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Clarity of the Black Sea – historical measurements of Secchi Depth

Ioan-Daniel ȘERBAN[1,2,*], Sorin CONSTANTIN[1,2], Georgiana ANGHELIN[1,2], Alexandru NEDELEA[1]

[1] University of Bucharest, Faculty of Geography, 050663, Bucharest, Romania
[2] Terrasigna, 020581, Bucharest, Romania
* *Corresponding author*: ioan.serban@drd.unibuc.ro

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Abstract

Water transparency is a primary indicator used to evaluate the status of marine ecosystems. Although a subjective measure, Secchi Depth (Z_{SD}) is one of the "oldest" and most widely used optical parameters in studies that focus on surface water clarity, with probably millions of observations available in the last century. As recent satellite observations do not cover such extended periods from the past, a comprehensive understanding of the spatio-temporal dynamics of water transparency requires consistent historical data. In this regard, the present study aims to integrate information from archives of in situ Z_{SD} measurements available for the entire Black Sea. Several potential sources were investigated. Among them, two were identified to have historical measurements of Z_{SD} in the Black Sea, SeaDataNet and Black Sea Ecosystem Processes and Forecasting / Operational Database Management System (NATO SfP ODBMS). A database with all available observations was aggregated for this study, containing a total of 5100 records between 1960 and 2016. The analysis of the spatial variability of Z_{SD} was performed based on a square grid of 30 km x 30 km covering the entire Black Sea region. For each cell, statistics such as the average and the number of ZSD measurements were calculated. Moreover, the spatial and temporal homogeneity of the in-situ observations are assessed and discussed.
Keywords: *Secchi Depth, water transparency, Black Sea, in situ, historical measurements*

Introduction

Water transparency, or clarity, represents the ability of water to transfer light (Kirk, 2011). It is an essential factor often used to assess the ecological status of aquatic ecosystems in coastal and marine areas (Alikas and Kratzer, 2017; Lee et al., 2018). Secchi Depth (Z_{SD}) has been a widely utilized parameter in oceanographic studies that focused on water transparency (Aarup, 2002; Lee et al., 2018). This straightforward parameter to perform and understand measurement describes the visibility in the water column (Preisendorfer, 1986; Aas et al., 2014; Lee et al., 2015). It represents, in fact, an optical characteristic, strongly influenced by the constituents present in the water column (Doron et al., 2011; Aas et al., 2014; Lee et al., 2015; Gholizadeh et al., 2016). Depending on the optical regime of the waters, Z_{SD} is affected by the amount of suspended organic or inorganic particles, phytoplankton pigments and coloured dissolved organic matter (Lee et al., 2015; Gholizadeh et al., 2016; Luis et al., 2019). The Black Sea is a semi-enclosed sea, part of the Mediterranean Sea, connected with it through straits and basins: the Bosphorus Strait, the Sea of Marmara and the Dardanelles Strait (Antipa, 1941; Vespremeanu, 2005). Due to its unique characteristics, this region presents various and optically complex waters. The hydrological regime of rivers that flow into the Black Sea, especially in the north-western part, is a critical factor that determines the stable balance of the marine ecosystem. The sediment load (solid discharge) plays a pivotal role in the clarity of coastal waters, while liquid discharge can significantly impact primary productivity through the amount of nutrients carried into the sea (Bondar, 1973; McCarney-Castle et al., 2012; Constantin et al., 2016). Higher concentrations of these substances are one of the main causes of excessive phytoplankton development. All these mechanisms, along with the combined influence of other complementary factors (e.g. sunlight, salinity, waves regime, etc.), define the changes that occur in the optical regime of the waters (Barale and Murray, 1995; Kukushkin, 2018). A comprehensive archive of in situ Z_{SD} measurements can successfully contribute to a deeper understanding of spatio-temporal changes in water transparency occurring in the Black Sea.

The main objective of this study is to obtain an exhaustive overview of the availability of historically Z_{SD} in situ measurements in the Black Sea. Furthermore, an analysis of the spatio-temporal distribution of these observations over an extended period is also pursued. In this context, the aim is to define a database containing records from all the available sources that can be used in further studies concerning the long-term dynamics of water transparency and marine ecosystem changes.

Theoretical background

Z_{SD} is determined by lowering a white or an alternating black-and-white disk into the water. The depth at which is no longer visible to an observer is recorded and considered the Secchi Depth (Preisendorfer, 1986; Doron et al., 2011; Aas et al., 2014; Lee et al., 2015). It is named after the Italian astrophysicist Angelo Francesco Ignazio Baldassarre Secchi (1818 - 1878). As a result of his experiments onboard the papal corvette Immacolata Concezione (1865), Secchi was the first one who proposed a uniform and standardized methodology used to determine water clarity (Pitarch, 2020). During the campaign, that started from the port of Civitavecchia, he was responsible for conducting water optical measurements. These experiments explored the relationship between transparency and various factors – such as weather conditions, the Sun`s altitude in the sky, waves, or the observer`s perspective (Wernand, 2011; Pitarch, 2020). Before that, systematic research aimed at better understanding the factors influencing water transparency has been conducted in Europe since the early 18th century (Wernand, 2011; Lee et al., 2018). Various methods and "instruments" of different shapes and colours were used in this documentation process. However, Angelo Secchi's contributions remained a benchmark in the standardized monitoring of transparency (Pitarch, 2020).

Z_{SD} represents an optical property that can be easily measured and for which there are numerous records available. These were registered by a diverse range of individuals, from sailors to scientists (Wernand, 2011, Pitarch, 2020). Thus, it allows for the creation of a climatological time series of data, capable of providing continuity between the current state of marine ecosystems and that of over a century ago. The science of the Secchi disk has been adapted and continues to meet the standards of modern optical oceanography. As a result, in the last 150 years, approximately one million standardized Z_{SD} determinations are known to have been made, generally exhibiting a degree of uncertainty of 10% to 15% (Lee et al., 2018).

