Annual variations in suspended particulate matter within the Dover Strait

Suspended matter
Diatoms
Dover Strait
English Channel

Matière en suspension
Diatomées
Pas-de-Calais
Manche

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ABSTRACT

During a survey at six stations in the Dover Strait, from July 1990 to November 1991, water samples were collected to measure : suspended sediment load and its organic content; particle characteristics; photosynthesis pigments; and heavy metals. In this contribution, particle measurements are interpreted in terms of hydrodynamical effects and seasonal evolution.

Multi-modal grain size spectra are indicative of depth and cross-sectional variations, from the coastline to the central waters. Tidal variations, biological productivity and wind effects can be identified. Suspended particulate matter (SPM) components (determined using SEM, when combined with size spectra) illustrate hydrodynamical, geomorphological and biological effects on the composition of the suspended matter.

Living and non-living diatom valves, used as particulate tracers, provide information on the sources and hydrodynamic behaviour of the suspended particles.

Although the Seine input is high, riverine SPM input is not detected within the Dover Strait. SPM fluxes from the Eastern Channel into the southern North Sea, across the Dover Strait, originate mainly from: Atlantic waters; coastal and sea bed erosion; biological activity; and resuspension from the intertidal zone.

SPM studies in the Eastern Channel could provide information on the complex behaviour of river pollutants over the region.

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RÉSUMÉ

Les variations annuelles des matières en suspension dans le détroit du Pas-de-Calais

Au cours d'un suivi annuel (de juillet 1990 à novembre 1991) de six stations dans le détroit du Pas-de-Calais, des prélèvements d'eau ont été réalisés pour mesurer la charge particulaire, leur contenu organique, les pigments photosynthétiques, les métaux lourds et caractériser la composition du matériel

en suspension. Dans le cadre de ce travail, les analyses particulaires sont interprétées sur le plan des effets hydrodynamiques et des fluctuations saisonnières.

Les spectres granulométriques, réalisés au moyen d'un compteur de particules de type Coulter, présentent des variations liées à la profondeur des prélèvements et à leur localisation dans les gradients côte-large. Les fluctuations tidales, la productivité biologique et l'influence des vents sont également démontrées. La composition du matériel en suspension est déterminée grâce à l'observation au Microscope Électronique à Balayage. La combinaison de ces observations avec les spectres granulométriques permet de quantifier les principaux composants particulaires. Les fluctuations de composition permettent de préciser les conséquences des paramètres géomorphologiques, hydrodynamiques et biologiques.

L'utilisation des valves de diatomées, vivantes ou mortes, comme marqueur hydrodynamique des déplacements particulaires, fournit des informations à propos des origines et du devenir hydrodynamique des particules en suspension. Malgré le flux important de la Seine, les apports particulaires des rivières semblent peu déterminants dans le Pas-de-Calais. Le flux particulaire calculé entre la Manche orientale et la Mer du Nord provient essentiellement des apports de l'Atlantique, de l'érosion côtière, de l'érosion des fonds, de l'activité biologique et de la remise en suspension des sédiments intertidaux.

L'étude des matières en suspension en Manche orientale devrait contribuer à comprendre le devenir complexe de certains polluants déversés par les rivières.

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INTRODUCTION

This study is intended to demonstrate the contribution of methodological SPM measurements to the understanding of hydrodynamic, sedimentological and biological transport processes in a shallow water (strait) environment.

The long-term SPM dynamics across the Dover Strait is studied. Fourteen monthly surveys of SPM, together with the use of mineral and biological particulate tracers, demonstrate seasonal variations, wind effects and tidal variability in the various components.

Combined with output from an hydrodynamical numerical model, the SPM data were used to calculate SPM component fluxes (from the Eastern Channel into the southern North Sea). Such data, compared with geochemical measurements, are important also in the study of the behaviour of pollutants in the Eastern Channel (Guéguéniat *et al.*, 1988 ; Salomon *et al.*, 1991).

