



Litter on the Sea Floor Along European Coasts

F. GALGANI†*, J. P. LEAUTE‡, P. MOGUEDET‡, A. SOUPLET§, Y. VERIN††, A. CARPENTIER††, H. GORAGUER‡‡, D. LATROUITE‡‡, B. ANDRAL§§, Y. CADIOU†, J. C. MAHE†††, J. C. POULARD††† and P. NERISSON†

†IFREMER, BP 21105, 44340 Nantes, France

‡IFREMER, BP 7, 17137 l'Houmeau, France

§IFREMER, 1, rue J.Vilar, 34200 Sete, France

††IFREMER, BP 699, 62321 Boulogne, France

‡‡IFREMER, BP 70, 29280 Plouzané, France

§§IFREMER, BP 330, 83507 La Seyne/mer, France

†††IFREMER, rue F. Toullec, 56100 Lorient, France

The distribution and abundance of large marine debris were investigated on continental shelves and slopes along European Seas, including the Baltic Sea, the North Sea, the Celtic Sea, the Bay of Biscay and different areas in the north-western basin of the Mediterranean Sea and the Adriatic Sea. On the basis of 27 oceanographic cruises undertaken between November 1992 and August 1998, different types of debris were enumerated, particularly pieces of plastic, plastic and glass bottles, metallic objects, glass, and diverse materials including fishing gear. The results showed considerable geographical variation in concentrations, which ranged from 0 to 101 000 pieces of debris per km². In most stations sampled, plastic (mainly bags and bottles) accounted for a very high percentage (more than 70%) of total number of debris, and accumulation of specific debris, such as fishing gear, was also common. In some areas, only small amounts of debris were collected on the continental shelf, mostly in canyons descending from the continental slope and in the bathyal plain where high amounts were found down to more than 500 m. Dives using the manned submersibles Cyana and Nautille between 50 and 2700 m allowed accumulation areas to be detected on the sea floor. Analysis of these results revealed the influence of geomorphologic factors, local anthropic activities and river inputs. Temporal trends indicated a stable situation in the Gulf of Lion and seasonal variations in the northern part of the Bay of Biscay. Accumulation areas were detected 200 km west of Denmark, in the southern part of the Celtic Sea and along the south-east coast of France. © 2000 Published by Elsevier Science Ltd. All rights reserved.

Keywords: environment; European coasts; litter; debris; continental shelf; continental slope.

Introduction

Since the 1970s, various studies have dealt with the problem of debris in the marine environment, mainly in terms of quantitative analysis (Pruter, 1987; Gilligan *et al.*, 1992) and the effects on marine fauna (Laist, 1987). Most of the data concern floating debris (Day and Shaw, 1987; Lecke-Mitchel and Mullin, 1992) or litter along the coast, particularly on beaches where it is abundant (Pruter, 1987). Although the debris are quite variable in type, plastics account for the major part because of their extensive use. Glass or metal objects, as well as fishing nets, are also found in appreciable quantity. The consequences of this pollution are considerable. The entanglement of marine species, particularly turtles (Carr, 1987; Duguy *et al.*, 1998), but also mammals and birds (Coe, 1990), has been frequently described. Moreover, the thousands of tons of plastics in the sea constitute a considerable source of pollutants, notably polyethylene and polypropylene, which can affect organisms (Burgess-Cassler *et al.*, 1991). The aesthetic impact of large debris (> 1 cm²) is also another objectionable effect. Finally, the repercussions on coastal economic activity, particularly fishing, have been demonstrated (Nash, 1992; Takehama, 1990).

The distribution of the debris is another important factor. High concentrations of floating debris are found near shipping lanes (Gottfried *et al.*, 1987), around fishing areas (Pruter, 1987) and in oceanic current convergence zones (Pruter, 1987). Conditions on French coasts have been surveyed in a complete study of beaches (Loubersac and Bodennec, 1982), indicating the influence of currents on the distribution of debris.

Little information is currently available concerning large debris on the coastal continental shelf since considerable means are required for undertaking a study of such magnitude. Recently, the presence of large

*Corresponding author.

amounts of debris has been reported on continental shelves of both the eastern Mediterranean (Bingel *et al.*, 1987; Stefatos *et al.*, 1999) and the Bay of Biscay and around north-western Mediterranean towns (Galgani *et al.*, 1995a,b). The presence of debris has also been recorded on the deep sea floor in the eastern Mediterranean (Galil *et al.*, 1995) and the Sicily Channel (Cannizarro *et al.*, 1995). Accumulations have also been found in canyons off the French Mediterranean coast (Galgani *et al.*, 1996). In the present study, debris distribution was evaluated on the continental shelves of European coasts. Temporal trends were studied in the Bay of Biscay and the Gulf of Lion. The presence of accumulation areas was also investigated, and the results analysed in terms of hydrodynamic and geomorphologic conditions.

