



Geo-chemical and optical characterizations of suspended matter in European coastal waters

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Abstract

Suspended particulate matter of various marine European coastal waters has been the subject of geo-chemical and optical characterization during a series of oceanographic surveys in 1998. The Loire, Seine, Thames, Rhine, Humber, and Weser/Elbe River plumes were sampled in May 1998. Another survey was conducted in September 1998 in the English Channel (Plymouth coast), North Sea (Texel area), German Bight, and the Baltic Sea. Variations and covariations in total particulate carbon (TPC), particulate organic carbon (POC), particulate nitrogen (PN), and total suspended matter (TSM) have been examined. The POC:PN ratio was found to be variable within the sampling sites. The high POC:PN ratio (average = 9.6) observed in the Baltic Sea probably reflects the peculiar nature of this water body, characterized by a high content of organic matter in TSM as well as in the dissolved phase. The TSM demonstrated to be an effective tracer for POC in the North Sea and in the Baltic Sea, and, generally, for the non-carbonatic inorganic matter (NCIM) because of the good correlation displayed with these two parameters. The light absorption coefficient of non-living particulate matter (aNLPM) was found to correlate generally with POC, but with varying coefficients between sites. In the Baltic Sea, variations of the organic-rich TSM (36% in POC) do not determine significant variations of aNLPM as in the other sites where TSM is dominated by inorganic matter (e.g. in the North Sea and in the English Channel).

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1. Introduction

In coastal waters, the biogenic and mineral fractions of suspended particles are responsible, in addition to the photosynthetic pigments and the chromophoric dissolved organic matter (CDOM), for the absorption and scattering of the visible light. For instance, the total suspended matter (TSM), formed by algal and non-algal particles, contributes to the total absorption coefficient (between 400 and 500 nm) in the water: from a minimum of less than 10% of the total absorption in the Baltic Sea, where CDOM absorption is prevalent (Ferrari & Dowell, 1998) to a maximum of ca. 40% in the North Sea and in the English Channel (Babin et al., 2003), where the high TSM originates from fluvial transport, coastal and tidal currents, and bottom re-suspension.

In particular, in the southern North Sea, in addition to the regional horizontal circulation (Eisma & Kalf, 1987; Prandle, Jago, Jones, & Tappin, 1993), TSM is also influenced by vertical mixing with associated chemical and biological processes (Morris & Howarth, 1998). Light absorption of the suspended particles is dependent on their size, their mineral and chemical composition. Variations in the light-absorption coefficient and spectral slope, in the visible range, depend on the organic content as well as on the composition of the inorganic matrix able to bond in various permanent forms to the organic material. The POC and PN relationships represent a source of important information for studies on the cycling of organic matter, which are generally lacking in real data relative to the different coastal areas. Particulate inorganic carbon (PIC) acts as a tracer of the TSM carbonate composition. This article presents optical and geo-chemical data, with relative relationships, in order to help understand the bio-geo-optical behavior of the

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particles in different coastal waters, and to obtain new findings for refining algorithms to retrieve parameters, such as TSM and POC, using remote-sensing techniques.

2. Methods

2.1. Sampling

This study was conducted in the framework of the COAST/ OOC (COAstal Surveillance Through Observation of Ocean Color) research project, focused on documenting inherent optical properties in coastal waters (Babin et al., 2003). The investigated areas were selected so as to cover the maximum of variability in bio-geo-optical properties of two European hydrographic zones on the continental shelf (depth < 200 m). During the first survey (C5), conducted onboard the German R/V Poseidon in May 1998, 60 stations were visited along short transects across the following river plumes: Loire in the Gulf of Biscay, Seine, and Thames in the English Channel, Rhine, and Humber (Humber refers to an extended area off the East-Anglia coast as shown in Fig. 1) in the North Sea, Weser and, Elbe in the German Bight. The second survey (C6) was conducted in September 1998 using an innovative sampling and in situ measurement system deployed from a helicopter platform. This approach resulted in 178 sta-

tions being visited in relatively short time. The C6 survey covered the coastal area of Plymouth (UK) in the English Channel, the southern North Sea between the semi-closed Wadden Sea, and the open sea through the narrow passage between Den Helder and Texel Island (Marsdiep), the German West-Frison and Helgoland Islands areas in the German Bight, and the Oder River deltaic system in the Baltic Sea. The study area and the sampling location are illustrated in Fig. 1. Discrete water samples were collected close to surface using 8-l Niskin bottles. The water samples were stored in 6-l Nalgene containers and processed immediately, (C5) or transported within less than 2 h and processed at the land-based laboratory located close to the heliport.

