

Reproduction of In-water Optical Environment in Tokyo Bay Using Coupled Biogeochemical and Bio-optical Models

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Abstract—The reproduction of satellite-observed Remote-Sensing Reflectance (R_{rs}) within marine Biogeochemical (BGC) models is a key process in the development of ocean-color data assimilation frameworks. Assimilation approaches based on R_{rs} can avoid the uncertainties associated with satellite-derived water quality products and are therefore expected to be particularly applicable to coastal waters. However, in optically complex coastal environments, the reliability of the bio-optical models and radiative transfer processes used to reproduce the in-water light field remains limited, and the applicability of these processes within coupled BGC modeling frameworks is not yet fully established. In this study, we developed a coupled BGC–bio-optical modeling framework capable of reproducing R_{rs} in Tokyo Bay, an optically complex, eutrophic, semi-enclosed coastal system. To represent region-specific inherent optical properties, we conducted bay-wide shipboard observations and developed a bio-optical model that incorporates key processes, including the chlorophyll pigment package effect and chlorophyll fluorescence. This model was coupled to a BGC model tuned for Tokyo Bay. The simulated R_{rs} was evaluated against satellite observations from GCOM-C/SGLI and in-situ measurements from an autonomous radiometer system. The model reproduced the spatial distribution and temporal variability of R_{rs} , including enhanced long-wavelength reflectance during river flood events. These results demonstrate the feasibility of using R_{rs} as an observational constraint for ocean-color data assimilation in optically complex coastal waters, offering a more robust alternative to conventional methods.

Keywords—BGC model, Bio-optical model, ocean color, remote sensing, data assimilation, Tokyo Bay

I. INTRODUCTION

Marine Biogeochemical (BGC) models are widely used to analyze material cycling in support of predicting coastal environmental variability and informing policy decisions related to environmental management [1]. In recent years, the importance of data assimilation, which updates model states using observational data, has increased for improving the reliability of such analyses [2]. Satellite remote sensing ocean-color data provide extensive spatial coverage, motivating growing interest in their assimilation into BGC models [3]. However, satellite-derived water quality products in coastal regions contain large uncertainties and have generally been considered unsuitable for assimilation into BGC models [4].

To address this limitation, Jones *et al.* [5] proposed an alternative approach in which the in-water optical environment is simulated within a BGC model and remote-sensing reflectance (R_{rs}), a more direct satellite-observed quantity, is assimilated. By avoiding the optical assumptions inherent in conventional satellite water quality retrieval algorithms, this approach is expected to be applicable to

coastal regions characterized by diverse and complex optical conditions.

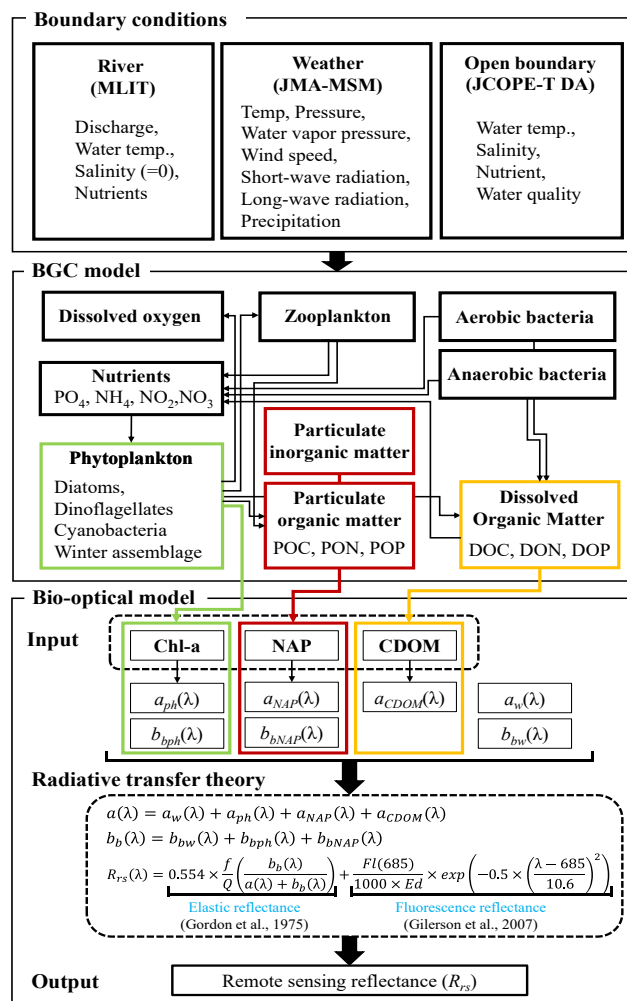


Fig. 1. Schematic diagram of proposed integrated modeling framework. The system consists of a BGC model and a bio-optical model, which translates simulated in-water constituents into R_{rs} based on radiative transfer theory.

