

Bio-optical properties of coastal waters in the Eastern English Channel

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Abstract

Strong tidal currents, shallow water and numerous freshwater inputs characterize the coastal waters of the eastern English Channel. These case 2 waters were investigated through an intensive sampling effort in 2000 aiming to study the distribution and variability of the Chromophoric Dissolved Organic Matter (CDOM), Non-Algal Particles (NAP) and phytoplankton absorption at the mesoscale. Four cruises were carried out in February, March, May and July and more than 80 stations each cruise were sampled for hydrographical, chemical and bio-optical analyses. Results showed two distinct situations, the winter period characterized by the strong dominance of CDOM absorption over the particulate matter, and the spring–summer period when phytoplankton and CDOM represented the same contribution. Meteorology was the main factor driving the bio-optical properties of the water column in winter whereas in spring–summer the biological activity seemed to be the more active driving force. The algal community composition in term of dominant cell size and, therefore pigment packaging, is the main factor driving the phytoplankton specific absorption in the water column. Photoprotective pigments did not significantly influence algal absorption, due to turbid and highly mixed water masses. This feature also explained the bio-optical homogeneity found along the water column. On the mesoscale, distinct bio-optical provinces were defined in relation with the observed bio-hydrographical variability.

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1. Introduction

The application of the ocean color remote sensing technique in coastal areas still needs to be validated and calibrated and requires the study of inherent optical properties (IOPs) at regional scale (IOCCG, 2000; Babin et al., 2003). This is of considerable significance for oceanographers since coastal ecosystems are among the most productive and rich in biodiversity of marine systems. However, they represent complex systems at ecological and optical levels, in relation with high frequency variability in time and space due to hydrodynamics

(e.g. tidal currents, coastal fronts, turbulence) and freshwater input fluctuations. From an optical point of view, these ecosystems correspond mostly to case 2 waters (Morel and Prieur, 1977) where the lack of direct relationship between the absorption of non-chlorophyllous components and phytoplankton makes difficult general parameterization of their optical properties on the contrary to the case 1 oceanic waters (Bricaud et al., 1995; Cleveland, 1995; Bricaud et al., 1998). Recently, coastal ocean optics have been the topic of numerous studies (e.g. Babin et al., 2003; Gallegos et al., 2005; Simis et al., 2005; Tilstone et al., 2005), highlighting the necessity of bio-optical measurements at regional scale, which is a crucial step in improving the accuracy of coastal bio-optical algorithms.

Freshwater inputs are assumed to be the major source of Chromophoric Dissolved Organic Matter (CDOM) in coastal

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waters (Siegel et al., 2002) even though biological sources (e.g. from phytoplankton and/or bacterioplankton) cannot be neglected (Nelson et al., 1998; Rochelle-Newall and Fisher, 2002; Gallegos et al., 2005). The CDOM absorption and spectral signature can change over time and space, in relationship with its composition and origin (Carder et al., 1989), and, for instance, with processes such as bacterial degradation, photo-degradation, coagulation or selective sedimentation (Carder et al., 1989; Gao and Zepp, 1998). In contrast to CDOM, variations in the absorption coefficient of Non-Algal Particles (NAP) in coastal waters are less well described (e.g. Sydor and Arnone, 1997; Gallegos and Neale, 2002; Babin et al., 2003; Bowers and Binding, 2006). However, absorption of NAP seems to depend on particle size and composition, which vary from site to site and on a seasonal scale (e.g. Ferrari et al., 2003; Gallegos et al., 2005). In certain cases, phytoplankton may also represent the main contributor to the overall absorption in coastal waters, even though it is not a general rule (Schofield et al., 2004). Indeed, it depends on the high variability in space and time of the algal growth and dynamics, which is the result of the interactions between abiotic (nutrients, light) and biotic (grazing) factors depending on physical and climatic events. The absorption properties of phytoplankton mainly rely on the pigment composition, which is a function of community composition and physiological state, and on the packaging effect (Hoepffner and Sathyendranath, 1991; Bricaud et al., 1995; Sosik and Mitchell, 1995). Recent works by Ciotti et al. (2002) and Bricaud et al. (2004) showed that changes in the dominant cell size of the algal community, and subsequent changes in pigment packaging, can explain a major part of the natural variability observed in the spectral shape of algal absorption.

The general aim of this study is to quantify the contribution of the three main absorption components of seawater, and its variability on seasonal (winter, spring and summer periods), meso- and vertical scale in the eastern English Channel. Strong tidal currents, numerous freshwater inputs and shallow water masses characterize this highly productive coastal sea. The biological and environmental variability is further increased by the distinction of two ecosystems, located south and north of the region (e.g. Brunet et al., 1996) and by the development of a non-permanent tidal front separating the coastal and offshore waters (Brylinski et al., 1996). All these features make this area an interesting test site for studies dealing with relationships between bio-optical properties and environmental (biotic and/or abiotic) forcing.

2. Materials and methods

2.1. Sampling and hydrology

Four cruises were carried out in February, March, May and July 2000 from the Bay of Seine to the North of Boulogne sur mer (Table 1, Fig. 1). The sampling grid, consisted of 82 stations distributed along 18 coastal-offshore transects, and covered the different water masses present in the area, from estuarine (in relationship with the Seine and Somme rivers)

Table 1

Periods of sampling and number of stations and samples analyzed for CDOM, particulate (NAP and phytoplankton) absorption and ancillary parameters ("Ancil. Param.": pigments, nutrients, flow cytometry, particulate carbon)

Cruise	Period	Ancil. Param.	CDOM	Particulate	Stations
Bioptel 1	14–18 February	50	12	50	26
Bioptel 2	30–31 March	125	53	125	82
Bioptel 3	29–31 May	115	46	115	82
Bioptel 4	29 June–01 July	142	58	142	82

to the coastal and offshore waters. In February, the number of stations sampled was of 26 (southern part of the sampling grid) due to the occurrence of bad meteorological conditions.

At each sampling station, profiles of salinity, temperature and density were recorded with a CTD (Seabird 25) equipped with a PAR quantummeter (Li-Cor, LI-193SA), a fluorometer (WetLabs – Wetstar) and a transmissiometer (WETLabs) measuring light, chlorophyll *a* fluorescence and turbidity, respectively. Density profiles were used to estimate the Brunt-Väisälä frequency (N^2 in s^{-2}) used as an index of water mass vertical stability:

$$N^2 = (g/\sigma)(\Delta\sigma/\Delta z) \quad (1)$$

where, g is the acceleration due to gravity ($m\ s^{-2}$), σ the mean density of the water column ($kg\ m^{-3}$) and $\Delta\sigma$ the difference of density between surface and bottom (Δz , m).

Water samples were collected at two depths, 2 m below the surface and 2 m above the bottom, using 5 liters Niskin bottles for chemical, biological and bio-optical measurements (Table 1).