To evaluate the dry weight of TSM and for the C and N analyses, pre-combusted (at 450 °C for 2 h) and pre-weighed glass fiber filters (Whatman, GF/F) were used. Particles were collected in duplicate by filtering a variable volume of seawater under low vacuum. Duplicates allowed to estimate the error inherent to TSM dry-weight determination, and to have additional filters for organic nitrogen, and organic and total carbon analyses. After filtration, all the filters were rinsed with 20–30 ml of Milli-Q water to eliminate any trace of salt and dissolved organic matter (DOM). DOM can be adsorbed in labile form and is, therefore, removable from the particles by Milli-Q rinsing (Altabet, Bishop, & McCarthy, 1992). The samples were immediately stored in polycar-

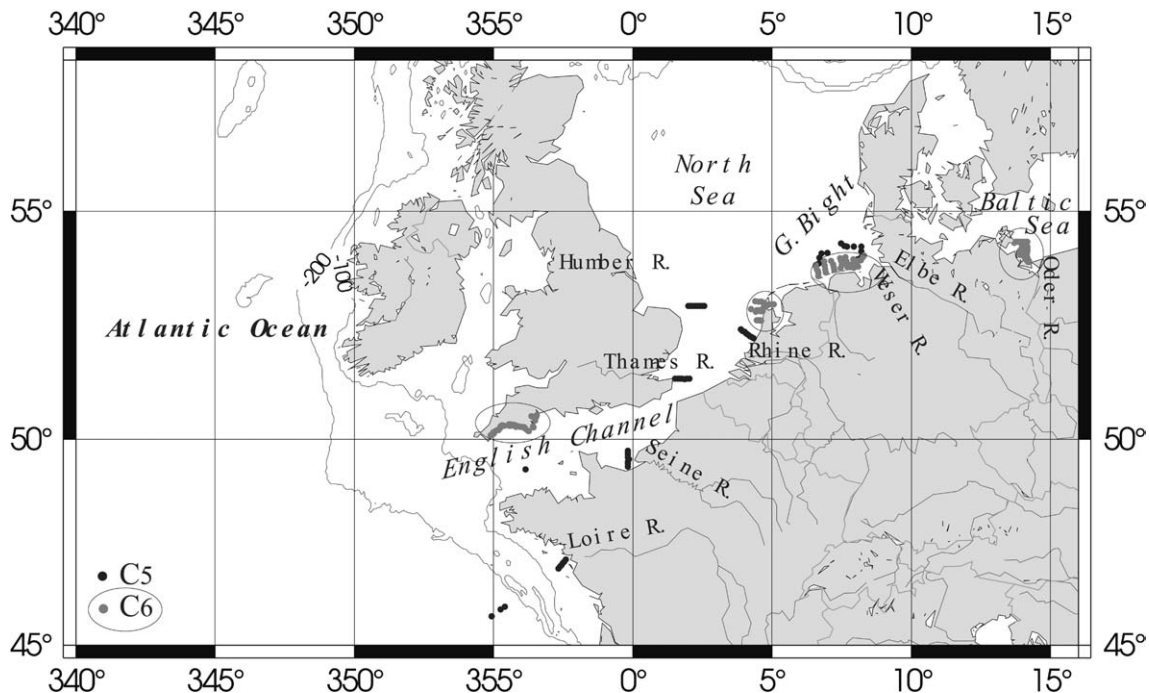


Fig. 1. Map showing the location of the sampling stations relative to the C5 (in black for river plumes) and the C6 (in gray circled for English Channel, Plymouth coast; for the North Sea, Texel area; for the German Bight, Wilhelmshaven; and for the Baltic Sea, Heringsdorf) surveys in May and September 1998, respectively.

bonate petri dishes and were preserved in liquid nitrogen until analyses, less than 3 months later.

In the protocol for the determination of the TSM dry weight, the filter rinsing just after filtration is a critical step. In coastal waters, the risk to underestimate the TSM dry weight because of the cell-wall rupture, caused by osmotic gradient when rinsing with Milli-Q water, and associated loss of cellular material, is certainly lower than the overestimation due to residual salt on the filter (Van der Linde, 1998). On a population of 167 replicated samples, an averaged relative difference of 25% was found. Consequently, with the expected source of error, it was decided to consider only the smallest of the duplicates when the relative difference was more than 10%, and the average of duplicates when the relative difference was less than 10%.

A Carlo Erba NCS 2500 Elemental Analyzer was used for simultaneous determination of particulate carbon and nitrogen. The principle of the operation is based on sequential steps. First, the filters are dried in a 60 °C oven for 12 h and then a sub-sample (a disk of 78.5 mm² obtained with a stainless steel punch) is held in a light-weight tin capsule and is energetically (1000 °C in oxygen and WO₃ as catalyst) and quantitatively oxidized. The gas mixture obtained is subsequently reduced on copper to obtain a final gas mixture formed by N₂, CO₂, H₂O, SO₂. Water is fixed on an anhydron trap, and the resulting three components are eluted and separated by Poropack PQSW column and are detected by a thermo-conductivity detector (TCD) in the sequence: N₂, CO₂, SO₂. The instrument was calibrated with 5-chloro-4-idroxy-3-methoxy benzil-isotiurea. A filter furnace at 450 °C for 2 h was used as blank. On 10 observations of averaged differences within two sub-samples of the green alga *Scenedesmus obliquus*, the SD was found equal to ±1.9% for the carbon and ±4% for the nitrogen. The second test was aimed to check the difference between two replicate filters of the same alga. For 14 couples of samples, the SD of the average of the differences resulted in ±3.7% for the carbon and ±6.8% for the nitrogen. On one of the duplicates, total particulate carbon (TPC) and particulate nitrogen (PN) were determined. For the second one, a treatment with HCl fumes (for 24 h) was applied to remove the inorganic carbon (carbonates), and particulate organic carbon (POC) and PN were determined. The difference between TPC and POC yielded the concentration of PIC. Because TPC and POC were measured on two different filters, the concentration data presented may be affected by an erratic difference between the two filters. Some discrepancies were found between PN measurements made before and after the treatment with HCl, made to remove the inorganic carbon. The averaged difference was found to be equal to -3.7%. This variability seems to be independent of the contribution of N to TSM, but includes that due to the difference between two replicate filters. For this reason,