Nevertheless, Jones *et al.* [5] focused on relatively clear coastal waters around the Great Barrier Reef, and significant challenges remain in extending this approach to eutrophic, semi-enclosed bays where high turbidity persists throughout the year. Specifically, these challenges include concerns about the spatial representativeness of Inherent Optical Properties (IOPs), as they are derived solely from measurements of light absorption and attenuation coefficients conducted in limited areas near river mouths; large uncertainties arising from the estimation of the particulate backscattering coefficient (b_{bp}) from light absorption and attenuation coefficients rather than from direct observations;

and the omission of optical processes essential for reproducing R_{rs} in eutrophic waters, such as the chlorophyll pigment package effect [6] and chlorophyll fluorescence [7].

In this study, with future applications to data assimilation in mind, we developed a BGC modeling framework capable of realistically reproducing R_{rs} in Tokyo Bay, an optically complex, eutrophic, semi-enclosed coastal system. To represent Specific Optical Properties (SIOPs) in Tokyo Bay, we conducted comprehensive shipboard observations covering the entire bay and constructed a bio-optical model based on simultaneous measurements of optical properties, including b_{bp} , and water quality parameters. Furthermore, by coupling this bio-optical model with a BGC model tuned for Tokyo Bay, we enabled a consistent representation of the spatiotemporal variability of the in-water optical environment associated with river flood events and enhanced primary production. The architecture of this coupled system, where the biogeochemical variables are translated into R_{rs} through the bio-optical modeling component, is illustrated in Fig. 1. Finally, simulated R_{rs} was compared with satellite observations and in-situ measurements obtained from autonomous radiometers to quantitatively assess the validity and reproducibility of the modeled in-water optical environment.

II. METHOD

A. Study Area

The study area is Tokyo Bay, which is located within the Tokyo metropolitan region. Tokyo Bay is a semi-enclosed inner bay with a mean depth of approximately 19 m and a surface area of about 920 km². Because of its geomorphology, exchange with the open ocean is restricted. The bay is surrounded by the Tokyo metropolitan region, one of the world's largest megacities, and consequently receives substantial inputs of organic matter and nutrients from the dense human population and intensive industrial activity. Tokyo Bay has therefore long been recognized as highly susceptible to eutrophication, leading to environmental problems such as water quality degradation and hypoxia in bottom waters.

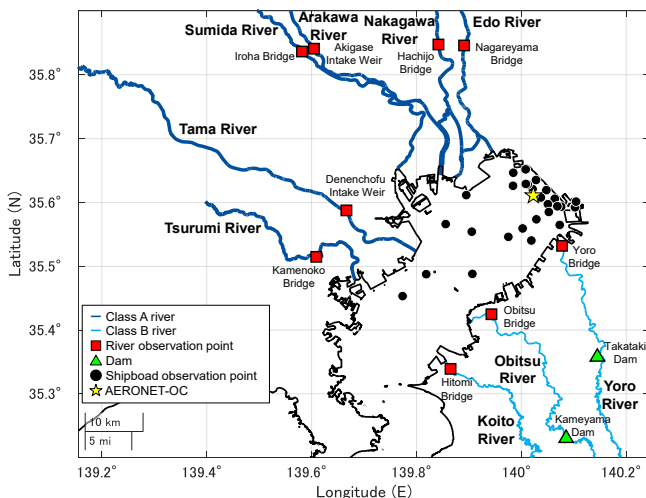


Fig. 2. Locations of shipboard observation sites (black dots), river monitoring stations (red squares), and the AERONET-OC deployment site (yellow star) in Tokyo Bay.

As shown in Fig. 2, six Class A rivers and three major Class B rivers discharge into Tokyo Bay, transporting large quantities of terrestrially derived material from surrounding urban areas. These riverine inputs have a marked effect on material cycling and primary production within the bay and are therefore critical to understanding the spatiotemporal variability of water quality and ecosystem dynamics. Nihei *et al.* [8] found that the mean annual discharge decreases in the following order: Arakawa, Edo, Naka, Tama, and Tsurumi rivers. Conversely, interbasin transfer of municipal and irrigation water has resulted in higher discharge in the more urbanized Naka and Tsurumi rivers, and lower discharge in the Edo, Arakawa, and Tama rivers. The Sumida River has likewise been reported to exhibit patterns similar to those for the Naka and Tsurumi rivers.

