Suspended particulate matter fluxes through the Straits of Dover, English Channel: observations and modelling

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Abstract – Suspended Particulate Matter (SPM) concentrations at various levels within the water column, together with salinity and temperature, were measured using water samples collected from six stations across the Straits of Dover. The sampling programme covered a 16-month period, undertaken during 23 cruises. On the basis of the spatial variability in the concentrations, the water bodies are divided by several boundaries, controlled by tidal and wind conditions. Within the water column, SPM concentrations were higher near the sea bed than in the surface waters. Throughout the cross-section, maximum concentrations occurred adjacent to the coastlines. Temporal variability in the SPM concentration exists on daily and seasonal scales within the coastal waters (4.2 to 74.5 $mg \cdot L^{-1}$): resuspension processes, in response to semi-diurnal tidal cycles (with a period of around 12.4 h) and spring-neap cycles (with a period of 15 days) make significant contributions. Distinctive seasonal/annual concentration changes have also been observed. In the offshore waters, such variability is much less significant (0.9 to 6.0 $mg \cdot L^{-1}$). In the summer the English Coastal Zone is associated with relatively high SPM concentrations: the Central Zone has a low and stable SPM concentration between these zones, there is a Transitional Zone, where there is a rapid response of SPM concentration to wind forcing. Finally, the French Coastal Zone is characterized by variable (sometimes high) SPM concentrations. Because of the zonation, SPM fluxes within the Dover Strait are controlled by different transport mechanisms. Within the Central Zone, the flux can be represented by the product of mean water discharges and SPM concentrations. However, within the coastal zones fluctuations in SPM concentrations on various time-scales must be considered. In order to calculate the maximum and minimum SPM fluxes, 10 cells were divided in the strait. A simple modelling calculation has been proposed for this complex area. The effect of spring-neap tidal cycles and seasonal changes can contribute significantly to the overall flux, which is of the order of 20×10^6 $t \cdot yr^{-1}$ (through the Dover Strait, towards the North Sea). Such an estimate is higher than most obtained previously. © 2000 Ifremer/CNRS/IRD/Éditions scientifiques et médicales Elsevier SAS

suspended particulate matter / flux / transport mechanisms / straits / English Channel

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Résumé – Flux de matière particulaire en suspension dans le détroit du Pas-de-Calais : observations et modélisation. Les concentrations pondérales de matières en suspension (MES) ont été mesurées, conjointement à la salinité et la température, sur six stations dans le détroit du Pas-de-Calais, au cours de 23 campagnes en mer programmées sur une période de 16 mois. Les variabilités spatiales des concentrations de MES permettent d'identifier des masses d'eaux dont les limites sont contrôlées par les conditions de marée et de vent. Dans la colonne d'eau, les concentrations de MES sont plus fortes près du fond qu'en surface. Dans le détroit du Pas-de-Calais, les concentrations maximales sont observées le long des côtes. Des variations temporelles des concentrations de MES sont observées à l'échelle journalière et saisonnière dans les eaux côtières (de 4,2 à 74,5 $mg \cdot L^{-1}$), variations liées principalement à des phénomènes de remise en suspension au cours des cycles semi-diurnes de marée (période moyenne de 12,4 h) et au cours de cycles vives-eaux / mortes-eaux (période de 15 j). Des modifications de concentrations de MES à l'échelle saisonnière ou annuelle ont été également observées. Dans les eaux du large, ces variations sont nettement moins significatives (de 0,9 à 6,0 $mg \cdot L^{-1}$). Pendant la période estivale, la zone côtière anglaise est caractérisée par des concentrations relativement fortes de MES, la zone centrale du Pas-de-Calais conservant de faibles valeurs de concentrations. Entre ces deux zones, se trouve une zone de transition, où l'élévation des concentrations de MES peut être rapide, en raison de la houle. Enfin, la zone côtière française est caractérisée par des concentrations de MES variables dans le temps. Les flux de MES dans le détroit du Pas-de-Calais sont contrôlés par des mécanismes de transport différents selon la zone considérée. Dans les eaux centrales, le flux peut être représenté par le produit des flux moyens d'eau par les concentrations de MES. Dans les eaux côtières, les variations des concentrations de MES doivent être appréhendées à plusieurs échelles de temps. Pour calculer les flux particulaires minimum et maximum, le détroit a été subdivisé en dix cellules. Un calcul simple de modélisation est proposé pour cette zone très complexe. Les cycles vives-eaux / mortes-eaux et les variations saisonnières peuvent modifier significativement le flux total, qui est de l'ordre de 20×10^6 t par an à travers le Pas-de-Calais, de la Manche vers la Mer du Nord. Cette estimation est plus élevée que celles obtenues antérieurement.

matières en suspension / flux / mécanismes de transport / détroit / Manche

1. INTRODUCTION

The English Channel is an important link between the Atlantic Ocean and the North Sea (*figure 1*), in terms of exchanges of water, sediment and chemical substances. With regard to the fine-grained sediment budget of the eastern English Channel, a major output to the North Sea appears to be through the Strait of Dover. The suspended sediment supply from the Channel to the Southern Bight of the North Sea has been estimated to account for 60 % of the total supply [12].

A number of calculations have been undertaken to estimate the fluxes of Suspended Particulate Matter (SPM) through the Dover Strait [12, 23, 24, 27, 34, 37], with the annual SPM discharge being estimated to range between 4×10^6 and 17×10^6 tonnes. Nevertheless, Postma [24] has demonstrated that there is a need for "an extensive programme measuring suspended matter concentrations over an extended period across the Strait of Dover". This comment was made in response to the situation that many previous estimates were based upon limited information on the SPM concentration and some oversimplified methods for the calculation. There is a general lack of long-term measurements of SPM concentrations. The historical data are concerned mainly with summer seasons, collected from some parts of the Strait and over short periods [11, 36]. Furthermore, in most of these studies, the spatial variability of SPM fluxes across the Channel has not been sufficiently considered [39].

