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Browning of the Baltic Sea

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ABSTRACT: The decreasing water transparency of the Baltic Sea over the last century has been documented by *in situ* measurements of the Secchi disk depth (z_{SD}) as well as by satellite measurements over recent decades. While the decrease in transparency for the Baltic Sea in general has become negligible from about 2013 onwards, satellite-detected light attenuation of the violet and blue light (k_d412) has increased, particularly from 2013 onwards. In the Gulf of Bothnia (particularly in the Bothnian Bay), eastern Gulf of Finland and eastern Gulf of Riga, k_d412 has increased significantly, indicating a dramatic increase in the concentration of colored dissolved organic matter (CDOM). These findings are partly supported by *in situ* CDOM data. The increase in CDOM concentration is probably due to climate change induced shifts in hydrology and greening of the land, all related to global warming. The increase in CDOM concentration and its effect on light availability may cause significant ecological changes and deterioration of the aquatic food chains.

KEY WORDS: Water transparency · Baltic Sea · Browning · Eutrophication · Secchi depth · Light attenuation · CDOM · Brownification

1. INTRODUCTION

It has been known for decades that the water transparency in the Baltic Sea is decreasing (Launiainen et al. 1989, Sandén & Håkansson 1996, Fleming-Lehtinen & Laamanen 2012, Dupont & Aksnes 2013). However, less is known about the changing color of the Baltic Sea water. Water transparency and color are important ecological characteristics that affect processes such as primary production, solar bleaching of organic material, phytoplankton physiology and behavior of zooplankton and fish. Water transparency has been traditionally measured as depth of the Secchi disk (z_{SD}) (Pitarch 2020). While shipborne z_{SD} measurements have a long history, these measurements are typically sparse and inconsistent in space and time, do not fully capture the high spatial and temporal variability and do not contain any additional spectral information. In contrast, satellite data have high and consistent resolution in both space and time, although until recently, the time series were often too short to resolve climate scale variability (Cael et al. 2023). As an additional benefit, satellite data provide information on transparency in different spectral bands. Kahru et al. (2022) merged Baltic Sea shipborne Secchi depth measurements with satellite estimates and created a time series dating back to the early 1900s. Here we extend the time series until 2025 and evaluate trends in satellite-derived transparency during 1997–2025. In particular, we analyze the attenuation of violet/blue light at 412 nm (k_d412) that is related to the concentration of colored dissolved organic matter (CDOM). The latter originates mainly from the degradation of terrestrial and aquatic plant material and strongly absorbs light in the ultraviolet and blue regions of the spectrum (Stedmon et al. 2000, 2010).

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2. DATA AND METHODS

The data source and processing methods are similar to those described in Kahru et al. (2022), with some differences. The European Space Agency (ESA) Ocean Colour Climate Change Initiative (OC-CCI; Sathyendranath et al. 2019, https://esa-oceancolour-cci.org/) dataset version 6.0 was used instead of version 5.0. This allowed extending the time series by 5 yr, until June 2025. OC-CCI data are merged from multiple ocean color sensors (Sathyendranath et al. 2023) with the main goal of producing a compatible time series by removing inter-sensor differences. As in Kahru et al. (2022), we applied the Lee et al. (2015) algorithm to calculate z_{SD}. As input to the algorithm, we used the ESA-CCI total light absorption coefficients $a(\lambda)$, backscattering coefficients $b_b(\lambda)$ and remote sensing reflectances $R_{rs}(\lambda)$ in 6 spectral bands (412, 443, 490, 510, 560, 665 nm) at about 4.5 km spatial resolution. As part of the Lee et al. (2015, 2018) algorithm, we computed the coefficients of diffuse light attenuation (k_d) for the 6 spectral bands and found the spectral band with minimal k_d. The calculations were made at daily resolution, and the daily datasets were composited into monthly means. The monthly means were used to calculate monthly climatologies, i.e. climatologically mean monthly values for the full time period. By subtracting the monthly climatology from each monthly dataset, we obtained the monthly anomalies of z_{SD} and of the 6 bands of $k_d(\lambda)$. As wintertime satellite measurements of ocean color are limited by the low sun elevation, and ice and cloud cover, particularly in the northern parts of the Baltic Sea, we excluded all December to January data and used very limited November and February data in the annual means.

While ESA-CCI satellite data are available from late 1997 (September 1997), the early data (1997–2002) are based on a single sensor (SeaWiFS). It appeared that the early period was noisy, probably due to the lower signal to noise ratio of SeaWiFS compared to the more modern sensors (Hu et al. 2012). We therefore used the period 2003–2025 when estimating trends in spectral k_d.

Statistical significance of pixelwise trends was evaluated using the nonparametric Sen's slope estimator (Sen 1968, Gilbert 1987) and the nonparametric Mann-Kendall test (Salmi et al. 2002). Unless stated otherwise, results were considered significant at $p < 0.05$. Key statistics (e.g. p-values) of linear regressions were calculated with the Analysis ToolPak in Microsoft Excel Version 2603.

The subdivision of the study area (Fig. 1) is based on the Helsinki Commission (HELCOM) open-sea regions excluding coastal areas approximately 4 km from the coast (HELCOM 2018a). Compared with Kahru et al. (2022), we excluded the Kattegat, Great Belt and Sound when calculating mean values for the whole Baltic Sea. We defined the Baltic Proper as the combination of Bornholm Basin, Western Gotland Basin, Eastern Gotland Basin and Northern Baltic Proper (Fig. 1). Spatial domains for making time series were selected based on coherent patterns in maps of change (see Figs. 3 & 5). For example, we show time series of z_{SD} in the Gulf of Bothnia where z_{SD} continued to decrease after 2013, while for k_d412, we show time series for Bothnian Bay, Gulf of Finland Eastern and Gulf of Riga due to the coherent increasing pattern there.