Methods

The data were acquired during trawling cruises (nets with otter boards, 20 mm in the codend, trawling time ranging from 20 to 150 min) conducted mainly by IFREMER between November 1992 and September 1998. Information on the cruises and trawling stations is provided in Fig. 1 and Table 1. The enumeration of debris on the south-eastern coast of France and on the abyssal plain was taken from trawling operations performed in 1996, 1997 and 1998 during the DEPRO 1996, DEPRO 1997 and SUMA 1998 cruises, which used a pole trawl with 20 mm in the codend and trawling time ranging from 5 to 30 min. After trawling, the debris was classified in different categories (plastics; plastic bottles; glass, metal, leather, cloth or rubber objects; fishing gear; and diverse forms). The data are shown in debris density (number per hectare, pd/ha) and presented in areal distribution maps.

Measurements relating to the diversity of the debris were determined for the North Sea, the Bay of Biscaye and the Gulf of Lion from the Shannon index (1948):

$$\text{Div} = 1/\log 2 \sum (D_i/D_{\text{tot}}) \times \log(D_i/D_{\text{tot}}),$$

where Div is the index of diversity for a station, D_i the density of a category of debris at a station (with $D_i > 0$), and D_{tot} the total quantity of debris at a station. Seven categories of debris were used to quantify the waste, except for the North Sea cruise (IBTS) in which an additional category was included for worked wood. The value of the diversity index allows the samples from a given station to be characterized. The mapping (notably the Kriging) of the values of this index allows areas of low or high diversity to be localized.

Observations and estimations of densities at depth were performed during the CYATOX, CYLICE and OBSERVHAL cruises with the IFREMER submersibles Cyana and Nautille. The bathymetric maps are based on multibeam data from the R/V Atalante. The results are shown in pieces of debris per km (pd/km) of

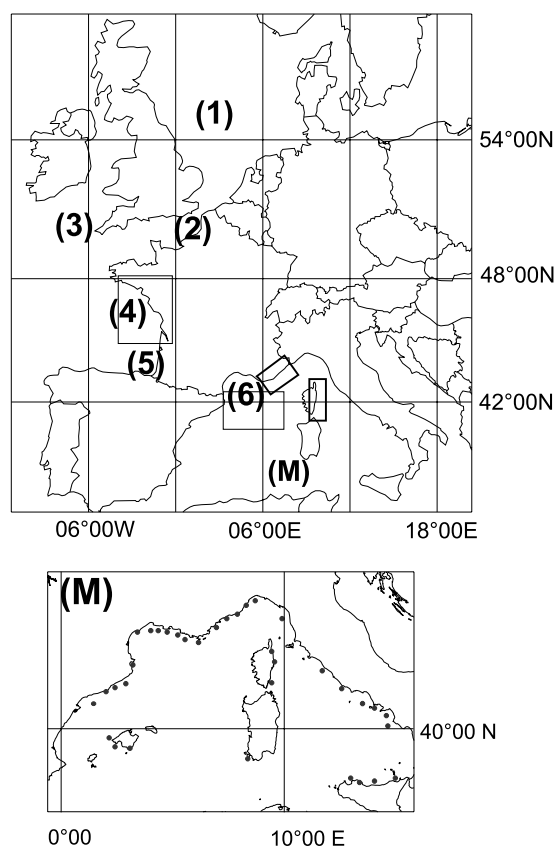


Fig. 1 Location of sampling for trawling experiments. Kriging was performed on data from cruises IBTS (1), CGFS (2), EVHOE98 (3), EVHOE94 (4), Adour (5) and MEDITS (6) as described in Materials and methods. Sampling points are described directly in corresponding figures from Results. Squares (□) show sampled areas without kriged data. The map (M) represents sampling sites for the cruise in the north-western basin of the Mediterranean Sea (cruise METROMED).

observation because of technical reasons for evaluating surfaces with a submarine. The distance covered per dive ranged from 730 to 6500 m.

The contouring of the data was performed by Kriging with SURFER VI software using 46×50 (IBTS, North Sea), 50×35 (Adour98, Basque country), 50×33 (Medits, Gulf of Lion), 50×45 (Channel west, CGFS), 50×70 (EVHOE94, Bay of Biscaye), 40×50 (RESS-GASC, Bay of Biscaye) and 50×17 (EVHOE98, Celtic Sea) grids.