METHODOLOGY

Sampling strategy

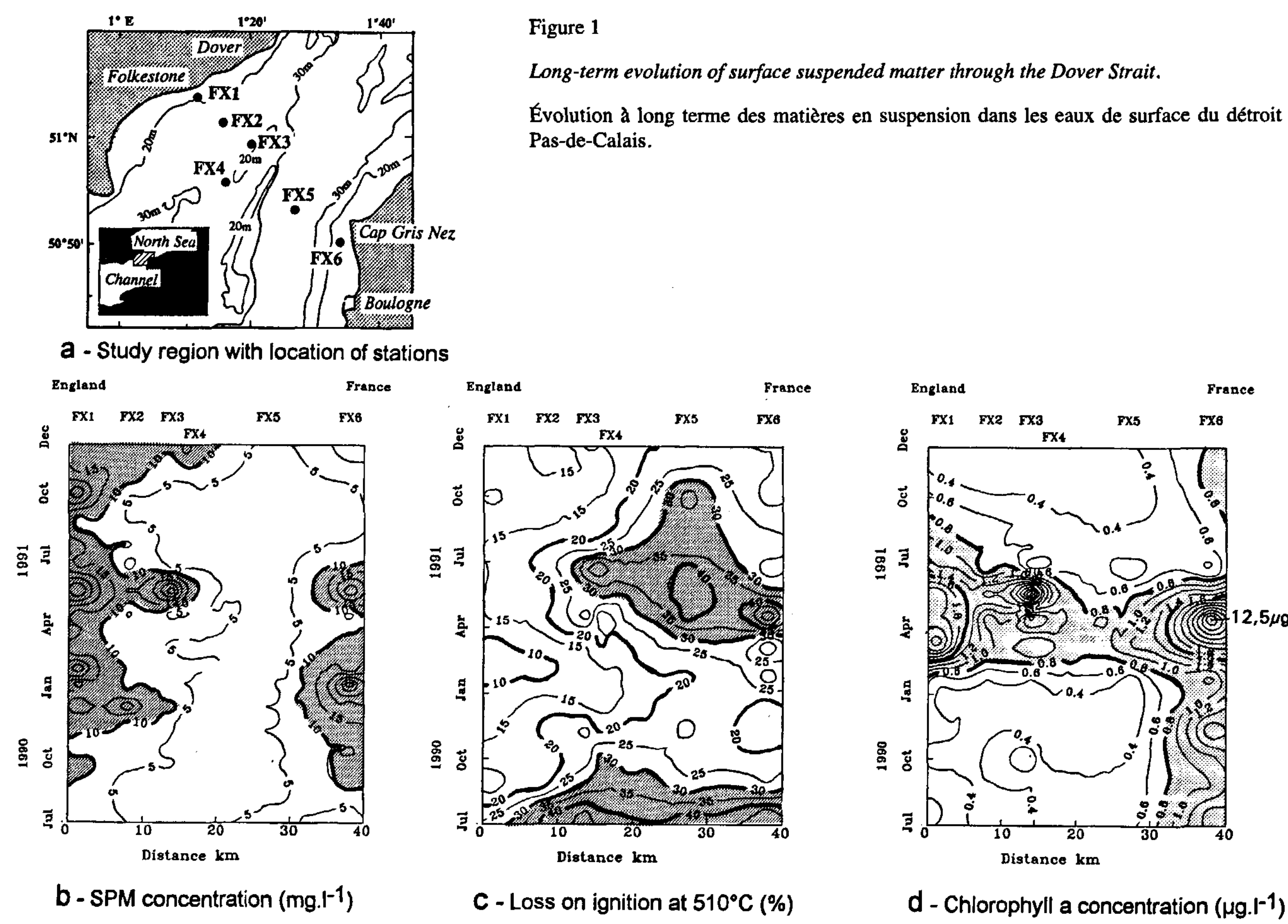
Six stations were established across the Dover Strait (Fig. 1 *a*). Samples of near-surface and bottom waters were collected, using Niskin bottles or a teflon diaphragm pump (at depths of 5 and 15 m below the surface water), for monthly measurements of suspended matter and geochemical characteristics.

Salinity, temperature, nephelometric and (sometimes) fluorimetric measurements were obtained for the surface waters, across the Dover Strait. Vertical and/or oblique discontinuities (Brylinski *et al.*, 1984; 1991; Brylinski and Lagadeuc, 1990 ; Dupont *et al.*, 1991) have been identified elsewhere for along the French coastal waters. These hydrological structures indicate strong differences between the French coastal station (FX6) and the deep-water station (FX5).

Analysis of suspended matter

GFF 47 mm diameter filters (with an approximate pore size of 0.7 µm) and cellulose acetate 47 mm filters (0.45 µm pore size) were used for comparison and calibration with nephelometer measurements. Weight measurements are reported in relation to filtered volumes. The loss on ignition (LOI) was used to estimate organic matter content. Ignition tests at 510°C on differents components indicate that the weight loss is higher for organic matter (> 70 %) than for chalk (< 2.5 %) and clays (2-8 %). The high percentages plotted on Figure 1 *c* (10, 20 and > 30 %) indicate that the weight loss is mainly due to the presence of organic matter. Aceton extracts, on freezed filtrates, were used to determine chlorophyll *a* content.

The Coulter Counter was used for the analysis of grain sizes, from 0.9 to 173 µm (*i.e.* the equivalent sphere diameter of the volume measurements). These data are expressed in $mm^3.l^{-1}$. The ratio SPM ($mg.l^{-1}$)/total particulate volume provides an apparent mean density of the suspended matter.



a - Study region with location of stations

b - SPM concentration ($mg.l^{-1}$)

c - Loss on ignition at 510°C (%)

d - Chlorophyll a concentration ($\mu g.l^{-1}$)

Figure 1

Long-term evolution of surface suspended matter through the Dover Strait.

Évolution à long terme des matières en suspension dans les eaux de surface du détroit du Pas-de-Calais.

For the Eastern Channel waters, Lafite *et al.* (1986) and Lafite (1990) have demonstrated the diversity of the SPM components. An inventory of the main SPM components, with an estimate of volume for each one, is established here using SEM observations. Combining these measurements with the Coulter Counter data, the semi-quantitative grain size distribution (in $mm^3.l^{-1}$) is derived of plankton, mineral grains, chalk coccoliths, and organic-clay aggregates. This approach is applied to each size range within the grain size spectra.

Diatom contents were studied using 10 to 50 ml of water, filtered on polycarbonate filters (25 mm diameter, 1.2 µm pore size). The filters were mounted on glass slides and rendered translucent, to enable the diatom valves to be counted. These data are then "normalized" with respect to water volume.

RESULTS

Long-term evolution of surface SPM (Fig. 1)

The central surface waters always are associated with the lowest SPM concentrations (Fig. 1 *b*), especially the deeper waters (station FX5). The SPM concentrations along the English coastline (FX1, less so for FX2) are usually higher than those along French coastline (FX6) - except during January, 1991.

