



Assessing temporal trends in ocean transparency using GlobColour products from the Copernicus Marine Service and accounting for associated uncertainties

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Abstract.

Ocean transparency refers to the ability of water to transmit light, which directly influences the depth to which sunlight penetrates the water column. This parameter is crucial for marine ecosystems, as it determines the availability of light for photosynthesis, a process vital for phytoplankton, the primary producers of the ocean. Phytoplankton not only form the base of the marine food web but also contribute significantly to biogeochemical cycles, including the carbon cycle. A decline in transparency can limit photosynthesis by reducing the depth of the euphotic zone, potentially disrupting ecosystems and impacting carbon sequestration.

Transparency has traditionally been measured using the Secchi disk, a simple yet effective tool for assessing water clarity. More recently, satellite-derived products have revolutionized the study of transparency, enabling large-scale and long-term observations. But whatever the method employed to measure transparency, robust evaluation of long-term trends depends on properly accounting for the inherent uncertainties of the observations. This issue is especially critical for remote sensing datasets, as the succession of sensors across two decades can introduce biases in long-term trend detection.

In this study, we accounted for observational uncertainties in the products by using a Monte Carlo approach, which incorporates the Seasonal Mann-Kendall test to evaluate trend detection reliability and the Theil–Sen slope estimator to quantify trend magnitude. In parallel, seasonal and inter-annual variability in transparency were also examined in relation to in situ data of water discharge, providing insights of riverine influences on transparency dynamics. Study areas include turbid French estuaries (Gironde and Loire), the semi-sheltered Gulf of Morbihan waters, tropical waters around Mayotte, and the oligotrophic North-East Atlantic, representing a broad range of hydrographic and climatic regimes.

The results reveal pronounced spatial contrasts: strong variability and decreasing transparency linked to high-flow events in the Gironde estuary, weaker but noticeable trends in the Loire estuary, no significant changes observed in the North-East Atlantic, and stable conditions for clear waters off Mayotte. The gulf of Morbihan exhibited strong variability that prevailed any trend detection from the long-term signal. Resolution analyses highlighted the importance of finer-scale products for capturing local estuarine processes, while coarser resolution provided more robust basin-scale patterns. This study confirms the value of satellite-derived transparency indicators and highlights the need to integrate uncertainties, resolution effects and call for synergies with in situ data to improve water quality assessments.



1 Introduction

Water transparency is a critical indicator of coastal ecosystem health, as it governs light availability for primary productivity and shapes the habitat conditions for a wide range of marine organisms. Transparency is influenced by both natural processes and human-induced pressures, including sediment inputs, nutrient enrichment, and physical disturbances. Monitoring transparency across diverse marine environments is essential for understanding the impacts of environmental change and anthropogenic activity on coastal and oceanic systems.

This study investigates long-term and seasonal variability in water transparency across a selection of contrasted marine and coastal environments using satellite-derived Secchi disk depth (ZSD) estimates from 1998 to 2022. The study sites include the estuary of Gironde and Loire rivers, the Gulf of Morbihan, the coastal waters around Mayotte in the Indian Ocean, and the broader region of the North-East Atlantic basin. These regions span a range of climatic and hydrographic regimes, from turbid estuarine systems subject to strong riverine influence and seasonal variability, to tropical reef ecosystems under increasing anthropogenic pressure, and oligotrophic offshore waters. This spatial diversity allows for a comprehensive evaluation of the natural and anthropogenic drivers of the transparency variability.

The objective of this study is threefold. First, we investigate seasonal and interannual variability in each study area and explore correlations with environmental drivers such as river discharge, extreme weather events and climatic fluctuations. Second, we assess long-term trends in Secchi disk depth over the 1998-2022 period, placing particular emphasis on the role of the uncertainty in the trend detection process. Uncertainty from satellite products is explicitly integrated in the trend estimation to improve the robustness of the analysis. Third, we examine how spatial resolution (1 km vs 4 km) influences the characterisation of these trends and evaluate the implications for monitoring in coastal environments. Together, these analyses aim to enhance our understanding of transparency dynamics in diverse marine settings and contribute to the development of reliable, satellite-based indicators for long-term water quality assessment.

2 Material and Methods

To assess the influence of environmental and anthropogenic drivers on water transparency, five regions were selected to represent a range of contrasting marine environments (Figure 1). These include: (1) the coastal waters off Morbihan, a semi-sheltered temperate system influenced by moderate urban and agricultural pressures; (2) the Gironde and (3) Loire estuaries, characterized by strong fluvial inputs, seasonal turbidity maxima, and intensive land use in their catchments; (4) Mayotte, a tropical coral reef lagoon system subject to both oceanic conditions and increasing anthropogenic stress; and (5) a broader domain encompassing the North-East Atlantic basin, which enables the analysis of spatial gradients and large-scale trends in transparency from coastal to open-ocean environments.