Atlases, maps and studies of water transparency based on in situ Z_{SD} measurements have been produced since the early 20th century. In this regard, there is an abundant number of initiatives covering the topic at both global and regional levels in the specialized literature. Among them, the most relevant are worth mentioning. Margaret Anne Frederick (1970) published a study capturing the global distribution of Z_{SD} measurements that included records available until 1969 at the National Oceanographic Data Center (USA) (Frederick, 1970). In 1972, Robert R. Dickson realized a map of the Atlantic Ocean's transparency based on over 5000 in situ Z_{SD} observations from multiple sources and extended over regions between latitudes 60º north and 15º south (Dickson, 1972). Robert Arnone published a Z_{SD} atlas for coastal areas with water depths of less than 500 m, between 40º north and south latitudes. About 23,000 in situ observations were identified and used (Arnone et al., 1984). A global seasonal analysis of water transparency based on over 120,000 in situ records was conducted by Marlon Lewis et al. in 1988 (Lewis et al., 1988). Other studies, like V. I. Voitov et al. in 1983, used approximately 300,000 – 320,000 Z_{SD} observations held by the Shirshov Institute of Oceanography of the Russian Academy of Sciences (Aarup 2002). Special attention has been given to water clarity in the Baltic and North Sea, regions that have waters with complex optical characteristics. Standardized Z_{SD} measurements have been conducted in these areas since 1902. However, until 1970, these measurements were sporadic, primarily covering the central and northern parts (Aarup, 2002). In this regard, Thorkild Aarup (2002) presents the results of a data mining study collecting all these Z_{SD} records for the transition zone between the North Sea and the Baltic Sea. Over 40,500 measurements were collected, most of which were provided by oceanographic research institutions from the surrounding countries (Aarup, 2002).

The first systematic observations of water transparency in the Black Sea waters, based on the Secchi disk method, were recorded in the early 1920s (Vladimirov et al., 1996). Since then, a vast number of historical in situ data were later integrated into the oceanographic studies of the area, focusing on the optical properties of the waters, phytoplankton characteristics, the relationship between river solid discharges and Z_{SD} in coastal areas, water quality assessment (eutrophication) or the impact of human activities on the clarity of deep waters. Vladimir Vladimirov et al. (1996) conducted a seasonal and long-term variability of the water clarity in the Black Sea (1922-1995). This study used a vast set of optical parameters data including more than 13,000 Z_{SD} measurements (Vladimir Vladimirov et al., 1996). A detailed analysis of underwater visibility depending on the physical characteristics of the Secchi disk was documented by Vladimir Haltrin (1998) during his expeditions in the Black and Aegean Seas (Haltrin, 1998). The seasonal and interannual variability of the transparency of the Azov Sea was investigated by Vera Sorokina and Valerii Kulygin. This analysis was based on a temporal series of data comprising 12,623 Z_{SD} records made between 1922 and 2009 (Sorokina and Kulygin, 2013). Long-term observations of Z_{SD} (16,000 records between 1923 and 2000) were used to assess the main particularities of spatial and temporal distribution variations of Z_{SD} in the deep areas of the Black Sea (Kukushkin, 2014). The effects of river discharge on water clarity in the coastal area of the north-western Black Sea were also analyzed based on 4954 historical measurements (between 1947 and 1986) (Kukushkin, 2018). The present study not only illustrates an integrated approach for the entire Black Sea area concerning historical data exploitation, but more importantly, defines a reference point for future research on water transparency that relies on modern techniques, such as satellite observations (Doron et al., 2011).

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Methodology

Nowadays, Z_{SD} provides a qualitative, cost-effective and easy to understand assessment of water transparency. The in situ methodology used to determine Z_{SD} is based on ISO/WD 7027-2 standard, which defines the characteristics of the equipment and the procedures that must be followed (ISO 7027-2:2019). The main objective of this study is to identify and obtain a detailed picture of in situ Z_{SD} measurements availability in the Black Sea over an extended period. In this direction, various infrastructures, initiatives and archives containing oceanographic observations were inspected. Among them, worth mentioning: The AERONET (AErosol RObotic NETwork), ARGO, European Environment Agency (EEA), NASA bio-Optical Marine Algorithm Dataset (NOMAD), Oceanographic Mediterranean and Black Sea Data Management (PERSEUS), Worldwide Ocean Optics Database (WOOD) from Office of Naval Research and Johns Hopkins Univ. Applied Physics Laboratory, SeaDataNet, Black Sea Ecosystem Processes And Forecasting / Operational Database Management System (NATO SfP ODBMS). Only two of the mentioned data sources, SeaDataNet and NATO SfP ODBMS, were identified as containing available Z_{SD} measurements made in the Black Sea.

SeaDataNet represents a Pan-European network that allows the exchange and management of oceanographic data from 35 countries bordering European seas. Access to data is generally free to all users, except for some specific datasets. A number of 1676 records of Z_{SD} conducted between 1992 and 2016 were acquired from SeaDataNet, most of them (1196) provided by the Ukrainian Scientific Center of Ecology of Sea. It also has to be mentioned that 12 measurements carried out by the National Environmental Agency of the Ministry of Environment Protection and Natural Resources (Georgia) in 2016 only cover a small area in the eastern part of the Black Sea, close to the Georgian coastline. Those actually represent the only identified observations for that particular year.

A synthesis of Z_{SD} measurements obtained through SeaDataNet is presented in Table 1. For this study, an additional number of Z_{SD} observations (over 1,000, during the period 2005-2008) held by Odessa National I.I.Mechnikov University were also identified in the SeaDataNet portal. Unfortunately, access to these data is restricted. Furthermore, an unknown number of transparency measurements made by the Marine Hydrophysical Institute (Ukraine) and the Institute of Maritime Science (Ukraine) in the Black Sea and the Azov Sea (Vladimirov et al. 1996) since the 1920s are known to exist, but are not publicly available.

Table 1: Synthesis of in situ Z_{SD} measurements available through SeaDataNet

Institution	Country	Temporal coverage	Number of measurements
National Institute for Marine Research and Development Grigore Antipa	Romania	2011-2014	169
Ukrainian Scientific Centre of Ecology of Sea	Ukraine	1992-1996, 1998-2000, 2009, 2010, 2012, 2013, 2015	1196
Bulgarian National Oceanographic Data Centre	Bulgaria	2001, 2004, 2007-2008	74
National Institute of Meteorology and Hydrology Bulgarian Academy of Sciences	Bulgaria	2009-2011	225
National Environmental Agency of the Ministry of Environment Protection and Natural Resources	Georgia	2016	12
		Total	1676

The second significant source of in situ measurements for the current research is the database of oceanographic parameters created within the NATO SfP ODBMS. This project was initiated in 1998 and aimed to improve co-operation between the main research entities from the 6 countries bordering the Black Sea, with support from the NATO "Science for Peace" subprogram. A comprehensive interdisciplinary database was created, including in situ observations of the main physical, chemical, and biological variables throughout the Black Sea basin. Institutions that contributed to the creation of the historical database are: Institute of Biology of the Southern Seas (Ukraine), Institute of Marine Sciences (Turkey), Marine Hydrophysical Institute (Ukraine), Odessa Branch of the Institute of Biology of Southern Seas (Ukraine), National Institute for Marine Research and Development "Grigore Antipa" (Romania), Shirshov Institute of Oceanology (Russia) and Southern Branch of Shirshov Institute of Oceanology (Russia). Within the NATO SfP ODBMS initiative, 3463 in situ Z_{SD} measurements for the entire Black Sea were identified, between the years 1960 and 1995. These cover a particularly important period in the evolution of the Black Sea ecosystem, mainly capturing major changes that occurred in the last two decades of the 20th century (Vespremeanu and Golumbeanu, 2018; Lazăr et al., 2019). Table 2 presents a summary of in situ Z_{SD} records available through NATO SfP ODBMS.