B. Field Data

1) Shipboard observations

For the construction of a bio-optical model, a simplified radiative transfer model to reproduce the in-water light environment, we conducted 35 field campaigns in the inner reaches of Tokyo Bay between 2010 and 2022, as indicated by the black dots in Fig. 2 (see Higa *et al.* [9] for further details). Chlorophyll-a (Chl-a) was determined from seawater samples using fluorometry [10] through 2013 and using high-performance liquid chromatography [11] from 2017 onward. Dissolved Organic Carbon (DOC) was measured using the high-temperature catalytic oxidation method [12], and Total Suspended Solids (TSS), organic suspended solids, and inorganic suspended solids were quantified using the gravimetric (dry-weight) method [13]. In addition, the slope of the regression line between Chl-a and organic suspended solids was derived. Using this slope coefficient and Chl-a concentration, Phytoplankton Suspended Solids (PSS) were estimated as $PSS = 0.0687 \times \text{Chl-a}$. Non-Algal Particles (NAP) were then obtained by subtracting PSS from TSS.

At each station, a spectroradiometer (RAMSES ACC/ARC; TriOS Optical Sensors) was used to measure water-leaving radiance and above-surface downwelling spectral irradiance, from which R_{rs} was computed as their ratio. Concurrently, a backscattering sensor (Hydroscat-6P; HOBI Labs) was used to obtain vertical profiles of b_{bp} . Using the site-specific fraction of PSS in TSS, b_{bp} was partitioned into phytoplankton backscattering (b_{bph}) and NAP backscattering (b_{bNAP}). Furthermore, a spectrophotometer (V-550; JASCO) was also used to measure surface absorption coefficients for phytoplankton (a_{ph}), Colored Dissolved Organic Matter (CDOM) (a_{CDOM}), and NAP (a_{NAP}). The sample sizes for each measurement are summarized in Table 1.

Table 1. Measured parameters and sample sizes during shipboard field observations

Parameter	Number of Samples
Remote-sensing reflectance, R_{rs}	141
Phytoplankton absorption coefficient, a_{ph}	76
CDOM absorption coefficient, a_{CDOM}	71
NAP absorption coefficient, a_{NAP}	71
Phytoplankton backscattering coefficient, b_{bph}	47
Chlorophyll-a, Chl-a	94
Total suspended solids (TSS)	86
Dissolved organic carbon (DOC)	19

2) AERONET-OC Kemigawa-Offshore

To evaluate the fidelity of the water-leaving reflectance values reproduced by the BGC model, we employed in-situ measurements from the Aerosol Robotic Network-Ocean Color (AERONET-OC), an autonomous radiometer system installed on the Kemigawa-Offshore observation tower in Tokyo Bay [14]. AERONET-OC is a global network designed primarily for coastal and inland waters, providing continuous, fixed-point observations of atmospheric and aquatic optical properties [15, 16]. Because it enables high-frequency match-up observations with satellite ocean-color sensors at a relatively low cost, it is widely used for sensor calibration and product validation. While satellite observations offer broad spatial coverage, they often suffer from uncertainties in coastal areas due to atmospheric correction errors [17, 18]. Therefore, in addition to satellite-based spatial comparisons, we utilized AERONET-OC in-situ measurements as a highly reliable, independent reference for model validation. These in-situ measurements provided a more robust basis for assessing the model's accuracy.

In Tokyo Bay, measurements have been conducted since 2018. The Kemigawa-Offshore tower is located in the inner bay (35.611°N, 140.023°E) (Fig. 2), where river flood events strongly influence optical conditions through inflows of suspended matter and nutrients from the Arakawa, Edo, and

Naka rivers.

Level-2.0 normalized water-leaving radiance (L_{wn}) from AERONET-OC for the period September 2019 to January 2022 was obtained from the official AERONET portal (https://aeronet.gsfc.nasa.gov/new_web/data.html). The L_{wn} data were converted to R_{rs} using the top-of-atmosphere solar spectral irradiance described by Thuillier *et al.* [19]. The resulting R_{rs} spectra were then linearly interpolated to match the observation bands of the Second-generation Global Imager (SGLI).

3) Observation dataset of public water areas

For the development of riverine load estimation formulas for the BGC model and for evaluating the validity of the data assimilation, we used water quality data from the routine monitoring of public water bodies. These observations of rivers, lakes, and coastal seas are conducted monthly by local governments and are publicly available via the Water Information System (<https://www1.river.go.jp/>) administered by the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT).

To construct the nutrient load estimation formulas for river inputs, we used concurrent measurements of chemical oxygen demand, total nitrogen, and total phosphorus concentrations together with river discharge at monitoring stations located along the mainstream reaches of each inflowing river (Table 2).