The continuous recordings of nephelometry in the surface waters indicate that:

a) station FX6 has on the edge of the French coastal turbid plume which is, in itself, limited by a strong discontinuity in water properties [*cf.* Brylinski *et al.* (1991) and Dupont *et al.* (1991)]; and

b) stations FX1 and, to a lesser extent, FX2 characterize the English coastal turbid plume, which usually decreases in concentration from the coastline to the central waters.

The long-term SPM concentrations show two maxima, represented more clearly in the French coastal waters: the first during winter, due to wind effects ; the second in spring, due to biological activity (*see* below).

According to the well-established pattern of seasonal phytoplankton productivity, the highest chlorophyll *a* (Fig. 1 *d*) is observed during spring (*i.e.* from March to June) across the whole of the strait. Nevertheless, higher phytoplankton productivity is present during winter in French coastal waters (FX6).

The percentage weight loss (LOI) after burning (Fig. 1 *c*) is higher during spring in response to phytoplankton productivity. Increases begin in April, following the first phytoplankton bloom of March; these continue into summer in response to biological activity by zooplankton and other macro-organisms.

Chlorophyll *a* is always higher along the French than along the English coastline; this could be linked to

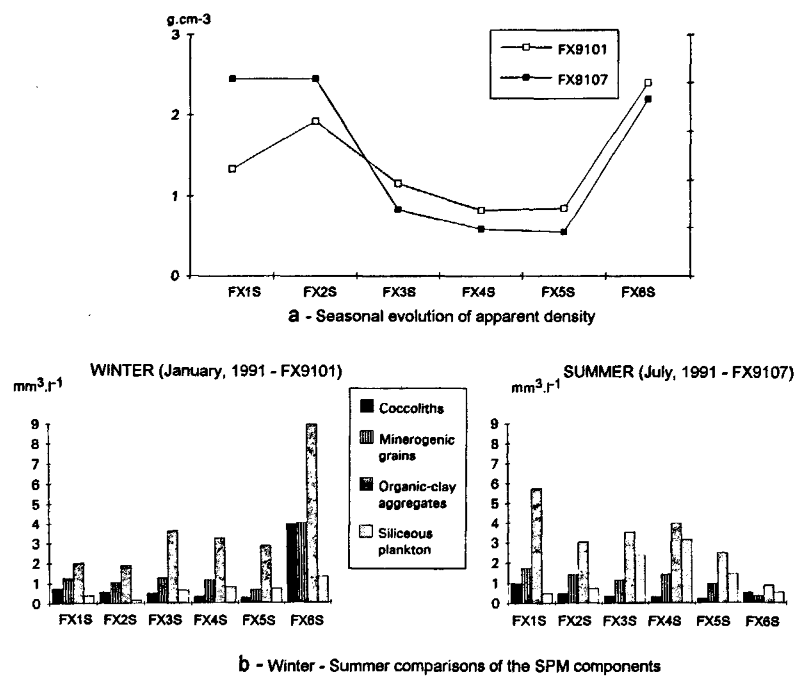


Figure 2

Seasonal variation in suspended matter in the surface waters: a) apparent density comparison between summer (July 1991) and winter (January 1991); b) winter/summer comparisons of the SPM components.

Fluctuations saisonnières des matières en suspension dans les eaux de surface : a) densité apparente comparée entre l'été (juillet 1991) et l'hiver (janvier 1991) ; b) comparaisons été/hiver des composants des matières en suspension.

biological productivity (highest along French coast) or to higher mineral input to the English coastal waters (causing smaller variations in the organic matter ratios).

Seasonal variations in SPM components (Fig. 2)

The surface water SPM data collected in January 1991 (FX9101, during a calm period on a neap tide, followed by a stormy period with SW winds) are compared now to those collected in July 1991 (FX9107, during a stormy period on spring tides and with SW winds).

According to the long-term evolution of the percentage weight loss (LOI) after burning, despite of the superimposed hydrodynamic and meteorological conditions, the apparent densities (Fig. 2 *a*) in summer are lower than in winter. This feature is well demonstrated by results obtained from the central (FX5 and also FX3 and FX4) and French coastal waters, but is not characteristic of the English coastal waters. In the latter case, SPM concentrations are higher in July than in January. The lowest values of January on FX1 and FX2 are in response to hydrodynamic conditions (*i.e.* neap tide and a calm period). SPM concentrations within the coastal turbid plume increase in July, on a spring tide and during a stormy period.

The meteorological influence is not noticeable along the French coast (FX6) in January, because this neap tide and calm period is followed by a stormy period (SW winds); this increases the SPM concentrations in the French coastal turbid plume. This pattern can be linked to the geomorphology of the coastline and the origins of the various SPM components (*e.g.* coastal erosion).

Combining the grain size analyses and the SEM observations, the main SPM component concentrations (Fig. 2 *b*) can be compared as follows: siliceous plankton concentrations within the central waters (FX5, FX4, FX3 and less in FX2) are higher in July, in response to biological productivity, than in winter; organic-clay aggregates are less mineralogical in content (*i.e.* with more flattened aggregates) in July - this is more characteristic of the central waters, than of those along the English coastline; and in January, the more dense particles (chalk coccoliths and mineral grains) are more concentrated within the French coastal waters, and less concentrated in English coastal waters, than in July.