it is difficult to state that HCl significantly attacks the PN. In our analysis, we consider the average of PN obtained during the TPC and POC analyses.

The light absorption coefficient of particles ($a_p(\lambda)$) retained onto a glass fiber filter was measured with the transmittance–reflectance (T–R) technique (Tassan & Ferrari, 1995a,b) using a dual beam spectrophotometer equipped with 60-mm integrating sphere, between 380 and 750 nm with 1-nm increments. Correction for path-length amplification was achieved with the method reported by Tassan and Ferrari (1995a). The absorption coefficient of non-living particulate matter (aNLPM) was determined in the same way, after pigment oxidation using sodium hypochlorite, as described in Ferrari and Tassan (1999). The comprehensive data are shown in Table 1.

3. Results

3.1. Relationship between POC and PN

POC and PN have been found linearly related, without intercept, for the entire data set in the coastal environments with strong fluvial inputs; the POC vs. PN relationship we observed was not significantly altered by anthropogenic or mineral pollutants (oils). The POC:PN ratio varied overall between 5.1 in the Seine plume and 9.6 in the Baltic Sea. In most coastal systems visited, the average POC:PN ratio was between the classical value for plankton of 6.58 (Redfield, 1934) and the one for averaged plankton 5.7 (Fleming, 1940). Low POC:PN values such as 4.8–5.6 in the Seine plume may reflect the occurrence of phytodetritus and active bacteria (Nelson & Robertson, 1993). Conversely, in the Baltic Sea, the high POC:PN ratios might be explained by the decomposition of the large amounts of non-living organic matter (NLOM) whose C:N ratio increases as it decomposes (Davidson et al., 1995). NLOM can originate in the Baltic Sea from organic debris, which can be alloctonous or derived from phytoplankton (where chlorophyll concentration (average) was found to be equal to 9.47 µg/l; Babin et al. (2002)). Also zooplankton can be, as some authors note (Jumars, Penry, Baross, Perry, & Frost, 1989; Strom, Benner, Ziegler, & Dagg, 1997), a possible source of colored DOM (CDOM) and dissolved organic carbon (DOC), whose concentrations are typically high in the Baltic Sea (Ferrari & Dowell, 1998; Ferrari, Dowell, Grossi, & Targa, 1996). On the other hand, the organic-compounds absorption on, and their interaction with, the mineral substrates in marine particles are studied and widely recognized (Hedges, 1977; Hedges & Hare, 1987, and Ramson, Kim, Kastner, & Wainwright, 1998).

Fig. 2 shows the POC:PN ratio as a function of TSM concentration for the C6 survey. Where TSM

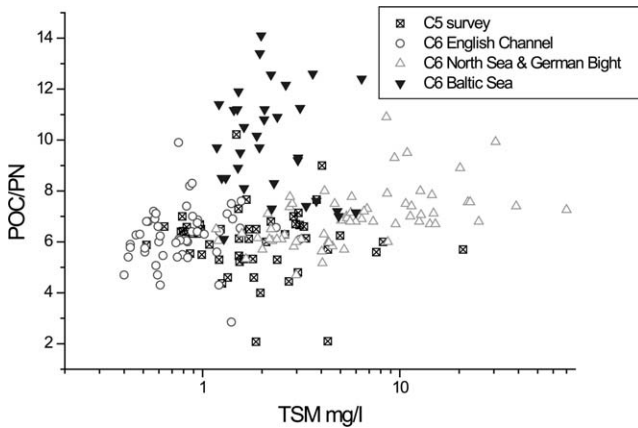


Fig. 2. POC:PN ratio for the C6 data plotted against TSM. It is evident from the cluster of the points relative to the sampling sites.

concentration is low (<1 mg/l), as in English Channel, the POC:PN ratio is also low and indicative of living organic matter, as it has been found by [Bale and Morris \(1998\)](#) in the southern North Sea. Conversely, in the Baltic Sea, to relatively low TSM (1–4 mg/l) correspond high POC:PN (average = 9.6) ratios. In the southern North Sea and German Bight, TSM concentration largely varies (1–70 mg/l), with the range of variation in the POC:PN ratio relatively narrow. For the C5 survey, the scatter in the plot POC:PN vs. TSM concentration is too large to draw similar considerations.

