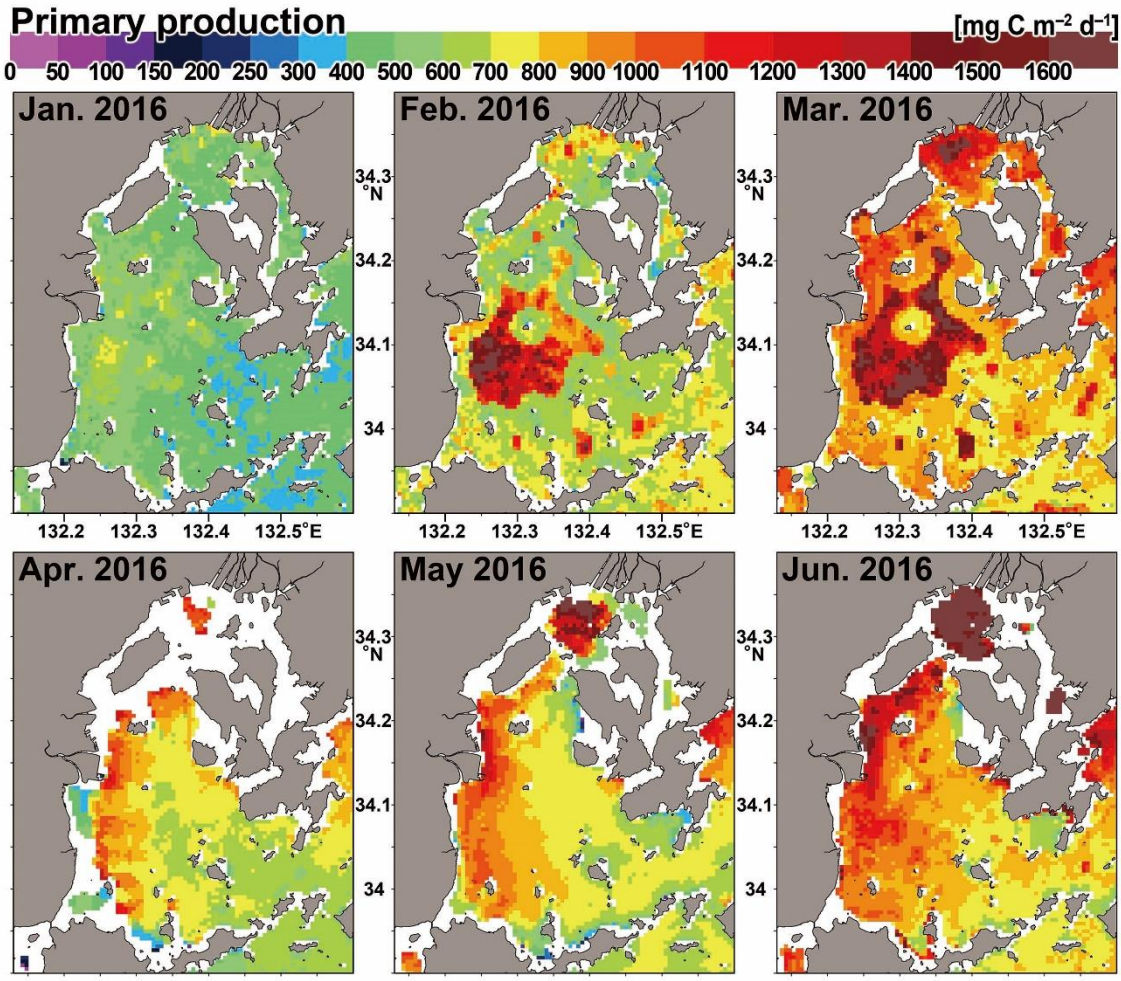


Fig. 7 PP in Hiroshima Bay in 2016

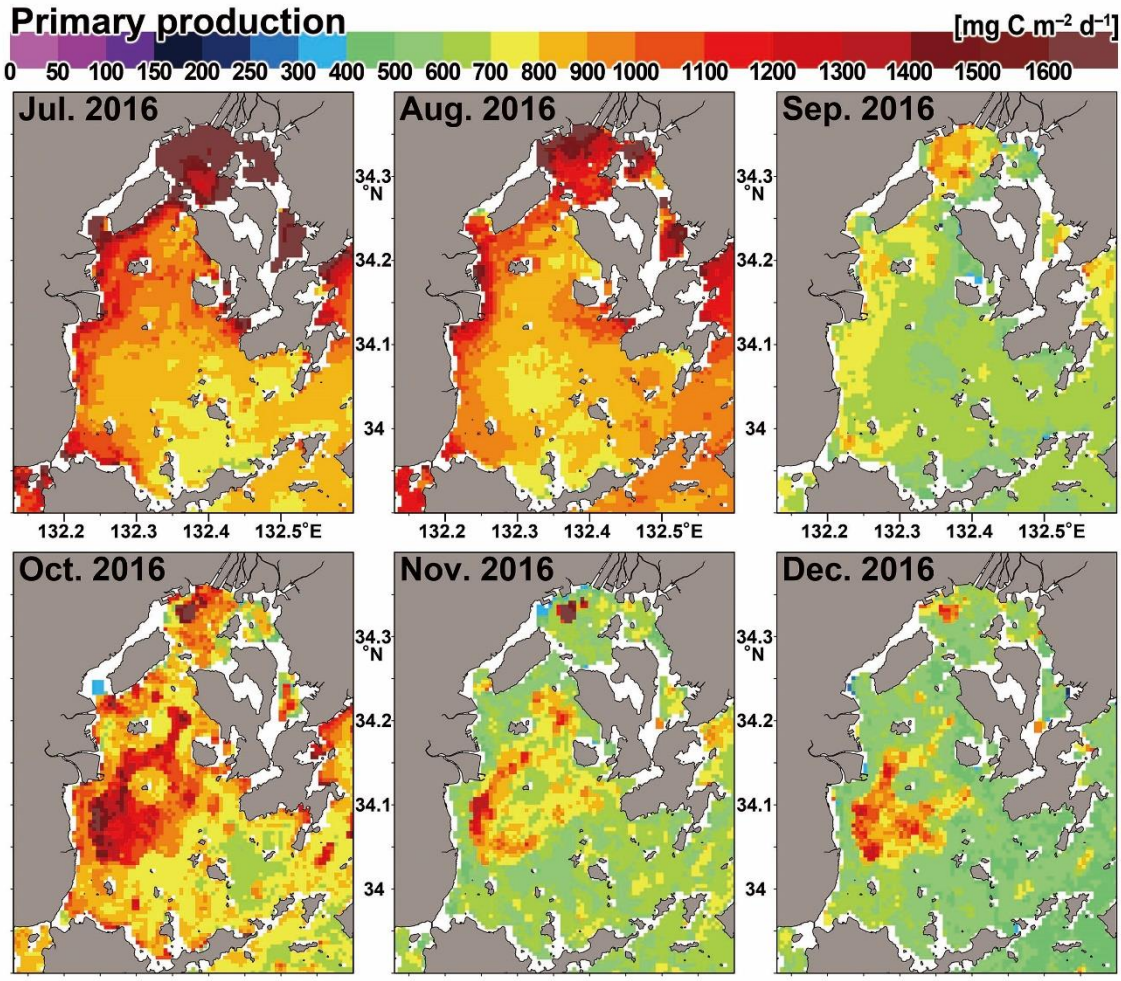


Fig. 7 Hiroshima Bay in 2016 (Continued)

