

Article

Optical Characterization of Coastal Waters with Atmospheric Correction Errors: Insights from SGLI and AERONET-OC

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Abstract: This study identifies the characteristics of water regions with negative normalized water-leaving radiance ($nL_w(\lambda)$) values in the satellite observations of the Second-generation Global Imager (SGLI) sensor aboard the Global Change Observation Mission–Climate (GCOM-C) satellite. SGLI Level-2 data, along with atmospheric and in-water optical properties measured by the sun photometers in the AEROSOL ROBOTIC NETWORK-Ocean Color (AERONET-OC) from 26 sites globally, are utilized in this study. The focus is particularly on Tokyo Bay and the Ariake Sea, semi-enclosed water regions in Japan where previous research has pointed out the occurrence of negative $nL_w(\lambda)$ values due to atmospheric correction with SGLI. The study examines the temporal changes in atmospheric and in-water optical properties in these two regions, and identifies the characteristics of regions prone to negative $nL_w(\lambda)$ values due to atmospheric correction by comparing the optical properties of these regions with those of 24 other AERONET-OC sites. The time series results of $nL_w(\lambda)$ and the single-scattering albedo ($\omega(\lambda)$) obtained by the sun photometers at the two sites in Tokyo Bay and Ariake Sea, along with SGLI $nL_w(\lambda)$, indicate the occurrence of negative values in SGLI $nL_w(\lambda)$ in blue band regions, which are mainly attributed to the inflow of absorptive aerosols. However, these negative values are not entirely explained by $\omega(\lambda)$ at 443 nm alone. Additionally, a comparison of in situ $nL_w(\lambda)$ measurements in Tokyo Bay and the Ariake Sea with $nL_w(\lambda)$ values obtained from 24 other AERONET-OC sites, as well as the inherent optical properties (IOPs) estimated through the Quasi-Analytical Algorithm version 5 (QAA_v5), identified five sites—Gulf of Riga, Long Island Sound, Lake Vanern, the Tokyo Bay, and Ariake Sea—as regions where negative $nL_w(\lambda)$ values are more likely to occur. These regions also tend to have lower $nL_w(\lambda)$ values at shorter wavelengths. Furthermore, relatively high light absorption by phytoplankton and colored dissolved organic matter, plus non-algal particles, was confirmed in these regions. This occurs because atmospheric correction processing excessively subtracts aerosol light scattering due to the influence of aerosol absorption, increasing the probability of the occurrence of negative $nL_w(\lambda)$ values. Based on the analysis of atmospheric and in-water optical measurements derived from AERONET-OC in this study, it was found that negative $nL_w(\lambda)$ values due to atmospheric correction are more likely to occur in water regions characterized by both the presence of absorptive aerosols in the atmosphere and high light absorption by in-water substances.

Keywords: ocean color satellite; GCOM-C/SGLI; AERONET-OC; SeaPRISM; Tokyo Bay; Ariake Sea; atmospheric correction; inherent optical properties

1. Introduction

Satellites with various observational capabilities are well suited to vast oceanic observations, and are thus expected to play a crucial role in monitoring changes in marine environments. Coastal areas, though smaller than open oceans, are very productive as they receive nutrients and organic matter from the land. The continuous monitoring of these areas is thus vital, considering climate change. Coastal areas are also closely intertwined with human activities, necessitating environmental monitoring for the sustainable preservation, conservation, and management of water environments, as well as the protection of fishery resources.

The satellite Global Change Observation Mission–Climate (GCOM-C) with the Second-generation Global Imager (SGLI), which enables high-resolution imaging at $250\text{ m} \times 250\text{ m}$, was launched by the Japan Aerospace Exploration Agency (JAXA) in December 2017 [1,2]. It is expected to be utilized for the long-term monitoring of rapidly changing water bodies, such as coastal areas and lakes, with high spatial resolution, facilitating the continuous observation of environmental changes [3–5]. However, in coastal areas where there is material supply from rivers, various species and compositions of phytoplankton, colored dissolved organic matter (CDOM), and inorganic suspended matter are intricately mixed, often resulting in consistently high concentrations of in-water substances. In addition, absorptive aerosols from sources such as yellow sand or urban exhaust gases tend to influence the atmospheric optical properties [6–8]. As a result, the accuracies of atmospheric correction and water quality estimation performed via ocean color satellites are often compromised due to the complexity of the optical characteristics in water and atmospheric environments [9–11]. In particular, a significant problem arises during atmospheric correction processing when aerosol reflectance is overestimated, leading to physically unrealistic negative values in the remote sensing reflectance ($R_{rs}(\lambda)$) and normalized water-leaving radiance ($nL_w(\lambda)$) [8,12,13]. When the water surface reflectance becomes negative, accurate water quality estimation becomes difficult, and in some cases, the analysis itself may become impossible.

In atmospheric correction algorithms for ocean color remote sensing, it is generally assumed that water-leaving radiance in the near-infrared (NIR) region is almost entirely absorbed, with the assumption that all radiance detected by the satellite is of atmospheric origin. This allows for relatively straightforward atmospheric correction [14,15]. However, in regions where suspended particulate matter increases and the water-leaving radiance in the NIR band becomes significant, it becomes difficult to extract purely atmospheric information from the satellite-detected radiance [16]. To address this issue, various atmospheric correction algorithms have been developed over the past 20 years. These include methods based on the allocation of NIR contributions from aerosols or water, the use of shortwave infrared bands, the application of blue or ultraviolet bands, correction or modeling techniques for regions where water-leaving radiance in the NIR is non-negligible, and atmospheric-water inversion methods based on neural networks or optimization techniques [17–39]. Although accuracy evaluations using these different types of atmospheric correction methods have been conducted, the occurrence of negative values in $R_{rs}(\lambda)$ or $nL_w(\lambda)$ resulting from atmospheric correction remains a challenge, and it is recommended that these be flagged in the data processing steps [40].

Researchers have proposed various techniques to mitigate the occurrence of negative $R_{rs}(\lambda)$ and $nL_w(\lambda)$ values resulting from such atmospheric correction. One method increases the in-water reflectance at wavelengths where negative values occur, and then re-estimates aerosol reflectance [8,41]. Another method proposed a simple and effective approach that utilizes the linear relationship between R_{rs} near 550 nm and R_{rs} at 412 nm, allow-

ing for error estimation between these wavelengths and linear error estimation across the visible spectrum [42,43]. The methods proposed for reducing negative in-water reflectance are not based on a theoretical model of atmospheric and in-water optical properties. Developing appropriate atmospheric correction models for optically complex coastal areas requires elucidating the factors that contribute to negative in-water reflectance and clarifying the conditions under which they occur. Analyzing atmospheric correction errors requires matchup data between satellite data and in situ measurements. However, optical matchup data for coastal areas are often limited in sample size. Therefore, in this study, we utilize observation from the National Aeronautics and Space Administration (NASA) observation network Aerosol Robotic Network–Ocean Color (AERONET-OC) [44,45]. AERONET-OC has been extensively utilized for various applications, including the evaluation of satellite-derived ocean color data [44,46–48], atmospheric correction [32,49], and the validation of bio-optical and water quality estimation models [50,51]. It has also been employed for assessing alternative calibration methods [52]. AERONET-OC's sun photometers are located close to terrestrial regions, facilitating the continuous monitoring of the optical properties of both the atmosphere and water. This setup enables the acquisition of a significant amount of matchup data in coastal areas, enhancing the understanding and analysis of atmospheric correction errors in such regions.

The purpose of this study is to analyze the factors that cause negative $nL_w(\lambda)$ values in satellite observations, and to clarify the conditions under which such negative values occur, using $nL_w(\lambda)$, aerosol optical depth ($\tau_a(\lambda)$), and Single Scattering Albedo ($\omega(\lambda)$) observed by AERONET-OC. First, we focus on Tokyo Bay and the Ariake Sea, two representative semi-enclosed water regions in Japan characterized by an influx of absorptive aerosols and high concentrations of water substances. We examine the factors leading to atmospheric correction errors when the satellite-derived $nL_w(\lambda)$ values become negative in these areas. These two regions have been selected because previous studies have confirmed atmospheric correction errors in GCOM-C/SGLI data [48,51], and because they have significantly different water quality characteristics. Next, we use atmospheric and in-water optical data from AERONET-OC sites around the world to compare these two regions with other water bodies, aiming to identify the characteristics of regions where $nL_w(\lambda)$ values are more prone to becoming negative.

2. Materials and Methods

2.1. Target Water Regions

In this study, we focus on Tokyo Bay and the Ariake Sea, as shown in Figure 1a,b, which are representative semi-enclosed water bodies in Japan located near urban areas. Previous studies have confirmed that $nL_w(\lambda)$ estimates from SGLI atmospheric correction processing tend to result in negative values in these regions [48,51]. Therefore, this study primarily targets these water regions to investigate the factors contributing to the occurrence of negative $nL_w(\lambda)$ values due to atmospheric correction.

Tokyo Bay is situated in central Japan (35.00–35.40°N, 139.40–140.05°E). It spans approximately 50 km north to south and 10 to 30 km east to west, with an area of 960 km² (Figure 1a). The bay has an average depth of around 15 m, and due to its semi-enclosed shape, seawater exchange is gradual. The total volume of the bay is estimated to be 15.0 km³, with an annual inflow from rivers ranging from 8 to 12 billion m³. The residence time of water within the bay is approximately 1.5 months. Tokyo Bay is characterized by eutrophication, with significant organic pollution, and experiences approximately 70 occurrences of red tide annually [53]. The Kemigawa Offshore Tower is located at 35.611°N, 140.023°E, as shown in Figure 1a. CIMEL's Sun Sky Lunar Multispectral Photometer (CE318TV-12 OC), which is registered with AERONET-OC, is installed on top of the tower. The measurement system for atmospheric and in-water radiance based on CE318 is known as SeaPRISM (Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Photometer Revision for Incident Surface Measurements). It operates across a range of 400 to 1020 nm, covering approximately 10 central wavelengths. Utilizing measurements at multiple azimuth angles, SeaPRISM

measures both atmospheric and sea surface radiance [44,45,54–57]. At the Kemigawa Offshore Tower, during the summer season, there is a significant increase in the chlorophyll-a (Chl-a) concentration, leading to occurrences of red tide, and north winds can induce the upwelling of bottom water, resulting in blue tide areas characterized by a bluish-white change in ocean color [58–60]. Therefore, it is an ideal location for capturing changes in ocean color due to the presence of red and blue tides in eutrophic waters. Furthermore, a previous study measured $\tau_a(\lambda)$ using a sun photometer (Prede PSF-100) at approximately 3.5 km away from the Kemigawa Offshore Tower, at 35.62°N, 140.06°E, from 1999 to 2005 [61]. The Angstrom exponent was calculated based on the observations. $\tau_a(\lambda)$ exhibited seasonal variations, with lower values (<0.2) during autumn and winter and higher values (~0.5) during spring and summer. In addition, the Angstrom exponent ranged from 0.5 to 1.8, indicating a relatively significant influence of anthropogenic particles.