3.2. Relationship between POC and TSM

Fig. 3 illustrates the degree of relationship between POC and TSM. This is statistically significant (linear regression) only for the data set of Texel area ($R = 0.92$), the German Bight ($R = 0.71$), and the Baltic Sea ($R = 0.85$). The average ratios POC:TSM in [Tables 1 and 2](#) display the variability of the organic carbon fraction in the particulate matter, both within the river plumes (C5) and among the sites of the C6 survey. In the river plumes, the highest POC content was found to be 32% of TSM in the Seine, while a minimum of POC was measured in the Thames. In the C6 survey, the maximum POC:TSM was found in the Baltic Sea (38.8% in POC), where the high slope of the linear regression in [Fig. 3](#) suggests the presence of a low specific weight TSM with high organic matter component and a low concentration in water. Conversely, in the North Sea and German Bight, TSM is dominated by inorganic material. [Fig. 4](#) shows a comparison between the four points derived from the log–log curve traced by [Maybeck \(1982\)](#) relative to the % of POC on TSM for several world rivers, and the data of the C6 campaign described in this study. In [Fig. 4](#), it appears that the Baltic Sea particulate matter presents the same high %POC characteristic of the rivers while, for the other environments, the inorganic compounds prevail.

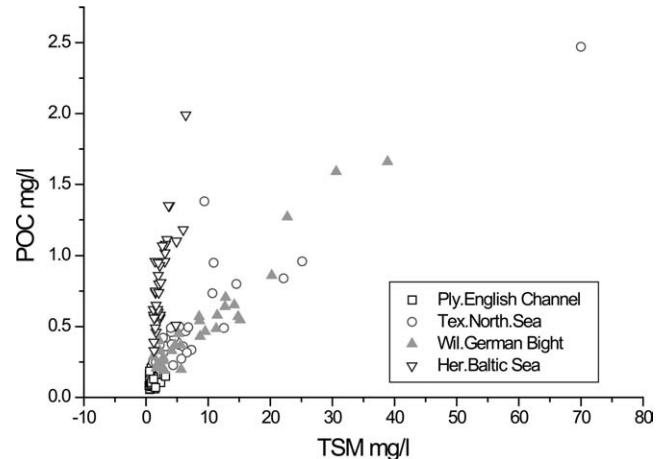


Fig. 3. Relationship between POC and TSM for C6 survey.

3.3. Relationship between PIC, NCIM, and TSM

Considering the PIC, obtained as difference TPC–POC, plotted with TSM, the high scattering of the points, especially in the low values of TSM, suggests that, at least for the sites studied, TSM seems to be a poor tracer for the carbonatic fraction of TSM. The contribution of PIC to TPC varies from a minimum of ~3% in the Loire plume up to 31% in the Thames plume, while in the Baltic Sea, it is similar to that typically found in open ocean waters, i.e. 10% ([Wangersky, 1994](#)). The non-carbonatic inorganic matter (NCIM) is the remaining inorganic fraction of TSM (clay material) defined here as:

$$\text{NCIM} = \text{TSM} - [(\text{POC} \times 2.5) + (\text{PIC} \times 8.33)]$$

The factor 2.5, which empirically transform POC into particulate organic matter (POM), is taken from [Van Raaphorst and Melschaert \(1996\)](#). PIC is assumed to consist exclusively of CaCO_3 . The possible presence of MgCO_3 does not significantly alter the CaCO_3 value. The regression coefficients are listed in [Table 2](#). In the North Sea, the main part of TSM (74–79%) is inorganic non-carbonatic and displays a good correlation with TSM. Conversely, in the Baltic Sea, this fraction is reduced to less than 50%, evidence that the clay fraction in TSM is not dominant in those waters.

3.4. Relationship between aNLPM, TSM, and POC

Absorption of NLPM (aNLPM) data were obtained using the procedure described in [Section 2](#). aNLPM at 380 nm and the respective spectral slope S , defined as:

$$\text{aNLPM}(\lambda) = \text{aNLPM}(\lambda_0) \exp - S(\lambda - \lambda_0)$$

have been related to TSM and POC concentrations. We have described earlier how TSM is generally correlated with its organic fraction ([Fig. 3](#)), although the

Table 1

List of data, averages per area (Plymouth/English Channel, Texel/North Sea, Wilhelmhaven/German Bight, and Heringsdorf/Baltic Sea) with the maximum and the minimum values, relative to TSM analysis