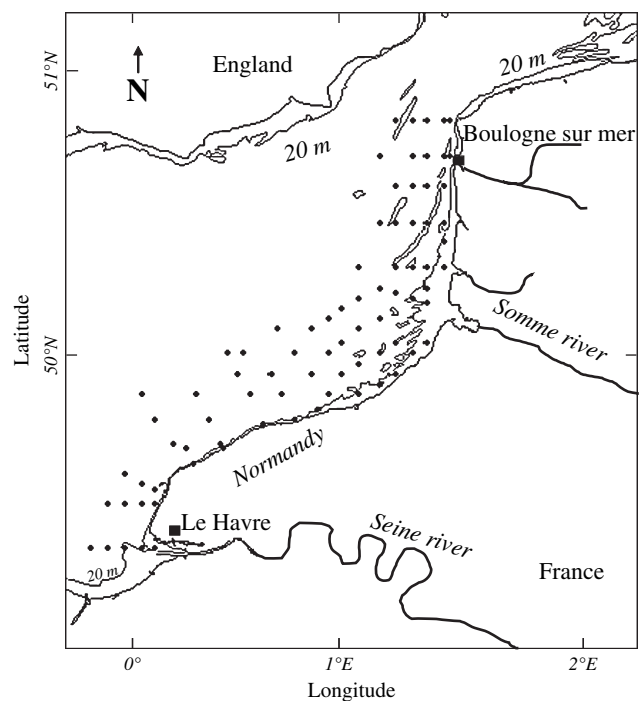


Fig. 1. Location of the stations sampled during the 4 cruises. In February, only the six more south transects has been sampled (see also Table 1).

2.2. CDOM absorption

Seawater samples (500 ml) were filtered on 0.22 μm Millipore membrane and the filtrates were stored in 250 ml brown glass bottle and conserved at 4 °C. Just before analysis, the samples were adapted to room temperature to prevent any bias induced by temperature differences between sample and blank (Milli-Q water). Absorbance spectra of CDOM were measured every nanometer between 250 and 800 nm using a 10 cm quartz cuvette and the absorbance values were transformed in absorption coefficients using a classical Napierian conversion. The mean value of the interval 680–690 nm was subtracted from the spectrum (baseline correction, Babin et al., 2003). The spectral slope (S_{CDOM}) was calculated using a non-linear exponential fit function:

$$a_{\text{CDOM}}(\lambda) = a_{\text{CDOM}}(\lambda_{\text{ref}}) \times \exp(-S_{\text{CDOM}}(\lambda - \lambda_{\text{ref}})) \quad (2)$$

where, $a_{\text{CDOM}}(\lambda_{\text{ref}})$ corresponded to the CDOM absorption (m^{-1}) at a reference wavelength λ_{ref} (375 nm) and S_{CDOM} was the absorption spectral slope (nm^{-1}). This equation was applied to the domain [350–500 nm] (Babin et al., 2003).

2.3. Phytoplankton and NAP absorptions

One litre of seawater was filtered on 47 mm Whatman GF/F filters and immediately frozen in liquid nitrogen and stored in the dark until laboratory analysis. The absorbance spectrum (dimensionless) was measured between 400 and 1000 nm with 1 nm increment on a dual beam spectrophotometer (Hewlett Packard HP-8453E) equipped with an integrating sphere (Labsphere RSA-HP-53). As recommended in Mitchell et al. (2000), a multiplication factor of 0.72 was applied on the optical densities to correct the bias induced by using a Hewlett Packard diode array system. Correction for pathlength amplification (Tassan and Ferrari, 1995), needed to convert absorbance of particles retained on the filter (A_s) to equivalent absorbance of particles in an aqueous suspension (A_{sus}), was performed following the formulation of Cleveland and Weidemann (1993):

$$A_{\text{sus}}(\lambda) = 0.378A_s(\lambda) + 0.523A_s(\lambda)^2 \quad (3)$$

Assuming a zero-absorption by the particles in the infrared region (Babin and Stramski, 2002), the mean absorbance value between 790 and 800 nm was subtracted to the entire spectrum in order to correct for scattering effects (Mitchell et al., 2000). The values of absorbance have been then converted into absorption coefficient (m^{-1} , Tassan and Ferrari, 1995):

$$a_p(\lambda) = 2.3A_{\text{sus}}(\lambda)/(V/A) \quad (4)$$

where $a_p(\lambda)$ the particles absorption coefficient (m^{-1}), V the filtered volume (m^3) and A the clearance area of the filter (m^2).

The non-algal absorption spectrum (a_{NAP}) was obtained after disrupting phytoplankton pigments with sodium hypochlorite (NaClO , Ferrari and Tassan, 1999), and was fitted to a non-linear exponential function (Bricaud et al., 1995):

$$a_{\text{NAP}}(\lambda) = a_{\text{NAP}}(\lambda_{\text{ref}}) \times \exp(-S_{\text{NAP}}(\lambda - \lambda_{\text{ref}})) \quad (5)$$

where, S_{NAP} was the slope of the spectrum (nm^{-1}) and $a_{\text{NAP}}(\lambda_{\text{ref}})$ corresponded to the absorption (m^{-1}) of NAP at the reference wavelength (440 nm).

The phytoplankton absorption spectrum (a_{ph}) was obtained by subtracting the non-algal particle absorption (a_{NAP}) to the total particle absorption spectra (a_p):

$$a_{\text{ph}}(\lambda) = a_p(\lambda) - a_{\text{NAP}}(\lambda) \quad (6)$$

The phytoplankton specific absorption coefficient ($a_{\text{ph}}^*(\lambda) = a_{\text{ph}}(\lambda)/[\text{chl}a]$, in $\text{m}^2 (\text{mg chl}a)^{-1}$), was partitioned into photosynthetic ($a_{\text{ps}}^*(\lambda)$) and non-photosynthetic ($a_{\text{nps}}^*(\lambda)$) components. The absorption of photoprotective (non-photosynthetic) pigments was estimated using the following relationship (Babin et al., 1996):

$$a_{\text{ps}}^*(\lambda) = a_{\text{ph}}^*(\lambda)[1 - \text{Fnps}(\lambda)] \quad (7)$$

where, $\text{Fnps}(\lambda)$ represented the part of phytoplankton absorption attributed to photoprotective carotenoids, with:

$$\text{Fnps}(\lambda) = [\sum a_i^*(\lambda) c_i]_{\text{nps}} / [\sum a_i^*(\lambda) c_i]_{\text{all}} \quad (8)$$

where, $a_i^*(\lambda)$ was the specific absorption coefficient of the pigment i in solution ($\text{m}^2 \text{mg}^{-1}$, Bidigare et al., 1990) and c_i its concentration (mg m^{-3}).

2.4. Phytoplankton pigments

One liter of seawater was filtered through 47 mm Whatman GF/F filters immediately frozen in liquid nitrogen. Pigments were analyzed using a Hewlett Packard Series 1100 HPLC, equipped with a 3- μm C₈ BDS column (100 \times 4.6 mm) and detected both using a HP photodiode array detector Model DAD Series 1100 (at 440 nm) a fluorometer HP series 1100 (using a 410 nm excitation wavelength and a 665 nm emission wavelength). The method adopted is equivalent to that in Vidussi et al. (1996). The quantification of pigments was performed using chlorophyll and carotenoid standards obtained from the VKI (Water Quality Institute) International Agency for ¹⁴C Determination, Denmark. The sum of photoprotective carotenoids (PPC: diatoxanthin, diadinoxanthin, zeaxanthin, antheraxanthin and β carotene), photosynthetically active carotenoids (PSC: fucoxanthin, 19' Butanoyloxyfucoxanthin, 19' Hexanoyloxyfucoxanthin, peridin, prasinoxanthin and violaxanthin) and chlorophyll a degraded products (Degr = pheophorbides a + pheophytin a) were estimated. The relative proportion of pico-, nano- and microphytoplankton was computed using the chemotaxonomic pigment ratios described in Vidussi et al. (2001). The contribution of the main algal groups to total biomass was obtained using the conversion factors published by Casotti et al. (2000).