Water transparency was analysed using satellite-derived Secchi depth (ZSD) estimates from the Copernicus Marine Service. For the regions of interest (1), (2), (3), and (5), the dataset used was the North Atlantic ocean colour multi-sensor merged



product (Mercator Ocean International, 2025a), which provides daily composites at 1 km spatial resolution. For Mayotte
 (4), we used the global ocean colour multi-sensor merged product (Mercator Ocean International, 2025b), which directly
 provides monthly composites at 4 km resolution. In both cases, ZSD estimates were derived using the algorithm of Morel et al.
 (2007), which links chlorophyll-a concentrations to water clarity through bio-optical relationships. A detailed description of
 the datasets, their processing chain, and associated quality assessment is available in the corresponding Copernicus Marine
 Service Quality Information Documents (QUID) (Garnesson et al., 2025a). In addition to the satellite datasets, mean monthly
 river discharge data products were obtained from the SANDRE Hydrologic Service through the Eau France HydroPortail
 (Eaufrance, 2025), in order to evaluate the potential influence of freshwater inputs on transparency.

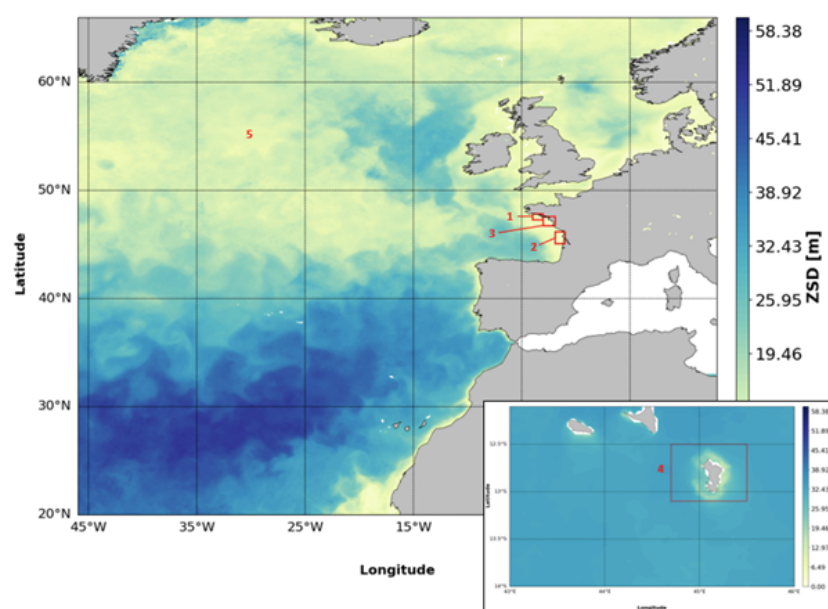


Figure 1. Map of Secchi disk depths for January 2020, showing the locations of the selected sites.

Prior to analysis, the daily satellite products were aggregated into monthly composites, using the arithmetic mean for ZSD
 values and the quadratic mean for the associated uncertainties. Monthly products were preferred as they reduce short-term
 noise, mitigate data gaps from cloud cover, and enhance the robustness of long-term trend detection by averaging out high-
 frequency variability and emphasizing persistent signals. For the Atlantic study sites, only pixels with at least 30% revisit
 coverage over the entire time series were retained to ensure sufficient temporal consistency.

To assess trends in ocean transparency while accounting for observational uncertainty, a Monte Carlo framework was im-
 plemented, combined with the Seasonal Mann-Kendall (SMK) test (Hirsch et al., 1982) and Theil-Sen's slope estimator (Hipel
 and McLeod, 1994). For each time step, normally distributed synthetic values were generated based on the reported relative
 uncertainties of the ZSD measurements. This process was repeated across a large number of simulations ($n=5000$) to produce
 ensembles of time series that reflect the inherent uncertainty in the observations. The SMK test was applied to each realization



75 to assess trend significance, while Theil-Sen's slope provided an estimate of the trend magnitude. By aggregating the outputs, we derived robust confidence intervals for the trend slope and calculated the frequency of statistically significant outcomes, thereby quantifying both the strength and reliability of observed trends in transparency. In parallel, the SMK test and Theil-Sen's slope estimator were also applied directly to the original time series at each study site without incorporating uncertainties, in order to provide a baseline reference for comparison with the Monte Carlo-based results.

