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Distribution of suspended and dissolved matter and its absorption properties in the Gulf of Gdańsk (Baltic Sea) in the summer season

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Abstract
Analyses of the spatial and interannual variability of suspended particulate matter (SPM) and chromophoric dissolved organic matter (CDOM) concentrations were carried out in the waters of the Gulf of Gdańsk in the summer season in 2016–2020. Additionally, the absorption properties of those substances were analyzed. The inflowing waters of the Vistula River are characterized by high concentrations of SPM, chlorophyll *a* (Tchl*a*) and CDOM, significantly affecting the absorption properties in the mixture of river and sea waters. The high contribution of particulate organic matter, POM, in the total SPM in the Gulf of Gdańsk (80% on average) indicates high phytoplankton productivity in the summer. High concentrations of pigments characteristic of different size classes of algae and cyanobacteria (fucoxanthin and zeaxanthin, chlorophyll *b*, peridinin and alloxanthin) were recorded, being markers of diatoms, cyanobacteria, green algae, dinophytes and cryptophytes, respectively. Analysis of interannual variability showed changes of SPM, Tchl*a* and CDOM concentrations, depending on volume and direction of the river inflow and weather conditions. The composition of individual pigments changed year to year in a mosaic (heterogeneous) manner. The average contribution of CDOM, phytoplankton and detritus in the total light absorption was determined (at 443 nm – 50%, 34% and 16%, and at 675 nm – 41%, 54% and 5%). Spatial and temporal variability of the light absorption coefficients by suspended particles and CDOM in sea water was examined, and the relationships between the individual light absorption coefficients by sea water components were determined as a function of the dependence on SPM and Tchl*a*.

Keywords
Gulf of Gdańsk (Baltic Sea); Vistula River water distribution; Suspended and dissolved matter; Absorption by particles and CDOM; Taxonomic markers of phytoplankton; Summer season

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1. Introduction

Rivers are the main source of suspended and dissolved anthropogenic matter entering sea basins. In the Gulf of Gdańsk located in the southern region of the Baltic Sea, the Vistula River, the longest river in Poland, plays the largest role, significantly affecting the inflow of suspended particles (Damrat et al., 2013; Szymczak and Burska, 2019) and dissolved organic matter from land (Kowalczuk et al., 2005a). At river mouths, water density gradients cause the river waters to spread out into the sea in a fan-like shape (Wright, 1978; Sagan, 2008). Depending on the wind direction and intensity, the horizontal range of the Vistula River in the Gulf of Gdańsk ranges from 2 to 15 nautical miles from the river mouth, and the vertical range of freshwater ranges from 0.5 to 12 m (Cyberski and Krężel, 1993). The variability of river water flow, including transported suspensions and dissolved substances, depends, among others, on hydrological factors related to the flow rate, sea state and wave movement (Matciak and Nowacki, 1995; Sagan, 2008). In the mixing zone, a hydrological front forms, defined as a transition layer between water masses characterized by different flow velocities and directions (Magnuszewski and Soczyńska, 2001), with notable differences in salinity and temperature. In such variable conditions, the boundary between freshwater and seawater becomes a barrier that limits further movement of suspensions from riverine discharges (Bradtke and Krężel, 1994).

Suspended particles (SPM) in sea water play an impor-

tant role in ecosystem functioning. Suspended matter is a mixture of organic and inorganic matter, the composition of which varies spatially and temporally depending on physical and biogeochemical factors (D'Sa and Ko, 2008; Eleveld et al., 2014; Meler et al., 2023). The concentration of suspended organic particles indicates the productivity of phytoplankton. The concentration of SPM in the Gulf of Gdańsk is higher than in the Baltic Proper, mainly due to the constant inflow of matter from the Vistula River and high plankton productivity (Cyberska and Krzymiński, 1988) in this area. The absorption properties of suspended particles vary significantly depending on their type. The light absorption coefficient by phytoplankton ($a_{ph}(\lambda)$) results from the composition of pigments contained in the algal cells and has two main maxima in the chlorophyll and carotenoid bands (approx. 400–490 nm and 660–690 nm). The light absorption spectrum for the detritus and mineral particles ($a_d(\lambda)$) is characterized by a monotonic decrease with increasing wavelengths of an exponential shape. The relationships between the coefficients $a_{ph}(\lambda)$ and $a_d(\lambda)$ and the concentration of suspended substances in water across different water bodies are the subject of many studies (e.g.: Babin et al., 2003; Woźniak et al., 2011, 2022; Meler et al., 2016 a,b, 2017, 2018; Castagna et al., 2022).

The absorption properties of the Gulf of Gdańsk waters are also greatly influenced by chromophoric dissolved organic matter (CDOM), which is delivered by the Vistula River (Kowalczuk, 1999; Kowalczuk et al., 2006, 2015). The absorption effect of CDOM, $a_{\mathrm{CDOM}}(\lambda)$, is most visible in the UV and blue radiation range, and then decreases exponentially with increasing wavelength.

The waters of the southern part of the Baltic Sea, including the Gulf of Gdańsk, are characterized by seasonal phytoplankton blooms. The principal factor affecting the variability of the inherent optical properties of Baltic waters in the euphotic zone is the seasonal cycle of biological activity (Sagan, 1991; Olszewski et al., 1992; Kowalczuk et al., 1999, 2005a,b; Meler et al., 2016a,b). This cycle is governed by physical, biological and chemical processes, which cause the biomass and species composition to vary with time. As a consequence, there are three main phytoplankton blooms: a spring bloom of cryophilous diatoms, which then transforms into a bloom of dinoflagellates; a summer bloom of cyanobacteria; and an autumn bloom of thermophilous diatoms (Witek and Pliński, 1998; Wasmund et al., 2001; Thamm et al., 2004). The spring blooms typically occur from early March to May, summer blooms from July to August, and the autumn ones from September to October (Wasmund et al., 1996; Wasmund and Uhlig, 2003; Thamm et al., 2004). In winter, the biological activity is minimal.

The maximum river runoff occurs at the turn of April and May, and it often coincides with the spring bloom of phytoplankton initiated by increasing air and water temperature and higher sunlight exposure. River waters carry large amounts of dissolved organic matter (DOM) and nutrients that enhance phytoplankton blooms, which reduces water transparency. Periodic summer floods, following heavy rainfall and strong winds, may trigger upwelling events. These events affect the optical properties of waters in the coastal zone and Gulf of Gdańsk (Olszewski et al., 1992; Kowalczuk, 1999; Sagan, 2008). This study focuses on the summer season, which is less known in terms of the distribution of suspended and dissolved particles in the profile from the mouth of the Vistula River to the depths of the Gulf of Gdańsk, with limited knowledge about their absorption properties compared to other seasons regularly monitored during research cruises. Another important aspect of analyzing the summer season was the attempt to investigate the occurrence of cyanobacteria, which in the Baltic Sea appear only in this season (Kahru and Elmgren, 2014; Kahru et al. 2020; Konik et al., 2023). The main objective of the study was to determine the variability of Tchl*a*, SPM concentrations and absorption properties of suspended particles and CDOM in the Gulf of Gdańsk in the summer seasons of 2016–2020. The specific objectives included: (1) determination of the distribution of Tchl*a* and SPM concentrations in the profile from the Vistula River mouth to the center of the Gulf of Gdańsk, including interannual variability, (2) determination of the variability of the absorption properties of suspended particles, including detritus and phytoplankton and CDOM in the profile from the Vistula River mouth to the center of the Gulf of Gdańsk, including interannual variability.

This type of study is crucial for understanding the ecological processes in the Gulf of Gdańsk, particularly the impact of the Vistula River on the coastal environment. The Vistula is a major river and its discharge significantly affects the water quality and biological activity in the Gulf of Gdańsk. That it is increasingly important to develop seasonal climatologies of biological and bio-optical properties of coastal waters to facilitate ecosystem modelling and also to monitor for climate-driven changes in the southern region of Baltic Sea, especially in the Gulf of Gdańsk. The presented results can be used to improve remote sensing algorithms, adapting them to the unique optical conditions of the Baltic Sea. Analysis and characterization of fine-scale variability of optical properties of Baltic waters, especially in the Gulf of Gdańsk, will allow for better determination of the impact of these changes on the quality of remote sensing measurements and support the calibration and validation of Baltic Sea remote sensing algorithms.

2. Material and methods

2.1 Description of study area and sampling procedures

Empirical data were collected in the Gulf of Gdańsk (Baltic Sea) between 2016 and 2020 during 15 one-day research cruises carried out in the summer season, from June to September. These cruises were carried out on board the

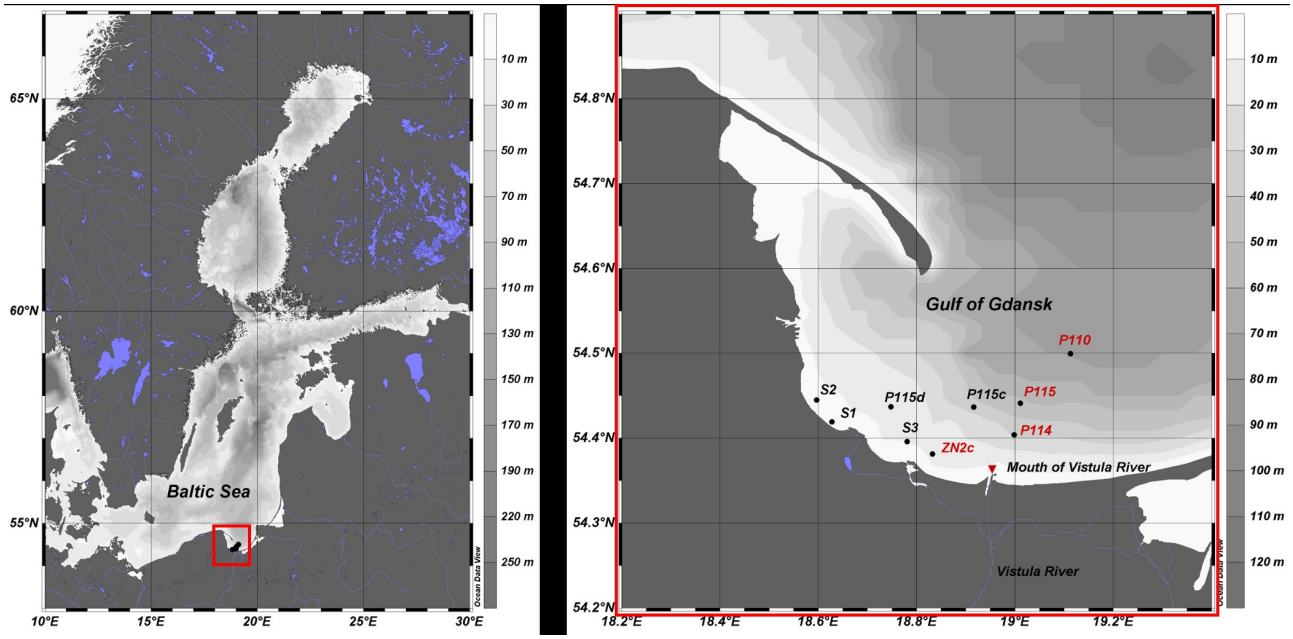

Figure 1. Location of measurement stations (permanent monitoring stations marked in red font, 'the other' stations marked in black font). The inverted red triangle indicates the mouth of the Vistula River.

m/y Sonda II operated by the Institute of Oceanology of the Polish Academy of Sciences (IOPAN), and focused mainly on four stations with varying optical properties ZN2c, P114, P115 and P110 (Figure 1, font in red). These stations were located from the mouth of the Vistula towards the central part of the Gulf of Gdańsk and were selected due to their location, showing the distribution of river waters, which significantly influences the biogeochemical and optical properties of sea waters. Additionally, measurements were carried out in 2018 and 2020 at several other stations in the Gulf of Gdańsk: S1, S2, S3 and P115c and P115d. These supplementary stations were selected due to notable phytoplankton blooms observed there, and because they do not overlap with regular monitoring stations, they constitute a separate data set and are referred to as 'the other' stations in this study. Table 1 lists the stations and measurements dates. Figure 2 provides satellite images of the study area, obtained from the Sentinel-2 satellite via sentinel-hub.com website. Most of the images do not exactly match the measurement days (due to image unavailability or cloud cover); available images from 2–3 days before or after the measurements are shown. The images show composition with the use of the filter Ulyssys Water Quality Viewer (Sentinel Hub EO Browser Custom Script for qualitative views of aquatic chlorophyll and suspended sediment concentrations, Zlinshky and Padányi-Gulyás, 2020).

At each measurement site, physical parameters (temperature and salinity) and water transparency were recorded, and approximately 20 L of surface seawater were collected. Temperature and salinity of water were measured immediately after collection into the tank using a Schott Instruments Handylab LF12/STE salinometer. Water transparency was determined with a Secchi disk (ZSD, [m]). Water filtration and laboratory measurements of concentrations of Tchl$a$, and accessory pigments (AP), SPM divided into organic (POM) and inorganic (PIM) fraction, coefficients $a_p(\lambda)$, $a_d(\lambda)$, $a_{ph}(\lambda)$, and $a_{\mathrm{CDOM}}(\lambda)$ were performed in the laboratory at the Institute of Oceanology of the Polish Academy of Sciences in Sopot. A total of 58 sets of data from monitoring stations and 'the other' stations were collected.

2.2 Measurements of parameters characterized of suspended particulate matter

The concentrations of SPM (g m^{-3}), POM, and PIM were determined using the gravimetric method and the loss-on-ignition technique (Pearlman et al., 1995; Woźniak et al., 2018) according to the methodology described in details in Meler et al. (2023). To determine SPM, POM and PIM concentrations, measured volumes of seawater samples (from 10 to 1150 mL depending on the content of suspended matter in the sample) were passed through Whatman glass filters (GF/F, 25 mm diameter, nominal retention of particles with sizes down to 0.7 µm) that had been pre-combusted (for 4.5 h at 450°C), rinsed with clean, deionized water, then dried and weighed using a scale accurate to 0.01 mg. After the seawater samples had been filtered, each filter was rinsed with at least 30 mL of clean, deionized water to prevent the accumulation of sea salt on the filter surface. The filters were then dried (for 24 h at 60°C), stored in low humidity conditions, and reweighed. The next treat-

Table 1. List of measurement stations and days in 2016–2020.

