Turk. J. Fish.& Aquat. Sci. 24(SI), TRJFAS26568
https://doi.org/10.4194/TRJFAS26568

RESEARCH PAPER

Turkish Journal of FISHERIES and AQUATIC SCIENCES

Long-Term Changes in Light Attenuation in the Sea of Marmara

İlayda Destan Öztürk[1,2]*, Dilek Ediger[1], Hüsne Altiok[1]

[1]Istanbul University, Institute of Marine Sciences and Management, Department of Physical Oceanograph and Marine Biology, İstanbul, Türkiye
[2]Turkish Marine Research Foundation, İstanbul, Türkiye.

How to Cite

Ozturk, I. D., Ediger, D., Altiok, H. (2024). Long-term Changes in Light Attenuation in the Sea of Marmara. *Turkish Journal of Fisheries and Aquatic Sciences*, *24(SI)*, *TRJFAS26568.* https://doi.org/10.4194/TRJFAS26568

Article History
Received 03 September 2024
Accepted 16 December 2024
First Online 19 December 2024

Corresponding Author
E-mail: destanozturk@istanbul.edu.tr

Keywords
Attenuation coefficient
Photosynthetically active radiation
Sea of Marmara

Abstract

Primary production, which drives the development of marine ecosystems, is largely dependent on the light present in the water column. Therefore, understanding the attenuation coefficient (Kd (PAR)) is crucial for describing underwater light variability. This study reveals the regional and seasonal characteristics of light attenuation in the Sea of Marmara for the first time. A 10-year time series (2000-2009) of Kd from the northeastern Sea of Marmara was analyzed and compared with seasonal values from the entire Sea of Marmara in 2021. Between 2000 and 2009, the coefficient ranged from 0.139 to 0.539 m^{-1}, with a mean of 0.220 m^{-1} and a standard deviation of 0.063. The highest values occurred in winter and spring, while the lowest were in autumn and summer. Variations in attenuation coefficients were inversely related to the euphotic zone depth. In 2021, Kd values ranged from 0.123 to 0.443 m^{-1}, with a mean of 0.247 m^{-1}. During the summer of 2021, when mucilage was present, the attenuation coefficient was lowest at the surface and increased with depth, indicating that larger mucilage aggregates affect light penetration significantly. Coastal areas and bays were classified as turbid, while deeper areas were moderately turbid based on the attenuation coefficient. This work will serve as an important reference for research on marine ecosystems, water quality, modeling, remote sensing and climate change, and will improve our understanding of their impacts at the ecosystem level. These insights are vital for both science and policy, particularly in the areas of conservation, resource management and climate resilience. The results can lead to practical outcomes such as improved monitoring tools, better predictive models and more effective management strategies.

Introduction

Light, along with nutrients, is a key factor that regulates primary production and photosynthetic processes in the marine environment (Kirk, 1994), as phytoplankton rely on the wavelengths between 400 and 700 nm, known as photosynthetically active radiation (PAR), for photosynthesis (Falkowski and Raven, 1997). The attenuation coefficient (Kd), which indicates the decrease of light throughout the water column, is a crucial parameter for understanding primary productivity, which controls the development of marine ecosystems (Castillo-Ramirez, et al., 2020). Kd(PAR) is essential in equations and models that quantify primary production with depth (Kettle and Merchant, 2008). Kd(PAR) is widely applied in aquatic and marine environmental monitoring programs as a measure of water clarity (Fleming-Lehtinen and Laamanen, 2012). Additionally, it serves as an important indicator in determining and classifying seawater quality (Lee et al., 2007) and eutrophication (Andersen et al., 2011).

In the study area, a permanent halocline separates two distinct water bodies, where partial mixing occurs. This halocline prevents mixing between the layers, although significant vertical mixing takes place during the winter months due to wind forcing (Beşiktepe et al., 1994; Aydoğdu, et al., 2018). This halocline is significant because, as noted by Ediger and Yılmaz (1996), the depth of the euphotic zone in the Sea of Marmara does not extend below the halocline. Therefore, in a stratified sea where seasonality is crucial, it is important to examine how light attenuation varies seasonally in the upper layer where the euphotic zone is confined. The optical properties of water, which are affected by factors such as the amount of light in the environment, the angle of incident radiation, and optically active materials like chlorophyll a, total suspended solids, and dissolved organic matter (Koenings and Edmundson, 1991; Kirk, 1994; Effler et al., 2017), are significantly influenced by the conditions in the study area. This area is situated in a region surrounded by major cities with substantial anthropogenic pressure and is affected by nutrient-rich upper waters flowing from the Black Sea. The influx of these nutrients profoundly impacts primary production and alters the concentration of particulate matter, further influencing the optical properties of the water.

Accurate estimation of the attenuation coefficient is important not only for understanding physical processes such as heat transfer in the upper layers of the sea and oceans but also for gaining insight into biological parameters such as photosynthesis occurring in the euphotic zone of the sea and oceans. An important relationship among optical parameters established in previous studies is between the attenuation coefficient and Z_{SD} (Secchi disk depth). This relationship is used to estimate the attenuation coefficient, an important parameter, from Z_{SD} data, represented by the equation: $Kd = \alpha / (Z_{SD})$. For the world's seas and oceans, the ratio $Kd * Z_{SD}$ (α) typically ranges between 1.27 and 2 in the literature (Lee et al., 2018). Estimating Kd from Z_{SD} measurements is a cost-effective approach that can be systematically employed in oceanographic studies because of its straightforward implementation. While fixed values obtained from studies conducted in various regions are available, it is crucial to develop region-specific constants for an enclosed sea like the Sea of Marmara, where oceanographic characteristics are unique and seasonality plays a significant role. This development should be based on long-term data to account for anthropogenic impacts. Unfortunately, such an in-depth examination has not been previously undertaken. One of the objectives of this study is to determine the region-specific alpha constant for the Sea of Marmara.

Extended records of the diffuse attenuation coefficient are scarce because sampling strategies generally emphasize spatial resolution, which leaves time-related variations unaddressed (Lund-Hansen, 2004). Bio-optical studies conducted in the seas of Türkiye are also quite limited. In this study, data on the attenuation coefficient obtained from monthly sampling conducted in the northeastern Sea of Marmara between 2000 and 2009 were seasonally examined and compared with attenuation coefficient values obtained from seasonal study covering the entire Sea of Marmara in 2021. Therefore, the aim is to offer a comprehensive and detailed perspective on the long-term variability of the attenuation coefficient in the Sea of Marmara, with the objective of highlighting its changes over time and establishing a reference point for researchers focusing on marine water optics. For instance, the attenuation coefficient (Kd) has been approached using various methods in different studies. While some studies report Kd only as a subsurface value, others provide it as an average value for the euphotic zone (Lee et al., 2007; Devlin et al., 2008) The field study conducted in 2021 allowed for a detailed analysis of underwater light calculations. Consequently, the data distribution for both Kd surface and Kd mean values for the Sea of Marmara was examined, and the suitability of each method was evaluated to identify which would be more appropriate for the Sea of Marmara. In summary, the main objectives of the study are to address the following questions: 1) How is the long-term variability of the attenuation coefficient characterized in the Sea of Marmara? 2) Does light attenuation exhibit seasonal variations in a region where seasonality is significant? 3)Is it possible to obtain a region-specific constant value for the attenuation coefficient based on the Secchi disk measurements? 4) Are there regional differences in the attenuation coefficient across the Sea of Marmara?

Materials and Methods

Study Site

The Sea of Marmara, an enclosed sea connecting the Black Sea to the Mediterranean via the İstanbul (Bosphorus) and Çanakkale (Dardanelles) straits (Figure 1) constitutes an oceanographic system called the “Turkish Strait System” (TSS). It is a transit basin providing water exchange between the Mediterranean and Black Seas. Water masses from these two seas form the unique Marmara ecosystem including biological components with different origins. The surface layers are influenced by the Black Sea, which has low salinity (around 20 ‰), while the deeper waters (beyond 20 meters) contain more saline water (up to 39 ‰) from the Mediterranean. The brackish waters (approximately 20 ‰) flow out of the Black Sea through the narrow İstanbul Strait, entering the Sea of Marmara, where they remain for several months before moving on to the Dardanelles and eventually the Mediterranean. This two-layer flow creates a stable pycnocline, leading to distinctly different ecosystems in the Black Sea and the Sea of Marmara (Ünlüata et al., 1990; Beşiktepe et al., 1994).

