
# New RV Belgica

## Specific call for research proposals 2021

## *PiNS*

## *Particles in the Nort Sea*

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# PiNS

## Particles in the Nort Sea

**Contract – RV/21/PiNS**

## FINAL REPORT

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## ABSTRACT

Suspended particulate matter (SPM) is composed of minerals and organic matter (OM). Their interactions are driven by physical, chemical and biological processes, such as sorption of organic molecules to mineral surfaces, inclusion of smaller organic particles into small clay mineral aggregates, incorporation of organic particles into flocs. These processes vary along the land-ocean transition, leading to spatial and temporal variability in the size, shape, composition, concentration and transport pathways of the SPM. We have collected in situ data in the North Sea to characterise the SPM composition and concentration. Measurements of SPM, particulate organic carbon (POC), nitrogen (PON), transparent exopolymer particles (TEP), pigment and nutrient concentrations and mineralogical composition have been used to provide complementary information on the POC composition, such as the fresh, mineral-associated, detritus, slowly degrading, phytoplankton and heterotrophic fractions. Further a new approach of combining a pair of optical-acoustic sensors to estimate the total concentration and sand/mud composition of the SPM has been applied to long-term sensor data. The aim of the proposal is to change the scope of in situ observations from merely the collection of data towards the improvement and validation of mechanical or empirical models that describe fundamental aspects of SPM composition and its fluxes in whole the North Sea and the English Channel.

Keywords: Suspended particulate matter, Particulate organic matter, Dissolved organic matter, Clay minerals, Mixed sediments

# 1. INTRODUCTION

Suspended particulate matter (SPM) is present in all natural waters and plays a key role in biogeochemical, biological, and geological processes. Suspended particulate matter (SPM) is present in all natural waters and plays a key role in biogeochemical, biological, and geological processes. SPM drives key processes: transport, settling, deposition and resuspension of mineral and biogenic material, remineralization of organic matter (OM) and cycling of elements like carbon, nitrogen, and phosphorus. It has an important impact on aquatic ecosystems, as it influences light and nutrient availability and thus primary production, serves as a food source for suspension feeding organisms and impacts water quality. SPM is a mixture of mineral grains, microorganisms (such as bacteria and phytoplankton), detritus, adsorbed organic substances and xenobiotic particles (Ho et al. 2023; Huynh et al. 2024). OM in sediments is primarily associated with the mineral phase (Hedges & Keil 1995). In contrast, the particulate OM (POM) in suspension have a large range of lability and reactivity depending on environmental conditions, such as the dissolved oxygen concentration, mineral protection, priming effects or microbial activity (Ittekkot 1988; Mayer 1994; Arndt et al. 2013; Hemmingway et al. 2019; Liu et al. 2024). Particle interactions, controlled by physical, chemical, and biological processes, vary from nearshore to offshore, creating large spatial and temporal changes in SPM size, composition, and concentration.

The organic and mineral components interact on molecular to mm scale are ubiquitous. The primary interaction between them takes place on molecular to nano scale; they have been well described in reviews (Keil & Mayer 2014; Deng et al. 2022; Zhao et al. 2023). These interactions range from adsorption of organic molecules via hydrogen bonds or van der Waals forces to intercalation into expandable clay minerals and occlusion within clay mineral aggregates (flocculi). These organo-mineral associations form the building blocks or primary particles of complex biomineral (Lee et al. 2012; Shen et al. 2018). The interactions between organic molecules and minerals through adsorption/desorption kinetics show that a transition between the dissolved (organic molecules) and the particulate phase occurs (Kleber et al. 2021). The interactions of minerals and OM may stabilize part of the organic carbon or prevent further degradation (Hemingway et al. 2019). Organo-mineral association and other stable OM are found in marine sediments. Before being sequestered, they have been transported in suspension; an accurate estimation of this OM fraction in the SPM is up to now lacking.

These organo-mineral interactions and the dynamics (turbulence) of the ecosystem, explain why the particulate organic matter (POM) content of the SPM, increases with decreasing SPM concentrations (Schartau et al. 2019; Fettweis et al. 2022). This shift in the SPM composition across the cross-shore gradient, coupled with the influence of the physical forcing, is significantly impacting the SPM behaviour, such as size, density and settling velocity (Moulton et al. 2023; Yu et al. 2023). Offshore conditions characterized by lower turbulence and higher POM content promote formation of low-density organic aggregates (Fettweis et al. 2006; Maerz et al. 2016; Lee et al. 2019). Conversely, in nearshore shallow waters, lower organic content and greater turbulence make large low-density organic aggregates more volatile, as they break up and form during tidal cycles (Fugate & Friedrichs 2003; Maggi & Tang 2015; Maerz et al. 2016).

## 2. STATE OF THE ART AND OBJECTIVES

Shelf seas, such as the North Sea, are dynamic systems where fine-grained sediments interact with organic matter, significantly influencing the fate of both the components. We investigated the seasonal dynamics of POC and dissolved (DOC) organic carbon pools together with the inorganic components (minerals) along SPM concentration gradients from nearshore to offshore in the North Sea. The objective of the PiNS project is to characterize the SPM features in the English Channel and the southern North Sea along nearshore to offshore transects and along the water column through the collection of in situ data on concentration, composition and settling velocity. The PiNS project is linked to the Belspo BG-Part project (Desmit et al. 2025).

## 3. METHODOLOGY

To address the objectives a combination of field measurements, laboratory methods, data analysis, and a mechanistic modelling approach was used. The project relied on ship-based campaigns. However, due to the RV Belgica's non-availability in the second half, only two of the four planned campaigns were executed. We mitigated data gaps by incorporating existing in situ and sensor data from the Belgian part of the North Sea.

State-of-the-art field and analytical approaches have been used to characterize particle dynamics, particle size, turbulence, organic matter parameters, dissolved nutrients, salinity, and mineral composition. Optical and multi-frequency acoustic sensor measurements on benthic landers enabled identification of sand and mud components in the benthic layer. SPM samples (taken with the on-board centrifuge) have been analysed for the mineralogy using XRD method.

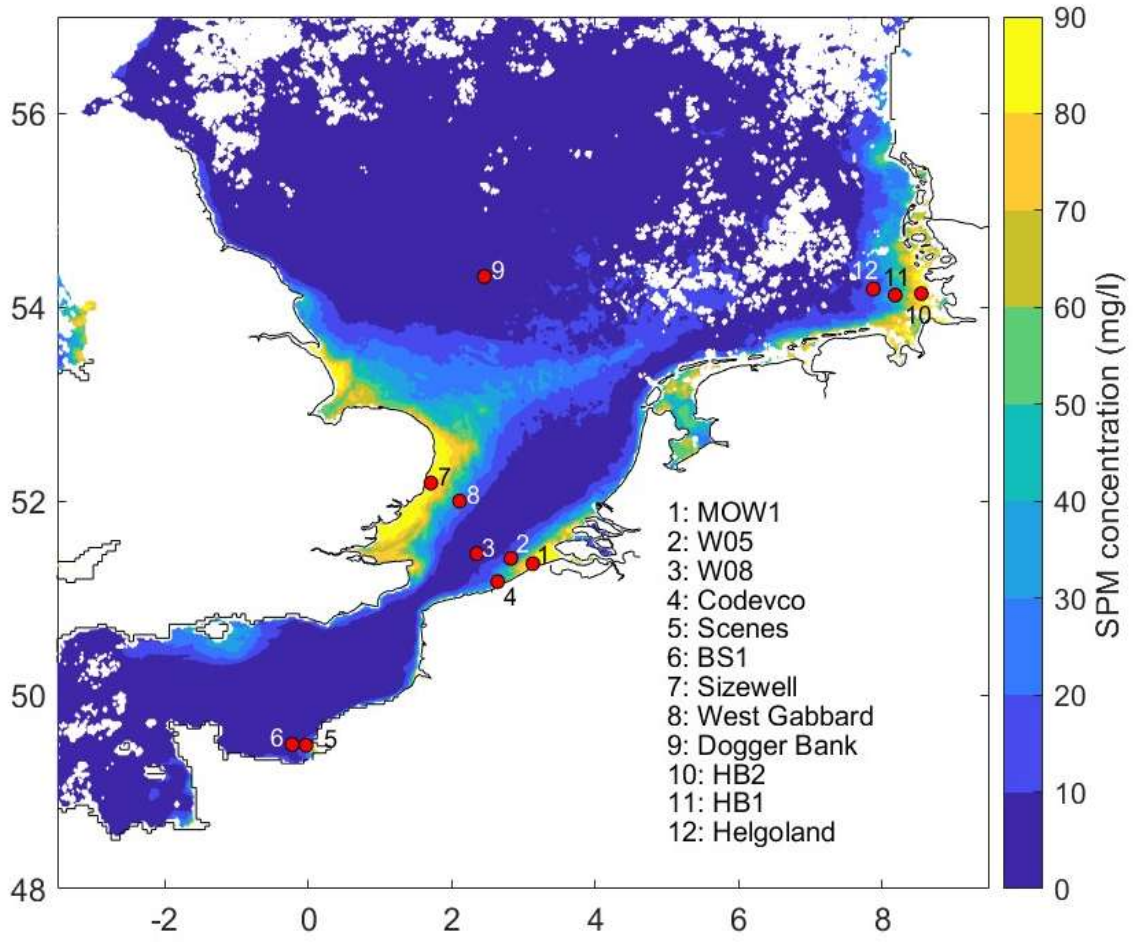


**Figure 1: Map of the sampling stations in the English Channel and southern North Sea. The background displays the averaged near surface SPM concentrations from Sentinel-3/OLCI images between November 2019 and March 2020.**

### *3.1 In situ sample collection and analysis*

The samples were taken in 12 stations all located along a cross-shore transect that ranges from the high turbid nearshore to the low turbid offshore in the English Channel and the southern North Sea in spring (March-April) and winter (December) 2023, see Figure 1. The Belgian stations MOW1, W05,

W08 and Codevco and the UK stations West Gabbard and Sizewell are in the Southern Bight of the North Sea; stations Scenes and BS1 in the Seine Bay (France), stations HB2, HB1 and Helgoland in the German Bight and station Dogger Bank in the central North Sea.

The sampling was done with Niskin bottles and a centrifuge with a water inlet at about 4 m below the surface. The data set from Niskin bottles consists of 1.5 or 2 hourly samples at the surface and near the bed collected during thirteen full tidal cycles and eight half tidal cycles, and two times two samples in one location. The centrifuge was collecting SPM during the full or half tidal cycle in all stations except for Dogger bank where the collection was done during transit (started 3 h before arrival until 3 after leaving the station). For station MOW1, W05 and W08 additional water samples data are available: MOW1 hundred full tidal cycles since 2004, W05 forty full and half tidal cycles since 2018 and W08 thirty-seven full and half tidal cycles since 2019.

The water samples were filtered on board and analysed in the laboratory to obtain the concentration of SPM, POC, particulate organic nitrogen (PON), Chlorophyll-*a* (Chl*a*), Phaeophytin-*a*, transparent exopolymer particles (TEP), inorganic nutrients and dissolved organic carbon (DOC). Bulk and clay mineralogy was determined for the centrifuge samples using X-ray diffraction. The analytical procedures are described in Fettweis et al. (2022; 2025) and Silori et al. (2025a; 2025b).