80 2.1 Results and discussion

2.1.1 Seasonal variability and climatic driver

Time series of Secchi disk depth (ZSD) provide valuable insights into both the seasonal variability of water transparency and its interannual variability across the study regions. A first-order analysis reveals that among the regions considered (North-East Atlantic, Gulf of Morbihan, Loire Estuary, Gironde Estuary, and Mayotte), the deepest ZSD values are observed at the Mayotte
 85 site. This is consistent with its clear, oligotrophic waters, which are not influenced by major river inputs, yielding an average ZSD of 26 m. The Northeast Atlantic ranks second, with an average ZSD of 20 m. This relatively high transparency is explained by the predominance of offshore conditions, where sediment inputs and terrigenous influence are minimal. In contrast, water transparency is lower in coastal sites, with average ZSD values of 5.3 m, 6.4 m, and 8.1 m in the Gironde Estuary, Loire Estuary, and Gulf of Morbihan, respectively.

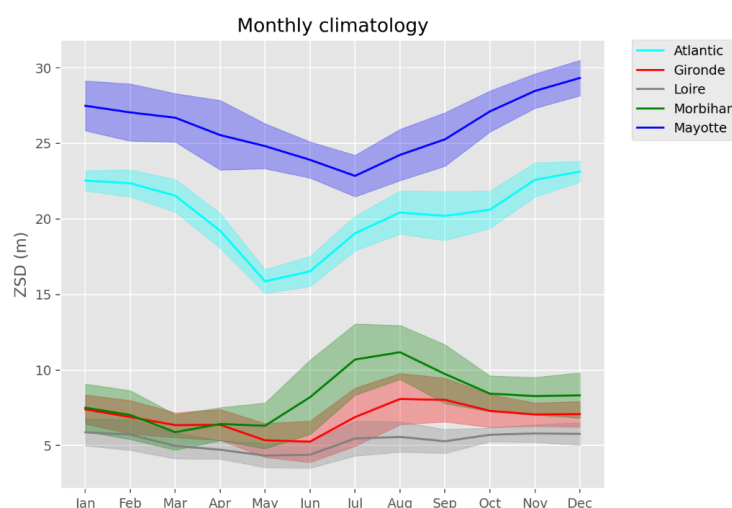


Figure 2. Monthly climatology of ZSD over the archive 1998-2022 for the region of interest. The shaded contours correspond to the standard deviation of each month.

90 Each of the studied regions exhibits its own characteristic seasonal pattern (Figure 2). To quantify this variability, a climatology of ZSD was constructed for each site (monthly means over the entire archive). The amplitude of the seasonal cycle varies across regions. The Gulf of Morbihan shows the strongest seasonal signal, with ZSD varying by up to 65% relative to the



annual mean between the most transparent and least transparent months. Notably, this site also shows the strongest interannual variability, averaging 20% and reaching up to 30% in June. At the opposite end, Mayotte displays the weakest relative seasonality (on average a 25% difference, or about 5.3 m, between the maximum and minimum ZSD). However, given the overall deep transparency at this site, the absolute seasonal amplitude remains significant between the two extremes. By contrast, the Loire Estuary presents the weakest absolute seasonality, with an average difference of only 1.5 m between seasons.

In the North East Atlantic, the clearest waters (maximum ZSD) occur in December, while the lowest transparency is observed in May. A similar seasonal pattern is found in the Loire Estuary, with the highest ZSD in January and the lowest in May. In the Gironde Estuary and the Gulf of Morbihan, minimum transparency is observed in June and March, respectively, whereas maximum values occur in August. These patterns highlight the influence of rainfall, late-winter mixing, and river discharge, with clearer waters typically occurring in summer when terrigenous inputs are reduced.

In Mayotte, the tropical climate induces different dynamics compared to metropolitan French sites. Counterintuitively, the lowest transparency occurs in July, during the dry season, while the maximum ZSD is recorded in December, during the rainy season. This suggests the presence of a temporal lag between meteorological seasons and water transparency cycles.

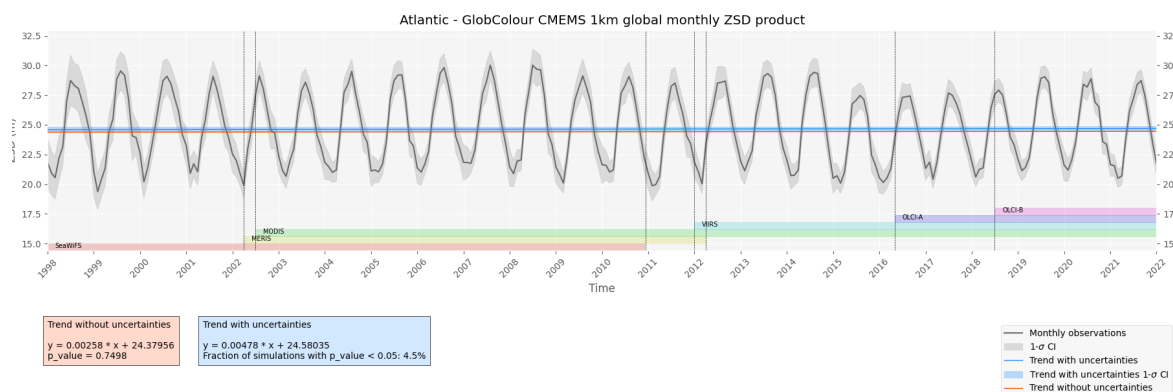
The correspondence between river discharge and precipitation data may provide valuable insights into interannual variability and the occurrence of significant climatic events. For instance, in the Gironde Estuary (Figure 3b), a pronounced minimum in water transparency (< 4 m) was recorded in June 2004, following a high discharge of the Garonne River ($> 2000 \text{ m}^3 \text{ s}^{-1}$), which transported large amounts of suspended sediments into the coastal zone. A similar situation occurred in May 2020, when sustained high river discharge during the preceding winter also resulted in reduced transparency.