In such circumstances, the project FLUXMANCHE has been designed to deal with the issue of material fluxes in the English Channel. During the first phase of the project, SPM concentrations were obtained from six stations across the Strait of Dover, over a 16-month period (from July 1990 to November 1991); these included measurements undertaken during some specific events, such as stormy periods and high freshwater discharges. For this project, a two-dimensional hydrodynamic numerical model has been established [28]. Such a model provides instantaneous, vertically-averaged Eulerian flow within the Channel. Thus, the objectives of the present contribution are: (a) to analyse the SPM concentration data sets, in terms of the magnitude of the concentrations, SPM composition, and spatial and temporal variations; and (b) to calculate the fluxes of the SPM through the Strait of Dover, utilising the concentration data and the output of the hydrodynamic model, together with a discussion on the mechanisms of SPM transport.

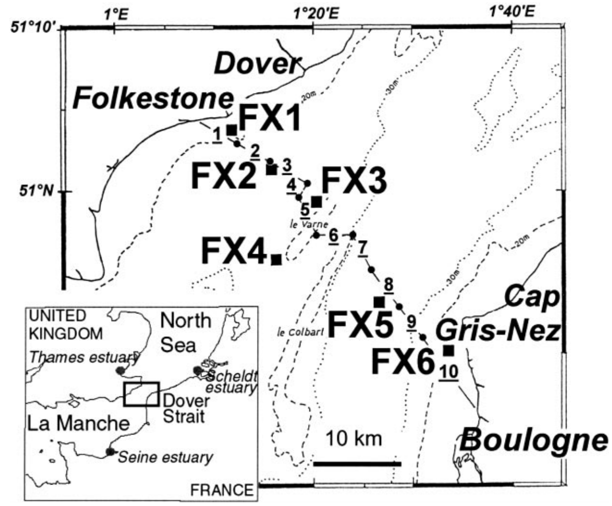

Figure 1. Locations of sampling stations (FX1 to FX6) and model grids (1–10) along a profile within the Strait of Dover.

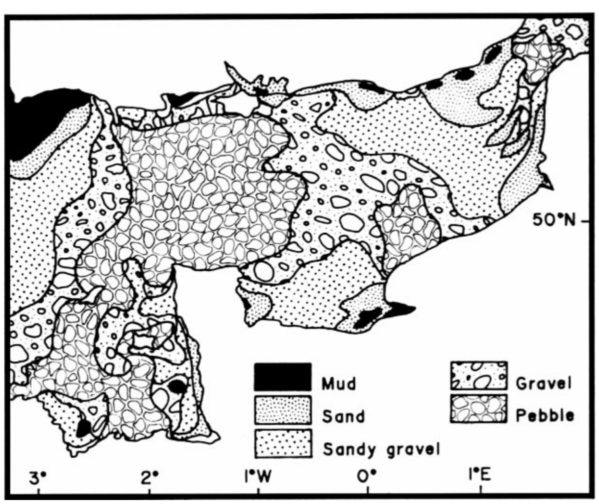

Figure 2. Schematic bottom deposits [38].

2. REGIONAL SETTING

Geological and geophysical surveys have been carried out over the region for more than a century [13, 15, 16, 40]. These investigations show that the Channel can be divided into three geological provinces [5]: i) the western province, which is characterized by Lower Palaeozoic to Miocene strata, with unconformities beneath the Upper Cretaceous and Eocene deposits; ii) the central province represented by Jurassic to Eocene strata with a number of large east–west trending faults; and iii) the eastern province associated mainly with Tertiary deposits. Over the central and eastern Channel areas, Tertiary deposits are up to 380 m in thickness (the sedimentary basin is known as the Hampshire-Dieppe Basin) [5]. Here, a complex valley system was developed during low sea level periods in geological history. Subsequently, these valleys were infilled partially with sediments of up to 200 m in thickness [6, 7]; they may have been modified during the middle Holocene, in response to a catastrophic breaching of the Dover Straits [31].

An erosion surface was formed due to the sea level rise during the Holocene [4, 33]. Hence, bedrock is exposed in some places. The sea floor is covered over a large part with gravelly sediments (*figure 2*), representing lag deposits. Sandy material is distributed mainly over the western and eastern sections of the Channel. There is a significant correlation between the maximum tidal currents and the mean grain size of the seabed material: strong currents are associated with gravelly sediments (*figures 2* and *3*) [18, 22, 38]. Because of the strong tidal currents, longitudinal gravel furrows and ridges, gravel waves, and sand ribbons are formed over the Channel floor [1, 34, 38].

Within the Channel, there are two narrow locations or cross-sections: the Dover Strait (35 km in width) with a cross-sectional area below mean sea level of 1.37×10^6 m^2 (*figure 1*); and between the Isle of Wight and Cherbourg (around 100 km in width) (to the west of the section shown on *figure 1*).

The Channel represents generally a macrotidal environment, with a tidal range of 6 to 10 m on springs

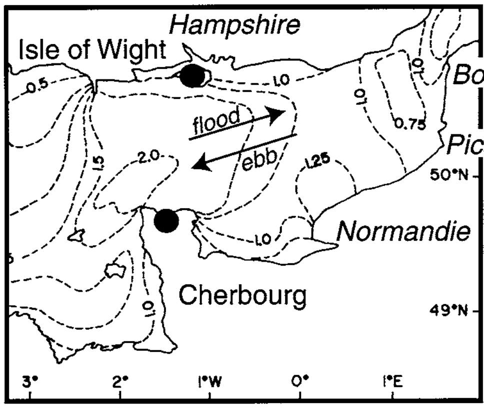

Figure 3. Maximum tidal current speed ($m \cdot s^{-1}$) [38].

Table I. Cruise summary for temperature, salinity and suspended particulate matter concentration measurements.

Data	Stations visited	Tidal range at the Dover Strait (m)
1990		
17–18 July	13	5.5–5.4
21–22 August	13	7.7–8.1
22–24 September	13	6–7
2 October	6	6.4
5 October	6	8.3
8 November	6	6
20 November	6	6.6
4 December	6	7.9
17 December	6	6.6
1991		
12 January	6	4.5
21 January	6	6.7
6 February	6	5.3
21 February	6	5.7–6.3
4 March	6	7.7
22 March	6	6.1
5–19 April	148	3.2–5.5
14 May	6	7.7
19–20 June	6	5.7
10–13 July	41	7.0–8.1
31 July	6	6.8
25 September	6	7.8
24 October	6	7.8
21 November	6	7.4

over most of its area. The smallest tidal range occurs along the south western English coastline where the spring tidal range is around 1 m. Tidal currents are strong, ranging between 0.5 and 2.0 $m \cdot s^{-1}$ over the central (*figure 3*), deeper part of the Channel around the cross-section between the Isle of Wight and Cherbourg (see above), on springs.