### *3.2 Sensor measurements and SCI method*

Accurate observation of SPM concentration typically requires a combination of one or more optical and acoustic (O/A) sensors with gravimetric measurements of filtered water samples (Sutherland et al. 2000; Bux et al. 2019, Fettweis et al. 2019). This is because both optical turbidity and acoustic sensors indirectly measure the backscattered signals of an optical beam or the acoustic backscatter as a proxy of SPM concentration. Whereas the gravimetric measurements of filtered water samples directly provide the ground truth reference of SPM concentration; a regression model needs to be acquired for the indirect sensor measurements of SPM concentrations. Owing to the strong dependence on particle size, density and shape, all sensors and the regression model must be recalibrated as soon as the SPM composition changes (Fettweis et. al. 2019; Haalboom et. al. 2021; Downing 2006; Voulgaris & Meyers 2004). All particles in a suspension respond to both O/A signals under a similar mechanism, albeit at great different degree, optical sensors are more sensitive to fine particles and flocs (<63 μm) (Downing 2006; Voulgaris & Meyers 2004) and acoustic sensors are more sensitive to coarser and denser particles (Hoitink & Hoekstra 2005; Bass et. al. 2007). Combining optical and acoustic sensors enhances detection of mud (optical) and sand (acoustic) providing a more complete information of the SPM composition.

A 3 MHz SonTek Acoustic Doppler Profiler (ADV) acoustic backscatter sensors and a D&A optical backscatter sensor (OBS) have been deployed in the Belgian nearshore area at the coastal observatory (MOW1), see Fettweis et al. (2016). This study uses the Sediment Composition Index (SCI) method to couple optical-acoustic measurements to infer SPM compositions and concentrations without or with limited water sampling calibrations. The concept and application of the SCI have been introduced and validated through a series of laboratory experiments and in situ studies in (Pearson et al. 2021; Tran et al. 2024). The proposed SCI concept, which is $SCI = 10\log_{10}(OBS_{signal}) - ADV_{signal}$, describes the relationship between the OBS and ADV signals.

# 4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

## *4.1 The transition between coastal and offshore areas in the North Sea*

Shelf regions' dynamic nature drives the strongly fluctuating patterns in SPM concentration. This variability is particularly pronounced within nearshore areas where fine-grained sediments are abundant (Figure 1). SPM concentration consistently shows a cross-shore gradient, high SPM concentrations in the shallow coastal waters and lower ones offshore. For the southern North Sea Postma (1984) stressed the importance of tidal asymmetries and particle trapping by density circulation and proposed the concept of a 'line of no return' located at some distance from the coast. This line would represent a boundary away from the coast beyond which any cross-transport of SPM towards the coast becomes improbable. Therefore, particulate organic matter (POM) produced nearshore tends to be processed within the coastal area and POM produced beyond the line tends to remain offshore. A nearshore utilisation and recycling of organic compounds is known to be significant when quantifying the fate of nutrient inputs from land (for example Asmala et al. 2017). In this perspective, only dissolved compounds (nutrients and dissolved organic matter) are exchanged across the line, which in turn may promote POM production further offshore. From another perspective, the line of no return can be interpreted as the outer limit of a transition zone between coastal and offshore areas, which depends on the width of a surf zone of a specific depth range. Within a transition zone the aggregated particles or flocs may also exhibit maxima in sinking velocity (Maerz et al. 2016). Likewise, such a transition zone can be associated with comparable concentrations of fresh and slowly degradable POM (Schartau et al. 2019; Fettweis et al. 2022), and it may also reveal significant changes in phytoplankton order richness (Jung et al. 2017).

We analysed temporal variations in SPM concentration and composition along the nearshore to offshore transition using the water samples collected during the sampling campaigns and from satellite images. Our hypothesis is that changes in the amount and composition of SPM over time and space, is needed to better distinguish between nearshore waters, where particles are controlled primarily by turbulence, resuspension, flocculation and deposition, and offshore regions, where variations in SPM concentration and composition are significantly controlled by the production and decay of plankton and detritus in the water column. Our approach applies a semi-empirical model (Fettweis et al. 2022) onto field data of SPM and particulate organic nitrogen (PON) concentration to extract PON properties (such as fresh, $PON_{fresh}$, and a refractory PON, $PON_{ref}$) along their cross-shore gradient. The model equations are then applied to remote sensing derived SPM concentration at the surface of the southern North Sea and the English Channel to derive the POM properties in a larger domain. We refer to Desmit et al. (2024) for the whole study, including a description of the methods, the results, and the discussion.

Using the model's best parameter estimates, we derived PON, $PON_{ref}$ and $PON_{fresh}$ concentrations from SPMC and applied it pixel wise to the satellite images in the southern North Sea and the English Channel. The uncertainties in the model parameters enhance the errors of the pixel wise values for $PON_{fresh}$ and $PON_{ref}$ in comparison with the satellite SPM concentration they are derived from. However, for geographical entities, which extend over tens of kilometres and comprise a larger number (10 to 100) of pixels, they still reveal robust patterns. We use ΔPON, the difference between $PON_{ref}$ and $PON_{fresh}$ concentrations ($PON_{ref}$ - $PON_{fresh}$), to highlight the spatio-temporal variations of the PON dynamics and composition. It is shown for the months of January and April 2020 in Figure 2.

ΔPON varies in time and space as both fractions $PON_{ref}$ and $PON_{fresh}$ undergo biogeochemical transformations. In winter, ΔPON shows the highest values at the coast due to the dominance of $PON_{ref}$ and rapidly decreases towards the offshore, where values are typically closer to zero as both $PON_{ref}$ and $PON_{fresh}$ are low and closer in concentration (Figure 2a). A notable exception offshore is the turbid Thames River plume carrying SPM from East Anglia across the sea to the German Bight and the coast of Denmark, and where $PON_{ref}$ dominates. In the spring (Figure 2b), ΔPON shows its minimum values in a narrow area close to the coast. In that area, the freshly produced fraction of PON in spring is found in higher concentrations than $PON_{ref}$, which leads to negative values of ΔPON. While $PON_{fresh}$ concentration in spring is a proxy for phytoplankton biomass, $PON_{ref}$ always reflects the mineral fraction of SPM, which predominantly originates from resuspended sediment particles.

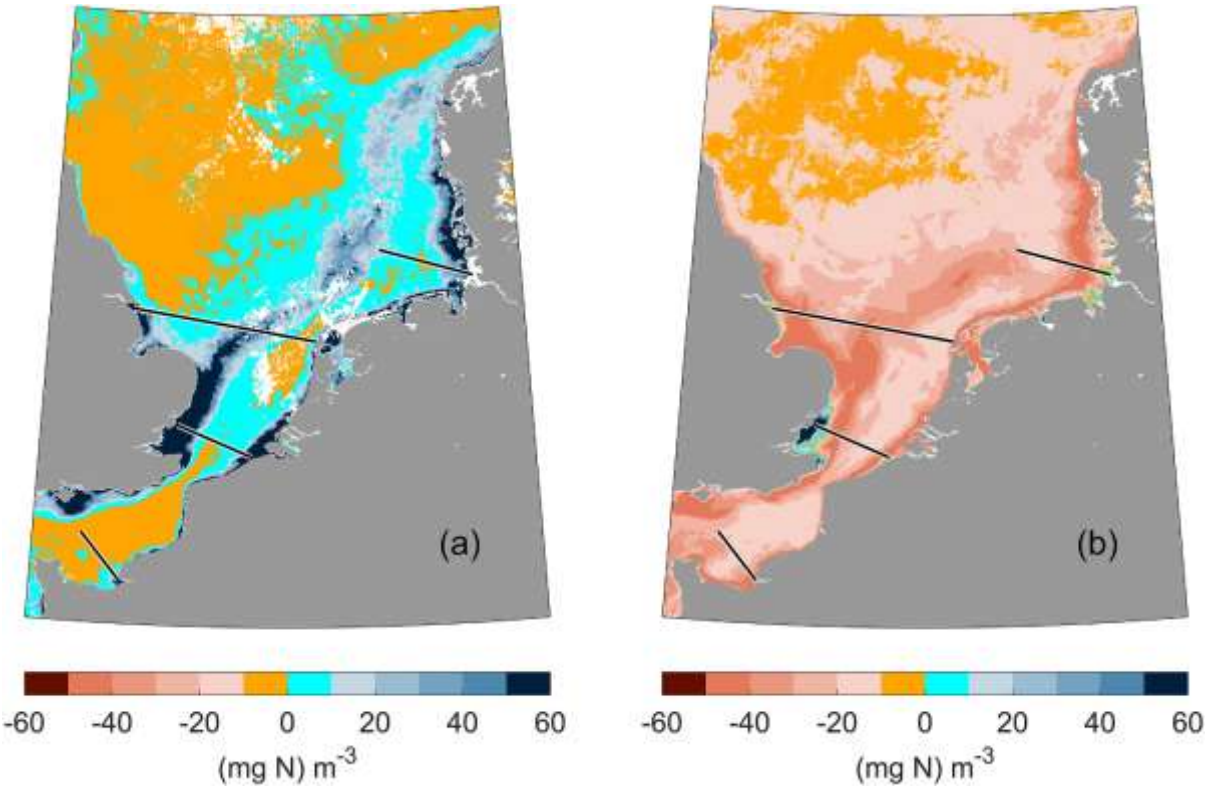


**Figure 2: Surface ΔPON (PONref-PONfresh) concentration [(mg N) m-3] in 2020, January (a) and April (b).**

Coastal areas with elevated SPM concentration, and with strong alongshore, weak cross-shore currents, and horizontal salinity gradients, feature a land-ocean transition zone that can be identified based on changes in particle compositions. Spatial and seasonal variabilities dominate the particle dynamics, suggesting that basin morphology and biological activity mainly control the processes at play. Bathymetry plays an important role in determining the turbulence effects on the flocculation and settling of particles. Our study shows that the coastal SPM concentration maximum and thus the maximum settling of particles generally occurs within depths below 20 m. The seasonal production of phytoplankton should enhance the particle settling and thus the accumulation of freshly produced particles at the bottom during the summer period. Due to vertical and horizontal density gradients and hydrodynamic (tidal) forcings, the particles in the transition zone may become subject to a near-bottom net transport towards the coast, hence maintaining the cross-shore gradient of particles. The offshore limit of the transition zone can thus be regarded as the 'line of no return' put forward by Postma (1984) across which any transport of SPM and its organic matter components becomes small

throughout the year, especially in the growing season. The dynamics of particles in the transition zone influence the fate of organic matter. The freshly produced POM and a substantial part of the refractory POM tend to remain in the shallower areas of the coastal waters, while a minor fraction of the refractory POM is exported to the offshore during the winter. The impact of such particle dynamics on the carbon and nitrogen cycles in shelf seas should be further quantified in the future with additional data on vertical profiles modelling tools.

### *4.2 Vertical profiles of SPM and Chl-a concentrations*

Whereas the cross-shore and seasonal patterns in SPM concentrations and composition are increasingly understood (Maerz et al. 2016; Desmit et al. 2024, see previous section), vertical and short-term variations in SPM composition remain poorly resolved. Studies demonstrate a relatively simple relationship between the concentration and the composition of the SPM along cross-shore transects where concentration changes by one to two orders of magnitude (Schartau et al. 2019; Fettweis et al. 2022). Due to tidal action, shallow coastal waters can also have a substantial variation in SPM concentrations over short time intervals, in addition to a vertical gradient in SPM concentrations (Winterwerp 2001; Sommerfield & Wong 2011). However, it remains unclear how SPM composition varies both over tidal cycles and within the vertical water column. Analogous to the cross-shore gradient in SPM composition, we expect a corresponding variation in POM content within the water column. Specifically, we anticipate the organic content of SPM to be greater near the surface than in deeper waters where SPM concentrations are higher. Either because of a greater contribution of less organic resuspended bed material to deeper waters or due to differential settling, which retains organic particles in the upper water column.

Short-term changes in SPM composition and subsequently in the behaviour of SPM flocs that often incorporate phytoplankton cells (Ho et al. 2022) may have important implications for phytoplankton light exposure in dynamic turbid coastal waters, where spring phytoplankton blooms develop over alternating spring-neap cycles (Blauw et al. 2012; Zhao et al. 2019). Hence understanding the vertical distribution of Chl*a* concentrations relative to SPM concentrations may provide insights into how phytoplankton deal with light limitation while being subject to tidal mixing. We hypothesize a temporally varying association between phytoplankton cells and SPM, subject to phytoplankton's response to environmental drivers. During periods characterized by close coupling, where phytoplankton cells actively participate in the formation and breakup of SPM flocs, we anticipate vertical Chl*a* profiles to closely mirror SPM concentration profiles in the water column. Conversely, during phases of decoupling from mineral SPM particles, phytoplankton cells may exhibit distinct resuspension and settling patterns within the water column influencing their residence times in the photic zone.