Tidal cycle variations

In order to examine tidal variability in the components, the various SPM characteristics (concentrations, particle volume spectra, apparent densities and components) and associated current speeds were measured over a number of tidal cycles. The observed patterns are described now in terms of their geographical locations.

English coastal waters (station FX1 , Fig. 3 a*)*

Tidal variation in SPM concentrations have changed the particule volume data, but not the apparent densities; this indicates a relatively tidally-homogeneous composition of the SPM components.

South Varne (station FX4 , Fig. 3 b*)*

Small tidal variations in SPM concentrations are observed, but strong variations in particulate volume measurements; this corresponds to the cyclic increases in the planktonic ratios.

French coastal waters (station FX6 , Fig. 3 c)

The SPM concentrations vary greatly during the tidal series. At the same time, particulate volume measurements remain constant. This observation indicates strong tidal variations in the apparent densities, from a dominant planktonic SPM (*i.e.* lower than 1 g cm^{-3}) to one dominated by high mineral SPM content (> 2 g cm^{-3}).

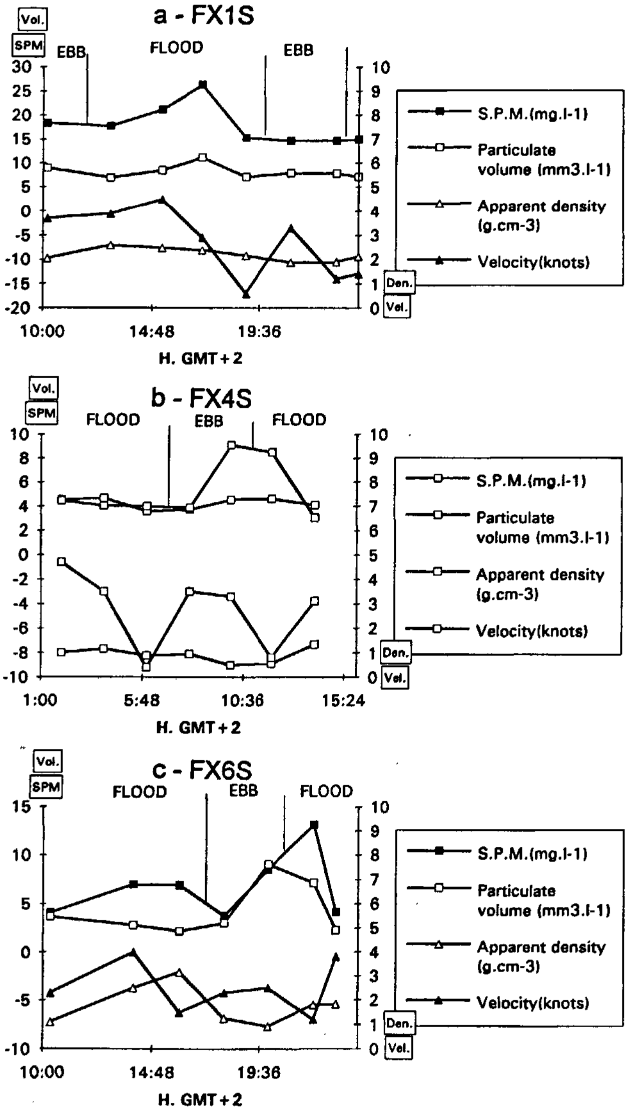


Figure 3

Tidal variations in suspended matter characteristics in the surface waters (July 1991): a) English coastal waters (FX1); b) South Varne waters (FX4); c) French coastal waters (FX6).

Variations des caractéristiques des matières en suspension dans les eaux de surface au cours d'un cycle tidal (juillet 1991) : a) eaux côtières anglaises (FX1) ; b) eaux du sud du banc de Varne (FX4) ; c) eaux côtières françaises (FX6).

Diatoms as hydrodynamical particulate tracers

On the basis of previous ecological studies on diatoms (Denys, 1991; Hendey, 1964; Hustedt, 1957; Van der Werff and Huls, 1957-1974), the determination (113 species) and the counting of living/dead diatom contents of suspended matter during five of the cruises (September 1990-FX9009, January 1991-FX9101, May 1991-FX9105, transect and time series in July 1991-FX9107, September 1991-FX9109) enables quantification of the contributions of ecological diatom communities (Fig. 4) to be quantified.

Multivariate factor analyses on an array between samples and the counting of ecological diatom communities (Fig. 4) indicate that two axes account for 73.9 % of all the sample variance. On the plot of factor loading, three main groups of variables appear: the main marine planktonic diatoms (MP), as opposed to the marine benthic tychoplanktonic diatoms (MTP) on axis 1; the benthic group (specifically MSB and MB) on axis 2; and the intertidal zone benthic diatoms (BT), shown negatively on axis 2.

The stations are ordered, however, by three groups of variables: station FX6, influenced specifically by the tidal BT group; stations FX4, FX3 and FX5, influenced strongly by the benthic group; and the English coastal stations, ranging from the tidal BT group for coastal waters (FX1 to FX2) to the benthic group of the open sea (FX2 to FX3).

The samples of tidal-time series in FX1, FX4 and FX6 are included respectively in the entire annual pattern of FX1, FX4 and FX6 (Fig. 4). For each of the time series, samples are plotted closely together.