Results

Density of debris

Overall debris density ranged from 0 to 1010 pd/ha (the latter occurring during the SUMA 1998 cruise at position 4342.84N/722.98E). Mean densities are shown in Table 2. The values ranged from 0.072 ± 0.058 pd/ha in Seine Bay to 19.35 ± 6.33 for the north-western basin of the Mediterranean Sea. On some local areas, densities in the Mediterranean produced lower mean values, ranging from 1.43 pd/ha (Gulf of Lion) to 3.78 (Adriatic Sea). The lowest mean values were found in

TABLE 1
Sampling dates, location and type of sampling for the collection of data on litters.

Cruise	Date	Location	Type of sampling (opening, mesh in the codend)	Number of samples (tows or dives)
RESSGASC	Nov 1992–May 1998 (2–4 cruises/year)	North Biscaye	Trawling (14 m, 20 mm)	18–35/cruise
CGFS	Oct 1998	Eastern Channel	Trawling (10 m, 20 mm)	83
IBTS98	Feb 1998	Southern North Sea	Trawling (16 m, 20 mm)	80
ALKOR96	Sep 1996	West Baltic Sea	Trawling (10 m, 20 mm)	5
ADOUR98	Sep 1998	Basque country	Trawling (14 m, 20 mm)	32
EVHOE94	Oct 1994	Biscaye	Trawling (16 m, 20 mm)	73
EVHOE98	Oct 1998	Celtic Sea	Trawling (16 m, 20 mm)	50
SUBIO	Mar 1993	Bay of Seine	Trawling (14 m, 20 mm)	8
MEDITS	Jun 1994–Jun 1997 (1 cruise/year)	Gulf of Lion	trawling (16 m, 10 mm)	70/cruise
METROMED	Apr 1994	NW Mediterranean	Trawling (10 m, 20 mm)	35
BIOMAR	Mar 1998	Adriatic Sea	Trawling (10 m, 20 mm)	11
DEPRO96	Aug 1996	Gulf of Lion (SW)	Pole trawling (6.2 m, 10 mm)	15
DEPRO97	Aug 1997	Gulf of Lion (SE)	Pole trawling (4.4 m, 10 mm)	9
SUMA	Jul 1998	France(SE)/ Ligurian Sea	Pole trawling (4.4 m, 10 mm)	20
CYATOX	Dec 1995	Marseille, Nice	Dives (CYANA)	16
OBSERVHAL96	Jun 1996	Biscaye & Celtic Sea	Dives (CYANA)	10
CYLICE	Jun 1997	NW Mediterranean	Dives (CYANA)	28
OBSERVHAL98	May 1998	Biscaye	Dives (NAUTILE)	6

TABLE 2
Mean concentrations (items per hectare) of total debris and plastics in different locations around the European coasts.^a

Area	Area sampled per run	Total debris/ha	Plastics/ha
BALTIC SEA	22 224	1.26 (0.82)	0.45 (0.29)
NORTH SEA	59 264	1.56 (0.368)	0.754 (0.183)
CHANNEL EAST	155 000	0.176 (0.067)	0.149 (0.062)
BAY OF SEINE	155 000	0.72 (0.058)	0.064 (0.051)
CELTIC SEA	59 264	5.28 (2.47)	1.56 (0.54)
BAY OF BISCAYE	155 000	1.42 (0.25)	1.128 (0.0233)
GULF OF LION	44 448	1.43 (0.19)	0.92 (0.122)
NW MEDITERRANEAN	27 800	19.35 (6.33)	N.C
EAST-CORSICA	44 448	2.29 (0.72)	1.05 (0.36)
ADRIATIC SEA	27 800	3.78 (2.51)	2.63 (1.08)

^a (): Standard Deviation.

Seine Bay (0.072 pd/ha) and, at a larger scale, in the channel (0.176 pd/ha). The mean value for debris from the Celtic shelf was 5.28 ± 2.27 pd/ha (Table 2). However, percentage of plastic was found to be very low (29.5%).

Distribution of debris

The mapping of results revealed areas of higher concentration of debris and showed the influence of hydrodynamic and geomorphologic factors on their distribution.

Atlantic Seas. For the North Sea, two high-concentration zones were detected (Fig. 2). The larger one was located 200 km west of Denmark (centred on 55°50'N–05°20'E), with densities above 6 pd/ha. This zone extended over an area north–south and east–west greater than 120 miles. The smaller zone was detected in the western part of the North Sea (centred on 54°20'N–01°30'E).