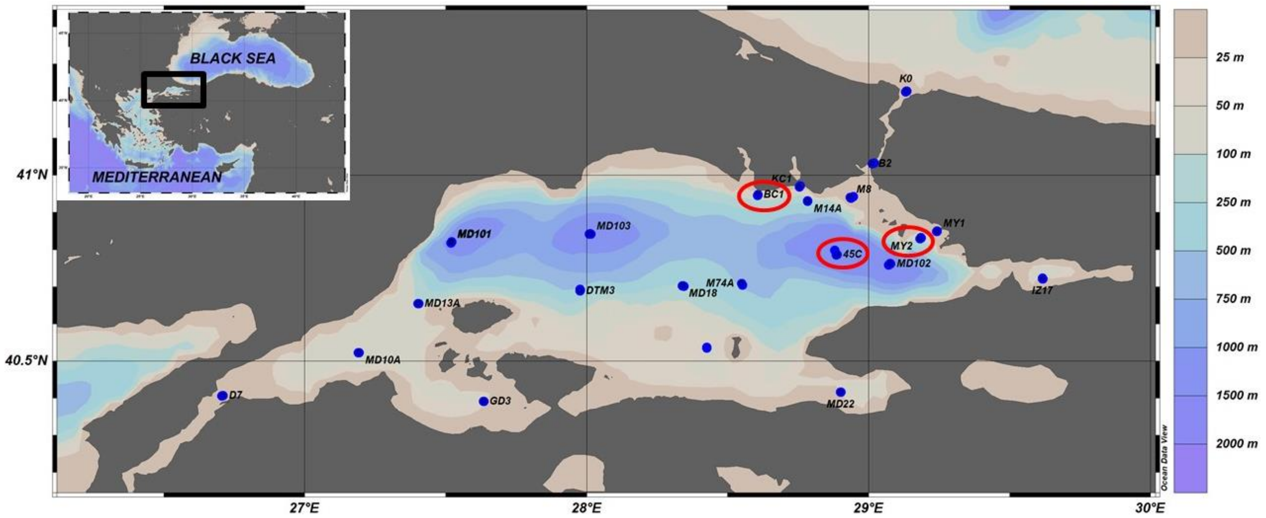

Figure 1. Sampling map in the Sea of Marmara, stations in red circle are studies between 2000 – 2009 while the others sampled in January, April and July 2021.

Due to the significant salinity difference between the waters exchanged between the Marmara and Black Seas, a permanent two-layer ecosystem is established in the Sea of Marmara. A sharp halocline, about 15-20 meters thick, separates the upper and lower layers of water throughout the basin. The brackish upper layer, which is relatively thin (10-15 meters), is consistently occupied by Black Sea water and exhibits seasonally varying hydrochemical properties. This halocline significantly restricts vertical mixing and, consequently, the ventilation of the salty deep waters of Mediterranean origin. Solar irradiance occasionally penetrates down to the lower boundary of the halocline in summer months and thus primary production is always confined to in the upper layer waters including the halocline depths during the less productive periods (Polat and Tuğrul, 1995). However, in recent decades, the marine habitat has severely deteriorated due to significant nutrient inputs from the Black Sea and direct wastewater discharges, primarily from the city of Istanbul (Tuğrul and Polat, 1995).

Sampling

The manuscript analysis two separate datasets, comprising photosynthetic active radiation measurements obtained with a CTD system. The first dataset was collected monthly by the R/V ARAR of Istanbul University, Institute of Marine Science and Management (IMSM-IU), between March 2000 and December 2009. The in-situ data were obtained by using QSP-200L Biospherical Instruments underwater quantum sensor with SBE9/11 CTD system. The second dataset was collected by the R/V TUBITAK Marmara of the TUBITAK Marmara Research Center (MRC) as part of the “Integrated Marine Pollution Monitoring 2020–2022 Program” led by the Turkish Ministry of Environment and Urbanization and TUBITAK-MRC. Conductivity, temperature, and depth (CTD) measurements were obtained using the SeaBird SBE 25Plus instrument from the surface to the sea bottom.

The data used in this study is primarily composed of two different datasets. The first dataset consists of monthly data collected over a ten-year period from 2000 to 2009. The three stations from which this dataset was obtained are marked with red circles on the map (Figure 1). The second dataset covers a much larger area and allows for a regional examination of the entire Sea of Marmara. All stations involved in this study, conducted over three seasons in 2021, are indicated with blue symbols on the map. The results for the region examined monthly over ten years in the first dataset have allowed for a comparison with the subsequent ten years, facilitated by the second dataset.

Data Processing

Underwater irradiance decreases exponentially with depth (Devlin et al., 2008). The attenuation coefficient (Kd, m^{-1}) is estimated from the photosynthetically active radiation (PAR) data of vertical profiles of downwelling irradiance using the Lambert–Beer equation (Kirk, 2010). It is calculated from the slope of the irradiance and depth. The Kd value for each data profile is the average value for the euphotic zone, derived from the calculated Kd values for each meter.

$$Kd = \ln(I_0/I_Z)/z$$

Where: Kd= light attenuation coefficient, I_Z = light at depth (m), I_0= light at the surface, z = depth (m)

In this study, 161 PAR profiles from the 2000-2009 dataset and 66 PAR profiles from the 2021 dataset were used, resulting in a total of 233. Data that did not meet the criteria were excluded due to presumed shadowing in the water column by the vessel, too few data points, or no data points from surface or bottom layers. The failed casts were randomly distributed throughout the time series.

Seasonal variations in light attenuation were examined using a One-Way Repeated Measures ANOVA to assess differences across the four seasons. Additionally, a linear regression analysis was conducted on monthly data from 2000 to 2009 to evaluate the temporal trend in light attenuation coefficient (Kd) values and identify any significant long-term changes in the decade.

Results

Ten Years of Monthly Light Attenuation Data in the NE Sea of Marmara (2000–2009)

Table 1 presents the minimum, maximum, mean, and standard deviation values of 161 data points from three stations where monthly measurements were conducted between 2000 and 2009. These values illustrate how the attenuation coefficient varied in the NE Sea of Marmara during the specified years. Overall, the attenuation coefficient ranges from 0.139 m^{-1} to 0.539 m^{-1}, with a mean value and standard deviation of 0.220±0.063 m^{-1}, respectively. To examine how these values vary across different stations and seasons, the data was also analyzed regionally and seasonally (Table 1). The values observed across stations were generally similar, with mean values showing close proximity to one another throughout the study area, as can be seen in Table 1; only MY2 station presented any notable variation. However, the seasonal analysis revealed that low average attenuation coefficient values were recorded in the summer and autumn months, while higher values were obtained in the winter and spring months.

The seasonal variation in average attenuation coefficients shown in Table 1 is detailed in Figure 2 with a boxplot. The results in Table 1, which indicate that average values are lower in the summer and autumn months and higher in the spring and winter months, are also supported. It is evident from Figure 2 that the range of attenuation coefficient values is broader in the spring and winter months, with higher values observed in these seasons. Additionally, some outlier values were observed during the summer months. Seasonal variations in light attenuation were assessed using a One-Way Repeated Measures ANOVA. The analysis revealed a statistically significant difference among the four seasons (P<0.001). Post hoc pairwise comparisons with revealed significant differences in light attenuation coefficients between winter and autumn (P=0.006) and between spring and autumn (P=0.011). This indicates that the elevated light attenuation observed during winter and spring is primarily distinct from the values recorded in autumn.