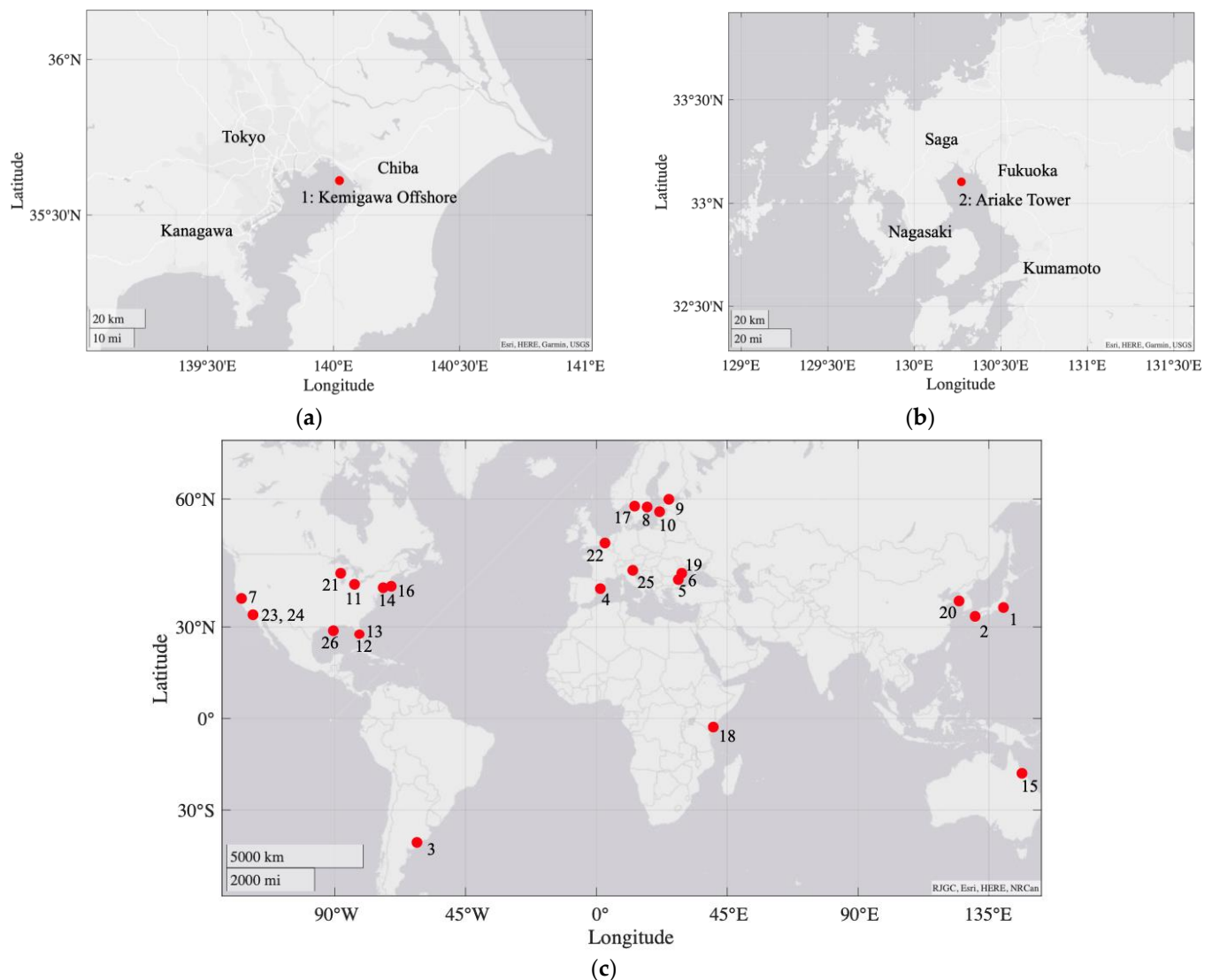


Figure 1. Map of target water regions and installation locations of SeaPRISM in AERONET-OC: (a) Kemigawa Offshore Tower in Tokyo Bay, Japan, (b) Ariake Sea Observation Tower in Japan, and (c) AERONET-OC sites in various countries. The numbers shown next to each site correspond to the AERONET-OC site numbers listed in Table 1.

Table 1. Locations where SeaPRISM is installed in AERONET-OC and associated water regions.

	Location	Water Region	Coordinates
1	Kemigawa Offshore Tower	Tokyo Bay	35.611°N, 140.023°E
2	Ariake Tower	Ariake Sea	33.104°N, 130.272°E
3	Bahia Blanca	Argentine Sea	39.148°S, 61.722°W
4	Casablanca Platform	Balearic Sea	40.717°N, 1.358°E
5	Galata Platform	Black Sea	43.045°N, 28.193°E
6	Gloria *	Black Sea	44.600°N, 29.360°E
7	Grizzly Bay	Grizzly Bay	38.108°N, 122.056°W
8	Gustav Dalen Tower	Baltic Sea	58.594°N, 17.467°E
9	Helsinki Lighthouse	Gulf of Finland	59.949°N, 24.926°E
10	Irbe Lighthouse	Gulf of Riga	57.751°N, 21.723°E
11	Lake Erie	Lake Erie	41.826°N, 83.194°W
12	Lake Okeechobee *	Lake Okeechobee	26.902°N, 80.789°W
13	Lake Okeechobee N *	Lake Okeechobee	27.139°N, 80.789°W
14	Long Island Sound Coastal Observatory (LISCO)	Long Island Sound	40.955°N, 73.342°W
15	Lucinda	Great Barrier Reef	18.520°S, 146.386°E
16	Martha's Vineyard Coastal Observatory (MVCO)	East Coast of United States of America	41.325°N, 70.567°W
17	Palgrunden	Lake Vanern	58.755°N, 13.152°E
18	San Marco Platform	Indian Ocean	2.942°S, 40.215°E
19	Section-7 Platform *	Black Sea	44.546°N, 29.447°E
20	Socheongcho	Yellow Sea	37.423°N, 124.738°E
21	South Greenbay	Green Bay (Lake Michigan)	44.596°N, 87.951°W
22	Thornton C-power	North Sea	51.532°N, 2.955°E
23	USC SEAPRISM *	Long Beach	33.564°N, 118.118°W
24	USC SEAPRISM 2 *	Long Beach	33.564°N, 118.118°W
25	Venice	Adriatic Sea	45.314°N, 12.508°E
26	Wave-Current-Surge Information System (WaveCIS) Site CSI-6	Gulf of Mexico	28.867°N, 90.483°W

* Due to their nearly identical locations, the data are combined and treated as reflecting one location.

The Ariake Sea is located in the northwestern part of Kyushu, Japan (32.30–33.10°N, 130.10–140.40°E). It spans approximately 100 km north to south and 20 km east to west, covering an area of 1700 km² (Figure 1b). The average depth of the bay is around 20 m, with a total volume of 34.0 km³. The combined annual discharge from eight rivers flowing into the sea totals 11×10^9 m³, with 40% of it originating from the Chikugo River. The annual inflow from rivers ranges from 8 to 12×10^9 m³. The residence time within the sea is approximately 1.7 months. The Ariake Sea is subject to eutrophication, with approximately 35 occurrences of red tide annually, and it has the largest tidal range in Japan, reaching up to approximately 6 m. This substantial tidal range contributes to significant turbidity, as it can resuspend the sediment from the tidal flats [62,63]. As shown in Figure 1b, the Ariake Sea Observation Tower of Saga University [64], equipped with SeaPRISM, is located at 33.104°N, 130.272°E. The analysis of in-water optical characteristics of the Ariake Sea using SeaPRISM was conducted by Ishizaka et al. [51].

When comparing the water quality characteristics of Tokyo Bay and the Ariake Sea, there are notable differences in the composition of suspended particulate matter. Tokyo Bay is predominantly characterized by organic matter, leading to high light absorption, while the Ariake Sea shows inorganic suspended matter, resulting in considerable light scattering.

For a relative comparison of the optical characteristics of enclosed water bodies such as Tokyo Bay and the Ariake Sea, optical measurement results from 24 locations registered with AERONET-OC, shown in Figure 1c and Table 1, were utilized.

2.2. AERONET-OC

In this study, the optical parameter for representing in-water measurements by AERONET-OC is $nL_w(\lambda)$, and those for atmospheric measurements are $\tau_a(\lambda)$ and the inverse product $\omega(\lambda)$. $nL_w(\lambda)$ is expressed as

$$nL_w(\lambda) = L_w(\lambda, \theta, \varphi) C_{\Re Q}(\lambda, \theta, \varphi, \theta_0, \tau_a, \text{IOPs}, W) \times C_{\frac{f}{Q}}(\lambda, \theta_0, \tau_a, \text{IOPs}) \left[D^2 t_d(\lambda) \right]^{-1} \quad (1)$$

$$C_{\Re Q}(\lambda, \theta, \varphi, \theta_0, \tau_a, \text{IOPs}, W) = \frac{\Re_0}{\Re(\theta, W)} \frac{Q(\lambda, \theta, \varphi, \theta_0, \tau_a, \text{IOPs})}{Q_n(\lambda, \theta_0, \tau_a, \text{IOPs})} \quad (2)$$

$$C_{\frac{f}{Q}}(\lambda, \theta_0, \tau_a, \text{IOPs}) = \frac{f_0(\lambda, \tau_a, \text{IOPs})}{Q_0(\lambda, \tau_a, \text{IOPs})} \left[\frac{f(\lambda, \theta_0, \tau_a, \text{IOPs})}{Q_n(\lambda, \theta_0, \tau_a, \text{IOPs})} \right]^{-1} \quad (3)$$

Equation (2), which includes $\Re(\theta, W)$ and $\Re_0$ (the value of $\Re(\theta, W)$ at $\theta = 0$), represents the reflection and refraction of the sea surface. In addition, $Q(\lambda, \theta, \varphi, \theta_0, \tau_a, \text{IOPs})$ and $Q_n(\lambda, \theta_0, \tau_a, \text{IOPs})$ are the anisotropic distributions of the in-water radiative field at viewing angle θ and directly beneath the sea surface ($\theta = 0$), respectively. They include the parameters θ , φ , θ_0 , and $\tau_a(\lambda)$ and the inherent optical properties (IOPs) of seawater. In Equation (3), $f(\lambda, \theta_0, \tau_a, \text{IOPs})$ is a function related to the apparent optical properties and the IOPs [55]. $f_0(\lambda, \tau_a, \text{IOPs})$ and $Q_0(\lambda, \tau_a, \text{IOPs})$ are the values of $f(\lambda, \theta_0, \tau_a, \text{IOPs})$ and $Q_n(\lambda, \theta_0, \tau_a, \text{IOPs})$, respectively, at $\theta_0 = 0$. In addition, D^2 in Equation (1) is the day-to-day variation in the distance between the Sun and Earth and $t_d(\lambda)$ is the atmospheric diffuse transmittance calculated from the measured $\tau_a(\lambda)$ before the measurement of $L_T(\lambda, \theta, \varphi)$ [57]. $\tau_a(\lambda)$ is expressed as

$$\tau_a(\lambda) = \int \alpha_{ext}(\lambda) dz \quad (4)$$

$\omega(\lambda)$ is expressed as

$$\omega(\lambda) = \frac{\alpha_{scat}(\lambda)}{\sigma_{ext}(\lambda)} = \frac{\alpha_{scat}(\lambda)}{\alpha_{abs}(\lambda) + \alpha_{scat}(\lambda)} \quad (5)$$

where $\alpha_{ext}(\lambda)$ is the total extinction coefficient, $\alpha_{abs}(\lambda)$ is the absorption coefficient, and $\alpha_{scat}(\lambda)$ is the scattering coefficient, with $\alpha_{ext}(\lambda) = \alpha_{abs}(\lambda) + \alpha_{scat}(\lambda)$. Equation (5) represents the relationship between the absorption and scattering of light by aerosols. Since scattering predominates over absorption in the atmosphere, $\omega(\lambda)$ generally approaches a value close to 1. As it increases, the influence of atmospheric absorption becomes more significant, leading to a decrease in $\omega(\lambda)$ from 1. The $nL_w(\lambda)$, $\tau_a(\lambda)$, and $\omega(\lambda)$ data obtained from SeaPRISM for each water body were downloaded from the AERONET-OC website (https://aeronet.gsfc.nasa.gov/new_web/data.html) (accessed on 1 July 2024). For Tokyo Bay, measurements from July 2019 to January 2022 were utilized; for the Ariake Sea, measurements from January 2020 to January 2022 were utilized.