Station	Coordinates	Depth [m]	Distance from Vistula [km]	Date of measurements
Permanent monitoring stations				
ZN2c	18.8325 E 54.3813 N	~10	~8.5	2016: 28 June; 25 August;
P114	18.9984 E 54.4039 N	~26	~4	2017: 12 July; 20 July; 28 August
P115	19.0109 E 54.4411 N	~52	~9	2018: 27 June; 19 July; 23 August
P110	19.1132 E 54.4995 N	~69	~16	2019: 19 July; 22 August
				2020: 4 June; 17 June 10 July; 17 August*
'The other' stations				
S1	18.6277 E 54.4193 N	<10	~22	
S2	18.5965 E 54.4450 N	<10	~26	2018: 30 July
S3	18.7810 E 54.3957 N	<10	~13	
P115c	18.9163 E 54.4365 N	~40	~9.5	2020: 17 August
P115d	18.7480 E 54.4367 N	~15	~14.5	

* only stations Zn2c and P115.

ment involved combusting the filters with the collected suspended particles (4.5 h at 450°C) and reweighing them. The SPM concentration was calculated from the weight difference of filters before and after filtration, while the POM concentration was calculated from the weight difference before and after combustion. PIM concentration was derived by subtracting POM from SPM, with SPM and POM concentration values corrected based on the regularly performed reference filters measurements. Measurements precision for 95% of the triplets of samples was below 15%, and for all data sets the average was 6%.

Total concentrations of chlorophyll *a*, which is the sum of chlorophyll *a*, optical isomers of chlorophyll *a* and unidentified derivatives of chlorophyll *a*, (Tchl*a* [mg m^{-3}]), and accessory pigments, total content of chlorophyll *b* and its derivatives (Tchl*b*), chlorophyll *c* and its derivatives (Tchl*c*), total content of photosynthetic carotenoids (PSC), content of photoprotective carotenoids (PPC), [mg m^{-3}] were determined by reversed-phase high-performance liquid chromatography (RP-HPLC). For pigment analysis, specific volumes of seawater (from 15 mL to 1150 mL) were filtered through Whatman glass filters (GF/F, 25 mm). Filters with suspension were stored in liquid nitrogen or in deep-freeze conditions until analysis. Extraction of dyes from algal cells was performed using 90% acetone by mechanical grinding and incubated for 2 h in darkness. Then the extracts were purified and subjected to chromatographic analyses following the methodology described by Stoń and Kosakowska (2002) and Stoń-Egiert and Kosakowska (2005).

2.3 Measurements of light absorption coefficients

The measurements of the absorption coefficients of light by suspended particles (a_p), including detritus (a_d) and phytoplankton (a_{ph}) were performed using a Perkin-Elmer Lambda 650 spectrophotometer equipped with an integrating sphere with a diameter of 15 cm. Whatman filters (GF/F, 25 mm) were used for the analyses, through which 5 mL to 150 mL of seawater was filtered. The filters with the suspension were stored in liquid nitrogen or in deep-freeze conditions until the measurements. The spectra of the absorption coefficients of light were measured in the spectral range of 290–860 nm according to the methodology described by Tassan and Ferrari (1995, 2002) and Woźniak et al. (2011). Transmission and reflectance (T-R) measurements were performed for filters with suspension and for the same filters bleached with 2% sodium hypochlorite $NaClO_2$ (Meler et al., 2020). In order to correct the optical path extension of light incident on the filter with suspension in relation to the same suspension in water, the so-called beta factor proposed by Stramski et al. (2015) was applied. This allowed to determine the spectra of the light absorption coefficient by all particles ($a_p(\lambda)$), as well as the absorption by bleached and mineral particles, conventionally designated as detritus ($a_d(\lambda)$). The light absorption coefficients by phytoplankton pigments ($a_{ph}(\lambda)$) were then calculated as the difference between $a_p(\lambda)$ and $a_d(\lambda)$ coefficients.

Seawater for the determination of light absorption coefficients of CDOM ($a_{\mathrm{CDOM}}(\lambda)$ (m^{-1})), underwent two-stage filtration. Initial filtration was performed using Whatman filters (GF/F, 47 mm) with nominal pores of 0.7 µm, followed by filtration through Sartorius acetate membrane filters (47 mm) with 0.2 µm pore size. Until the analyses, the filtrate was stored in amber bottles at +4°C. Measurements of $a_{\mathrm{CDOM}}(\lambda)$ were performed spectrophotometrically using a Perkin Elmer Lambda 650 spectrophotometer, following procedures described by Kowalczuk et al. (2015). Measurements were performed in the spectral range of 200–700 nm in 10 cm quartz cuvettes. Deionized water was used as a reference. The optical density OD(λ) was converted to the absorption coefficients of CDOM by multiplying OD(λ) by the factor 2.303 and then dividing by the optical path length l (m). Finally, the spectra were corrected for residual scattering according to Kowalczuk et

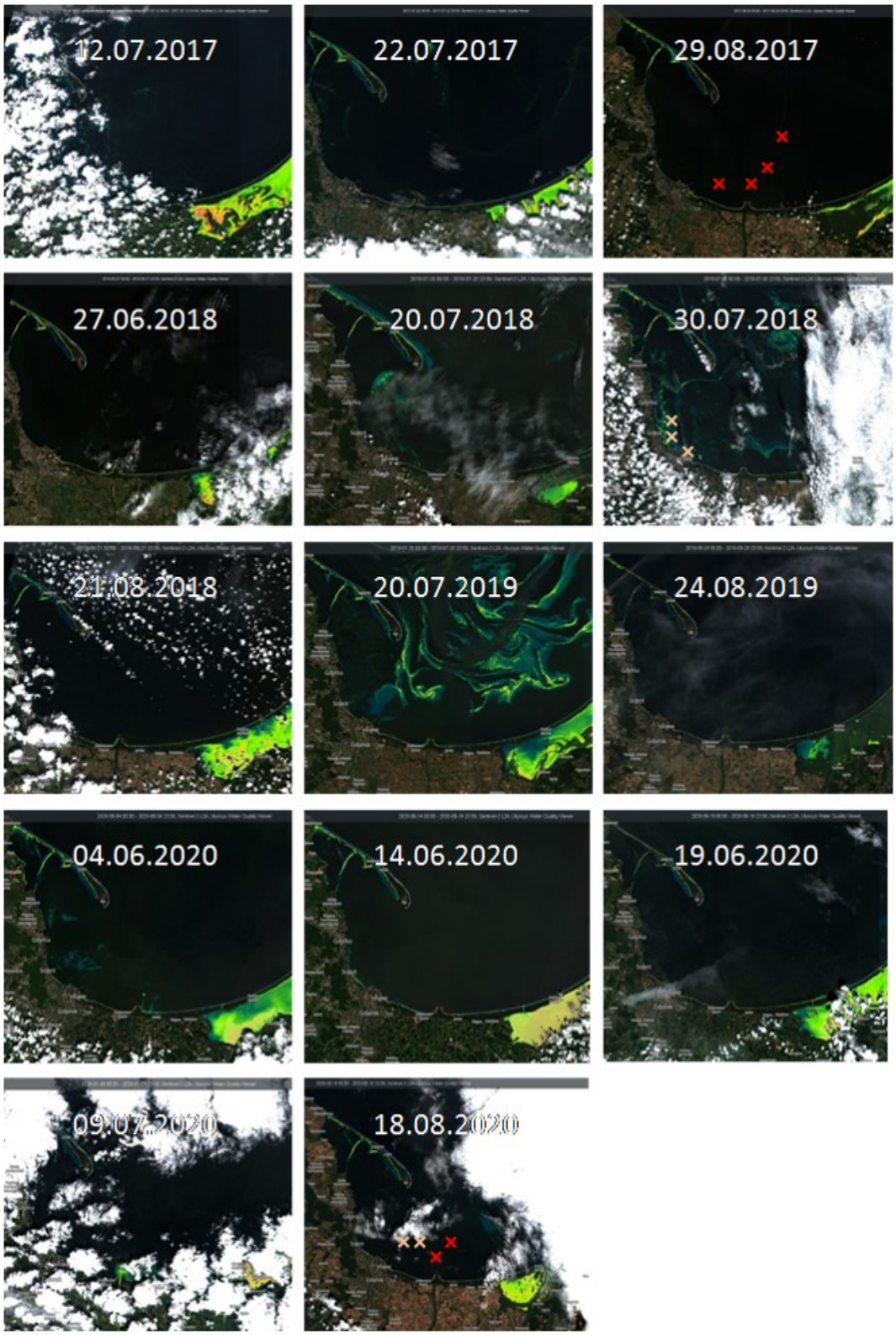

Figure 2. Satellite images of the Gulf of Gdańsk in natural colors from available measurement days or preceding or following days obtained from the sentinel-hub.com website with a filter Ulyssys Water Quality Viewer (sedimentation and chlorophyll *a* content). Red crosses show our monitoring measurement stations, cream crosses show stations with observed phytoplankton blooms.

al. (2006). The slope coefficients of the CDOM absorption spectra in the 300–600 nm range were calculated using the nonlinear least squares approximation in Matlab R2013 (Stedmon et al., 2000; Kowalczuk et al., 2006).

3. Results

3.1 Physical and biogeochemical properties of suspended matter in the summer season

The analyzed data set reveals significant variability of physical and biogeochemical parameters characterizing suspended matter in seawater. Figure 3 illustrates the variability ranges of salinity, temperature, and transparency of seawater measured using a Secchi disc, in the Gulf of Gdańsk from 2016 to 2020 ($n = 58$). During this period, salinity varied from 0.8 to 7.8, temperature ranged between 13.0°C and 26.1°C, while water transparency varied from 1.0 m to 5.5 m. Monitoring measurements were performed at four stations: ZN2c ($n = 14$), P114 ($n = 13$), P115 ($n = 14$), and P110 ($n = 13$). In late July 2018, an abundant phytoplankton bloom was observed in the coastal zone of the Gulf of Gdańsk, and measurements were performed at three additional stations: S1, S2, S3. In mid-August 2020, a bloom of cyanobacteria and macroalgae occurred, and additional measurements were performed at stations P115c and P115d and two monitoring stations: ZN2c and P114. Stations other than the monitoring stations are hereafter referred to as 'the other' (five in total). Satellite images (Figure 2) indicate a significant bloom around July 20, 2019, however, the measurements taken on July 19 did not capture this bloom.

The highest salinity variability was observed at stations ZN2c and P114 (from 0.8 to 7.7), located the closest to the mouth of the Vistula River, while station P110 (7.1–7.8), located in the central Gulf of Gdańsk, showed the least variability. Salinity at the remaining stations varied from 4.4 to 7.5, reflecting the influence of the Vistula River discharge. Similar variability was observed in the individual measurement seasons across the years 2016–2020. Temperature variability, both temporally and spatially, was characterized by similar changes as salinity. The highest water temperatures were observed at 'the other' stations, with a general decrease in temperature from the Vistula River mouth to the center of the Gulf of Gdańsk. However, in 2018 and 2019, average water temperature at the analyzed stations was relatively uniform at around 20°C at the monitoring stations and approximately 26°C at 'the other' stations (S1, S2, S3).

Table 2. Ranges of variability of SPM, POM, PIM, and Tchla concentrations and selected pigments: fucoxanthin (fuco), peridinin (peri), alloxanthin (allo), 19′hex-fucosanthin (19′hex), chlorophyll *b* (Tchl*b*), and zeaxanthin (zea), as well as relative proportions of POM/SPM, Tchl*a*/SPM, along with means and standard deviations, calculated for all data.

Quantity	Average ± SD	Median	Minimum-maximum
SPM [g m^{-3}]	12.2 ± 40.1	4.11	0.69–275.7
POM [g m^{-3}]	10.9 ± 38.9	3.27	0.37–265.6
PIM [g m^{-3}]	1.35 ± 1.72	0.74	0-10.1
Tchl*a* [mg m^{-3}]	21.3 ± 52.5	7.87	0.92–350.6
Fuko [mg m^{-3}]	4.29 ± 15.2	0.59	0.02–111
Peri [mg m^{-3}]	0.28 ± 0.48	0.13	0.004–2.30
Allo [mg m^{-3}]	0.22 ± 0.25	0.14	0.01–1.29
19′hex [mg m^{-3}]	0.90 ± 0.94	0.38	0.05–2.62
Tchl*b* [mg m^{-3}]	0.95 ± 1.01	0.56	0.04–5.19
Zea [mg m^{-3}]	1.66 ± 2.90	1.08	0.18–18.45
POM/SPM	0.8 ± 0.13	0.79	0.53–1
Tchl*a*/SPM	0.0027 ± 0.0037	0.002	0.0002–0.0278

Table 2 presents the concentration values of suspended particulate matter (SPM), organic (POM) and inorganic (PIM) particulate matter, as well as the concentrations of chlorophyll *a*, Tchl*a*, and selected pigments considered as diagnostic markers for phytoplankton taxonomic groups assigned to three main size classes defined as microplankton, nanoplankton and picoplankton: fucoxanthin (fuco) ($n = 58$), peridinin (peri) ($n = 35$), chlorophyll *b* (Tchl*b*)

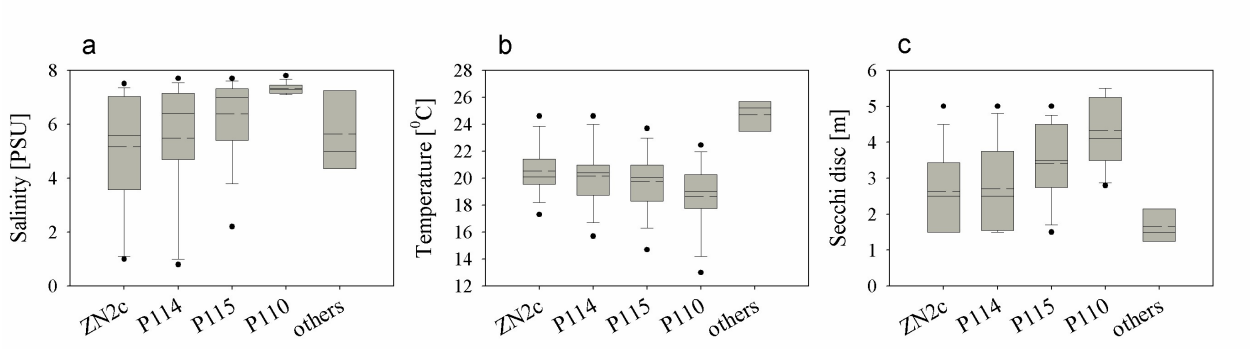

Figure 3. Ranges of variability of salinity, temperature and water transparency in the summer season in 2016–2020, at the analyzed water stations of the Gulf of Gdańsk (others-S1, S2, S3, P115d, P115c). Boxes show the range from the 25th to the 75th percentile, whiskers between the 10th and 90th percentile. The straight line indicates the median, the dashed line the mean, and the dots show the minimum and maximum values.