2.5. Associated parameters

Bacterial and picophytoplankton cell numbers were determined by flow cytometry using a FACScalibur flow cytometer (Becton Dickinson) equipped with a standard laser and filter set and using 0.22 μm filtered seawater as the sheath fluid. All the details on the preparation, conservation and analysis of samples are given in Casotti et al. (2000).

Particulate Organic and Inorganic Carbon (POC and PIC, respectively) and Particulate Organic Nitrogen (PON) concentrations were estimated using a CHN analyzer (Carbo-Erba, 1106) on 1-liter seawater sample filtered on pre-combusted 47 mm Whatman GF/F filters.

Nutrient concentrations (nitrite, nitrate, phosphate and silicate) were determined using an auto-analyzer Technicon II.

2.6. Statistical analysis

Mean, standard deviations, correlation coefficients and comparisons of means (Student's *t*-test) were computed with the Systat 11[®] program. Two principal component analyses (PCA, Legendre and Legendre, 1998) were performed using a data set composed by bio-optical parameters and the environmental and biological variables considering correlation matrices and using Statistica 7[®] software.

3. Results

3.1. Hydro-biological situation

Freshwater inputs were found to be continuously decreasing from winter (309 $\text{m}^3 \text{s}^{-1}$) to summer (129 $\text{m}^3 \text{s}^{-1}$, Table 2), and could be one of the reason of the (low) increase in the salinity of the coastal area during the same period (from 31.3 to 33.7) as well as of the lowering of the stratification of the water column (Table 2), as suggested by the parallel evolution between N^2 and river flows. The situation observed in May appeared to be peculiar, due to high wind speed ($>10 \text{ m s}^{-1}$) during the two weeks before the cruise, which has induced an homogenization of the water column ($N^2 = 0.37 \times 10^{-2} \text{ s}^{-2}$, Table 2). On the spatial scale, a decreasing gradient of salinity appeared from the coast to the offshore waters (e.g. in May, Fig. 2A). As for salinity, the chlorophyll biomass presented a recurrent pattern during the different cruises, with higher *chl a* concentrations located near to the Seine and Somme estuaries (up to 40 $\mu\text{g l}^{-1}$) and in the shallow waters of the north part of the area, while the lowest biomass was observed in the offshore waters and in the coastal waters of Normandy ($<4 \mu\text{g l}^{-1}$, e.g. in May, Fig. 2B). On a time scale, the mean *chl a* concentration increased from February (0.75 $\mu\text{g l}^{-1}$) to May (15.15 $\mu\text{g l}^{-1}$) remaining quite high in July (12.28 $\mu\text{g l}^{-1}$) while the bacterial abundance was continuously increasing from February to July (from 0.88×10^5 to $22.2 \times 10^5 \text{ cells ml}^{-1}$, Table 2). The onset of the spring bloom, occurring in March, was related to an increase in the mean algal cell size (Table 2), which was also shown by the significant relationship found between

Table 2

Means of *chl a* concentration, class size contribution, bacteria concentration, accessory pigment ratio, phytoplankton group contribution, Brunt-Väisälä frequency (N^2) and river flows for the 4 cruises. PSC: PhotoSynthetic Carotenoids, PPC: PhotoProtective Carotenoids (see Section 2.4). River flows corresponded to the overall regional mean values considering the 2 weeks preceding each cruise (data from the "Agences de l'Eau" "Normandie", "Picardie" and DIREN "Nord-Pas-de-Calais")

	February	March	May	July
<i>Chl a</i> ($\mu\text{g l}^{-1}$)	0.75	5.11	15.15	12.28
Picoplankton (%)	9.57	3.60	0.61	1.34
Nanoplankton (%)	24.41	14.61	4.49	4.78
Microplankton (%)	66.02	81.79	94.90	93.88
Cyanophytes (%)	7.5	0.6	0.2	1.5
Cryptophytes (%)	10.8	10.6	4.2	2.6
Dinoflagellates (%)	8.4	4.7	1.4	2.8
Green algae (%)	12.3	5.2	1.0	0.5
Prymnesiophytes (%)	10.4	23.1	14.2	29.9
Diatoms (%)	50.6	55.8	79.0	62.7
PSC/ <i>chl a</i>	0.54	0.81	1.05	0.79
PPC/ <i>chl a</i>	0.09	0.08	0.12	0.12
Bacteria concentration ($10^6 \text{ cells ml}^{-1}$)	0.88	1.07	1.33	2.22
River flow ($\text{m}^3 \text{ s}^{-1}$)	309	263	163	129
N^2 (10^{-2} s^{-2})	1.92	1.25	0.37	0.64

chl a and the proportion of microphytoplankton ($p < 0.001$, Fig. 3A). Diatoms and prymnesiophytes greatly dominated the algal community (from ~ 60 to 90%, Table 2), with diatom's contribution increasing from February to May, while the contribution of prymnesiophytes (including *Phaeocystis* sp.) was the highest in summer.

The photoprotective carotenoids vs *chl a* ratio (PPC/*chl a*) was rather constant during the study period (0.08 to 0.12), whereas the photosynthetic carotenoids vs *chl a* ratio (PSC/*chl a*) was more variable where the highest value was observed in May (1.05) while the other cruises ranging from 0.54 to 0.79 (Table 2). Concentrations of accessory carotenoids (PPC + PSC) were highly correlated to *chl a* following a log-linear relationship (Fig. 3B) in accordance with Trees et al. (2000) parameterization.

3.2. CDOM absorption

The three components, $a_{\text{CDOM}}(\lambda)$, $a_{\text{NAP}}(\lambda)$ and $a_{\text{ph}}(\lambda)$ has similar values between surface and bottom (Student's *t*-test, $p > 0.05$) and co-varied in these two depths (Spearman correlation, at least $p < 0.01$) allowing us to consider only the surface depth for the spatial distribution analysis.

The main factor determining the spatial distribution of $a_{\text{CDOM}}(375)$ seemed to be the freshwater inputs (Fig. 2C) as revealed by the significant relationship between $a_{\text{CDOM}}(375)$ and salinity (Spearman correlation, $p < 0.001$). When considering separately the three cruises (February was taken into consideration due to the low number of data), the relationships between these two parameters (Fig. 4) showed similar slopes in March and May (ranging between