There is a relatively large fetch for wind wave generation. Furthermore, the region is exposed to swell waves from the Atlantic Ocean. In response to these factors, wave height increased to 8 m, especially during storms. Thus, wave action is intensive along the coastlines, although its influence may be insignificant over the central Channel because of the large water depths (up to 60 m). In response to storm surges, water level can be enhanced by around 1 m in some ports and estuaries within the Channel.

3. METHODS

3.1. Field observations

A profile across the Dover Strait was established, which consisted of six stations (i.e. FX1 to FX6, on *figure 1*). Over a 16-month period, temperature, salinity, and SPM concentrations were measured using a Sea Bird CTD coupled with a Sea Tech transmissometer to record vertical variations. Surface water variations have been obtained using a pumping system and continuous recording of CTD and HACH nephelometer, fitted to onboard measurement. Results of transmissometer and nephelometer have been calibrated using water sampling (surface and bottom) collected during 23 cruises (*table I*). For most of the monthly observations, the six stations were visited once during the cruise. The cruise in April 1991 continued for two weeks i.e. over a neap-spring tidal cycle; hence data sets in the form of a time-series were obtained for the stations. For the other cruises, the tidal range varied (*table I*), representing different tidal phases including neap, intermediate and spring tides.

In the laboratory, the water samples collected during the cruises were analysed to determine the SPM concentration, organic content, particle characteristics, photosynthesis pigments and heavy metals [8, 32].

In addition, tidal cycle measurements of SPM concentrations were undertaken during three cruises, in April (spring tide), July (neap tide) and September (intermediate tide) 1991, respectively. For these measurements, a transmissometer was used to record SPM concentrations. The measurements were carried out within the whole of the water column during the April cruise, but only for surface layers during the remainder of the cruise.

3.2. Techniques of computing the fluxes

The mean discharge of suspended sediment is defined as :

$$\bar{Q}_s = \frac{1}{T}\int_0^T \int_0^B \int_0^H V \cdot C \cdot dh \cdot dB \cdot dt \quad (1)$$

where Q_s is sediment discharge, T is the time-scale on which net discharge is considered, B is the width of the Strait, H is water depth, V is the component of current velocity perpendicular to the cross-section, C is suspended sediment concentration, and the over bar represents temporal and spatial mean values.

Generally, the sediment discharge cannot be expressed as the product of the mean values of the cross-sectional area, current speed and sediment concentration, except if certain of assumption are made [12, 24, 36, 37]. According to previous investigations into suspended material flux through the Dover Strait [8], the flux varies significantly across the Strait. This characteristic implies that the cross-section can be divided into several sub-sections (with different widths) as some authors have suggested [12, 19, 36]; for each of the subsections, the sediment discharge can be dealt with individually. Hence, equation (1) can be re-written as

$$\bar{Q}_s = \frac{1}{T}\sum_{i=1}^{N}\int_0^T \int_{yi-1}^{yi} \int_0^H V \cdot C \cdot dh \cdot dB \cdot dt \quad (2)$$

where N is the number of the sub-sections. The time-averaged discharge may be decomposed into a number of 'advective' and 'dispersive' terms [10, 35]. The relative importance of the terms depends upon temporal changes in the water surface level and spatial distribution patterns of the SPM concentration and current velocity. If, for a sub-section, the amplitude of water level changes is small compared with the water depth and the SPM concentration is almost homogeneous within the water column, then the SPM discharge for the i^{th} sub-section becomes

$$\bar{Q}_{s,i} = \frac{1}{T}\int_0^T \int_{yi-1}^{yi} \int_0^H V \cdot C \cdot dh \cdot dB \cdot dt = \bar{Q}_{w,i} \cdot \bar{C} \quad (3)$$

where Q_w is water discharge and the overbar represents an average value. However, if the two conditions stated above are not satisfied, then the use of equation (3) will cause large error in the estimate of the discharge. Over shallow water areas, the tidal range is not small in comparison with the water depth, and the SPM concentration may vary in response to resuspension processes. In such cases, the discharge may be written as

$$\bar{Q}_{s,i} = \frac{1}{T}\int_0^T \int_{yi-1}^{yi} \int_0^H V \cdot C \cdot dh \cdot dB \cdot dt = \alpha \cdot \bar{Q}_{w,i} \cdot \bar{C} \quad (4)$$

where the parameter α (coefficient) is a function of temporal changes in the cross-sectional area and the distribution of current velocities and SPM concentrations over the cross-section in relation to tidal phases. Such an approach can be compared in complexity to estuarine flux calculation [17]. The magnitude of parameter α cannot be calculated here, because the time-series of SPM concentrations are not available in this study. Nevertheless, the possible range of this parameter may be estimated individually for each of the sub-sections, this utilises the information on the current velocity, SPM concentration, salinity, temperature and other variables obtained from the field observations and measurements, on the basis of the method described below.

From a statistical point of view, any time-series can be decomposed and expressed by the sum of a number of sine or cosine curves with different amplitudes, periods and phases. Hence, water flux data can be written as :

$$Q_w = \bar{Q}_w + \sum_{j=1}^{m} Q_{w,j} \cdot \cos\left(\frac{2\pi}{T_j} + \phi_j\right) \quad (5)$$

where Q_w is the water flux (with the overbar representing the mean value), ϕ is the phase and m is the number of the cosine curves. Similarly, the time-series of SPM concentrations becomes:

$$C = \bar{C} + \sum_{k=1}^{n} C_k \cdot \cos\left(\frac{2\pi}{T_k} + \psi_k\right) \quad (6)$$

where ψ is the phase and n is the number of the cosine curves. Thus, over a long period of time and omitting small terms, the average SPM flux is:

$$\bar{Q}_s \approx \bar{Q}_w \cdot \bar{C} + \sum_{i=1}^{N} \frac{1}{T} \int_0^T A_{Q,i} \cdot A_{C,i} \cdot \cos\left(\frac{2\pi}{T_i}t + \phi_i\right) \cdot \cos\left(\frac{2\pi}{T_i}t + \psi_i\right) \cdot dt \quad (7)$$

where A is cross-sectional area and N is the number of components with large amplitudes. Using the above equation, although the mean SPM flux is unknown due to the lack of the concentration data, the range of the flux may be estimated if the amplitudes of water flux and concentration fluctuations of the various time-scales are known. The mean SPM flux reaches a maximum when the water flux and SPM concentration data have the same phases $\phi_i = \psi_i$. Therefore, we have

$$\bar{Q}_{s,max} = \bar{Q}_w \cdot \bar{C} + \sum_{i=1}^{n} \frac{1}{2} A_{Q,i} \cdot A_{C,i} \quad (8)$$