In the channel (Fig. 3a), isoconcentrations curves permit to demonstrate, in spite of the generally weak densities and the order of 1 debris per hectare, an increase of debris densities not only near inshore rivers such as the Seine or the Somme in France and the Rother in United Kingdom but also in an area located in the north-east of the channel.

This type of sources can be completed by those from shipping. Indeed, the survey of the litters distribution on the Celtic shelf demonstrated a zone of concentration (49°00'N, 04°30'W) located in the south-east part of the shelf (Fig. 3b). Concentrations were found above 50 items per hectare and the percentage of debris from fishing can reach 100%.

Bay of Biscaye. Evaluation of density of litter was performed in the Bay of Biscaye during the EVHOE1994 cruise (Fig. 4a) covering the whole shelf of the bay. Density was shown to vary from 0 to more than 4 pd/ha with higher amounts in front of the Gironde and

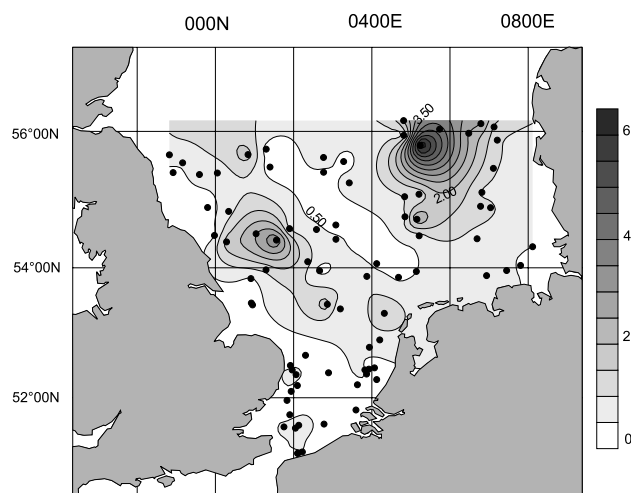


Fig. 2 Isoconcentration curves for total debris in the North Sea. Results were obtained after kriging data from the cruise IBTS98 (see Materials and Methods) and are expressed in items per hectare. (●): Sampling sites.

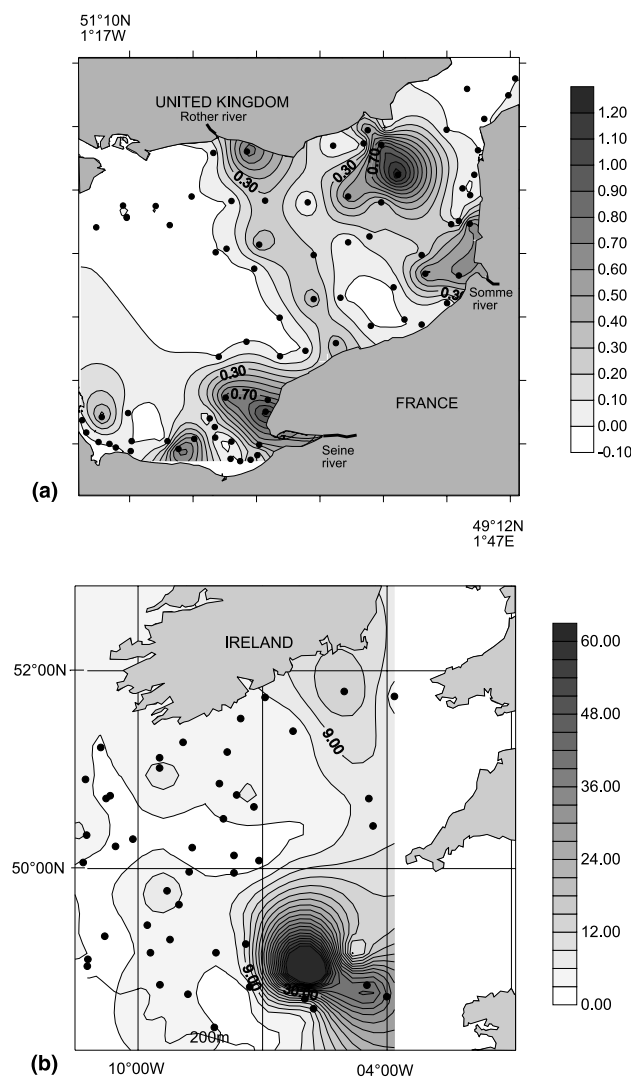


Fig. 3 Isoconcentration curves for total debris in the eastern part of the channel (a) and the continental shelf of the Celtic Sea (b). Results were obtained after kriging data from the cruise CGFS98 (a) and EVHOE98 (b) (see Materials and Methods) and are expressed in items per hectare. (●): Sampling sites.