Table 2. Names and coordinates of monitoring stations along each river flowing into Tokyo Bay

River	Station	Latitude (°N)	Longitude (°E)
Arakawa	Akigase Intake Weir	35.841	139.604
Edo	Nagareyama Bridge	35.846	139.891
Tamagawa	Denenchofu Intake Weir	35.588	139.666
Nakagawa	Hachijo Bridge	35.847	139.842
Sumida	Iroha Bridge	35.836	139.582
Tsurumigawa	Kamenoko Bridge	35.515	139.609
Yoro	Yoro Bridge	35.532	140.078
Obitsu	Obitsu Bridge	35.425	139.943
Koito	Hitomi Bridge	35.339	139.865

4) Global change observation mission—climate/second-generation global imager

Global Change Observation Mission—Climate/Second-generation Global Imager (GCOM-C/SGLI), a high-resolution ocean-color satellite launched by JAXA in December 2017, acquires observations over Tokyo Bay every two to three days at a spatial resolution of 250 m × 250 m. In addition to the 11 visible bands listed in Table 3, the sensor collects data in six infrared bands and two polarization bands, for a total of 19 bands. The Level 2 version 3 data used in this study were obtained from JAXA's Earth observation data distribution system, G-Portal. The imagery was resampled to a 0.0025° grid.

Table 3. Spectral bands of GCOM-C/SGLI

Band ID	Central wavelength (λ , nm)	Bandwidth ($\Delta\lambda$, nm)
VN01	380.0	10.6
VN02	412.5	10.3
VN03	443.2	10.1
VN04	489.8	10.3
VN05	529.6	11.9
VN06	566.2	13.8
VN07	672.0	22.0
VN08	672.1	11.9
VN09	763.1	11.4
VN10	866.8	20.9
VN11	867.1	30.6

C. Simulation of R_{rs} from BGC model

1) BGC model description

We employed the Ecological Hydrodynamics Simulation System of the Port and Airport Research Institute (EcoPARI) [20–22] as the numerical model. EcoPARI is a nonhydrostatic, three-dimensional coupled hydrodynamic–ecosystem model developed by the Port and Airport Research Institute to simulate coastal and estuarine environments.

The computational domain spans 35.1728°–35.6798°N and 139.621°–140.118°E. The model employs a horizontal resolution of 450 m with 35 vertical layers on an orthogonal Cartesian grid. The simulation period extends from January to October 2021, with the interval through June used for spin-up.

At the bay-mouth open boundary, water temperature, salinity, and sea level were obtained from the Japan Coastal Ocean Predictability Experiment—Third Generation Data Assimilation (JCOPE-T DA) [23] for the Tokyo Bay entrance. Meteorological forcing fields (i.e., air temperature, shortwave radiation, sea-level pressure, wind direction, wind speed, and precipitation) were obtained from the reanalysis data of the Japan Meteorological Agency Meso-Scale Model

(JMA-MSM) [24] and spatially interpolated onto the EcoPARI grid.

The ecosystem component represents four phytoplankton functional types (diatoms, dinoflagellates, cyanobacteria, and a winter assemblage), one zooplankton group, and organic matter decomposition by aerobic and anaerobic bacteria.

Nine river inflows (Edo, Arakawa, Naka, Tama, Tsurumi, Sumida, Yoro, Obitsu, and Koito rivers) were included. River discharge was estimated using stage-discharge rating curves following Suzuki [25]. River water temperature was obtained from hourly observations of the Tone River at Fukawa (35.852°N, 140.139°E) as a representative time series. Riverine salinity was set to zero throughout the simulation.

2) Bio-optical model for Tokyo Bay

In this study, we developed a bio-optical model, coupled to the BGC model, based on in-situ observations in Tokyo Bay [26]. Following Gordon [27], the above-water remote-sensing reflectance, $R_{rs}(\lambda)$ [1/str], is expressed in terms of the absorption coefficient, $a(\lambda)$, and the backscattering coefficient, $b_b(\lambda)$, as:

$$R_{rs}(\lambda) = 0.554 \frac{f}{Q} \left(\frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \right) \quad (1)$$

where λ is the wavelength, f is the angular distribution (flux) factor for the incident light field, which depends on the solar zenith angle and the optical properties of seawater, and Q is the ratio of subsurface upwelling irradiance to subsurface upwelling radiance. For nadir-viewing observations, $\frac{f}{Q}$ has been reported to be approximately constant across coastal and open-ocean waters. In this study, we used a value of 0.0922 [28].