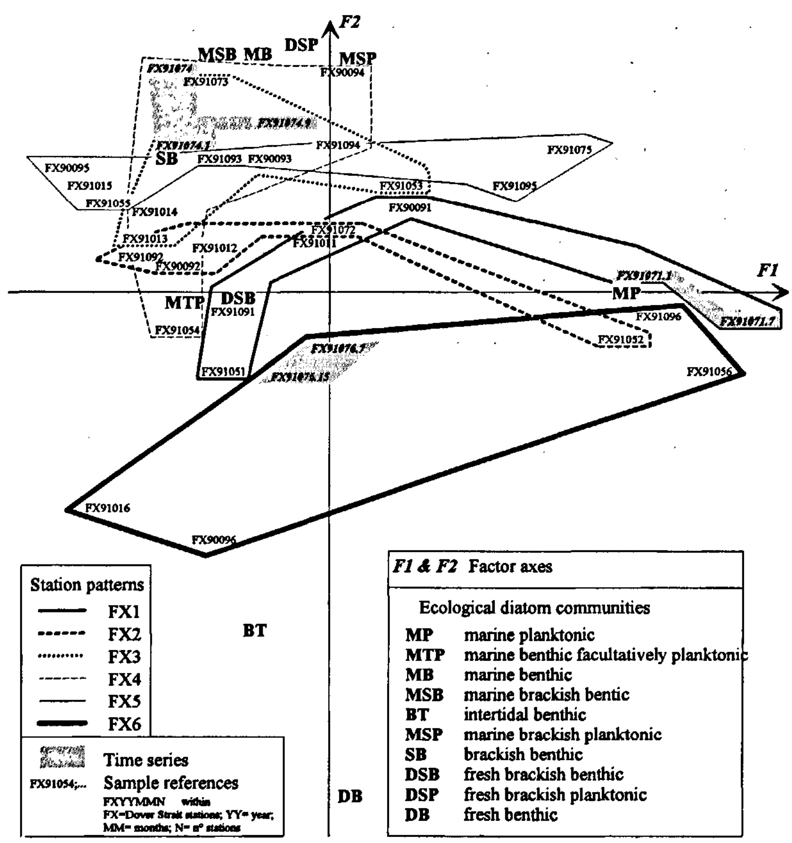


Figure 4

Plot of factor loading on the two first factor axes of the samples and the ecological diatom communities.

Projection des échantillons et des communautés écologiques de diatomées au plan factoriel 1/2.

This multivariate analysis indicates that ecological diatom communities can be used as hydrodynamic tracers, to describe suspended sediment sources and exchanges between water masses.

Coastal erosion

The characterization and concentrations of particulate tracers are used now to establish the source of material in the turbid coastal plume.

Chalk coccoliths (Fig. 5 a*)*

Chalk coccoliths are the main component of the finer-grained suspended sedimentary material of the coastal waters; they originate from erosion of the English and French Cretaceous chalk cliffs, which are composed mainly of the same material. The chalk coccolith concentrations (*i.e.* isolated chalk coccoliths/chalk coccoliths within organic-clay aggregates) of each of the water samples are described below.

This type of material in suspension is observed to increase during stormy periods (Fig. 5 *a*). The Figure represents the chalk coccolith content along two surface water transects of the Dover Strait: January 1991 (FX9101 with NW, following a period of strong SW winds), and May 1991 (FX9105, following an extended period of storms).

During the May sampling period, chalk coccolith concentrations are highest along the English coast (FX1); they decrease from FX1, to FX3 and FX4. Along the other side of the Channel, there are also high concentrations (FX6). The lowest concentrations were observed at station FX5 (confirmed during each month of the annual survey). This pattern is an indication of the prevailing hydrodynamical and geomorphological characteristics of this deeper water zone.

In January 1991, a preceding stormy period with SW winds is responsible for the higher concentrations at FX6; this indicates a large increase in concentration within the turbid coastal plume. The plume does not influence the concentration at FX5, which induces a strong SPM discontinuity between the French coastal waters and deeper marine waters (according to Brylinski *et al.*, 1991 and Dupont *et al.*, 1991). In contrast, the SW winds do not affect the English turbid coastal plume, although a low chalk coccolith concentration is observed at FX1 and there is a small decrease from FX1 to FX4.

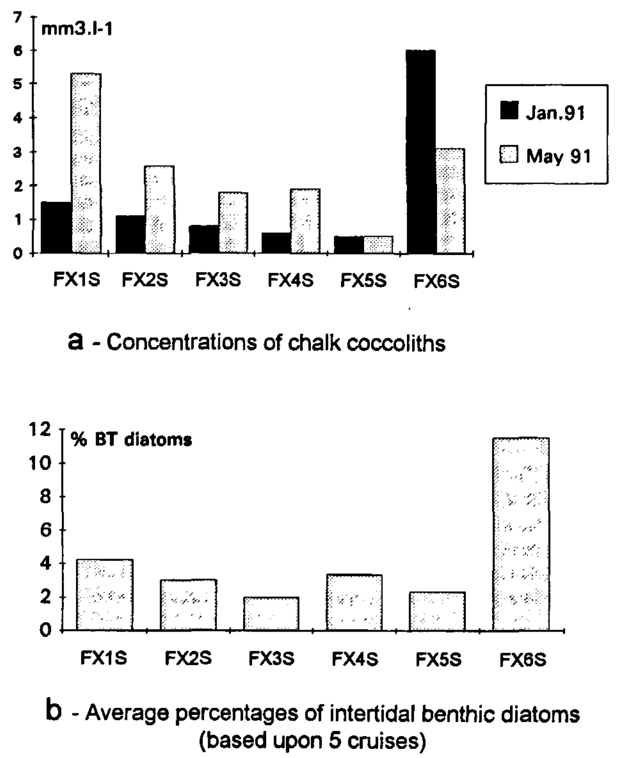


Figure 5

Particulate tracers originating from coastal erosion, in the surface waters.