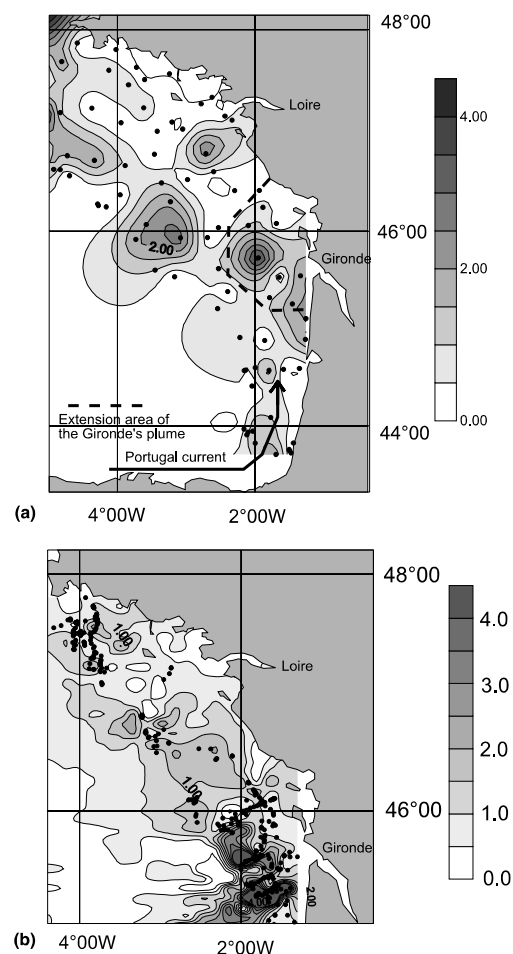


Fig. 4 Isoconcentration curves for total debris in Bay of Biscay. Results (items per hectare) were obtained after kriging data from the cruises EVHOE94 (74 sites sampled in September). (●): Sampling sites.

Loire estuaries. Additional data were obtained using a compilation of the results from the 15 ressgasc cruises (483 tows) performed during the four seasons in the Northern part of the Bay of Biscay (Fig. 4b) between November 1992 and May 1998. Density was shown to range from 0 to 16.645 pd/ha. Seven tows gave densities above 10 pd/ha, all of them located in front of the Gironde estuary.

Seasonal variations were found at the scale of the Bay of Biscay (Table 3). This situation was particularly apparent during the winter of 1993 when mean density for the whole shelf of the bay (complete data from Ressgasc cruises) reached concentrations of 4.94 ± 1.43 pd/ha. The correlation (Pearson's linear correlation coefficient) between densities for the entire sampling area and the mean monthly flow of the Gironde during the sampling periods was 0.66.

Average density of debris in the area offshore the Gironde estuary (data extracted from Ressgasc cruises between November 1992 and 1998 within latitudes $45^{\circ}02' - 46^{\circ}00'N$ and longitudes $02^{\circ}32' - 01^{\circ}20'W$) were also following seasonal changes (Table 4) with mean values ranging from 0.38 ± 0.14 pd/ha in this area during

TABLE 3

Mean quantities of plastics and total debris in the Bay of Biscaye according to seasonal variations.^a

Cruise	Stations (number)		North Biscaye	
	Total	With debris	Plastics	Total debris
Nov 1992	35	35	0.65 (0.17) ^b	0.8 (0.14)
Feb 1993	43	43	4.51 (1.43)	4.94 (1.43)
May 1993	38	35	1.95 (0.62)	2.17 (0.56)
Aug 1993	49	44	0.45 (0.09)	0.26 (0.1)
Nov 1993	35	31	0.82 (0.8)	1.16 (1.13)
Feb 1994	35	35	1.06 (0.79)	1.31 (0.91)
May 1994	39	39	0.56 (0.49)	0.76 (0.59)
Aug 1994	34	33	0.32 (0.24)	0.7 (0.39)
Nov 1994	32	31	0.85 (1.23)	1.06 (1.31)
Aug 1995	42	42	0.25 (0.17)	0.49 (0.25)
Nov 1995	44	44	0.5 (0.35)	0.85 (0.8)
May 1996	33	33	0.6 (0.344)	0.82 (0.41)
Dec 1996	30	30	0.56 (0.49)	0.85 (0.62)
Jan 1997	32	32	1.36 (1.06)	1.74 (0.99)
Aug 1997	42	41	0.22 (0.15)	0.28 (0.16)

^a Data were obtained from the Ressgasc cruises. The units are given in quantities of debris per hectare (mean \pm S.D.).