Likewise, the flux reaches a minimum when the phase difference between the water flux and SPM concentration data is π. This implies that

$$\bar{Q}_{s,min} = \bar{Q}_w \cdot \bar{C} - \sum_{i=1}^{n} \frac{1}{2} A_{Q,i} \cdot A_{C,i} \quad (9)$$

On the basis of equations (8) and (9), the range of the parameter in equation (4) can be estimated. In order to obtain the values of water fluxes and SPM concentrations required to calculate the maximum and minimum SPM fluxes defined by equations (8) and (9), 10 cells were divided (*figure 1*). For each of the cells, SPM concentration data were derived from the measurements from Stations FX1 to FX6 (except for Station FX4 which was displaced from the profile and influenced by a linear sandbank system), on the basis of linear interpolation.

4. RESULTS AND DISCUSSION

4.1. Characteristics of the water masses and SPM concentrations

Measurements obtained from the surface waters show a seasonal change in temperature; it varied from 17 °C in summer to 7 °C in winter (*figure 4a*). No significant spatial variations were observed across the Strait: the temperature of the central areas was similar to that of the (English and French) coastal waters.

The spatial variability in salinity was relatively pronounced (*figure 4b*), especially along the French coastlines. Over the central areas, salinity within the surface layers varied generally between 35 and 35.4. Along the French coastline, a constant low salinity indicates a discontinuity between the coastal and offshore waters: the front was located between FX5 and FX6. Such a front system was observed also

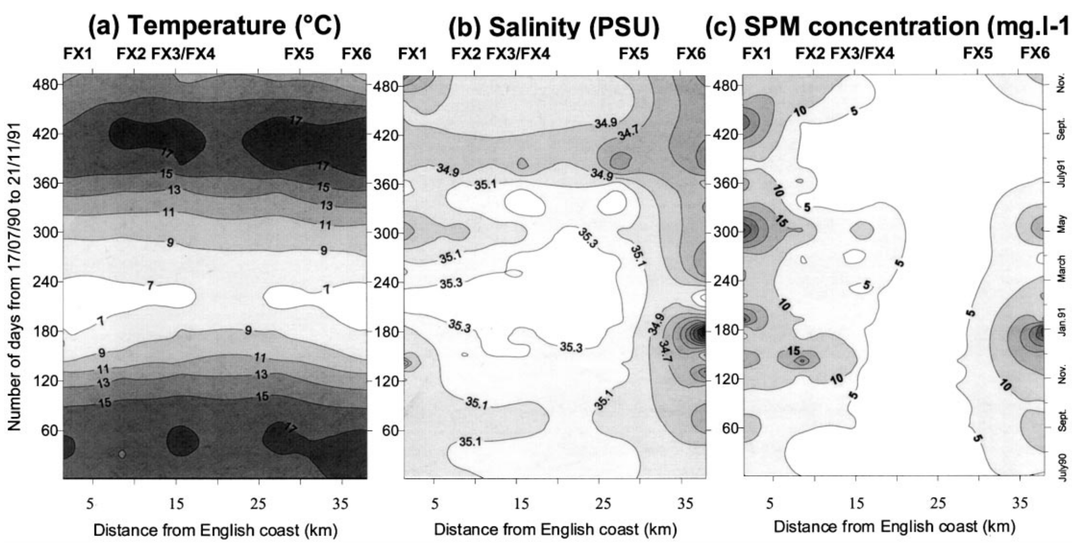

Figure 4. Hydrological data for surface waters within the Strait of Dover: (a) temperature (°C); (b) salinity; and (c) SPM concentration (mg·L^{-1}). For station locations, see *figure 1*.

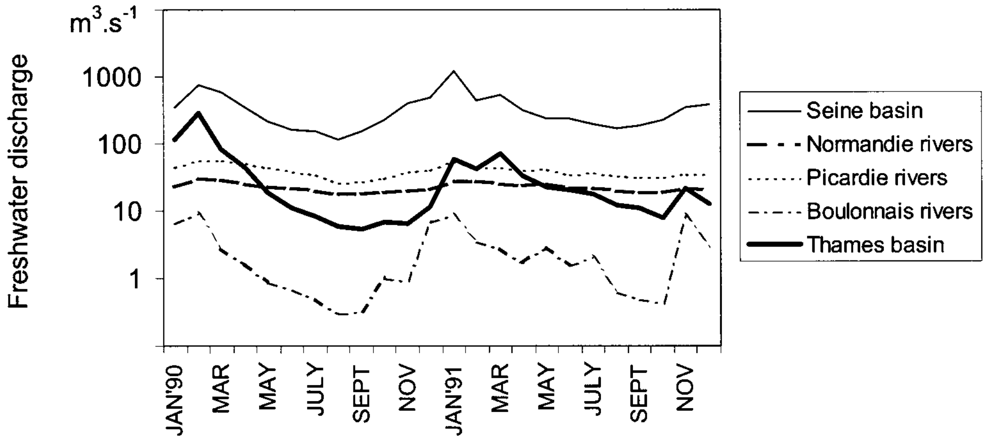

Figure 5. Monthly freshwater discharges (1990) from the major rivers of the region (data abstracted from the Service Hydrologique Centralisateur du Bassin Artois-Picardie, the Service Régional de l'Agence de l'Eau Seine-Normandie, the Cellule anti-pollution de la Seine à Rouen, and the National Rivers Authority (Thames Region, UK).

during previous investigations [9]. Monthly freshwater discharges during the research period (*figure 5*) show large discharges in January 1991 and November 1991 for all the rivers and in March 1991 for the Thames. During this winter period, local rivers must have influenced significantly the coastal salinity. Freshwater issue from large rivers (the Seine and Thames) takes a relatively long time to reach the Strait. Radionucleide experiments on the transit-time of waters in the Channel [30] indicate that at least three months are needed for the central waters to reach the Strait, from Cherbourg. An even longer delay (of probably 4 to 8 months) may be required for waters influenced by the Seine to reach the Strait [14]. Thus, a general decrease in salinity in May 91, which was observed across the Strait, might be related to the peak discharges, during winter 1991, of the Seine and Thames rivers.