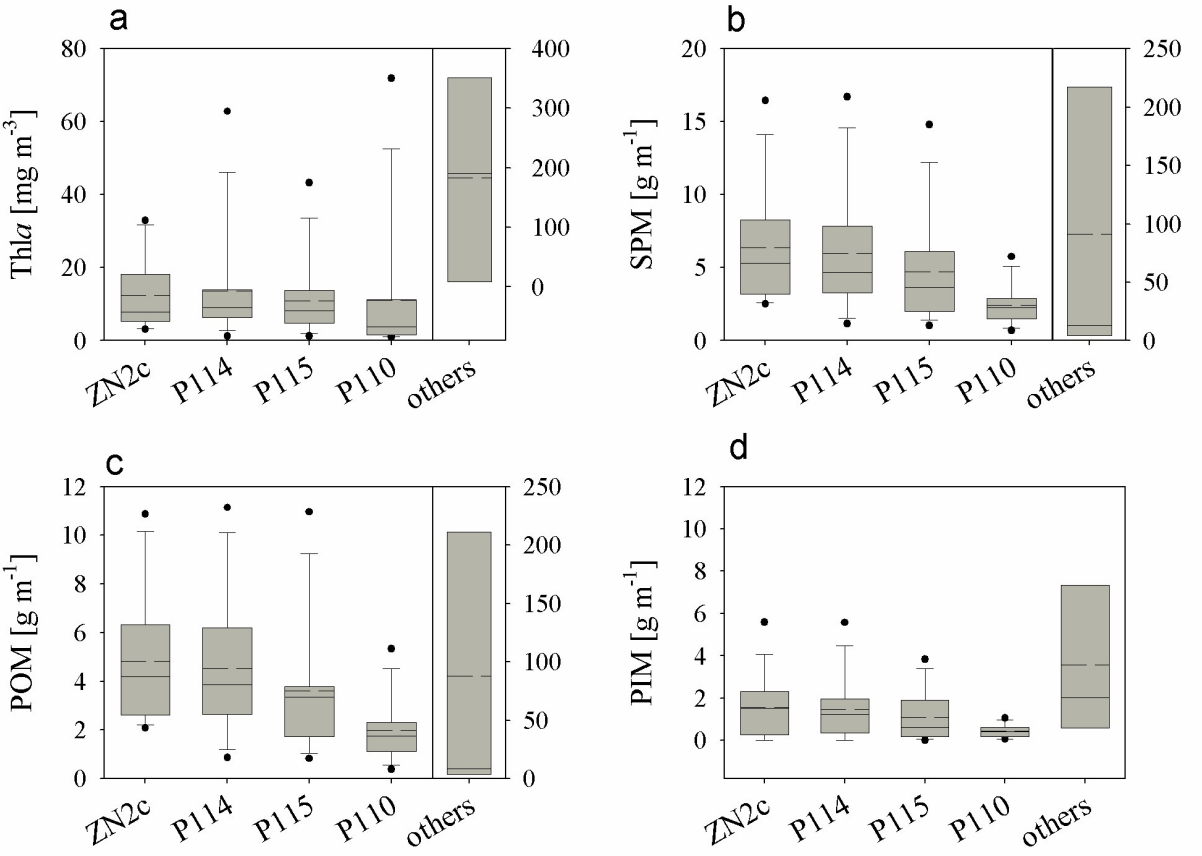

Figure 4. Ranges of variability of Tchl*a* (a), SPM (b), POM (c) and PIM (d) concentrations in the summer season in 2016–2020 at the analyzed water stations of the Gulf of Gdańsk. For 'the other' stations: S1, S2, S3, P115d, P115c, the right axis of values applies. Only in the case of PIM the scale is the same for all stations. Boxes show the range from the 25th to the 75th percentile, whiskers between the 10th and 90th percentile. The straight line indicates the median, the dashed line the mean, and the dots shows the minimum and maximum values.

($n = 57$), alloxanthin (allo) ($n = 55$), zeaxanthin (zea) ($n = 48$) and 19′hex-fucoxanthin (19′hex) ($n = 6$), 19′but-fucoxanthin (19′but) was not identified in the analyzed data set. Additionally, the table displays ranges of relative POM/SPM and Tchl*a*/SPM concentrations.

Concentrations of Tchl*a* and SPM in the summer seasons for all data in the years 2016–2020 varied over 3 orders of magnitude (Figure 4). In the case of Tchl*a*, concentrations ranged from 0.92 to 350.6 mg m^{-3}, with an average of 21.3 mg m^{-3}, and the highest Tchl*a* values were obtained during the phytoplankton bloom in 2018 at the closest landward stations S1, S2, and S3. The ranges of SPM and POM were 0.69–275.7 g m^{-3} (average: 12.2 g m^{-3}) and 0.37–265.6 g m^{-3} (average: 10.9 g m^{-3}), respectively.

Figure 5 shows the variability of the average values of Tchl*a*, SPM and POM at stations along the profile from the mouth of the Vistula River to the central Gulf of Gdańsk and at 'the other' stations from 2016 to 2020. The year-to-year variability of chlorophyll, SPM and POM concentrations at the monitoring stations and the other stations highlights distinct differences among individual years, which is related to weather conditions and the amount of river water inflow to the Gulf of Gdańsk. For example, at station ZN2c, located the closest to the mouth of the Vistula River, high average chlorophyll *a* concentrations occurred in 2017, 2018 and 2020, and the lowest in 2019. Station P114 showed a high average Tchl*a* concentration in 2020, which was caused by the phytoplankton bloom recorded at that time. At station P110, located in the center of the Gulf of Gdańsk, the highest average Tchl*a* concentration was observed in 2016. It can also be noted that high average Tchl*a* concentration did not always coincide with high average SPM concentrations.

Figure 6a–b shows the relationships of Tchl*a* vs. SPM and POM vs. SPM concentrations for the analyzed data set, divided into the main monitoring stations (ZN2c, P114, P115, and P110) and 'the other' stations, including stations S1–S3 with recorded phytoplankton blooms in 2018. The lowest Tchl*a* vs. SPM concentrations were observed at station P110 (cyan points), the farthest from the Vistula

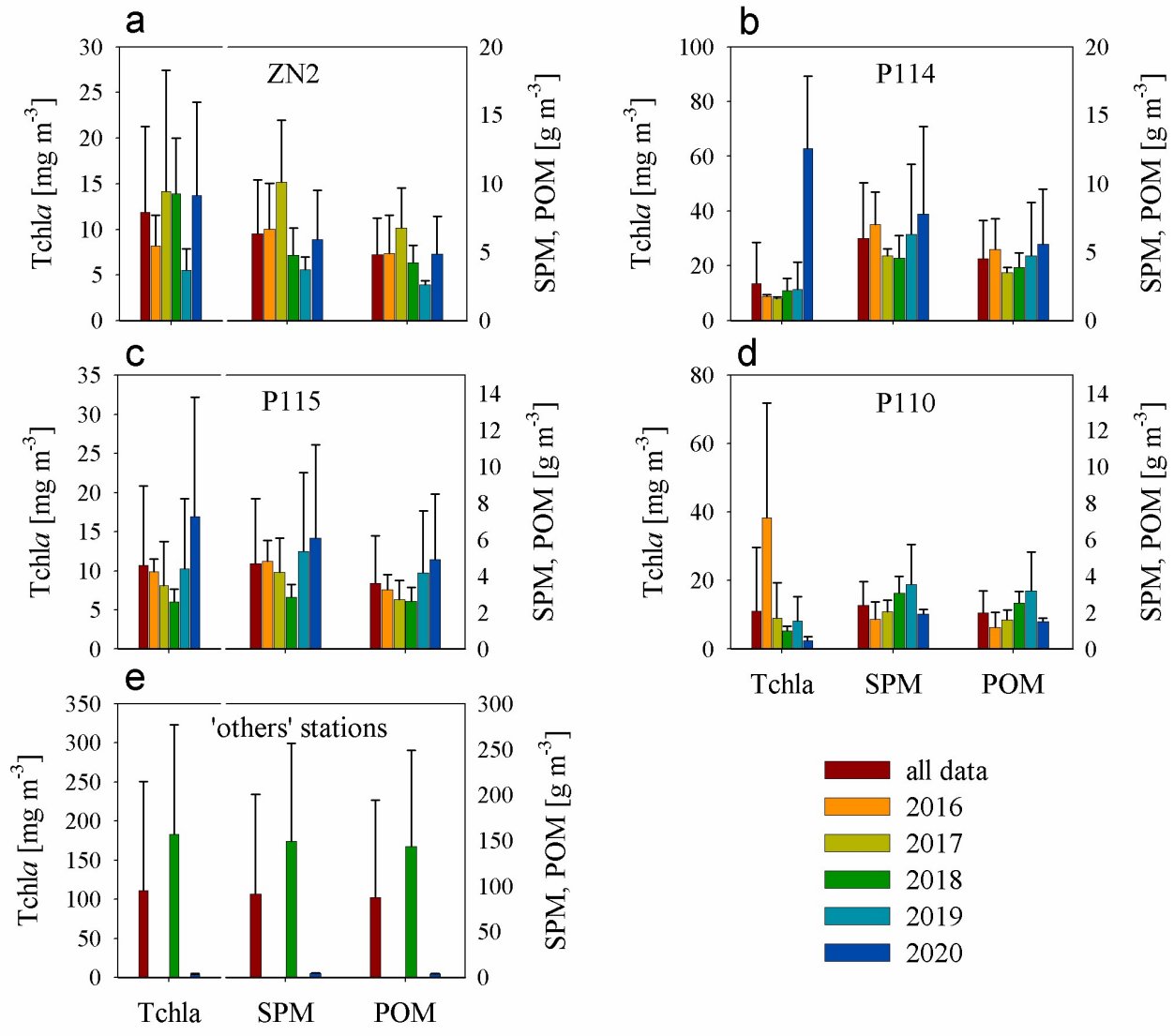

Figure 5. Variability of mean concentrations of Tchl*a*, SPM and POM for all data and in individual years at the analyzed water stations of the Gulf of Gdansk: ZN2 (a), P114 (b), P115 (c), P110 (d), 'the other' stations (e).

River mouth, while higher concentrations of both Tchl*a* and SPM were observed closer to the Vistula River mouth (blue, light green, and dark green points). The highest values were observed at stations S2 and S1 (black points). A similar pattern is evident in the POM vs. SPM relationship, with lower values observed at greater distance from the Vistula River mouth. The POM vs. SPM relationship in the summer season is shown in Figure 6b, and the exponent of 1.009 indicates that this is practically a linear relationship.

Figure 6c shows the proportion of organic matter in the total mass of SPM (POM/SPM ratio) in the Gulf of Gdańsk. The POM/SPM ratio can vary from 0 (100% mineral suspension) to 1 (100% organic suspension). The analyzed data set was divided into 5 classes, reflecting changes in particle composition. POM/SPM values varied from 0.53 to 1, indicating a predominance of organic particles in the analyzed data set. The average POM/SPM ratio was 0.80 ± 0.13.

The pigment composition of phytoplankton cells and their mutual proportions are characteristic of different classes of algae and cyanobacteria. The qualitative and quantitative proportions of pigments differ even in cells of organisms belonging to the same class (Rowan, 1989; Wright et al., 1991). Some quantitatively dominant carotenoids are considered as taxonomic markers of phytoplankton. Figure 7 shows the variability of these taxonomic marker pigments observed in the Gulf of Gdańsk in the summer season (2016–2020), divided into monitoring stations and others. It is important to note the different scales on

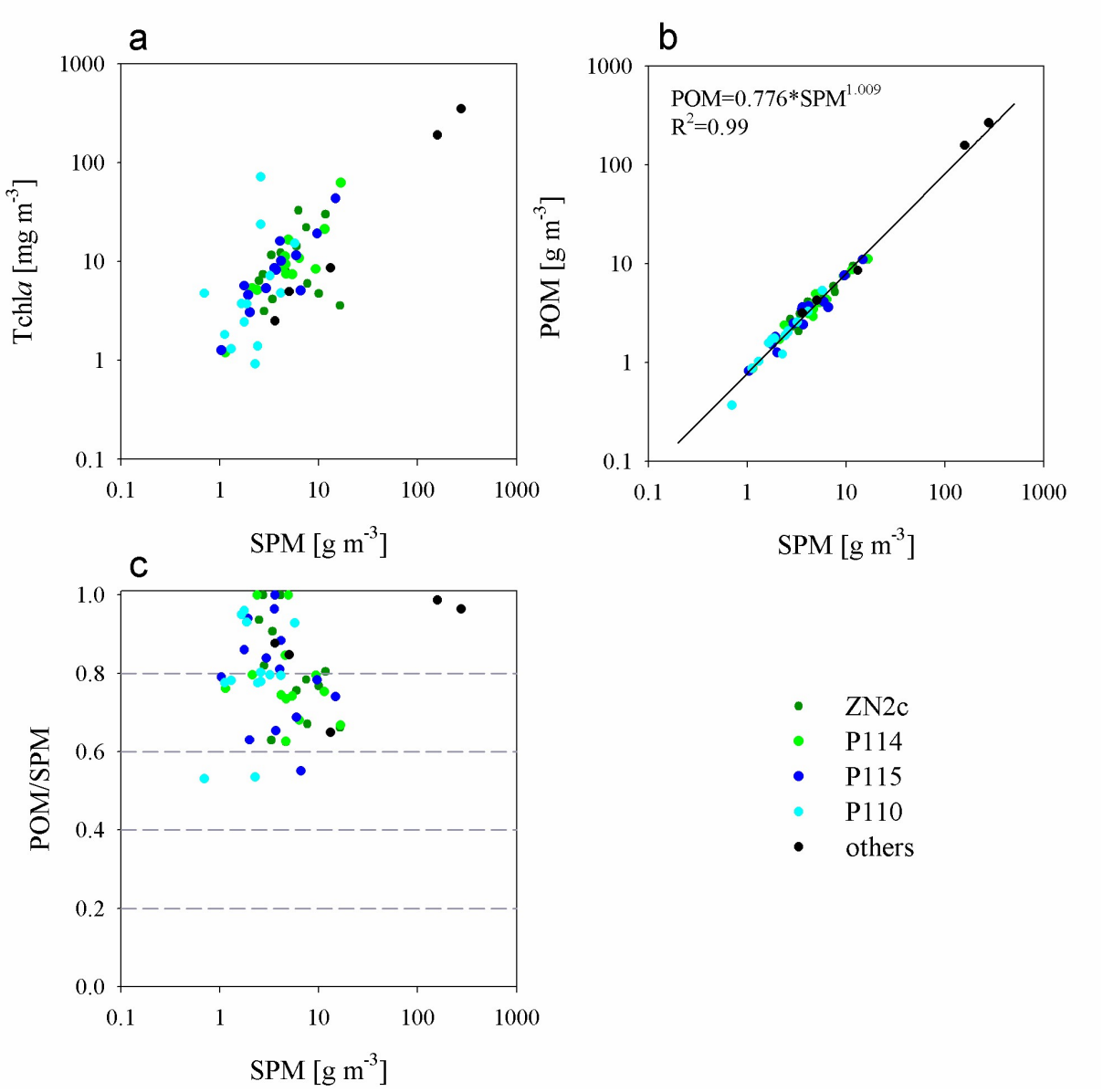

Figure 6. Relationships between the values characterizing the biogeochemical composition of sea water samples collected in the Gulf of Gdańsk at measurement stations in the Vistula estuary profile and others-S1, S2, S3, P115d, P115c in the summer season of 2016–2020: (a) Tchl*a* as a function of SPM, (b) POM vs. SPM relationship, (c) POM/SPM vs. SPM ratio.