To compare the optical characteristics of Tokyo Bay and the Ariake Sea relative to other water bodies, we used AERONET-OC data, namely, $nL_w(\lambda)$, $\tau_a(\lambda)$, and $\omega(\lambda)$, for 21 water bodies at 24 sites around the world that have been well measured since December 2017, when GCOM-C/SGLI started its observations, as shown in Table 1. The AERONET-OC data are provided as Level 1.0 data (raw data) measured by SeaPRISM, Level 1.5 data with NASA quality control, and Level 2.0 data (calibrated data). In this study, to minimize bias from data uncertainty, we utilized the Level 1.5 data and excluded any cases that resulted in theoretically impossible negative values across all measured spectra. Additionally, we removed the data where the nL_w at 1020 nm exceeded 0.1, likely due to the effects of sunglint. To compare SeaPRISM and SGLI $nL_w(\lambda)$ wavelengths, we applied the method proposed by Mélin and Sclép [65] for wavelength-to-wavelength interpolation based on the quasi-analytical algorithm (QAA) technique to the SeaPRISM $nL_w(\lambda)$.

2.3. In Situ Data

In this study, the water quality data obtained from the multi-parameter water quality meter (YSI Nanotech 599502-02) at the Tokyo Bay Environmental Information Center were utilized. This instrument, installed at the Kemigawa Offshore Tower (see Figure 1), is operated in conjunction with the CE318TV-12 OC. It measures various parameters, including water depth (m), temperature ($^{\circ}\text{C}$), conductivity (mS/cm), salinity, turbidity (NTU), Chl-a ($\mu\text{g/L}$), dissolved oxygen (DO) (% and mg/L), pH, and oxidation–reduction potential (mV). An automatic lifting mechanism allows the instrument to capture the vertical water quality distribution by ascending and descending every 15 min (starting from midnight). We focused on fluorescence-based Chl-a and salinity data measured at the surface (depth: 1 m) since July 2019. The Chl-a measurement range is from 0 to 400 $\mu\text{g/L}$ with a resolution of 0.1 $\mu\text{g/L}$ and the salinity measurement range is from 0 to 70 with a resolution of 0.01. To align the measurement times with those of $nL_w(\lambda)$ measured by SeaPRISM, we performed a linear interpolation on the 15 min-interval data of Chl-a and salinity.

2.4. Specification of SGLI

The SGLI instrument aboard GCOM-C is composed of three main components (see Table 2), namely, the visible and near-infrared radiometer with non-polarization channels (VNR-NP), which spans 11 bands from 380 to 868 nm in the near-ultraviolet to near-infrared range, the visible and near-infrared radiometer with polarization channels (VNR-PL), which observes polarization in two bands centered at red (673 nm) and near-infrared (868 nm) wavelengths, and the infrared scanner (IRS), which consists of four bands from 1.05 to 2.2 μm in the shortwave infrared region, along with two bands in the thermal infrared region ranging from 11 to 12 μm . The instruments scan $\pm 35^{\circ}$ to the left and right from a polar orbit at an altitude of approximately 800 km around 10:30 local time, covering a swath width of 1150 km (1400 km for IRS). Key features of SGLI for ocean color include a 250 m resolution across all bands (380 to 868 nm) used for ocean color estimation and an observation band in the near-ultraviolet region (380 nm), which is shorter than the shortest wavelength (412 nm) used in conventional ocean color sensors. SGLI primarily uses a solar diffuser as the main calibrator, supplemented by lamp data to confirm shifts at the time of launch and lunar observations to monitor long-term changes [66]. Additionally, vicarious adjustments over the ocean are conducted, and the results are compared with the onboard calibration methods and other satellite sensors in collaboration with international communities and the CEOS Cal/Val group.

A duration of approximately 2.5 days per observation and a high spatial resolution of 250 m allow for detailed environmental observations, particularly in relatively small water regions such as coastal regions and lakes. In this study, Level 2 ocean color products data with atmospheric correction processing version 2 were downloaded from JAXA's G-Portal [67]. In SGLI with atmospheric correction version 2, the process adheres to the atmospheric correction methods used by SeaWiFS and MODIS [15], as well as techniques using Japan's ocean color satellite sensors, ADEOS/OCTS [68] and ADEOS-II/GLI [7]. The atmospheric correction processing flow for each pixel includes several steps: correction for ozone absorption transmittance, Rayleigh reflectance correction, high reflectance pixel check, sunglint correction, whitecap correction, aerosol reflectance correction, cloud identification processing, and Bidirectional Reflectance Distribution Function (BRDF) correction. Through these processes, normalized water-leaving $nL_w(\lambda)$ and $R_{rs}(\lambda)$ are calculated. Additionally, this method uses iterative computation to calculate aerosol reflectance based on underwater models, as proposed by Ahn et al. [69] and Lee et al. [70].

Table 2. Channel number, central wavelength, bandwidth, and resolution of SGLI sensor mounted on GCOM-C satellite. (SWI, short-wavelength infrared; TIR, thermal infrared; IFOV, instantaneous field of view).

		Center Wavelength	Bandwidth	IFOV
		VNR, SWI: nm TIR: μm	nm	m
Visible and near-infrared radiometer	Non-polarization channels	VN1	380	10
		VN2	412	10
		VN3	443	10
		VN4	490	10
		VN5	530	20
		VN6	565	20
		VN7	673.5	20
		VN8	673.5	20
		VN9	763	12
		VN10	868.5	20
		VN11	868.5	20
	Polarization channels	P1	673.5	20
		P2	868.5	20
Infrared scanner	SWI channels	SW1	1050	20
		SW2	1380	20
		SW3	1630	200
		SW4	2210	50
	TIR channels	T1	10.8	0.74
		T2	12	0.74

Atmospheric correction processing version 3 for SGLI was released in October 2021. In this version, if the atmosphere-corrected water-leaving reflectance becomes negative, a reselection of aerosol models that do not result in negative water-leaving reflectance is conducted, followed by the calculation of aerosol reflectance [41]. The primary objective of this study was to analyze the factors that cause negative water-leaving reflectance. For this purpose, we utilized the version 2 products data where negative value correction was not applied.

3. Results

3.1. Results of $nL_w(\lambda)$, $\tau_a(\lambda)$, and $\omega(\lambda)$ Obtained from SeaPRISM

Figure 2 shows the results of $nL_w(\lambda)$, $\tau_a(\lambda)$, and $\omega(\lambda)$ obtained from AERONET-OC for Tokyo Bay and the Ariake Sea. The gray lines represent the measured data and the black lines and error bars denote the mean and standard deviation at each wavelength, respectively. The $nL_w(\lambda)$ for Tokyo Bay was generally lower across all observed wavelengths compared to that for the Ariake Sea. This discrepancy is attributed to Tokyo Bay being dominated by organic matter, which leads to stronger light absorption effects, and hence lower reflectance [60,71,72]. Conversely, the Ariake Sea experiences large tidal variations and contains abundant inorganic suspended matter originating from rivers and bottom sediments [73], resulting in significant light scattering.

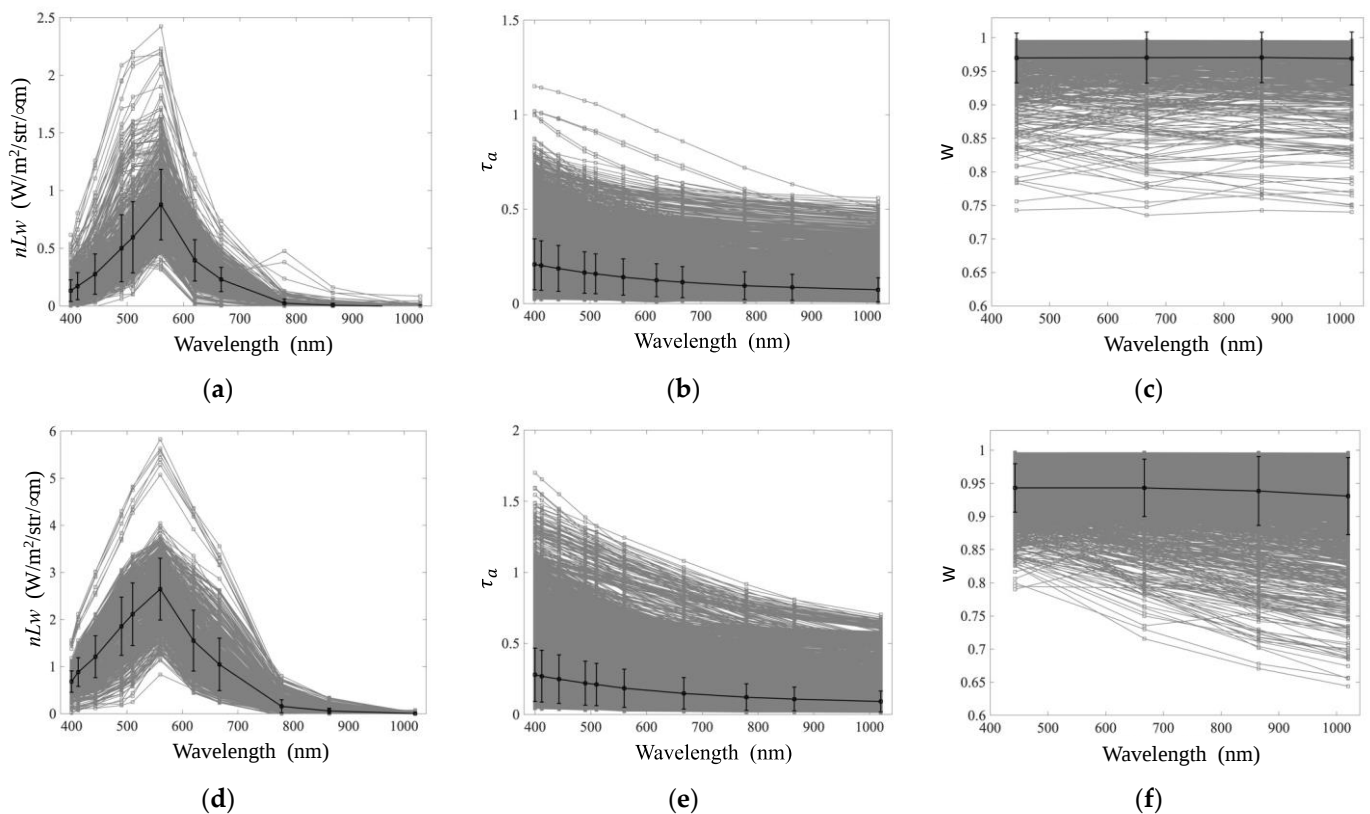


Figure 2. SeaPRISM optical measurements for Tokyo Bay (top panels) and the Ariake Sea (bottom panels). Panels (a,d) show $nL_w(\lambda)$, (b,e) show $\tau_a(\lambda)$, and (c,f) show $\omega(\lambda)$ for Tokyo Bay and the Ariake Sea, respectively. Gray lines represent individual measurement samples, with square markers indicating the measured wavelengths. Black lines denote the mean values across all measured samples, with circle markers representing the observed wavelengths and error bars indicating the standard deviation.