The *in situ* data for CDOM light absorption were from 2008, 2009, 2010 and 2012 reported in Simis et al. (2017), complemented by previously unpublished data from 2025 (cruises COMBINE2 and COMBINE3 by the Finnish Environment Institute). For the latter, discrete surface water samples were filtrated, stored and analyzed according to Simis et al. (2017) and

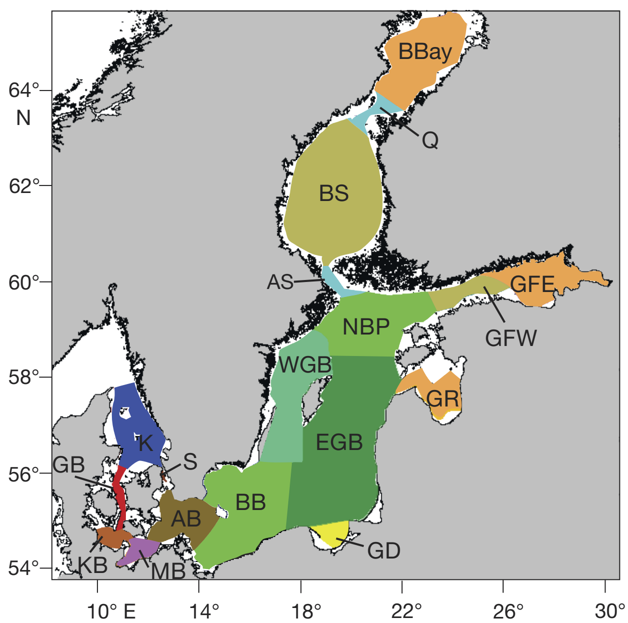

Fig. 1. Study areas in the Baltic Sea based on the HELCOM open sea subregions Kattegat (K), Great Belt (GB), Sound (S), Kiel Bay (KB), Mecklenburg Bay (MB), Arkona Basin (AB), Bornholm Basin (BB), Gdansk Basin (GD), Eastern Gotland Basin (EGB), Western Gotland Basin (WGB), Gulf of Riga (GR), Northern Baltic Proper (NBP), Gulf of Finland Western (GFW), Gulf of Finland Eastern (GFE), Åland Sea (AS), Bothnian Sea (BS), Quark (Q) and Bothnian Bay (BBay). The combination of BB, WGB, EGB and NBP (green) is defined as the Baltic Proper. The combination of BBay, GFE and GR (orange) is used for the interpretation of k_d412 observations due to the similar characteristics of these regions

absorption coefficients at 375 nm ($a_{CDOM}(375)$) were calculated.

3. RESULTS

3.1. Validation of satellite-derived k_d412 estimates

Daily estimates of k_d412 at about 4.5 km spatial resolution were validated using 394 near-surface measurements of $a_{CDOM}(375)$. There were 44 match-ups within ±1 d time difference and 17 same day match-ups between the satellite and *in situ* measurements (Fig. 2). The spatial distribution of the match-ups covered major domains of the northern and central Baltic Sea and is shown in Fig. S1 in the Supplement at www.int-res.com/articles/suppl/meps15210_supp.pdf. Considering the inherent spatial aliasing between the approximately 4.5 × 4.5 km satellite pixels and *in situ* samples, the agreement between satellite and *in situ* measurements is good with $r^2 = 0.62$ ($p < 10^{-9}$) for the ±1 d match-ups and $r^2 = 0.67$ ($p < 10^{-4}$) for the same day match-ups. While the slope of the regression in Fig. 2 seems to be steeper for 2025 than for 2008–2012, the small number of match-ups made it impossible to determine if a time-dependent correction was necessary.

Validation of the z_{SD} estimates was provided in Kahru et al. (2022).

3.2. Satellite time series of the Secchi disk depth

The spatial pattern of the trends in water transparency (z_{SD}) (Fig. 3) showed that while z_{SD} decreased significantly over the whole Baltic Sea during the full period (1997–2025), during the most recent part (2013–2025), the decrease continued in the Gulf of Bothnia (in both the Bothnian Sea and Bothnian Bay) with no significant changes in the rest of the Baltic Sea. Limited areas in the Baltic Proper (Northern Baltic Proper, Eastern Gotland Basin, Bornholm Basin) even experienced an increase in z_{SD} during 2013–2025 (Fig. 3B).

The time series of z_{SD} anomaly averaged over certain regions confirmed the cessation of the decrease in water transparency in most of the Baltic Sea (including the Baltic Proper, Fig. 4A) but a continuation or even acceleration of decreasing water transparency in the Gulf of Bothnia (Fig. 4B). When averaged over the whole Baltic Sea (excluding the Gulf of Bothnia), most of the decline in z_{SD} happened during the approximately first half of the time series (1997–2012, splitting done by visual inspection) with a slope