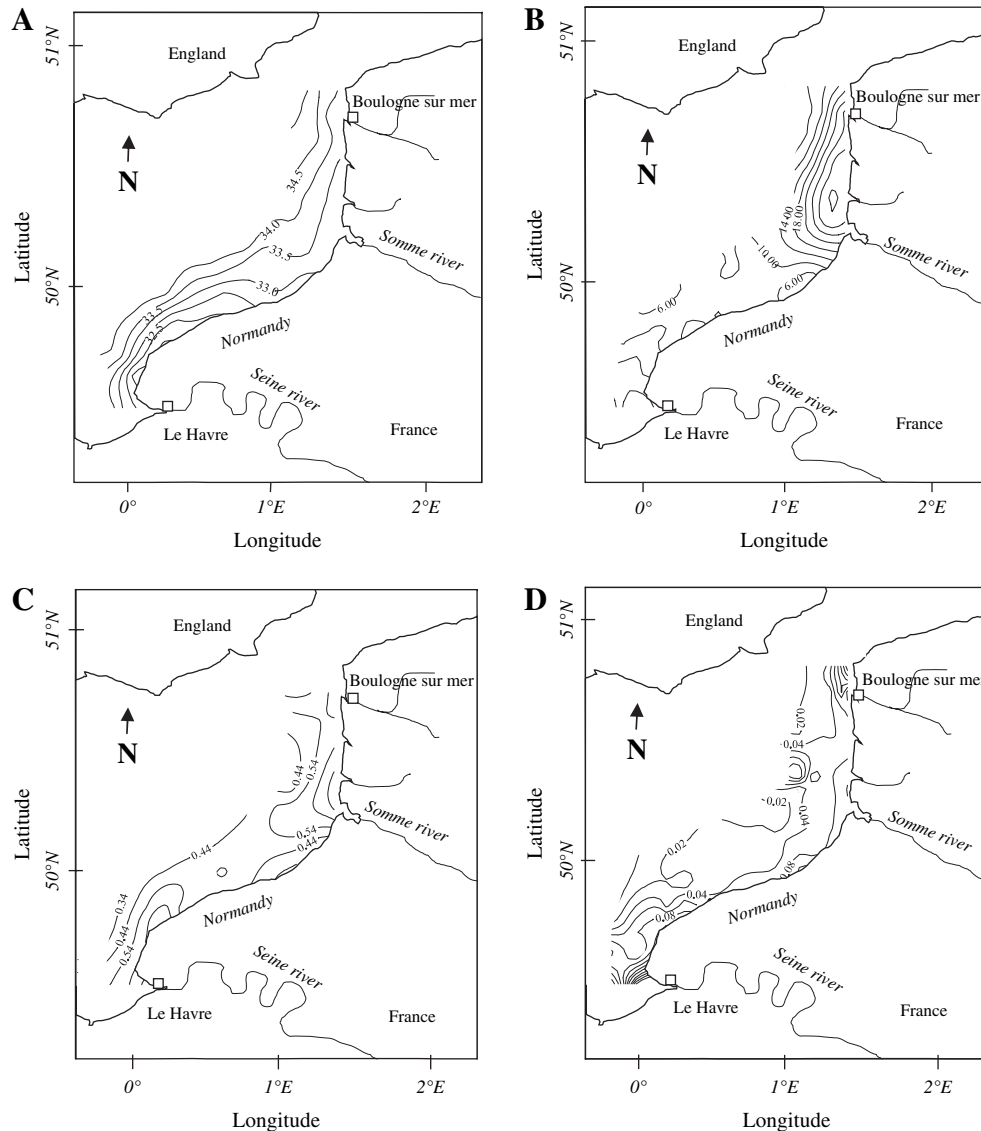


Fig. 2. Spatial distribution at surface (2 m depth) of the salinity (A); chl *a* concentration ($\mu\text{g l}^{-1}$, B); CDOM absorption coefficient at 375 nm (m^{-1} , C); and NAP absorption coefficient at 440 nm (m^{-1} , D) in May 2000.

−0.058 and −0.066) whereas the slope significantly decreased in July (−0.161).

The seasonal variability of the mean of $a_{\text{CDOM}(375)}$ was characterized by a decrease from winter (February) to spring (March), and a further increase to summer (July, Table 3), which did not respect the river input evolution, decreasing continuously from February to July (Table 2). A PCA analysis was performed on the dataset composed by $a_{\text{CDOM}(375)}$ and biological and environmental data from March to July, i.e. excluding the wintertime which appeared very different than the spring–summer period. Significant relationship between $a_{\text{CDOM}(375)}$ and chl *a* biomass, microplankton, bacterial abundance and phytoplankton degradation products was shown (Fig. 5), whereas no relationship between $a_{\text{CDOM}(375)}$ and river flows or salinity was found, suggesting that change in terrestrial inputs was not the main process explaining the temporal evolution of CDOM during the spring–summer

period (Fig. 5). The mean of S_{CDOM} (Table 3, all data pooled together: 0.01488 nm^{-1} , S.D. = 0.0020 nm^{-1}) regularly decreased from winter (0.0177 nm^{-1} , S.D. = 0.0033 nm^{-1}) to summer (0.0133 nm^{-1} , S.D. = 0.0013 nm^{-1}).

3.3. NAP absorption

The spatial distribution of $a_{\text{NAP}(440)}$ showed a decreasing coast-to-offshore gradient (Fig. 2D) and was significantly correlated to the salinity (Spearman correlation, $p < 0.01$). The highest values were found in the water influenced by the Seine and Somme rivers as well as along the coast of the Normandy region and in the coastal part of the Strait of Dover (north of the study area) while the lowest value were observed in the offshore stations influenced by the Atlantic waters.

With respect to the seasonal variability, higher mean values of $a_{\text{NAP}(440)}$ were observed in February and May (Table 4,

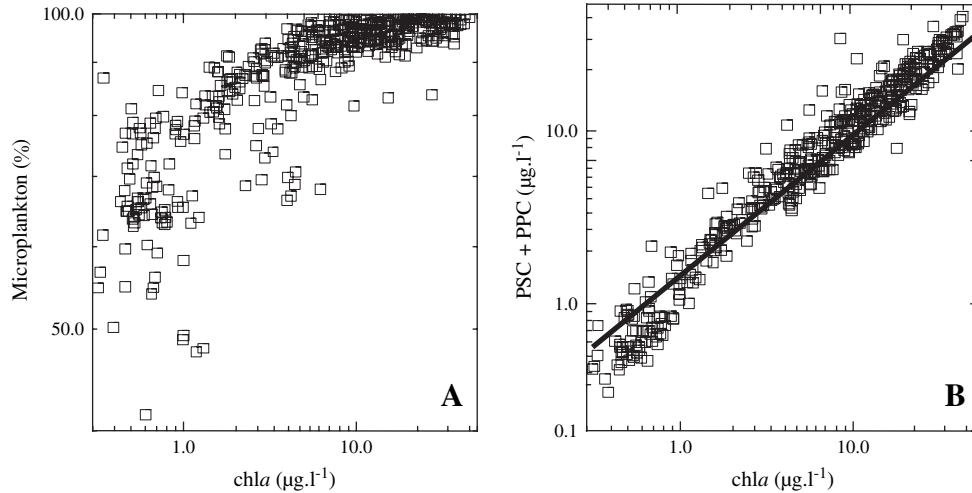


Fig. 3. Scatterplot (logarithmic scales) between chl a ($\mu\text{g l}^{-1}$) and contribution of microplankton (A); and total accessory pigment concentration ($\mu\text{g l}^{-1}$, B). On the panel (B) the solid line represents the parameterization of Trees et al. (2000).

0.084 m^{-1} , S.D. = 0.070 m^{-1} and 0.047 m^{-1} , S.D. = 0.030 m^{-1} respectively) while the lower values were measured in March and July (0.030 m^{-1} , S.D. = 0.018 m^{-1} and 0.027 m^{-1} , S.D. = 0.018 m^{-1} , respectively). $a_{\text{NAP}}(440)$ was correlated with the PIC concentration considering the whole dataset ($p < 0.001$) suggesting a permanent influence of inorganic sediments on the NAP absorption signal. This feature was particularly pronounced in May (Spearman coefficient 0.634, $n = 77$). Conversely, the influence of organic material was emphasised by the high correlations ($p < 0.001$) found between $a_{\text{NAP}}(440)$ and POC in February, when the POC/PIC ratio was very low (3.2, Table 4), and July when the POC/PIC ratio was the highest (8.5, Table 4) presumably due to the decline of the spring bloom as also revealed by the relationship with the phytoplankton degradation products and chl a concentration (Spearman correlation, $p < 0.001$).

Conversely to $a_{\text{NAP}}(440)$, the S_{NAP} varied slightly at both temporal and spatial scales (Table 4), with an overall mean of 0.0115 nm^{-1} (S.D. = 0.0014 nm^{-1} , $n = 421$).