^b (): Standard Deviation.

summer 1997 to 9.33 ± 2.72 in March 1993 period confirming accumulation in that part of the bay. For this area, the correlations (Pearson's linear coefficients) between plastics, debris from fishing and total debris with the flow rate of the Gironde were respectively 0.33, 0.09 and 0.34 ($n = 15$) indicating the poor contribution of the river to the presence of debris from fishing in this part of the bay.

The Basque country. On a more local scale, the map for debris distribution around the Adour estuary showed a gradient related to estuarial inputs. The observations, performed at the end of August during a

period of calm, allowed localization of the area influenced by the river (Fig. 6). The maximal densities measured were greater than 50 pd/ha in the area around the estuary, which were the highest densities found in the Bay of Biscay.

Mediterranean coasts. The distribution of debris in the Gulf of Lion has been similar in recent years with accumulation in the same areas (Fig. 5). The results show low concentrations of debris on the continental shelf and larger amounts in the eastern canyons and, in a lower extent, in western canyons of the gulf (centered on $43^{\circ}00'N$ – $05^{\circ}00'E$ and $42^{\circ}37'N$ – $03^{\circ}37'E$). The amounts were lower in the central part of the gulf down to great depths.

Typological Analysis

Typological analysis of the debris found on the continental shelves from the Bay of Biscaye and the Gulf of Lion showed a high percentage of plastics which ranged from 50% to 95% depending on the zone and mean values of $62.2 \pm 2.3\%$ and $70.5 \pm 5.4\%$, respectively. In the case of debris in the form of fishing gear, the percentage was variable, with a maximum of 40% (Fig. 8a) and mean values of $5.7 \pm 1.0\%$ and $2.7 \pm 1.5\%$ for the Bay of Biscaye and the Gulf of Lion. In the case of the Celtic shelf, this value is high on average and at the scale of the area (50 tows performed), 65% of debris were from fishing (3.84 ± 0.73 pd/ha). In general, the mapping showed a good correlation between accumulation zones of fishing debris and overall debris (Figs. 2 and 7a and Figs. 3b, 7b). The distribution of a particular type, expressed as a percentage of overall debris using a compilation of data collected between 1992 and 1998 during the Ressgasc cruises for the Bay of Biscaye and between 1994 and 1997 during the Medits cruises in the

TABLE 4

Mean quantities of total debris offshore the Gironde Estuary according to seasonal variations.^a

Date	Stations (number)	Plastics ^b	Debris from fishing ^b	Total debris ^b	Flow rate ^c
Nov 92	22	2.03 (0.89)	ND	2.24 (0.96)	816
Mar 93	18	8.73 (2.57)	ND	9.33 (2.72)	1358
May 93	14	0.54 (0.27)	0.04 (0.03)	0.69 (0.32)	1194
Aug 93	22	0.37 (0.119)	0.06 (0.03)	0.56 (0.16)	332
Nov 93	12	1.77 (0.73)	0.01 (0.01)	2.22 (0.84)	816
Feb 94	15	1.40 (0.56)	0.06 (0.04)	1.66 (0.64)	1636
May 94	19	0.68 (0.32)	0.023 (0.01)	0.88 (0.39)	1194
Aug 94	11	0.48 (0.217)	0.076 (0.05)	0.74 (0.26)	332
Nov 94	12	1.77 (1.06)	0.042 (0.05)	2.05 (1.1)	816
Aug 95	18	0.27 (0.09)	0.007 (0.01)	0.49 (0.15)	332
May 96	14	0.42 (0.22)	0.08 (0.02)	0.60 (0.27)	1194
Dec 96	15	0.76 (0.35)	0.08 (0.02)	1.10 (0.45)	1356
Jan 97	13	1.81 (0.79)	0.01 (0.01)	2.14 (0.82)	1467
Aug 97	15	0.21 (0.09)	0.005 (0.01)	0.38 (0.14)	332
May 98	15	ND ^d	ND ^d	0.85 (0.31)	1194

^a Data within latitudes $45^{\circ}02'$ – $46^{\circ}10'N$ and longitudes $02^{\circ}32'$ – $01^{\circ}20'W$ were obtained from the Ressgasc cruises between 1992 and 1998. The units are given in quantities of debris per hectare (mean \pm S.D.).