Comparable events are observed in other regions. In the Loire Estuary (Figure 3c), strong discharges appear to explain the transparency minima (< 4 m) recorded in May 2001. Conversely, river discharge time series can also shed light on periods of unusually high transparency. For example, during spring–summer 2011, the Loire River discharge remained low for several consecutive months, reflecting reduced rainfall. Consequently, particle input to the coastal zone was lower than in other years, leading to increased water transparency ($\text{ZSD} > 8$ m).

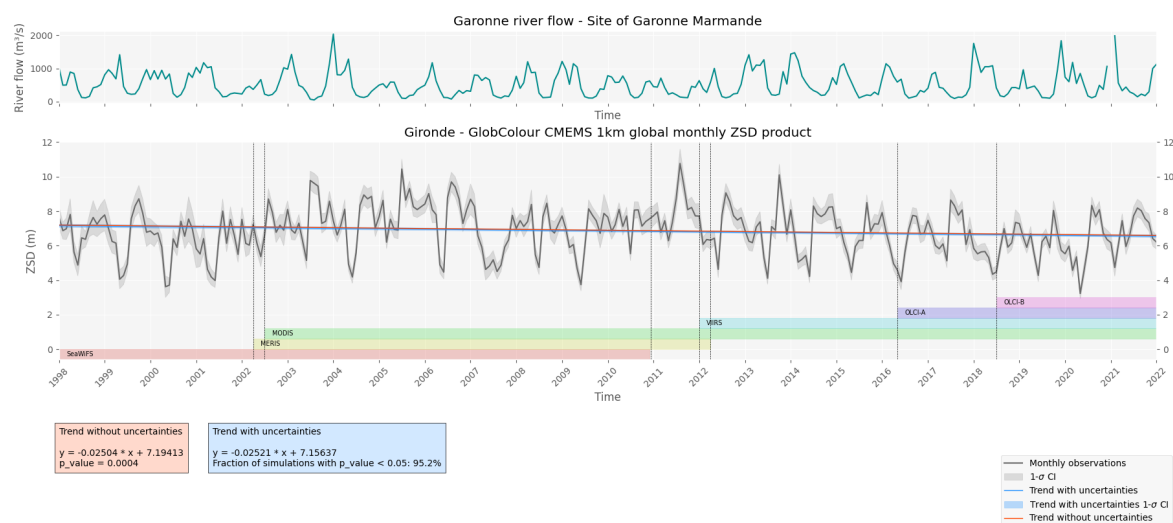
However, there are also periods when high river discharge does not coincide with marked minima in transparency. This suggests that, while river flow plays a key role in shaping seasonal variability, its influence on extreme transparency events is less consistent across the studied regions.

2.1.2 Long-term trend analysis

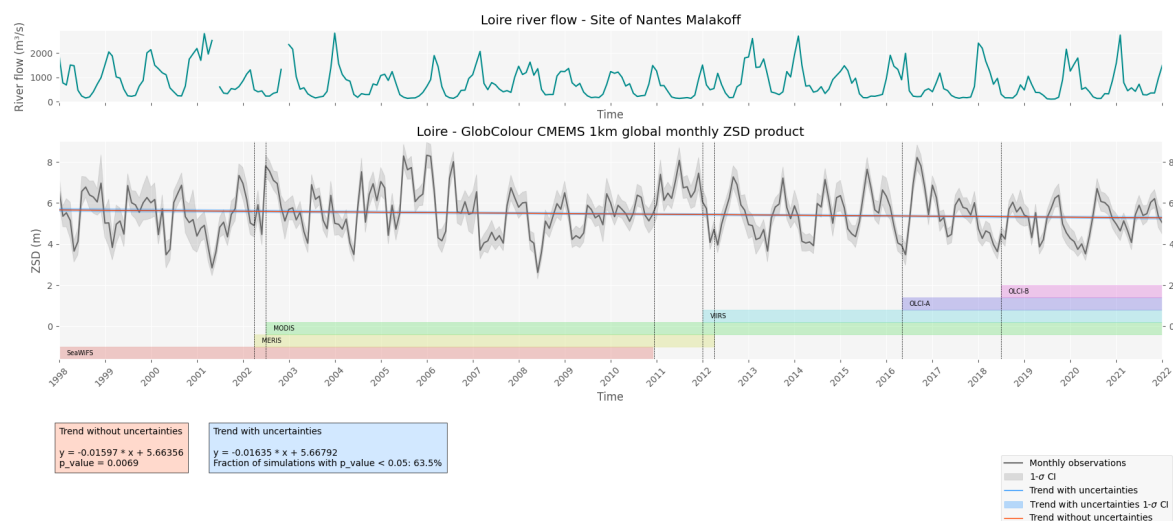
As detailed in the methods, long-term trends in water transparency were assessed using the Seasonal Mann–Kendall (SMK) test combined with Theil–Sen’s slope estimator, applied both directly to the ZSD time series and within a Monte Carlo framework that accounted for observational uncertainties (Figure 3). This dual approach allowed us to estimate trend magnitudes, test their statistical significance, and evaluate their robustness under uncertainty.