The total absorption coefficient, $a(\lambda)$, is then expressed as follows:

$$a(\lambda) = a_w(\lambda) + a_{ph}(\lambda) + a_{CDOM}(\lambda) + a_{NAP}(\lambda) \quad (2)$$

$$a_{ph}(\lambda) = a_{ph_{est}}^*(\lambda) \times \text{Chl-a} \quad (3)$$

$$a_{ph_{est}}^*(\lambda) = \frac{a_{ph}^*(\lambda)}{a_{ph}^*(440)} \times 0.237 \times \text{Chl-a}^{-0.556} \quad (4)$$

$$a_{CDOM}(\lambda) = \exp\{-0.0175(\lambda - 443)\} \times a_{CDOM}(443) \quad (5)$$

$$a_{NAP}(\lambda) = \exp\{-0.0137(\lambda - 440)\} \times a_{NAP}^*(440) \times \text{NAP} \quad (6)$$

where $a_w(\lambda)$ is the absorption coefficient for pure water and $a^*(\lambda)$ is the mass-specific absorption coefficient per unit constituent concentration. We used field-mean specific coefficients of $a_{ph}^*(440) = 0.0578$ and $a_{NAP}^*(440) = 0.0872$. To account for the well-known decrease in phytoplankton mass-specific absorption with increasing Chl-a concentration [6], $a_{ph_{est}}^*(\lambda)$ was estimated dynamically from Chl-a using Eq. (4).

Similarly, the total backscattering coefficient, $b_b(\lambda)$, is given by:

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bph}(\lambda) + b_{bNAP}(\lambda) \quad (7)$$

$$b_{bph}(\lambda) = b_{bp}^*(\lambda) \times \text{PSS} \quad (8)$$

$$b_{bNAP}(\lambda) = b_{bp}^*(\lambda) \times \text{NAP} \quad (9)$$

$$b_{bp}^*(\lambda) = b_{bp}^*(550) \times \left(\frac{\lambda}{550} \right)^{1.0315} \quad (10)$$

where $b_{bw}(\lambda)$ is the backscattering coefficient for pure water and $b_{bp}^*(\lambda)$ is a mass-specific particle backscattering coefficient per unit TSS concentration. We used a field-mean value of $b_{bp}^*(550) = 0.003615$.

To account for phytoplankton fluorescence [7], Eq. (1) was modified for computing $R_{rs}(\lambda)$ as follows:

$$R_{rs}(\lambda) = 0.554 \frac{f}{Q} \left(\frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)} \right) + \frac{Fl(685)}{1000 \times E_d(685)} \exp\left(-0.5 \left(\frac{\lambda - 685}{10.6} \right)^2\right) \quad (11)$$

$$Fl(685) = \frac{0.0375 \times \text{Chl-a}}{1 + 0.32 \times \text{CDOM} + 0.01 \times \text{NAP} + 0.032 \times \text{Chl-a}} \quad (12)$$

where $Fl(685)$ is the amplitude of the fluorescence peak in R_{rs} at 685 nm and $E_d(685)$ is the downwelling irradiance at 685 nm, which was set to 1.1 W/m²/nm under clear-sky conditions based on a Hydrolight simulation [7].

3) Coupling of bio-optical model with BGC model

We developed a modeling framework in which a bio-optical model is coupled to a BGC model. The framework enables forward simulation of $R_{rs}(\lambda)$ by converting the BGC model's near-surface (0.25 m) outputs into three bio-optical inputs: Chl-a, $a_{CDOM}(443)$, and NAP.

Chl-a was computed from the species-resolved phytoplankton carbon concentrations, PHY_i [molC/m³], and the chlorophyll-to-carbon conversion factor, $CHL_C^{PHY,i}$ [mg/molC], as:

$$\text{Chl-a} = \sum_i^{N_{PHY}} CHL_C^{PHY,i} \cdot PHY_i \quad (13)$$

The ecosystem parameter $CHL_C^{PHY,i}$ was uniformly set to 187.5 for all phytoplankton species.

Numerous studies have demonstrated a significant correlation between CDOM and DOC in coastal waters [29–32]. In this study, the CDOM absorption at 443 nm, $a_{CDOM}(443)$, was estimated from concurrent observations within Tokyo Bay using the following linear regression (Fig. 3):

$$a_{CDOM}(443) = 0.0066 \times \text{DOC} - 0.164 \quad (14)$$

where DOC is in $\mu\text{molC/L}$.

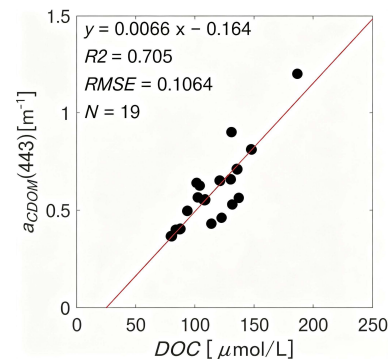


Fig. 3. Relationship between DOC and $a_{CDOM}(443)$ in Tokyo Bay.

NAP was defined as the sum of inorganic suspended solids [g/m^3] and particulate organic carbon [molC/m^3] converted to mass.