the graphs, in particular, in case of fucoxanthin and zeaxanthin measurements at 'the other' stations. The highest concentrations were recorded for fucoxanthin – a diatom indicator. During the bloom in 'the others' stations, the average fucoxanthin concentration was 32.6 mg m^{-3}. At the stations from the mouth of the Vistula River to the center of the Gulf of Gdańsk, fucoxanthin concentrations decreased steadily with averages from 3.40 mg m^{-3} to 0.29 mg m^{-3}. The second dominant pigment was zeaxanthin, a marker of cyanobacteria. The highest concentration of zeaxanthin was also observed at 'the other' stations – an average of 7.36 mg m^{-3}. A decreasing trend in zeaxanthin content was also observed combined with the growing distance from the mouth of the Vistula River, from 1.37 mg m^{-3} to 0.87 mg m^{-3}. Chlorophyll *b* (Tchl*b*) an indicator of green algae, showed high concentrations at monitoring stations – an average of 0.97 mg m^{-3}. With the distance from the river mouth, Tchl*b* decreased from 1.60 mg m^{-3} to 0.29 mg m^{-3}. Contrary, the average Tchl*b* concentration at 'the other' stations was 0.47 mg m^{-3}. The concentrations of peridinin, a dinoflagellate indicator, were about 10 times lower than fucoxanthin. In the case of other stations, peri-

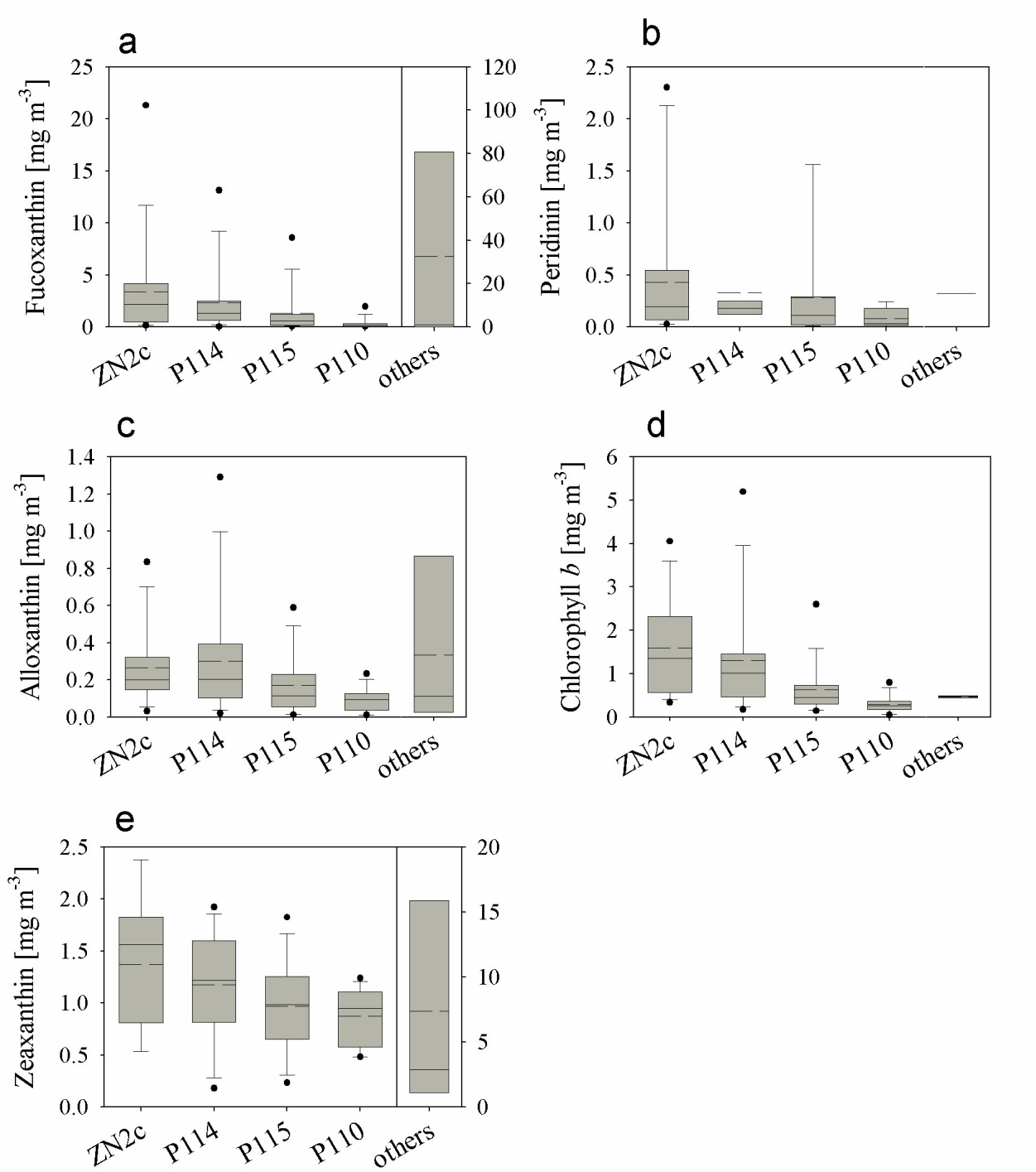

Figure 7. Ranges of variability of pigments considered as taxonomic markers of phytoplankton occurring in summer seasons (2016–2020) in the Gulf of Gdańsk at stations in the profile from the Vistula mouth (scale on the left-hand axis) and others (scale on the right-hand axis): (a) Fucoxanthin, (b) Peridinin, (c) Alloxanthin, (d) Chlorophyll *b*, (e) Zeaxanthin. Boxes show the range from the 25th to the 75th percentile, whiskers between the 10th and 90th percentile. The straight line indicates the median, the dashed line the mean, and the dots shows the minimum and maximum values.

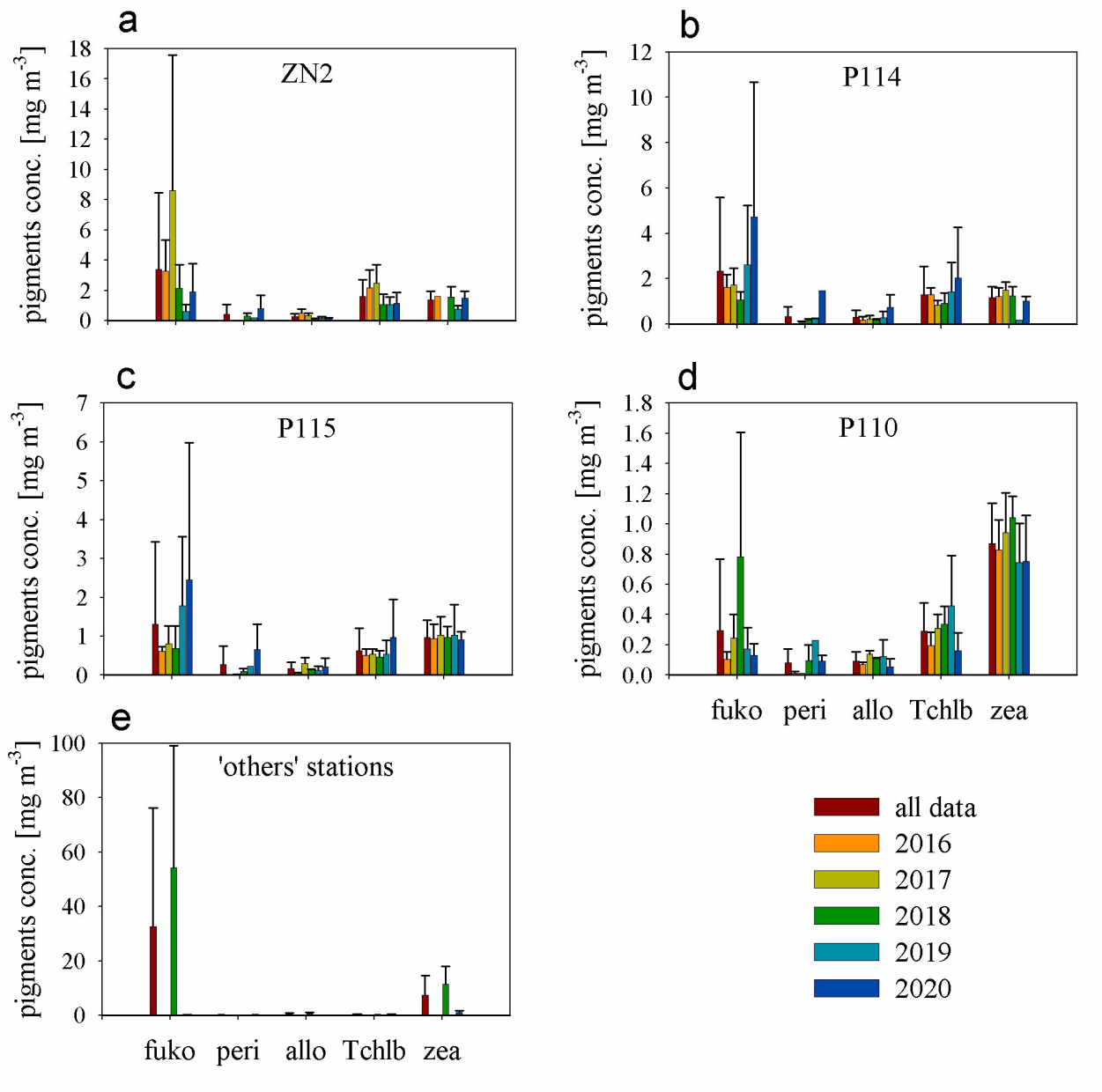

Figure 8. Variability of mean concentrations of fucoxanthin, peridinin, alloxanthin, chlorophyll *b* and zeaxanthin for all data and in individual years at the analyzed water stations of the Gulf of Gdańsk: ZN2 (a), P114 (b), P115 (c), P110 (d), other stations (e).

dinin was identified in only one sample (at station P115d) with a concentration of 0.4 mg m^{-3}. The concentrations of alloxanthin, an indicator of cryptophytes, in the analyzed data set were characterized by low values in the profile from the mouth of the Vistula River to the center of the Gulf of Gdańsk (averaging from 0.15 mg m^{-3} to 0.3 mg m^{-3}). Only for 'the other' stations, the average alloxanthin concentration was higher, approximately 0.4 mg m^{-3}. The prymnesiophytes marker, 19'hex-fucoxanthin, was identified only in 6 cases across four stations (ZN2c, P115 P114, and P110). The average concentration of 19'hex was 0.90 mg m^{-3}. The highest concentrations of 19'hex-fucoxanthin were recorded at stations P114 and P115, and the lowest at station P110 (all in June 2020).