3.4. Phytoplankton absorption

The $a_{\text{ph}}^*(\lambda)$ mean spectra mainly differed between winter (pre-bloom period) and the other seasons (Fig. 6A) with the $a_{\text{ph}}^*(440)$ about 2 times greater in winter ($0.048 \text{ m}^2 (\text{mg chl a})^{-1}$, S.D. = $0.024 \text{ m}^2 (\text{mg chl a})^{-1}$) than in spring or summer. Conversely, mean $a_{\text{ph}}^*(440)$ presented very low variations between March ($0.023 \text{ m}^2 (\text{mg chl a})^{-1}$, S.D. = $0.009 \text{ m}^2 (\text{mg chl a})^{-1}$), May ($0.018 \text{ m}^2 (\text{mg chl a})^{-1}$, S.D. = $0.004 \text{ m}^2 (\text{mg chl a})^{-1}$) and July ($0.022 \text{ m}^2 (\text{mg chl a})^{-1}$, S.D. = $0.007 \text{ m}^2 (\text{mg chl a})^{-1}$). The spatial distribution of $a_{\text{ph}}^*(440)$ was characterized by a high heterogeneity, being more accentuated in February and March (coefficient of variation: 51% and 38%, respectively) than in May and July (coefficient of variation: 26% and 30%, respectively). The higher values of $a_{\text{ph}}^*(440)$ (Fig. 6B) were found in low chl a areas, characterized by high proportions of pico and nanoplanktonic cells (Fig. 6C) and where pigments from cryptophytes, prasinophytes, dinoflagellates and cyanophytes were detected. On the contrary, the areas with low $a_{\text{ph}}^*(440)$ values, mainly located near to the Seine and Somme estuaries (Fig. 6B), were characterized by high chl a concentrations

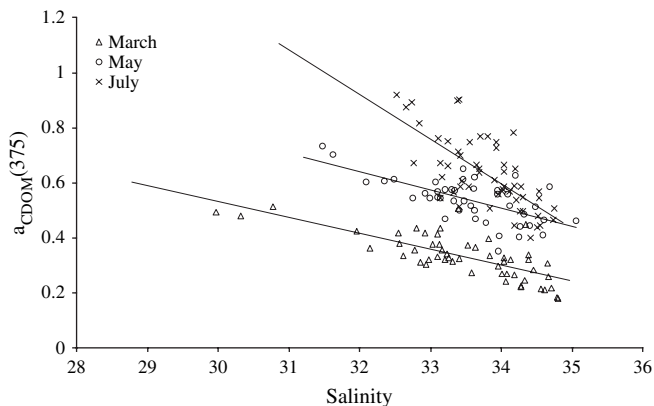


Fig. 4. Scatterplot and linear regression (least square estimation, Gauss-Newton method, $p < 0.001$) between salinity and $a_{\text{CDOM}}(375)$ for March, May and July cruises. March: $a_{\text{CDOM}}(375) = -0.058S + 2.26$, $R^2 = 0.56$, $n = 53$, May: $a_{\text{CDOM}}(375) = -0.066S + 2.7$, $R^2 = 0.43$, $n = 43$, July: $a_{\text{CDOM}}(375) = -1.61S + 6.1$; $R^2 = 0.48$, $n = 54$.

Table 3

Mean, standard deviation (S.D.) of $a_{\text{CDOM}}(375)$ (m^{-1}) and S_{CDOM} (nm^{-1}) for the 4 cruises

	$a_{\text{CDOM}}(375)$ (m^{-1})	S_{CDOM} (nm^{-1})
February	1.76 (0.45)	0.01770 (0.00330)
March	0.33 (0.08)	0.01540 (0.00230)
March	0.54 (0.14)	0.01350 (0.00190)
July	0.67 (0.15)	0.01330 (0.00130)
Mean	0.82 (0.20)	0.01488 (0.00200)

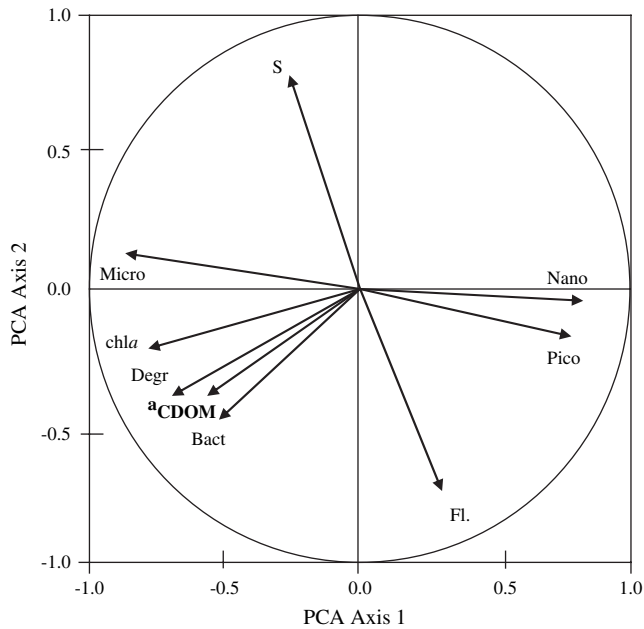


Fig. 5. First and second axes (explaining 38 and 24% of the variance of the dataset, respectively) of the PCA performed on a dataset composed by a_{CDOM} (375) and the following environmental variables: rivers flow scaled by the distance of each station to the coast (Fl), salinity (S), bacterial abundance (Bact), phytoplankton biomass (chla), chla degradation products (Degr), and the contribution of pico-, nano- and microphytoplankton.

and dominated by large phytoplankton cells such as diatoms (Fig. 6C). The spatial and temporal variations of $a_{\text{ps}}^*(440)$, i.e. taking into consideration only the photosynthetic pigments, were equivalent to those previously described for $a_{\text{ph}}^*(440)$ ($p > 0.05$). Differences between $a_{\text{ps}}^*(440)$ and $a_{\text{ph}}^*(440)$ were very low (less than 10% in mean in the surface waters for each cruise), revealing the very low effect of photoprotection on the phytoplankton absorption properties.

The PCA performed on a data set composed by $a_{\text{ph}}^*(440)$ and $a_{\text{ps}}^*(440)$ together with biological and environmental parameters (Fig. 7) showed strong relationships between $a_{\text{ph}}^*(440)$ and the nano- and pico-plankton biomass contributions as well as with the pigment markers of cryptophyte, prasinophyte, cyanophyte, dinoflagellate, green algae and prymnesiophyte (alloxanthin/chla, prasinoxanthin/chla, zeaxanthin/chla, peridinin/chla, chl b /chla and 19' HF/chla, respectively). On the contrary, $a_{\text{ph}}^*(440)$ vector was opposed to the chla biomass, microplankton contribution, diatoms marker (fucoxanthin/chla). No relationship was found between

phytoplankton absorption and photoprotection ratio (e.g. Dt/(Dt + Dd) ratio) nor with nutrient concentration and ratios.

4. Discussion

The bio-optical properties in the coastal area of the eastern English Channel present a pronounced seasonal variation, with relevant differences between winter and spring–summer periods. During winter, the CDOM largely dominates the total absorption (up to 91%, Table 5), in relationship with the high freshwater inputs. The predominant role of river inputs for the modulation of dissolved and particulate matter is a general pattern of the coastal waters (Kowalczyk, 1999; Warnock et al., 1999; Siegel et al., 2002). The allochthonous origin of the particulate matter is suggested by an elevated presence of mineral and non-living organic – probably in decomposition – matter (e.g. Davidson et al., 1995; Ferrari et al., 2003 and references therein), as revealed by the high absorption of NAP together with the low value of POC/PIC and the high values of POC/PON. Even though the $a_{\text{ph}}^*(\lambda)$ is higher than during the spring–summer periods, in relation to the high presence of small (pico- and nano-) phytoplankton cells, the phytoplankton absorption contribution over the total absorption budget remains very low in winter (<5%), due to the weak biomass level during the pre-bloom period.