To this end, we analysed data collected over several tidal cycles from the MOW1 station in the Belgian coastal zone. We test the hypotheses that i) a vertical gradient in the POC content of SPM exists within the water column, analogous to the cross-shore gradient, with higher POC content in surface than in bottom waters, ii) this gradient in POC content is accompanied by differences in POC composition between surface and bottom waters reflecting differences in source contribution, as indicated by compositional indicators such as particulate organic carbon to nitrogen (POC/PON) and POC/ Chl*a* ratios, and iii) the Chl*a* and SPM association varies seasonally, with strong coupling in winter and partial decoupling during the productive period in spring, potentially indicating seasonal shifts in

dominant phytoplankton functional types. We refer to Silori et al. (2025a) for the whole study, including a description of the methods, the results, and the discussion.

Analysis of hourly profiles of SPM and Chl*a* concentrations during tidal cycles in spring (April 2019) and winter (November 2019) revealed notable disparities between the two seasons. Throughout both tidal cycles, SPM concentrations exhibited a tendency to increase towards the bed during periods of maximum current velocities, whereas they remained relatively constant on the vertical exhibiting lower values on average during the slack periods (Figure 3a and 3b). Concurrently, Chl*a* concentration profiles in November closely mirrored the corresponding SPM patterns (Figure 3b). However, in April, distinct differences emerged between the vertical profiles of Chl*a* and SPM concentrations. Most notably, about half of the Chl*a* profiles in April exhibited inversions, where concentrations decreased towards the bed (Figure 3a, Profiles 1–4, 7–8). Similar patterns as in November have been found during the months May–August and October–November and as in April during the months March and September. Van der Hout et al. (2017) observed consistently high Chl*a* concentrations closer to the bed in the Dutch coastal turbidity maximum. The authors suggest a uniform Chl*a* distribution with an increase only near the bed, contrasting with the exponential increase in SPM concentrations towards the bed. While these findings align with our observation of increasing Chl*a* content on moving up the water column, we also note higher Chl*a* concentrations closer to the surface and relatively lower concentrations closer to the bottom during the spring months. This contrasts with the suggestion of uniform Chl*a* distribution throughout the large part of the water column, which appears unlikely based on our data.

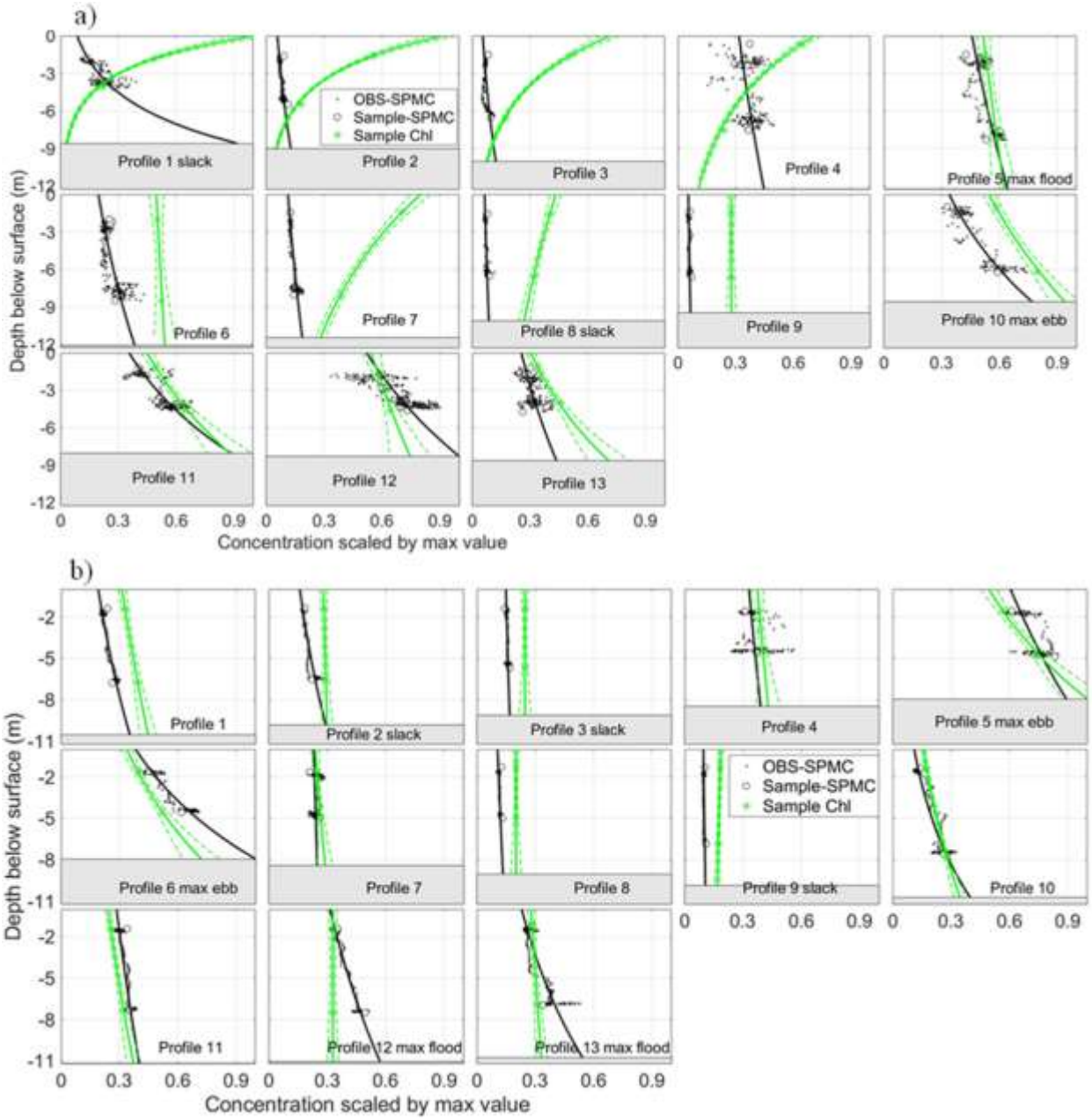


**Figure 3: Hourly vertical profiles of SPM (black line) and Chla (green line) concentrations scaled by the maximum value during the tidal cycle in April 2019 (SPM: 366 mg/l, Chla: 33 µg/l) (a) and November 2019 (SPM: 272 mg/l, Chla: 11 µg/l) (b). The Chla profile uncertainty (expressed as a standard deviation is shown as dashed lines. The SPM profile uncertainty, expressed as R2, is between 0.5 and 0.9, except for profiles 4, 8, 9 and 13 in April and profiles 4, 7 and 9 in November). The light grey box represents the seabed.**

To better quantify the accumulation of Chl*a* in the surface waters, we determined the average mass of SPM and Chl*a* within the estimated photic layer (generally between 0.5 and 3 m). The depth-integrated concentration of SPM within the photic layer during a tidal cycle remains conservative across seasons (Figure 4a). This lack of variability aligns with expectations, considering that the vertical light attenuation coefficient, which determines the photic layer, is mainly controlled by SPM concentrations. However, the mass of Chl*a* within the photic layer during a tidal cycle exhibits seasonal variation, being higher during spring and summer compared to winter and autumn, yet it remains constant within each of these seasons (Figure 4a). Further we calculate the percentage of SPM and

Chl*a* within the photic layer (Figure 4b). The results reveal that the percentages of Chl*a* and SPM within the photic layer are identical during a tidal cycle in winter. However, during spring, the Chl*a* percentage in the photic layer approaches 10%, while the SPM percentage is notably lower at 3%. Similarly, in summer, the Chl*a* percentage increases up to 30%, whereas the percentage of SPM in the photic layer rises to 18%. This observation substantiates the enrichment of Chl*a* compared to SPM in the photic layer and aligns with the established POC/SPM relationship, indicating an inverse correlation between SPM concentration and the POC content.

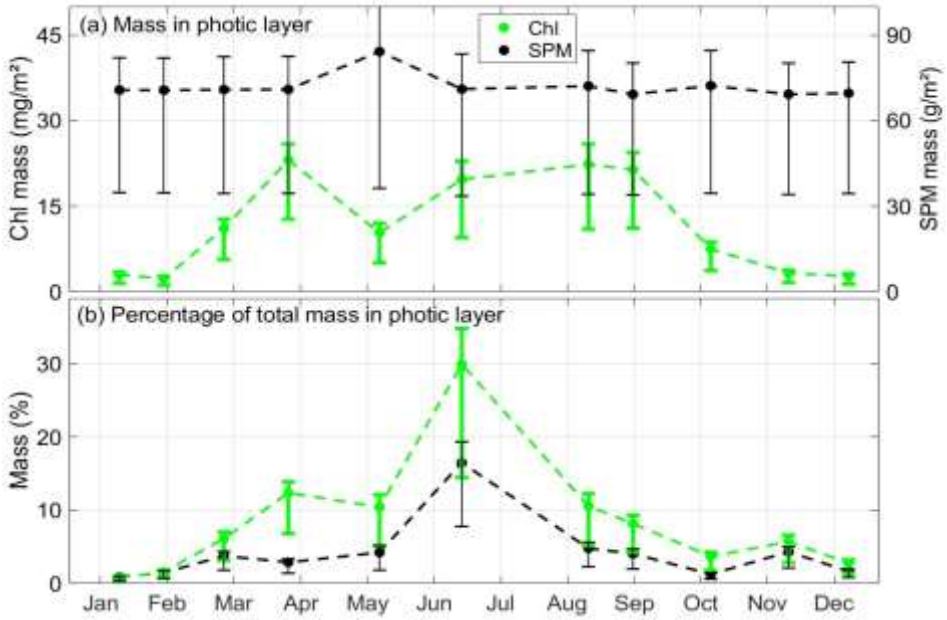


**Figure 4: (a) Mass of Chla and SPM integrated over the photic layer per tide and unit area. (b) Percentage of Chla and SPM in the photic layer with respect to their total mass available for resuspension during a tide. The dashed lines consider a photic layer for a = 4.6 (1% light attenuation, see eq. 2), the error bars do not represent random uncertainties, but encompass photic layers between a = 6.9 and a = 2.3 (0.1% and 10% light attenuation).**

Our results show that the vertical enrichment of POM at the surface is governed by the same process as along the horizontal nearshore-offshore gradient, i.e. differential settling of mineral vs organic rich particles, a fundamental property of SPM in turbid areas. Additionally, the seasonal variation in the composition of SPM between surface and bottom waters, peaking in summer, corresponds to notable differences POM quality at these depths. This highlights the importance of sampling both surface and bottom waters, particularly for particulate parameters exhibiting vertical gradients, even in well-mixed waters like MOW1. Our analysis of the mass of SPM within the photic layer, which remains conservative across months, suggests that the seasonally varying composition of SPM (Chl*a*/SPM) plays a more significant role. This calls for looking in more detail at the strategies deployed by different types of phytoplankton to increase their buoyancy or associate with mineral particles. Such associations influence the settling properties of particles and understanding them can improve modelling approaches to better estimate the fate of organic carbon in coastal waters.