Table 1. Seasonal, spatial and overall minimum, maximum, mean and standard deviation values of attenuation coefficient (Kd m^{-1}) for the northeast Sea of Marmara (2000 – 2009)

		Winter	Spring	Summer	Autumn	45C	BC1	MY2	Overall
Kd (m^{-1})	Minimum	0.153	0.147	0.139	0.153	0.147	0.139	0.158	0.139
	Maximum	0.436	0.359	0.539	0.281	0.406	0.436	0.539	0.539
	Mean	0.233	0.227	0.220	0.193	0.218	0.217	0.249	0.220
	St. Dev.	0.068	0.050	0.076	0.037	0.053	0.062	0.101	0.063

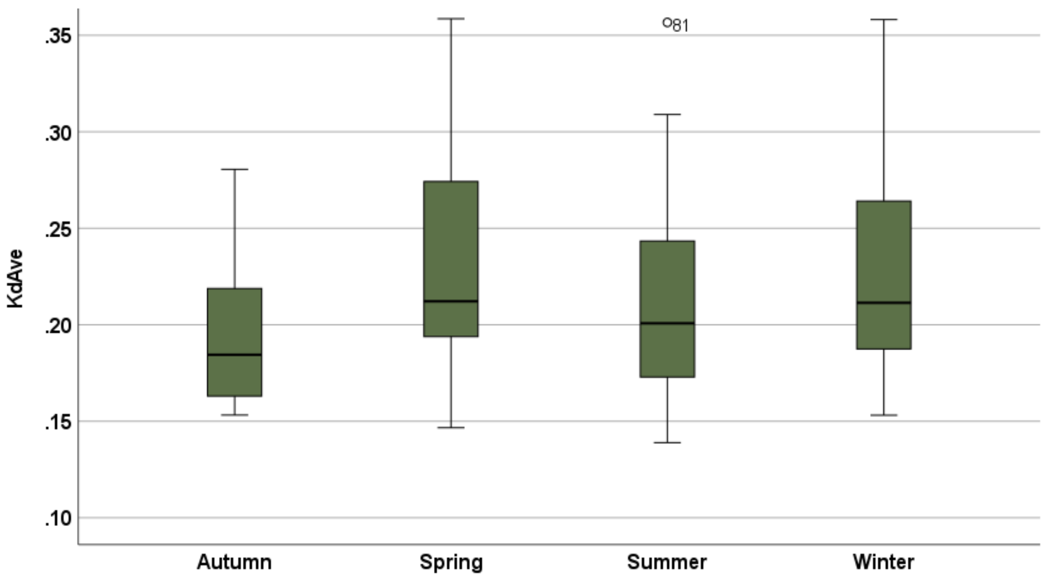

Figure 2. Boxplot representation of seasonal mean attenuation coefficient values (Kd m^{-1}) between 2000 – 2009 in the NE Sea of Marmara.

This dataset not only provides previously unavailable information on the attenuation coefficient in the NE Sea of Marmara for these years but also allows to estimate the attenuation coefficient from Secchi disk depth. (Table 2). The overall average value and standard deviation for the NE Sea of Marmara obtained in this study are 1.87±0.53. The minimum and maximum values also span a wide range (0.66–3.56) due to varying Secchi disk values. The seasonal and regional average values for this estimated value, referred to as the alpha constant in the literature, are presented in Table 2. Due to the varying Secchi disk depths, regional variation is higher than seasonal variation for this constant.

This long-term monitoring study dataset helps us understand how the attenuation coefficient has changed in the northeastern Sea of Marmara. Monthly data from the period between 2000 and 2009 were analyzed to assess the trend in light attenuation coefficient (Kd) values in the Sea of Marmara, as illustrated in Figure 3. A linear regression analysis revealed a significant positive trend, with a slope of 0.209 ($P<0.001$), indicating a gradual increase in Kd values over the decade. The figure clearly demonstrates an upward trend in average Kd values across the years, with notable annual fluctuations, including significant increases in 2003 and 2008, and decreases in 2005 and 2009. Another finding is that changes in the attenuation coefficient also follow a seasonal trend. This result corroborates the seasonal variation in the attenuation coefficient observed in Table 1 and Figure 2, highlighting higher values during the winter and spring months and lower values during the summer and autumn months in the Sea of Marmara.

Seasonal Changes in Light Attenuation in the Sea of Marmara (2021)

In the second dataset of this study, Table 3 presents the minimum, maximum, mean, and standard deviation values of the attenuation coefficient measured in 66 profiles completed during the three-season sampling in 2021 in the Sea of Marmara. According to studies in the literature (Koenings and Edmundson, 1991; Bracchini et al., 2009; Lee et al., 2018) recent research shows that the attenuation coefficient is presented in different ways: subsurface

Table 2. Seasonal, spatial and overall minimum, maximum, mean and standard deviation values of attenuation coefficient (Kd m^{-1}) * Secchi disk depth (Z_{SD} m) for the northeast Sea of Marmara (2000 – 2009)

		Winter	Spring	Summer	Autumn	45C	BC1	MY2	Overall
Kd * Z_{SD}	Minimum	0.66	1.06	1.29	1.16	0.66	0.99	1.39	0.66
	Maximum	3.30	3.08	3.56	2.87	3.39	3.08	3.56	3.56
	Mean	1.78	1.89	1.94	1.88	1.92	1.78	2.10	1.87
	St. Dev.	0.57	0.51	0.52	0.48	0.51	0.49	0.66	0.53

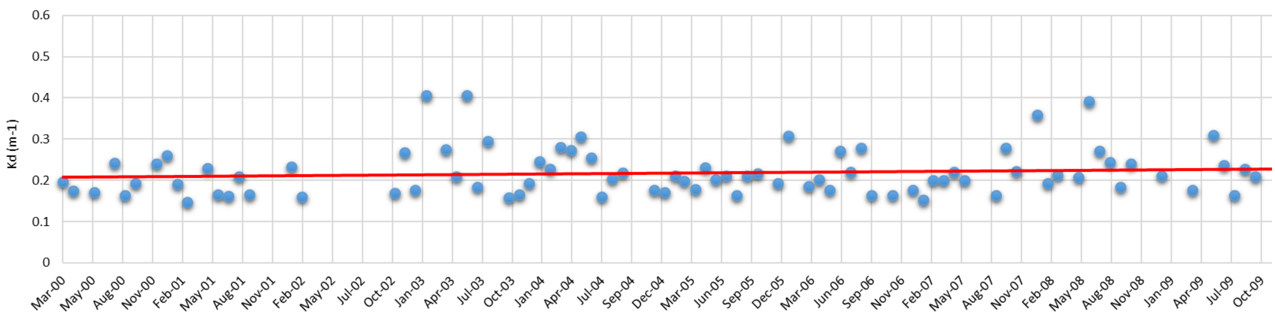

Figure 3. Analysis of light attenuation coefficient (Kd) values over the 10-year period, the trend in this decadal data shown in red line (slope=0.209, p<0.001).

Table 3. Seasonal and overall minimum, maximum, mean and standard deviation values of attenuation coefficient (Kd m^{-1}) subsurface and attenuation coefficient (Kd m^{-1}) mean for the Sea of Marmara (2021)

		January	April	July	Overall
Kd (Sub-Surface)	Minimum	0.034	0.144	0.133	0.034
	Maximum	0.482	0.599	0.982	0.982
	Mean	0.293	0.240	0.263	0.265
	St. Dev.	0.105	0.093	0.174	0.131
Kd (Mean)	Minimum	0.123	0.149	0.201	0.123
	Maximum	0.294	0.347	0.443	0.443
	Mean	0.205	0.267	0.270	0.247
	St. Dev.	0.056	0.043	0.052	0.059

values and average values for the euphotic layer. The variability of Kd values throughout the water column differs across various seas and oceans. However, despite this variability, some common constant values and standardized methods are still applied, which may not represent the most accurate approach. In previous studies, the Kd value determined over a broader depth range resulted in a lower Kd and consequently a lower alpha value, whereas when the Kd was calculated within a narrower, near-surface layer, the higher Kd led to a correspondingly higher alpha value. In addition to the variation in Kd, the turbidity of the study area is also influential, as a clearer area will have a larger Secchi Depth (Z_{SD}), which will consequently result in a higher alpha value (Holmes, 1970; Davies-Colley and Vant, 1988; Koenings and Edmundson, 1991). To determine which would be more appropriate for use in this study, it was assessed whether the data followed a normal distribution (Figure 4).

As indicated in Table 3, the surface Kd values were observed to be higher than the mean Kd values, consistent with previous studies. Additionally, the surface Kd values exhibited a much wider range for minimum and maximum data and a larger standard deviation compared to the mean Kd values. To determine whether the data followed a normal distribution, a histogram was analyzed. According to the distribution of Kd mean data shown in Figure 4, the most frequently occurring range is between 0.25 and 0.32.