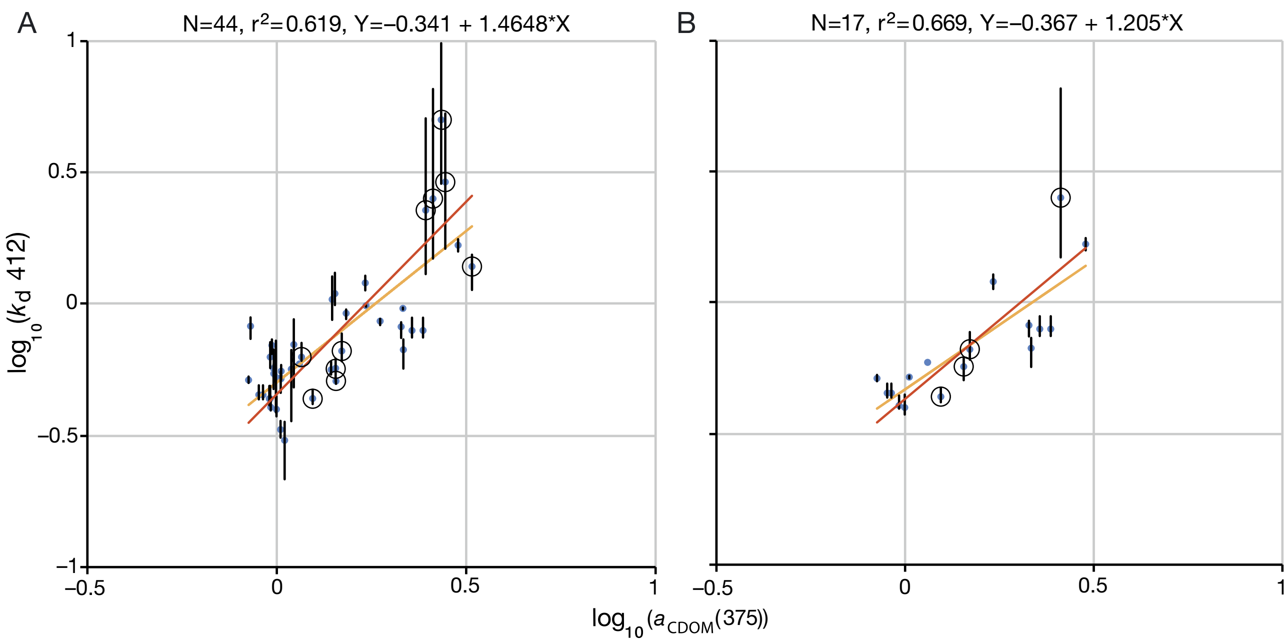

Fig. 2. Match-ups between satellite-derived k_d412 versus *in situ* $a_{CDOM}(375)$ ($\log_{10}$ of both variables). (A) Time difference between the satellite and *in situ* samples allowed up to ±1 d; (B) time difference of 0 d. The blue points are the means of the 3 × 3 satellite pixels centered at the locations of the *in situ* samples and the vertical lines show the minimum to maximum range of the 3 × 3 satellite pixel values. Match-ups from 2025 (10 in A and 4 in B) are circled. The yellow line is the ordinary least squares regression, and the orange line is the Type II regression

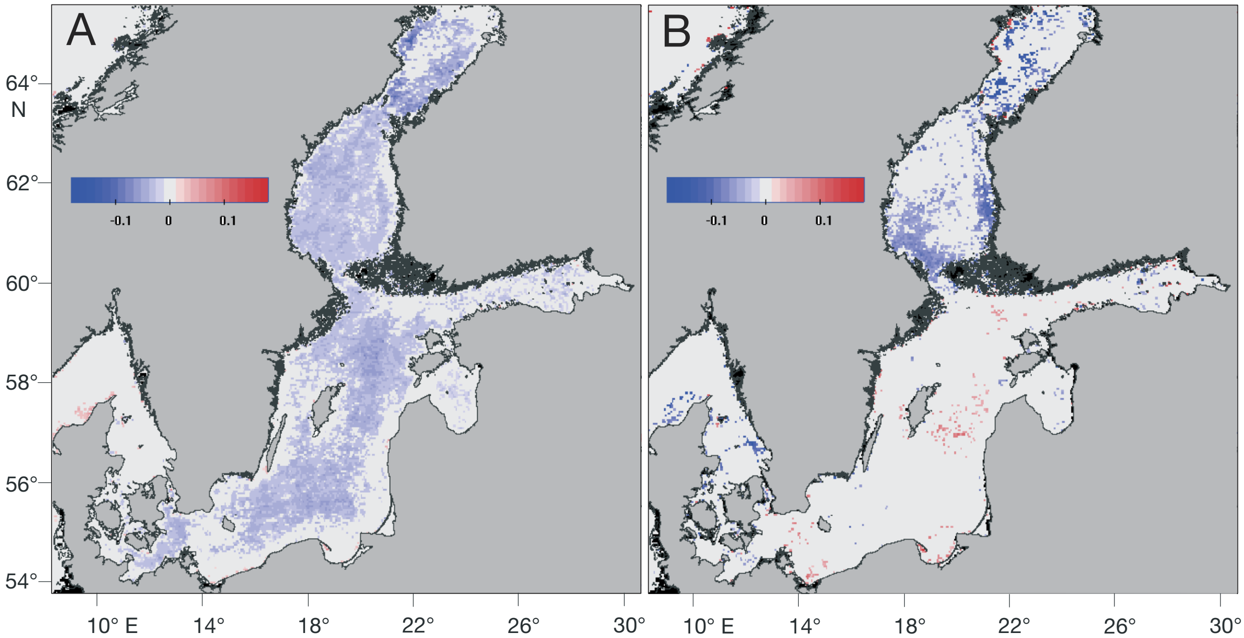

Fig. 3. Sen's slope (m yr^{-1}) of the annual satellite-derived Secchi depth (z_{SD}) anomalies calculated for (A) the full time series 1997–2025 and (B) the most recent part 2013–2025. Estimated trends below the 95% confidence level are shown in white