^b Items per hectare (standard deviation).

^c Average monthly flow rate calculated for the last 30 years (m^3 per second).

^d Not determined.

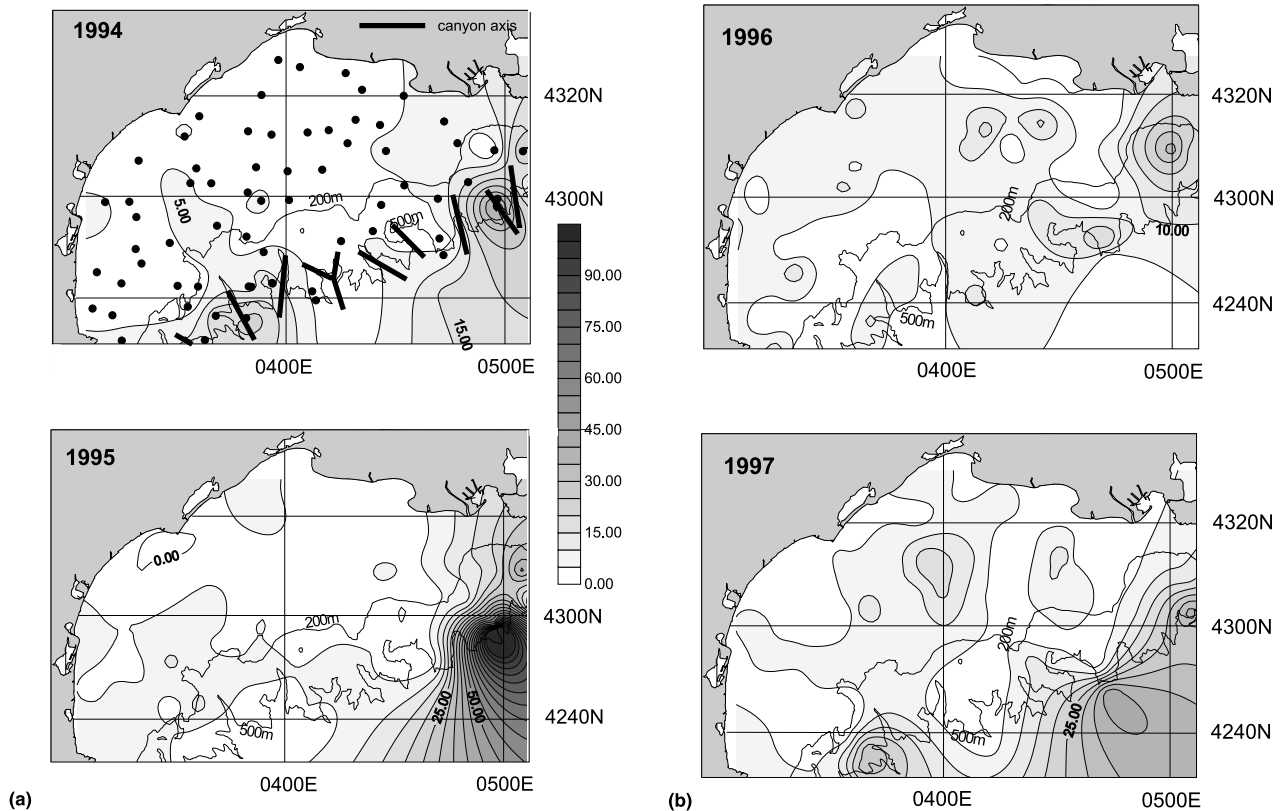


Fig. 5 Isoconcentration curves for total debris in the Gulf of Lion. Results were obtained after kriging data from the cruises Medits between June 1994 and June 1997 as described in Materials and Methods. Units are items per hectare. Sampling sites (●) are indicated on map 1994.

Gulf of Lion (Fig. 8), confirmed the importance of plastics but also indicated areas in which fishing gear was a common form, namely the South Brittany zone for the Atlantic Ocean and the zone defined by $42^{\circ}37'N$ – $03^{\circ}37'E$ as well as four coastal zones for the Mediterranean Sea.