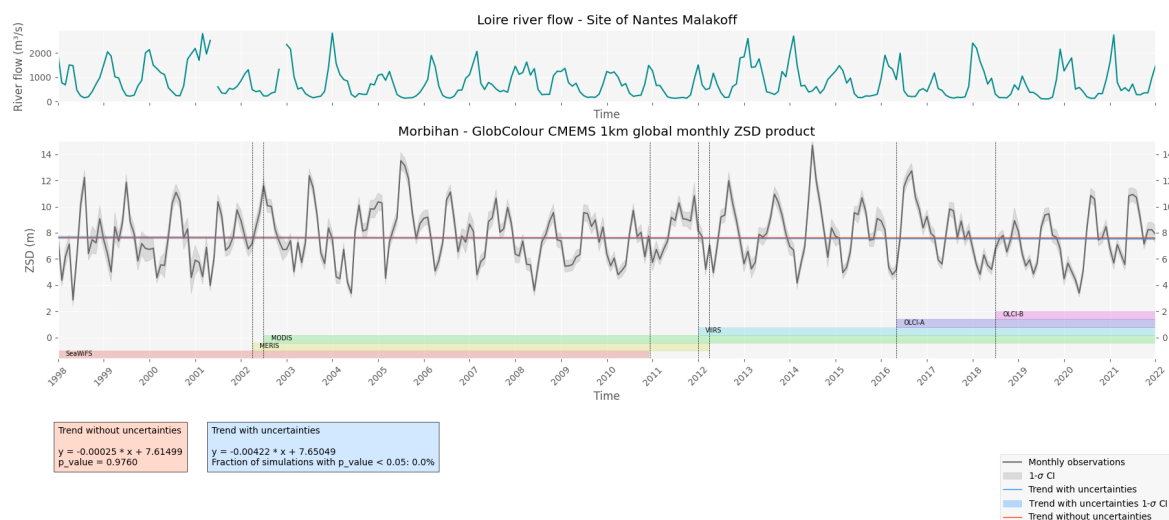
(a) North-East Atlantic, 1 km



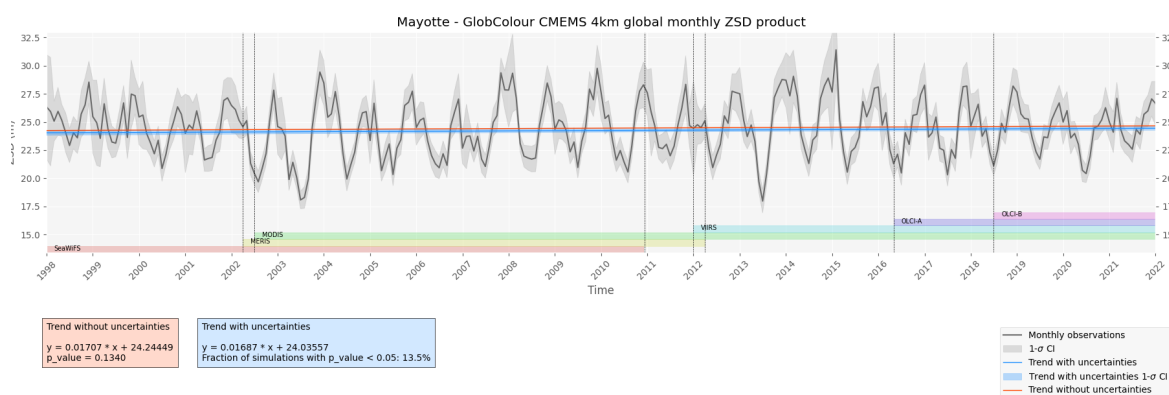
(b) Gironde, 1 km



(c) Loire, 1 km



(d) Morbihan, 1 km



(e) Mayotte, 4 km

Figure 3. Secchi disk depth (ZSD) time series from 1998 to 2022 across all regions of interest (grey), with trend estimates derived with (blue) and without (red) consideration of observational uncertainties.