Site	Period	Number of Sampling	TSM (mg/l)	TPC (mg/l)	POC (mg/l)	PN (mg/l)	PIC (mg/l)	nCInM (mg/l)	POC:PN ratio	aNLPM per m (380 nm)	NLPM S per nm (350–750 nm)
Loire plume	May-1998	9	1.91	0.436	0.42	0.066	0.0125	0.79	6.36	0.152	0.0108
			0.86–2.3	0.4–0.51	0.3–0.59	0.06–0.08	0.01–0.02	0–1.24	2.1–7.3	0.076–0.257	0.0084–0.0125
Seine plume	May-1998	9	2.73	0.81	0.61	0.12	0.15	0	5.1	0.192	0.0101
			1.2–4.31	0.52–1.09	0.35–0.89	0.08–0.21	0.02–0.55		2.2–6.5	0.077–0.418	0.0088–0.0129
Thames plume	May-1998	7	5.6	0.35	0.238	0.037	0.11	4.05	6.4	0.274	0.0119
			0.77–20.9	0.19–0.87	0.16–0.4	0.03–0.07	0.03–0.47	0.13–16	5.3–9.1	0.076–0.76	0.0098–0.0137
Rhine plume	May-1998	10	3.5	0.71	0.59	0.093	0.115	1.09	6.34	0.203	0.0109
			1.87–7.63	0.31–0.96	0.26–0.86	0.04–0.14	0–0.45	0–4.5	5.6–7.2	0.03–0.4	0.0092–0.0142
Humber plume	May-1998	8	2.53	0.41	0.328	0.054	0.08	1.04	6.07	0.125	0.0103
			0.76–8.22	0.2–1.44	0.14–1.2	0.02–0.2	0.02–0.24	0.33–3.22	4.1–7.6	0.041–0.21	0.0089–0.0142
German Bight	May-1998	17	1.55	0.278	0.24	0.04	0.03	0.74	6	0.084	0.0109
			0.6–6.7	0.17–0.4	0.09–0.4	0.02–0.07	0–0.17	0–5.1	5.2–10.2	0.034–0.266	0.0093–0.0123
Plymouth English Channel	September-1998	51	1.05	0.143	0.12	0.0192	0.025	0.58	6.25	0.0577	0.0119
			0.4–3.13	0.09–0.25	0.06–0.22	0.01–0.03	0–0.058	0–2.02	4.3–7.6	0.016–0.155	0.009–0.014
Texel North Sea	September-1998	33	8.9	0.69	0.52	0.074	0.196	6	7.02	0.48	0.0114
			1.17–70.1	0.31–4.16	0.25–2.47	0.04–0.34	0.006–1.7	0.14–51.4	5.2–7.9	0.07–1.97	0.0102–0.0125
Wilhelmhaven German Bight	September-1998	32	10.1	0.79	0.54	0.08	0.211	7.1	6.75	0.71	0.01157
			1.2–38.9	0.26–2.59	0.19–1.66	0.03–0.17	0–1.02	0.52–28.1	4.7–10.9	0.11–1.64	0.0095–0.0124
Heringdorf Baltic Sea	September-1998	51	3.2	0.86	0.79	0.082	0.0857	0.58	9.6	0.25	0.0129
			0.51–5.98	0.39–1.83	0.38–1.35	0.04–0.18	0–0.49	0–2.1	6.1–14.1	0.12–0.75	0.0095–0.0147

Table 2

Ratios POC:TSM with relative average and SD, for the river plumes (C5 survey) and for the stations of C6 survey, and the relationship between NCIM (mg/l) with TSM (mg/l) for C6 survey only

Site	POC:TSM	Site	POC:TSM
C5 Loire	0.203 (± 0.07)	C6 English Channel	0.158 (± 0.07)
C5 Seine	0.32 (± 0.09)	C6 North Sea	0.093 (± 0.04)
C5 Thames	0.081 (± 0.05)	C6 German Bight	0.077 (± 0.04)
C5 Rhine	0.197 (± 0.087)	C6 Baltic Sea	0.358 (± 0.1)
C5 Humber	0.162 (± 0.064)		
C5 Weser/Elbe	0.23 (± 0.06)		
C6 English Channel	NCIM = $-0.17(\pm 0.049) + 0.79(\pm 0.045)$ TSM		R = 0.9
C6 North Sea	NCIM = $-0.27(\pm 0.14) + 0.74(\pm 0.01)$ TSM		R = 0.997
C6 German Bight	NCIM = $-0.59(\pm 0.34) + 0.77(\pm 0.029)$ TSM		R = 0.96
C6 Baltic Sea	NCIM = $-0.3(\pm 0.15) + 0.425(\pm 0.06)$ TSM		R = 0.85

POC:TSM ratio varies within the sites (Table 3). The plot between aNLPM and the geo-chemical parameters (TSM and POC) displays different results. Despite the low slopes (Table 3), aNLPM shows a significant dependency on TSM with no substantial difference within the sites. Conversely, POC correlates linearly with aNLPM with different slopes relative to the sites, thus reflecting the various contributions (optical) of the organic/inorganic components. In the Baltic Sea, as well as in the Seine and Rhine plumes, the low slopes (0.28 and 0.32, respectively) are evidence of a consistent, but low absorbing, organic component of TSM. Conversely, in the North Sea and German Bight, aNLPM is mainly affected by the (colored) inorganic fraction, especially in the high level of TSM. Another informative source is represented by the relationship between the spectral slope S and the ratio of aNLPM at 380 nm and POC as displayed in Figs. 5 and 6. In the North Sea and in the German Bight, the slope S increases with increasing aNLPM:POC ratio, demonstrating that the chemical-optical characteristics of NLPM depend on the

inorganic substrate of the TSM. However, it seems that a constant ratio aNLPM:POC (0.02 and 0.025) is coupled to a wide variation of S in the Baltic Sea, Seine, Rhine, and Weser/Elbe plumes (Figs. 5 and 6).