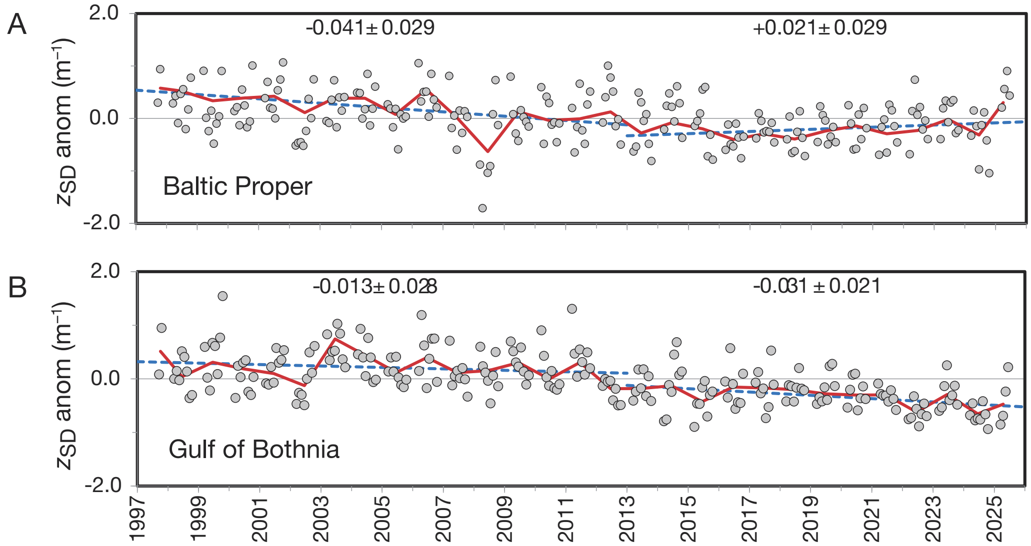

Fig. 4. Mean anomaly of the satellite-derived Secchi depth (z_{SD}) (A) in the Baltic Proper (BB + WGB + EGB + NBP, see Fig. 1) and (B) in the Gulf of Bothnia (BS + Q + BBay). Monthly averages from March to October (circles) and annual means (red lines) are shown. Slopes of linear regressions (blue dashed lines) for periods 1997–2012 and 2013–2025 are shown with 95% confidence limits

of −0.048 ± 0.025 m yr^{-1}. During the most recent period (2013–2025) of the time series, the decrease in z_{SD} was not significant in most of the Baltic Sea. For example, in the Baltic Proper (Fig. 4A), the slopes of z_{SD} change were −0.041 ± 0.029 m yr^{-1} for 1997–2012 and +0.021± 0.029 m yr^{-1} for 2013–2025. Note the slight increase (not significant at $p = 0.05$) during the 2013–2025 period. In contrast, in the Gulf of Bothnia (Fig. 4B), the decrease in z_{SD} was not significant during the approximately first half of the time series (1997–2012), but accelerated from 2013 (slope for 2013–2025 was −0.031 ± 0.021 m yr^{-1}, $p < 0.008$). Also, the month-to-month variability was higher in the Gulf of Bothnia (and particularly in the Bothnian

Bay), probably due to both natural variability and the measurement errors at high latitudes.

3.3. Satellite time series of spectral light attenuation

While light attenuation coefficients computed for the 6 spectral bands, particularly in the most transparent bands, were inversely correlated with z_{SD}, their individual time series revealed additional patterns. The spatial pattern of the trends in k_d412 (Fig. 5) showed that during the full period (2003–2025), k_d412 increased over the whole Baltic Sea but most dramatically in the Bothnian Bay, eastern Gulf of Finland and Gulf of Riga. During the most recent period (2013–2025), the main increase happened in the Bothnian Bay and the eastern parts of the gulfs of Finland and Riga, while changes in the rest of the Baltic were relatively minor. In the extreme northeastern Bothnian Bay, the trends were partly nonsignificant due to the high variability and missing data resulting from ice cover and low sun elevation.

The time series of k_d412 anomaly averaged over different areas showed that there was no significant change during 2003–2012 in the Baltic Proper but an increase after 2013 (Fig. 6A). In the Bothnian Bay, eastern Gulf of Finland and Gulf of Riga, the increase in k_d412 continued after 2013 (Fig. 6B, Fig. S2). The increase in k_d412 anomaly was highest in the Bothnian Bay. The rates of change in the different k_d bands provide some indication of the water constituents that caused the changes in water transparency. The increase in k_d, particularly in k_d412, was fastest in the Bothnian Bay (Fig. 7A,B), and the slopes were all positive ($p < 0.05$) for the full (2003–2025) and the latest (2013–2025) periods. When averaged over the Baltic Proper (Fig. 7C), the increase during the full 2003–2025 period was significant only for k_d412 and was not significant for any band during the most recent period of 2013–2025 (Fig. 7D). As the absorption coefficient was considerably higher at 412 nm than at other bands, we also evaluated the relative change by dividing the slope of k_d (m^{-1} yr^{-1}) with the respective mean over the full period and multiplying by 100% (Fig. 8). The increase in k_d412 was high, not only in absolute terms, but also as a percentage of the mean. During the full 2003–2025 period, the average annual increase in k_d412 anomaly was over 5% for the Bothnian Bay, over 3% in the Gulf of Bothnia and about 1.5% in the Baltic Proper. The recent increase in k_d412 was concentrated in the Bothnian Bay and the eastern gulfs of Finland and Riga, and the differences between the mean k_d spectra in the high k_d412 areas and elsewhere have increased (Fig. 9A). The change in the mean interannual k_d412 from 2003–2012 to 2013–2025 was fastest in the Bothnian Bay compared to the eastern Gulf of Finland where the starting levels were higher