Along the English coast, surface SPM concentrations were at a constant high level during most of the survey period (> 10 mg·L^{-1}, *figure 4c*), with maxima in December 1990, May–June 1991 and December 1991. Over the central areas of the Strait, the SPM concentration was relatively low (generally < 5 mg·L^{-1}). Along the French coasts, maximum concentrations occurred during the same periods as on the English side, in July 1990 to July 1991; the concentration was also greater than 10 mg·L^{-1} for most of the time. However, the concentration was low along the French coast between July and December 1991, in response to a seaward dispersion of high SPM concentration waters from the English coastline (*figure 4c*). In most other cases, the high concentrations were correlated with the low salinity waters (*figures 4b*, *4c*); hence, the high concentrations may be a characteristic of river input, in addition to resuspension in the shallow water coastal areas.

The turbidity varied throughout a tidal cycle on either springs or neaps (*figure 6*); during slack waters, the SPM concentration decreased. The concentration was on average higher on springs than on neaps. The difference between spring and neap concentrations was much larger at stations near the coastlines (FX 1 and FX 6) than at the station at the central part of the Strait (FX4). During an intermediate tide, the concentration was the highest within the data sets obtained. This pattern is likely to be caused by relatively strong south-westerly winds, during that particular tidal cycle. These observations show that resuspension takes place in response to tidal velocity changes (particularly in shallow coastal areas) and winds. However, the effect of resuspension appeared to be insignificant over the central part of the Strait, where the SPM concentration varied only during periods of strongest winds observed (*figure 7*). Wind direction has a strong influence on coastal resuspension: on FX2 and FX3, NE wind is more efficient than WNW wind even speed is lower (*figure 7*). On the basis of a calculation undertaken using the data from Station FX1, a tidally-averaged concentration was estimated to be 18.1 mg·L^{-1} for springs and 9.8 mg·L^{-1} neaps: at Stations FX4 and FX6, the concentration was much lower (*figure 6*). Therefore, the English side of the Channel is characterized by relatively high SPM concentrations; this is consistent with the annual patterns shown on *figure 4c*.

Within the water column, two SPM concentration maxima occurred during a tidal cycle, at Stations FXl and FX6; concentrations were higher in the bottom than in the surface layers (*figure 8*). Large differences occur between the surface and bottom concentrations. In contrast, vertical and tidal variations were insignificant at Station FX4. This observation, once again, is indicative of the effect of resuspension over the shallow water areas.

During each of the cross-sectional series of measurements, variations in SPM concentrations were greater laterally than vertically (*table II*). Likewise, the annual variation indicates constantly low SPM concentrations in the central waters and distinctive changes along the coastline (*table II*). Compared with the data derived from previous studies [12, 36], the present data set reveals higher concentrations. Such conditions occur because the FLUXMANCHE data were obtained: i) throughout the year, including stormy periods; and ii) the concentrations listed in

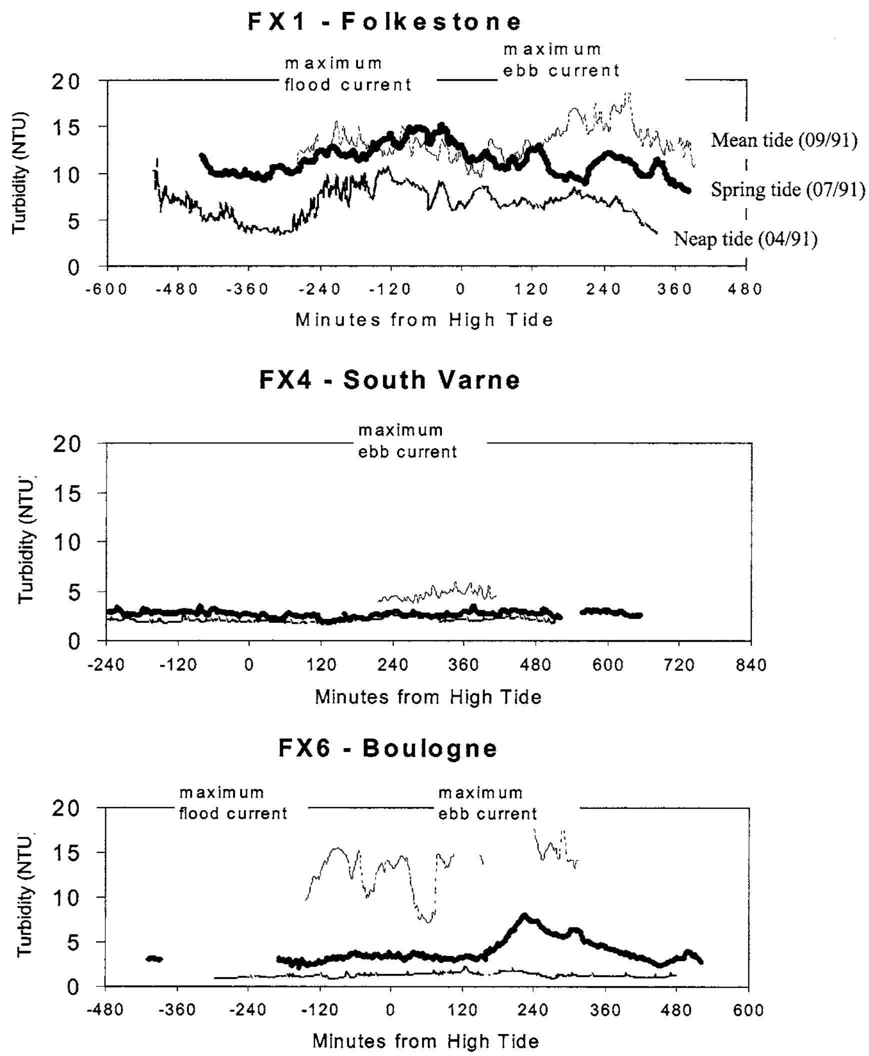

Figure 6. Effects of tidal variations on turbidity within the surface layers of the water column.