4. Discussion and conclusions

This study has shown that the constituent measurements of TSM in coastal waters contain useful information on the bio-geo-chemistry of this parameter, which can be ‘observed’ synoptically by remote-sensing techniques.

Substantial variations have been noted in the different sites visited. The relationship between POC and PN has given results with variability consistent with the literature. The ratio POC:PN=9.6 found in the Baltic Sea reflects the peculiar nature of this water body, which is characterized by high CDOM and DOC. The high percentage of POC on TSM, compared with the Maybeck (1982) data (Fig. 4), suggests that TSM in the Baltic Sea (at least relative to the area investigated)

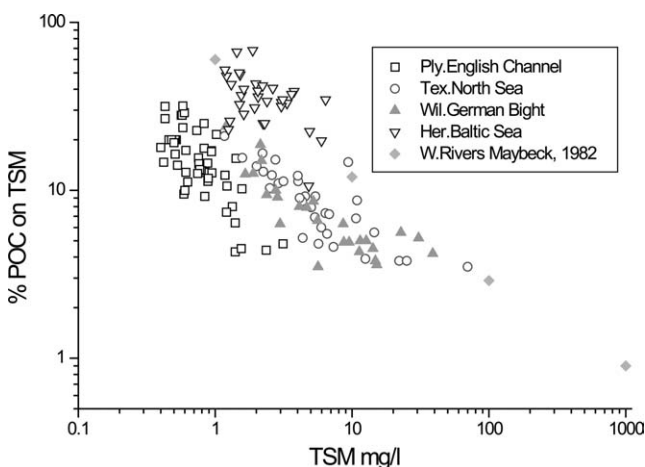


Fig. 4. Log-log plot showing the dependency of %POC on TSM vs. TSM for C6 survey. The superimposed four points are derived from the log-log best fit for the same parameters relative to world rivers (Maybeck, 1982).

Table 3

Relationships of aNLPM (per meter) with TSM (mg/l) and POC (mg/l) for C5 and C6 surveys

aNLPM = $0.078(\pm 0.018) + 0.062(\pm 0.003)$ TSM	C6, all the data
R = 0.87	
aNLPM = $0.07(\pm 0.03) + 0.07(\pm 0.01)$ TSM	C6, Baltic Sea
R = 0.65	
aNLPM = $-0.08(\pm 0.03) + 1.4(\pm 0.07)$ POC	C6, excluding the Baltic Sea
R = 0.86	
aNLPM = $0.023(\pm 0.06) + 0.28(\pm 0.07)$ POC	C6, Baltic Sea
R = 0.61	
aNLPM = 0.32 POC	C5, Seine and Rhine plume
R = 0.87	
aNLPM = $-0.35 + 2.63$ POC	C5, Thames plume
R = 0.85	
aNLPM = $-0.15 + 0.92$ POC	C5, Weser/Elbe plume
R = 0.81	

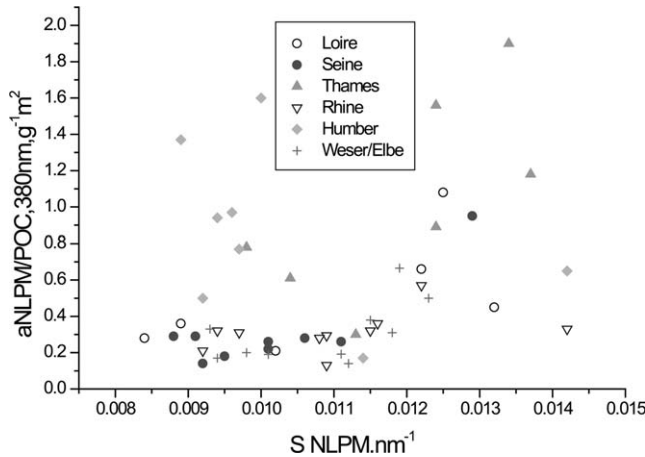


Fig. 5. Plot of the spectral slope S of aNLPM vs. the ratio aNLPM:POC for the C5 survey.

is similar to that of the rivers and is consequently of continental nature. On the other hand, in the same environment, the high-POC particles can be, in addition to that introduced by rivers and streams, a possible local source of CDOM and DOC via bacterial degradation. TSM can be a tracer for POC using a linear expression, only in the measurement interval, for the North Sea and the Baltic Sea. The average ratios POC:TSM can be divided in two groups characterized by: (1) TSM–organic matter-dominated waters with low specific weight characterized by high slope as found in the plumes of the Loire, Seine, and Weser/Elbe Rivers, and especially in the Baltic Sea (Fig. 3); and (2) TSM–inorganic matter-dominated waters with high specific weight characterized by low slope such as found in the North Sea. TSM has been proven to be an ineffective tracer for PIC, the carbonatic fraction of TSM. However, TSM is a good tracer for the NCIM, which represents from 50 (Baltic Sea) to 79% (North Sea) of TSM.