The two water bodies share common characteristics as enclosed coastal areas, with SeaPRISM installations located relatively close to estuarine areas, making them susceptible to riverine influences and promoting the proliferation of phytoplankton. Consequently, the absorption of phytoplankton, CDOM, and non-algal particles strongly affects blue wavelengths of light, leading to a decreasing trend in blue band regions.

$\tau_a(\lambda)$ exhibits a characteristic spectral shape, generally decreasing gradually from shorter to longer wavelengths. The mean $\tau_a(\lambda)$ values for the Ariake Sea are approximately 1.3 times higher than those for Tokyo Bay across all measured wavelengths. Tokyo Bay shows a consistent decrease in $\omega(\lambda)$ across all wavelengths, whereas the Ariake Sea shows a slight decrease in the near-infrared region. The mean $\omega(\lambda)$ values for Tokyo Bay and the Ariake Sea have a difference of approximately 3% across all measured wavelengths.

SeaPRISM and multiparameter water quality sensors are installed at the Kemigawa Offshore Tower (see Figure 1) in Tokyo Bay. Figure 3 illustrates the fluctuation characteristics of $nL_w(\lambda)$ in relation to Chl-a and salinity. The results in Figure 3a,b show $nL_w(\lambda)$ color-coded by Chl-a concentrations and indicate a significant decrease in radiance in the range of 350 to 550 nm as Chl-a increase. This result indicates that the decrease in $nL_w(\lambda)$ on the short wavelength side in Tokyo Bay can be largely explained by the concentration of phytoplankton. Furthermore, from the results in Figure 3c,d, it can be confirmed that the $nL_w(\lambda)$ around 350 to 550 nm decreased significantly when the salinity dropped below 20. This suggests that the inflow of riverine water masses, containing CDOM and phytoplankton, influenced the increase in light absorption. These findings indicate that the decrease in short-wavelength $nL_w(\lambda)$ at the Kemigawa Offshore Tower can largely be explained by the increase in Chl-a and the inflow of low-salinity water masses.

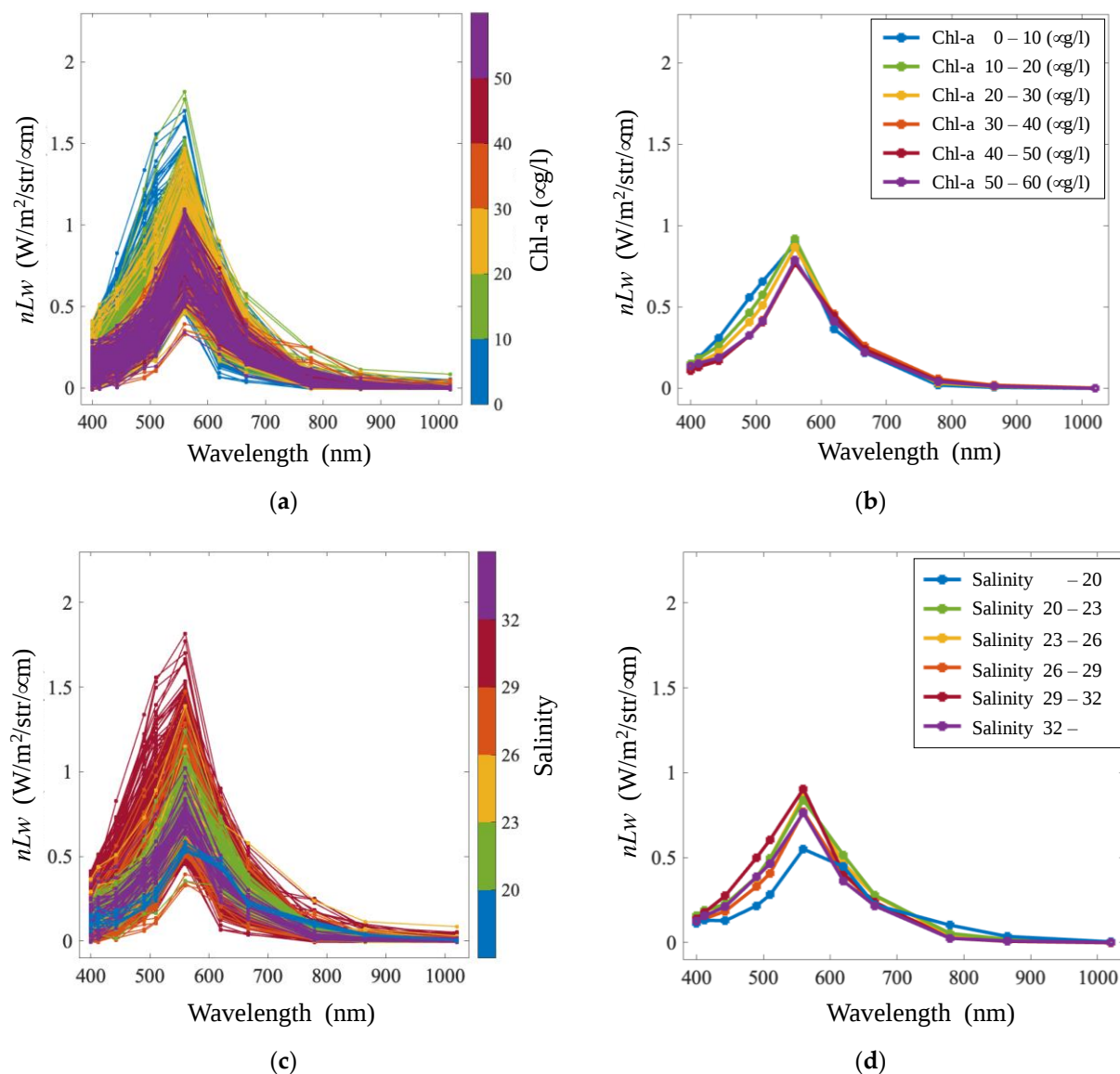


Figure 3. SeaPRISM $nL_w(\lambda)$ measurements for Tokyo Bay, illustrating the relationships between $nL_w(\lambda)$ and water quality parameters. (a) Shows individual measurements of $nL_w(\lambda)$ across varying Chl-a concentrations, and (b) is the mean of each Chl-a range. Relationship between $nL_w(\lambda)$ and salinity for (c) individual salinity values and (d) mean of each salinity range. Circles in each spectrum represent the observed wavelengths.

Figure 4 shows time series comparisons of SeaPRISM-measured and SGLI-estimated $nL_w(412)$ measurements, as well as the time series of $\omega(443)$, for Tokyo Bay and the Ariake Sea. Since the shortest wavelength at which ω is measured is 443 nm, the results at this wavelength are used in this study. The $\omega(443)$ and $nL_w(412)$ measured by SeaPRISM features missing periods from June 2020 to March 2021 in Tokyo Bay, and from November 2020 to February 2021 in the Ariake Sea. The black line for ω represents the monthly average and standard deviation. From the $nL_w(412)$ for each water region, it can be observed that within the areas enclosed by dashed lines, for Tokyo Bay, there are instances of estimated $nL_w(412)$ values decreasing from March 2020 and 2021 and from July 2021 onwards, compared to the measured values, resulting in negative values.

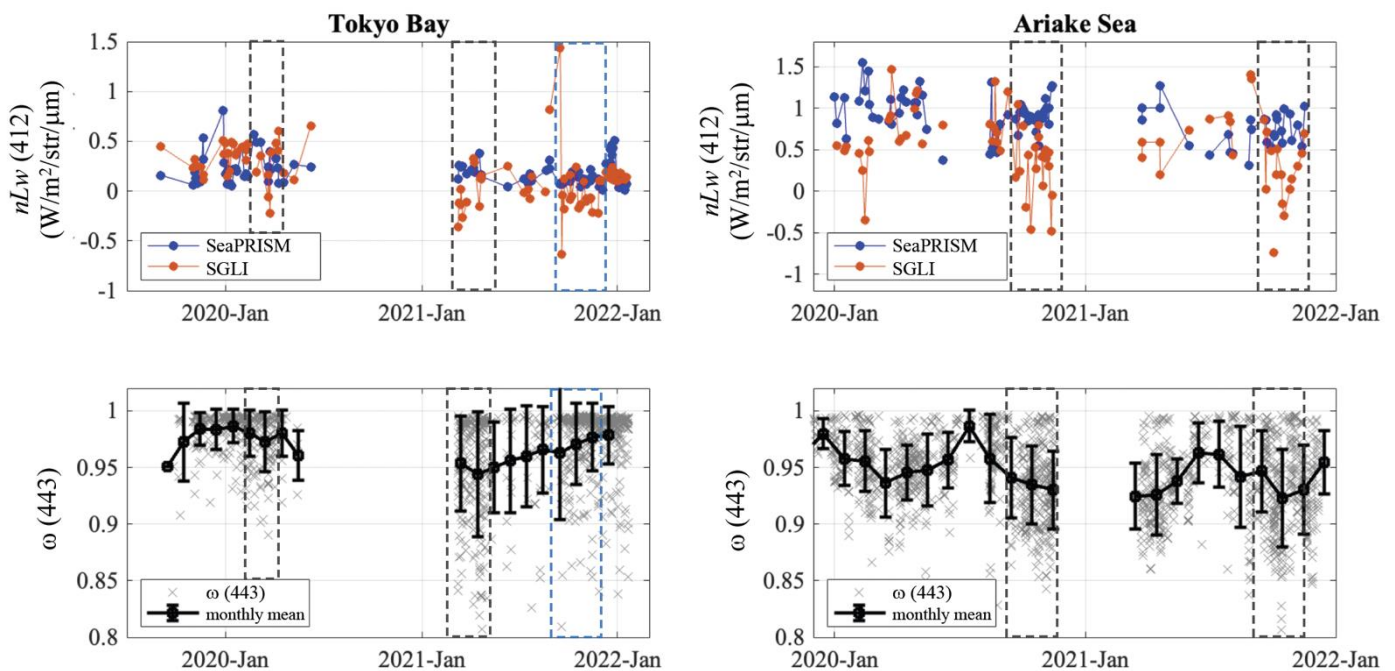


Figure 4. Time series results of $nL_w(412)$ and $\omega(443)$ measured by SeaPRISM for Tokyo Bay and the Ariake Sea from January 2020 to December 2021. For $nL_w(412)$ results, the blue and oranges lines represent the values measured by SeaPRISM, and the values obtained after atmospheric correction by SGLI, respectively. For $\omega(443)$ results, “x” symbols indicate measurement samples, and the black lines represent the monthly averages (error bars show their standard deviations).