Interannual and spatial variations of pigment markers (fucoxanthin, peridinin, alloxanthin, Tchl*b*, and zeaxanthin) concentrations are presented in Figure 8 Zeaxanthin, fucoxanthin, Tchl*b*, and alloxanthin were present in the samples in all analyzed years, which indicates the presence of cyanobacteria, diatoms, green algae, and cryptophytes. There is a heterogeneous distribution (in the form of patches) of phytoplankton populations, indicating dif-

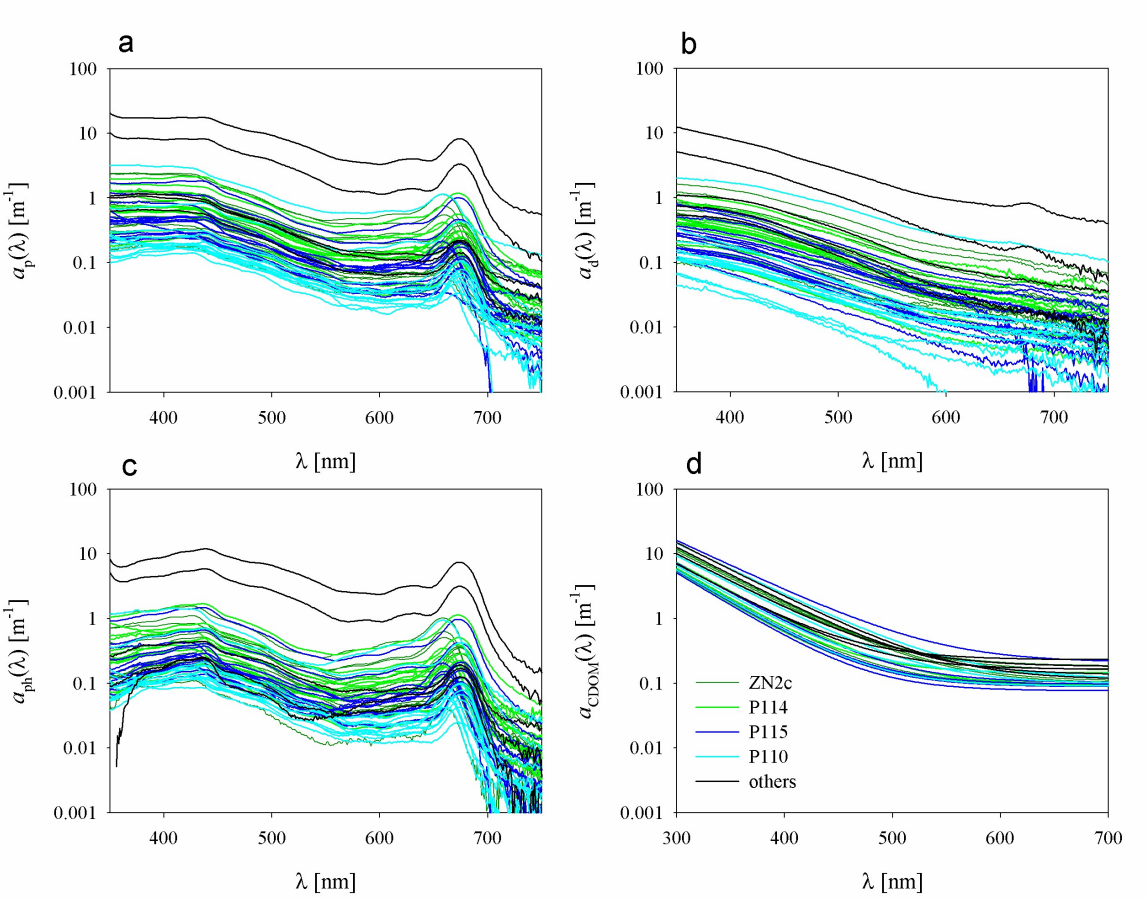

Figure 9. Variability of light absorption coefficients by: (a) suspended particles ($a_p(\lambda)$), (b) detritus ($a_d(\lambda)$), (c) phytoplankton ($a_{ph}(\lambda)$), and (d) chromophoric dissolved organic matter ($a_{\mathrm{CDOM}}(\lambda)$) in the summer season of 2016–2020, at the analyzed water stations of the Gulf of Gdańsk. The legend in the 9d subplot applies to the entire figure.

ferent numbers and species composition, called a mosaic structure of phytoplankton distribution, resulting from the combined influence of biological and physical factors. The mosaic diversity of individual phytoplankton groups is evident at the studied stations, even though these stations are closely located. This is related to different weather conditions in individual years and the size of the inflow of river waters into the Gulf of Gdańsk.

Table 3. Recorded ranges of variability of light absorption coefficient values $a_p(\lambda)$, $a_d(\lambda)$, $a_{ph}(\lambda)$ [m^{-1}] for selected wavelengths of 443 nm and 675 nm and $a_{\mathrm{CDOM}}(\lambda)$ or wavelengths of 400 nm and 443 nm and spectral slope $S_{300-600}$, along with means and standard deviations.

Quantity ($n = 58$)	Average ± SD	Minimum-maximum
$a_p(443)$ [m^{-1}]	1.000 ± 2.370	0.106–17.000
$a_p(675)$ [m^{-1}]	0.412 ± 1.136	0.023–8.250
$a_d(443)$ [m^{-1}]	0.349 ± 0.739	0.020–5.290
$a_d(675)$ [m^{-1}]	0.041 ± 0.110	0.001–0.824
$a_{ph}(443)$ [m^{-1}]	0.649 ± 1.649	0.077–11.710
$a_{ph}(675)$ [m^{-1}]	0.371 ± 1.030	0.018–7.426
$a_{\mathrm{CDOM}}(400)$ [m^{-1}]	1.270 ± 0.632	0.558–2.840
$a_{\mathrm{CDOM}}(443)$ [m^{-1}]	0.607 ± 0.320	0.201–1.424
$S_{300-600}$ [m^{-1}]	0.021 ± 0.002	0.018–0.024

3.2 Light absorption coefficient spectra of suspended particles, including detritus and phytoplankton, and chromophoric dissolved organic matter

The analyzed data set is characterized by a relatively high variability of $a_p(\lambda)$, $a_d(\lambda)$, $a_{ph}(\lambda)$, and $a_{\mathrm{CDOM}}(\lambda)$ coefficients in the summer season, as illustrated in Figure 9. In the entire spectral range studied, the variability of the $a_p(\lambda)$, $a_d(\lambda)$, and $a_{ph}(\lambda)$ coefficients was over two orders of magnitude, with the highest values observed during phytoplankton blooms. For the selected wavelength of 443 nm, the $a_p(443)$ values varied from 0.106 m^{-1} to 17.000 m^{-1}, while the $a_d(443)$ and $a_{ph}(443)$ values varied from 0.002 m^{-1} to 5.290 m^{-1} and from 0.077 m^{-1} to 11.710 m^{-1}, respectively. The range of variability of the $a_{\mathrm{CDOM}}(443)$ coefficients was about an order of magnitude in the entire spectral range with values varying from 0.201 m^{-1} to 1.424 m^{-1} (see Table 3). The average $a_{\mathrm{CDOM}}(\lambda)$ slope coefficient ($S_{300-600}$), a parameter defining the diversity

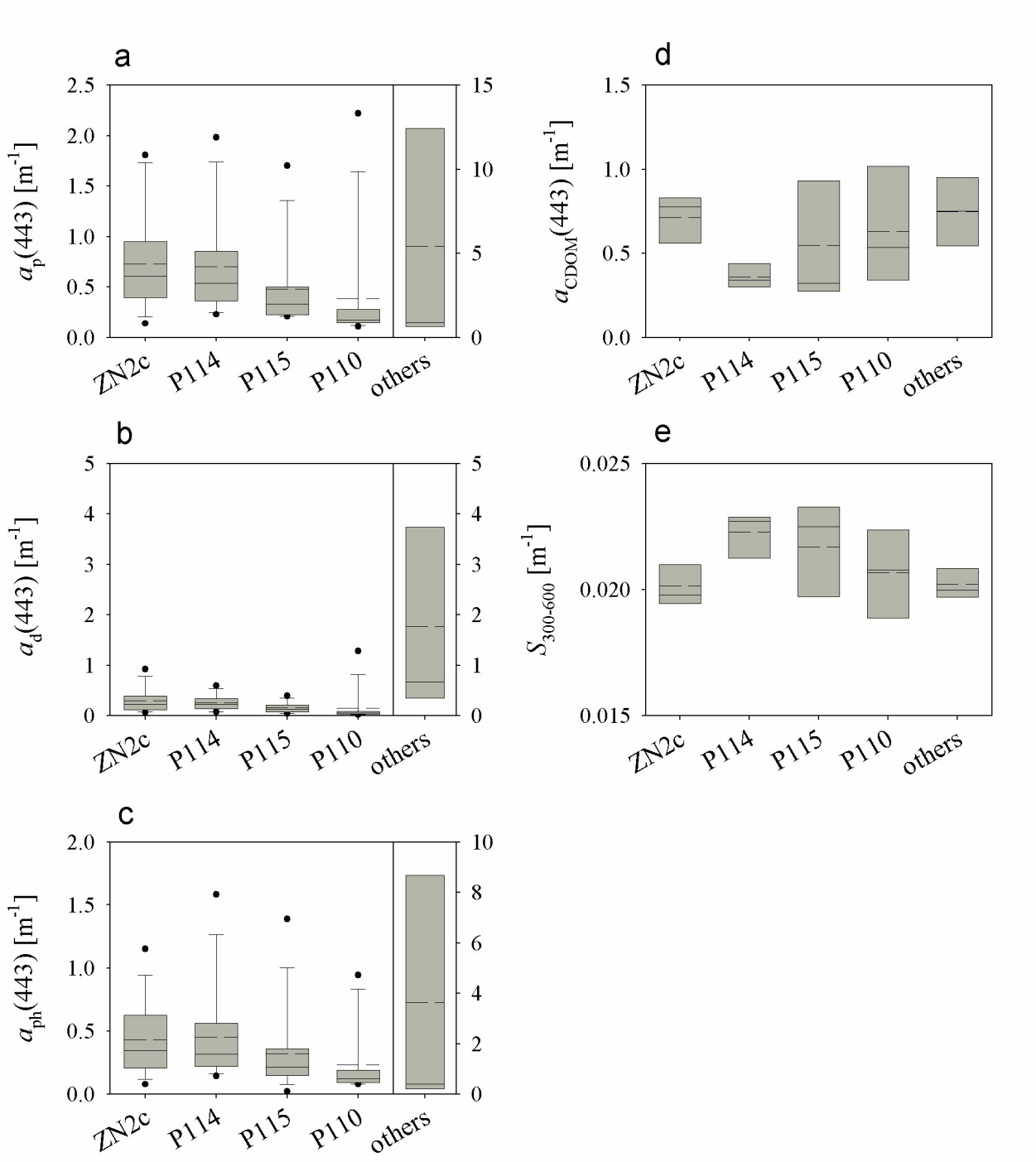

Figure 10. Ranges of variability of the (a) $a_p(443)$, (b) $a_d(443)$, (c) $a_{ph}(443)$, (d) $a_{\mathrm{CDOM}}(443)$ coefficients and (e) the spectral slope coefficient $S_{300-600}$ for the four main stations from the Vistula mouth profile and the remaining ones ('the others' – S1, S2, S3, P115d, P115c) in the summer season of 2016–2020. Boxes show the range from the 25th to the 75th percentile, whiskers between the 10th and 90th percentile. The straight line indicates the median, the dashed line the mean, and the dots shows the minimum and maximum values.

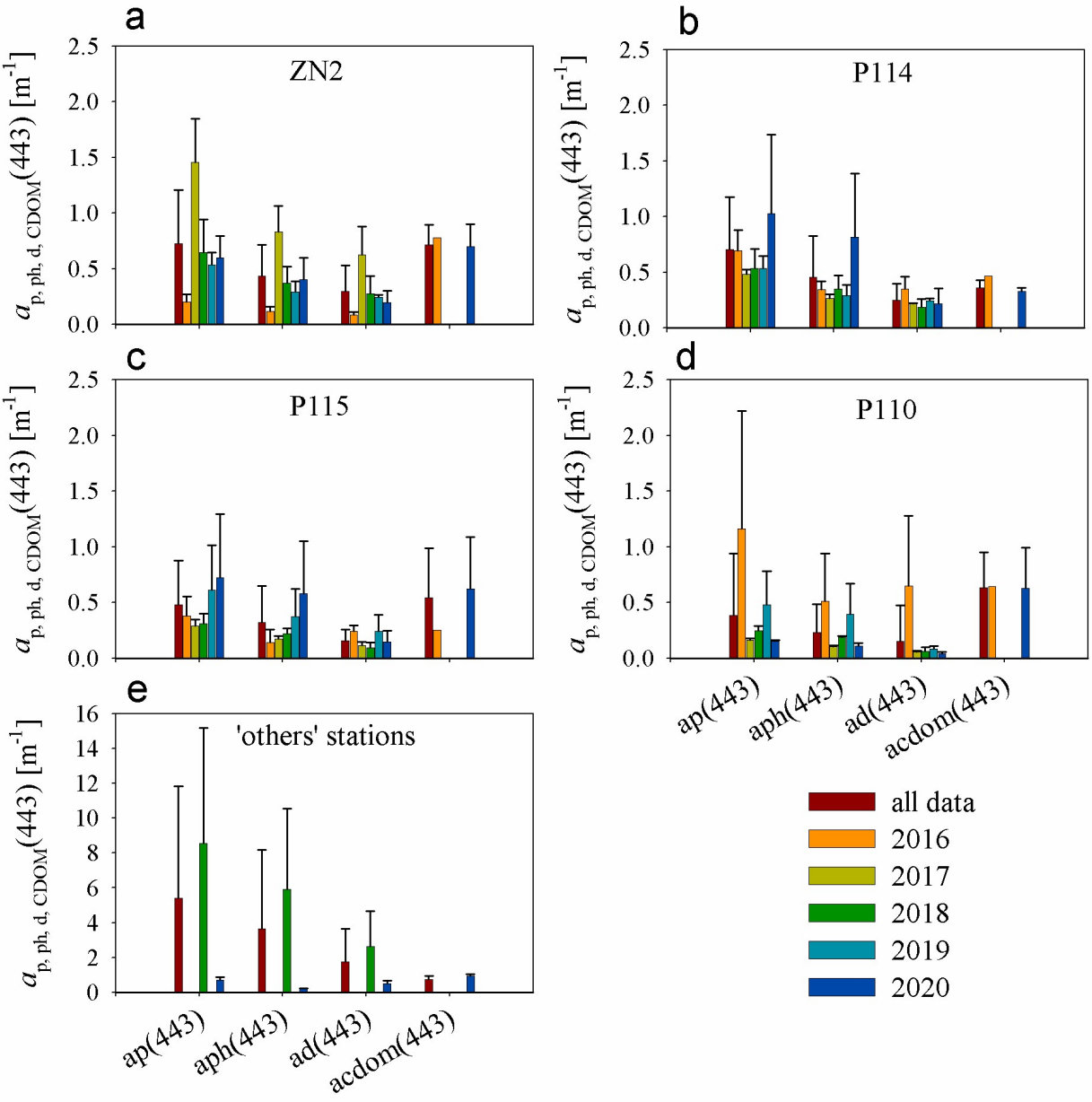

Figure 11. Variability of the mean values of the coefficients (443), $a_d(443)$, $a_{ph}(443)$ and $a_{\mathrm{CDOM}}(443)$ for all data and in individual years at the analyzed stations (a) ZN2c, (b) P114, (c) P115, (d) P110 and (e) others (S1, S2, S3, P115c, P115d).

of organic substances dissolved in seawater in terms of the content of humic and fulvic acids, was 0.0210 ± 0.0016 m^{-1}.