In contrast to the wintertime, the bio-optical properties of the water mass are mainly biologically driven during the spring–summer period. The phytoplankton absorption increases, accounting for 42%, on average, of the total absorption at 440 nm, while 49% is due to CDOM and 9% to NAP (Table 5). No significant change in these proportions occurs during the spring–summer transition (from March to July), in relationship with the long-lasting bloom period (two to three months) due to species succession in the algal community, which is dominated by diatoms and *Phaeocystis* sp. (Brunet et al., 1996; Breton et al., 2000). The contribution of phytoplankton to the total absorption agrees with results obtained from other coastal waters (Babin et al., 2003; Tilstone et al., 2005) and contrasts with case 1 waters in which phytoplankton absorption usually dominates the absorption in the blue part of the spectrum (Bricaud et al., 1998).

Phytoplankton specific absorption, as a function of the cell size and intracellular pigment composition and concentration (packaging effect, Bricaud et al., 1995), is dependent on the algal community composition and physiological state (Hoepffner and Sathyendranath, 1991; Sosik and Mitchell, 1995). In the eastern English Channel, the temporal variations of $a_{\text{ph}}^*(440)$ seem to be mainly related to the packaging effect, in relation with changes in the dominating cell size inside the algal community, which is in agreement with results from Ciotti et al. (2002) and Bricaud et al. (2004) in other coastal areas.

The algal cell size increases from winter to spring–summer period, in agreement with the results from Breton et al. (2000) who reported the dominance of small diatom cells (e.g. *Thalassiosira* sp., *Lauderia* sp.) during winter and the main occurrence of large diatom cells (e.g. *Rhissolenia stoltherforthii*,

Table 4

Mean, standard deviation (S.D.) of $a_{\text{NAP}}(440)$ (m^{-1}), S_{NAP} (nm^{-1}), POC/PIC ratio (Particulate Organic Carbon vs Particulate Inorganic Carbon) and POC/PON (Particulate Organic Carbon vs Particulate Organic Nitrogen) ratios for the 4 cruises

	$a_{\text{NAP}}(440)$ (m^{-1})	S_{NAP} (nm^{-1})	POC/PIC	POC/PON
February	0.084 (0.070)	0.0121 (0.0010)	3.2 (2.9)	8.9 (2.7)
March	0.030 (0.018)	0.0112 (0.0011)	4.8 (5.2)	7.3 (3.3)
May	0.047 (0.030)	0.0110 (0.0012)	3.8 (3.2)	5.0 (1.1)
July	0.027 (0.018)	0.0119 (0.0016)	8.5 (7.5)	8.3 (3.2)

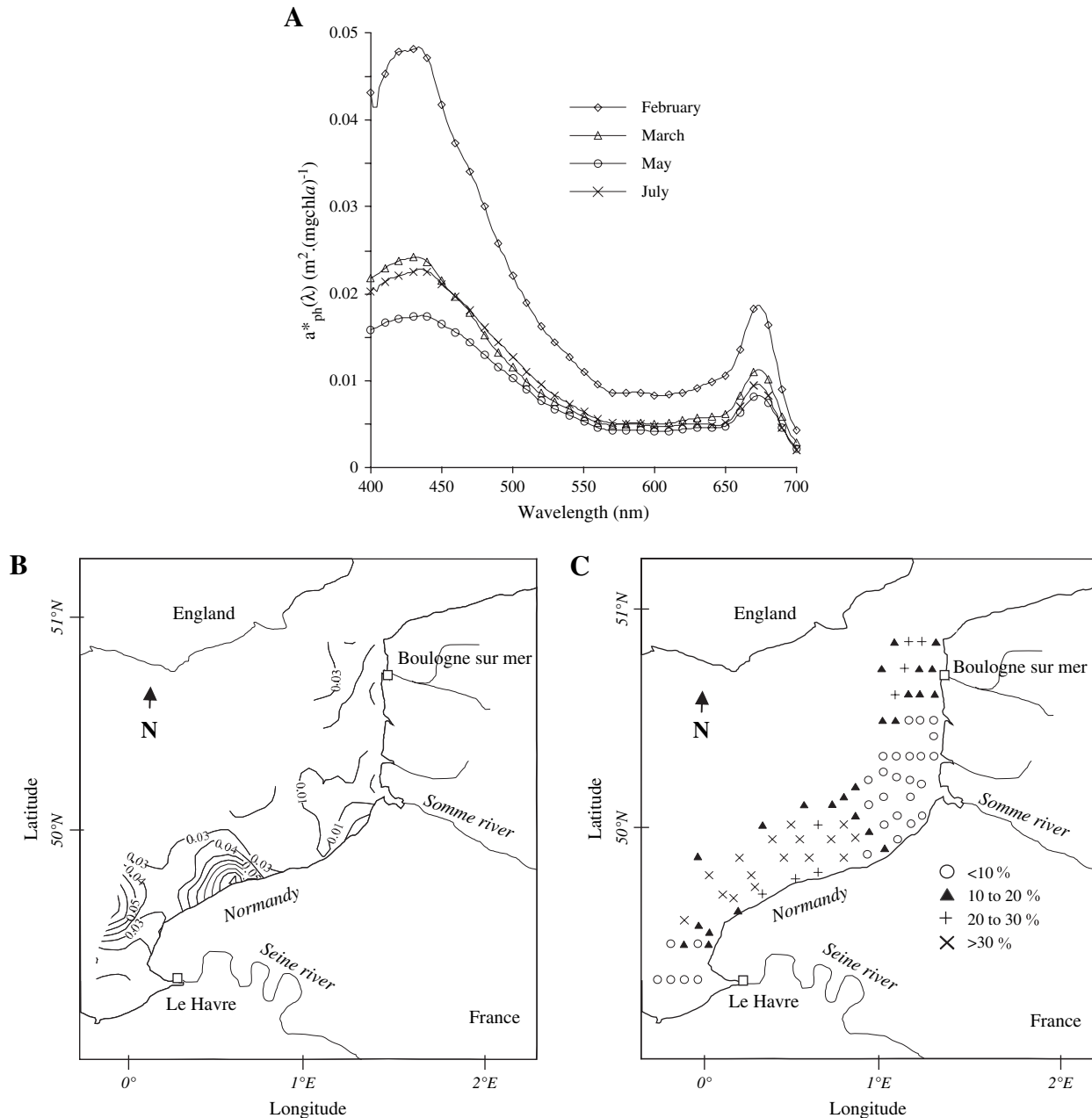


Fig. 6. (A) Specific absorption spectra means ($a_{ph}^*(\lambda)$) in $\text{m}^2 (\text{mg chl } a)^{-1}$, surface + bottom for the 4 cruises; (B) Spatial distribution of $a_{ph}^*(440)$ in $\text{m}^2 (\text{mg chl } a)^{-1}$; and (C) of the picoplankton + nanoplankton proportion in March 2000 at 2 m depth.