Since the subsurface values contained many peak values and did not show a normal distribution, whereas the average values did present a normal distribution, the mean values were preferred for spatial distributions, even though Table 3 shows both sets of values. This allowed for understanding how the current values of the attenuation coefficient varied seasonally for both coastal and deep regions of the Sea of Marmara (Figure 5). When examining the seasonal variation of the average attenuation coefficient Kd, it was observed that it increased from January to July (Table 3). During the winter period, the attenuation coefficient varied between 0.123 and 0.294 m^{-1} across the Sea of Marmara, while this range increased to 0.149–0.347 m^{-1} in the spring and further to 0.201–0.443 m^{-1} in the summer period. The average attenuation coefficient values were 0.205±0.056 m^{-1} in January, 0.267±0.043 m^{-1} in April, and 0.270±0.052 m^{-1} in July.

In Figure 5, the mean attenuation coefficient values are examined for 22 stations seasonally in a spatial context. In January, the spatial assessment indicates that small increase of Kd values was observed in the Istanbul Strait and the northern Sea of Marmara. On the other hand, high values were measured in Erdek, Gemlik, and İzmit Bays in April. A comparison of the values observed in April and July indicates that the interior of the Sea of Marmara exhibits relatively high values in April. However, Erdek Bay and Izmit Bay demonstrate higher values than those observed in April,

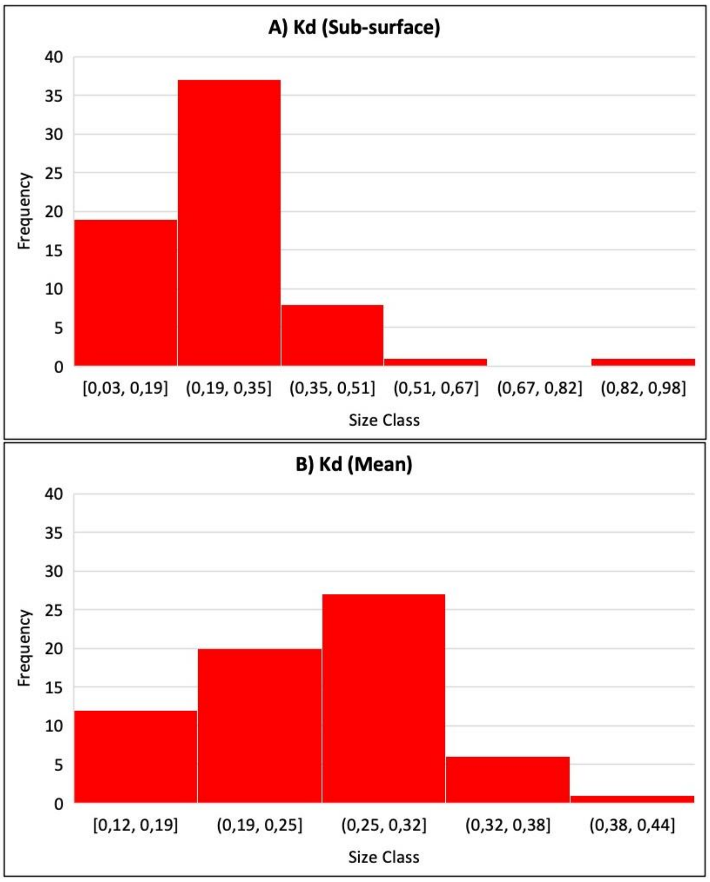

Figure 4. Data distribution of A) Attenuation coefficient subsurface values; B) Attenuation coefficient mean.

which explains why the mean values for these two months are similar. In July, the highest values were recorded in the İzmit Bay throughout the sampling period.

On the other hand, the ten-year data consistently showed that the lowest attenuation coefficient values were measured during the summer and autumn seasons in contrast to the 2021 spring and summer season. In order to reveal of this feature, the PAR values for the three seasons in 2021 were examined in detail for the first 30 meters of the water column at five selected stations, as illustrated in Figures 6. These five stations were selected to represent the Sea of Marmara, including both open water and coastal influence areas, particularly those within bays.

Photosynthetically active light values represented by the green line, corresponding to the summer season, shows a rapid decrease within the first 10 meters, particularly at stations MD101, GD3, and M74A (Figure 6). In contrast, during the winter months, indicated in red—when the euphotic zone is expected to be the shallowest—the 1% light level (thickness of the euphotic zone) decreases more gradually compared to the other seasons, as observed at the IZ-17 station. During winter, the January attenuation coefficient remained lower throughout the water column compared to other periods, which is reflected thickness of the euphotic zone being approximately 10 meters or more deeper than in July. It is clear that the depth of the euphotic zone was reduced in July due to the effects of mucilage.

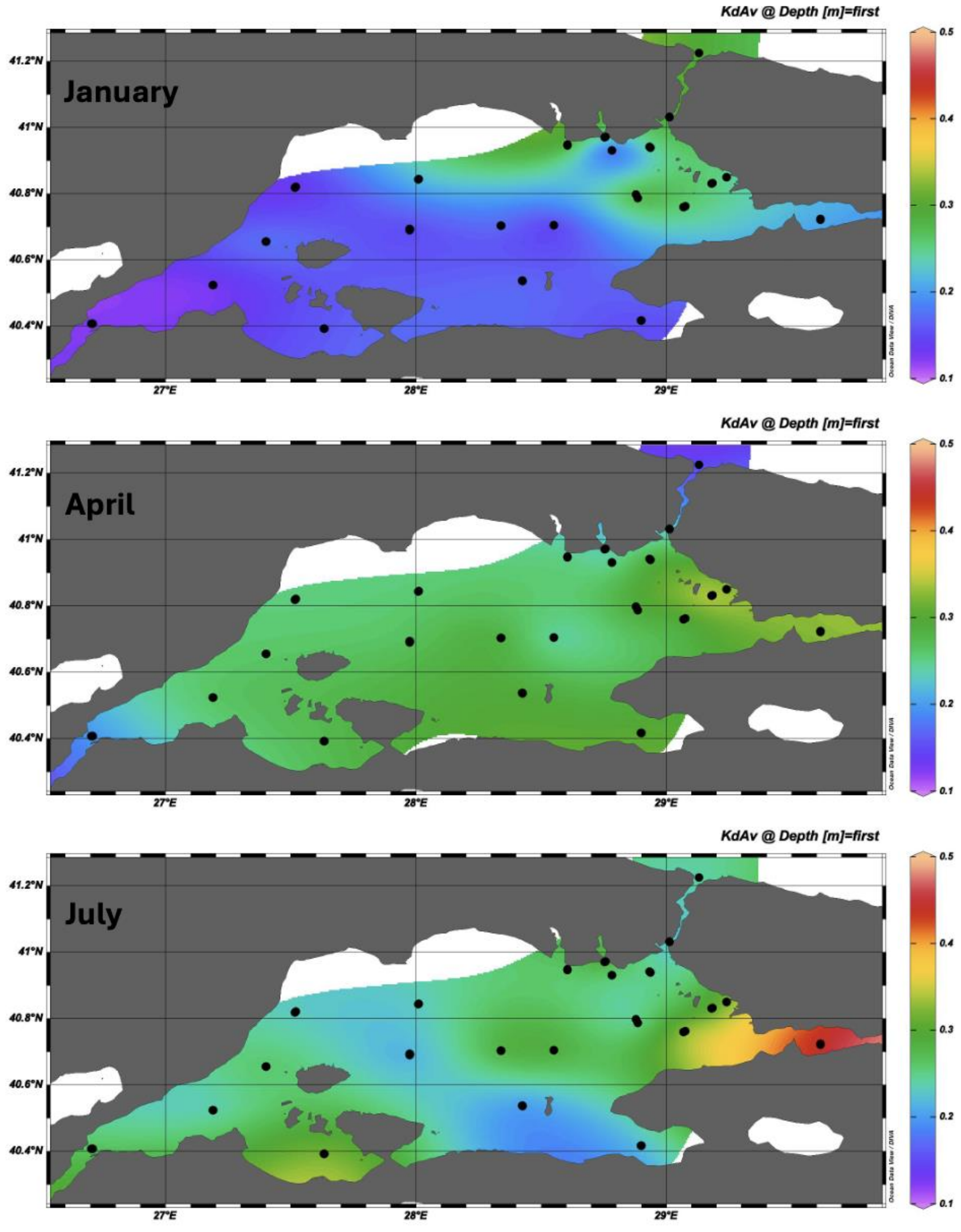

Figure 5. Spatial representation of the mean attenuation coefficient in the Sea of Marmara (2021), The map was created using Ocean Data View software, with DIVA gridding applied for enhanced spatial representation.