For the Ariake Sea, negative values of $nL_w(412)$ are observed between October and December 2020 and 2021. An examination of the areas enclosed by the black dashed lines in Figure 4 indicates that in areas where $\omega(443)$ is decreasing, there are instances of $nL_w(412)$ becoming negative, suggesting the influence of the inflow of absorptive aerosols. However, there are instances, such as in the areas enclosed by blue dashed lines for Tokyo Bay in October and November 2021, where an explanation based solely on $\omega(443)$ is insufficient. Since judgement based on qualitative assessment alone is difficult, the next section examines the optical characteristics of each water region by comparing them with those of other water regions where SeaPRISM is installed to identify factors that cause the negative estimates commonly found for Tokyo Bay and the Ariake Sea.

3.2. Relative Comparison of Optical Properties among Tokyo Bay, Ariake Sea, and AERONET-OC Sites

A comparison of the measured $nL_w(\lambda)$ at each AERONET-OC site with the estimated $nL_w(\lambda)$ from SGLI is shown in Figure 5. Each figure shows scatter plots for wavelengths of 412, 443, 490, 530, 565, and 673.5 nm (380 nm, the central wavelength of SGLI observations, is excluded). The scatter plots in the left column represent the distribution of each sample and those in the right column show the mean and standard deviation of each wavelength in the given water region. The red and blue filled circles are the results for Tokyo Bay and the Ariake Sea, respectively, while the other circles correspond to various AERONET-OC sites. Tables 3 and 4 show the mean and standard deviation of $nL_w(\lambda)$ for SeaPRISM-measured values and SGLI-estimated values at each site. Among the AERONET-OC sites, Bahia Blanca in the Argentine Sea showed the highest $nL_w(\lambda)$, with an average $nL_w(\lambda)$ of 3.479 W/m²/str/μm and a standard deviation of 0.339 W/m²/str/μm. For the other sites, $nL_w(673.5)$ ranged from 0 to 0.7 W/m²/str/μm, indicating significant water absorption in the near-infrared region. The water region with the lowest average $nL_w(\lambda)$ across all wavelengths was the Helsinki Lighthouse in the Gulf of Finland, with a mean of

0.355 W/m²/str/μm and a standard deviation of 0.194 W/m²/str/μm, albeit with a small sample size of N = 29.

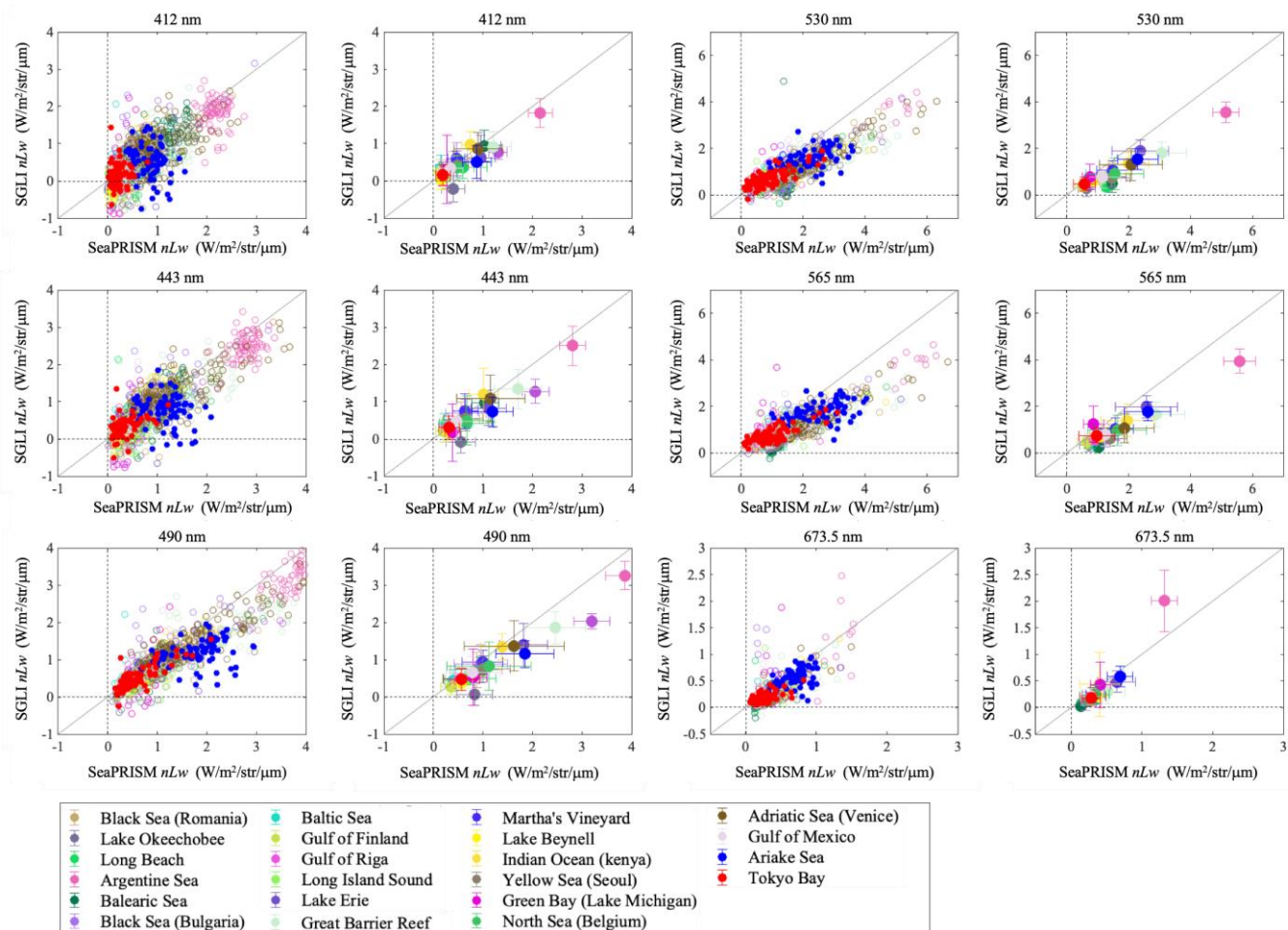


Figure 5. Comparison of $nL_w(\lambda)$ measured by SeaPRISM and estimated by SGLI. The target wavelengths are 412, 443, 490, 530, 565, and 673.5 nm. Results for 23 AERONET-OC sites are shown. The left panel for each wavelength shows the individual measurements during the observation period, and the right panel for each wavelength shows the average measured and estimated values for each site, along with their standard deviations.

Table 3. Sample size, mean, and standard deviation of $nL_w(\lambda)$ measured by SeaPRISM at each AERONET-OC site.

AERONET-OC Site	Water Region	Wavelength (nm)														
		N	Mean							Standard Deviation						
			380	412	443	490	530	565	673.5	380	412	443	490	530	565	673.5
Ariake Tower	Ariake Sea	96	-	0.879	1.197	1.854	2.292	2.610	0.693	-	0.289	0.417	0.584	0.661	0.740	0.182
Bahia Blanca	Argentine Sea	87	-	2.160	2.808	3.872	5.132	5.579	1.320	-	0.245	0.268	0.399	0.426	0.509	0.184
Casablanca Platform	Balearic Sea	209	-	1.026	1.046	0.960	1.466	1.031	0.142	-	0.330	0.274	0.170	0.115	0.118	0.020
Galata Platform	Black Sea	246	-	0.468	0.656	0.956	1.442	1.264	0.212	-	0.301	0.411	0.543	0.499	0.409	0.073
Gustav Dalen Tower	Baltic Sea	85	-	0.155	0.223	0.394	0.665	0.778	0.219	-	0.118	0.116	0.167	0.205	0.227	0.059
Helsinki Lighthouse	Gulf of Finland	29	-	0.139	0.201	0.360	0.534	0.653	0.243	-	0.141	0.149	0.210	0.268	0.303	0.092
Irbe Lighthouse	Gulf of Riga	71	-	0.189	0.283	0.505	0.780	0.916	0.263	-	0.090	0.114	0.169	0.275	0.325	0.111
Kemigawa Offshore Tower	Tokyo Bay	94	-	0.196	0.315	0.572	0.840	0.965	0.287	-	0.142	0.210	0.361	0.531	0.577	0.125

Table 3. Cont.

		Wavelength (nm)														
AERONET-OC Site	Water Region	Mean								Standard Deviation						
		N	380	412	443	490	530	565	673.5	380	412	443	490	530	565	673.5
LISCO	Long Island Sound	103	-	0.234	0.413	0.805	1.141	1.345	0.375	-	0.100	0.149	0.247	0.389	0.452	0.119
Lake Erie	Lake Erie	17	-	0.963	1.116	1.822	2.378	2.577	0.644	-	0.289	0.360	0.490	0.917	0.999	0.268
Lake Okeechobee	Lake Okeechobee	64	-	0.403	0.559	0.831	0.648	0.729	0.367	-	0.237	0.293	0.366	0.269	0.316	0.149
USC SEAPRISM	Long Beach	117	-	0.599	0.672	0.724	1.276	1.007	0.150	-	0.484	0.548	0.536	0.135	0.101	0.022
Lucinda	Great Barrier Reef	78	-	1.207	1.714	2.464	3.070	2.887	0.515	-	0.364	0.484	0.607	0.797	0.934	0.248
MVCO	East Coast of	22	-	0.463	0.640	0.994	1.486	1.583	0.338	-	0.172	0.255	0.411	0.522	0.575	0.134
Palgrunden	Lake Vanern	97	-	0.167	0.296	0.560	0.857	1.082	0.377	-	0.094	0.103	0.158	0.254	0.318	0.108
San Marco Platform	Indian Ocean	53	-	0.744	1.011	1.394	1.986	1.963	0.400	-	0.156	0.290	0.443	0.649	0.849	0.280
Socheongcho	Yellow Sea	82	-	0.481	0.652	0.995	1.465	1.385	0.244	-	0.229	0.349	0.559	0.584	0.573	0.107
South Greenbay	Green Bay	42	-	0.279	0.390	0.810	0.752	0.871	0.413	-	0.134	0.156	0.273	0.254	0.320	0.141
Thornton C-power	North Sea	35	-	0.489	0.685	1.126	1.548	1.634	0.348	-	0.322	0.495	0.845	0.942	0.951	0.193
Venice	Adriatic Sea	224	-	0.900	1.158	1.632	2.080	1.857	0.307	-	0.482	0.695	1.013	1.010	0.959	0.185
WaveCIS Site CSI-6	Gulf of Mexico	84	-	0.345	0.473	0.793	1.147	1.237	0.286	-	0.251	0.335	0.553	0.609	0.639	0.152

Table 4. Sample size, mean, and standard deviation of $nL_w(\lambda)$ estimated by SGLI at each AERONET-OC site.