4) Model assessment

The predictive performance of the model simulation was evaluated using three metrics. Each metric compares n observations (O) with their corresponding model estimates (M).

a) Root-Mean-Square Error (RMSE)

The RMSE quantifies the overall magnitude of the discrepancies between the estimates and the observed data:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (O_i - M_i)^2}{n}} \quad (15)$$

A lower RMSE indicates that the model estimates are closer to the observed values.

b) Mean Absolute Percentage Error (MAPE)

The MAPE measures the average relative magnitude of the errors expressed as a percentage:

$$APE = \frac{1}{n} \sum_{i=1}^n \left| \frac{O_i - M_i}{O_i} \right| \times 100 \quad (16)$$

c) Pearson correlation coefficient (R)

R assesses the degree of linear association between the estimates and observations over time, indicating the tendency of the two variables to vary together:

$$R = \frac{\sum_{i=1}^n (O_i - \bar{O})(M_i - \bar{M})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (M_i - \bar{M})^2}} \quad (17)$$

where $\bar{O}$ and $\bar{M}$ represent the mean values of the observations and estimates, respectively.

III. RESULTS AND DISCUSSION

Fig. 4 shows the simulated R_{rs} on 10 July, 2021. In the red band (673.5 nm), high R_{rs} is evident near river mouths, reflecting particle-dominated scattering associated with elevated suspended matter concentrations during river high-flow events. This indicates that the model reproduces this phenomenon well. In comparison with satellite imagery, the model accurately reproduces bay-wide patterns. However, at the mouths of the Edo, Naka, and Sumida rivers, R_{rs} is overestimated, which is attributable to an overestimation of suspended particulate concentrations. Conversely, in the near-UV band (380 nm), R_{rs} is relatively small across the eutrophic bay because of absorption by phytoplankton and CDOM. Relative to the model, the satellite retrievals show a pronounced negative bias, particularly near river mouths.

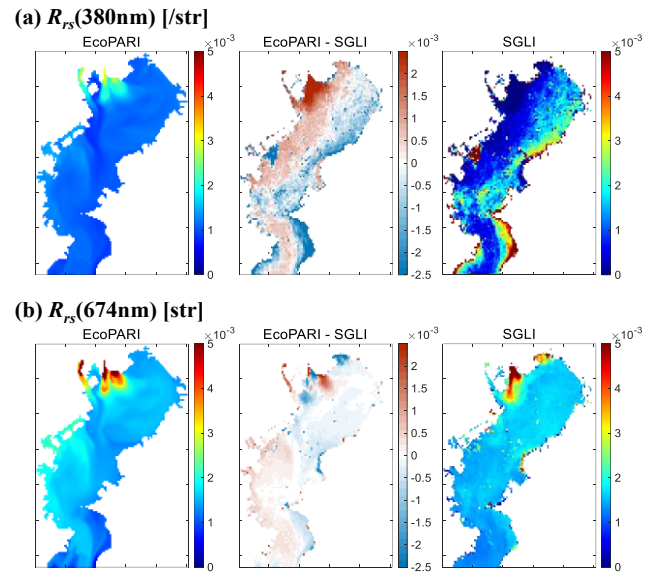


Fig. 4. EcoPARI-simulated R_{rs} (left), differences (EcoPARI-SGLI; center), and SGLI-observed R_{rs} (right) on 10 July, 2021. (a) 380 nm and (b) 674 nm.

Table 4. Statistical comparison between SGLI-observed and EcoPARI-simulated R_{rs}

Wavelength [nm]	R	RMSE $\times 10^{-3}$ [1/str]	MAPE [%]	p -value
380	-0.153	1.988	308.94	<0.01
412	-0.032	1.465	165.00	<0.05
443	0.175	1.181	49.82	<0.01
490	0.350	0.928	34.70	<0.01
530	0.468	1.109	25.09	<0.01
565	0.454	1.179	23.28	<0.01
674	0.515	0.613	21.30	<0.01

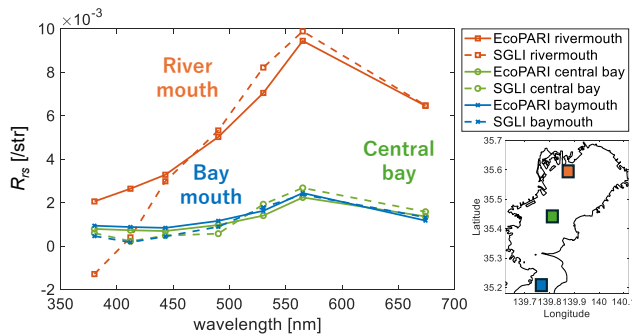


Fig. 5. Spectral distribution of R_{rs} at sites located at the river mouth (orange), central bay (green), and bay mouth (blue). Solid lines denote EcoPARI simulations and dashed lines denote SGLI observations.