### *4.3. Clay minerals and the lability of organic carbon in suspension*

The OM plays an important role in many coastal and estuarine processes, such as the formation of biomineral deposits and the sequestration of carbon; the variation in water clarity and its influence

on primary production; flocculation and the settling of biomineral flocs; or the transport of pollutants (see for example Pedersen & Calvert 1990; Mayer 1995; Chen et al. 2016; Singh et al. 2016; Blattmann et al. 2019; Opdal et al. 2019; Fettweis et al. 2022; Silori et al. 2025a). The interactions of minerals and OM may stabilize part of the organic carbon or prevent further degradation (Hemingway et al. 2019). We argue in this study (see Fettweis et al. 2025 for the whole study, including a description of the methods, the results and the discussion) that the organic matter in suspension can be classified into three groups: A mineral-associated, a slowly degrading or non-metabolizable, and a fresh and consumable fraction that encompasses the living cells and their exudates. This classification reflects the various organo-mineral interactions better than the two types of POM (refractory and fresh) that were put forward by Schartau et al. (2019) in their semi-empirical POM-SPM model (see also section 4.1). We splitted their refractory fractions (called $POC_{ref}$ in section 4.1) into a slowly degrading fraction ($POC_{slow}$) and a truly mineral-associated fraction ($POC_{mineral}$). The latter comprises the organic carbon (OC) that is adsorpt onto mineral surfaces, and which depends on the specific surface area of minerals (Keil & Mayer, 2014). Our study estimates three POC fractions in SPM through a mineralogical analysis of the SPM and the application of the Fettweis et al. (2022) POC-SPM model.

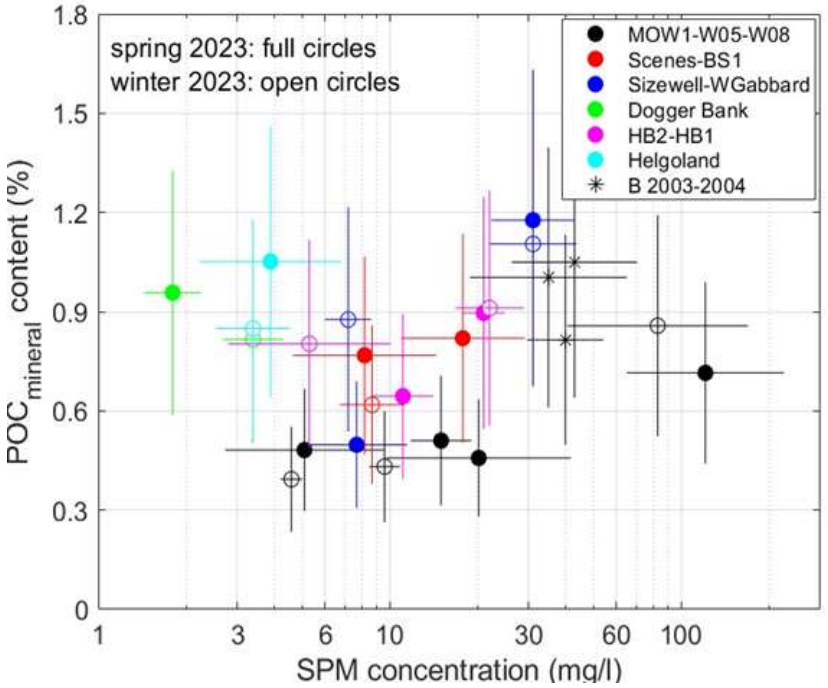


**Figure 5: $POC_{mineral}$ content of the SPM derived from mineral SSA as a function of SPM concentration. The vertical error bars are the standard deviation from the SSA of the minerals and the horizontal ones the standard deviation from the full or half tidal averaging. The location of the stations is shown in Figure 1. 'B 2003-2004' are additional data from the Belgian part of the North Sea.**

The bulk POC content is calculated from water samples (POC and SPM concentration) and provides a value that is based on the filterability of the particles. It is our reference for the total POC content of the SPM. The mineral-associated fraction ($POC_{mineral}$ content) is derived from the mineral specific surface area (SSA) as described by Keil & Mayer (2014). The $POC_{mineral}$ fraction is, however, not necessarily constant in composition as it may occur in an actively reversible sorption equilibrium (Blattmann et al. 2019; Kleber et al. 2021). With the SPM-POC model, two fractions are obtained, one that contains the fresh and consumable fraction that encompasses the living cells and their exudates (Fettweis et al. 2022). This $POC_{fresh}$ fraction has a seasonal cycle driven by phytoplankton production

and hence light, nutrient availability and temperature and a large fraction of it is rapidly recycled (Muylaert et al. 2006; Schartau et al. 2019). The other fraction, $POC_{ref}$, contains the mineral- associated fraction and a fraction with a longer, but variable, turnover time. It may consist amongst others of POC that is protected by occlusion into small clay mineral aggregates (flocculi) and other slowly degradable OM. The partitioning of organic carbon into two pools has been widely used in the literature, however, no clear definition exists on what constitutes labile or refractory material as it depends on the interactions between the OM and the environment. Therefore, many authors consider the degradability of the POC as a continuum between two different extremes: fast degradation within hours to days and preservation on geological time scales (Middelburg et al. 1993; Mayer 1995; Dauwe et al. 1999; Liu & Xue 2020; Baltar et al. 2021). Our approach makes a distinction within the non-fresh fraction. The $POC_{mineral}$ fraction is the most refractory one and is only varying with the mineral composition of the SPM (considering that available mineral surfaces are always saturated with their associated OM). The POC fraction that remains after subtraction of the $POC_{mineral}$ from the bulk POC concentration can be split into a fresh and labile fraction ($POC_{fresh}$) and a fraction that is slowly degradable ($POC_{slow}$) The total POC concentration can then be written as:

$$POC = POC_{mineral} + POC_{slow} + POC_{fresh} \qquad (1)$$

The $POC_{mineral}$ content of the SPM in the measuring stations as a function of SPM concentration is shown in Figure 5. The large spread in the data is related to the heterogeneity in clay mineral content and clay mineral composition. This variability may occur on spatial and temporal scales, for instance when comparing Helgoland to the nearshore HB2, or HB1 in winter and in spring. Despite the large spreading, an increase in $POC_{mineral}$ content with increasing SPM concentration can be observed in most areas, with the exceptions of Dogger Bank, Helgoland and HB1 in winter. Irion et al. (1987) report that under normal conditions (without human activities), river sediments are trapped in the estuaries (Elbe, Weser). They argue that the recent mud accumulation SE of Helgoland is the result of loss of SPM by dredging operations in the estuaries, increasing the natural sediments discharge, and thus favouring export of SPM towards the German Bight. This finding might explain the peculiar result from Helgoland and/or HB1, which are more typical for the nearshore. The differences between regions, for example the lower increase in $POC_{mineral}$ content in the Belgian stations (MOW1-W05-W08 and Codevco) when compared to the German and UK stations indicates the heterogeneity of SPM composition in the study area, and underlines that the SPM in the North Sea has different provenances (Adriaens et al. 2018). A mineralogical composition in space and time is therefore needed to differentiate accurately between the more refractory POC fractions ($POC_{mineral}$ and $POC_{slow}$).

A typical feature of shelf seas is the persistence of a horizontal cross-shore gradient, with higher SPM concentrations in the shallow coastal waters and lower concentrations offshore. Desmit et al. (2024) confirmed the concept of 'line of no return' of Postma (1984) by using the POM composition and content of the SPM (see section 4.1). Such a line is located at some distance from the coast and functions as a zone with low cross transport of SPM. The data from the Belgian (MOW1, W05, W08), UK (Sizewell, West Gabbard) and German (HB2, HB1) stations show a decrease in clay mineral content towards the offshore and confirm that a transition zone exists, not only in the POC content and composition but also in the mineral content and composition. The line of no return can be interpreted as the outer limit to a transition zone where similar concentrations of $POC_{fresh}$ and $POC_{ref}$ prevail (Desmit et al. 2024), changes in phytoplankton order richness take place (Jung et al. 2017) and lowering of the mineral specific surface area per unit of SPM occur. We can distinguish two $POC_{mineral}$

contents: one offshore and one inshore the transition zone, see Table 1. The POC is thus less refractory offshore than nearshore.

**Table 1: Averaged $POC_{mineral}$ content (± uncertainty) of the SPM in cross-shore direction for 4 regions in the North Sea and English Channel based on Figure 5 (data 2023).**

| | high turbid | low turbid |
|---|---|---|
| Belgian transect | $0.79 \pm 0.22$ | $0.45 \pm 0.09$ |
| UK, F and G transect | $0.98 \pm 0.17$ | $0.58 \pm 0.13$ |
| Helgoland | - | $0.90 \pm 0.20$ |
| Dogger Bank | - | $0.89 \pm 0.24$ |

### *4.4 $POC_{mineral}$ and DOC*

The sample-POC:DOC ratios as a function of SPM concentration are displayed in Figure 6. The figure shows that DOC concentrations exceed the POC concentration at low SPM concentration, while above about 30 mg/l the POC concentration is higher. The classification of OC into particulate and dissolved components can be distorted by the interaction of smaller dissolved molecules with mineral particles (Keil et al. 1994). These molecules, though intrinsically bound to be dissolved or colloidal, may be retained on filters due to their association with minerals, increasing the measured amount of POC. From a compositional point of view, only $POC_{fresh}$ and $POC_{slow}$ depend on phytoplankton production, remineralization, erosion or terrestrial input as opposed to $POC_{mineral}$, which depends only on the mineral composition. This effect is likely to be pronounced in nearshore turbid waters, which have higher mineral particle concentrations compared to clearer offshore waters.

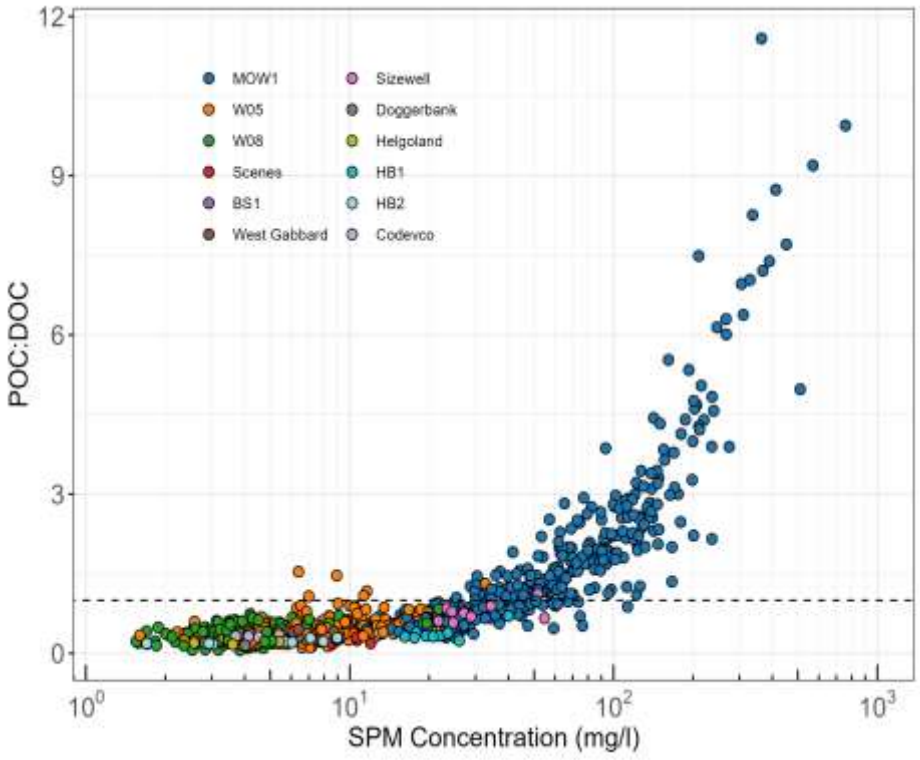


**Figure 6: Sample-POC:DOC ratio (1:1 dashed line shown) as a function of SPM concentration. Additional data have (2019-2023) been added for stations MOW1, W05, and W08.**