		Wavelength (nm)														
SGLI Site	Water Region	Mean								Standard Deviation						
		N	380	412	443	490	530	565	673.5	380	412	443	490	530	565	673.5
Ariake Tower	Ariake Sea	96	0.173	0.503	0.726	1.155	1.523	1.777	0.585	0.415	0.442	0.424	0.360	0.449	0.403	0.191
Bahia Blanca	Argentine Sea	87	0.901	1.825	2.502	3.254	3.555	3.945	2.002	0.326	0.385	0.310	0.381	0.450	0.521	0.577
Casablanca Platform	Balearic Sea	209	0.547	0.942	0.964	0.828	0.495	0.256	0.027	0.312	0.422	0.358	0.238	0.389	0.123	0.028
Galata Platform	Black Sea	246	0.283	0.562	0.695	0.883	0.767	0.618	0.125	0.366	0.469	0.485	0.509	0.456	0.371	0.173
Gustav Dalen Tower	Baltic Sea	85	0.207	0.348	0.376	0.441	0.526	0.508	0.125	0.303	0.350	0.315	0.290	0.264	0.295	0.096
Helsinki Lighthouse	Gulf of Finland	29	0.108	0.246	0.206	0.272	0.408	0.459	0.129	0.266	0.320	0.273	0.205	0.257	0.287	0.079
Irbe Lighthouse	Gulf of Riga	71	0.074	0.187	0.280	0.431	0.577	0.575	0.145	0.275	0.324	0.255	0.193	0.234	0.222	0.077
Kemigawa Offshore Tower	Tokyo Bay	94	0.002	0.160	0.303	0.477	0.650	0.746	0.184	0.253	0.276	0.248	0.297	0.350	0.320	0.082
LISCO	Long Island Sound	103	0.049	0.086	0.293	0.563	0.755	0.837	0.226	0.300	0.316	0.311	0.193	0.245	0.257	0.130
Lake Erie Lake	Lake Erie Lake	17	0.304	0.623	0.833	1.406	1.878	1.985	0.484	0.448	0.607	0.655	0.574	0.498	0.473	0.199
Okeechobee USC	Okeechobee Lake	64	0.137	0.221	0.087	0.062	0.279	0.358	0.216	0.316	0.353	0.335	0.291	0.343	0.298	0.154
SEAPRISM	Long Beach	117	0.130	0.366	0.416	0.498	0.362	0.242	0.062	0.245	0.300	0.259	0.179	0.163	0.131	0.095
Lucinda	Great Barrier Reef	78	0.382	0.917	1.335	1.852	1.809	1.659	0.301	0.320	0.415	0.427	0.437	0.469	0.533	0.237
MVCO	East Coast of Lake Vanern	22	0.320	0.596	0.745	0.927	1.068	1.023	0.242	0.149	0.209	0.257	0.331	0.404	0.467	0.168
Palgrunden	Lake Vanern	97	−0.063	0.037	0.178	0.382	0.602	0.691	0.218	0.223	0.262	0.174	0.152	0.171	0.204	0.079
San Marco Platform	Indian Ocean	53	0.652	0.965	1.191	1.346	1.352	1.397	0.435	0.345	0.359	0.370	0.352	0.472	0.701	0.600
Socheongcho	Yellow Sea	82	0.134	0.408	0.542	0.747	0.729	0.609	0.112	0.232	0.261	0.261	0.353	0.342	0.328	0.058
South Greenbay	Green Bay	42	−0.012	0.310	0.167	0.523	0.769	1.229	0.426	0.689	0.918	0.758	0.758	0.546	0.766	0.426
Thornton C-power	North Sea	35	0.179	0.353	0.498	0.826	0.917	0.967	0.239	0.257	0.341	0.443	0.644	0.676	0.655	0.171
Venice	Adriatic Sea	224	0.441	0.863	1.089	1.366	1.289	1.060	0.200	0.347	0.452	0.542	0.680	0.685	0.633	0.168
WaveCIS Site CSI-6	Gulf of Mexico	84	0.176	0.337	0.467	0.663	0.770	0.784	0.207	0.258	0.329	0.368	0.429	0.480	0.487	0.151

For Kemigawa Offshore Tower in Tokyo Bay, the $nL_w(\lambda)$ was relatively low compared to that for other AERONET-OC sites, with a mean value of $0.529 \text{ W/m}^2/\text{str}/\mu\text{m}$ and a standard deviation of $0.324 \text{ W/m}^2/\text{str}/\mu\text{m}$, ranking as the fourth lowest among the sites. The average $nL_w(412)$ and $nL_w(443)$ values for Kemigawa Offshore Tower were 0.196 and $0.315 \text{ W/m}^2/\text{str}/\mu\text{m}$, respectively, with standard deviations of 0.142 and

0.21 W/m²/str/μm, respectively, ranking it the fifth lowest among the sites. Regarding the SGLI results for Tokyo Bay, it can be observed that negative $nL_w(\lambda)$ was prone to occur at 412 and 443 nm, making Tokyo Bay one of the areas where negative values of $nL_w(\lambda)$ are common in SGLI estimations. Similarly, Lake Okeechobee exhibited a tendency for negative $nL_w(\lambda)$ values in SGLI estimations. Other water regions with relatively low $nL_w(412)$ and $nL_w(443)$ included the Helsinki Lighthouse in the Gulf of Finland (mean—0.139, 0.201 W/m²/str/μm; standard deviation—0.141, 0.149 W/m²/str/μm), Dalen Tower in Baltic Sea Gustav (mean—0.155, 0.223 W/m²/str/μm; standard deviation—0.118, 0.116 W/m²/str/μm), Palgrunden in Lake Vanern (mean—0.167, 0.296 W/m²/str/μm; standard deviation—0.094, 0.103 W/m²/str/μm), and Irbe Light-house in the Gulf of Riga (mean—0.189, 0.283 W/m²/str/μm; standard deviation—0.09, 0.114 W/m²/str/μm). For Ariake Tower in the Ariake Sea, the average $nL_w(\lambda)$ at each wavelength was the third highest, after those for Bahia Blanca in the Argentine Sea and Lucinda in the Great Barrier Reef (mean—0.198 W/m²/str/μm, standard deviation—0.572 W/m²/str/μm). The average $nL_w(\lambda)$ for Ariake Tower was 1.588 W/m²/str/μm, with a standard deviation of 0.479 W/m²/str/μm. However, in the SGLI-derived $nL_w(\lambda)$ values for Ariake Tower, many samples were underestimated, particularly at the shorter wavelengths of 412 and 443 nm, where negative values occurred.

Figure 6 shows the relationship between SGLI $nL_w(412)$ and SeaPRISM $\tau_a(412)$ (top panel), and that between SGLI $nL_w(412)$ and SeaPRISM $\omega(443)$ (bottom panel). In the top panel, there is no clear relationship between $nL_w(412)$ and $\tau_a(412)$, making it difficult to explain the occurrence of negative nL_w values based on τ_a fluctuations alone. In the bottom panel, although a slight decrease in $\omega(443)$ was observed when $nL_w(412)$ decreased, there is no clear relationship between the occurrence of negative $nL_w(\lambda)$ in blue band regions and the decrease in $\omega(443)$. This lack of clarity was observed for both Tokyo Bay (red circles) and the Ariake Sea (blue circles). These results suggest that even when absorptive aerosols that reduce $\omega(443)$ are present, negative $nL_w(\lambda)$ does not necessarily occur. Therefore, the water quality conditions at the time of observation are as important as the influence of absorptive aerosols.

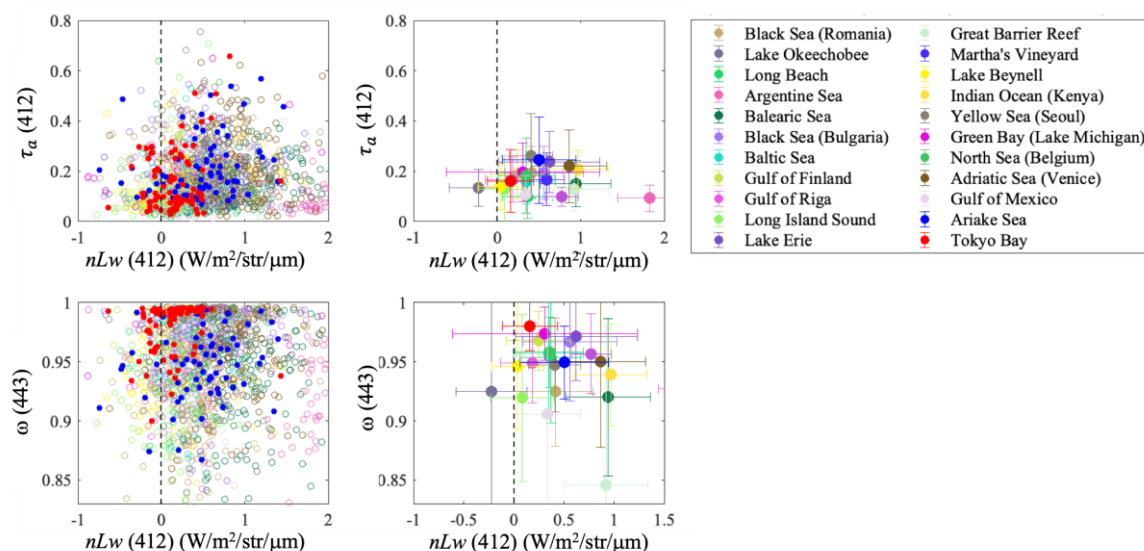


Figure 6. Scatter plots of SGLI-derived $nL_w(412)$ versus SeaPRISM-measured $\tau_a(412)$ (top panels) and scatter plots of SGLI-derived $nL_w(412)$ versus $\omega(443)$ (bottom panels) for various AERONET-OC sites. Red and blue circles indicate Tokyo Bay and the Ariake Sea, respectively. The left plots show individual sample points for each target product and the right plots show the average results and standard deviation for each water region (see legend).

4. Discussion

Table 5 shows the number and percentage of data points where SGLI $nL_w(\lambda)$ at short wavelengths (380, 412, and 443 nm) was negative, relative to the total dataset size, for various AERONET-OC sites. The sites in Table 5 exclude water bodies where the total number of matchup data points between SGLI and SeaPRISM $nL_w(\lambda)$ was within 30 based on statistical considerations of the sample mean distribution, as described in Table 1. As shown in Table 5, the percentage of negative values for $nL_w(380)$ exceeded 30% for six sites: Long Beach, the Gulf of Riga, Long Island Sound, Lake Vanern, the Ariake Sea, and Tokyo Bay. Although the percentage of negative values decreased overall for $nL_w(412)$ compared to $nL_w(380)$, more than 10% of data points remained negative for all of these sites except Long Beach. Moreover, although the overall percentage of negative values at 443 nm was relatively small for five sites (the Gulf of Riga, Long Island Sound, Lake Vanern, the Ariake Sea, and Tokyo Bay), indicating limited occurrence, their presence suggests significant influences of aerosols or in-water light absorption, particularly in blue band regions.