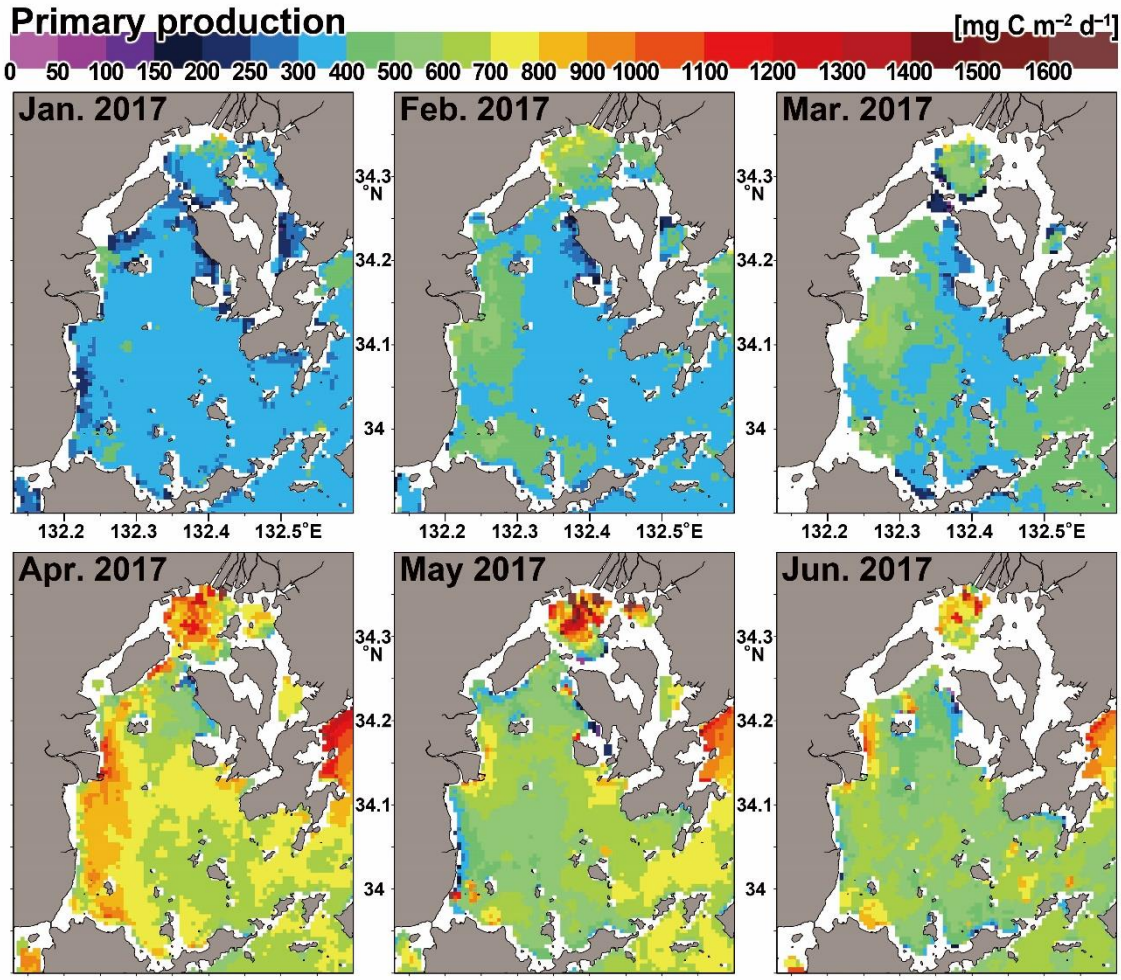


Fig. 8 Hiroshima Bay in 2017

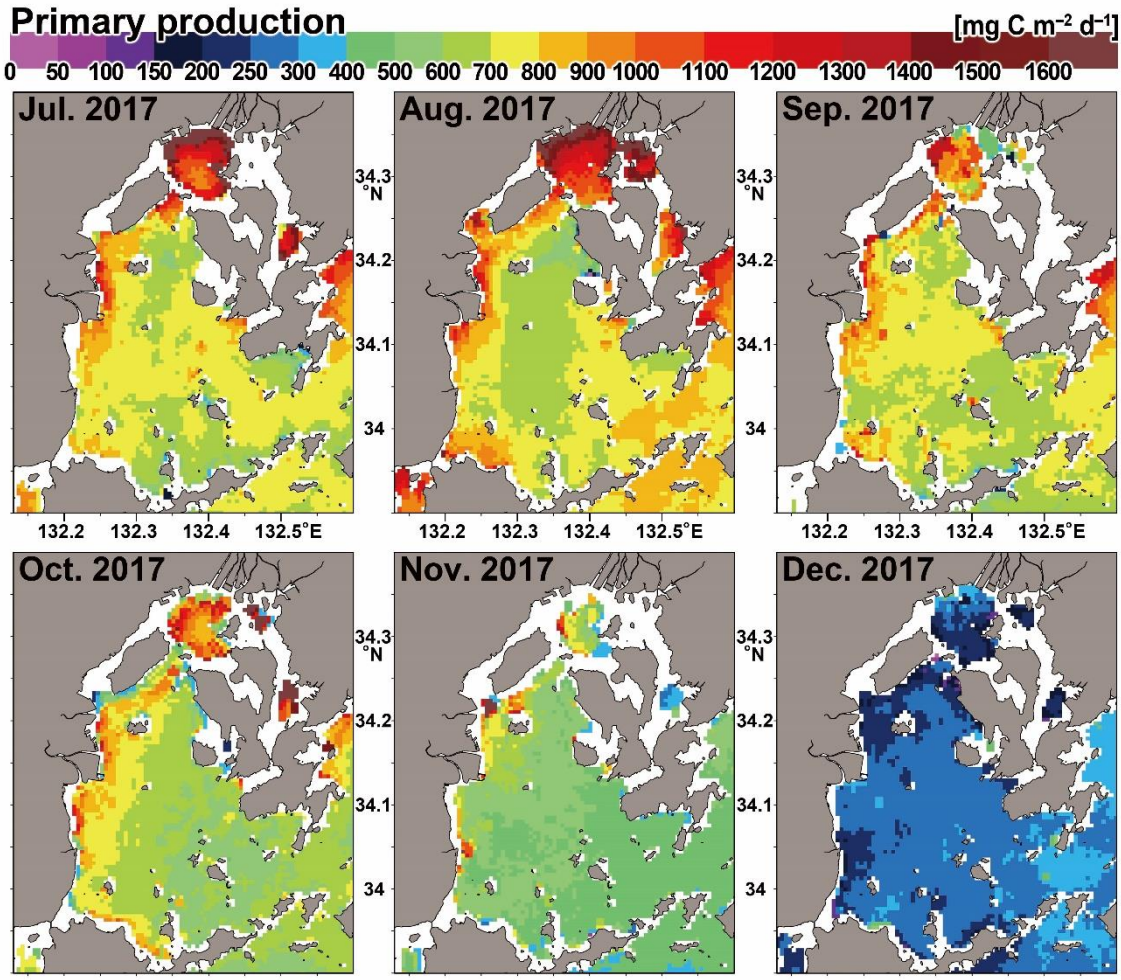
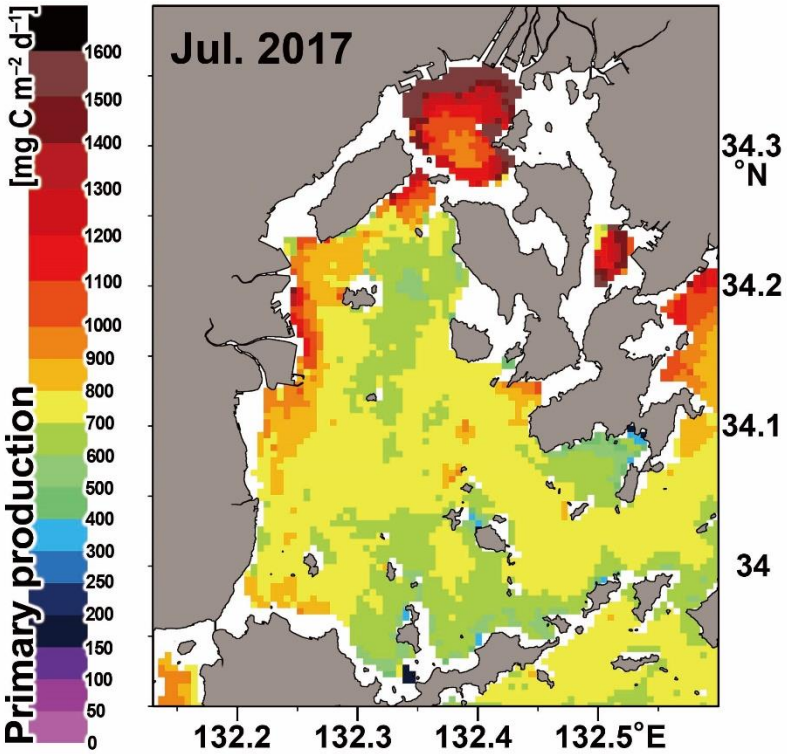


Fig. 8 Hiroshima Bay in 2017 (Continued)

Table 1　Comparison with the primary production estimated by the VGPMs

Observed vs. estimated PP	This study	Behrenfeld & Falkowski (1997)	Kameda & Ishizaka (2005)
RSME	165	245	379
RMSE(%)	31.2	48.6	122
Bias	10.8	-14.0	-208
Slope	1.00	1.08	1.69
r^2	0.750	0.462	0.109

Graphical abstract



Primary production Hiroshima Bay, Japan estimated by the proposed method.