In the spectral distributions of R_{rs} at sites located at the river mouth, central bay, and bay mouth shown in Fig. 5, the model and satellite observations are in good agreement.

However, at the river-mouth sites, the short-wavelength bands (380 and 412 nm) are markedly underestimated in the satellite retrievals, consistent with the tendencies seen in the spatial distributions.

Although the GCOM-C/SGLI standard atmospheric correction includes a scheme to compensate for negative R_{rs} in coastal areas [33], this validation study reveals that significant underestimation persists. This is particularly evident where the effects of absorbing aerosols from urban areas such as Tokyo overlap with the high concentrations of NAP and CDOM from river discharge. As shown by the statistical indices in Table 4, R and MAPE demonstrate that the accuracy of the simulation improves significantly toward longer wavelengths. In the short-wavelength bands (380 and 412 nm), the model and satellite values show a marked discrepancy, with negative R values and MAPE exceeding

160%. Conversely, the performance improves at longer wavelengths, reaching an R value of 0.515 and a MAPE of

21.30% at 674 nm, quantitatively confirming the wavelength dependence of the model–satellite agreement.

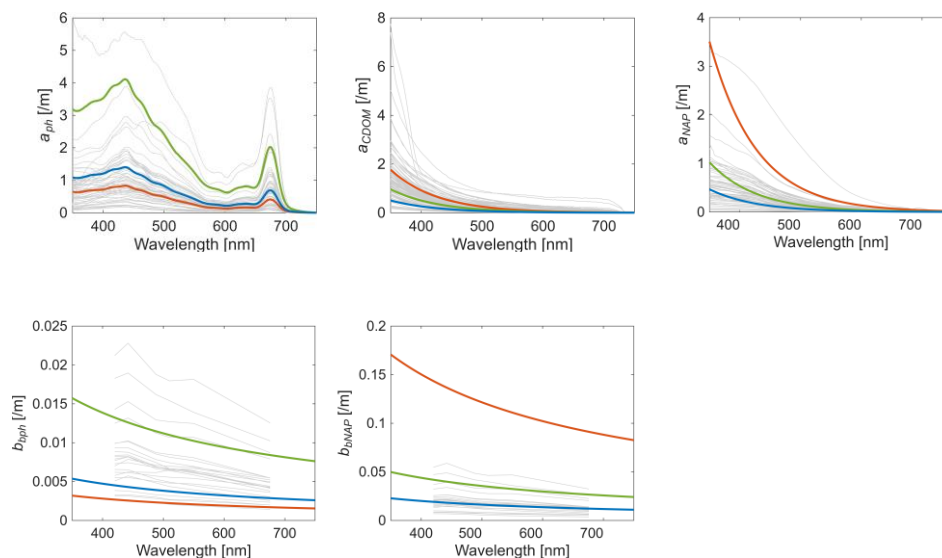


Fig. 6. Spectral distribution of model-computed IOPs at sites at river mouth (brown), central bay (green), and bay mouth (blue). Gray lines indicate in-situ measurements.