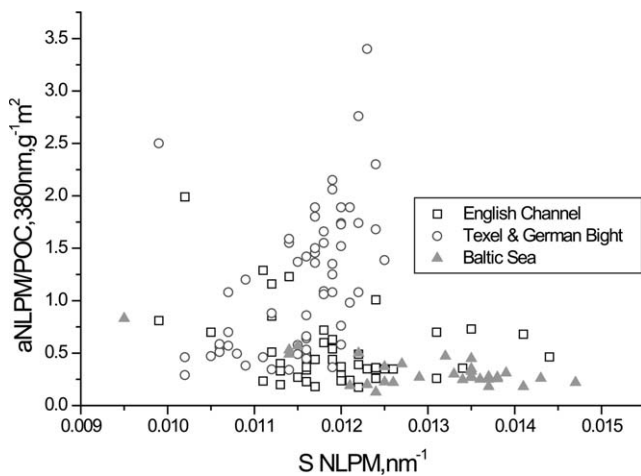


Fig. 6. Plot of the spectral slope S of aNLPM vs. the ratio aNLPM:POC for the C6 survey.

The inference of qualitative and quantitative information on TSM from its optical properties, is a major challenge for environmental remote-sensing technology. Several efforts have been made, with satisfactory results, for the retrieval of photosynthetic pigments and, indirectly, of the primary production (Sathyendranath, Longhurst, Caverhill, & Platt, 1995). Nevertheless, considerable work is still to be done before CDOM and TSM concentrations can be detected when these parameters are not correlated with chlorophyll (Case-2 waters). The results of this work are a step in this direction. The scope of this work, however, was not to discuss the specific ocean color algorithms and models parametrized with absorption coefficients of the water constituents. The objective was to demonstrate, having an optical (absorption) parameter of TSM (in this case aNLPM and the relative S , which could be remotely derived), the possibility to infer geo-chemical information on C, N, and TSM concentrations, in a synoptic view, as compared with historical data obtained in discrete measurement. The results, despite limited to one seasonal condition, are sufficient to derive general information on the site visited and can be summarized as follow:

- NLPM may be a tracer for TSM ‘in toto’ for all the sites, but the low slope (0.038–0.07) does not suggest the use (little variations of aNLPM correspond to large variations of TSM concentrations).
- POC, measured independently by TSM weight, and TSM have been found to be correlated with higher slopes (from 0.28 to 2.63), and with significant differences between the sites. The low slopes of the Baltic Sea (0.28) and river plumes, Seine and Rhine, are clear indication of organic-rich TSM. Further, POC variation in the particulate matter affects the aNLPM in different ways. In other words, the organic-rich TSM (as in Baltic Sea, where $POC \sim 36\%$ of TSM) does not determine strong variations of aNLPM as in other sites, where TSM is dominated by inorganic matter.
- Qualitative considerations on NLPM can be deduced by the plot within the spectral slope S of aNLPM and aNLPM per unit of POC. In the absorption spectrum, S is the parameter that characterizes how rapidly the absorption decreases with increasing wavelength. S is therefore considered a ‘quality’ parameter because it is dependent on the electronic structure of the absorbing molecule. Our findings indicate that, in the Baltic Sea, Seine, and Rhine plumes, to a variation of the kind of absorbing molecules (mainly organic, with S varying from 0.0115 to 0.0145), it corresponds a constant ratio aNLPM:POC (~ 0.025). Conversely, in the North Sea and German Bight, with inorganic-dominated TSM, the plot assumes a quasi-exponential shape, with a large scatter of the

aNLPM:POC ratio (from 0 to 0.35), whose variations can be determined by the load of the absorbing inorganic molecules of the particles characterized by *S* varying from 0.0095 to 0.0125.

This discussion leads to the conclusion that this approach to environmental study, conceived as support to remote-sensing sea-truth data collection, has provided useful results in the consideration of the rapid sampling performed. During the C6 campaign using the helicopter, despite the bad weather, samplings in 178 stations in four test-sites in 4 weeks have been performed. Combining fast sampling, rapid laboratory methods (C, N) coupled with statistical analysis, we can dispose of a useful tool to integrate and verify the results obtained, applying the traditional approach, site per site, of the geo-chemical coastal studies.