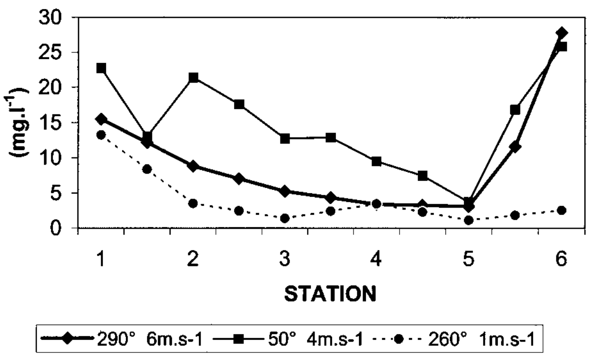

Figure 7. Wind effects on the SPM concentration. Values are depth averaged.

table II are depth-integrated, rather than for surface waters alone. On average, the SPM concentration in the coastal waters was estimated as 15.3 mg·L^{-1} and in the central waters as 4.4 mg·L^{-1}.

On the basis of the concentration data obtained during the present study, the Dover Strait cross-section can be divided into 4 zones: i) the English Coastal Zone, with relatively constant high SPM concentrations and significant fluctuations; ii) a Transitional Zone, located between the English coastline and the central part of the Strait, with low SPM concentrations, but where there is a response of the SPM concentration to wind effect; iii) a Central Zone, with a constant lowest SPM concentrations; and (iv) the French Coastal Zone, characterized by a variable, sometimes high, SPM concentration. Such zonation implies that SPM fluxes within the Dover Strait should be calculated separately for these, distinctive zones.

4.2. SPM fluxes through the Strait of Dover, using water discharge for 1990

Net SPM transport is controlled by residual water flows, velocity distribution patterns over the cross-section and temporal/spatial variation in SPM concentration, as implied by equations (1) to (4). In the following analyses, the 10 cells which belong to the different zones (as described above) will be treated individually; this is because these cells may be dominated by different SPM transport mechanisms.

The overall water discharge through the Dover Strait varies with changes in tidal, wind and wave conditions. Salomon et al. [29] have calculated monthly and annual water discharges for nine years (1983–1991), using a two-dimensional model which includes tidal and wind effects. The monthly-averaged discharges varied between − 8 000 m^3·s^{-1} (towards the Channel, in December 1988) and 288 000 m^3·s^{-1} (in December 1989). However, the derived annual mean

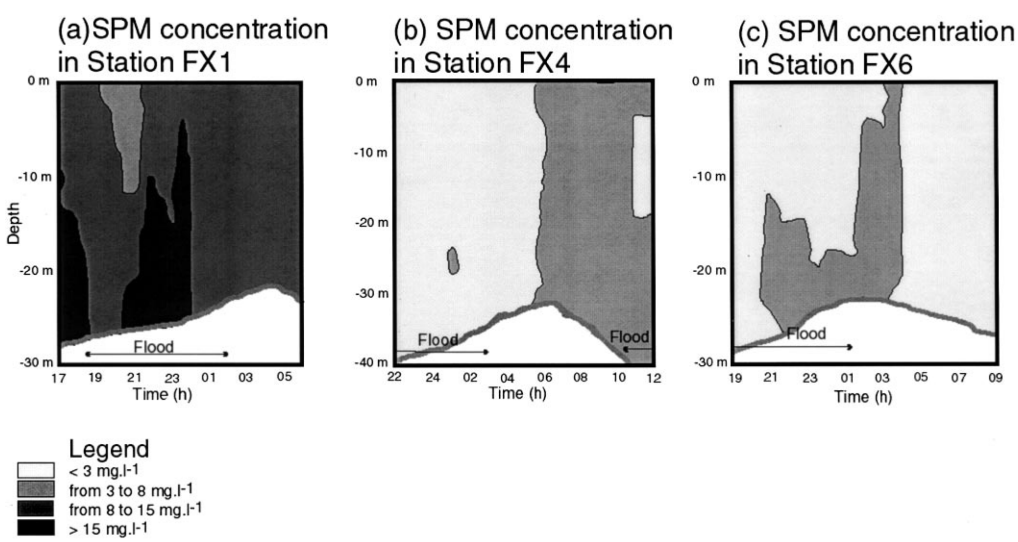

Figure 8. Temporal (tidal) variations in the mean turbidity (expressed as beam attenuation, from transmissometer measurements) within the water column for: (a) Station FX1; (b) Station FX4; and (c) Station FX6. Calibration with SPM concentration is expressed for 3 values: 3, 8 and 15 mg·L^{-1}. Time-series obtained during RV Challenger '77 cruise in April '91.

Table II. SPM concentrations (in mg l^{-1}) in the Dover Strait (for locations, see Figure 1).

Data	FX1 Surface	FX2 surface	FX3 surface	FX4 surface	FX5 surface	FX6 surface	FX1 bottom	FX2 bottom	FX3 bottom	FX4 bottom	FX5 bottom	FX6 bottom
1990												
17 July	10.1	5.0	3.8	4.7	4.7	4.2	–	–	–	–	–	–
21 August	8.5	2.2	3.2	3.3	2.3	11.4	10.9	8.5	3.4	3.9	2.2	19.3
23 September	16.4	7.2	5.8	4.3	5.5	15.4	18.1	9.8	7.5	4.3	5.2	19.7
2 October	7.0	5.3	3.9	2.8	2.1	8.3	12.8	9.1	4.7	5.1	2.9	13.0
5 October												
8 November	11.1	10.2	5.8	3.7	5.8	13.2	12.8	11.2	6.4	5.2	5.8	16.2
20 November	11.2	7.4	6.9	2.5	2.2	16.5	20.6	9.9	5.0	4.1	4.9	37.9
4 December	20.4	28.3	13.3	7.0	6.0	17.3	26.5	27.8	16.4	7.5	6.2	19.0
17 December	13.6	11.7	8.9	7.2	2.0	20.6	26.6	24.9	13.7	11.8	9.2	35.3
1991												
12 January	5.9	7.1	7.0	4.6	3.9	43.5	10.4	8.5	6.8	7.5	5.1	57.3
21 January	35.0	10.8	6.6	6.9	3.2	8.4	45.8	12.9	7.2	8.7	6.7	9.5
6 February												
21 February	7.7	5.6	5.9	6.5	3.2	16.7	7.8	5.6	6.0	6.5	3.2	17.7
4 March	13.9	5.1	3.2	2.1	2.3	12.5	20.2	6.8	3.7	3.3	3.4	27.0
22 March	16.3	8.2	10.3	11.0	3.9	9.6	24.2	8.9	9.9	10.7	3.3	13.5
10 April	10.0	3.4	1.4	3.4	0.9	1.8	16.5	3.7	–	3.6	1.3	3.3
14 May	44.5	19.1	9.2	8.0	1.7	13.6	74.5	21.3	10.0	11.2	2.5	22.4
19 June	11.3	1.5	0.7	2.3	1.7	8.4	10.2	2.6	1.8	2.0	1.1	13.5
12 July	18.4	11.6	5.1	4.3	2.3	6.1	23.1	16.0	5.1	6.1	4.0	9.1
31 July	6.2	4.3	2.0	1.5	1.5	2.0	8.5	4.7	2.2	2.7	1.8	2.0
25 September	30.0	4.9	3.6	1.7	1.4	4.1	–	6.9	3.3	3.5	1.5	5.9
24 October	13.2	15.9	6.4	8.1	2.1	6.3	30.2	24.2	6.6	7.1	2.4	11.1
21 November	14.0	12.3	9.8	4.6	2.5	13.0	24.0	26.5	17.8	15.8	4.5	–