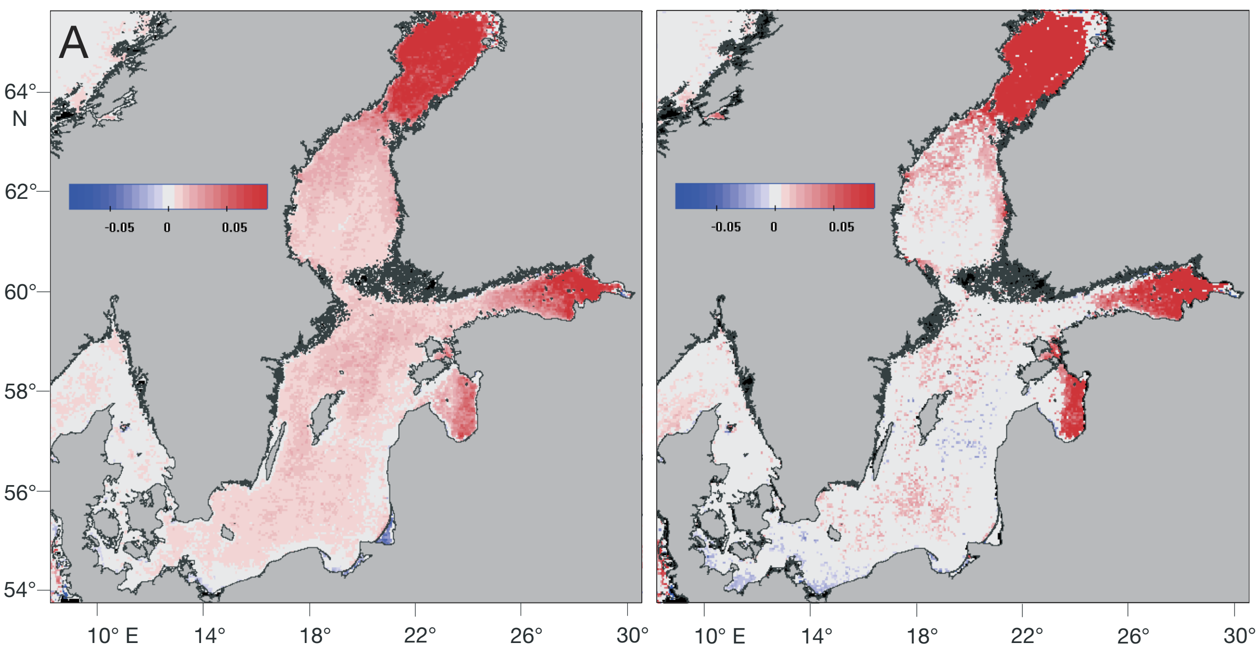

Fig. 5. Sen's slope of the annual k_d412 anomalies calculated for (A) 2003–2025 and (B) the most recent part 2013–2025. Estimated trends below the 95% confidence level are shown in white

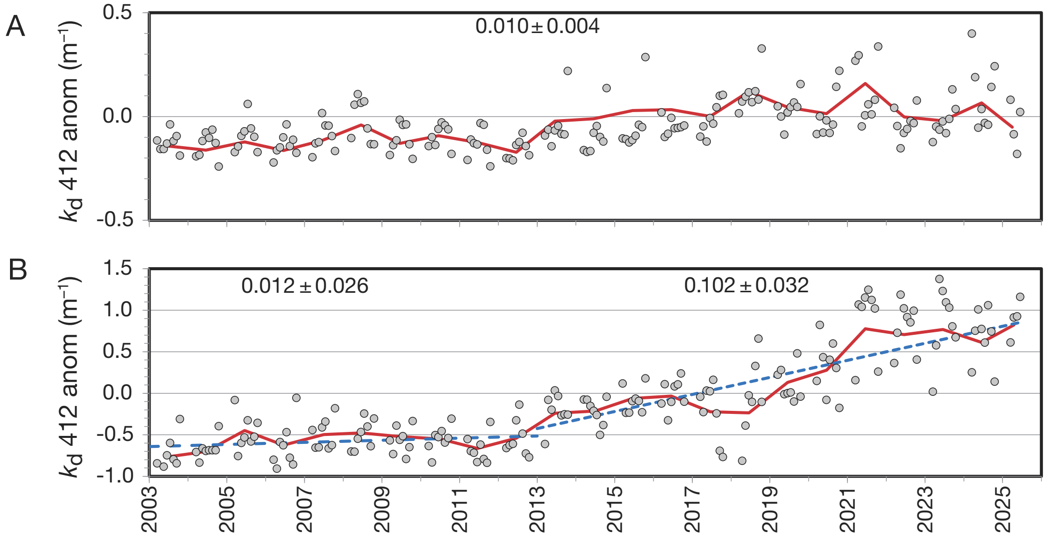

Fig. 6. Mean anomaly of the coefficient of diffuse attenuation at 412 nm (k_d412) (A) in the Baltic Proper (BB + WGB + EGB + NBP, see Fig. 1) and (B) in the Bothnian Bay. Note the different scales on the *y*-axis. Monthly averages from March to October (circles) and annual means (red lines) are shown. Slopes of linear regressions (blue dashed lines) for periods 2003–2012 and 2013–2025 with 95% confidence limits are shown for (B). Similar regressions for (A) are not significant (not shown) but the regression for the whole 2003–2025 period (slope 0.010 ± 0.004) is significant ($p < 0.05$)

(Fig. 9B). In the Gulf of Riga, an increase between the periods appeared only in the k_d412 band (Fig. S3). From 2003–2012 to 2013–2025, the mean annual k_d412 increased from 0.58 to 0.81 m^{-1} in the Baltic Proper, from 0.93 to 1.73 m^{-1} in the Bothnian Bay, and from 1.13 to 1.73 m^{-1} in the combined area of Both-