Supplemental materials

Estimation of spatial distribution of coastal ocean primary production in Hiroshima Bay, Japan, with a geostationary ocean color satellite

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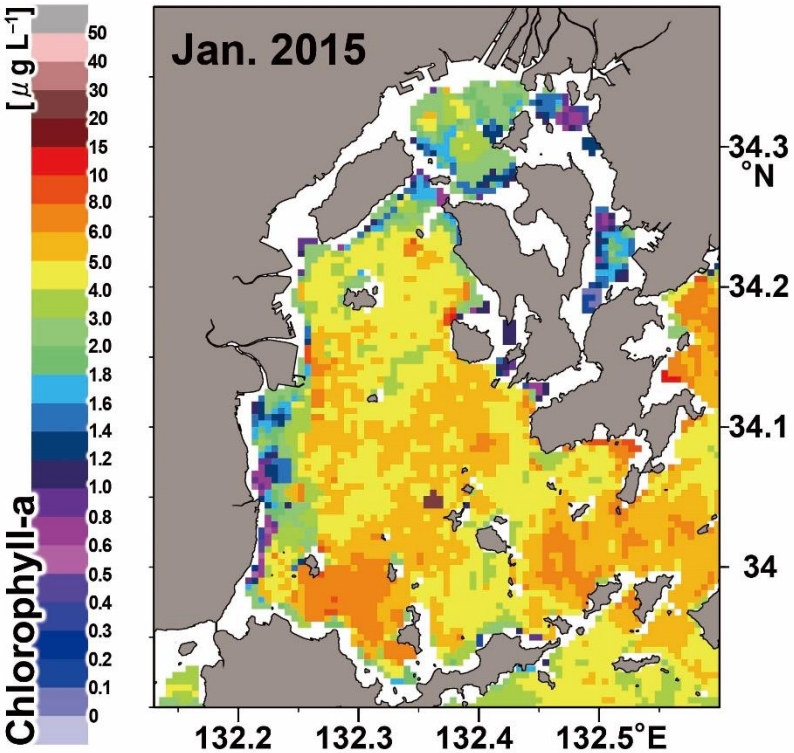