Table 5. Number of negative $nL_w(380)$, $nL_w(412)$, and $nL_w(443)$ values from SeaPRISM at AERONET-OC sites from January 2018 to December 2021. The site, water region, total matchup data count, and number of data points where $nL_w(\lambda)$ was negative for three wavelengths are shown. Water regions with total matchup data counts below 30 were excluded.

SGLI Site		N	Number of Negative $nL_w(\lambda)$ Values			Percentage of Negative $nL_w(\lambda)$ Values Relative to All Data (%)		
			380 nm	412 nm	443 nm	380 nm	412 nm	443 nm
Galata Platform	Black Sea	211	40	14	0	19	7	0
USC SEAPRISM	Long Beach	85	28	2	0	33	3	0
USC SEAPRISM 2								
Bahia Blanca	Argentine Sea	68	1	0	0	2	0	0
Casablanca Platform	Balearic Sea	157	2	0	0	2	0	0
Galata Platform	Balearic Sea	211	31	5	0	15	3	0
Gustav Dalen Tower	Baltic Sea	73	10	9	0	14	13	0
Irbe Lighthouse	Gulf of Riga	60	20	16	5	34	27	9
LISCO	Long Island Sound	83	50	28	3	61	34	4
Lucinda	Great Barrier Reef	53	2	0	0	4	0	0
Palgrunden	Lake Vanern	84	48	33	10	58	40	12
Socheongcho	Yellow Sea	59	11	3	0	19	6	0
Venice	Adriatic Sea	194	12	1	0	7	1	0
WaveCIS Site CSI-6	Gulf of Mexico	68	12	2	0	18	3	0
Ariake Tower	Ariake Sea	70	21	7	3	30	10	5
Kemigawa Offshore Tower	Tokyo Bay	82	32	21	1	40	26	2

Figure 7 shows the relationship between SeaPRISM and SGLI $nL_w(\lambda)$ for various sites, with five water bodies (identified for their tendency to produce negative $nL_w(\lambda)$ results due to optical characteristics) highlighted in different colors. The left panel compares individual samples, and the right panel shows the results averaged by water body, along with standard deviations. For the five highlighted water bodies (Tokyo Bay, the Ariake Sea, the Gulf of Riga, Long Island Sound, and Lake Vanern), the mean values of $nL_w(412)$ were 0.196, 0.879, 0.189, 0.234, and 0.167 W/m²/str/μm, respectively, with standard deviations of 0.142, 0.289, 0.090, 0.100, and 0.094 W/m²/str/μm, respectively. These sites showed relatively low values, except for the Ariake Sea, which had exceptionally high $nL_w(\lambda)$ values, along with relatively large standard deviations. The significant tidal range in the Ariake Sea leads to the increased resuspension of inorganic suspended matter due to tidal action [52,63,64]. Considering the relatively high $nL_w(\lambda)$ values in the visible and near-infrared regions, the increase in light scattering due to the higher concentration of suspended matter is a plausible explanation.

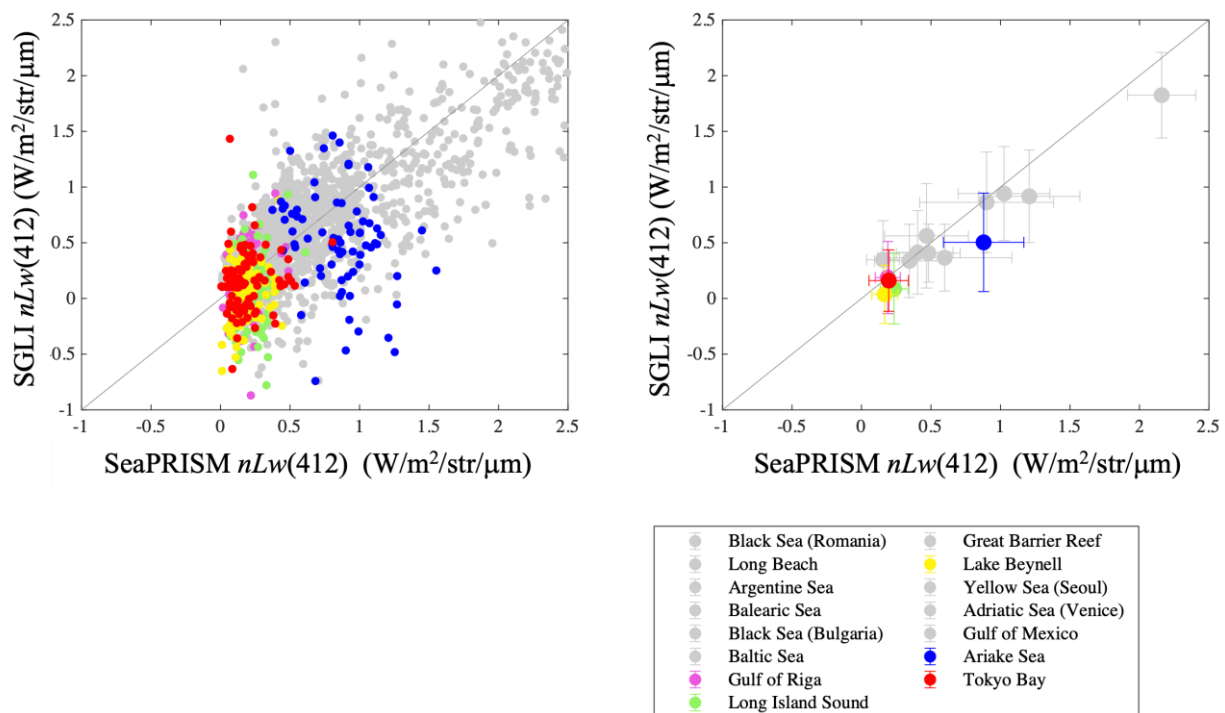


Figure 7. Relationship between $nL_w(\lambda)$ from SeaPRISM and SGLI in water regions with more than 30 matchup data points. The left panel compares individual samples, and the right panel shows the mean and standard deviation for each water region. The colored regions represent the five water regions where negative $nL_w(\lambda)$ values are more likely to occur (red—Tokyo Bay, blue—the Ariake Sea, pink—the Gulf of Riga, green—Long Island Sound, yellow—Lake Beynell). The gray circles denote results from the other 10 water regions.

To quantitatively analyze the effects of light absorption in the atmosphere and water, we estimated the IOPs from the $nL_w(\lambda)$ measurements obtained by SeaPRISM inversion to examine the characteristics of each water body. For the inversion of IOPs, SeaPRISM's $nL_w(\lambda)$ measurements were converted to the observation wavelengths of SGLI using the interpolation method proposed by Mélin and Sclap [66]. The QAA_v5 algorithm [74] was utilized for the estimation of IOPs, including the light absorption coefficient of phytoplankton (a_{ph}), the light absorption coefficient of CDOM and non-algal particles (a_{dg}), and the backscattering coefficient (b_{bp}) from the global AERONET-OC $nL_w(\lambda)$ dataset. Figure 8 shows the relationship between $b_{bp}(565)$ and $a_{ph}(443)$ and that between $b_{bp}(565)$ and $a_{dg}(443)$. a_{ph} is the absorption at a wavelength of 443 nm, which represents the absorption band of Chl-a, and a_{dg} represents the characteristics of blue light absorption at 443 nm. For b_{bp} , which is relatively less affected by light absorption in the visible range, a wavelength of 566 nm, corresponding to the observation wavelength of SGLI, was selected. Figure 8a shows the relationship between $b_{bp}(565)$ and $a_{ph}(443)$ for each sample and Figure 8b shows their mean values and standard deviations. Similarly, Figure 8c shows the relationship between $b_{bp}(565)$ and $a_{dg}(443)$ for each sample, and Figure 8d shows their mean values and standard deviations. The five water bodies identified as having optical characteristics prone to producing negative $nL_w(\lambda)$ results in Table 5 are highlighted in different colors.

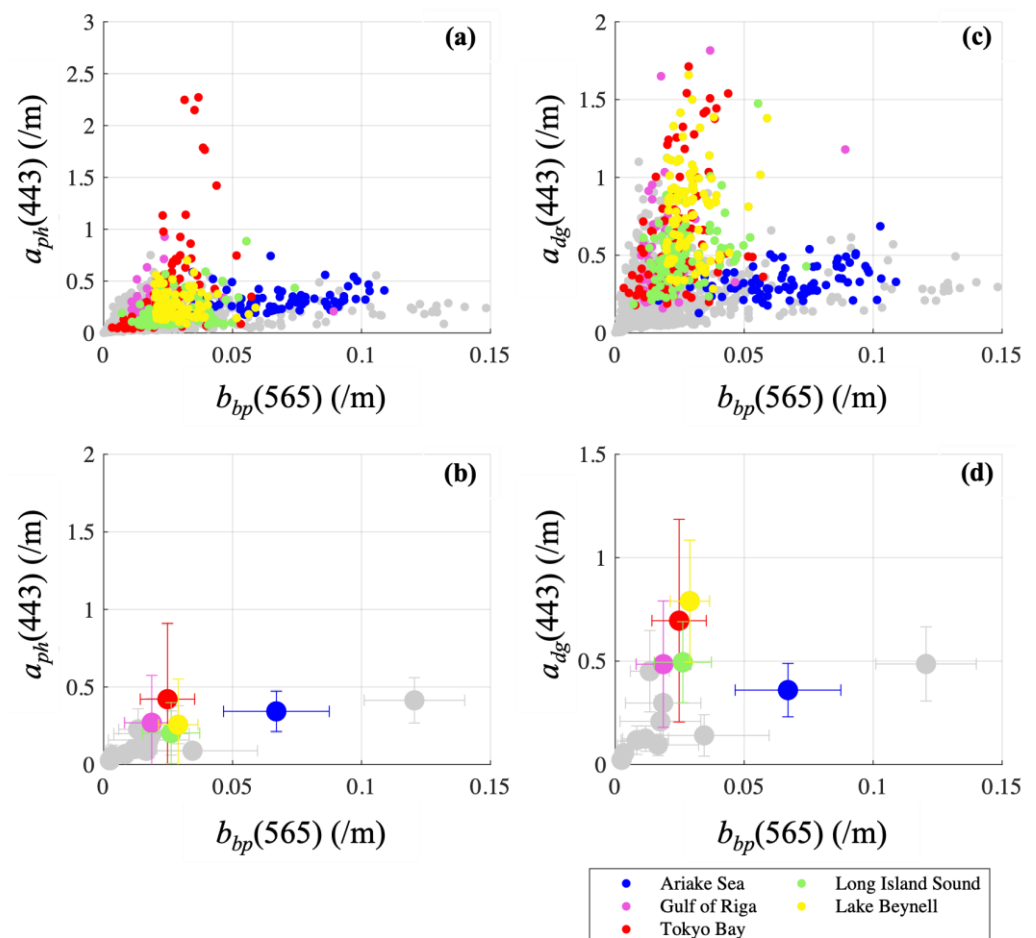


Figure 8. Relationships between $a_{ph}(443)$ and $b_{bp}(565)$ and between $a_{dg}(443)$ and $b_{bp}(565)$ estimated using QAA based on $nL_w(\lambda)$ measurements from SeaPRISM as input. The top row (a,c) shows the relationships for individual samples and the bottom row (b,d) shows the mean and standard deviation for each water region. The colored regions represent the five water regions where negative $nL_w(\lambda)$ values are more likely to occur (red—Tokyo Bay, blue—the Ariake Sea, pink—the Gulf of Riga, green—Long Island Sound, yellow—Lake Beynell). The gray circles denote results from the other 10 water regions.