Long-term trend analysis revealed contrasting patterns across the study areas. In the Atlantic zone, no significant trend was detected, regardless of whether uncertainties were considered (p -value = 0.7498, fraction of significant simulations = 4.5%) (Figure 3a). This lack of trend is consistent with the area being dominated by open waters, which are largely unaffected by external natural or anthropogenic inputs.

In the Gironde estuary, a significant decreasing trend in ZSD of 2.5 cm per year was observed using both approaches (p -value = 0.0004, fraction of significant simulations = 95.2%), indicating a robust and clear signal (Figure 3b). This decreasing trend can be linked to the increasing frequency of flood events observed in the monthly mean discharge of the Garonne River, which is the main source of sediment inputs in the study area. Specifically, five flood-related events with average monthly discharges



exceeding $1200 \text{ m}^3 \text{ s}^{-1}$ were recorded between 2010 and 2022, compared to only two such events during the earlier period 1998–2010.

In the Loire estuary, a decreasing trend in ZSD was detected only when uncertainties were not taken into account (p-value = 0.0069) (Figure 3c). However, when observational uncertainties were incorporated into the Monte Carlo framework, the proportion of simulations yielding a significant trend dropped to 63.5%. This discrepancy illustrates how failing to account for uncertainties may lead to overconfident interpretations of trend significance. It also suggests that, although a potential decrease in transparency is plausible, the signal remains close to the detection threshold, and conclusions should therefore be drawn with caution.

In the Morbihan gulf, no long-term trend in ZSD was identified (Figure 3d). As outlined above, the strong interannual variability of the signal complicates the detection of persistent changes and may obscure subtle long-term tendencies. Around Mayotte, no significant trend was detected either (Figure 3e). This result is consistent with the relatively stable environmental conditions in this region reducing the likelihood of detecting significant long-term variations.

2.1.3 Spatial comparison and regional implications

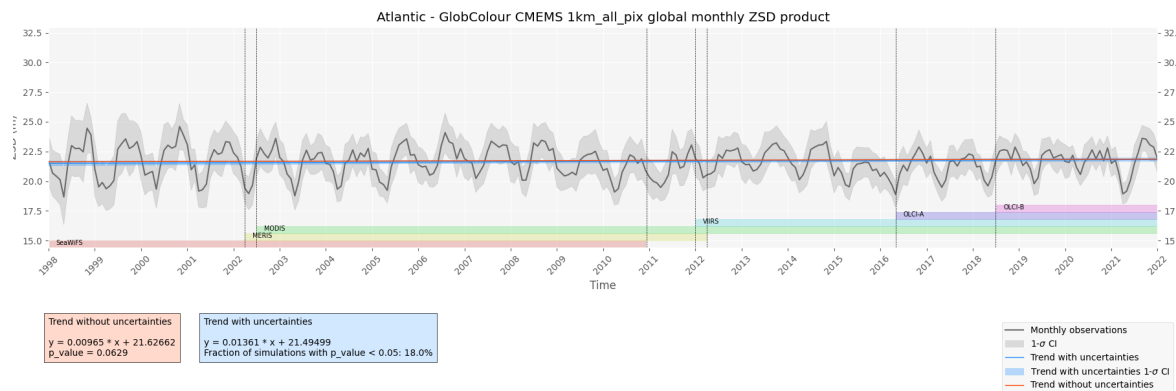
A comparative analysis of the Atlantic 1 km and 4 km products was conducted to evaluate potential differences in ZSD time series and associated trends. For both products, the study area was restricted to the North-East Atlantic, excluding the Mediterranean Sea, and no pixel revisit mask was applied to ensure consistency.

The seasonal ZSD signal exhibits a broadly similar pattern at both resolutions, though the 1 km product shows stronger inter-annual variability, likely reflecting its higher sensitivity to sub-mesoscale heterogeneity and localized dynamics. A systematic offset was observed, with mean ZSD values of 21.67 m for the 1 km product and 22.50 m for the 4 km product. This difference is attributable to the finer spatial resolution of the 1 km dataset, which better captures turbid coastal waters influenced by riverine inputs, resuspension, and elevated phytoplankton biomass, while the coarser 4 km resolution smooths these nearshore contributions. Uncertainty levels are comparable across resolutions, with averages of 1.40 m and 1.44 m for the 1 km and 4 km products, respectively.