Table 2: Synthesis of in situ Z_{SD} measurements available through NATO SfP ODBMS

Institution	Country	Temporal coverage	Number of measurements
Institute of Biology of Southern Seas	Ukraine	1991-1995	118
Institute of Marine Sciences METU	Turkey	1992-1995	127
Marine Hydrophysical Institute	Ukraine	1960-1994	1011
Institute of Oceanology of Bulgarian Academy of Sciences	Bulgaria	1993	27
National Institute for Marine Research and Development Grigore Antipa	Romania	1963-1995	2114
Southern Branch of P.P.Shirshov Institute of Oceanology	Russia	1991	24
P.P.Shirshov Institute of Oceanology	Russia	1978-1989	42
		Total	3463

The database utilized in this study contains all available in situ observations available through the above-mentioned sources. Measurements performed in adjacent coastal lakes as well as those from inland rivers close to the shore were excluded from subsequent analysis. The final dataset contains 5,100 Secchi Z_{SD} records covering the entire Black Sea Basin between 1960 and 2016. While these originate from multiple sources, a significant part of them, approximately 44% (2,279), were collected and archived by the National Institute for Marine Research and Development "Grigore Antipa" in Constanța.

Visual interpretation of water clarity changes based on point locations where Z_{SD} was measured can sometimes be challenging or inaccurate due to uneven distribution or overlaps in certain areas. In order to overcome these limitations and provide a clear and consistent picture of the spatial variability of Z_{SD}, a square grid of 30 km x 30 km covering the entire Black Sea region was defined. Z_{SD} statistics (e.g. averages, number of measurements, etc.) were calculated for each grid cell, based on all available samples within a particular square.

Results and discussions

In the early 1960s, oceanographic research in the Black Sea intensified and became more structured, initiating a systematic approach to the monitoring of the marine ecosystem (Vespremeanu and Golumbeanu, 2018). This period also coincides with the earliest measurements identified in the Black Sea that have been integrated into the current study.

A preliminary and intuitive observation concerning all the 5100 Z_{SD} samples is their spatial heterogeneity (Figure 1). Most of the available data cover the north-western part of the basin, overlapping the continental shelf, which has a significant extension in this area. Coastal regions, and especially the ones close to the Danube River mouths, are generally rich in such measurements. In contrast, samples found in the open sea are usually sparse. Distance from the shoreline for each point was calculated. The analysis revealed that 1439 (28.21%) in situ observations were performed at less than 10 km from the coastline, while 2545 (49.9%, almost half) were within 30 km range. To gain a better perspective of the spatial distribution, the number of measurements for each 30 km x 30 km square grid covering the entire Black Sea was also calculated (Figure 1b). This analysis reinforces the first observation, highlighting the very large number of measurements (areas coloured in yellow, orange or red) in the western and north-western parts of the Black Sea (especially the coastal waters of Romania and Ukraine). Furthermore, this high spatial concentration, together with consistent temporal extension, can offer a detailed and comprehensive picture of specific aspects of Z_{SD}.

Another important aspect refers to the overall observed values for the Z_{SD} (Figure 1a). As a general rule, water transparency tends to increase as samples are taken further away from the main source of suspended particles (river solid discharge and resuspension in shallow coastal waters).

The absolute maximum Z_{SD} value in the Black Sea between 1960 and 2016 is 29 m. This was recorded on August 24, 1964, in the deep waters of the central part of the eastern basin of the Black Sea (latitude: 43.0283; longitude: 38.2999). The minimum observed Z_{SD} was 0.2 m. This was reported in three locations in front of the mouths of the Chilia Secondary Delta during a campaign conducted by the Ukrainian Scientific Centre of Ecology of the Sea on October 27, 2010. Another 11 measurements indicating a Z_{SD} of 0.2 m were identified in the bays near the city of Sozopol (Bulgaria) between June 2009 and July 2010. The average Z_{SD} value, for the entire Black Sea, computed based on our dataset is 7.00 m, while the median value is 6.00 m. Certainly, given the uneven distribution of measurements, previously discussed, these

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figures should not be considered completely representative for the entire Black Sea and especially not for its deep parts. Some areas with high turbidity, such as those in front of the Danube mouths or the Dnieper-Bug estuary, are highlighted (Figure 1a). Even though the spatial coverage and number of measurements are limited, the unique optical regime of the Azov Sea, where Z_{SD} values usually range between 2.5 m and 3 m, can also be distinguished. However, establishing precise limits for certain areas where waters have similar optical characteristics, such as the Danube's influence zone, is a real challenge. In the north-western region of the Black Sea, where the number of measurements is substantially higher, a gradual change in Z_{SD} can be observed. Brackish waters with lower Z_{SD} values are identified near the river mouths, while more transparent waters are found in the central part of the western basin.