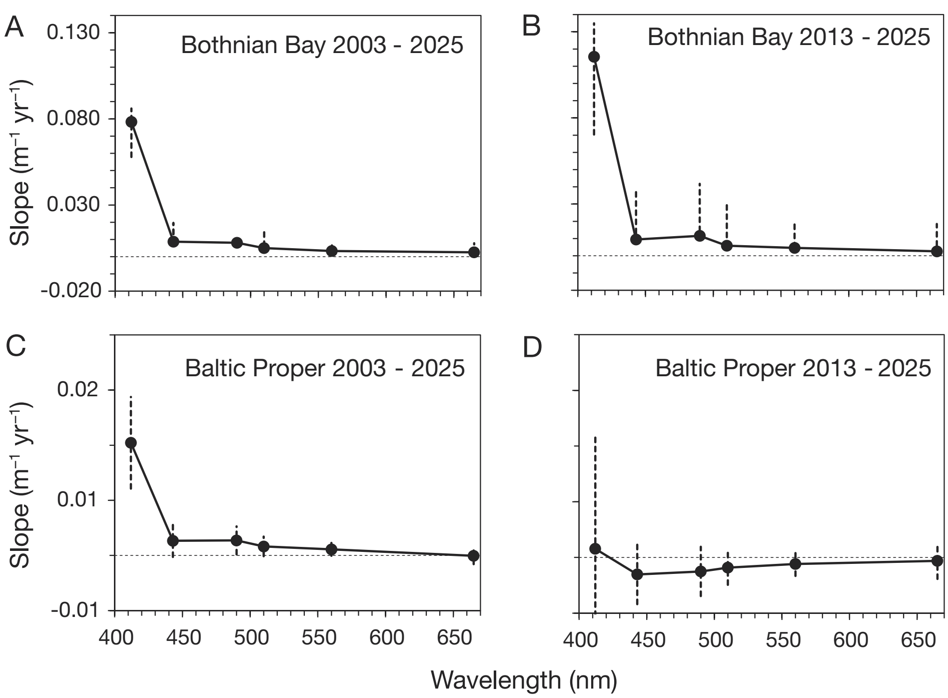

Fig. 7. Mean slope of the linear change in time of the spectral light attenuation coefficient k_d for the 6 wavelengths (412, 443, 490, 510, 560, 665 nm) in (A,B) the Bothnian Bay and (C,D) the Baltic Proper (BB + WGB + EGB + NBP, see Fig. 1) for (A,C) the full 2003–2025 period and for (B,D) 2013–2025. The 95% confidence limits are indicated by dashed vertical lines. Note the different scales on the *y*-axes

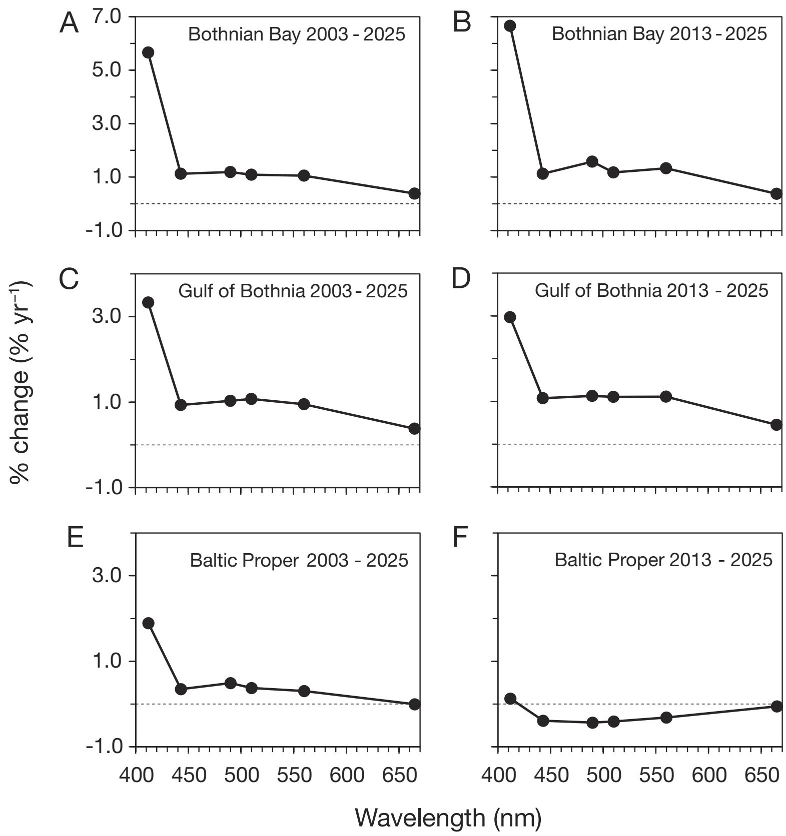

Fig. 8. Mean normalized slopes of the linear change in time of the spectral light attenuation coefficient k_d for the 6 wavelengths (412, 443, 490, 510, 560, 665 nm) in (A,B) the Bothnian Bay, (C,D) the Gulf of Bothnia and (E,F) the Baltic Proper for (A,C,E) the full 2003–2025 period and for (B,D,F) 2013–2025

nian Bay, eastern Gulf of Finland and Gulf of Riga.

For the Gulf of Bothnia, we analyzed *in situ* CDOM absorption data for 2008–2009 (Simis et al. 2017) and for 2025, both measured using methods given in Simis et al. (2017). Comparison of the linear relationships between salinity and $a_{CDOM}(375)$ ($p < 0.001$ for both datasets 2008–2009 and 2025) confirmed the increase in CDOM. If salinity is extrapolated to zero, the increase in $a_{CDOM}(375)$ in the freshwater end-member was 33% between the period 2008–2009 and 2025, or approximately 2.0% yr^{-1} (Fig. 10). The increase is consistent (from 2.0 to 2.1%) throughout the salinity gradient from 0 to 5.

4. DISCUSSION

While the satellite data used here (OC-CCI version 6) produced reasonable results, we also acknowledge that assessment of in-water parameters from ocean color in high CDOM environments is subject to large errors (Tilstone et al. 2022). A recent evaluation by González Vilas et al. (2024) of multiple versions of atmospheric correction