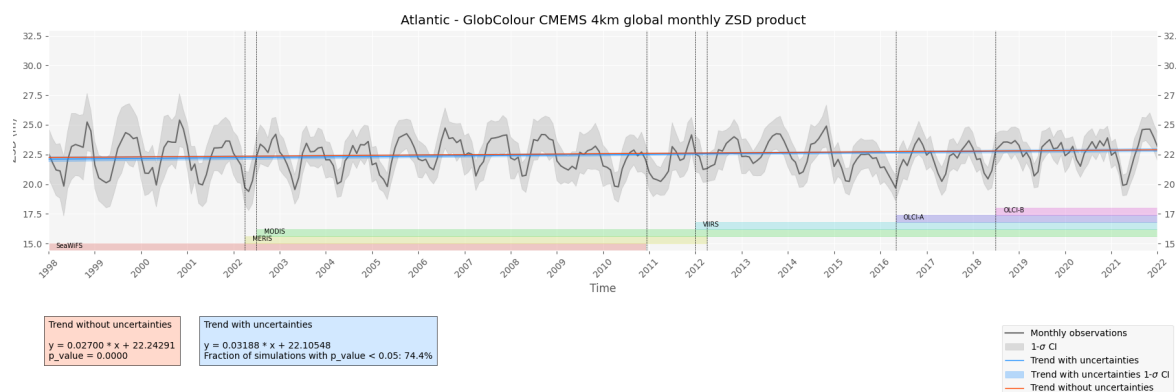
Trend analyses reveal a weak long-term increase in transparency across the North-East Atlantic basin. For the 1 km product, the Theil-Sen's slope indicates an average increase of 0.9 cm.yr^{-1} , with the SMK test yielding a marginally non-significant result (p-value = 0.0629). In comparison, the 4 km product suggests a stronger increase of 2.7 cm.yr^{-1} , with the trend highly significant (p-value < 0.0001). This difference in trend detection is also observed the same way across all other study areas. While the coarser product appears to provide a more statistically robust detection, this does not necessarily imply a more reliable representation of the underlying physical reality. The 1 km dataset, despite its higher sensitivity to small-scale variability and noise, better integrates fine-scale coastal and localized processes that are critical for accurately characterizing the actual evolution of water transparency in these areas. Consequently, both resolutions provide complementary insights: the 4 km product emphasizes the large-scale, smoothed signal, while the 1 km product captures localized dynamics that may ultimately drive the long-term trajectory of transparency.



165 It is worth noting the marked differences between the ZSD signals derived from the 1 km product and those obtained from
the 1 km product restricted to pixels revisited at least 30% of the time (Figure 4 and Figure 3, respectively). In the non-masked
case, the signal amplitude is lower, and a much higher interannual variability is observed. When all pixels are included, the
signal integrates more heterogeneous observations, particularly in coastal areas or near clouds where data are available more
sporadically. This tends to smooth the mean values, reducing the amplitude of the detected variations, but introduces greater
170 interannual variability due to differences in pixel coverage and availability from one year to the next.



(a) 1 km resolution



(b) 4 km resolution

Figure 4. Comparison of Secchi disk depth (ZSD) time series for the North-East Atlantic region over the period 1998–2022, derived from satellite products at 1 km and 4 km spatial resolutions. No pixel revisit mask applied.



3 Conclusions

This study provides a comprehensive assessment of water transparency dynamics across contrasting marine and coastal environments using satellite-derived Secchi disk depth (ZSD) over the period 1998–2022. By combining multi-decadal time series, robust statistical approaches, and explicit consideration of retrieval uncertainties, the analysis yields new insights into both the drivers and limitations of satellite-based transparency monitoring.

The results highlight pronounced spatial contrasts in transparency, ranging from highly turbid estuarine systems to oligotrophic tropical and offshore waters. Seasonal variability is strongly site-dependent, with riverine influence and climatic forcing emerging as primary drivers in temperate estuaries of the French metropolitan coast, while tropical systems such as Mayotte show distinct seasonal signatures, likely reflecting the interplay of meteorological and hydrodynamic processes. On an interannual scale, extreme river flow events strongly influenced transparency, though their impacts were not uniform across regions.

Long-term trend analysis revealed contrasting outcomes among sites. A robust and significant decrease in transparency was detected in the Gironde estuary, consistent with the rising frequency of high-flow events from the Garonne River. In the Loire estuary, a potential decrease was suggested but its significance weakened when observational uncertainties were considered, underlining the importance of explicitly accounting for product errors. In contrast, no persistent trend was observed in the North-East Atlantic, reflecting the dominance of stable open-ocean waters; in the Gulf of Morbihan, strong interannual variability likely masked any long-term tendencies; and around Mayotte, transparency remained stable due to the relative constancy of its clear, oligotrophic waters.

The comparison of 1 km and 4 km products further demonstrated that spatial resolution critically influences both mean transparency values and trend detection. While the coarser dataset yields more stable and statistically robust basin-scale patterns, the finer-resolution product captures essential local variability in estuarine and coastal waters.