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References

- Altabet, M. A., Bishop, J. K. B., & McCarthy, J. J. (1992). Differences in particulate nitrogen concentration and isotopic composition for samples collected by bottles and large volume pumps in Gulf Stream warm-core ring and Sargasso Sea. *Deep-Sea Research* 39(1), S405–S417.
- Babin, M., Stramski, D., Ferrari, G. M., Claustre, H., Bricaud, A., Obolensky G., & Hoepffner, N. (2003). Variations in the light absorption coefficients of phytoplankton, non-algal particles, and dissolved organic matter in coastal waters around Europe. *Journal of Geophysical Research* (in press).
- Bale, A. J., & Morris, A. W. (1998). Organic carbon in suspended particulate material in the North Sea: Effect of mixing re-suspended and background particles. *Continental Shelf Research* 18, 1333–1345.
- Davidson, E., Agren, G., Daniel, O., Emeis, K. C., Largeau, C., Lee, C., Mopper, K., Oades, G. M., Reeburgh, W. S., Schimel, D. S., & Zepp, R. G. (1995). What are the physical, chemical, and biological processes that control the formation and degradation of non-living organic matter? In R. G. Zepp, & Ch. Sontag (Eds.), *Role of non-living organic matter in the Earth's carbon cycle* (pp. 7–43). New York: Wiley.
- Eisma, D., & Kalf, J. (1987). Distribution, organic content and particle size of suspended matter in the North Sea. *Netherlands Journal of Sea Research* 21, 265–285.
- Ferrari, G. M., & Dowell, M. D. (1998). CDOM absorption characteristics with relation to fluorescence and salinity in coastal areas of southern Baltic Sea. *Estuarine, Coastal and Shelf Science* 47, 91–105.
- Ferrari, G. M., Dowell, M. D., Grossi, S., & Targa, C. (1996). Relationship between the optical properties of chromophoric dissolved organic matter and total concentration of dissolved organic carbon in the southern Baltic Sea region. *Marine Chemistry* 55, 299–316.
- Ferrari, G. M., & Tassan, S. (1999). A method using chemical oxidation to remove light absorption by phytoplankton pigments. *Journal of Phycology* 35, 1090–1099.
- Fleming, R. H. (1940). The composition of plankton and units for reporting populations and production. *Sixth pacific science congress, California, 1936 proceedings* (pp. 3535–3540).
- Hedges, J. I. (1977). The association of organic molecules with clay minerals in aqueous solutions. *Geochimica and Cosmochimica Acta* 51, 1119–1123.
- Hedges, J. I., & Hare, P. E. (1987). Amino acid adsorption by clay mineral in distilled water. *Geochimica and Cosmochimica Acta* 51, 225–259.
- Jumars, P. A., Penry, D. L., Baross, J. A., Perry, M. J., & Frost, B. W. (1989). Closing the microbial loop: dissolved carbon pathway to heterotrophic bacteria from incomplete ingestion, digestion and adsorption in animals. *Deep-Sea Research* 36, 483–495.
- Maybeck, M. (1982). Carbon, nitrogen, and phosphorus transport by world rivers. *American Journal of Science* 282, 401–450.
- Morris, A. W., & Howarth, M. J. (1998). Bed stress induced sediment resuspension (SERE 88/89). *Continental Shelf Research* 18, 1203–1213.
- Nelson, J. R., & Robertson, C. Y. (1993). Detrital spectral absorption: laboratory study of visible light on phytodetritus absorption, bacterial spectral signal, and composition to field measurements. *Journal of Marine Research* 51, 181–207.
- Prandle, D., Jago, C. F., Jones, S. E., & Tappin, A. (1993). The influence of horizontal circulation on the supply and distribution of contaminants. *Philosophical Transactions of the Royal Society* 343(1669), 405–421.
- Ramson, B., Kim, D., Kastner, M., & Wainwright, S. (1998). Organic matter preservation on continental slopes: importance of mineralogy and surface area. *Geochimica and Cosmochimica Acta* 62, 1329–1345.
- Redfield, A. C. (1934). On the proportion of organic derivatives in sea water and their relation to the composition of plankton. *James Johnstone memorial volume* (pp. 176–192). Liverpool: Liverpool University Press.
- Sathyendranath, S., Longhurst, A., Caverhill, C. M., & Platt, T. (1995). Regionally and seasonally differentiated primary production in the North Atlantic. *Deep-Sea Research* 42(10), 1773–1812.
- Strom, S., Benner, S., Ziegler, S., & Dagg, M. (1997). Planktonic grazers are a potentially important source of marine dissolved organic carbon. *Limnology and Oceanography* 42, 1364–1374.
- Tassan, S., & Ferrari, G. M. (1995). An alternative approach to absorption measurements of aquatic particles retained on filters. *Limnology and Oceanography* 40, 1358–1368.
- Tassan, S., & Ferrari, G. M. (1995). Proposal for the measurements of backward and total scattering by mineral particles suspended in water. *Applied Optics* 34, 8345–8353.
- Wangersky, P. J. (1994). Sampling and analysis of particulate and dissolved matter. In R. S. Wotton (Ed.), *The biology of particles in aquatic systems* (2nd ed., pp. 7–43). Boca Raton: Lewis.
- Van der Linde, D. W. (1998). *Protocol for determination of total suspended matter in oceans and coastal zones* (182 pp.). CEC-JRC-Ispra, Technical note no. I.98.
- Van Raaphorst, W., & Malschaert, J. F. P. (1996). Ammonium adsorption in superficial North Sea sediments. *Continental Shelf Research* 16(11), 1415–1435.