Traceurs particulaires provenant de l'érosion côtière.

Intertidal benthic zone diatoms (Fig. 5 b*)*

Living or dead diatom contribution to the suspended matter contents indicate the presence of intertidal benthic zone diatom species such as *Delphineis surirella*, *Rhaphoneis amphiceros* and, to a lesser extent, *Scoliopleura tumida*. These benthic zone diatoms act as particulate tracers of intertidal resuspension from the English and French coastlines. Across the Dover Strait, their counts within the surface waters (Fig. 5 *b*) provide a quantitative assessment of the suspended particulate exchange between the coastal and central waters.

The concentrations of intertidal benthic zone diatoms are usually high along the French coast (FX6), especially during stormy periods associated with SW to NW winds (transects FX9009 and FX9101). These diatom concentrations decrease markedly at stations FX3 and FX5.

Along the English coastline (FX1), the concentrations of intertidal benthic zone diatoms are low, when this zone is sheltered from the wind (FX9009, FX9101); they are higher than those of station FX6 during periods associated with E to SW winds (FX9105 and FX9109 transects). These concentrations decrease progressively to seaward, towards the Varne bank (FX3).

Seabed (subtidal) erosion

Multivariate analysis of the diatom data (Fig. 4) has shown that the contribution of the marine benthic diatoms can distinguish the coastal waters from central Channel waters, especially at stations FX3 and FX4 (associated to resuspended particles from the Varne bank).

Nitzschia panduriformis, *Pleurosigma marinum* and *Trachyneis aspera* are the main marine benthic diatoms present in the waters. The highest concentrations are found usually within the waters overlying the Varne bank (stations FX3 or FX4, especially in September 1990 and January 1991; Fig. 6 *a*). This observation confirms the erosion of bottom sediments around the bank. Enrichment of marine benthic diatom concentrations occur, during

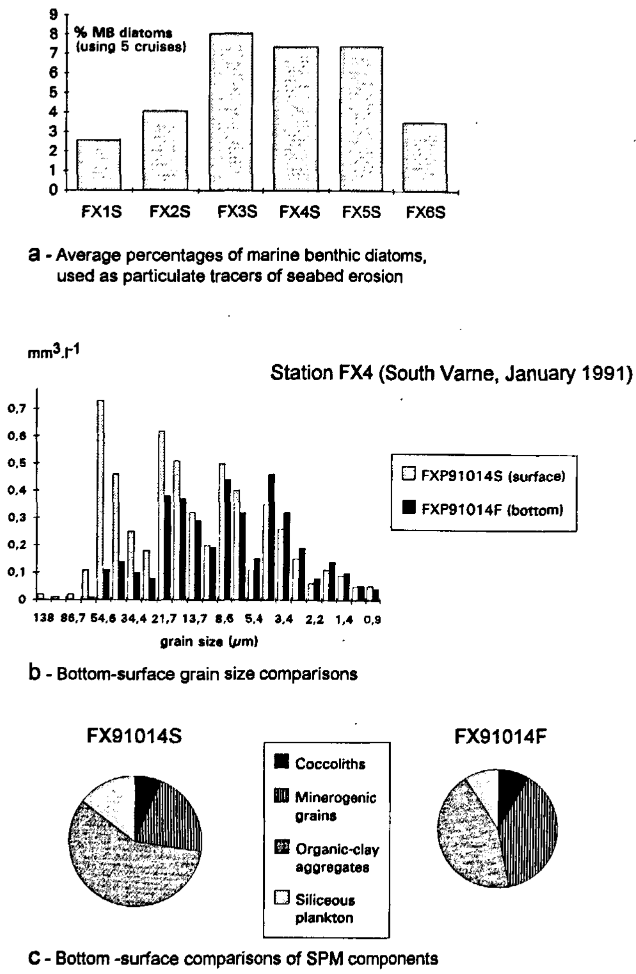


Figure 6

Suspended particulate matter, derived from seabed erosion .

Matières en suspension provenant de l'érosion du fond.

stormy periods, along the English coastline in July and September 1991 and along the French coastline in May and July 1991. These peaks in concentration are related to wind effects.

According to previous results, the results from station FX4, in January 1991, have been selected to compare bottom and surface SPM data. This comparison indicates a higher SPM load, a lower particle volume and a higher apparent density in the bottom sample. The grain size spectra (Fig. 6 *b*) indicate higher concentrations of coarser-grained particles within the surface samples. In combination with SEM observations, such enrichment of coarser particles appears to arise from an enrichment of siliceous plankton and organic-clay aggregates. The sectorial representation of the semi-quantitative data of the SPM components (Fig. 6 *c*) indicates a decrease in the ratio of the more dense particles (mineral grains and chalk coccoliths) from the bottom to the surface waters. In contrast, there is an increase in the ratio of the less dense particles (siliceous plankton and organic-clay aggregates) in the same direction.

Station FX4 is located some distance from the English and French coastlines; hence, the coastal mineral input here is low. Enrichment of mineral grains within the bottom water samples arises, however, from resuspension of the sea-bed sediments. In response to meteorological conditions, this dense material rises into the surface waters. Despite the absence of near-bed boundary layer samples, the bottom and surface samples describe adequately the gradient of resuspended material throughout the water column.