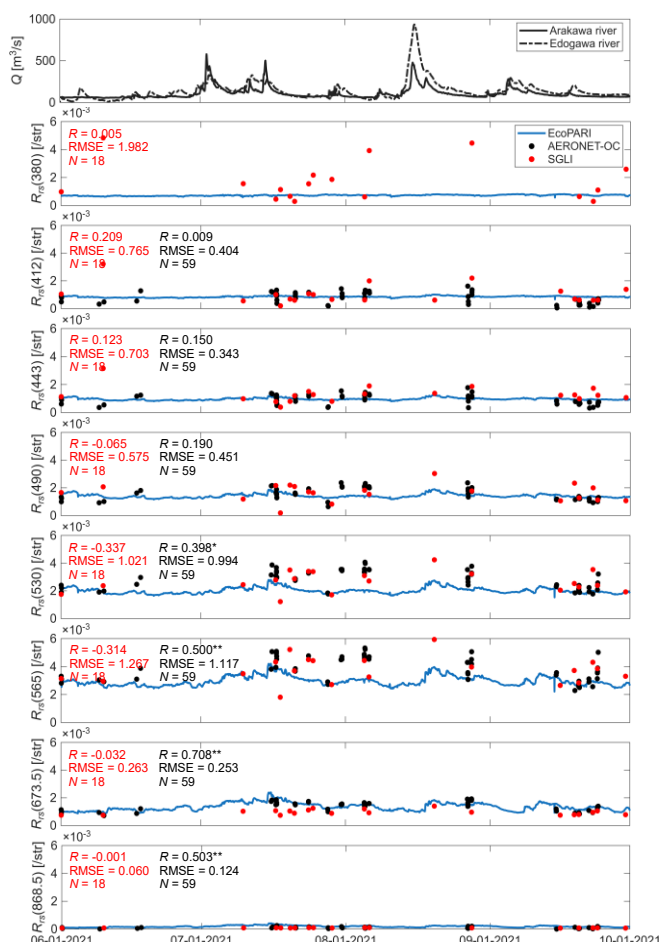


Fig. 7. Time-series comparison of river discharge from Edogawa and Arakawa rivers and R_{rs} at Kemigawa-Offshore monitoring station. Statistical metrics in black text indicate comparisons between the model and AERONET-OC observations, while those in red text indicate comparisons between the model and SGLI satellite retrievals. Asterisks indicate the statistical significance of the Pearson correlation coefficient (R): ** p -value < 0.01 and * p -value < 0.05 . The unit for RMSE is $\times 10^{-3}$ [str].

These errors necessitate caution when using short-wavelength bands in river-mouth regions for model evaluation or data assimilation, as the resulting uncertainties

can affect the interpretation of model performance. To mitigate these effects, the application of atmospheric correction algorithms tailored for optically complex coastal waters [18], or the preferential use of longer-wavelength bands, which are less sensitive to such uncertainties, should be considered.

Fig. 6 presents modeled IOPs at the sites corresponding to those in Fig. 5. Gray curves indicate in-situ shipboard measurements. Overall, the absorption and backscattering components of each constituent are reproduced satisfactorily. The departure of $b_{bNAP}(\lambda)$ from the range of prior observations reflects the absence of measurements at river mouths during flood events.

The bio-optical model employed in this study was previously validated by Salem *et al.* [26], where its effectiveness was demonstrated through a comparative analysis of satellite-derived Chl-*a* retrieval algorithms in Tokyo Bay and Lake Kasumigaura. Nevertheless, it is important to note that the model's performance has not yet been fully evaluated under extreme conditions, such as the exceptionally high turbidity and CDOM concentrations frequently observed at river mouths during discharge events.

Extreme conditions pose challenges for the current parameterization of mass-specific light absorption and backscattering coefficients. Further validation in such optically complex environments remains a key objective for future research, as it will allow us to more clearly define the model's operational limits and enhance its overall robustness.

Fig. 7 presents a time-series comparison of EcoPARI R_{rs} estimates with AERONET-OC and SGLI R_{rs} observations. The AERONET-OC site is located in the inner bay (see Fig. 2) and is influenced by flood discharges from the Arakawa and Edo rivers. During the flood events observed in July–August, R_{rs} increased at longer wavelengths (565–673.5 nm), indicating that the model realistically reproduced increases in b_{bNAP} associated with riverine suspended matter inputs. Subsequently, R_{rs} gradually declined, reflecting the combined effects of reduced scattering as NAP settled, increased a_{ph} with nutrient-stimulated primary production, and a growing

relative contribution of a_{CDOM} . The high accuracy of the model in reproducing the entire time-series of R_{rs} , including both the abrupt increases and the subsequent recovery phases, is quantitatively validated by significant positive correlations with AERONET-OC ($R = 0.500\text{--}0.708$, $p < 0.01$).

IV. CONCLUSION

In this study, we developed a BGC model that enables quantitative comparison between satellite observations and BGC model outputs through R_{rs} for Tokyo Bay. Comparison with GCOM-C/SGLI imagery demonstrated that the model successfully reproduced bay-wide spatial patterns of R_{rs} , particularly the enhancement in the red band at river mouths during flood events, indicating that riverine suspended matter effects on light scattering were realistically represented. Furthermore, time-series validation against AERONET-OC measurements in the inner bay confirmed that the model reproduced the temporal evolution of R_{rs} during summer flood events. An increase in long-wavelength R_{rs} associated with enhanced b_{bNAP} was followed by a gradual decline driven by particle settling, increased a_{ph} , and an increasing relative contribution of a_{CDOM} .

The proposed framework provides a basis for future application to data assimilation using R_{rs} as a direct observation constraint. Because R_{rs} is not affected by uncertainties inherent in satellite-derived water quality products, it can be utilized as a more stable and consistent observational quantity for data assimilation. This approach is expected to enable ocean-color data assimilation in optically complex coastal waters, where conventional methods based on retrieved water quality variables have remained challenging.

As a next step, explicitly accounting for the vertical profiles of IOPs in the forward modeling of R_{rs} is expected to enable a more rigorous treatment of radiative transfer processes, thereby improving the physical consistency of modeled R_{rs} with satellite observations. Furthermore, while this study established the framework for Tokyo Bay, the evaluation of its applicability to other coastal regions with diverse optical properties remains a key future task.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

T.N. and H.H. jointly conceptualized the study and collected the data; T.N. developed the methodology, performed the data analysis, and wrote the manuscript; H.H. supervised the research. All authors reviewed and approved the final version.

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