Figure 10 shows the variability of the $a_p(443)$, $a_d(443)$, $a_{ph}(443)$, and $a_{\mathrm{CDOM}}(443)$ coefficients divided into 4 stations from the Vistula River mouth profile and 'the other' stations. For stations ZN2c, P114, P115, P110, a trend of decreasing average values of the $a_p(443)$, $a_d(443)$, and $a_{ph}(443)$ with increasing distance from the Vistula River mouth was observed. In contrast, the remaining stations (S1, S2, S3 and P115c, and P115d), which include sites where summer phytoplankton blooms were observed (S1-S3), are characterized by significantly higher average values of the light absorption coefficients by particles, including phytoplankton and detritus (note scale on the right side of Figure 10a–c).

The interannual variability of the mean $a_p(443)$, $a_d(443)$, $a_{ph}(443)$, and $a_{\mathrm{CDOM}}(443)$ coefficient values was also examined for each monitoring station and 'the other' stations in the analyzed data set (Figure 11). The highest mean annual values of particle absorption coefficients were observed in 2017 at station ZN2c, in 2016 at station P110, and in 2020 at station P114. In general, the highest values of absorption coefficients were observed during

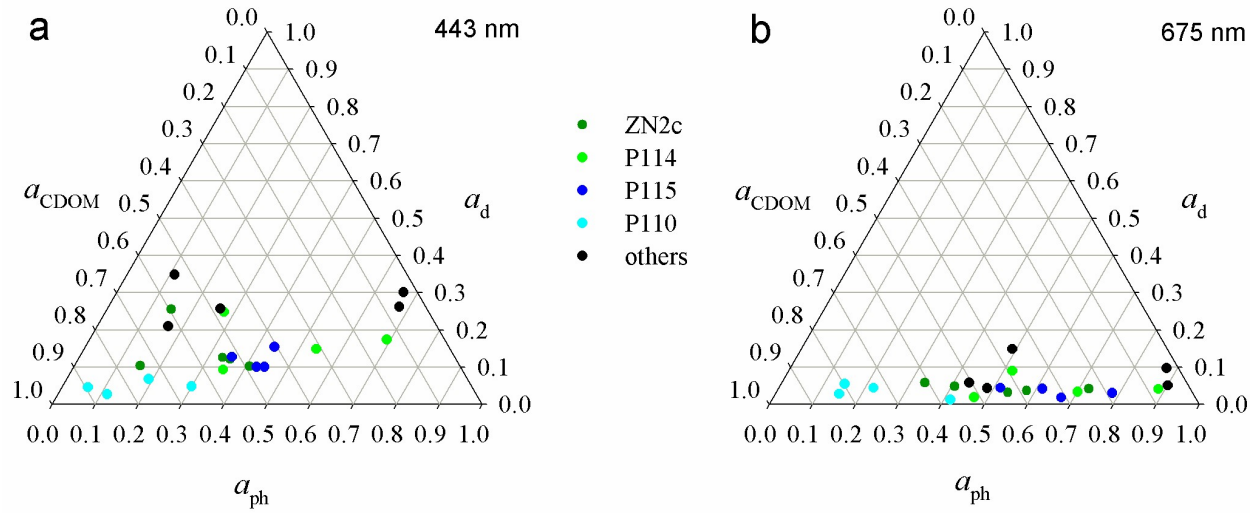

Figure 12. Ternary plot representing the relative contribution of CDOM, detritus and phytoplankton to the total light absorption by seawater components (except water itself) for selected wavelengths of 443 nm (a) and 675 nm (b).

the phytoplankton bloom in 2018 at stations S2 and S1. The mean values of $a_{\mathrm{CDOM}}(443)$ did not show a decreasing trend with the increasing distance from the Vistula mouth.

The obtained light absorption coefficients: $a_{ph}(\lambda)$, $a_d(\lambda)$ and $a_{\mathrm{CDOM}}(\lambda)$, allowed the calculation of the light absorption budget for the selected wavelengths of 443 nm and 675 nm (Figure 12). For the analyzed data set, the average proportion of phytoplankton of light absorption at 443 nm was $34\% \pm 18\%$, while detritus particles contributed on average $16\% \pm 9\%$. The largest proportion in the total light absorption was the absorption of light by CDOM: $51\% \pm 22\%$. At 675 nm, phytoplankton dominated light absorption with an average contribution of $54\% \pm 21\%$, while detritus particles contributed the least, on average: $5\% \pm 3\%$. CDOM's contribution to the light absorption at 675 nm was, on average, $41\% \pm 22\%$.

4. Discussion

The study analyses the spatial and temporal distribution of suspended and dissolved matter and its absorption properties, from the mouth of the Vistula River to the center of the Gulf of Gdańsk in summer seasons from 2016 to 2020. The finding confirms that the inflow of freshwater into the Gulf of Gdańsk, as a result of the circulation system of the Gulf of Gdańsk waters, leads to a concentration of riverine water east of the mouth of the Vistula River, flowing along the Vistula Spit before moving northeastward (Kowalczuk, 2001; Sagan, 2008).

4.1 Variability of biogeochemical parameters characterizing the suspended matter

The spatial and seasonal variability of SPM and Tchl*a* is very diverse not only in the Gulf of Gdańsk itself, but also in other regions of the Baltic Sea. In the analyzed summer data set (2016–2020), high average SPM and Tchl*a* in the Gulf of Gdańsk were observed: 12.2 g m^{-3}, and 20.2 mg m^{-3}. These values are notably higher than those reported by Meler et al. (2017) for the summer season, where the average SPM and Tchl*a* concentrations in the Gulf of Gdańsk were much lower (1.86 g m^{-3} and 7.68 mg m^{-3}). In the open waters of the southern Baltic Sea, the mean SPM and Tchl*a* concentrations were even lower (0.93 g m^{-3} and 3.19 mg m^{-3}). Seasonal comparison by Meler et al. (2017) also shows lower values: spring SPM in the southern Baltic Sea was 3.3 g m^{-3} – approximately one-fourth of the summer values from the analyzed data set. Autumn and winter were similarly lower, with means of 1.72 g m^{-3}, and 2.85 g m^{-3}, respectively. In the Gulf of Gdańsk, Meler et al. (2017) reported spring, autumn and winter average SPM concentrations of 3.36 g m^{-3}, 1.54 g m^{-3}, and 3.05 g m^{-3}, respectively, substantially below summer values from our study. Average Tchl*a* concentrations in the southern Baltic Sea and the Gulf of Gdańsk, reported by Meler et al. (2017), followed the same pattern: in spring 10.5 mg m^{-3} and 13 mg m^{-3}, in autumn 5.79 mg m^{-3} and 5.66 mg m^{-3}, and in winter 3.52 mg m^{-3} and 3 mg m^{-3}. Thus, compared to the summer season analyzed in this work, average Tchl*a* values represent a substantial reduction across seasons.

The median Tchl*a* (7.78 mg m^{-3}) observed in the analyzed data set is nearly double the value obtained by Soja-Woźniak et al. (2017) (4.11 mg m^{-3}) for the Gulf of Gdańsk for late spring and summer (May–September) seasons in the years 2012–2013. The average Tchl*a* (20.2 mg m^{-3}) observed in the analyzed data set for the Gulf of Gdańsk is also more than 4 times higher for the summer values obtained by Simis et al. (2017) for the Baltic Sea (including

the Gulf of Gdańsk) in years 2008–2012, and roughly 50% higher in spring. Similar trends were observed for SPM (12.2 g m^{-3}), which exceeded values reported by Simis et al. (2017) by a factor of four in spring and nearly five in summer. This indicates that different regions of the Baltic Sea are very diverse, with the Gulf of Gdańsk being characterized by much higher phytoplankton productivity than other regions of the Baltic Sea. This conclusion is further confirmed by Harvey et al. (2019), whose summer observation (June–September) in 2010–2014 in the Bothnian Sea, Baltic Proper, and Skagerak reported lower average SPM: 3.3 g m^{-3} and 6.5 g m^{-3} in Baltic Proper and Skagerak, respectively. In the Bothnian Sea, the average SPM in summer was almost an order of magnitude lower. The average Tchl*a* in those regions ranged from 2.4 mg m^{-3} to 7.4 mg m^{-3}, much below values recorded in our data set.

There are numerous references in the literature on satellite studies of SPM and Tchl*a* variability in the Baltic Sea covering different regions and seasons. Kyryliuk and Kratzer (2019) analyzed the summer SPM variability in different regions of the Baltic Sea in 2009–2011 based on satellite data from the MERIS (Medium Resolution Imaging Spectrometer) sensor. The average SPM concentration for the Gulf of Gdańsk was 2.80 g m^{-3}. For the North Baltic Proper (according to HELCOM division – Helsinki Commission, also known as the Baltic Marine Environment Protection Commission) 0.86 g m^{-3}, and in the Easter Gotland Basin and Bornholm Basin, it was 0.84 g m^{-3} and 0.8 g m^{-3}. These values were significantly lower than those obtained in our study. Bukanova et al. (2018) analyzed the distribution of SPM in the south-eastern Baltic Sea in the years 2003–2016, based on field and satellite studies. The research was conducted from March to October along the Sambia Peninsula (a peninsula in Russia separating the Vistula Lagoon from the Curonian Lagoon), covering the Russian part of the Baltic Sea, the Gdańsk Deep and the transect towards Gotland. The average monthly SPM from in situ data from 2003–2016 for the summer months was: June – about 2.9 g m^{-3} (coastal waters) and about 1.4 g m^{-3} (open waters), July – about 2.4 g m^{-3} and 1.51 g m^{-3}, August – about 3 g m^{-3} and 1.5 g m^{-3}. These values are also several times lower than our results from the summer season.

In the analyzed data set, organic matter was the predominant component, with POM accounting for 80% of SPM. Similar results were observed by Woźniak et al. (2011) for the Baltic Sea in spring and autumn seasons (80%) and Meler et al. (2017) for all seasons (76%). However, in recent years (2017–2020), the proportion of POM/SPM has been decreasing, as noted by Woźniak and Meler (2020) and Woźniak et al. (2022), who reported the average values of 61% and 62%, respectively. For data from different seasons in Meler et al. (2023) POM/SPM was only 58%. This long-term variability of POM/SPM indicates a higher proportion of mineral particles and detritus in the years 2017–2020. Potential reasons include the selection of measurement stations and variable weather conditions during measurement campaigns. Stations located in coastal waters have been sampled more frequently in recent years due to increased storm conditions, leading to a greater contribution of land-derived particles and/or sediment resuspension. It is also possible that there was reduced river inflow compared to the period from 2009 to 2012. In recent years, due to climate change, Poland has been experiencing prolonged periods of drought, especially in the summer, leading to hydrological and agricultural drought (Bąk and Kubiak Wójcicka, 2017, 2018; Kalbarczyk and Kalbarczyk, 2022). Incidentally, also in summer, there are so-called heavy rains causing a very large inflow of water in a short time (>40 mm per hour), which can lead to local flooding and floods (Szydłowski et al., 2023). In May 2010, one of the largest floods occurred, which introduced significant amounts of organic matter of terrestrial origin into the Gulf of Gdańsk, as well as various types of pollutants (e.g., mercury – Saniewska et al., 2014). Further heavy rains occurred in mid-July 2016 and at the end of July 2017 in the Gulf of Gdańsk, and additionally, as a result of winds from the north, sea waters receded, which led to the flooding of rivers and streams flowing into the Vistula, and then the return of waters to the Gulf of Gdańsk, which also caused the inflow of significant amounts of organic matter of terrestrial origin. In turn, at the end of May 2019, torrential rains occurred throughout Poland, and flood waves on the Vistula flowed along the entire length of the river, collecting various types of pollutants along the way, reaching the Gulf of Gdańsk in early June. Due to unpredictable periods of drought and heavy rain, the inflow of Vistula waters to the Gulf of Gdańsk varies from year to year.

The composition of phytoplankton in the Baltic Sea varies spatially and seasonally, which is related to hydrological and lighting conditions and the biological cycle. Many years of research conducted in the southern region of the Baltic Sea (Łotocka and Falkowski, 1994; Pliński, 1995; Stoń-Egiert et al., 2010) have identified the following classes of phytoplankton: cyanobacteria, Bacillariophyceae (diatoms), Dinophyceae (dinoflagellates), Cryptophyceae (cryptophytes), Chlorophyceae (green algae), Prasinophyceae (prasinophytes), Chrysophyceae (golden algae), Euglenophyceae (euglenines), as well as a group of unidentified nanoplankton (with cell sizes ranging from 3 to 15 μm). In summer, in the profile from the Vistula mouth to the center of the Gulf of Gdańsk, the phytoplankton population was dominated by diatoms, green algae and cyanobacteria, with additional occurrences of dinoflagellates and cryptophytes (Figure 6), similarly to Stoń-Egiert (2008), Stoń-Egiert et al. (2010), and Stoń-Egiert and Ostrowska (2022). The concentrations of pigments decrease with increasing distance from the Vistula River mouth.

However, the diversity of individual pigments at different stations changes in a mosaic manner, as previously observed by Stoń-Egiert (2008). Changes in the mutual proportions of different phytoplankton populations are influenced by prevailing hydrological conditions (temperature, salinity), light availability, river inflow, amount of organic matter, and others, all of which create conditions favorable for the growth and good physiological health of various phytoplankton organisms. A distinct diversity of phytoplankton species is noted in summer, between the Gulf of Gdańsk, where cyanobacteria and golden flagellates dominate, and the open waters of the southern Baltic Sea region, where cyanobacteria, golden flagellates, diatoms, euglenas, and green algae dominate (Janus et al., 2009). During the phytoplankton bloom recorded by us in 2018 at stations S1, S2, S3, the dominant phytoplankton species were diatoms, cyanobacteria, and cryptophytes. Similar patterns for the summer season in the Baltic Sea were observed by Simis et al. (2017), where the total biomass was dominated by cyanobacteria, including picocyanobacteria, and dinoflagellates.

The waters of the Gulf of Gdańsk are strongly influenced by the Vistula River and the surrounding land, which modify the thermal, nutritional, and salinity properties of these waters. The inflow of river waters to the Gulf of Gdańsk provides biogenic matter, necessary for the development, growth and functioning of algal cells, leading to a higher average content of chlorophyll *a* and other chlorophylls in the Gulf of Gdańsk compared to the open waters of the Baltic Sea. This increase is caused by more intensive phytoplankton growth fueled by the inflow of organic matter of terrestrial origin. Seasonal variability of the occurrence of individual pigments in Baltic phytoplankton, related to regular blooms of diatoms and dinoflagellates (Wasmund et al., 2001; Wasmund and Uhlig, 2003; Thamm et al., 2004; Olenina et al., 2006), determines the highest concentrations of Tchl*a*, Tchl*b*, and Tchl*c* in spring and autumn. In contrast, the diversity and variability of pigments in the summer season in the Baltic Sea is much less predictable than in spring or autumn season.