Estuarine particulate inputs

No appropriate mineral particulate tracers of continental inputs are available, although selective ecological diatom community indicators are available, as follows: fresh benthic diatoms; fresh/brackish benthic diatoms; and planktonic and brackish benthic diatoms. Annual variation in the counts of these components for each of the surface sample (Fig. 7) indicates:

a) some estuarine input into the central waters (FX3, FX4, FX5), which is indicative of SPM exchanges from the coastal to central waters;

b) normally low concentrations along French coast, showing that the "coastal flow" [described by Brylinski *et al.* (1991) and Guéguéniat *et al.* (1988)] does not constrain all the fluvial supplies from the Bay of Seine to the Dover Strait;

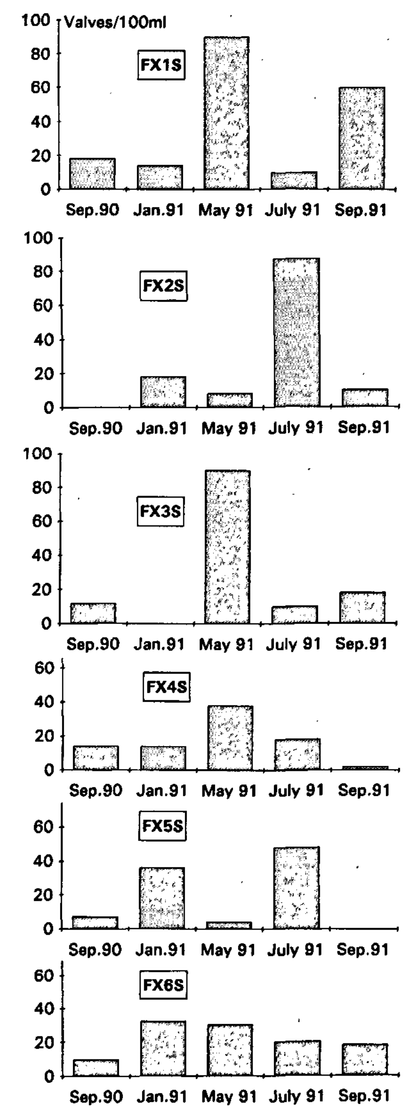


Figure 7

Annual variation in the concentrations of the fresh/brackish diatoms (benthic + planktonic).

Variation saisonnière des concentrations des diatomées d'eau douce à saumâtre (benthique et planctonique).

c) a decrease in concentrations in the French coastal waters, between January (the period of the highest French fresh water inputs during this particular survey) to May;

d) higher concentrations observed in May, through the Dover Strait - according to the salinity distributions, these estuarine inputs are especially marked from the English coastal waters to the Varne sandbank [an earlier stormy period, with N winds, suggests that it is associated with English fresh water inputs (especially from the Thames)].

DISCUSSION

SPM across the Dover Strait

The long-term evolution of SPM components at six stations across the Dover Strait, can be interpreted in terms of four hydrodynamical sections:

a) English coastal waters, which receive mainly suspended material from coastal erosion and tidal resuspension and cause a littoral turbid plume - this decreases in concentration from the English coast to the Varne sand bank, with a low biological activity;

b) French coastal waters, with the same littoral turbid plume - this is less wide and limited downstream by a strong discontinuity (around station FX6);

c) the deep marine (offshore) waters, which are always less turbid - these separate the English and French coastal waters;

d) the Varne waters, which can receive the outer waters of the English littoral turbid plume and resuspended material from the sandbank.

Low concentrations of ecological tracers of river input are present over the whole of the Dover Strait. At the same time, noticeable concentrations have been observed within the central waters, especially near Varne sandbank. These concentrations indicates : the small contribution of river SPM input across the Dover Strait; the low SPM input of the nearby coastal "rivers"; and exchange of the river SPM input, from coastal to central waters.

Except for the case of May 1991 data, indicative of a northern river SPM input (probably the Thames), the Seine estuary is the main river SPM input into the Eastern Channel. This estuarine input is also the main pollutant supply. The calculated total annual SPM flux (Lafite *et al.*, 1993) from the Eastern Channel to the North Sea is about 19.10^6 $t.y^{-1}$ for the present study. During the same period, the Seine SPM input was about 6.10^5 $t.y^{-1}$. Such values confirm the difficulty in detecting such an SPM input, following dilution within various marine inputs within the Dover Strait.

SPM component fluxes

Lafite *et al.* (1993) have calculated the daily and annual fluxes of SPM, from the Eastern Channel to the North Sea. The SPM components depended upon seasonal variations and the hydrodynamical controls. Changes in the SPM load fluxes cannot be represented completely, however, through the changes in the fluxes of the various SPM components. Using the same numerical model, quantification of SPM components on the Dover transects can provide daily fluxes of the SPM components.

Comparison of two daily fluxes during different seasons (Fig. 8) indicates that the overall particulate volume flux is higher in July than in January; this is associated with the water and SPM load fluxes. In July, the higher particulate volume is related to biological effects within the diatom valves, other debris and organic matter (with an increase in the organic clay aggregates). As the behaviour of some pollutants (*e.g.* heavy metals) depends upon that of the SPM components, such data could be important in explaining associated fluxes.

An example of heavy metal. SPM component correlation

SPM and Mn particulate data within the surface waters, from January and July 1991, are combined in Figure 9.