This dataset not only provides previously unavailable information on the attenuation coefficient in the NE Sea of Marmara for these years but also allows to estimate the attenuation coefficient from Secchi disk depth (Table 2). The overall average value and standard deviation for the NE Sea of Marmara obtained in this study are 1.87±0.53. The minimum and maximum values also span a wide range (0.66–3.56) due to varying Secchi disk values. The seasonal and regional average values for this estimated value, referred to as the alpha constant in the literature, are presented in Table 2. Due to the varying Secchi disk depths, regional variation is higher than seasonal variation for this constant. The season with the lowest value for this constant is winter, followed by autumn and spring. The highest values have been observed during the summer season.

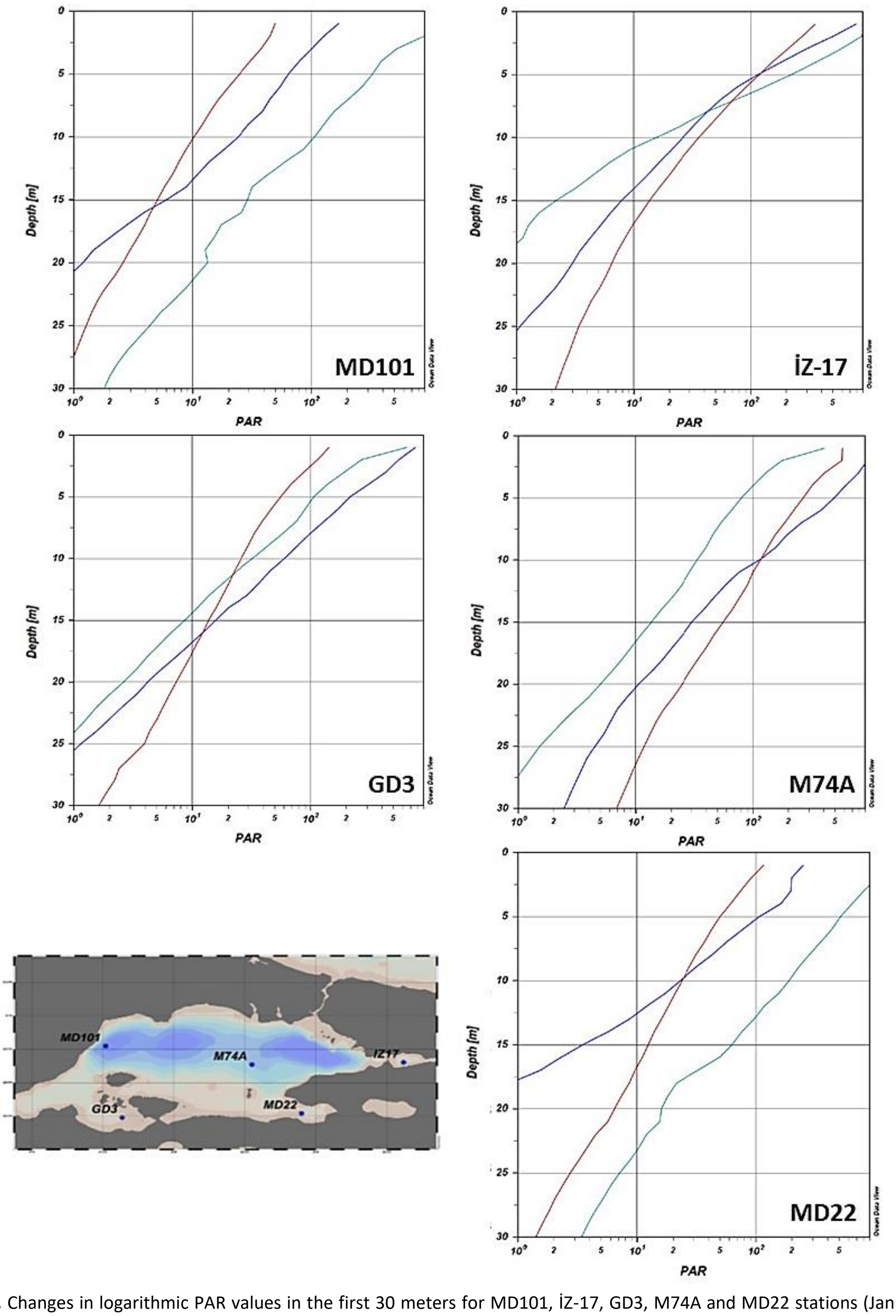

Figure 6. Changes in logarithmic PAR values in the first 30 meters for MD101, İZ-17, GD3, M74A and MD22 stations (January in red, April in blue, and July in green).

The alpha values for the seasonal data obtained in 2021 have been analyzed and are presented in Table 4. The mean value for the three seasons in 2021 is 1.49±0.36. While the standard deviation is lower compared to the 10-year data set, the mean value has decreased from 1.87 to 1.49. As seen in Tables 1 and 3, despite an increase in the average Kd value across both periods, the decline in the alpha value can only be explained by changes in Secchi disk depth. When examining seasonal variation, the mean value is lowest in winter, followed by spring and autumn. When examining the overall data, the minimum and maximum values range from 0.91 to 2.55.

Discussion

The attenuation coefficient of light is a crucial parameter that provides important information about light penetration and availability in seas and oceans. Accurate estimation of the attenuation coefficient is essential not only for understanding physical processes such as heat transfer in the upper layers of seas and oceans (Lewis et al., 1990; Morel and Antoine, 1994; Sathyendranath et al., 1991; Wu et al., 2007) but also for gaining insights into biological parameters like photosynthesis occurring in the euphotic zone of seas and oceans (Platt et al., 1988; Sathyendranath et al., 1989). Since light penetration in the water column is a significant component in ocean and atmospheric dynamic models, various studies have indicated that water turbidity can significantly impact ocean environments, influencing parameters like surface water temperature and ocean circulation (Kara et al., 2004, 2005; Subrahmanyam et al., 2008). The seasonal variation in average attenuation coefficient values, with lower values in summer and autumn and higher values in spring and winter, can be explained by environmental and biological factors. The observed vertical mixing in the Sea of Marmara during winter, along with the increase in phytoplankton biomass in the winter and spring months (Bayram Partal, 2022), is believed to be the primary reason for the elevated light attenuation observed during these two months. However, a detailed seasonal analysis of chlorophyll a concentration, suspended solids, and CDOM parameters should be conducted in future studies to provide a comprehensive understanding.

The attenuation coefficient generally shows high values (peak values) just below the surface and at specific depths such as the Chl-maximum, while at other depths, the attenuation coefficient decreases with depth (Kirk, 2010; Fleming-Lehtinen and Laamanen, 2012). However, extreme events can occur in marine waters, such as red tides, mucilage formation, and eutrophication. One such event was the mucilage outbreak that affected the entire Sea of Marmara in 2021 (Savun-Hekimoğlu and Gazioğlu, 2021; Ergül et al., 2021). This massive event caused significant changes in both the water surface and the water column, substantially impacting turbidity and, consequently, the diffuse attenuation coefficient (Kd). As illustrated in Figure 5 and 6, the depth-dependent variation of Kd in the water column was notably different during the summer of 2021. Öztürk et al. (2021) investigated how the typology of mucilage formed in the water column during the 2021 mucilage event in the Sea of Marmara changed and concluded that different typologies were specifically located at different depth ranges, with mucilage clusters growing and intensifying with depth. Öztürk and Ediger (2023) examined the impact of different mucilage clusters on the optical properties of light. This study demonstrated that the typologies of mucilage, which grow and thicken with depth in the Sea of Marmara, affected the attenuation of light and reduced the depth of the euphotic zone towards the surface.