Guinardia flaccida) during the spring–summer period. In relationship with the high turbidity and to the strong mixing rate (e.g. Brunet et al., 1993), light, through the pigment-mediated photo-protection process does not have a relevant effect on the spatio-temporal variations of $a_{ph}^*(\lambda)$, as revealed by the very similar patterns observed for $a_{ps}^*(\lambda)$ and $a_{ph}^*(\lambda)$. The photoprotective carotenoids (PPC) account for less than 10% of the total carotenoids and by consequence affects very few of the phytoplankton absorption characteristics (10% and 16% of $a_{ph}(490)$ in February and July, respectively). This is the opposite of the influence identified in case 1 waters (Sosik and Mitchell, 1995; Bouman et al., 2000) as well as for case 2 waters (Nelson and Guarda, 1995). Furthermore in contrast to

other coastal sites (Sosik and Mitchell, 1995), nutrient concentrations do not seem to have a significant role on the variation of $a_{ph}^*(\lambda)$ in the eastern English Channel, as revealed by the lack of correlation between nutrients and phytoplankton absorption.

During spring–summer, the significant relationships between CDOM and phytoplankton biomass, algal degradation products and bacterial abundance reveal an autochthonous production of CDOM in the coastal system of the eastern English Channel. The biologically mediated production of CDOM from bacterial production, phytoplankton exudation or degradation, cell lysis and/or zooplankton grazing is widespread over marine ecosystems (e.g. Rochelle-Newall and

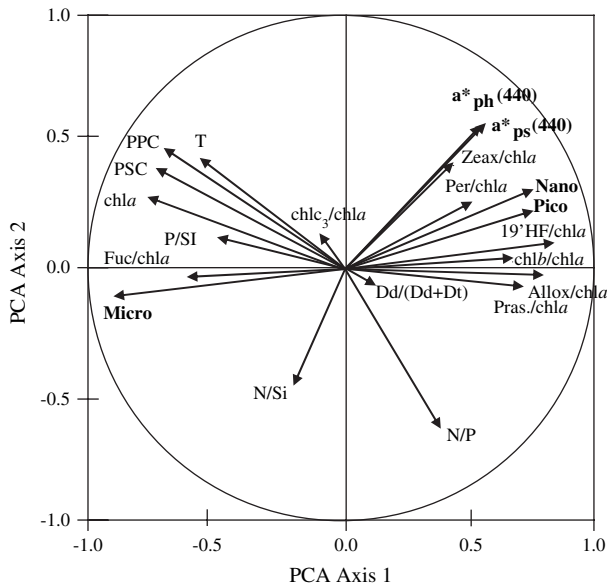


Fig. 7. First and second axes (explaining 43 and 14% of the variance of the dataset, respectively) of the PCA performed on a dataset composed by $a_{ps}^*(440)$ and $a_{ph}^*(440)$ and the following data: T (temperature, °C), N/P, N/Si, P/Si ratios (N: nitrate, P, Phosphate, Si: Silicate), chl a (chlorophyll a), PSC (PhotoSynthetic Carotenoids), PPC (PhotoProtective Carotenoids); the photoprotective index (Dd/(Dt + Dd) ratio with Dd = Diadinoxanthin and Dt = Diatoxanthin), contributions of pico-, nano- and microphytoplankton and the biomarker pigments vs chl a ratio (Zeax: Zeaxanthin, Per: Peridinin, 19' HF: 19' HexanoylFucoxanthin, chl b and chl c_3 : chlorophyll b and c_3 respectively, Allox: alloxanthin, Pras: Prasinolanthin, Fuc: Fucoxanthin).

Fisher, 2002; Siegel et al., 2002), however its relative importance in coastal ecosystems still remains uncertain. At the regional scale, the biological production of CDOM appears to be a major process for the seasonal modulation of this optical compartment as it largely compensates the decrease in terrestrial inputs during the spring bloom period. Recently, Rochelle-Newall and Fisher (2002) suggested that phytoplankton was not a direct source of CDOM supporting the idea that CDOM production results from bacterial degradation of non-chromophoric particulate and/or dissolved organic matter derived from algal cells. This could be the case in our area due to the significant co-variation of bacterial abundance and CDOM (Spearman correlation, $p < 0.001$, spring and summer data) and the spatial decoupling of CDOM and chl a concentration, as already noticed by other authors (e.g. Chen

et al., 2004). However, the decreasing trend of mean S_{CDOM} from winter (0.0177 nm^{-1}) to summer (0.0135 nm^{-1}) would seem to be in contrast with the assumption of a marine CDOM production during the spring–summer season. In general, marine-derived CDOM, which is fulvic-dominated, usually presents a higher spectral slope than the humic-dominated dissolved material originated from terrestrial ecosystems (Carder et al., 1989). However, the bacterially mediated production and/or bacterial degradation of CDOM can have a flattening effect on CDOM absorption spectra, which could lead to the formation of humic-like matter (Tranvik, 1993; Stedmon et al., 2000).

Our results also suggest that the by-products of the phytoplankton bloom can significantly contribute to the seasonal evolution of the NAP pool, in addition to a continuous mineral signal background (Dupont et al., 1993; Loisel et al., in press). In particular, the positive correlation found in summer between $a_{NAP}(440)$ and POC and chl a degradation product concentrations ($p < 0.001$) suggests a relationship between NAP and biological processes.

The effect of phytoplankton on the overall bio-optical properties of the water column is increased by the presence of the bloom colony-forming *Phaeocystis* sp. This species was estimated to account for one third of the community and is known to form large aggregates and mucilage favoring cell degradation or/and exudation processes (Thingstad and Billen, 1994). These aggregates can have a long residence time in the water column due to the successive resuspension/deposition processes in relation with tidal currents (Jones et al., 1998), and represent a propitious substrate for the establishment of a very active bacterial network (Lamy et al., 2006) which can act as local source of CDOM (Ferrari et al., 2003). The presence of low absorbing organic detritus all over the sampling area, suggested from the mean value of $0.28 \text{ g}^{-1} \text{ m}^2$ for the $a_{NAP}(380)/\text{POC}$ ratio in agreement with Ferrari et al. (2003) who reported a value of $0.32 \text{ g}^{-1} \text{ m}^2$ in the Seine river plume, can also be related to the previous statement (Rochelle-Newall and Fisher, 2002).

Super-imposed to this main seasonal scale of absorption property variations, peculiar meteorological events, such as wind stress, can significantly act on the regional bio-optical characteristics. This is very well marked by the situation of May, when high wind speed ($>10 \text{ m s}^{-1}$) occurred before the cruise leading to an increase of the resuspension rate of microphytobenthos (especially diatoms, Dupont et al., 1993; Huault et al., 1994; Brunet and Lizon, 2003), as it can be hypothesized from the higher value of diadinoxanthin/chl a ratio (Brunet and Lizon, 2003) with respect to the other sampling cruises (mean of 0.10 vs 0.050 to 0.075). The higher proportion of PSC in May with respect to the other cruises reveals the presence of shade-adapted and/or large phytoplankton cells, as microphytobenthic diatoms. The lower phytoplankton absorption efficiency, $a_{ph}^*(\lambda)$, with respect to March and July would be due to an increase of the packaging effect. The seabed and coastal erosion linked to high mixing rates in May explains the increase in NAP absorption, and its highly significant relationship with inorganic matter. It

Table 5
Mean value and standard deviation (S.D.) of the relative contributions of CDOM, NAP and phytoplankton to the total absorption coefficient of seawater (except pure water) at 440 nm for the cruises of February, March, May and July

	Phytoplankton $a_{ph}/(a_{ph} + a_{CDOM} + a_{NAP})$	CDOM $a_{CDOM}/(a_{ph} + a_{CDOM} + a_{NAP})$	NAP $a_{NAP}/(a_{ph} + a_{CDOM} + a_{NAP})$
February	0.03 (0.03)	0.91 (0.03)	0.06 (0.03)
March	0.42 (0.19)	0.46 (0.18)	0.12 (0.06)
May	0.44 (0.10)	0.47 (0.10)	0.09 (0.05)
July	0.42 (0.14)	0.53 (0.14)	0.05 (0.02)

clearly appears therefore that such climate events can have crucial impact in coastal ecosystems since they induce relevant changes in biological and optical properties of the water column as already revealed in other coastal ecosystems (Jones et al., 1998; Morris and Howarth, 1998).