In January, Mn concentrations increase with a decrease in the apparent densities. There is only a low contribution made by planktonic productivity during winter. The decrease in apparent densities is related mainly to an increase in the ratio of the organic-clay aggregates. It may be consequently concluded that Mn SPM is associated mainly with organic-clay aggregates during winter.

For July, the poor correlation can be explained by: the higher contribution of the non-reactive planktonic content at stations FX4 and FX5; higher Mn factory inputs at the

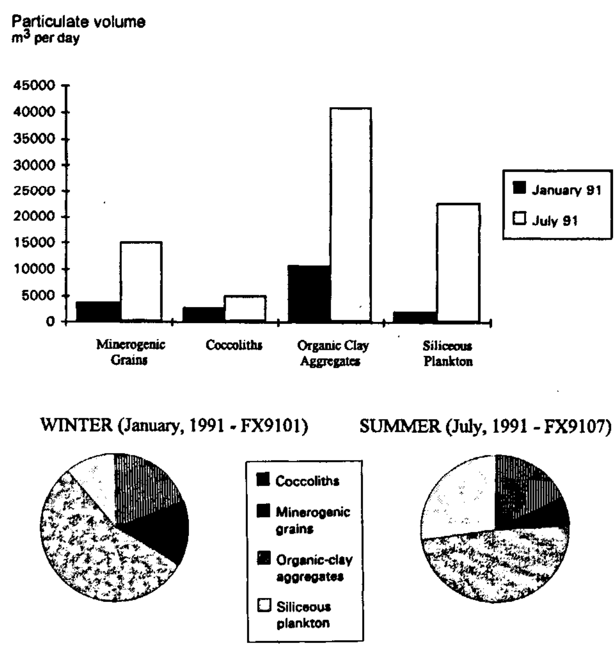


Figure 8

Daily flux of the suspended matter components in winter (12 January 1991) and in summer (21 July 1991).

Flux journalier des composants des matières en suspension en hiver (12 janvier 1991) et en été (21 juillet 1991).

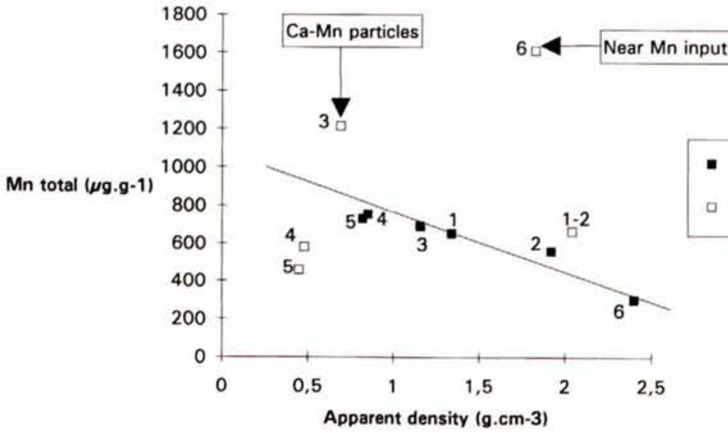


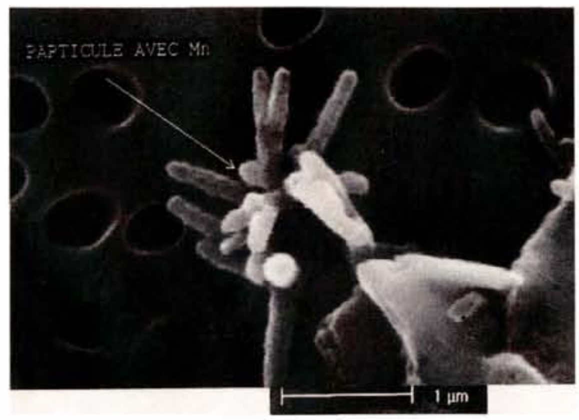
Figure 9

Relationships between Mn particulate and apparent densities of surface suspended matter.

Relations entre le manganèse particulaire et la densité apparente des matières en suspension dans les eaux de surface.

nearby sampling station (FX6); the good correlation established for the winter sampling, within the mainly mineral SPM content of the English coastal turbid plume (FX1 and FX2); and the high Mn concentration in the mainly organic SPM, of the FX3 sampling station.

The SEM observations indicate the presence of debris from a previous bloom of *Emiliana huxleyi* coccoliths, in the FX3 sample. The SEM research with the Mn content reveals the main Ca-Mn relationship for these particles (Plate), which can explain the Mn anomaly (Wartel *et al.*, 1991).



Plate

Debris from the coccoliths Emiliana huxleyi, *enriched with Mn.*

Débris du coccolithe *Emiliana huxleyi*, enrichi en manganèse.

CONCLUSIONS

Quantification of SPM fluxes between two shallow marine environments cannot be limited to overall determinations (load, photosynthesic pigments and organic matter), but requires investigations into the various components (by combining SEM observations with grain size analysis) as follows:

a) for the quantification of the particulate tracers, to define the origin and the hydrodynamic behaviour of the suspended matter;

b) for the quantification of SPM components, which can provide information on the component fluxes.

Combining time-series studies with cross-sectional observations, monthly surveys at six stations across a 30 km strait (with bottom and surface water sampling) has been shown to be sufficient to enable the hydrodynamical and seasonal effects on sedimentological processes to be established.

Such an approach should commence with a numerical model of the SPM transport; it may be associated also with geochemical studies of pollutant flux behaviour.

Acknowledgements

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