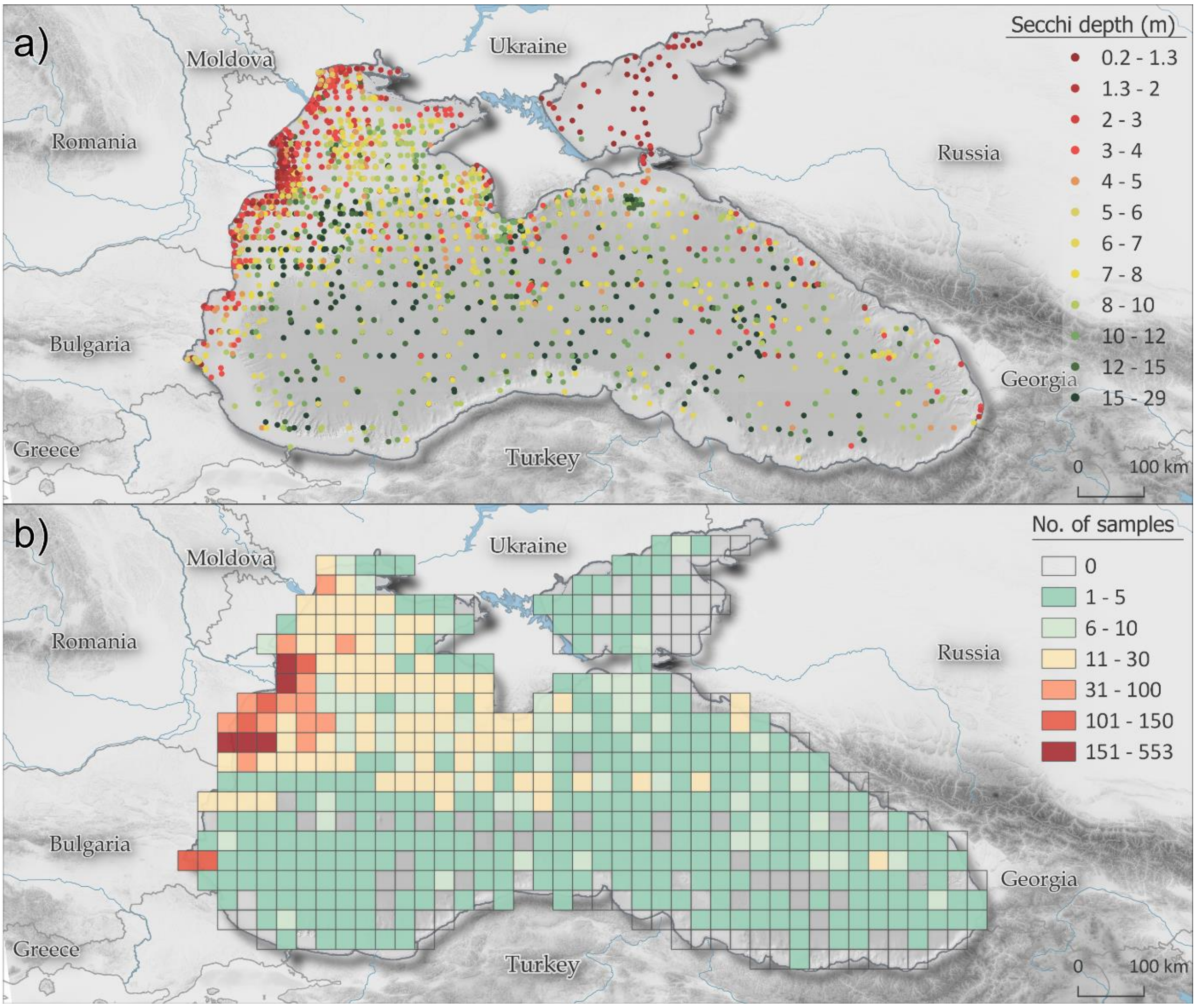

Figure 1: a) Locations of Z_{SD} records in the Black Sea (1960-2016), coloured according to the actual value of each observation; b) number of Z_{SD} measurements for each 30 km x 30 km square grid covering the entire Black Sea (1960-2016)

An overview of the entire Black Sea reveals both similarities and differences in the transparency regime of deep waters in the eastern and western parts. In the central regions of both compartments, similar Z_{SD}, predominantly greater than 10 m (as indicated by the green and dark green points on the map in Figure 1a), can be identified. Sporadic measurements indicating lower water clarity (Z_{SD} between 5 and 10 m) are also observed. A significant difference between the optical characteristics of the eastern and western compartments appears in the less deep waters. As previously mentioned, in the north-western part of the Black Sea, a gradual decrease in Z_{SD} can be observed from the shore toward the open sea. However, despite the low number of measurements, it can be noticed that the same optical characteristics are not encountered in the eastern compartment.

As illustrated in Figure 1b, measurements conducted in the Black Sea during the analysed period do not have a uniform spatial density. In order to highlight the accurate frequency in specific locations eloquently, this study proposes a detailed analysis of the locations where Z_{SD} was recorded. Consequently, each entry from the dataset was assessed to determine the occurrence of observations around every individual point. The total 5100 measurements were taken from 2164 unique locations, since some of them are recurring sampling stations. Out of these 2164, 5 of them were identified to have more than 100 Z_{SD} records (represented by purple dots on the map in Figure 2). These measurements were carried out along a transect perpendicular to the Romanian coastline during field campaigns of the National Institute for Marine Research and Development "Grigore Antipa". Notably, the eastern point of this transect corresponds to the highest number of observations, 234, carried out between 1963 and 1995. Additionally, in 31 other locations there were recorded more than 10 measurements (but less than 101), indicated by yellow dots on the map in Figure 2. Furthermore, there are 531 places in the Black Sea where Z_{SD} observations were conducted more than once between 1960 and 2016. The analysis of measurement frequency for a specific point has revealed another important aspect worthy of mention. A particular situation occurs in the area of Snake Island. A total of 87 observations were identified here, carried out between 2012 and 2013 by the Ukrainian Scientific Centre of Ecology of Sea. Although an initial assessment could indicate these may seem to be open sea records of Z_{SD}, a detailed spatial investigation revealed they were performed from a pier located in the northern part of the island. The Z_{SD} values range from 1.5 m to 8 m. This can be considered a distinctive example of how to inspect in situ data before drawing solid conclusions about its variability. It further illustrates that such measurements require a special assessment of spatial distribution before integrating them into more complex analysis.