As shown, Tokyo Bay, the Ariake Sea, the Gulf of Riga, Long Island Sound, and Lake Vanern exhibit relatively high values of both $a_{ph}(443)$ and $a_{dg}(443)$ compared to other water bodies (gray circles). For Tokyo Bay, the mean value of $a_{ph}(443)$ is particularly high, with a correspondingly high standard deviation. According to Higa et al. [72] and Salem et al. [71], the field measurements of water quality and optical properties for Tokyo Bay indicate a wide range of Chl-a concentrations (2.90 to 93.6 $\mu\text{g/L}$, with an average of 28.8 $\mu\text{g/L}$). Tokyo Bay is also prone to red tide occurrences. The observed range of $a_{ph}(443)$ values for Tokyo Bay varies significantly, from 0.23 to 4.00 m^{-1} , with an average of 1.15 m^{-1} . This variability in both Chl-a and $a_{ph}(443)$ is consistent with the results in Figure 8, indicating high variability and elevated values of a_{ph} , which are consistent with field observations.

To determine the influence of aerosol absorption in the atmosphere, not just in the water column, a comparison between $nL_w(443)$ and $\omega(443)$ is shown in Figure 9. The left panel shows the comparison for each sample and the right panel shows the mean values and standard deviations. For the five water bodies where negative values of $nL_w(\lambda)$ are prone to occur, a decrease in $\omega(\lambda)$ is observed when $nL_w(\lambda)$ becomes negative, suggesting that the presence of absorptive aerosols leads to the estimation of negative values of $nL_w(\lambda)$. However, the decrease in $\omega(\lambda)$ and the presence of absorptive aerosols are not limited to these five water bodies. Significant effects of absorptive aerosols are also observed in other

water bodies (gray circles). Therefore, the occurrence of negative values in $nL_w(\lambda)$ due to atmospheric correction cannot be solely explained by the influence of absorptive aerosols.

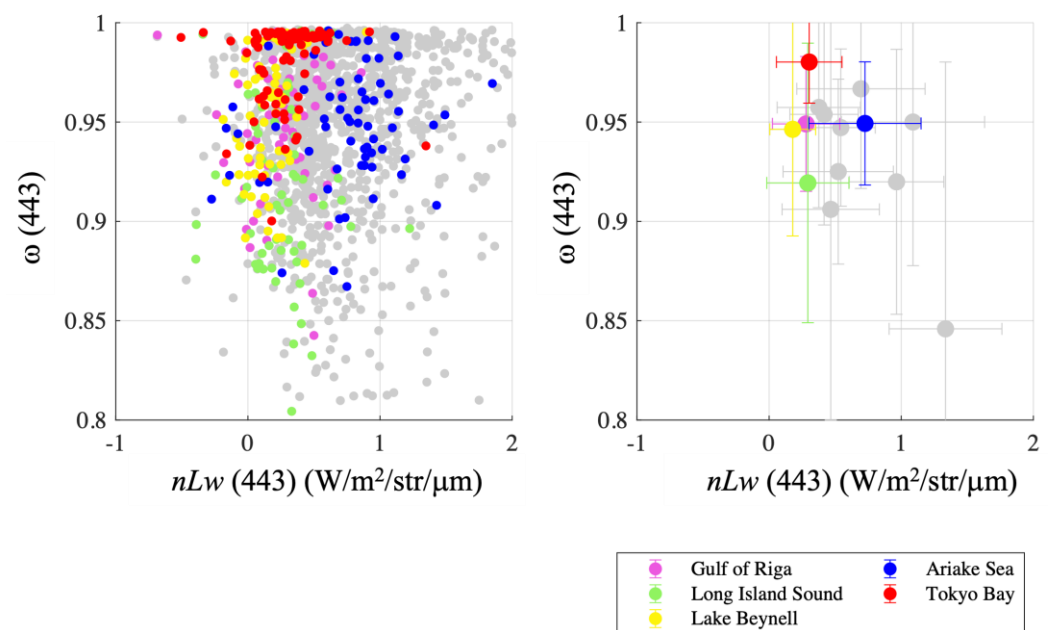


Figure 9. Relationship between $\omega(443)$ estimated by inversion using SeaPRISM and $nL_w(443)$. The left panel shows the relationship for individual samples and the right panel shows the mean and standard deviation for each water region. The colored regions represent the five water regions where negative $nL_w(\lambda)$ values are more likely to occur (red—Tokyo Bay, blue—the Ariake Sea, pink—the Gulf of Riga, green—Long Island Sound, yellow—Lake Beynell). The gray circles denote results from the other 10 water regions.

Atmospheric correction processing version 2 for SGLI, which was used in this study, is based on a method proposed by Gordon and Wang [15]. For the estimation of aerosol reflectance, which is prone to atmospheric correction errors, corrections are made from the top of the atmosphere reflectance to Rayleigh reflectance. In addition, two near-infrared wavelengths are utilized, and an appropriate aerosol model is selected after considering in-water reflectance using in-water models, followed by extrapolation to derive aerosol reflectance in the visible range, which is then subtracted [28]. According to Toratani et al. [68], the aerosol model is derived from calculations of the atmospheric radiative transfer model, incorporating a mixture of two types, namely, oceanic and tropospheric, resulting in nine models based on differences in the volume mixing ratio. However, the current model does not account for absorptive aerosols. Consequently, in cases where absorptive aerosols are present, aerosol reflectance is overestimated, resulting in an underestimation of $nL_w(\lambda)$. The cause of the overestimation of aerosol reflectance lies in the fact that when aerosols absorb light in the shorter wavelengths, the aerosol reflectance in these wavelengths decreases. However, the atmospheric correction model used does not account for this absorption effect in the assumed aerosol model, leading to an overestimation of aerosol reflectance in the shorter wavelengths [75]. Hence, in the water bodies indicated by grey circles, where $nL_w(\lambda)$ does not often become negative due to atmospheric correction, it is likely that the post-atmospheric correction $nL_w(\lambda)$ values are underestimated, possibly due to relatively high in-water reflectance. The extrapolation estimation of the spectral shape of aerosol reflectance in the visible range based on this aerosol model has been acknowledged to be a significant source of uncertainty in atmospheric correction processing [76].

It is evident that the characteristics of water bodies prone to negative values of $nL_w(\lambda)$ due to atmospheric correction are influenced by absorptive aerosols and in-water light absorption. Water bodies characterized by high absorption coefficients and a tendency for

low $nL_w(\lambda)$ in blue band regions are particularly sensitive to uncertainties in atmospheric correction. Therefore, the occurrence of negative values of $nL_w(\lambda)$ is increased due to the overestimation of aerosol reflectance in atmospheric correction processing caused by the presence of absorptive aerosols. In addition, it is noteworthy that two near-infrared wavelengths are used in aerosol model selection, and water reflectance is estimated by the water model beforehand to consider its impact on determining the slope of the aerosol model. However, in highly turbid waters, uncertainty also arises in the selection of the in-water model for aerosol selection, which may also influence the uncertainty in selecting the appropriate aerosol model.

The results of this study highlight the challenges of atmospheric correction processing for optically complex water bodies, particularly in closed coastal areas where the concentration of organic and inorganic suspended particulate matter is high, and where absorptive aerosols from land sources are prone to collect. For water bodies with such characteristics, consideration of absorptive aerosols is required in atmospheric correction and the selection of aerosol models.

In the future, consideration of the characteristics of aerosols (e.g., type, size distribution) could allow for a more detailed examination of factors that contribute to atmospheric correction errors. In addition, conducting atmospheric and in-water radiative transfer simulations may quantitatively demonstrate not only the applicability of atmospheric correction models, but also the propagation of errors into in-water models.

5. Conclusions

In this study, we investigated the optical characteristics of Tokyo Bay and the Ariake Sea, which are optically complex semi-enclosed coastal areas, using the atmospheric and in-water optical measurements obtained by SeaPRISM in AERONET-OC. For Tokyo Bay, a clear decreasing trend of shortwave $nL_w(\lambda)$ value with increasing Chl-a attributed to the light absorption effect of phytoplankton was observed based on the SeaPRISM-measured $nL_w(\lambda)$ values and the coincident Chl-a sensor data. Furthermore, the temporal results of SeaPRISM's atmospheric and in-water measurements for Tokyo Bay and the Ariake Sea, along with SGLI's $nL_w(\lambda)$ estimation at 412 nm, suggest that the error leading to negative $nL_w(\lambda)$ estimates in SGLI can be attributed to the influence of absorptive aerosols. However, it was confirmed that the negative $nL_w(\lambda)$ in the blue band region estimation could not be solely explained by $\omega(443)$ in all periods. This suggests that the occurrence of negative $nL_w(\lambda)$ estimates was not solely due to the presence of absorptive aerosols, but that other factors were also involved.

In addition, through a relative comparison of the $nL_w(\lambda)$ values obtained from SeaPRISM for Tokyo Bay and the Ariake Sea with those from 24 AERONET-OC sites worldwide, we identified the characteristics of regions where negative $nL_w(\lambda)$ values are more likely to occur from the perspective of atmospheric and in-water optical properties. As a result, in addition to Tokyo Bay and the Ariake Sea, the Gulf of Riga, Lake Beynell, and Long Island Sound were confirmed as regions where negative $nL_w(\lambda)$ estimates are more likely to occur. The common characteristics of these water bodies include low $nL_w(\lambda)$ values in the blue band regions and relatively high light absorption in the water. This suggests that the excessive correction of aerosol reflectance from originally low $nL_w(\lambda)$ during atmospheric correction processing increases the probability of the occurrence of negative $nL_w(\lambda)$ values. Thus, the relative comparison of atmospheric and in-water optical properties across various water regions at AERONET-OC sites in this study indicates that negative $nL_w(\lambda)$ values occur not only due to the presence of absorptive aerosols in the atmosphere, but also because of high light absorption by in-water substances.

The results of this study highlight the need for further analyses of the specific types, sources, and seasonal variations of aerosols in water regions where absorptive aerosols occur. A detailed understanding of the optical properties of aerosols in water regions with significant light absorption in the water or inflows of absorptive aerosols could enable the development and application of aerosol models tailored to specific water bodies. In

selecting aerosol models, the use of in-water models suited to turbid waters and approaches based on machine learning may also be considered effective.

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Data Availability Statement: The AERONET-OC data used in this paper can be downloaded from the following website: https://aeronet.gsfc.nasa.gov/new_web/ocean_color.html (accessed on 1 July 2024). Other original contributions provided in the study are included in this article, and further inquiries can be directed to the corresponding author.

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Conflicts of Interest: Author Kuniaki Takahashi is the CEO of HOLONIX International, authors Fabrice Maupin and Stephane Victori were employed by the company CIMEL. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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