Offshore waters generally exhibit sample-POC/DOC ratios well below 1, indicating a dominance of the DOC fraction (Osterholz et al. 2021), whereas ratios greater than 1 have been reported in turbid waters (Abril et al. 2002; Zhao & Gao, 2019). Herman & Heip (1999) demonstrated systematic variation in sample-POC/DOC ratios as a function of SPM concentrations in European estuaries, suggesting significant exchange between particulate and dissolved pools through adsorption and desorption processes. Similarly, along the Belgian transect, sample-POC/DOC ratios greater than 1 are frequently observed at MOW1 but become less common at comparatively deeper and less turbid stations like W05 and W08. The OC adsorbed onto mineral particles is dynamically exchanging with the DOC and thus influencing its fate and concentration. Clearly, such adsorption stabilizes the organic compound and may delay its degradation and loss (Keil et al. 1994; Hemingway et al. 2019), although some transformation of the adsorbed OC continuously occurs (Kleber et al. 2021). The desorption of organic compounds can lead to their further transformation and replacement by other organic compounds present in the marine system (Blattmann et al. 2019). However, this process is not sufficient to explain the variation in POC/DOC along the SPM concentration gradient as suggested by Herman & Heip (1999) for estuaries. Subtracting $POC_{mineral}$ from the sample-POC and adding it to the DOC concentration results in a lower POC/DOC ratio, however, it still remains 2-4 times higher nearshore than offshore. This higher nearshore $(POC-POC_{mineral})/(DOC+POC_{mineral})$ ratio can be further explained by phytoplankton production, advection and diffusion, density gradients and seabed erosion. The production of POC and DOC is higher nearshore because of a higher phytoplankton production due to higher nutrient concentration. This higher DOC production will be affected by down-gradient diffusion, tidal or wind-driven advection and by the occurrence of a horizontal density gradient, initiated by freshwater inflow by rivers that causes a net particle transport towards the coast (Desmit et al. 2024). For the Belgian nearshore, additional input of POC results from the erosion of OM rich muddy sediments (Adriaens et al. 2018).

### *4.5 Spatio-temporal variation in POC and DOC dynamics*

As a dissolved component, DOC is transported differently than POC in the aquatic systems, leading to distinct dynamics. Despite differing dynamics, DOC and POC are interconnected through continuous aggregation, disaggregation and degradation processes (Kharbush et al. 2020). One such mechanism is the adsorption and desorption of DOC molecules onto mineral surfaces, which shifts organic matter between the dissolved and particulate phases, maintaining a dynamic equilibrium (Hermann & Heip 1999; Abril et al. 2002, see section 4.4).

The main aim of this study was to characterize and quantify various contributors to POC in turbid shelf seas. We used established methods to estimate phytoplankton biomass ($POC_{phyto}$), heterotrophic biomass ($POC_{het}$), and POC adsorbed onto mineral surfaces ($POC_{mineral}$). Detrital carbon biomass ($POC_{det}$) is calculated by subtracting $POC_{phyto}$, $POC_{mineral}$, and $POC_{het}$ from the measured POC in water samples. $POC_{det}$ may include contributions from detritus of pelagic and benthic primary producers (e.g. microalgae), heterotrophic organisms (e.g. zooplankton and bacteria), and terrestrial POC. The approach here is somewhat different from the one presented in section 4.1 and 4.3, in that the fresh POC is not derived from the Fettweis et al. (2022) empirical model, but is the sum of the heterotrophic and autotrophic POC fraction estimated with the relationships of Jakobsen & Markager (2016), Gasol et al. (1997) and Duarte et al. (2000). Similar to equation 1, the total POC can than be written as:

$$POC = POC_{mineral} + POC_{det} + POC_{phyto} + POC_{het} \qquad (2)$$

The sum of $POC_{phyto}$ and $POC_{het}$ is approximately equal to $POC_{fresh}$ fraction and $POC_{slow}$ to $POC_{det}$:

$POC_{fresh} \approx POC_{phyto} + POC_{het;}$ $POC_{slow} \approx POC_{det}$

Estimating the POC components, particularly $POC_{phyto}$, is necessary to understand the seasonal and spatial variations in POM composition proxies (POC:PON and POC:Chl*a* ratios), especially when phytoplankton dominates POM. Our analysis is based on multi-year (2019–2023) SPM, POC, PON, and Chl*a* concentration data collected at three sampling locations across the Belgian coastal-offshore SPM concentration gradient (Figure 1). The seasonal variability of SPM, POM, and Chl*a* concentrations in Belgian waters has been described (Rousseau et al. 2006; Desmit et al. 2020; Fettweis et al. 2022), the variability of the different fractions composing POC (i.e. the compositional dynamics) remains poorly understood and has been investigated here. We refer to Silori et al. (2025b) for the whole study, including a description of the methods, the results and the discussion.

$POC_{phyto}$ shows seasonal variation somewhat similar to Chl*a* concentrations across all three stations (Figure 7a). At MOW1, $POC_{phyto}$ ranged from 0.08 to 0.67 mg/l, with a first peak in April and a second, higher peak in July (Figure 7b). In contrast, W05 and W08 displayed lower ranges (0.02–0.43 mg/l at W05 and 0.01–0.31 mg/l at W08), with a comparable first peak in April but a delayed, smaller second peak in August. The estimated $POC_{phyto}$:POC (%) values at MOW1 were generally lower than at the other stations, ranging from 1.2% to 40.1%, with values exceeding 15% only during summer and early autumn (Figure 7c). At W05, low winter values (January: 3.85%) steadily increased, with high value in April (≈35.29%) and remained high through summer (35.39–46.88%), before gradually declining into winter. Similarly, at W08, winter lows steadily rose to a peak in April (48.83%), but the values then decreased, with only a slight summer increase (17.46–27.45%) (Figure 7c). The monthly average POC:PON and POC:Chl*a* ratios at all three stations showed significant negative logarithmic regression with the $POC_{phyto}$:POC (%) ($p$<0.01), suggesting that the higher fractions of $POC_{phyto}$ are associated with lower POC:PON and POC:Chl*a* ratios (Figure 7d, e). Conversely, TEP:SPM ratio demonstrated a positive linear regression with $POC_{phyto}$: POC ($p$<0.01) (Figure 7f).

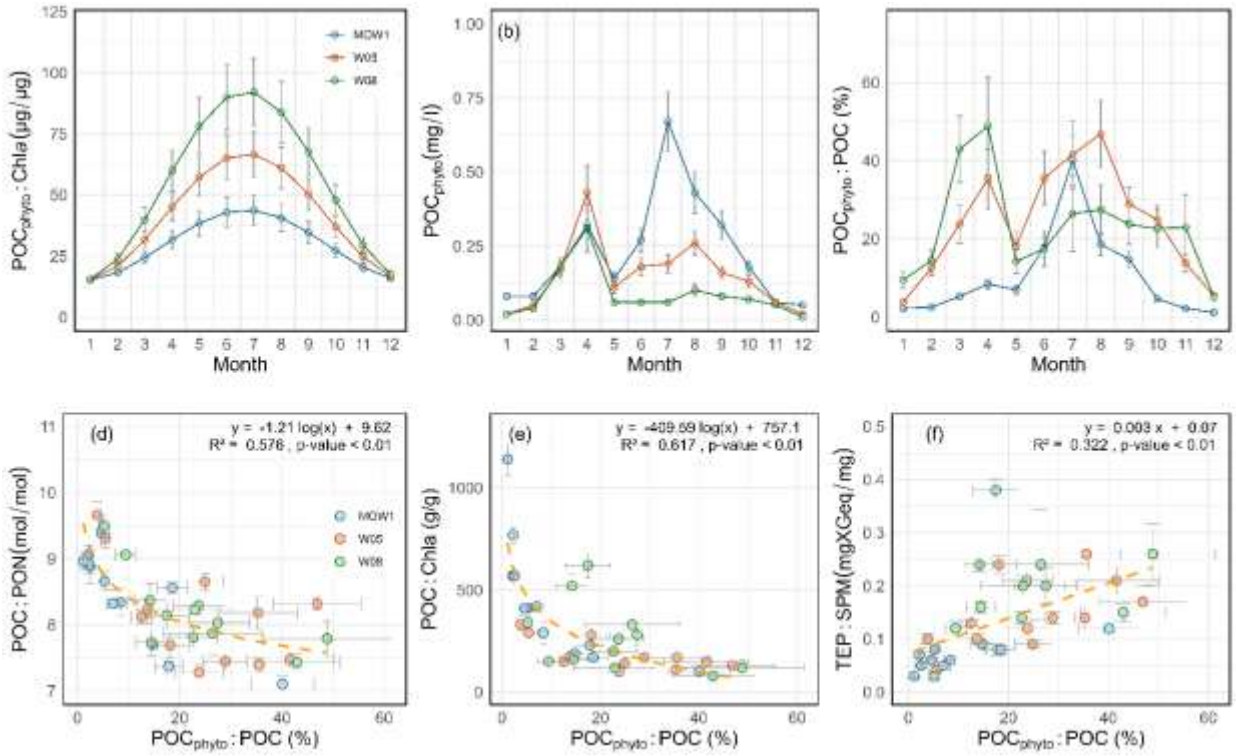


**Figure 7: Monthly mean values (climatology 2019-2023) of a) POCphyto:Chla (µg/µg), b) POCphyto (mg/l), and c) POCphyto:POC (%) at the three stations. Error bars represent the standard error from the monthly mean. Linear regression of monthly means of d) POC:PON (mol/mol), e) POC:Chla (g/g), and f) TEP:SPM (mg XG eq./mg) as a function of POCphyto:POC (%) at the three stations. Error bars represent the standard error from the monthly mean.**

At MOW1, $POC_{det}$ and $POC_{mineral}$ contribute substantially to the water column POC pool for most of the year, with $POC_{phyto}$ making a notable contribution (17–40%) only during the summer months (Figure 8). In contrast, at the other two stations, $POC_{mineral}$ remains consistently low (3–12%) year-round, reaching its lowest relative contribution in summer. At W05, $POC_{phyto}$ shows comparable relative abundance (18–47%) in spring and summer, whereas $POC_{det}$ dominates in late autumn and winter (46–78%). At W08, $POC_{phyto}$ peaks (42–48%) in March and April, followed by lower values (17–27%) in summer, whereas $POC_{det}$ remains the dominant fraction (35–69%) throughout the year, except during the spring peak.

To summarize, POC composition varied with SPM concentrations, showing clear differences between nearshore turbid and offshore clearer waters. Nearshore waters exhibited higher POC concentrations and elevated SPM concentrations and frequent tidal resuspension resulted in higher relative contributions of $POC_{mineral}$ and $POC_{det}$. These components, often more refractory, masked seasonal variations in the bulk POC pool. $POC_{mineral}$ represents organic matter adsorbed onto mineral surfaces, limiting enzymatic degradation, while $POC_{det}$ consists of a mixture of organic compounds at various degradation stages. In contrast, offshore waters showed reduced contributions of $POC_{mineral}$ and a higher relative abundance of fresher, more labile $POC_{phyto}$.