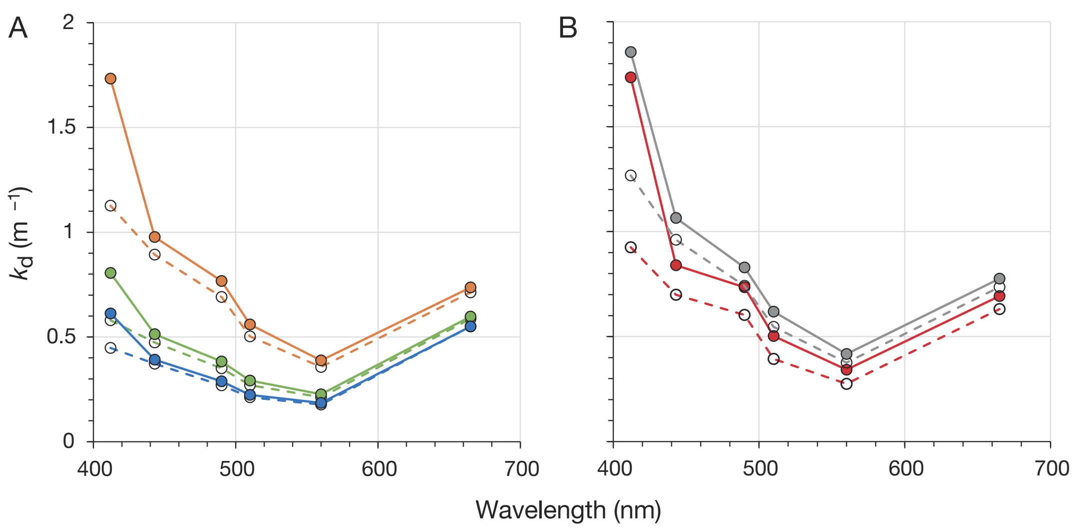

Fig. 9. Mean spectra of $k_d(\lambda)$ for the 6 wavelengths for different regions: (A) combined Bothnian Bay, Gulf of Finland Eastern and Gulf of Riga (orange); the whole Baltic Sea (green); the Baltic Proper (BB + WGB + EGB + NBP, blue); (B) Bothnian Bay (red), Gulf of Finland Eastern (gray). For each region, the averages for the 2 periods, 2003–2012 (open symbols connected with dashed lines) and 2013–2025 (filled symbols connected with solid lines), are shown

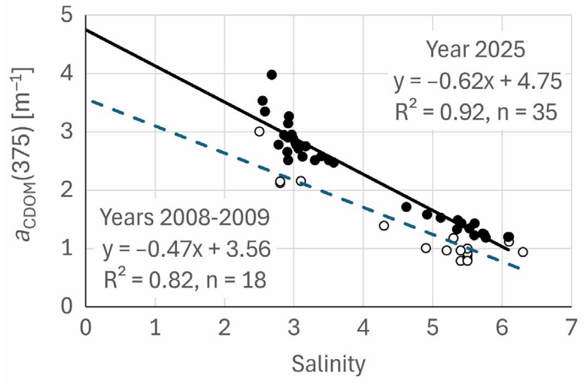

Fig. 10. Relationship between salinity and *in situ* $a_{\text{CDOM}}(375)$ for the Gulf of Bothnia (combined Bothnian Bay, with salinity <3.2, Quark, with salinity 3.2–4.2, Bothnian Sea, with salinity >4.3, also including northern parts of Åland Sea, with salinity >5.2). Observations and trendline from 2008–2009 are indicated by open circles and a dashed line, and observations from 2025 are indicated by black circles and a continuous line

in the Baltic Sea (including those used in OC-CCI version 6) showed improvement in all metrics compared to a previous version (4.2). While match-ups of our satellite-derived k_d412 with *in situ* CDOM absorption (Fig. 2) showed that k_d412 calculated from ESA-CCI version 6 data is a robust estimator of CDOM absorption, the errors can be large. While elaborate procedures are used to minimize the effect of changes in the composition of sensors included in the merged dataset, these effects cannot be totally excluded. The currently available match-up dataset is too small to evaluate the possibility of artificial temporal trends in the dataset.

Water transparency is an important habitat characteristic for all aquatic organisms that are affected by the optical environment (Dupont & Aksnes 2013). The long-term trend of decreasing water transparency in the Baltic Sea has been shown to be related to the increased nutrient loads enhancing primary production (e.g. Fleming-Lehtinen & Laamanen 2012). With the increasing length of the satellite-derived time series, it is now possible to better detect recent changes to various trends, also using spectral information. For example, the trend of decreasing water transparency measured as Secchi depth (z_{SD}) has practically stopped in the Baltic Sea as a whole and the transparency has even started to increase in the Baltic Proper (Figs. 3B & 4A, Kahru et al. 2022). In contrast, the decrease in z_{SD} in the Gulf of Bothnia has accelerated during the last decade, despite being less pronounced earlier (1997–2012, Figs. 3B & 4B).

It is obvious that the temporal patterns in k_d412 are quite different from those of z_{SD}. This is not surprising, as z_{SD} is primarily affected by the band with the highest transparency. In the Baltic Sea, this k_d minimum band is almost exclusively the 560 nm band, and switches only rarely to 510 nm in offshore waters before the phytoplankton spring bloom in February to March (Kahru et al. 2022). While the increasing z_{SD} in the Baltic Proper indicates a reduction in algal absorption, the increasing k_d412 indicates an increase in CDOM absorption.

The estimated rate of k_d412 increase was highest in the Bothnian Bay (~6% yr^{-1}), but was also evident in the whole Baltic Sea during the full 2003–2025 period. Light absorption in the ultraviolet and violet (412 nm) bands is mostly caused by the colored dissolved organic matter (CDOM) (e.g. Harvey et al. 2015). CDOM in the Baltic Sea is mainly of terrestrial origin and transported into the sea by river discharge (Hoikkala et al. 2015, Neumann et al. 2021), and displays a rather conservative behavior, characterized by decreasing CDOM with increasing salinity (Stedmon et al. 2000, 2010).

Asmala et al. (2019) calculated that the total riverine load of organic carbon (TOC) to the Baltic Sea ranged from 0.40 to 1.15 million tons (Mt) yr^{-1}, and during the period from 1993 to 2017, the annual rate of increase was 0.011 Mt yr^{-1}, thus 1.0 to 2.8% yr^{-1}. Similarly, while studying the browning of the Finnish headwaters and coastal areas, Räike et al. (2024) noted increasing trends in TOC for 37 out of 50 coastal sampling sites along the Finnish coast from 1990 to 2020, while the remaining 13 sites did not have any trends. On average the trend was 0.06 mg l^{-1} yr^{-1}, equaling on average 1.5% yr^{-1}, and it was mainly related to changes in hydrometeorology, decrease of acidic depositions and peatland drainage. In accordance with these findings from rivers and coastal stations, we show in this study that the increase in CDOM absorption ($a_{\text{CDOM}}(375)$) in the open sea areas of the Gulf of Bothnia was 2.0% yr^{-1} (Fig. 10). This is lower than the satellite estimate of ~3% annual change in k_d412 in the Gulf of Bothnia (Fig. 8C,D), but in the same range considering the different spatial and temporal domains, and the fact that changes in CDOM absorption do not directly translate to identical changes in light attenuation, which is also affected by light scattering and other light absorbing components. To confirm areal differences in more detail, and to estimate the actual increase in dissolved organic carbon requires further study, aggregating results from different sources, which is beyond the scope of this paper.