Fig. S1Chlorophyll concentration in surface seawater in January 2015

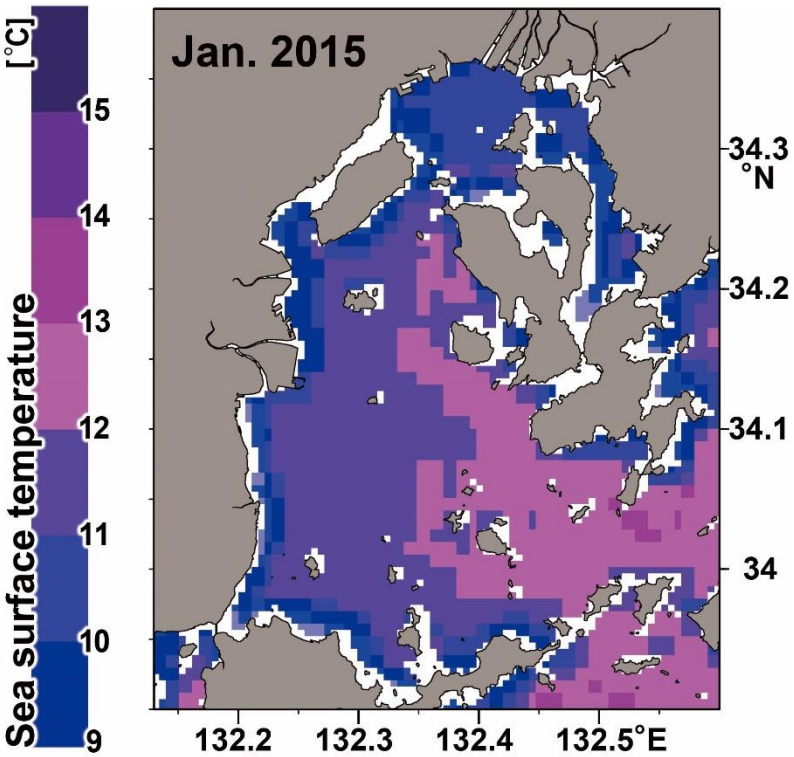

Fig. S2 Sea surface temperature in January 2015

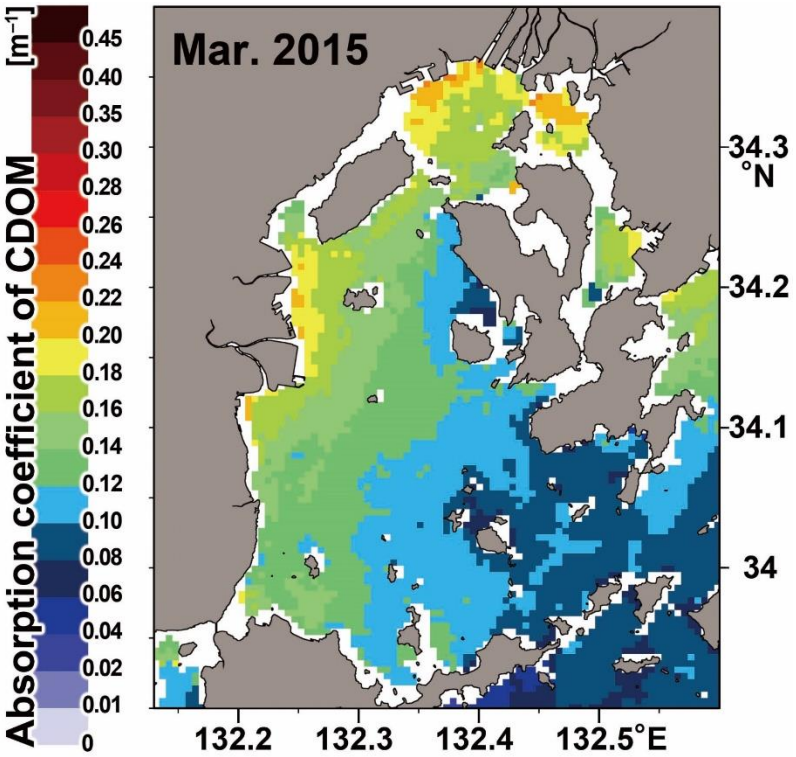

Fig. S3 CDOM in surface seawater in March 2015

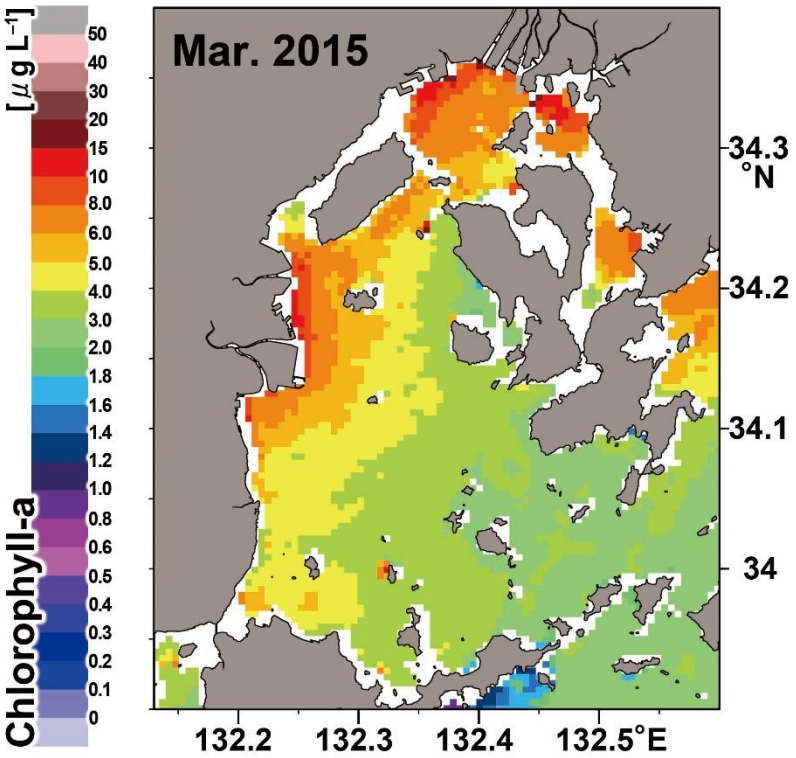