Together, these findings confirm the utility of satellite-based indicators for monitoring transparency but also stress the need to integrate uncertainty estimates and resolution effects. Strengthening synergies with in situ observations and biogeochemical models will be essential to improve the reliability of long-term water quality assessments and their application in ecosystem management.

Author contributions. AP, MB, PB, and AM contributed to the conception and design of the study. QJ helped with the provision and pre-treatment of data. AP and MB drafted the manuscript. PB and AM provided important advice on the scientific analysis and interpretation of the results.

Competing interests. The authors declare that they have no conflict of interest.



200 References

- Bertrand, X., Collobert, M., Besson, D., and Puechberty, R.: Guide pratique Intercomparaisons de mesures de débit en rivière, Tech. rep., Eaufrance, <https://hydro.eaufrance.fr/documentation/guide-pratique-intercomparaisons-de-mesures-de-debit-en-riviere>, last access: 1 September 2025, 2016.
- 205 Colella, S., Böhm, E., Cesarini, C., Jutard, Q., and Brando, V. E.: EU Copernicus Marine Service Product User Manual for the North Atlantic Ocean Colour Plankton, Reflectance, Transparency and Optics MY L3 daily observations, Tech. Rep. OCEAN-COLOUR_ATL_BGC_L3_MY_009_113, Issue 5.0, Mercator Ocean International, <https://documentation.marine.copernicus.eu/PUM/CMEMS-OC-PUM.pdf>, last access: 1 September 2025, 2024a.
- 210 Colella, S., Böhm, E., Cesarini, C., Jutard, Q., and Brando, V. E.: EU Copernicus Marine Service Product User Manual for the Global Ocean Colour (Copernicus-GlobColour), Bio-Geo-Chemical, L3 (daily) from Satellite Observations (1997-ongoing), Tech. Rep. OCEAN-COLOUR_GLO_BGC_L3_MY_009_103, Issue 5.0, Mercator Ocean International, <https://documentation.marine.copernicus.eu/PUM/CMEMS-OC-PUM.pdf>, last access: 1 September 2025, 2024b.
- Eaufrance: French national database Eaufrance: Hydroportail, Eaufrance [data set], <https://www.hydro.eaufrance.fr/>, last access: 1 September 2025, 2025.
- 215 Garnesson, P., Mangin, A., Bretagnon, M., and Jutard, Q.: EU Copernicus Marine Service Quality Information Document for the North Atlantic Ocean Colour Plankton, Reflectance, Transparency and Optics MY L3 daily observations, Tech. Rep. OCEAN-COLOUR_ATL_BGC_L3_MY_009_113, Issue 5.1, Mercator Ocean International, <https://documentation.marine.copernicus.eu/QUID/CMEMS-OC-QUID-009-101to104-111-113-116-118.pdf>, last access: 1 September 2025, 2025a.
- 220 Garnesson, P., Mangin, A., Bretagnon, M., and Jutard, Q.: EU Copernicus Marine Service Quality Information Document for the Global Ocean Colour (Copernicus-GlobColour), Bio-Geo-Chemical, L3 (daily) from Satellite Observations (1997-ongoing), Tech. Rep. OCEAN-COLOUR_GLO_BGC_L3_MY_009_103, Issue 5.1, Mercator Ocean International, <https://documentation.marine.copernicus.eu/QUID/CMEMS-OC-QUID-009-101to104-111-113-116-118.pdf>, last access: 1 September 2025, 2025b.
- Hipel, K. W. and McLeod, A. I.: Time series modelling of water resources and environmental systems, vol. 45, Elsevier, 1994.
- Hirsch, R. M., Slack, J. R., and Smith, R. A.: Techniques of trend analysis for monthly water quality data, *Water Resources Research*, 18, 107–121, <https://doi.org/10.1029/WR018i001p00107>, 1982.
- 225 Mercator Ocean International: EU Copernicus Marine Service Product: North Atlantic Ocean Colour Plankton, Reflectance, Transparency and Optics MY L3 daily observations, <https://doi.org/10.48670/moi-00286>, [data set], 2025a.
- Mercator Ocean International: EU Copernicus Marine Service Product: Global Ocean Colour (Copernicus-GlobColour), Bio-Geo-Chemical, L3 (daily) from Satellite Observations (1997-ongoing), <https://doi.org/10.48670/moi-00280>, [data set], 2025b.
- 230 Morel, A., Huot, Y., Gentili, B., Werdell, P. J., Hooker, S. B., and Franz, B. A.: Examining the consistency of products derived from various ocean color sensors in open ocean (Case 1) waters in the perspective of a multi-sensor approach, *Remote Sensing of Environment*, 111, 69–88, <https://doi.org/10.1016/j.rse.2007.03.012>, 2007.