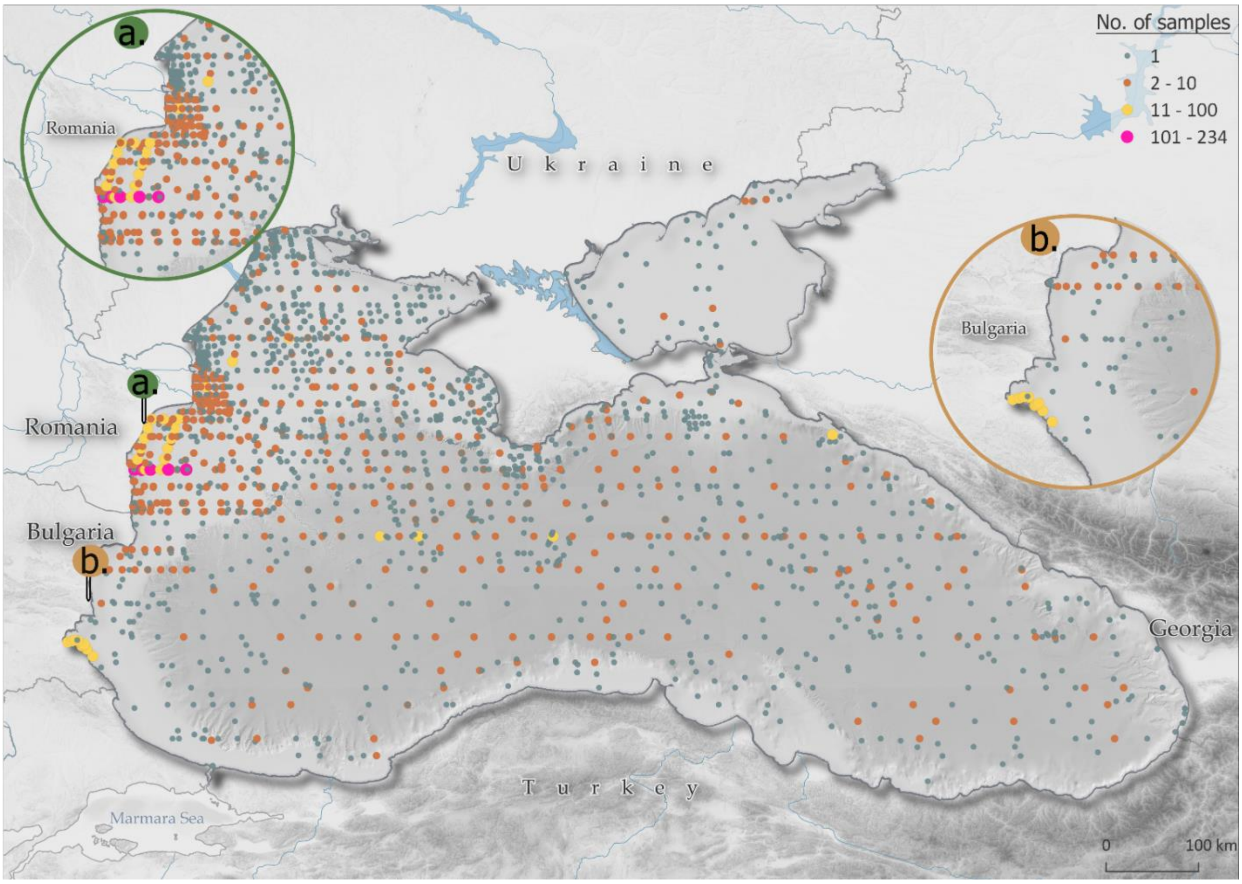

Figure 2: Frequency of Z_{SD} measurements in the Black Sea for single and recurring stations (1960-2016)

Temporal consistency is a crucial aspect to consider for such a vast climatological dataset. In this regard, the number and percentage of measurements available for each decade and month of the year are illustrated in Figure 3. A significant percentage of the entries were collected between 1970 and 1999, most of them, 1797 (35.2%), recorded in the 1990s (as shown on the top row diagrams in Figure 3). The high frequency of measurements during the mentioned decades could be a consequence of the expansion of water quality monitoring programs in the countries bordering the Black Sea. On an annual basis, there is also a non-uniform temporal distribution of data. Nearly one-fifth of the available recordings (19.3%) were performed in May, while the fewest observations occurred during the winter season (December, January, February). These results are likely a consequence of weather and marine conditions, which favour field campaigns between April and October.

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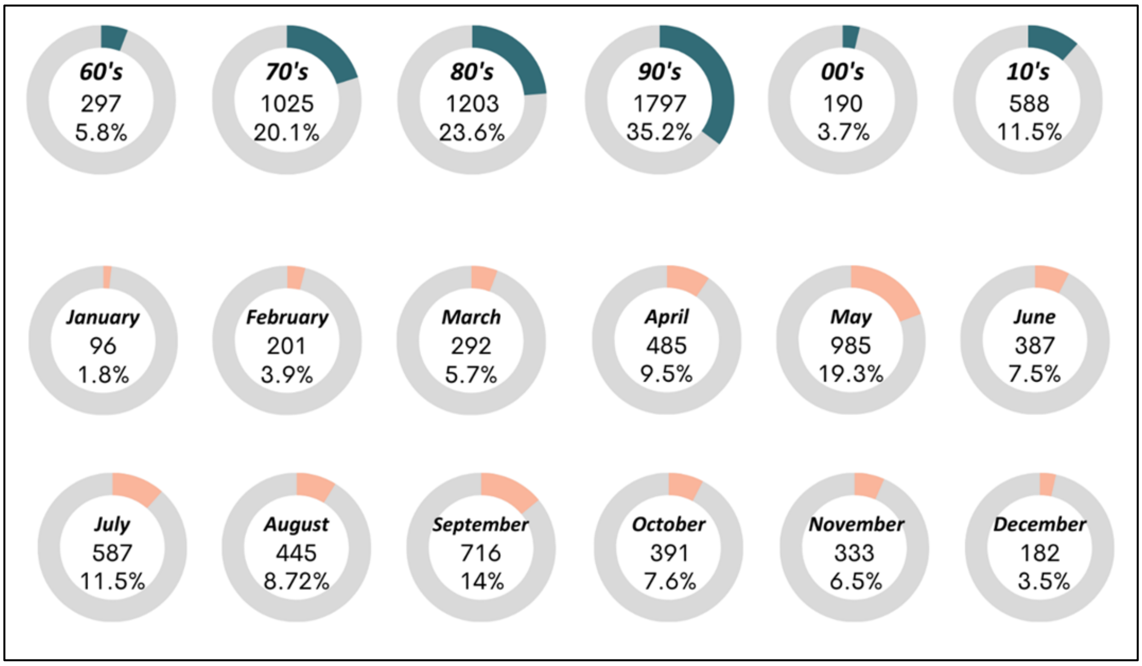

Figure 3: Temporal distribution of ZSD measurements in the Black Sea (1960-2016). Diagrams on the first row illustrate the number and percentage of records for each decade, while the second and third present the statistics for each month of the year

For a more detailed analysis of temporal consistency, a diagram (Figure 4) is used to illustrate the number of in situ measurements taken each month over the analysed interval (1960-2016). This representation provides a clear and detailed view of the temporal distribution and density of the data. A lack of homogeneity across the entire period is observed. Notably, data are either completely absent in certain intervals, such as the early 1960s, or significantly few, as observed between 1995 and 2005, even though there are sporadic months with over 50 or even over 100 measurements. The highest number of ZSD observations carried out during a month (181) was in July 1992, with around 60 of them, held by the Ukrainian Scientific Centre of Ecology of Sea. These are spread almost uniformly across the entire deep part of the Black Sea, except the Azov Sea. Over 150 records were also collected in May 1994 and 1995. Consequently, the in-situ data used for this study has a lack of temporal consistency.