Fig. S4 Chlorophyll concentration in surface seawater in March 2015

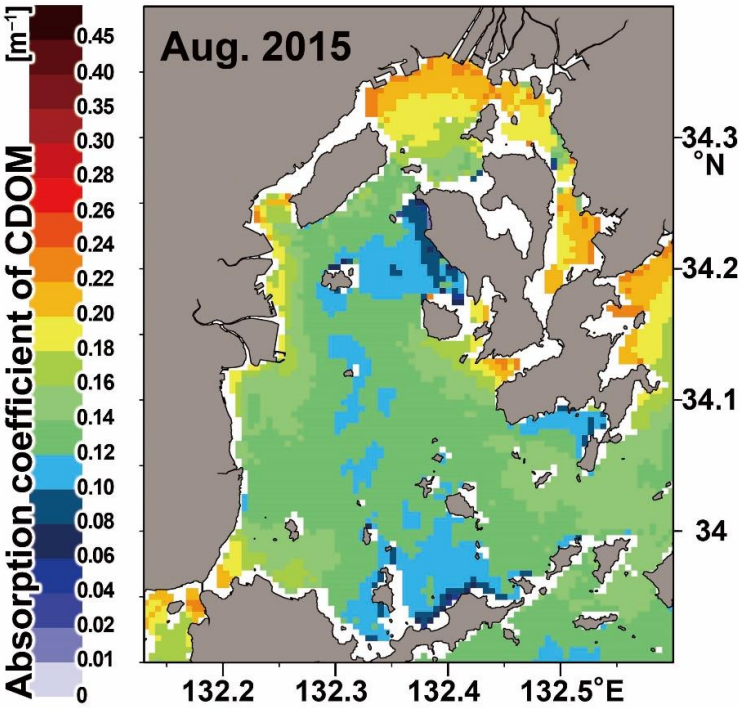

Fig.S5 CDOM in surface seawater in August 2015

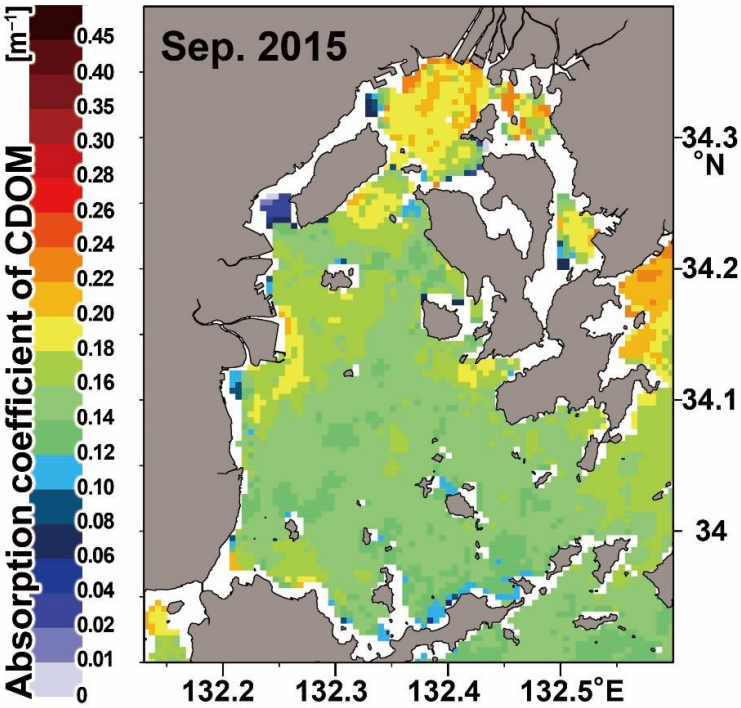

Fig. S6 CDOM in surface seawater in September 2015

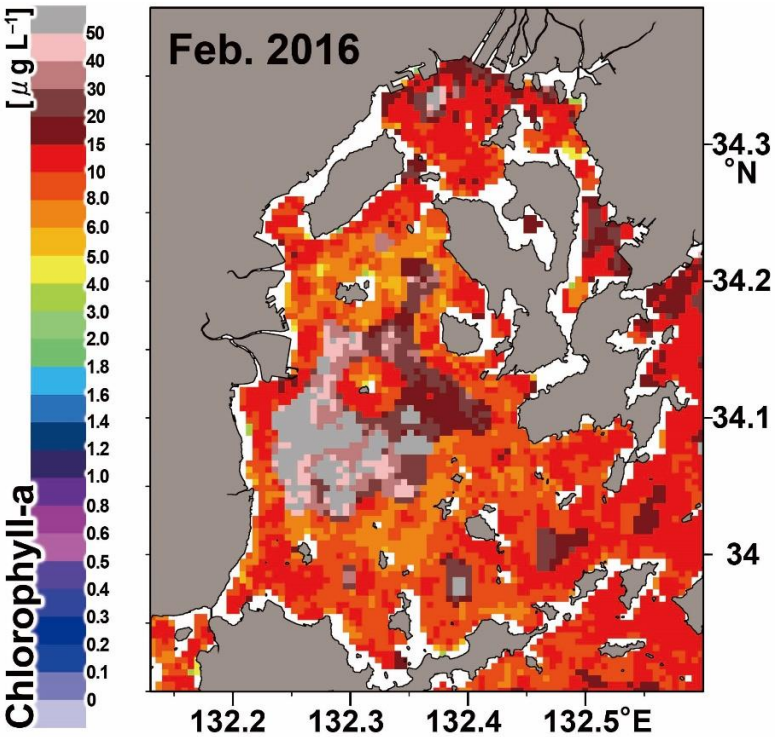

Fig. S7 Chlorophyll concentration in surface seawater in February 2016