4.2 Variability of the light absorption coefficients

The composition of suspended particles and phytoplankton pigments affects the variability of light absorption coefficients. In the analyzed data set, the average values of the coefficients $a_p(443)$, $a_d(443)$, and $a_{ph}(443)$ were: 1 m^{-1}, 0.35 m^{-1}, 0.65 m^{-1}, respectively. These values are approximately 2 times higher than those observed by Meler et al. (2017) in the Gulf of Gdańsk in the late summer season (late August – early September) (average $a_p(440)$, $a_d(440)$, and $a_{ph}(440)$, amounting to: 0.41 m^{-1}, 0.14 m^{-1}, and 0.26 m^{-1}, respectively). The data set analyzed in Meler et al. (2017) did not include data with recorded larger phytoplankton blooms. The observed average $a_p(440)$, $a_d(440)$, and $a_{ph}(440)$ coefficwere higher than in open waters but lower than in estuarine waters (including stations from the mouths of the Vistula, Odra, Świna, Dziwna, Rewa, and the Szczecin Lagoon). Similar analyses for the summer season in the part of the Gulf of Gdańsk (Puck Bay) were conducted by Soja-Woźniak et al. (2017). In their study, $a_{ph}(443)$, $a_d(443)$ coefficients were lower, while the variability of $a_{\mathrm{CDOM}}(443)$ was higher. Kowalczuk et al. (2006) reported higher $a_{\mathrm{CDOM}}(400)$ values and lower spectral slope coefficients $S_{350-550}$ for the summer season (August–September) in the Gulf of Gdańsk: 0.81 m^{-1} and 0.019 m^{-1}. In our data set, $S_{300-600}$ averaged 0.021. For bay waters, including the Gulf of Gdańsk (influenced by the Vistula River) and the Pomeranian Bay (influenced by the Oder River), Kowalczuk (1999) reported average $a_{\mathrm{CDOM}}(400)$ values of 0.90 m^{-1} and $S_{350-600}$ values of 0.019 m^{-1} for the summer season. For the remaining coastal waters of the southern Baltic Sea, the variability of $a_{\mathrm{CDOM}}(400)$ and $S_{350-600}$ was lower: 0.76 m^{-1} and 0.020 m^{-1}, respectively. The lowest variability of $a_{\mathrm{CDOM}}(400)$ and $S_{350-600}$ was observed by Kowalczuk (1999) in the open waters of the southern part of the Baltic Sea, on average: 0.75 m^{-1} and 0.019 m^{-1}.

The absorption budget presented in this paper for selected wavelengths of 443 nm and 675 nm shows the different proportions of individual seawater components in the total absorption of light. At 443 nm, CDOM accounted for the largest proportion of light absorption (50%), followed by phytoplankton (34%) and detritus (16%). At 675 nm, phytoplankton dominated (54%), with CDOM contributing 41% and detritus only 5%. Similar analyses for the summer season in the Gulf of Gdańsk were conducted by Soja-Woźniak et al. (2017), where the proportion of CDOM in the total absorption of light for the wavelength of 443 nm was higher (70%), with a lower proportion of phytoplankton (20%), and detritus (10%). At 665 nm, CDOM accounted for about 50%, phytoplankton 40%, and detritus about 10%. These differences in the proportion of individual water components in the Gulf of Gdańsk result from different hydrological conditions and the inflow of river waters.

Kratzer and Moore (2018) analyzed the absorption properties in the North Baltic Proper, specifically in Himmerfjarden (coast of Sweden), during the summer season. Their results for the 442 nm wavelength showed similar proportions to those reported by Soja-Woźniak et al. (2017). However, at 665 nm, the average light absorption proportions were higher, with approximately 90% attributed to $a_{ph}(665)$, and about 5% each to $a_d(665)$ and $a_{\mathrm{CDOM}}(665)$. Simis et al. (2017) obtained the following proportions in absorption for measurements carried out in different regions of the Baltic Sea in the summer season: $a_{ph}(442)$ about 15%, $a_d(442)$ about 5% and $a_{\mathrm{CDOM}}(442)$ about 80%; and $a_{ph}(674)$ about 80%, $a_d(674)$ about 5% and $a_{\mathrm{CDOM}}(674)$ about 15%. These findings highlight that various regions of the Baltic Sea differ from each other

in terms of absorption properties as well as in the values of SPM and Tchl*a* in the summer season. This season is characterized by a relatively high proportion of CDOM, compared e.g., to the data combining the spring seasons (March, April, May) and the late summer and autumn seasons (end of August, September, October and beginning of November) as was the case of Woźniak et al. (2011), who reported for the 440 nm wavelength an average proportions ($a_{ph}(440) + a_d(440)$) 45% and $a_{\mathrm{CDOM}}(440)$ 55%.

4.3 Variability of light absorption coefficients vs Tchl*a* and SPM

Figure 13 presents the values of light absorption coefficients of all suspended particles in seawater, as well as detritus and phytoplankton, and also of organic substances dissolved in water for the wavelength of 443 nm. These values are presented in relation to the concentration of Tchl*a* and SPM on a log-log scale. The data show the variability of light absorption coefficients from Tchl*a* and SPM levels at each station of the main profile from the mouth of the Vistula River to the middle of the Gulf of Gdańsk, and jointly at other stations (S1, S2, S3, P115c, P115d). For suspended particles, approximations were presented in the form of a power function ($y = AxB$), following Bricaud et al. (1998), while for CDOM in the form of a polynomial ($y = 10(A\log(x)2 + B\log(x) + D$) obtained in Meler et al. (2016a).

The relationships between $a_p(443)$, $a_d(443)$, and $a_{ph}(443)$ and the SPM concentration are characterized by better fits/approximations than those on the Tchl*a* concentration (Figure 13a–f). The coefficients of determination (R^2) for these dependencies are, respectively: 0.75, 0.63, and 0.75 (vs SPM) and 0.64, 0.40, and 0.70 (vs Tchl*a*). At station P110 (the farthest from the Vistula River mouth, cyan points), absorption coefficients values are lower at low Tchl*a* or SPM concentrations, while at station ZN2c (the closest to the Vistula mouth, dark green) these values are relatively higher even at lower Tchl*a* or SPM values. Figure 13g–h shows the relationships between aCDOM(443) and both Tchl*a* and SPM. They do not show a clear correlation.

In clean ocean waters, there is no significant dependence between Tchl*a* concentration and CDOM (Siegel et al., 2005). However, such relationship can exist in optically complex waters (Ferrari and Tassan, 1992; Vodacek et al., 1997). In the Baltic Sea such dependences were established by Kowalczuk and Kaczmarek (1996) and Kowalczuk (1999, 2001). In Figure 13g, we applied the dependence of $a_{\mathrm{CDOM}}(445)$ on Tchl*a*, developed by Meler et al. (2016a) for the combined data set from the Southern Baltic Sea (including Polish river mouths and the Szczecin Lagoon) and three Pomeranian lakes. In the data set analyzed by us, this relationship is weaker, taking into account the scatter of points around the curve. Similarly, no clear correlation is observed between $a_{\mathrm{CDOM}}(443)$ and SPM. Table 4 presents the regression parameters in the power function for the dependencies between the coefficients $a_{p,d,ph}(\lambda)$, (for $\lambda = 443$ nm or 675 nm) and the concentrations of Tchl*a* or SPM. Generally, the correlation of light absorption coefficients with the concentration of SPM was stronger than with Tchl*a*. Meler et al. (2017) presented similar dependencies for the wavelength of 440 nm for the summer season for the entire Gulf of Gdańsk, as well as for other seasons and regions of the Baltic Sea. The $a_{ph}(443)$ vs Tchl*a* relationship for the summer season in Meler et al. (2017) is consistent with our results. The $a_d(443)$ vs SPM relationships are slightly different (Figure 13), which may be caused by differences in the fitting of the curves (in this work, the coefficient of determination R^2 was 0.63, for the $a_d(443)$ vs SPM relationship, while in Meler et al. (2017), R^2 was only 0.47.

Different regions of the Baltic Sea are characterized by spatial and seasonal variability in the relationship between the $a_{ph}(440)$ and $a_d(440)$ coefficients and Tchl*a* or SPM. The greatest differentiation of these relationships between the regions of the southern part of the Baltic Sea was observed by Meler et al. (2017) in the spring season. In the spring and autumn seasons, the most distinctive relationships were in the estuarine area (including river mouths and the Szczecin Lagoon), usually characterized by completely different parameters A and B in the approximated power function (usually located above and under a different slope than for the other regions of the Baltic Sea: open waters, coastal waters, the Gulf of Gdańsk and the Pomeranian Bay). Simis et al. (2017) reported relationships for the summer season, which differ significantly for $a_p(442)$ vs Tchl*a*, while for $a_{ph}(442)$ vs Tchl*a* the relationship is similar to that obtained in this work and Meler et al. (2017). The influence of river waters in the Gulf of Gdańsk is characterized by higher absorption coefficients in relation to higher concentrations of Tchl*a* and SPM.

The relationships developed here between light absorption coefficients and Tchl*a* or SPM concentrations for the summer season in the Gulf of Gdańsk may significantly improve optical inversion models for mapping these biogeochemical components occurring in surface waters and lead to a better understanding of observed satellite images.

4.4 Empirical relationship between CDOM absorption and spectral slope coefficient

Table 3 presents the mean values, standard deviations, and ranges of variability of the $a_{\mathrm{CDOM}}(400)$ coefficients and the spectral slopes $S_{300-600}$ for all the analyzed data. The choice of the wavelength of 400 nm is justified by the fact that it is the beginning of the visible range of electromagnetic radiation. The variability of $a_{\mathrm{CDOM}}(400)$ and $S_{300-600}$ was in the ranges of 0.558–2.84 m^{-1}, with an average of 1.27 m^{-1} and 0.018–0.024 m^{-1}, with an average of 0.021 m^{-1}, respectively.

The slope coefficient $S_{300-600}$ was inversely and non-

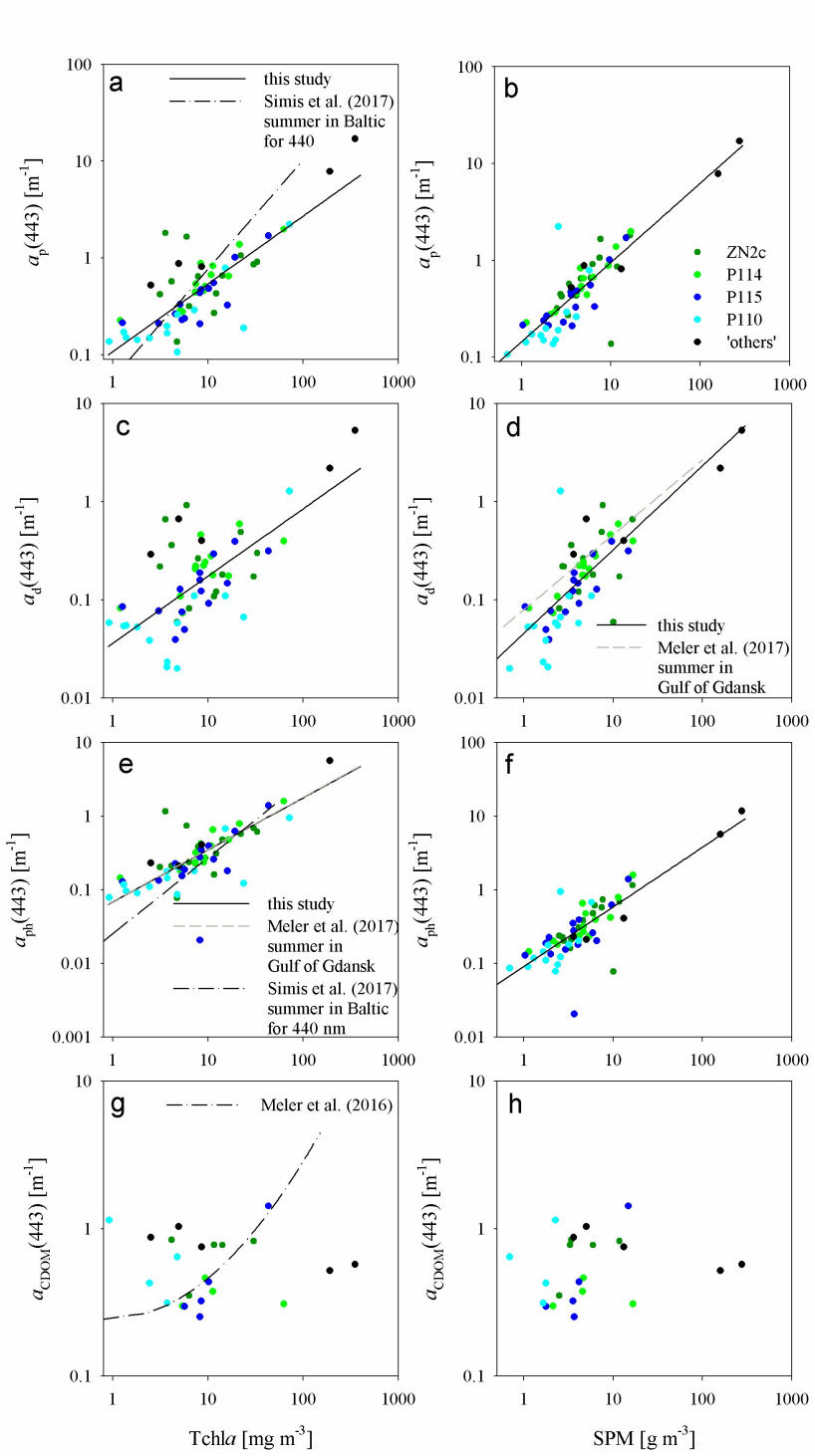

Figure 13. Relationships between coefficients $a_p(443)$: (a) and (b), $a_d(443)$: (c) and (d), $a_{ph}(443)$: (e) and (f), $a_{\mathrm{CDOM}}(443)$: (g) and (h), and concentrations of Tchl*a* (left panel) and SPM (right panel) for the selected wavelength of 443 nm. The gray dashed line additionally shows the dependencies calculated in Meler et al. (2017) for the summer season for the Gulf of Gdańsk (for the wavelength of 440 nm), and the black dashed line shows the results of Simis et al. (2017) for the Baltic Sea for the summer season. The black dashed line with dots shows the relationship presented in the work of Meler et al. (2016) determined for data from the Baltic Sea and three lakes of Pomerania. The legend (dots) in panel (b) applies to all panels.