Visual interpretation of water transparency spatial variations based on the Z_{SD} measurement points can sometimes be challenging and inaccurate due to their uneven distribution or overlap in certain areas (Figure 1). To resolve this issue and to obtain a clearer and more consistent picture of the spatial variability of Z_{SD}, a grid system of 30 km x 30 km covering the entire area of interest was empirically defined. The average Z_{SD} of all points falling within each square was calculated (Figure 5). Unlike the map showing the distribution of each station (Figure 1a), the grid-based illustration facilitates a more straightforward understanding of transparency gradients.

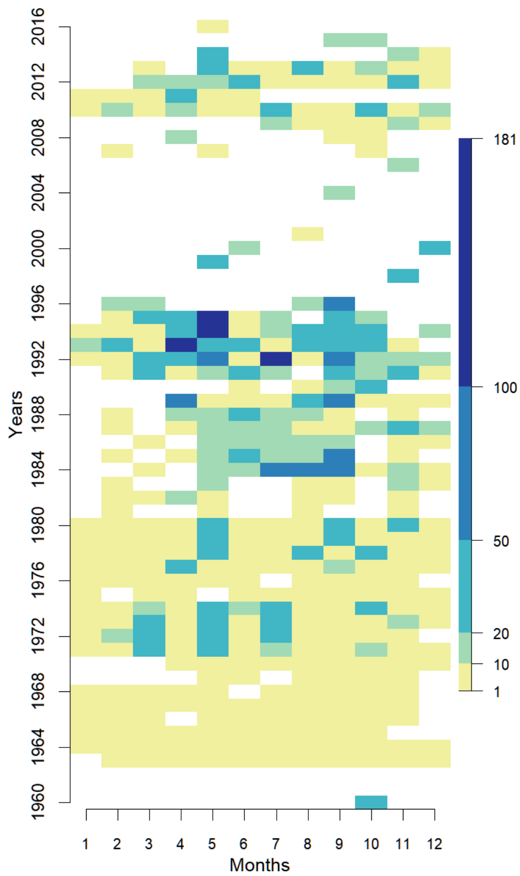

Figure 4: Monthly distribution of the number of available in situ Z_{SD} measurements in the Black Sea (1960-2016)

Representation highlights more eloquently the gradual change in Z_{SD}, from coastal turbid waters in the west and north-west region, featured in red and orange hues, to the clearer waters in the central parts of the Black Sea, depicted in shades of green and yellow. The observations captured in this map align with the existing knowledge concerning the optical properties of waters in this region. Notably, lower Z_{SD} averages are observed in front of the Danube River mouths (between 1.8 m and 2.5 m), where the sediment discharge from the river significantly impacts the water clarity.

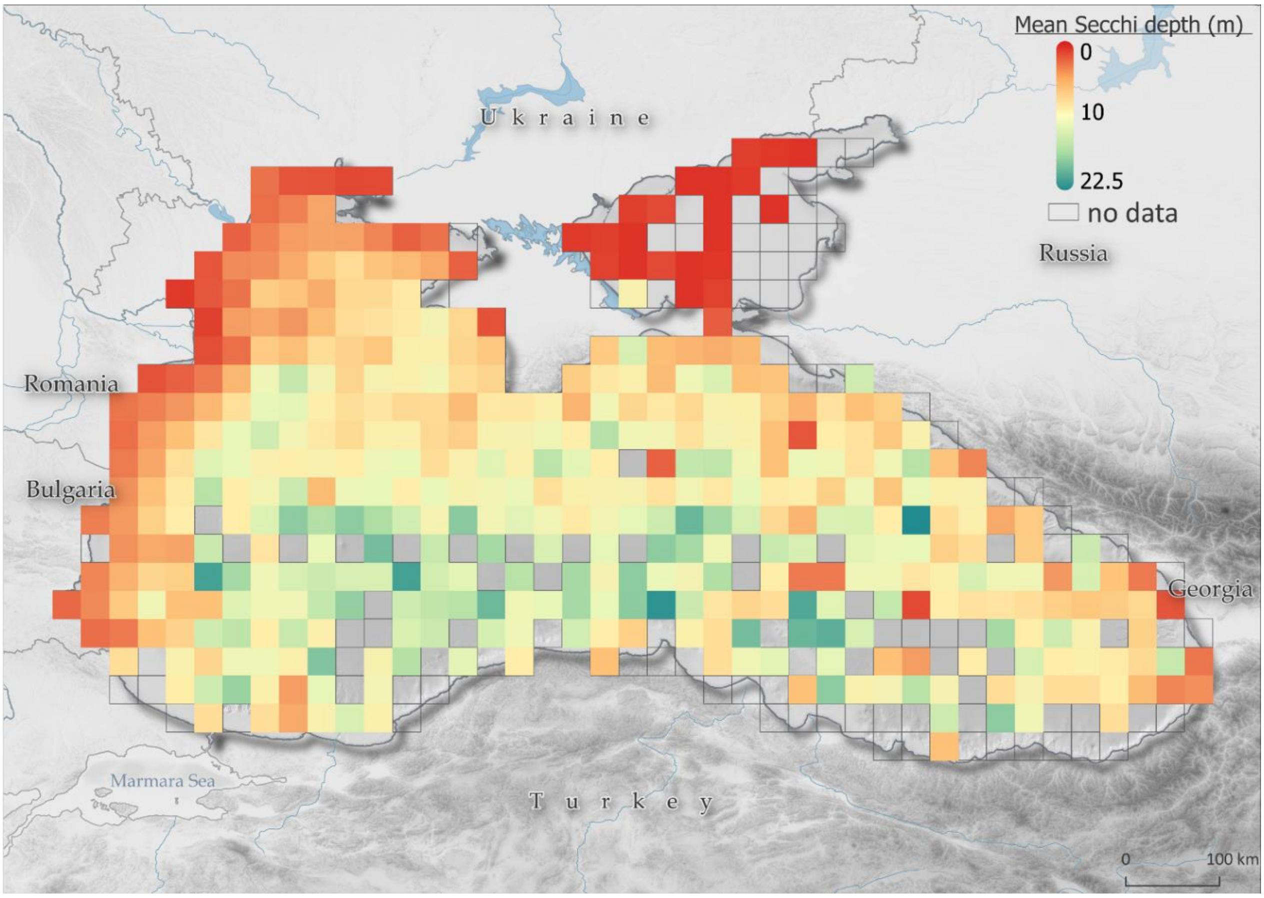

Figure 5: Multiannual mean of ZSD in the Black Sea (1960-2016)