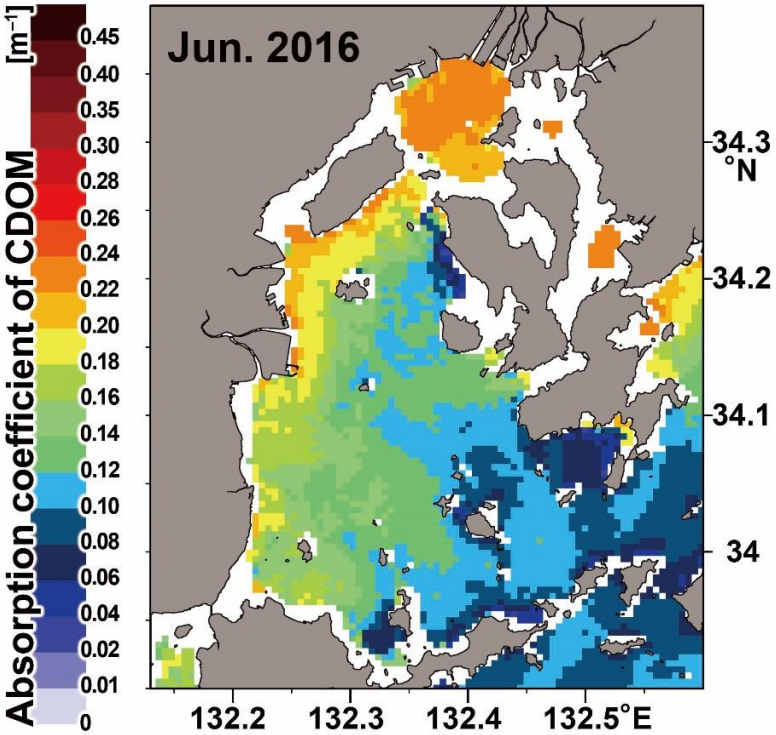

Fig. S8 CDOM in surface seawater in Jun 2016

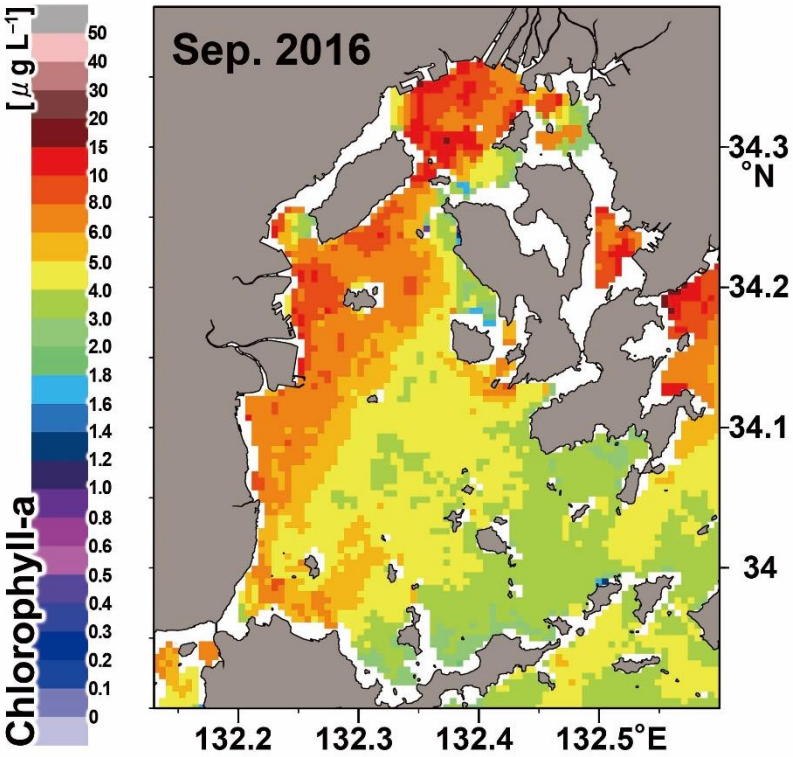

Fig. S9 Chlorophyll concentration in surface seawater in September 2016

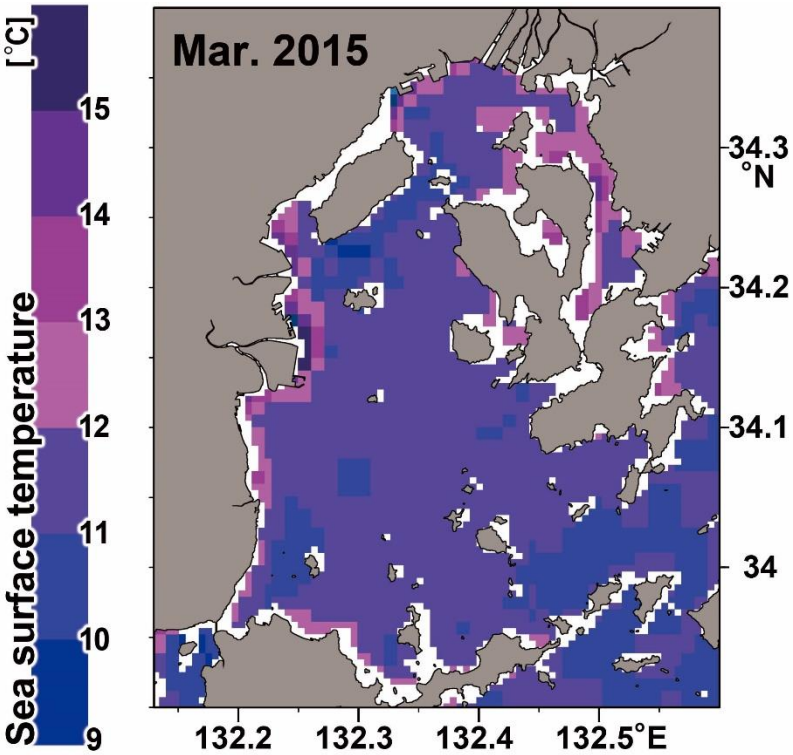

Fig. S10 Sea surface temperature in March 2015

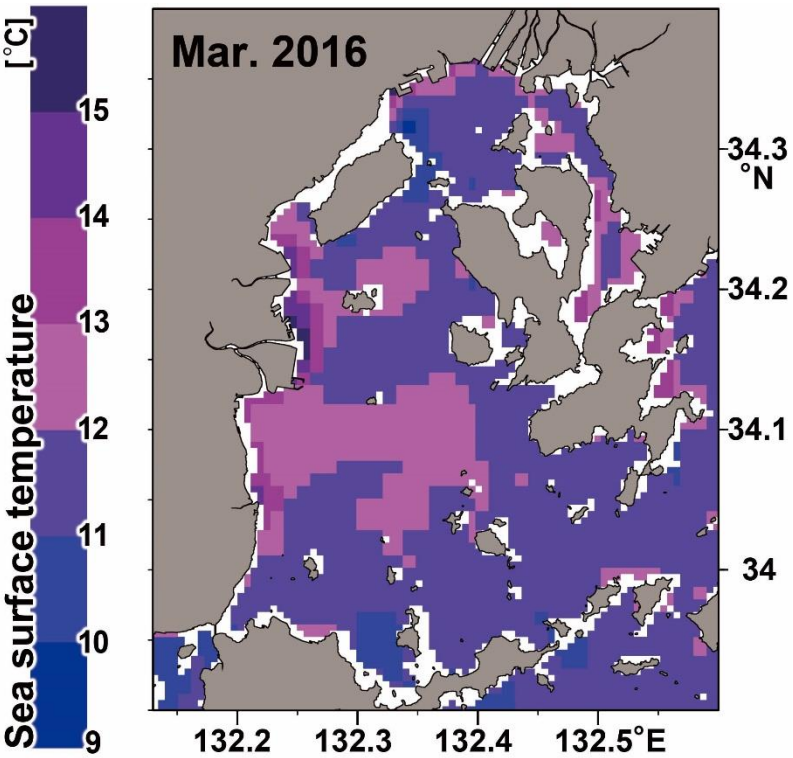