Table 4. Relationships between coefficients $a_p(443)$, $a_p(675)$, $a_d(443)$, $a_d(675)$, $a_{ph}(443)$ and $a_{ph}(675)$ and concentrations of Tchl*a* and SPM. Parameters A and B calculated according to the formula in the power form $X = A \times \text{Tchl}a^B$ or $X = A \times \text{SPM}^B$, R^2 – coefficient of determination, mean normalized bias (*MNB [%]), normalized root mean square error (**NRMSE [%]).

$n = 58$		A	B	R^2	MNB	RMSE
Tchl*a*	$a_p(443)$	0.1077	0.7006	0.68	17.6	77.9
	$a_d(443)$	0.0361	0.6845	0.52	37.1	117.6
	$a_{ph}(443)$	0.0684	0.7061	0.70	15.3	74.5
	$a_p(675)$	0.0313	0.7845	0.67	25.5	109.2
	$a_d(675)$	0.0039	0.6801	0.45	57.4	231.0
	$a_{ph}(675)$	0.0261	0.802	0.66	31.0	129.0
SPM	$a_p(443)$	0.1437	0.819	0.75	14.0	86.5
	$a_d(443)$	0.0457	0.8519	0.63	22.9	87.6
	$a_{ph}(443)$	0.0909	0.8086	0.75	15.4	95.4
	$a_p(675)$	0.0448	0.8837	0.69	25.5	139.8
	$a_d(675)$	0.0046	0.8599	0.56	41.8	186.9
	$a_{ph}(675)$	0.0386	0.8879	0.65	37.4	213.7

$$^{*}\text{MNB} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{X_{\text{calculated}} - X_{\text{measured}}}{X_{\text{measured}}}\right)$$

$$^{**}\text{RMSE} = \sqrt[2]{\frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_{\text{calculated}} - X_{\text{measured}}}{X_{\text{measured}}} - \frac{\text{MNB}}{100}\right)^2}$$

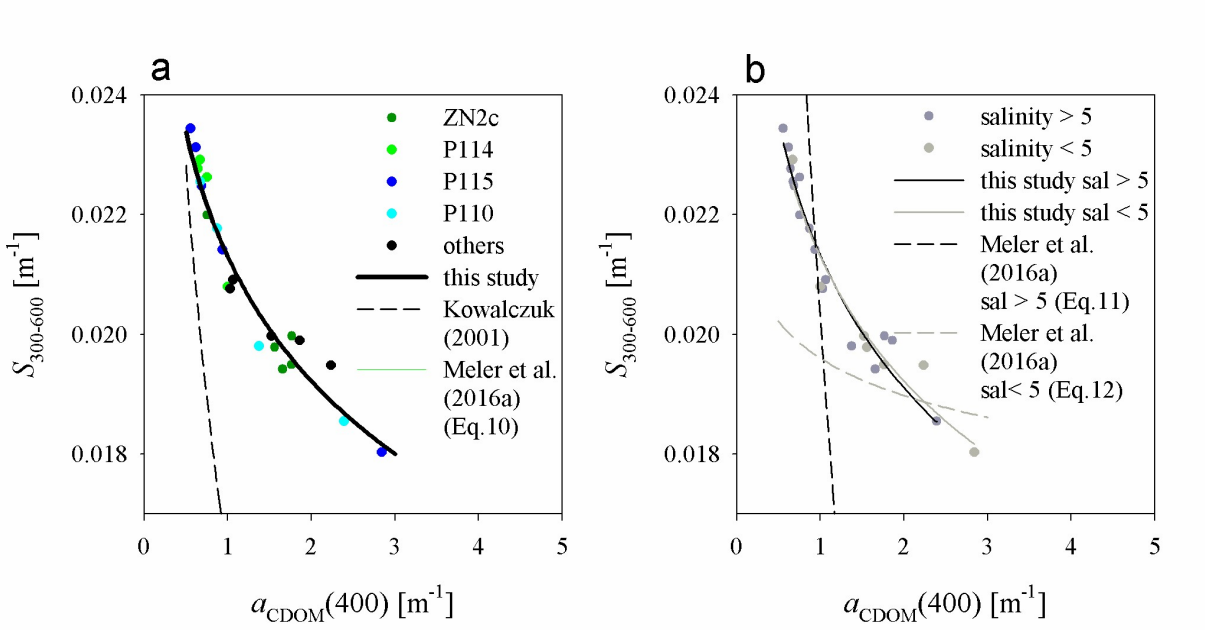

Figure 14. Relationships between the slope coefficient $S_{300\text{–}600}$ and the light absorption coefficient $a_{CDOM}(400)$: (a) with division into stations from the Vistula mouth profile and the remaining ones (S1, S2, S3, P115c, P115d) and (b) with division into salinity <5 and >5.

linearly related to the $a_{CDOM}(400)$ coefficient. To model this relationship, both hyperbolic (Stedmon and Markager, 2001; Kowalczuk et al., 2006) and logarithmic (Kowalczuk et al., 2005b) functions were applied. For consistency with Kowalczuk (2001) and Meler et al. (2016a), a log-linear fit was used to describe the relationship between $S_{300\text{–}600}$ and $a_{CDOM}(400)$ (Figure 14). Following the approach in Meler et al. (2016a), the data set was conventionally divided according to salinity: samples characterized by salinity >5 (sea water samples) and samples with salinity <5, which include the waters from the Vistula River mouth. Here too the threshold of salinity 5 in Meler et al. (2016a) was based on the conventional classification into marine-Baltic samples and samples from lakes, the Szczecin Lagoon, and various estuaries of Polish rivers: Vistula, Odra, Świna, Dziwna, Łeba, and Rewa. The relationships between $S_{300\text{–}600}$ and $a_{CDOM}(400)$ obtained for the respective data subsets are presented in Figure 14b.

The relationship between the spectral slope coefficient $S_{300–600}$ and $a_{CDOM}(400)$ presented in Figure 14a is the same as the dependence obtained in Meler et al. (2016a), although the data originate from different seasons and different regions of the southern part of the Baltic Sea, including the estuaries of the Odra – Szczecin Lagoon, and Vistula, and from three lakes in northern Poland. This consistency suggests that in the southern region of the Baltic Sea, taking into account the influence of river waters, the dependence of $S_{300–600}$ on $a_{CDOM}(400)$ remains unaffected by seasonal changes. The dashed line in Figure 14a shows the log-linear relationship obtained by Kowalczuk (2001) (only for the Baltic Sea data set), which differs from our data set. This may be due to significant differences between the data sets. The data set in Kowalczuk (2001) did not contain data from river estuaries alone, and the spectral slope of the $a_{CDOM}(400)$ coefficient was determined in the wavelength range from 350 nm to 550–600 nm, depending on the individual light absorption coefficient spectra.

The division of data by salinity (Figure 14b) into marine and "non-marine" samples did not prove effective. In the analyzed data set, typical river samples were not available, even though some samples were characterized by salinity <5. The relationships obtained in this work for both subsets do not differ significantly from each other. The relationships obtained by Meler et al. (2016a) also do not work. That may be explained by the lack of data characterized by: salinity <5, $S_{300–600}$ <0.0170 m^{-1}, and/or $a_{CDOM}(400)$ >1.75 m^{-1}.

4.5 Limitations of research

Measurements were taken in the summer months (June–September) in the period 2016–2020, on board the motor yacht Sonda II. The cruises took place on windless and sunny days, with little wave, so authors were able to collect a database composed of a complete set of 58 analyzed biogeochemical and physical parameters. This small data set enabled the analysis of the distribution of suspended and dissolved matter and their absorption properties in the Bay of Gdańsk (Baltic Sea) during the summer season. The empirical results presented in this paper should be considered in the light of certain limitations, related primarily to the fact that water samples collected in the Vistula profile are characterized by rapid variability in time. The water collected within an interval of a few or a dozen minutes at a selected station may have different biogeochemical and optical properties (Sagan, 2008). Additionally, the shapes of blooms are not homogeneous in the spatial distribution of phytoplankton cells as is shown in satellite images (e.g., Figure 2 – 20.07.2019). The aspect of the Vistula water flow in the case of heavy rainfall (including heavy rain and the associated flooding of rivers and streams flowing into the Vistula and then into the Gulf of Gdańsk), variable wind directions, and waves was not recognized. Nevertheless, the relationships obtained in the work are consistent with the data presented earlier in the literature for the Gulf of Gdańsk (Woźniak et al., 2011; Meler et al., 2016a,b, 2017, 2018). Due to the fact that so far few studies have been conducted on biogeochemical and absorption properties in the Vistula profile, the collected data set is a significant contribution to understanding the impact of the variability of these properties depending on the distribution of Vistula waters and their mixing with sea water. Work on this subject will be continued in the coming years, which will slowly lead to the successive expansion of the database and verification of the obtained relationships.

5. Summary

The presented analyses for the Gulf of Gdańsk during the summer season provide valuable information on the distribution of SPM and Tchl*a*, especially along the profile extending from the Vistula River mouth towards the open Baltic Sea. Furthermore, the study investigates the absorption characteristics of these suspended particles and CDOM. The analyses carried out showed a general trend of decreasing SPM concentrations, with increasing distance from the mouth of the Vistula River, while decreased Tchl*a* concentrations show less spatial variability. However, interannual variability shows that these trends are not always maintained from year to year, which may be related to differences in the inflow of Vistula River waters, as well as changing hydrological and meteorological conditions in the Gulf of Gdańsk region.

The high proportion of organic matter POM in total SPM (80% on average) indicates high productivity of the phytoplankton population in the summer season in the Gulf of Gdańsk. In the analyzed data set, high concentrations of pigments characteristic of different classes of algae and cyanobacteria were recorded. High concentrations of fucoxanthin and zeaxanthin were observed, as well as significant concentrations of chlorophyll *b*, peridinin, and alloxanthin. These findings suggest the occurrence of diatoms, cyanobacteria, green algae, dinophytes and cryptophytes in the summer season in the Gulf of Gdańsk, respectively, which is consistent with the literature data for the studied region. However, as shown in Figure 8, interannual variability is visible between the proportion of individual pigments, and thus the corresponding phytoplankton classes. Thus, in different years, the profile from the mouth of the Vistula to the center of the Gulf of Gdańsk may contain different phytoplankton assemblages. In the studied data set, most samples did not indicate a significant bloom at the time of sampling. Nevertheless, we identified a large phytoplankton bloom in 2018, which was distinguished by extremely high concentrations of SPM and Tchl*a*, and high concentrations of fucoxanthin, zeaxanthin, chlorophyll *b*, and alloxanthin.

The diverse composition of suspended and dissolved matter in water, including the phytoplankton population, affects the relatively large variability of the absorption

properties of this matter. The range of variability of the $a_p(\lambda)$, $a_d(\lambda)$, and $a_{ph}(\lambda)$ coefficients was over two orders of magnitude, and of $a_{\mathrm{CDOM}}(\lambda)$ was about an order of magnitude. Interannual variability of the $a_p(\lambda)$, $a_d(\lambda)$, $a_{ph}(\lambda)$ and $a_{\mathrm{CDOM}}(\lambda)$ coefficients was also observed at the analyzed stations. The analyses showed that the absorption properties of the waters of the Gulf of Gdańsk are dominated by absorption by CDOM, but to a lesser extent than in other regions of the Baltic Sea, respectively, about 50% for the wavelength of 443 nm and about 40% for the wavelength of 675 nm. In summer in the Gulf of Gdańsk, a large share of absorption occurs also for phytoplankton – about 35% for 443 nm and about 55% for 675 nm.

Measurements of light absorption coefficients of suspended particles, particularly normalized to Tchl*a* or SPM concentrations, are essential for developing optical inversion models to map the biogeochemical components present in surface waters (Lee et al., 2002; Favareto et al., 2018) and to better understand the origin of optical signatures in remote sensing studies. Due to the dynamic changes in the biogeochemical and absorption properties of water in the Gulf of Gdańsk, especially at the mouth of the Vistula River, it is very difficult to adapt remote sensing algorithms. The relationships we have determined between the coefficients $a_p(\lambda)$, $a_d(\lambda)$, $a_{ph}(\lambda)$, and the concentrations of Tchl*a* or SPM for the wavelength of 443 nm may be useful in local and regional studies of the biogeo-optical properties of suspended matter. Optical and biogeochemical observations conducted during the productive seasons of the Baltic Sea clearly indicate that bio-optical models and remote sensing methods should take into account the seasonal variability of the optical properties of Baltic waters. The Tchl*a* concentration is the most seasonally diversified indicator of phytoplankton resources in the Baltic Sea. However, it can be seen that the SPM variability is statistically often a better indicator of phytoplankton distribution in the southern Baltic Sea, as confirmed by our analyses (Table 4). However, Tchl*a* should not be abandoned as an indicator of phytoplankton distribution. It is important to take into account the seasonal variability of chlorophyll *a* concentration in the algorithms for remote monitoring of the Baltic Sea, as well as to develop methods for separating light absorption by CDOM and suspended particles.

In our opinion, the results of the analyses and relationships reported in this work should be taken into account when trying to better understand the variability of biogeochemical and absorption properties of mixed river and sea waters. The obtained results can also be helpful in a more precise interpretation of the results of various optical measurements, including remote sensing of ocean color, carried out in this environment. However, due to the qualitative nature of the collected data, it seems advisable to continue research on the relationships between the composition and absorption properties of suspended particles in this complex marine environment.

Data availability

The in situ light absorption data (absorption by particles, detritus, phytoplankton and CDOM) and biogeochemical data (concentration of Tchl*a* and SPM) can be acquired for scientific research purposes upon request from Justyna Meler.

Authors contribution

J.M. – conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft preparation, visualization, supervision; J.S.E. – data curation, methodology, review and editing; M.Z. – data curation, methodology, review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

None declared.

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