To understand the deviation from the seasonal patterns observed over the 10-year monitoring period, the attenuation within the critical first 20 meters of the water column (at depths of 1, 5, 10, 13, 15, and 20 meters) was compared for two seasons at the stations listed in Figure 6 (MD22, GD3, MD101, İZ-17, and M74A), as illustrated in Figure 7. Different colors represent the stations. Analysis of this graph indicates that the overall variation observed in January is consistent with both the 10-year data and existing literature, whereas the data for July reveals a significantly different pattern. The attenuation coefficient values, which are anticipated to decrease with depth and be lower in comparison to winter months, show unexpectedly higher values in July and an increasing trend with depth across all stations (Figure 7). This observation helps to explain the distinct difference in 2021, which can be attributed to the mucilage event. As stated by Öztürk and Ediger (2023), the typology of mucilage aggregates becomes larger and denser with depth, resulting in increased light attenuation.

Shi and Wang (2010) conducted a systematic analysis using the attenuation coefficient seasonally to measure and classify the turbidity of seas and oceans globally. As a result of their study, they categorized seas and oceans into three classes based on the attenuation

Table 4. Seasonal minimum, maximum, mean and standard deviation values of attenuation coefficient (Kd m^{-1}) * secchi disk depth (Z_{SD} m) for the Sea of Marmara (2021)

Kd * Z_{SD}	Minimum	0.91	0.82	1.11	0.82
	Maximum	1.97	2.55	2.29	2.55
	Mean	1.28	1.53	1.65	1.49
	St. Dev.	0.25	0.41	0.31	0.36

coefficient. The first class consists of open or clear waters, with an attenuation coefficient of less than 0.1 m^{-1}. The second class includes moderately turbid waters, with an attenuation coefficient range of 0.1 m^{-1} to 0.3 m^{-1}. The third class, which consists of turbid waters, has an attenuation coefficient greater than 0.3 m^{-1} (Shi and Wang, 2010). The third class primarily includes water bodies such as coastal waters, river mouths, and inland waters under significant anthropogenic influence. Moderately turbid waters encompass open seas and deep basins and have been found to be the most widely spread class. The attenuation coefficient values calculated for these studies conducted in January, April, and July in the Sea of Marmara are color-coded according to the Shi and Wang (2010) classification and shown in Table 5.

According to this classification, the January values, apart from two stations, represent the lowest attenuation coefficients across all study sites, indicating that the entire Sea of Marmara falls within the "moderately turbid water" category. However, even in January 2021, no station fell into the lowest turbidity category as defined by Shi and Wang (2010), meaning that no Kd value was below 0.1 m^{-1}. The two stations that diverge from this general trend, K0 and B2, are located at the Istanbul Strait and the Black Sea outflow of the Istanbul Strait, respectively (Figure 5 and Table 5). Therefore, their deviation from the general dataset is attributed to the influence of the surface waters from the Black Sea, which is considered a normal phenomenon. The regions with the lowest values are the entrance to the Çanakkale Strait (D7), the stations

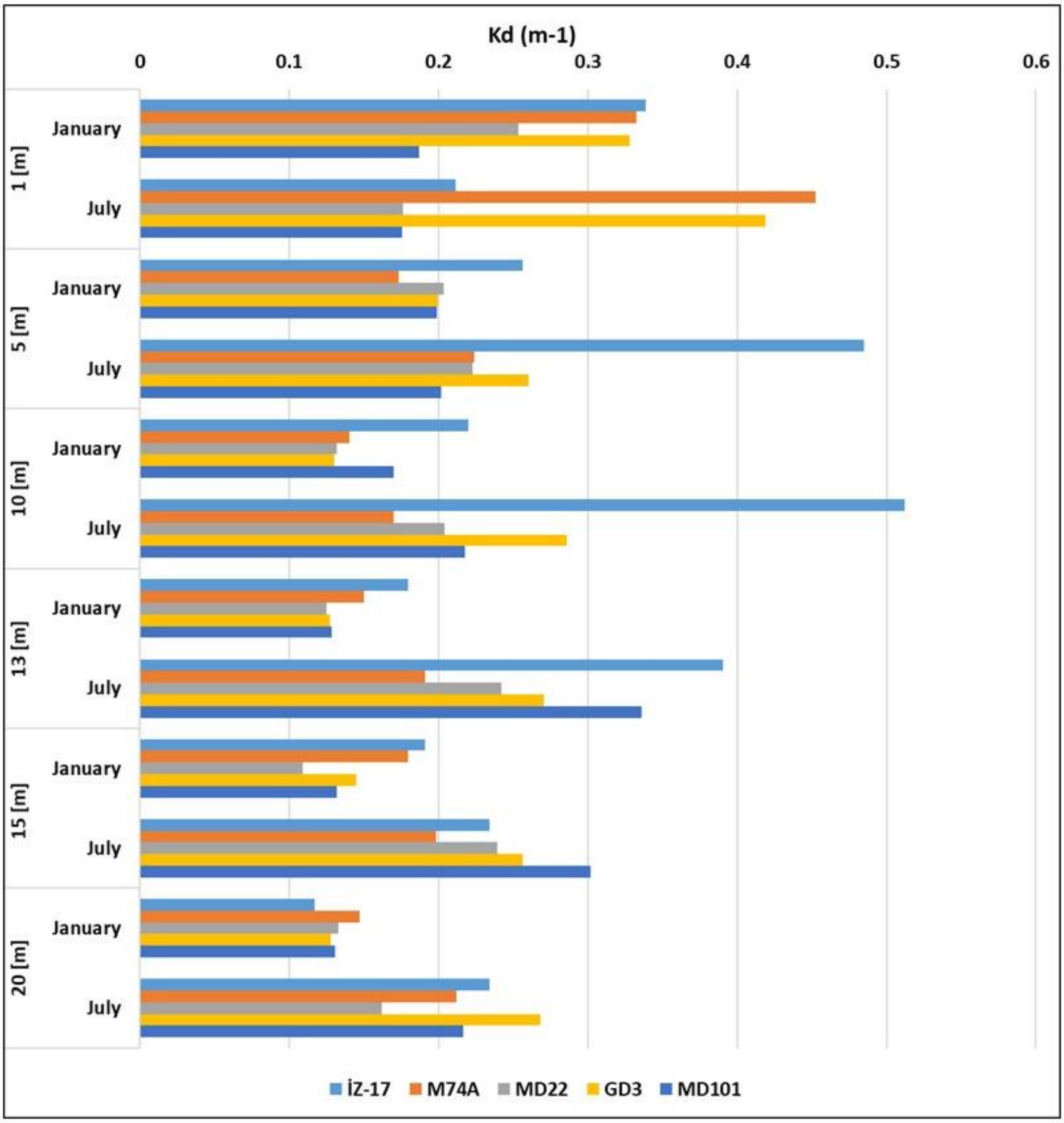

Figure 7. Comparison of January and July attenuation coefficients during the mucilage event in the Sea of Marmara (2021) for 1, 5, 10, 13, 15, and 20 meter depths.

located in the southwest (MD10A, MD13A), and the central axis (DTM3, M74A) of the Sea of Marmara. In April, based on this classification, it can be observed that stations around Istanbul (MY1, MY2), deep stations in the Çınarcık Basin (45C, MD102), and those in the İzmir and Gemlik Bay (İZ-17, MD19A, MD22) regions have transitioned from the moderately turbid water category to the turbid water category, as evidenced by the elevated Kd values.

Studies confirm that in these regions levels of particulates and production are significantly elevated due to anthropogenic influences (Okuş et al., 2002; Tüfekçi et al., 2010; Ediger et al., 2016). In July, the turbidity classification based on attenuation coefficients resembles that of April. Once again, stations around Istanbul are categorized as turbid with a red rank (KC1, MY1, MY2), while it is observed that the average values in Izmit Bay exceed 0.4 m^{-1} (İZ-17). Additionally, Erdek Bay also shows high values in July (GD3). As with all other seasons, in July, the attenuation coefficients do not fall below 0.1 m^{-1}, categorizing the waters as moderately turbid to turbid.