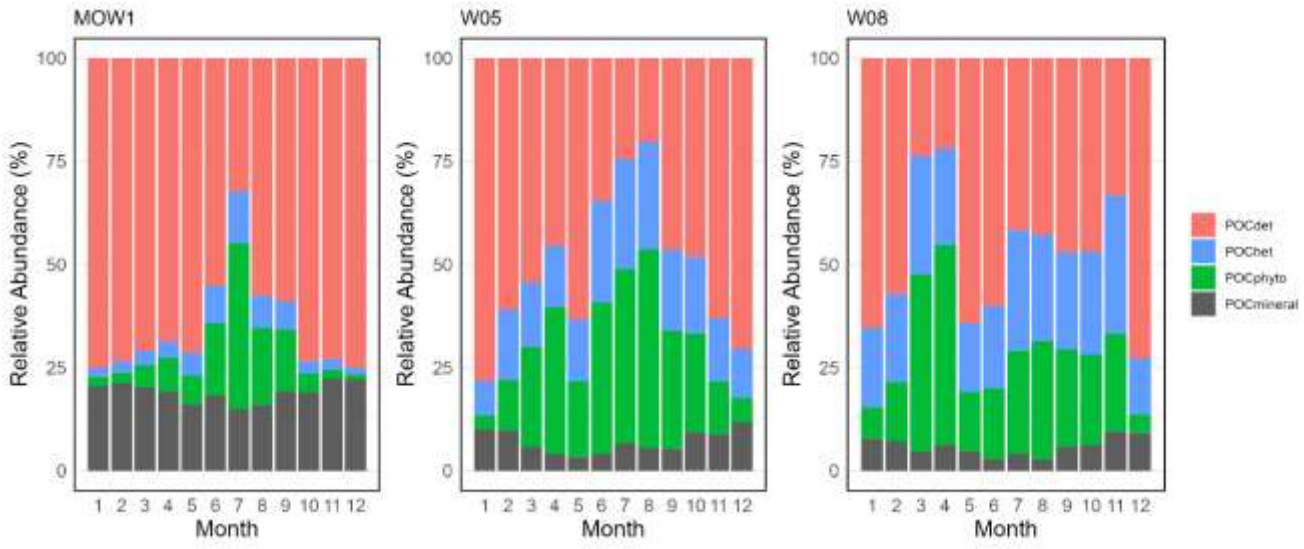


**Figure 8: Relative abundance of POC components over a climatological year (2019-2023) at MOW1, W05, and W08. POCdet stands for detrital organic matter (calculated after subtracting other components from measured POC). POChet stands for heterotrophic biomass, POCphyto stands for phytoplankton biomass, and POCmineral stands for mineral-associated organic matter (based on clay specific surface area available for organic matter adsorption).**

### *4.6 Near-bed sand and mud particles in suspension*

In the near-bed layer, the SPM consists often of mixed sediments, which are sand sized particles in suspension together with fine-grained particles. In this benthic layer almost no water samples are available, however, the composition can be estimated from sensor measurements. Figure 9 presents result from applying SCI method (see section 3.2) to field data collected at MOW1 station. The OBS and ADV data were obtained from a tripod deployment and have measured at 20 cm above the seabed. Overall, Figure 9 shows environmental transitions from muddy to sandy conditions, as reflected via SCI and $f_{sand}$ values (sand content of the SPM), in response to hydrodynamic shifts between neap and spring tides. For instance, during an energetic spring tide (days 70 – 74), sand is resuspended and contributes substantially to the total mass of SPM. These results indicate that the true SPM concentration in the near-bed layer exceeds that derived from conventional single-sensor measurements (OBS alone; Figure 9a, grey line with circle marker). Figure 9 further highlights the contrasting sensor sensitivities: OBS "see" mud (negative correlation with $f_{sand}$ Figure 9b vs. 9c), whereas ADV "hear" sand (positive correlation with $f_{sand}$ Figure 9b vs. 9d).

Applying SCI method for the whole year of 2013, Figure 10 illustrates key aspects of seasonal sediment dynamics at the station. The site is predominantly mud-dominated, with short sandy intervals associated with high spring tides and storm events. The highest sand-fraction recorded during the year was 62%, and sediments tended to be slightly sandier in winter and early spring than the rest of the year. Based on the SCI, bed shear stress, and altitude records (Figure 10b,c,d,f,h), episodes of advection, deposition, and erosion can be identified. For instance, during the largest storm event of the year (day 283.57), a period of erosion occurred prior to the storm, followed by substantial deposition after it had passed. The sediment active layer ranged between approximately 5 to 30 cm. Bed samples obtained using a Van Veen grab indicate that the seabed is primarily composed of fine-grained cohesive mud, overlain by a discontinuous sand veneer. This sedimentary structure suggests a limited sand supply at the bed surface, constraining the potential for sand resuspension under typical

hydrodynamic conditions. These observations are consistent with previous studies conducted in the area (Fettweis et. al. 2006, 2010; Baeye et. al. 2011, van Maren et. al. 2020). Another notable observation is that the traditional calibration of SPMC based solely on OBS measurements tends to underestimate total sediment concentrations, whereas the SCI approach reveals substantially higher concentrations during sandy periods (Figure 2xa yellow vs. red lines).

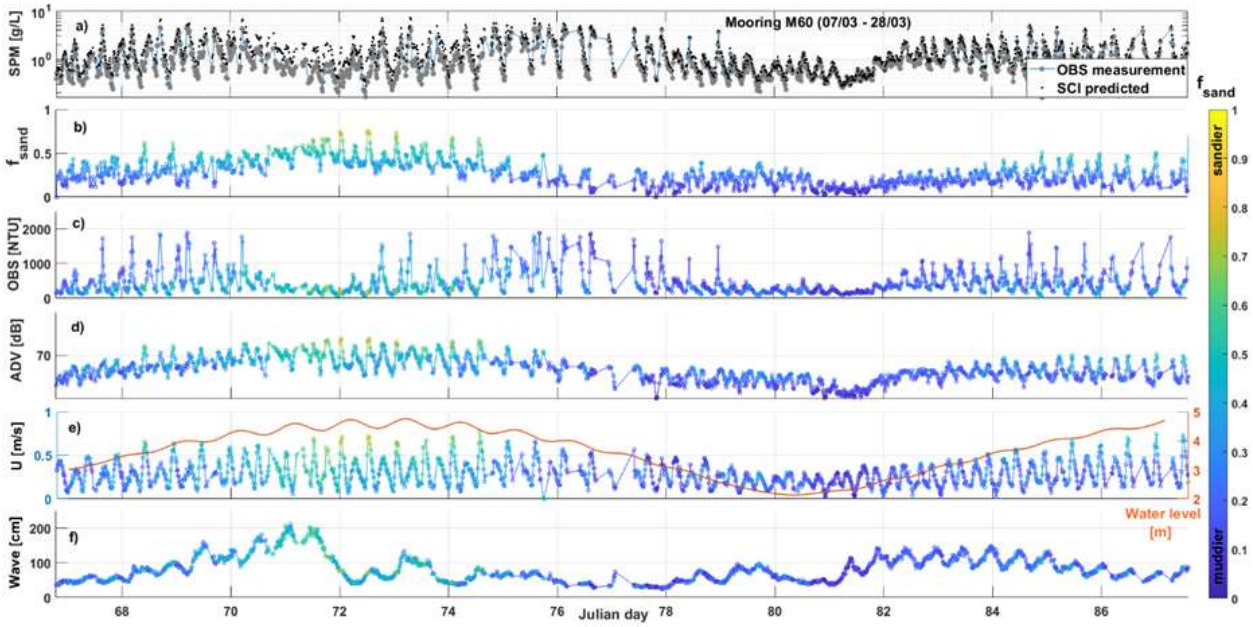


**Figure 9: Combination of raw optical/acoustic signals provides more comprehensive and accurate characterization of SPM concentration and fsand than using either optical or acoustic sensor alone.**

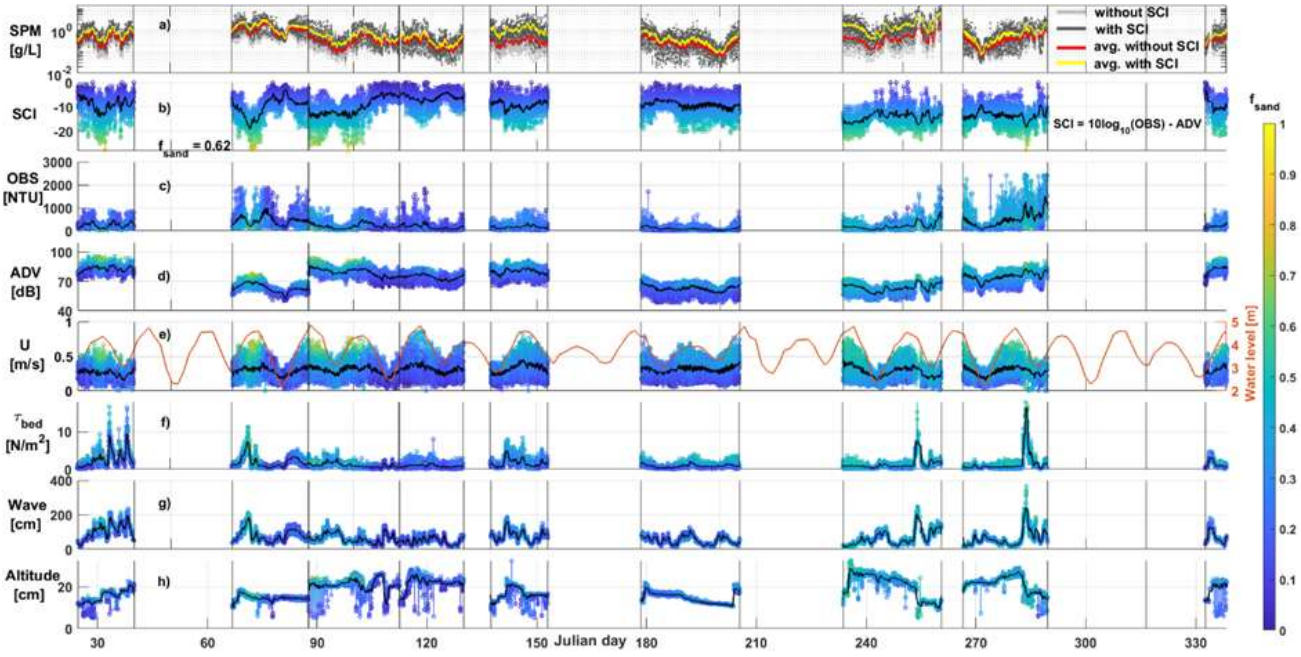


**Figure 10: Application of SCI functions for the entire year 2013. Black lines represent the averaged raw data for each parameter. Gray vertical lines indicate the boundaries between deployments. (b) The sand-fraction, fsand = 0.62, which is also the highest sand-fraction of the year, provides a more accurate reference for the colour scale.**

Two prominent benefits that make the SCI method stand out in comparison with other field measurement practices Downing (2006), Thorne & Hurther (2014), Agrawal et. al. (2019). First, it allows researchers to take advantage of the historical data to acquire new meaningful information, which are the fraction and concentration of sand/mud in suspension. In long-term sediment dynamics monitoring, both optical turbidity and acoustic sensors are often used together Fugate & Friedrichs (2002), Voulgaris & Meyers (2004), Sahin et. al. (2017), Fettweis et. al. (2019), Pearson et. al. (2021). However, they are treated as individual measurements and are calibrated separately for different purposes. For example, an ADV or ADCP is often deployed to measure flow conditions. On the other hand, OBS is used for SPM concentrations. As shown previously, the SCI method can provide the percentage of sand/mud, and hence, the proportion of mud and sand concentrations in suspension, respectively. Such information will provide crucial input and validation data to improve the performance of current sediment transport models, e.g., for 2D models relying on data obtained from profilers like ADCP. Projects related to port dredging and beach nourishment also directly benefit from long-term sand/mud dynamics data.

Second, the SCI method allows the use of customized paired sensors. Using five different instruments with different wavelengths and frequencies, Tran et. al. (2024) showcased the procedure of how SCI functions can be derived and applied. In practice, SCI functions can be directly obtained from field measurements with the pair of optical turbidity/acoustic sensors of interest. Although integrated optical-acoustic sensors, for example Agrawal et. al. (2019), have been developed, a key advantage of the SCI calculation is that it can rely on pairs of existing sensors that are already frequently deployed together in the field, without requiring a dedicated additional instrument.