The vertical scale seems to account for a very low variability in this coastal area, in agreement with a strong hydrographical homogeneity due to tidal currents. In contrast, tidal currents, rivers outflow and winds (Brylinski et al., 1991; Brylinski et al., 1996) can be responsible for advection of water masses, which is known to drive relevant mesoscale variability of the absorption properties (e.g. Gallegos and Neale, 2002).

The spatial variability of the phytoplankton absorption seems to be greater than the seasonal change and therefore should be considered for primary production modelling at the regional scale (e.g. Tilstone et al., 2005). Phytoplankton absorption variation is mainly dependent on the differentiation of high-biomass and low-biomass ecosystems, presenting the lowest and highest values of $a_{ph}(440)$, respectively. For instance, the $a_{ph}(440)$ ranged from 0.009 to 0.09 $m^2 mg\ chl a^{-1}$ in March (Fig. 6B) for $chl a$ concentration varying from 0.3 to 23.4 $mg\ m^{-3}$, in agreement with results reported both from case 1 (Bricaud et al., 1995, 1998) and case 2 waters (Babin et al., 2003; Bricaud et al., 2004; Tilstone et al., 2005). The co-occurrence of the two ecosystems, one with an almost exclusive presence of diatoms and the other one with a mixed community of diatoms and phytoflagellates could be due to different depth of the water column as well as light penetration, as already discussed by Brunet et al. (1996).

The spatial distribution of CDOM seems to be hydrologically-dependent as underlined by the significant relationships found between $a_{CDOM}(375)$ and salinity. This common feature in coastal areas (Nieke et al., 1997; Warnock et al., 1999; Keith et al., 2002) should also account for a complex seasonal-dependence. Indeed, the lower slope of the a_{CDOM} vs salinity relationship in July suggests a lesser diffusion of CDOM to the oceanic waters, in agreement with the low freshwater discharges in summer (Nelson and Guarda, 1995). However, the scattering of data as shown during the spring or summer on the Fig. 4 may suggest the presence of other sources of CDOM, e.g. biologically dependent material. Relationship between CDOM and salinity would not provide sufficient evidence to conclude on the origin of CDOM, and this feature indicates the need for complementary studies on this optical component in the English Channel.

Spatial variation of $a_{NAP}(440)$ is also particularly pronounced, with differences between minimal and maximal values of at least one order of magnitude (Fig. 2D), and seems to be dependent on a numerous factors, such as freshwaters inputs, biological activity and advection of water masses. When the South-West wind dominates (as in May) the high values of $a_{NAP}(440)$ present along all the coastline from the Seine estuary to the north area very rapidly drops towards the offshore (approximately near the 20 m isobath), revealing a clear differentiation between coastal and offshore water mass in agreement with other studies (Lafite et al., 1992; Dupont et al., 1993; Brylinski et al., 1996). The rapid decrease in

$a_{NAP}(440)$ reveals that inputs of NAP such as coastal and/or seabed erosion or freshwater discharges weakly affect the off-shore waters. The gradient of NAP absorption seems to be the higher in the bay of Seine. For instance, in May the $a_{NAP}(440)$ varied from 0.025 to 0.237 m^{-1} at 440 nm, which are values already measured by Ferrari et al. (2003) in the same area for the same season ([0.077–0.418 m^{-1}] at 380 nm corresponding approximately to [0.042–0.228 m^{-1}] at 440 nm). This complexity of the dynamics of NAP absorption in this ecosystem is further increased by the heterogeneity of the particulate matter pool composed by variable proportion of organic and mineral matter from diverse origin (Dupont et al., 1993) which might interact each other through aggregation processes (Ferrari et al., 2003). This feature has been illustrated very recently by Loisel et al. (in press) who described wide variations in the particulate scattering coefficient (from approximately 0.05 to 10 m^{-1} at 650 nm) and backscattering to scattering ratio (from 0.0024 to 0.0417 at 650 nm) at the regional scale. Moreover, these authors demonstrated that the phytoplankton bloom evolution and related changes in the amount of organic detrital material can have a significant influence on scattering properties of these waters, especially when considering the backscattering to scattering ratio. However, it seems that the different kind of NAP (mineral or organic) have a reduced effect on their absorption spectral signature, since spectral slope was almost constant over the space and season with an overall mean of 0.0115 nm^{-1} , in agreement with Babin et al. (2003).

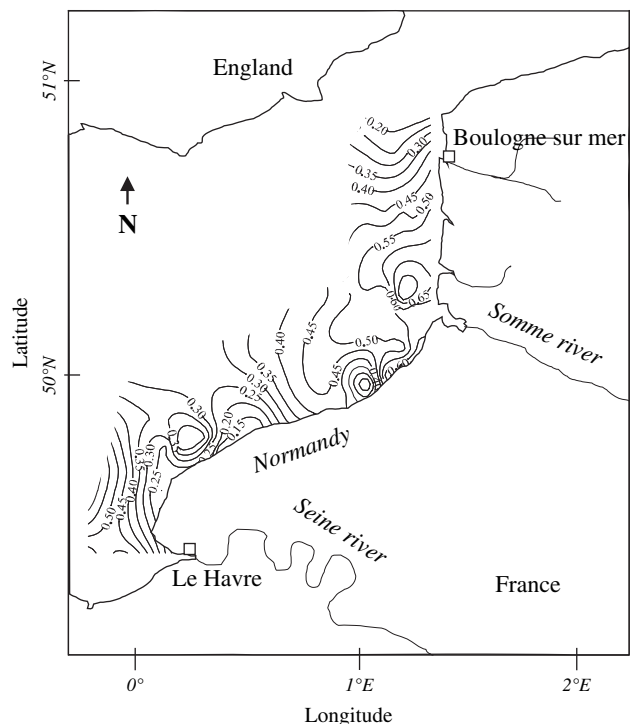


Fig. 8. Spatial distribution of the mean relative contribution at 440 nm (from the March, May and July data sets pooled together) of phytoplankton to total absorption of marine water (except pure water).

Our results on the spatial heterogeneity in NAP, CDOM and phytoplankton absorption coefficients illustrates the complexity of the coastal ecosystems of the eastern English Channel in terms of optical quality, which should be considered for ecological purposes as well as for the interpretation of remote sensing products (Nelson and Guarda, 1995; Gallegos and Neale, 2002). Phytoplankton contribution to the total absorption (excluding pure water, Fig. 8) can account for up to 75% in the north of the Somme River and in the more oceanic waters off the South area, and only for 20% in the coastal “Normandy ecosystem”. The elevated presence of non-phytoplankton matter revealed by the high values of $a_{\text{NAP}}(440)$ in this pelagic coastal layer is originated from the seabed erosion and from the coastal erosion of the Norman cretaceous chalk cliffs (Dupont et al., 1993). The reduction of light penetration in this ecosystem has been suggested as one of the main factors delaying the onset of the spring algal bloom in this area.

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