discharges were relatively stable, ranging between 96 000 $m^3 \cdot s^{-1}$ and 150 000 $m^3 \cdot s^{-1}$, with a deviation of around 25 % from the value averaged over the nine years i.e. 114 000 $m^3 \cdot s^{-1}$. These results are of similar orders of magnitude compared with a number of previous investigations [2, 3, 20–22, 25, 37, 41]. In particular, the data are close to the observed water fluxes, which are controlled by tidal and wind effects [26, 27]. In the model used by Salomon et al. [29], variations in residual currents within the water column were not considered, because the direction of the residual flow has been observed to be consistent throughout the water column, although notable temporal stratification exists near the coastlines of the Dover Strait [28]. Thus, on the basis of the model output, water discharges for the ten cells, using the overall water discharge for the year 1990 (102 000 $m^3 \cdot s^{-1}$) were calculated (*figure 9*).

Using the SPM concentration measurements described above, annually-averaged SPM concentrations were derived for the five stations (FX1, FX2, FX3, FX5 and FX6). Then, linear interpolation was applied to obtain the concentration values for the 10 cells (*figure 9*). The concentration distribution shows that: i) Cells 1 and 2 belong to the English Coastal Zone; ii) Cells 3 and 4 fall into the Transitional Zone; iii) Cells 4 to 9 represent the Central Zone, and iv) Cell 10 is located within the French Coastal Zone. In general, water discharge and SPM concentration data (*figure 9*) reveals a negative correlation between the

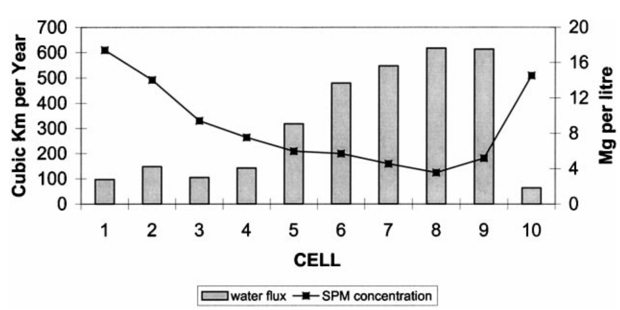

Figure 9. Annual water flux and concentration for the 10 cells (see *figure 1*), for 1/10/90 to 31/9/91.

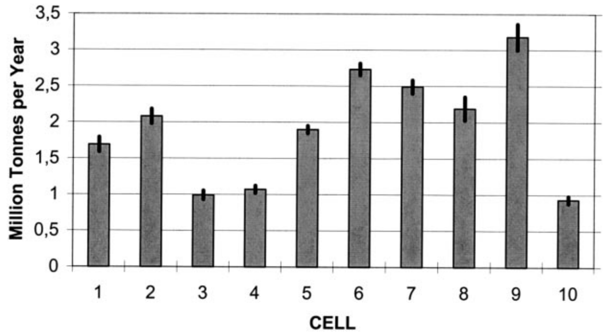

Figure 10. Suspended particulate matter (SPM) flux through the Dover Strait derived on the basis of equation (3) and the data presented in *figure 7*, for each of the cells. Bars represent standard deviation of total solid flux over a 95 days overlap period during these 16 months of survey.

Table III. Estimates for SPM discharge through the Dover Straits, for cells 1, 2, 3, 4 and 10.[a]

Cell number	SPM flux ($\times 10^6$ t.y^{-1})				
	Q_1	Q_2	Q_3	$Q_{s, max}$	$Q_{s, min}$
1	1.7	±0.06	±0.4	2.2	1.2
2	2.1	±0.10	±0.6	2.8	1.4
3	1.0	±0.03	±0.2	1.2	0.8
4	1.1	±0.05	±0.3	1.4	0.8
10	0.9	±0.03	±0.2	1.1	0.7

[a] Q_1 = SPM flux calculated using Eq. (3); Q_2 = SPM flux due to spring-neap variations in concentration; Q_3 = SPM flux due to seasonal variations in concentration; $Q_{s, max}$ = Maximum SPM flux, calculated using Eq. (8); $Q_{s, min}$ = Minimum SPM flux, calculated using Eq. (9).

two variables. High SPM concentrations along the (English and French) coastlines are associated with low residual flows: likewise, high residual water flows over the central part of the Strait are related to low SPM concentrations. Using Equation (3), the data shown in *figure 9* can be converted to SPM fluxes (*figure 10*). However, although the flux data for Cells 5 to 9 may be relatively accurate because of the vertical homogeneity (*figure 8b*) and relatively small seasonal variations (*figure 4c*) in the SPM concentration, those for the other cells are likely to be associated with larger errors. Assuming a lateral homogeneity in the concentration for each of the cells, variations within the water column and temporal changes corresponding to changes in water fluxes must be taken into account. This procedure is equivalent to an estimate in the value of alpha in equation (4).