During the PiNS project an extensive temporal-spatial database was collected that directly contributes to the further validation and development of the SCI method. We have been, and will continue, investigating the feasibility of applying SCI method to:

- Examine the influence of phytoplankton on sediment dynamics. We conducted two laboratory experiment studies (May and July 2024 at Ifremer, France) aiming to quantify the response of optical/acoustic signals to the presence of phytoplankton.
- Produce vertical profiles of sand/mud fraction and concentration using profilers, such as HydroScat, AQUAscat and ADP.
- Convert SCI functions between different pairs of optical/acoustic sensors, such as (Wetlabs and ADV) and (OBS and ADP) and (HydroScat and AQUAscat).

## 5. PUBLICATIONS

The results of the projects have been published in peer reviewed journals (5 published, 2 in revision) and have been presented at international and national conferences and workshops.

**Peer reviewed publications**

Desmit X, Schartau M, Terseleer N, Van der Zande D, Riethmüller R, Fettweis M. 2024. The transition between coastal and offshore areas in the North Sea unraveled by the suspended particle composition. Science of the Total Environment 915, 169966.

Fettweis M, Silori S, Adriaens R, Desmit X. 2025. Clay minerals and the stability of organic carbon in suspension along nearshore to offshore transects. Geochimica et Cosmochimica Acta 395, 229-237.

Fettweis M, Belliard JP, Silori S, Terseleer N, Tran D, Amadei Martinez L, Brun A, Sabbe K, De Rijcke M, Han HK, Lee BJ, Riethmüller R, Shen X, Verney R, Desmit X. Interactions of suspended mineral and organic particles from estuaries to oceans. Nature Reviews Earth and Environment (Dec 2025, in revision).

Huynh TT, Kim J, Lee SD, Fettweis M, Bi Q, Kim SS, Lee SY, Choi YY, Lee BJ. 2024. Spatiotemporal dynamics of suspended particulate matter in the water environment: A review. Water 16, 3613.

Lee BJ, Huyn TT, Pham TTT, Fettweis M, Hur J, Lee SD, Vrugt JA, Bi Q, Shen X, Terseleer N, Lee S, Choi YY. Diagnosing flocculation–transport dynamics of suspended particulate matter using a two-class population balance model and Bayesian calibration. Water Resources Research (Dec 2025, in revision).

Silori S, Desmit X, Fettweis M. 2025. Spatio-temporal variation in particulate and dissolved organic matter dynamics in the southern North Sea. Biogeochemistry 168.

Silori S, Desmit X, Schartau M, Terseleer N, Riethmüller R, Fettweis M. 2025. Vertical dynamics of suspended particulate matter and chlorophyll-a in a well-mixed coastal turbid system. Estuarine, Coastal and Shelf Science 326, 109545.

**Conference and workshop**

Fettweis M, Silori S, Desmit X. 2025. SPM concentration and composition along nearshore to offshore transects. Workshop on Particle Dynamics in Coastal Marine Environments, GTK Headquarters, 28 October, Espoo (Finland).

Fettweis M. 2025. Concentration and composition of suspended particulate matter along nearshore to offshore transects. Particles in Europe, 17-19 September, Ostend (Belgium).

Silori S, Desmit X, Schartau M, Terseleer N, Riethmüller R, Fettweis M. 2025. Vertical dynamics of suspended particulate matter and chlorophyll-a in a well-mixed coastal turbid system. Particles in Europe, 17-19 September, Ostend (Belgium).

Fettweis M, Silori S, Desmit M. 2025. Composition of SPM along nearshore to offshore transects. Workshop on Flocculation, 21 May, Delft (The Netherlands).

Silori S, Desmit X, Schartau M, Terseleer N, Riethmüller R, Fettweis M. 2025. Vertical dynamics of suspended particulate matter and chlorophyll-a in a well-mixed coastal turbid system. Workshop on Flocculation, 21 May, Delft (NL).

Desmit X, Riethmüller R, Silori S, Schartau M, Fettweis M. 2025. Budgeting the particulate organic matter from the suspended particulate matter in shelf seas. EGU General Assembly, 27 April - 2 May, Vienna (Austria).

Tran D, Verney R, Fettweis M. 2024. New insights into near-bed SPM concentration and sand/mud fraction. AGU Meeting, 9-13 December, Washington DC (USA).

Baeye M, Fettweis M, Verney R. 2024. On the effects of SPM composition on the inherent acoustic and optical particle properties of SPM. Physics of Estuaries and Coastal Seas, 23-27 September, Bordeaux (France).

Tran D, Verney R, Fettweis M. 2024. New insights into near-bed SPM concentration and sand/mud fraction in the use of Sediment Composition Index. Physics of Estuaries and Coastal Seas, 23-27 September, Bordeaux (France).

Fettweis M. 2024. A universe of particles in a sip of water: Composition, concentration and size along the land-ocean transition. Geo-Colloquium University Kiel, 18 June, Kiel (Germany).

Desmit X, Terseleer Lillo N, Fettweis M, Kallend A, Sabbe K, Dujardin J, De Rijcke M. 2024 Impact of plankton-mineral interactions on the carbon cycle in the Southern North Sea. Particles in Belgium workshop, 3 May, VLIZ, Ostend (Belgium).

Silori S, Fettweis M, Desmit X, Terseleer N, Riethmüller R, Schartau M. 2024. Vertical profiles of Chlorophyll and SPM in Turbid Well-Mixed Waters: Phytoplankton and mineral particle interaction at seasonal and tidal scale. Particles in Belgium workshop, 3 May, VLIZ, Ostend (Belgium).

Tran D, Fettweis M. 2024. Characterizing the composition of sand and mud suspension in coastal and estuarine environments using combined optical and acoustic measurements. Particles in Belgium workshop, 3 May, VLIZ, Ostend (Belgium).

Fettweis M, Silori S, Terseleer N, Desmit X, Lee BJ, Riethmüller R, Schartau M. 2023. Organic matter composition of biomineral flocs and its influence on SPM dynamics along a nearshore to offshore transect. Workshop on Pelagic Particle Dynamics, 4-6 October, Brussels (Belgium).

Silori S, Fettweis M, Desmit X, Lee BJ, Riethmüller R, Schartau M. 2023. Vertical profiles of Chlorophyll and SPM at seasonal and tidal scales in a turbid, well-mixed coastal zone. Workshop on Pelagic Particle Dynamics, 4-6 October, Brussels.

Tran D, Desmit X, Verney R, Fettweis M. 2023. Application of sediment composition index to predict suspended particulate matter concentration in the North Sea. 2023. Workshop on Pelagic Particle Dynamics, 4-6 October, Brussels.

Fettweis M, Delhaye L, Lee BJ, Riethmüller R, Schartau M, Silori S, Desmit X. 2023. Vertical variations of suspended particle composition reflect particle dynamics. INTERCOH, 18-22 September, Inha University, Incheon (Korea).

Ho QN, Fettweis M, Hur J, Lee SD, Lee BJ. 2023. The role of microalgae in cohesive sediment flocculation: Insights from stochastic modeling and laboratory experiments. INTERCOH, 18-22 September, Inha University, Incheon (Korea).

Tran D, Desmit X, Verney R, Fettweis M. 2023. Application of sediment composition index to predict suspended particulate matter concentration in the North Sea. INTERCOH, 18-22 September, Inha University, Incheon (Korea).

## 6. ACKNOWLEDGEMENTS

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## 7. REFERENCES

Abril G, Nogueira M, Etcheber H, Cabecadas G, Lemaire E, Brogueira MJ. 2002. Behaviour of organic carbon in nine contrasting European estuaries. Estuarine Coastal Shelf Science 54, 241–262.

Adriaens R, Zeelmaekers E, Fettweis M, Vanlierde E, Vanlede J, Stassen P, Elsen J, Srodon J, Vandenberghe N. 2018. Quantitative clay mineralogy as provenance indicator for recent muds in the southern North Sea. Marine Geology 398, 48–58.

Agrawal YC, Pottsmith HC, Dana D, Mikkelsen OA. 2019. Super-Turbidity Meter: LISST-AOBS Combines Optical Turbidity with Acoustics. E-proceedings of the 38th IAHR World Congress September 1-6, Panama City (Panama).

Arndt S, Jørgensen BB, LaRowe DE, Middelburg JJ, Pancost RD, Regnier P. 2013. Quantifying the degradation of organic matter in marine sediments: a review and synthesis. Earth Science Review 123, 53–86.

Asmala E, Carstensen J, Conley DJ, Slomp CP, Stadmark J, Voss M. 2017. Efficiency of the coastal filter: nitrogen and phosphorus removal in the Baltic Sea. Limnolology & Oceanography 62, S222–S238.

Baeye M, Fettweis M, Voulgaris G, Van Lancker V. 2011. Sediment mobility in response to tidal and wind-driven flows along the Belgian inner shelf, southern North Sea. Ocean Dynamics 61, 611-622.

Baltar F, Alvarez-Salgado XA, Arístegui J, Benner R, Hansell DA, Herndl GJ, Lønborg C. 2021. What is refractory organic matter in the ocean? Frontiers in Marine Science 8, 642637.

Bass SJ, McCave IN, Rees JM, Vincent CE. 2007. Sand and mud flux estimates using acoustic and optical backscatter sensors: measurements seaward of the Wash, southern North Sea. In: Coastal and Shelf Sediment Transport (eds. Balson P.S., Collins, M.B.), Geological Society of London.

Blattmann TM, Liu Z, Zhang Y, Zhao Y, Haghipour N, Montlucon DB, Plötze M, Eglinton TI. 2019. Mineralogical control on the fate of continentally derived organic matter in the ocean. Science 366, 742–745.

Blauw AN, Beninca E, Laane RW, Greenwood N, Huisman J. 2012. Dancing with the tides: fluctuations of coastal phytoplankton orchestrated by different oscillatory modes of the tidal cycle. PLoS One 7, 49319.

Bux J, Peakall J, Rice HP, Manga MS, Biggs S, Hunter TN. 2019. Measurement and density normalisation of acoustic attenuation and backscattering constants of arbitrary suspensions within the Rayleigh scattering regime. Applied Acoustics 146, 9–22.

Chen Y-M, Gao J-B, Yuan Y-Q, Ma J, Yu S. 2016. Relationship between heavy metal contents and clay mineral properties in surface sediments: implications for metal pollution assessment. Continental Shelf Research 124, 125–133.

Dauwe B, Middelburg JJ, Herman PMJ, Heip CHR. 1999. Linking diagenetic alteration of amino acids and bulk organic matter reactivity. Limnolology & Oceanography 44, 1809–1814.

Deng Z, Huang D, He Q, Chassagne C. 2022. Review of the action of organic matter on mineral sediment flocculation. Frontiers in Earth Science 10, 965919.

Desmit X, Nohe A, Borges AV, Prins T, De Cauwer K, Lagring R, Sabbe K. 2020. Changes in chlorophyll concentration and phenology in the North Sea in relation to de-eutrophication and sea surface warming. Limnology and Oceanography 65, 828-847.

Desmit X, Schartau M, Terseleer N, Van der Zande D, Riethmüller R, Fettweis M. 2024. The transition between coastal and offshore areas in the North Sea unraveled by the suspended particle composition. Science of the Total Environment 915, 169966.

Desmit X, Terseleer N, Sabbe K, De Rijcke M, Dujardin J, Kallend A, Fettweis M. 2026. BioGeochemical PARTicle interactions and feedback loops on the Belgian Continental Shelf, Final Report. Federal Policy Research (Belspo).

Downing J. 2006. Twenty-five years with OBS sensors: the good, the bad, and the ugly. Continental Shelf Research 26, 2299–2318.

Eisma D. 1986. Flocculation and de-flocculation of suspended matter in estuaries. Netherlands Journal of Sea Research 20, 183–199.

Etcheber H, Taillez A, Abril G, Garnier J, Servais P, Moatar F, Commarieu M-V. 2007. Particulate organic carbon in the estuarine turbidity maxima of the Gironde, Loire and Seine estuaries: Origin and lability. Hydrobiology 588, 245–259.