Seasonal variations of Z_{SD} for the entire Black Sea (1960-2016) are illustrated in Figure 6. In addition to these maps, Table 3 presents some brief statistics for each season. An approach that would have involved determining multi-year monthly averages was not feasible due to the low number of measurements in certain months (e.g. 96 in January and 182 in December). Moreover, poor spatial coverage is observed during the entire winter season (Figure 6a). However, maximum water clarity is recorded during autumn (7.36 m) and the minimum throughout the winter (6.47 m).

The absence of winter measurements from the southern part of the Black Sea, coupled with limited data in the eastern region, indicates the conclusions regarding spatial variability of Z_{SD} at the multi-annual level (Figure 4) are applicable only for the other three seasons at basin scale.

It is well-documented that marine environmental conditions influence biological productivity and consequently have an impact on water clarity. Throughout the year, there have been identified two periods when algal blooms reach their peak (Nezlin et al., 1999). Typically, these are known as winter/spring (February-March) and autumn blooms (September-October). The statistics presented in Table 3 also indicate that there is no clear association between the moments of maximum phytoplankton development and variations in the multiannual seasonal means of Z_{SD} illustrated in Figure 6. The lack of correlation between seasonal averages presented in Table 3 and the moment with maximum biological productivity, can also be related to the spatial distribution of the measurements. As already mentioned, almost half of them are located less than 30 km from the shoreline. In these coastal areas, waters are in general optically complex, transparency being primarily affected by the amount of suspended particulate matter.

Unlike spring and autumn, during summer (Figure 6c), in the north-western part of the Blak Sea, the transition from turbid waters in the coastal area to clearer ones located offshore is not gradual and smooth.

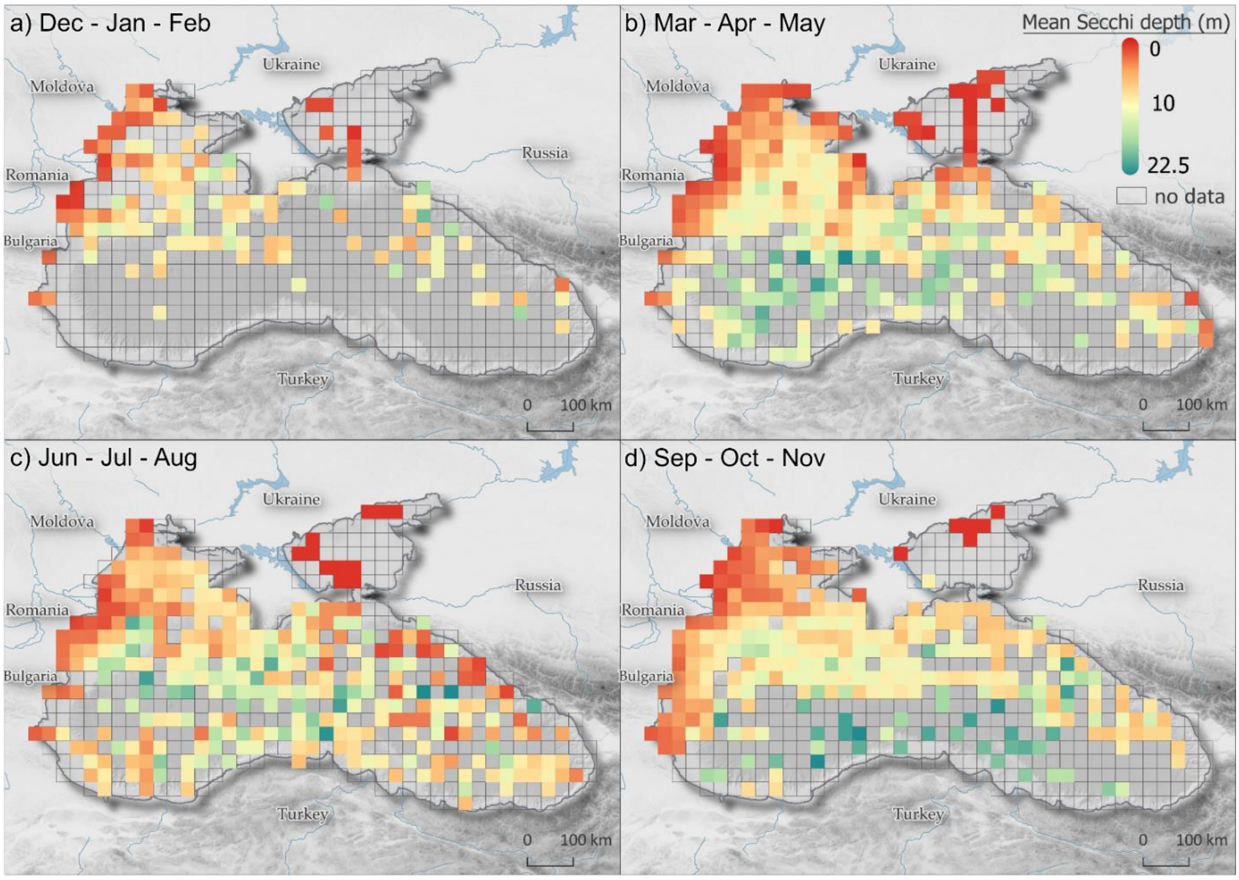

Figure 6: Multiannual quarterly mean of ZSD in the Black Sea (1960-2016) during a) winter (from December to January, b) spring (from March to May, c) summer (June to August and d) autumn (from September to November)

Table 3: Statistics of in situ Z_{SD} measurements in the Black Sea (1960 - 2016)

	Mean Z_{SD} (m)	Median Z_{SD} (m)	N
Winter	6.74	6.00	479
Spring	6.74	5.10	1762
Summer	7.15	6.00	1419
Autumn	7.36	7.00	1440
Annual	7.00	6.00	5100

In central areas of the western compartment, lower Z_{SD} averages are registered (orange squares), with values ranging from 5.5 m to 6.25 m. These regions are bordered to the north and west by less transparent waters (green and light green squares). Although a key factor is challenging to identify, an initial hypothesis would be that the optical properties of the waters in those areas are determined by coccolithophores bloom (Tyrell and Hooligan, 1999). These events are a distinctive feature of the Black Sea, leading to a prominent turquoise colour to the waters during peak development periods and consequently reducing transparency. In the Black Sea's surface layer, the most intense coccolithophore blooms typically occur at the beginning of summer, usually in May and June (Kubryakov et al., 2018).