The attenuation coefficients determined in this study are also influenced by environmental parameters, and high values were obtained in the presence of parameters affecting light transmissibility in coastal areas and the water column, as detailed in the results section. Although the Sea of Marmara is classified as moderately turbid water based on the attenuation coefficient, under adverse conditions such as mucilage, it falls into the highly turbid water category. In the study completed by Ediger and Yılmaz (1996) for the years 1986-1991, the average attenuation coefficient value calculated for the Sea of Marmara was 0.136±0.045 m^{-1}. In this study, for the year 2000, this value increased to 0.200±0.070 m^{-1}, to 0.220±0.070 m^{-1} in 2009, and finally to 0.247±0.059 m^{-1} in 2021. As a result, the 30-year review shows that the attenuation coefficient in the Sea of Marmara has increased.

In previous studies, the constant alpha value used to derive the attenuation coefficient from Secchi disk depth ranged between 1.27 and 2 (Poole and Atkins, 1929; Holmes, 1970; Idso and Gilbert, 1974; Koengings and Edmundson, 1991; Montes-Hugo and Alvarezborrego, 2005; Lee et al., 2018). No previous study has investigated this constant value in the context of long-term research specific to the Sea of Marmara. According to the findings of this study, the ten-year monthly monitoring yielded a value of 1.87 (Table 2), and even during extreme cases affecting water transparency, such as the mucilage event, the value of 1.49 (Table 4) remained within the range reported in the literature. The values for clear waters were found to be higher than those for turbid waters (Holmes 1970; Koenings and Edmundson 1991), and the low values observed in 2021 further highlight the impact of the mucilage event on the alpha values in the Sea of Marmara. Given the significance of seasonality highlighted in this study, it is crucial to conduct long-term, region-specific research in environments like the Sea of Marmara to develop unique constant values for optical parameters. These region-specific constants are vital for ensuring the accuracy of the information derived from such studies. On the other hand, in cases where light measurements cannot be conducted and, consequently, the attenuation coefficient cannot be determined, using these "region-specific constant values" will not only provide a different perspective for various studies but also shed light on past optical studies of the water column. In this study, the observed

Table 5. Seasonal attenuation coefficient values for 22 studies stations in the Sea of Marmara and their turbidity classification according to Shi and Wang (2010) Yellow: moderately turbid waters Red: turbid waters

	January	April	July
K0	0.300	0.149	0.243
B2	0.300	0.226	0.222
M8	0.246	0.286	0.249
M14A	0.165	0.246	0.254
KC1	0.243	0.239	0.300
BC1	0.284	0.253	0.261
MY1	0.247	0.325	0.329
MY2	0.256	0.347	0.301
İZ - 17	0.209	0.328	0.443
MD102	0.256	0.295	0.335
45C	0.278	0.291	0.249
MD22	0.155	0.303	0.221
MD19A	0.169	0.292	0.201
M74A	0.147	0.244	0.287
MD18	0.171	0.285	0.282
DTM3	0.153	0.268	0.216
MD103	0.219	0.258	0.233
MD101	0.135	0.255	0.232
MD13A	0.176	0.263	0.262
GD3	0.160	0.274	0.322
MD10A	0.128	0.263	0.238
D7	0.123	0.198	0.267

seasonal changes in light attenuation coefficients can significantly contribute to a deeper understanding of marine ecosystems health, particularly in ecosystem modeling, remote sensing studies and water quality. The findings will aid in refining remote sensing algorithms, improving ecosystem monitoring tools, and enhancing the understanding of climate change impacts on marine environments. These contributions will be particularly valuable for enhancing the accuracy of ecosystem models, development of improved monitoring tools and water quality predictions, thereby supporting policy decisions related to more effective conservation strategies and resource management.

Conclusion

The results of this study indicate that the parameters affecting it in the Sea of Marmara are significantly influenced by seasonal changes and regional dynamics. Therefore, developing region-specific algorithms for understanding the relationships between the euphotic zone and related parameters is crucial. To comprehend the changes in the euphotic zone and the influencing parameters, it is recommended to conduct regular monitoring and measurement studies covering the entire Sea of Marmara, which would capture regional differences and seasonal dynamics. Currently, the major challenges facing marine ecosystem conservation include biodiversity loss, climate change, eutrophication, chemical pollution, and land-based pollutants. For the sustainable management of the ecosystem, monitoring efforts in the Sea of Marmara should be approached with ecosystem-based strategies.

Ethical Statement

This study did not involve any human or animal subjects, and therefore no ethical approval was required.

Funding Information

No funding was received in relation to this study.

Author Contribution

İlayda Destan ÖZTÜRK: Conceptualization, Data Curation, Formal Analysis, Visualization, Writing -review and editing;

Dilek EDİGER: Data Curation, Formal Analysis, Methodology and Writing -original draft;

Hüsne ALTIOK: Data Curation, Writing -review and editing.

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank the staff of R/V ARAR for their effort in collecting the data for 10 years, and the “Integrated Marine Pollution Monitoring 2020–2022 Program” funded by the Turkish Ministry of Environment and Urbanization/General Directorate of EIA, Permit and Inspection/ Department of Laboratory, Measurement and coordinated by TUBITAK- MRC ECPI for the provisioning of the data used in this study. We also want to thank Sabri MUTLU for his help during the survey.

References

Andersen, J., Axe, P., Backer, H., Carstensen, J., Clausen, U., F.-Lehtinen, V., J¨ arvinen, M., Kaartokallio, H., Knuuttila, S., Korpinen, S., Kubiliute, A., Laamanen, M., L.-Pastuszak, E., Martin, G., Murray, C., Møhlenberg, F., Nausch, G., Norkko, A., & Villnas, A. (2011). Getting the measure of eutrophication in the Baltic Sea: towards improved assessment principles and methods. *Biogeochemistry* 106, 137–156. https://doi.org/10.1007/s10533-010-9508-4.

Aydoğdu, A.; Pinardi, N.; Özsoy, E.; Danabasoglu, G.; Gürses, Ö.; Karspeck, A. (2018). Circulation of the Turkish Straits System under Interannual Atmospheric Forcing. *Ocean Science*. 14, 999–1019.

Bayram Partal, F. (2022) Investıgation Of Phytoplankton Composition of Izmit Bay and The Northeastern Marmara Sea with Water Quality Variables, İstanbul University PhD. Thesis 188 p.

Beşiktepe, S., Sur, H.İ., Özsoy, E., Latif, M.A., Oğuz, T. & Ünlüata, Ü. (1994). Circulation and hydrography of the Marmara Sea. *Progress in Oceanography*, 34: 285- 334.

Bracchini, L., A. M. Dattilo, V. Hull, S. A. Loiselle, A. Tognazzi, & Rossi, C. (2009). Modelling Upwelling irradi- ance using Secchi disk depth in lake ecosystems. *Journal of Limnology*. 68: 83–91. https://doi.org/10.4081/jlimnol.2009.83

Castillo-Ramírez, A., Santamaría-del-Ángel, E., González-Silvera, A., Frouin, R., Sebastiá- Frasquet, M. T., Tan, J., & Enríquez-Paredes, L. (2020). A new algorithm to estimate diffuse attenuation coefficient from Secchi disk depth. *Journal of Marine Science and Engineering*, 8(8), 558.

Davies-Colley, R. J., & W. N. Vant. (1988). Estimation of optical properties of water from Secchi disk depths. *Water Resources Bulletin*. 24: 1329–1335. https://doi.org/10.1111/j.1752-1688.1988. tb03054.x

Devlin, M. J., Barry, J., Mills, D. K., Gowen, R. J., Foden, J., Sivyer, D., & Tett, P. (2008). Relationships between suspended particulate material, light attenuation and Secchi depth in UK marine waters. Estuarine*, Coastal and Shelf Science*, 79(3), 429-439.

Ediger, D., & Yilmaz, A. (1996). Variability of light transparency in physically and biochemically different water masses: Turkish Seas. *Fresenius Environmental Bulletin*, 5: 133-140.

Ediger, D., Beken Ç., Yüksek A., & Tugrul S. (2016). Eutrophication in the Sea of Marmara. In: *The Sea of Marmara; Marine Biodiversity, Fisheries, Conservation* *and Governance* (eds., Özsoy, E., Çağatay, M.N., Balkıs, N., Balkıs, N., Öztürk, B.) Turkish Marine Research Foundation (TUDAV) Istanbul, Turkey, Publication No.42, pp 723.