Fettweis M, Francken F, Pison V, Van den Eynde D. 2006. Suspended particulate matter dynamics and aggregate sizes in a high turbidity area. Marine Geology 235, 63–74.

Fettweis M, Francken F, Van den Eynde D, Verwaest T, Janssens J, Van Lancker V. 2010. Storm influence on SPM concentrations in a coastal turbidity maximum area (southern North Sea) with high anthropogenic impact. Continental Shelf Research 30, 1417-1427.

Fettweis M, Baeye M, Cardoso C, Dujardin A, Lauwaert B, Van den Eynde D et al. 2016. The impact of disposal of fine-grained sediments from maintenance dredging works on SPM concentration and fluid mud in and outside the harbor of Zeebrugge. Ocean Dynamics 66, 1497-1516.

Fettweis M, Riethmüller R, Verney R, Becker M, Backers J, Baeye M, et al. 2019. Uncertainties associated with in situ high-frequency long-term observations of suspended particulate matter concentration using optical and acoustic sensors. Progress in Oceanography, 178, 102162.

Fettweis M, Schartau M, Desmit X, Lee BJ, Terseleer N, Van der Zande D. et al. 2022. Organic matter composition of biomineral flocs and its influence on suspended particulate matter dynamics along a nearshore to offshore transect. Journal of Geophysical Research Biogeosciences 127, e2021JG006332.

Fettweis M, Silori S, Adriaens R, Desmit X. 2025. Clay minerals and the stability of organic carbon in suspension along nearshore to offshore transects. Geochimica et Cosmochimica Acta 395, 229-237.

Fugate DC, Friedrichs CT. 2002. Determining concentration and fall velocity of estuarine particle populations using ADV, OBS and LISST. Continental Shelf Research 22, 1867–1886.

Haalboom S, de Stigter H, Duineveld G, van Haren H, Reichart G-J, Mienis F. 2021. Suspended particulate matter in a submarine canyon (Whittard Canyon, Bay of Biscay, NE Atlantic Ocean): Assessment of commonly used instruments to record turbidity. Marine Geology 434, 106439.

Hansell, DA, Carlson, CA. (Eds.). (2014). Biogeochemistry of marine dissolved organic matter. Academic press.

Hedges JI, Keil RG. 1995. Sedimentary organic matter preservation: an assessment and speculative synthesis. Marine Chemistry 49, 81–115.

Hemingway JD, Rothman DH, Grant KE, Rosengard SZ, Eglinton TI, Derry LA, Galy VV. 2019. Mineral protection regulates long-term global preservation of natural organic carbon. Nature 570, 228–231.

Herman PM, Heip CH. 1999. Biogeochemistry of the Maximum TURbidity zone of estuaries (MATURE): Some conclusions. Journal of Marine Systems 22 89–104.

Ho QN, Fettweis M, Spencer KL, Lee BJ. 2022. Flocculation with heterogeneous composition in water environments: a review. Water Research 213, 118147.

Hoitink AJF, Hoekstra P. 2005. Observations of suspended sediment from ADCP and OBS measurements in a mud-dominated environment. Coastal Engineering 52, 103-118.

Huynh TT, Kim J, Lee SD, Fettweis M, Bi Q, Kim SS, Lee SY, Choi YY, Lee BJ. 2024. Spatiotemporal dynamics of suspended particulate matter in the water environment: A review. Water 16, 3613

Irion G, Wunderlich F, Schwedhelm E. 1987. Transport of clay minerals and anthropogenic compounds into the German Bight and the provenance of fine-grained sediments SE of Helgoland. Journal of the Geological Society 144, 153–160.

Ittekkot V. 1988. Global trends in organic matter in river suspensions. Nature 332, 436–438.

Jung AS, Bijkerk R, Van Der Veer HW, Philippart CJM. 2017. Spatial and temporal trends in order richness of marine phytoplankton as a tracer for the exchange zone between coastal and open waters. Journal of the Marine Biological Association. UK 97, 477–489

Keil RG, Montluçon DB, Prahl FG, Hedges JI. 1994. Sorptive preservation of labile organic matter in marine sediments. Nature 370, 549-52.

Keil RG, Mayer LM. 2014. 12.12 - Mineral matrices and organic matter. Treatise on Geochemistry (2nd Ed.) 12, 337–359.

Kharbush JJ, Close HG, Van Mooy BA, Arnosti C, Smittenberg RH, Le Moigne FA, Mohr W (2020) Particulate organic carbon deconstructed: molecular and chemical composition of particulate organic carbon in the ocean. Frontiers in Marine Science 7, 518.

Kleber M, Bourg IC, Coward EK, Hansel CM, Myneni SC, Nunan N. 2021. Dynamic interactions at the mineral–organic matter interface. Nature Review Earth & Environment 2, 402–421.

Lee BJ, Fettweis M, Toorman E, Molz F. 2012. Multimodality of a particle size distribution of cohesive suspended particulate matters in a coastal zone. Journal of Geophysical Research Ocean 117, C03014.

Liu Z, Xue J. 2020. The lability and source of particulate organic matter in the Northern Gulf of Mexico Hypoxic Zone. Journal of Geophysical Research Biogeosciences e2020JG005653.

Liu X, Lan C, Zhu L, Yan C, Wang N, Chen H, Zheng G, Che Y, Yang Z, Bao R. 2024. Sediment resuspension as a driving force for organic carbon transference and rebalance in marginal seas. Water Research 257, 121672.

Maerz J, Hofmeister R, van der Lee EM, Gräwe U, Riethmüller R, Wirtz KW. 2016. Maximum sinking velocities of suspended particulate matter in a coastal transition zone. Biogeosciences 13, 4863–4876.

Maggi F, Tang FH. 2015. Analysis of the effect of organic matter content on the architecture and sinking of sediment aggregates. Marine Geology 363, 102–111.

Mayer LM. 1994. Surface area control of organic carbon accumulation in continental shelf sediments. Geochimica et Cosmochimica Acta 58, 1271–1284.

Mayer LM. 1995. Sedimentary organic matter preservation: an assessment and speculative synthesis - a comment. Marine Chemistry 49, 123–126.

Middelburg JJ, Vlug T, Vandernat F. 1993. Organic-matter mineralization in marine systems. Global Planetary Change 8, 47–58.

Moulton M, Suanda SH, Garwood JC, Kumar N, Fewings MR, Pringle JM. 2023. Exchange of plankton, pollutants, and particles across the nearshore region. Annual Review in Marine Science 15, 167–202.

Muylaert K, Gonzales R, Franck M, Lionard M, Van der Zee C, Cattrijsse A, Vyverman W. 2006. Spatial variation in phytoplankton dynamics in the Belgian coastal zone of the North Sea studied by microscopy, HPLC-CHEMTAX and underway fluorescence recordings. Journal of Sea Research 55, 253–265.

Opdal AF, Lindemann C, Aksnes D.L. 2019. Centennial decline in North Sea water clarity causes strong delay in phytoplankton bloom timing. Global Change Biology 25, 3946–3953

Osterholz H, Kilgour DPA, Storey DS, Lavik G, Ferdelman TG, Niggemann J, Dittmar T. 2021. Accumulation of DOC in the South Pacific Subtropical Gyre from a molecular perspective. Marine Chemistry 231, 103955.

Pearson SG, Verney R, van Prooijen BC, Tran D, Hendriks EC, Jacquet M, Wang ZB. 2021. Characterizing the composition of sand and mud suspensions in coastal and estuarine environments using combined optical and acoustic measurements. Journal of Geophysical Research Oceans 126, e2021JC017354.

Pedersen T, Calvert S. 1990. Anoxia vs. productivity: what controls the formation of organic-carbon-rich sediments and sedimentary rocks? AAPG Bulletin 74, 454–466.

Postma H. 1984. Introduction to the symposium on organic matter in the Wadden Sea. Netherlands Institute of Sea Research - Publication Series 10, 15–22.

Rousseau V, Park Y, Ruddick K, Vyverman W, Parent JY, Lancelot C.(2006. Phytoplankton blooms in response to nutrient enrichment. In: Current status of eutrophication in the Belgian coastal zone. Presses Universitaire de Bruxelles, 45-59

Sahin C, Verney R, Sheremet A, Voulgaris G. 2017. Acoustic backscatter by suspended cohesive sediments: field observations, Seine Estuary, France. Continental Shelf Research 134, 39–51.

Schartau M, Riethmüller R, Flöser G, van Beusekom JEE, Krasemann H, Hofmeister R, Wirtz K. 2019. On the separation between inorganic and organic fractions of suspended matter in a marine coastal environment. Progress in Oceanography 171, 231–250.

Shen X, Toorman EA, Lee BJ, Fettweis M. 2018. Biophysical flocculation of suspended particulate matters in Belgian coastal zones. Journal of Hydrology 567, 238–252.

Silori S, Desmit X, Fettweis M. 2025b. Spatio-temporal variation in particulate and dissolved organic matter dynamics in the southern North Sea. Biogeochemistry 168.

Silori S, Desmit X, Schartau M, Terseleer N, Riethmüller R, Fettweis M. 2025a. Vertical dynamics of suspended particulate matter and chlorophyll-a in a well-mixed coastal turbid system. Estuarine, Coastal and Shelf Science 326, 109545.

Singh M, Sarkar B, Biswas B, Churchman J, Bolan NS. 2016. Adsorption- desorption behavior of dissolved organic carbon by soil clay fractions of varying mineralogy. Geoderma 280, 47–56

Sommerfield CK, Wong KC. 2011. Mechanisms of sediment flux and turbidity maintenance in the Delaware Estuary. Journal of Geophysical Research Oceans *116,* C1.

Sutherland TF, Lane PM, Amos CL, Downing J. 2000. The calibration of optical backscatter sensors for suspended sediment of varying darkness levels. Marine Geology 162, 587–597.

Thorne PD, Hurther D. 2014. An overview on the use of backscattered sound for measuring suspended particle size and concentration profiles in non-cohesive inorganic sediment transport studies. Continental Shelf Research 73, 97-118.

Tran D, Jacquet M, Pearson S, Van Prooijen B, Verney R. 2024. Estimation of mud and sand fractions and total concentration from coupled optical-acoustic sensors. Earth and Space Science 11, e2024EA003694.

Van der Hout CM, Witbaard R, Bergman MJN, Duineveld GCA, Rozemeijer MJC, Gerkema T. 2017. The dynamics of suspended particulate matter (SPM) and chlorophyll-a from intratidal to annual time scales in a coastal turbidity maximum. Journal of Sea Research 127, 105–118.

van Maren DS, Vroom J, Fettweis M, Vanlede J. 2020. Formation of the Zeebrugge coastal turbidity maximum: The role of uncertainty in near-bed exchange processes. Marine Geology 425, 106186.

Verdugo P. 2012. Marine microgels. Annual Review in Marine Science 4, 375–400.

Voulgaris G, Meyers S. 2004. Temporal variability of hydrodynamics, sediment concentration and sediment settling velocity in a tidal creek. Continental Shelf Research 24, 1659–1683.

Winterwerp JC. 2001. Stratification effects by cohesive and noncohesive sediment. Journal of Geophysical Research Oceans. 106; 22559-22574

Yu M, Yu X, Mehta AJ, Manning AJ, Khan F, Balachandar S. 2023. Persistent reshaping of cohesive sediment towards stable flocs by turbulence. Scientific Reports 13, 1760.

Zhao L, Gao L. 2019. Dynamics of dissolved and particulate organic matter in the Changjiang (Yangtze River) Estuary and the adjacent East China Sea shelf. Journal of Marine Systems 198, 103188.

Zhao C, Maerz J, Hofmeister R, Röttgers R, Wirtz K, Riethmüller R, Schrum C. 2019. Characterizing the vertical distribution of chlorophyll a in the German Bight. Continental Shelf Research 175, 127-146

Zhao T, Xu S, Hao F. 2023. Differential adsorption of clay minerals: implications for organic matter enrichment. Earth Science Review 246, 104598.