Conclusions

The current study aimed to define a database integrating historical Z_{SD} measurements, considering all potential sources. Two main initiatives containing vast archives of historical oceanographic observations from the Black Seas were identified. All data were acquired and organized in a standardized database comprising a total of 5100 entries conducted between 1960 and 2016. An illustrative representation of all information in the dataset was proposed using a grid system of 30 km x 30 km covering the entire Black Sea. In such a way, a clear and fluid image of Z_{SD} spatial variations in the area of interest was presented.

The analysis of in situ measurement also focused on three main aspects: distribution, density and frequency (occurrence in the same locations). The proximity to the shoreline for each point was computed revealing that almost half of the observations are located within 30 km from the coastline. Areas with the highest density of data are observed in the north-western part of the Black Sea, while the fewest are found in the south-eastern regions and the Azov Sea (60). The increased frequency of measurements in specific points proves that there could have been a systematic monitoring of water transparency in such locations. Unfortunately, such campaigns were conducted in just a few limited areas of the Black Sea (a transect of points perpendicular to the Romanian shore or observations in the northern part of Snake Island).

To draw reliable conclusions regarding long-time oscillations of Z_{SD}, a dataset with adequate temporal coverage and consistency is required. This study also proposed a preliminary evaluation of these aspects. As demonstrated, field campaigns conducted in the Black Sea between 1960 and 2016 did not uniformly cover the entire period. Furthermore, both the percentage of records for each decade and temporal distribution across every month of the year are also significantly varying. These initial findings provide a solid starting point for future analysis concerning the homogeneity of such a vast climatological in situ dataset.

Previous research focusing on the water transparency of the Black Sea, based on in situ Z_{SD} measurements, has provided insights into the spatio-temporal dynamics of this parameter (Sorokina and Kulygin, 2013; Kukushkin, 2014; Kukushkin, 2018). The preliminary evaluation of the spatial and temporal homogeneity of the dataset used in this study corresponds with these prior findings. The results emphasize that observations regarding the multi-annual and seasonal variations in transparency, based on historical Z_{SD} data, may have limited reliability. Of course, more detailed investigations are necessary to provide conclusive answers in this regard.

Integrating in situ measurements in studies that address spatio-temporal variations of Z_{SD} (or other water quality parameters) proved to be adequate when used to describe field conditions that closely resemble reality. However, this approach is limited to specific areas and may not offer sufficient temporal continuity and consistency. Depending on the duration or frequency of the campaigns, there is also the possibility that it might not provide a sufficiently comprehensive picture of the actual field conditions. Moreover, by its very nature, Z_{SD} is a subjective measurement and this can also lead to reading errors caused by the observer (Pitarch, 2017; Aas et al., 2014; Lee et al., 2015). Thus, handling such a large dataset, covering an extensive geographical area over more than 50 years (1960-2016), requires a cautious interpretation of the results and does not necessarily yield definitive conclusions.

The assumptions presented in the current research regarding the variability of Z_{SD} and the homogeneity of in situ data pertain to the obtained dataset, not to all the measurements conducted over time in the Black Sea. Access to certain observations, such as the one from Odessa National I.I. Mechnikov University or the identification of the ones mentioned by other studies (Vladimirov et al., 1996) would have provided a different spatial and temporal dimension to the dataset and emerging conclusions. Utilizing a historical dataset such as the one presented in this study can describe a general perspective on Z_{SD} dynamics. However, robust conclusions are difficult to draw due to the spatial and temporal heterogeneity. Regular in situ measurements conducted over a long period may be considered adequate for smaller geographic regions.

As preliminary shown in this study, although an in situ dataset can provide information regarding water quality parameters with a high degree of accuracy, the determination can sometimes be a time-consuming process with significant economic cost (Gholizadeh et al., 2016; IOCCG, 2018; Lee et al., 2018). Another limitation is their inability to offer a simultaneous perspective of the spatial distribution, not covering wide areas (providing a value in a specific point). Technological advances in the last decades have led to the development of algorithms used to estimate water quality parameters, including Z_{SD}, from Earth Observation data. Their integration into scientific studies resulted in a significantly enhanced monitoring of water transparency, thereby enabling a thorough characterization of spatial and temporal trends.

Previous studies demonstrated the usefulness of Earth Observation data for monitoring optical parameters in the Black Sea. Twelve years (2003-2014) of daily observations from Moderate Resolution Imaging Spectroradiometer (MODIS) sensors were exploited to calculate turbidity composite products (Constantin et al., 2017), using a previously developed regional algorithm (Constantin et al., 2016). The analysis focused on hourly, monthly, seasonal, annual and multiannual oscillations of turbidity for a region adjacent to the Danube river mouths (Constantin et al., 2017). More recently, a solid regional algorithm for Suspended Particulate Matter (SPM) estimation from Sentinel-3 OLCI data was also developed (Constantin et al., 2024).

In conclusion, the abundance of in situ Z_{SD} historical observations enables the creation of long-time archives of data, capable of providing an inherent image of past conditions in the marine ecosystem. The results presented in this study can also be used as a potential reference for future research that aims to evaluate water transparency in the Black Sea. However, further detailed investigation may highlight that conclusions regarding Z_{SD} variability based on in situ data should be considered carefully and cautiously interpreted due to the temporal and spatial consistency of measurements.

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Author contribution

Conceptualization, I-D. Ș. and S. C.; methodology, I-D. Ș. and S. C..; formal analysis, I-D. Ș.; investigation, I-D. Ș. and S. C.; writing—original draft preparation, I-D. Ș.; writing—review and editing, I-D. Ș., S. C., A. N. and G. A.; graphic and cartographic materials, G. A.

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Conflicts of interest

The authors declare no conflict of interest.

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