Parallel to the increase in CDOM in the freshwater endmember, the trend of increasing k_d412 in the Bothnian Bay and eastern Gulf of Finland corresponds to the trends of increasing freshwater content (FWC) in these basins (Raudsepp et al. 2023) resulting from increasing net precipitation and river runoff. The Bothnian Sea is the transition area from positive FWC trend to negative FWC trend in the Baltic Proper. Indications that the environment in the Gulf of Bothnia has been undergoing change during the last decades are accumulating from a number of studies. While the Bothnian Sea and Bothnian Bay have traditionally been considered not supportive for cyanobacteria blooms due to their high N:P ratio (Niemi 1979), increasing nitrogen limitation (Rolff & Elfwing 2015, Olofsson et al. 2021) and increasing cyanobacteria accumulations have been detected (Karlson et al. 2022; see also M. Kahru unpubl. report at https://www.wimsoft.com/mati/Kahru_Bothnia_2020_from_27-Sept-2020.pdf) in the Bothnian Sea in recent decades. Other factors that may be causing the increase in CDOM are the trends toward shorter ice seasons (most prominent in the Bothnian Bay) and toward reduced sea ice extent (Singh et al. 2025).

The reduction of energy in the violet and blue part of the spectrum due to an increase in CDOM is causing 'browning' (or brownification) of the water. This alters the availability of light as an energy source and environmental cue, impacting primary production, metabolic balance between autotrophy and heterotrophy, and species behavior, triggering cascading effects on higher trophic levels and food web stability (Capuzzo et al. 2015, Opdal et al. 2019, 2024, Wollschläger et al. 2021, Garnier et al. 2023, Striebel et al. 2023). While the timings of the spring season and the phytoplankton blooms in the Baltic Sea have become earlier than in the past (Kahru et al. 2016), browning can delay the seasonal phytoplankton bloom (Opdal et al. 2019) and switch the area from an annual sink of atmospheric CO_2 to a source (Bertin et al. 2025). In the Baltic Sea, browning has been indicated in the Gulf of Riga (Aigars et al. 2024), where the observed shifts from green to brown over the past 2 decades were attributed to milder winter conditions shortening the freeze–thaw period and increasing winter CDOM loads. Similar explanations could apply to the other areas with rapid k_d412 increase.

A related phenomenon called coastal darkening refers to the reduction in light availability due to increased suspended material, organic matter concentration and phytoplankton abundance. This has been recently observed globally across both coastal seas and the open ocean (Davies & Smyth 2025) and is impacting the intensity, spectra, timing and spatial distribution of underwater light (Aksnes et al. 2009, Dupont & Aksnes 2013, Opdal et al. 2019, Wollschläger et al. 2021). While coastal darkening may exacerbate eutrophication and increase the relative abundance of pelagic versus benthic algae (Garnier et al. 2023), increased river discharge may suppress phytoplankton biomass production and shift carbon flows toward microbial heterotrophy (Wikner & Andersson 2012).

Even though the Baltic Sea has been known for its high CDOM concentration and the original name for it ('Gelbstoff') was coined by Kalle (1937) based on his studies of the Baltic, the current increase in CDOM since 2012 seems unprecedented. The fastest increase of ~6% yr^{-1} in the k_d412 that we observed in the Bothnian Bay, as well as the increase in the low saline areas of the Eastern Gulf of Finland and Gulf of Riga (Fig. 5B; Fig. S2), seems to be indicative of a fundamental transformation with consequences for the ecosystem, food chain and fisheries. All 3 areas we identify as 'hot spots' of brownification have encountered a shortening of the ice period (Singh et al. 2025), and are characterized by drainage from major rivers (i.e. Kemijoki, Neva, Daugava; HELCOM 2018b). The Bothnian Bay and eastern Gulf of Finland also have the commonality of a large fraction of the drainage area being covered by forest (Mörth et al. 2007). In Swedish coastal areas, the concentration of CDOM is positively correlated with the area of wetlands, forests and meadows in the catchment area (Kratzer & Allart 2024).

The increase in k_d412 is almost undoubtedly a response to an increase in CDOM and dissolved organic matter in general, leading to browning of the water. Increase in CDOM is also a typical outcome of climate change in the Arctic (Mann et al. 2022) and is caused by the increased temperature, melting of permafrost and increased river runoff. The future changes in the environment of the Baltic Sea in general and of the most affected regions (e.g. Bothnian Bay) in particular should be carefully monitored, as our analysis indicates that the rate of browning has recently accelerated. The different behavior and mismatch between the trends of z_{SD} and k_d412 calls for reconsideration of the core indicator on water transparency within the HELCOM indicator framework, which currently relies on Secchi depth alone.

5. CONCLUSIONS

The trend of decreasing water transparency measured as satellite-derived Secchi disk depth (z_{SD}) ended for the Baltic Sea in approximately 2012, and transparency has been slightly increasing in the Baltic Proper since 2013. In contrast, transparency is still decreasing in the Gulf of Bothnia, and the process has accelerated since 2013.

While satellite measurement of remote sensing reflectance at 412 nm in a high CDOM environment is inherently difficult, it appears that light attenuation in the blue and violet part of the spectrum (k_d412) has increased everywhere, but most dramatically in the Bothnian Bay and the eastern parts of the gulfs of Finland and Riga. In the Bothnian Bay, the rate of increase in k_d412 was above 6% yr^{-1} over the last 12 yr. The whole Gulf of Bothnia as well as the eastern Gulf of Finland seem to be experiencing a major environmental change associated with 'browning', darkening and increasing CDOM concentration in response to climate change.

Strengthening effective monitoring of browning and its impacts in the Baltic Sea is timely and should be implemented by investing in more comprehensive *in situ* monitoring of the open sea and integrating such actions with existing river and coastal observations and satellite observations.

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