Fig. S11 Sea surface temperature in March 2016

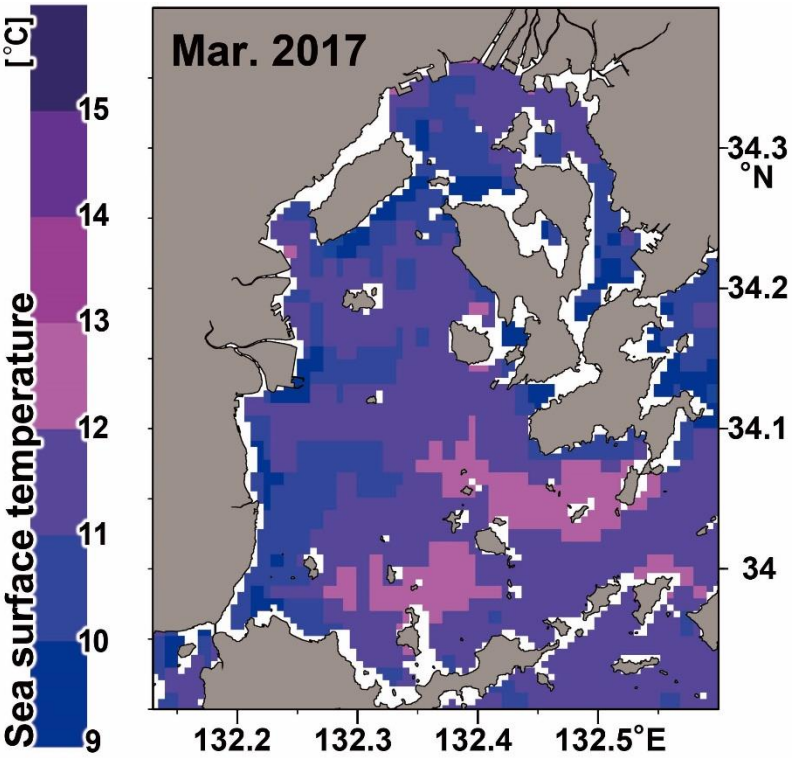

Fig. S12 Sea surface temperature in March 2017

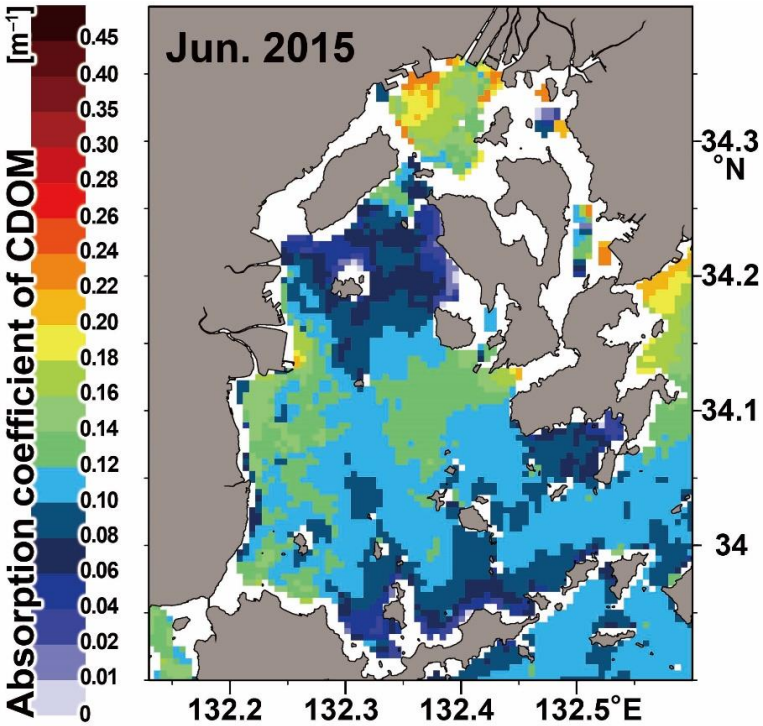

Fig. S13 CDOM in surface seawater in Jun 2015

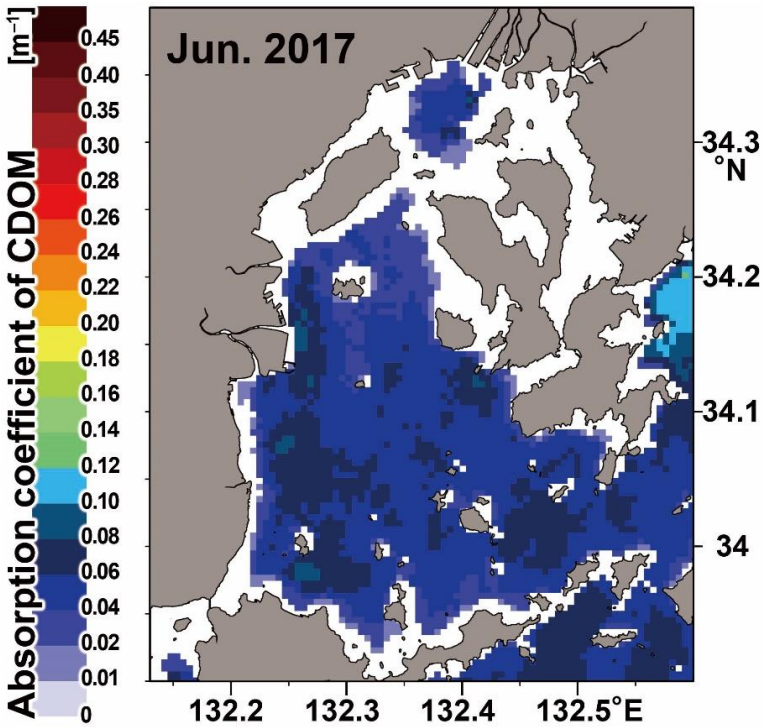

Fig. S14 CDOM in surface seawater in Jun 2017