Effler, S.W., Strait C., O'Donnell, D.M., Effler, A., Peng, F., Prestigiacomo, A.R., O'Donnell, S.M. & Perkins, M. (2017). A mechanistic model for Secchi disk depth, driven by light scattering constituents. *Water Air Soil Pollution*. 228: 153. https://doi.org/10.1007/s11270-017- 3323-7.

Ergul, H. A., Balkis-Ozdelice, N., Koral, M., Aksan, S., Durmus, T., Kaya, M., … & Canli, O. (2021). The early stage of mucilage formation in the Marmara Sea during spring 2021. *Journal of the Black Sea/Mediterranean Environment*, *27*(2).

Falkowski, P.G. & Raven, J.A. (1997) AquaticPhotosynthesis. Blackwell Science, Malden, MA. Fleming-Lehtinen, V., & Laamanen, M. (2012). Long-term changes in Secchi depth and the role of phytoplankton in explaining light attenuation in the Baltic Sea. Estuarine*, Coastal and Shelf Science*, 102-103, 1–10. https://doi.org/10.1016/j.ecss.2012.02.015.

Holmes, R. W. (1970). The secchi disk in turbid coastal waters 1. *Limnology and Oceanography*, 15(5), 688-694. https://doi.org/10.4319/lo.1970.15.5. 0688

Idso, S. B., & Gilbert, R. G. (1974). On the universality of the Poole and Atkins Secchi disk-light extinction equation. *Journal of Applied Ecology*, 399-401. https://doi.org/10.2307/2402029

Kara, A. B., Hurlburt, H. E., Rochford, P. A., & O'Brien, J. J. (2004). The impact of water turbidity of the interannual sea surface temperature simulations in a layered global ocean model, *Journal of Physical Oceanography*, 34, 345–359.

Kara, A. B., Wallcraft, A. J., & Hurlburt, H. E. (2005). Sea Surface Temperature sensitivity to water turbidity from simulations of the turbid Black Sea using HYCOM, *Journal of Physical Oceanography*, 35, 33–54.

Kettle, H., & Merchant, C. J. (2008). Modeling ocean primary production: sensitivity to spectral resolution of attenuation and absorption of light. *Progress in Oceanography*, *78*(2), 135-146.

Kirk, J. T.O. (1994). Light & photosynthesis in aquatic ecosystems. Univ. Press.

Kirk, J.T.O. (2010). Light and Photosynthesis in Aquatic Ecosystems. *Cambridge University Press*. 509 pp.

Koenings, J. P., & Edmundson, J. A. (1991). Secchi disk and photometer estimates of light regimes in Alaskan lakes: Effects of yellow color and turbidity. *Limnology and Oceanography,* 36: 91–105. https://doi.org/10.4319/lo.1991.36.1.0091

Lee, Z., Weidemann, A., Kindle, J., Arnone, R., Carder, K. L., & Davis, C. (2007). Euphotic zone depth: Its derivation and implication to ocean-color remote sensing. *Journal of Geophysical Research: Oceans,* 112(C3).

Lee, Z., Shang, S., Du, K., Wei, J. (2018). Resolving the long-standing puzzles about the observed Secchi depth relationships. *Limnology and Oceanography*, 63(6), 2321-2336. https://doi.org/10.1002/lno.10940.

Lewis, M. R., Carr, M. E., Feldman, G. C., Esaias, W., & McClain, C. (1990). Influence of penetrating solar radiation on the heat budget of the equatorial Pacific Ocean. *Nature*, 347(6293), 543-545.

Lund-Hansen, L. C. (2004). Diffuse attenuation coefficients Kd (PAR) at the estuarine North Sea–Baltic Sea transition: time-series, partitioning, absorption, and scattering. *Estuarine, Coastal and Shelf Science*, 61(2), 251-259. https://doi.org/10.1016/j.ecss.2004.05.004.

Montes-Hugo, M.A., & Álvarez-Borrego, S. (2005). Empirical relations to estimate PAR attenuation in San Quintín Bay, using Secchi depth and sighting range. *Ciencias Marinas*, 31, 685–695. https://doi.org/10.7773/ cm.v31i4.27

Morel, A. & Antoine, D. (1994). Heating rate within the upper ocean in relation to its bio–optical state. *Journal of Physical Oceanography*, 24(7), 1652-1665.

Okuş, E., Aslan-Yilmaz, A., Yüksek, A., Taş, S., & Tüfekçi, V. (2002). Nutrient distribution in the Bosphorus and surrounding areas. *Water science and technology*, *46*(8), 59-66.

Öztürk, İ.D., & Ediger, D. (2023) Effects of mucilage on the optical properties of water column in the Sea of Marmara*. Journal of the Black Sea/Mediterranean Environment,* 29(1): 73–86.

Öztürk, İ.D., Mutlu, S., Kaman, G., Partal, F.B., Demirtaş, A., Caglar, S., Kuzyaka, E., Altiok, H., & Ediger, D. (2021) Vertical distribution of mucilage typology in the water column after a massive mucilage formation in the surface waters of the Sea of Marmara. *Journal of the Black Sea/Mediterranean Environment*, 27(2): 184-201.

Platt, T., Sathyendranath, S., Caverhill, C. M., & Lewis, M. R. (1988). Ocean primary production and available light: further algorithms for remote sensing. *Deep Sea Research Part A. Oceanographic Research Papers*, 35(6), 855-879.

Polat, S. Ç., & Tugrul, S. (1995). Nutrient and organic carbon exchanges between the Black and Marmara Seas through the Bosphorus Strait. *Continental Shelf Research*,15(9), 1115-1132.

Poole, H. H., & Atkins, W. R. G. (1929). Photo-electric measurements of submarine illumination throughout the year. *Journal of the Marine Biological Association of the United Kingdom*, 16(1), 297-324. https://doi.org/10.1017/ S0025315400029829

Sathyendranath, S., Prieur, L., & Morel, A. (1989). A three-component model of ocean colour and its application to remote sensing of phytoplankton pigments in coastal waters. *International Journal of Remote Sensing*, 10(8), 1373-1394.

Sathyendranath, S., Gouveia, A. D., S. R. Shetye, P. Ravindran, & Platt, T. (1991). Biological control of surface temperature in the Arabian Sea, *Nature*, 349 (54 – 56).

Savun-hekimoğlu, B., & Gazioğlu, C. (2021). Mucilage problem in the semi-enclosed seas: Recent outbreak in the Sea of Marmara. *International Journal of Environment and Geoinformatics*, *8*(4), 402-413.

Shi, W., & Wang, M. (2010). Characterization of global ocean turbidity from Moderate Resolution Imaging Spectroradiometer ocean color observations. *Journal of Geophysical Research: Ocean*. (115) Issue C11. 148-227. https://doi.org/10.1029/2010JC006160

Subrahmanyam, B., Ueyoshi, K., & Morrison, J. M. (2008), Sensitivity of the Indian Ocean circulation to phytoplankton forcing using an ocean model, *Remote Sensing Environment*,112, 1488–1496.

Tugrul, S. & Polat, Ç. (1995). Quantitative comparison of the influxes of nutrients and organic carbon into the Sea of Marmara both from anthropogenic sources and from the Black Sea. *Water Science and Technology*, 32(2): 115-121.

Tüfekçi, V., Balkis, N., Beken, C. P., Ediger, D., & Mantikci, M. (2010). Phytoplankton composition and environmental conditions of the mucilage event in the Sea of Marmara. *Turkish Journal of Biology*, *34*(2), 199-210.

Ünlüata, Ü., Oğuz, T., Latif, M. A. & Özsoy, E. (1990). On the Physical Oceanography of the Turkish Straits, in: *The Physical Oceanography of Sea Straits*, L. J. Pratt (editor), NATO/ASI Series, Kluwer, Dordrecht, 25-60.

Wu, Y., Tang, C. C., Sathyendranath, S., & Platt, T. (2007). The impact of bio-optical heating on the properties of the upper ocean: A sensitivity study using a 3-D circulation model for the Labrador Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, *54*(23-26), 2630-2642.