At the shallow water stations (such as Station FX1), resuspension of fine-grained material is significant during a tidal cycle. However, the signal representing the period of SPM concentration variations may be different from that of the tidal current. For example, within the Dover Strait, tidal currents are dominated by the M2 constituent; however, the resultant SPM concentration (related to resuspension) may have a period half that of the M2 tides. In response to such processes, there may be two SPM concentration peaks during a tidal cycle: one during the flood and the ebb phase (e.g. *figure 8a*). In this case, the combination of the M2 tidal currents and the tidal changes in SPM concentrations could result in a zero transport - the net transport can be represented by the product of net water transport and the mean SPM concentration. Nevertheless, because of asymmetry in the flood and ebb tidal currents, the SPM concentration may have a constituent with the same period as that of the M2 tidal currents. For the present study, since the data sets are insufficient to estimate the amplitude of the SPM concentration changes (with M2 period), the contribution made by (M2) water transport/SPM concentrations cannot be estimated.

Other important variations include spring-neap tidal phase and seasonal cycles. At Station FXl (Cell 1), the difference between spring and neap SPM concentrations is of the order of 8 mg·L^{-1} (*figure 6*). Hence, the amplitude of SPM concentration fluctuations is around 4 mg·L^{-1}, for a spring-neap tidal phase. Further, the difference between the spring and neap water discharges can be estimated to be 1.0×10^3 m^3·s^{-1} for the year; this applies if a mean water discharge of 3.1×10^3 m^3·s^{-1} (calculated using the data from *figure 9*) is assumed and used discharge on a spring tide is assumed to be twice that on a neap tide. Therefore, according to equations (8) and (9), the contribution made by spring-neap variations is $\pm$ 0.1×10^6 t·yr^{-1}. On a seasonal (annual) temporal scale, the amplitude of the SPM fluctuations is of the order of 15 mg·L^{-1} for Station FX1. The amplitude of the water discharge is around 1.6×10^3 m^3·s^{-1} for 1990 assuming that maximum discharge during the year is three times the minimum values (on the basis of the monthly water discharge data abstracted from Salomon et al. [29]. Hence, the contribution in response to seasonal cycles of water discharge and SPM concentration variations is of the order of $\pm\ 0.4 \times 10^6$ t·yr^{-1}.

Using the same procedure of estimates, together with information presented in *figures 5* and *8* and from the study undertaken by Salomon et al. [29], spring-neap and seasonal contribution for Cells 2, 3, 4 and 10 have been obtained: these are listed in *table III*, together with data for Station/Cell 1. The results show that the deviation in the SPM flux, from the value calculated using equation (3) ranges between 20 % and 35 % for Cells 1, 2, 3, 4 and 10; this is equivalent to an alpha value in equation (4) of between 0.6 and 1.4. It should be noted that such deviations are caused by the effects of spring-neap cycles and seasonal cycles alone: if other periodic changes in the SPM concentration are included, then it is anticipated that the deviation will be increased further. Thus, errors in the estimate for the SPM flux lie mainly in the calculation of fluxes associated with the coastal waters.

Nevertheless, because the SPM fluxes for the cells within the Central Zone adds up to 12.5×10^3 t·yr^{-1} (*figure 10*), which is larger than the ranges of total flux in the coastal cells (6.8×10^6 t·yr^{-1} $\pm 1.9 \times 10^{-1}$ t·yr^{-1}), an estimate for the overall net SPM transport from the English Channel towards the North Sea of 20×10^6 t·yr^{-1} should be considered as being acceptable.

4.3. SPM fluxes under average water discharge and other conditions

In order to estimate inter-annual variation in the SPM fluxes, the average, maximum and minimum water discharges were also used to calculate the fluxes. These characteristic values have been derived for the period between 1983 and 1991 [29]; they are 114 000, 150 000 and 96 000 m^3·s^{-1}, respectively.

On the basis of the information on the SPM flux for the year 1990, net SPM transport can be estimated for these water discharge conditions (assuming that flux is proportional to the annually-averaged discharge). Hence, for average conditions (i.e. 114 000 m^3·s^{-1}), the overall SPM flux will be approximately $21.6\ \pm\ 2.1 \times 10^6$ t·yr^{-1}. This value is larger than results obtained in most of the previous studies [12, 22, 23, 36, 37], except for that of Eisma and Irion [11]. Such enhancement is due partly to the use of SPM data from both offshore and coastal waters.

Comparable fluxes are $28.4\ \pm\ 2.8 \times 10^6$ t·yr^{-1} and $18.2\ \pm\ 1.8 \times 10^6$ t·yr^{-1}, for the maximum and minimum water discharges, respectively. Such an estimate indicates that, in response to a 25 % deviation in water discharges, SPM flux deviations may be almost as large.

5. CONCLUSIONS

(1) On the basis of spatial and temporal SPM concentration distribution characteristics, the Dover Strait cross-section can be divided into 4 zones: i) the English Coastal Zone, with relatively constant high SPM concentrations and significant fluctuations; ii) a Transitional Zone, located between the English coastline and the central part of the Strait, with low SPM concentrations, but where there is a response of the SPM concentration to wind effect; iii) a Central Zone, with a constant lowest SPM concentrations; and iv) the French Coastal Zone, characterized by a variable (sometimes high) SPM concentration.

(2) In response to such zonation ((i), above), SPM fluxes within the Dover Strait are controlled by different transport mechanisms. Within the Central Zone, the net flux is related to the transport by the mean water discharge and SPM concentration. Over the coastal zones, however, transport due to variations in the SPM concentration (with different periods) becomes important. Based upon the SPM concentration data obtained and taking into account two of the most important temporal changes in concentration (spring-neap and seasonal cycles), the fluctuation may result in 20 % to 35 % deviations from a value derived on the basis of the mean values alone. The deviation may be enhanced further if other cycles are included.

(3) Within the context of the Channel, overall SPM flux for the Dover Strait is dominated by transport through the Central Zone. Hence, for 1990 water discharges an overall flux of 19.3×10^6 t·yr^{-1} (with a deviation of $\pm 1.9 \times 10^6$ t·yr^{-1}, due to coastal effects) is considered to be an acceptable estimate.

(4) For the mean, maximum and minimum water discharges of the Dover Strait, the overall SPM flux

is of the order of 20×10^6 t·yr^{-1} on average; the extreme variation is between 16×10^6 t·yr^{-1} and 31×10^6 t·yr^{-1}, in response to water discharge variations and coastal effects. The deviation from the mean annual flux is around double that for water discharges.

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