Kriging of Shannon index values for each station enabled us to localize areas of great diversity corresponding to various sources of debris (Fig. 9) as well as areas with low diversity indicative of a limited number of sources. This method needs however homogenous data. Since the importance of debris from fishing was very high in the south of the Celtic Sea and since the density of debris was very low in the channel, the calculation of this index was not performed in these areas. Results for areas in the North Sea, the northern part of the Bay of Biscay, and the Gulf of Lion revealed zones in which the diversity index was high. These zones corresponded to the main points of debris concentration in the North Sea (Fig. 2) and the Gulf of Lion (Fig. 5). Considerable debris was found in the North Sea zone centred on $54^{\circ}20'N$ – $01^{\circ}30'W$, whereas the diversity index was low. For the Bay of Biscay, the greater diversity was found in the zone centred on $47^{\circ}30'N$ – 03° .

Deep Sea experiments

The use of a pole trawl allowed us to enumerate debris at considerable depths. During three cruises in the southern Gulf of Lion and the south-eastern Mediterranean coast, debris densities ranged from 0 pd/ha (south of Toulon) to 1010 in the south-eastern coast (NE zone) (Fig. 10). The greatest densities were found at 50 to 100 m of depth in the north-eastern Mediterranean off the French coast as well as in Cannes Bay (80 km from the French–Italian border, 274 pd/ha at 700 m) or the submarine Rhone extension (520 pd/ha at 2200 m).

Analysis of 70 dives performed with the submersibles Nautile and Cyana in the north-western Mediterranean basin and in the Bay of Biscay revealed high concentrations of debris around urban areas as well as at great depths. Results are given in Fig. 11. For the Mediterranean, the highest values were found around Nice and Marseille [maximal densities of 104 pieces of debris per kilometer (pd/km)], but also at depths of more than 1000 m where densities close to 92 pd/km were recorded ($43^{\circ}45'N$ – $08^{\circ}43.5'E$, 1400–1300 m). At the deepest point sampled (2700 m), corresponding to the submarine off-shore extension of the Var, a coastal river emptying into Nice Bay, the density was 9.1 pd/km.

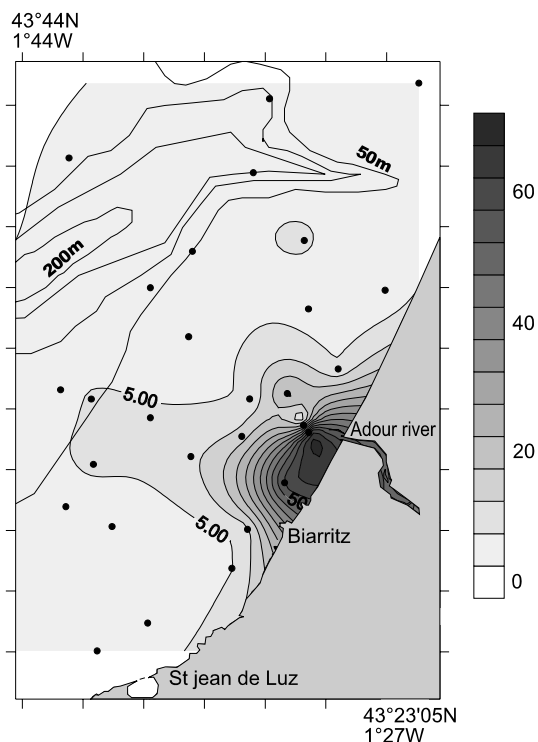


Fig. 6 Isoconcentration curves for total debris in the Basque country. Results were obtained after kriging data from the cruise Adour98 (see Materials and Methods) and are expressed in items per hectare. (●): Sampling sites.

For the Bay of Biscay, maximal densities were found in the two main canyons from the southern part of the Bay of Biscaye of Cape Breton ($43^{\circ}40'N$ – $02^{\circ}20'W$, 1850–1450 m, 22 pd/km) and Cape Ferret ($44^{\circ}44'N$ – $02^{\circ}08'W$, 1450–850 m, 16.53 pd/km) together with the area Meriadzec (South Celtic Sea, $47^{\circ}33'N$ – $07^{\circ}33'W$, 2400–2200 m, 14.86 pd/km). All dives conducted on the continental shelf showed densities of less than 10 pd/km.

Discussion

This study reports data on the quantity and distribution of debris on the continental shelf and the bathyal plain along European coasts. These studies were essentially selective and in many cases do not provide definitive conclusions concerning geographical variations and the amounts of debris actually present. In fact, some areas with high debris concentrations were not sampled (Cannizarro *et al.*, 1995). Moreover, the use of nets with otter boards in many operations gave satisfactory results in terms of sampling, but, because they are crafted for collecting nectobenthic rather benthic species, they probably underestimated the quantities present. In the context of our study, the comparison of stations and the mapping of debris remain coherent in terms of distribution, and the overall results are informative on a number of points.

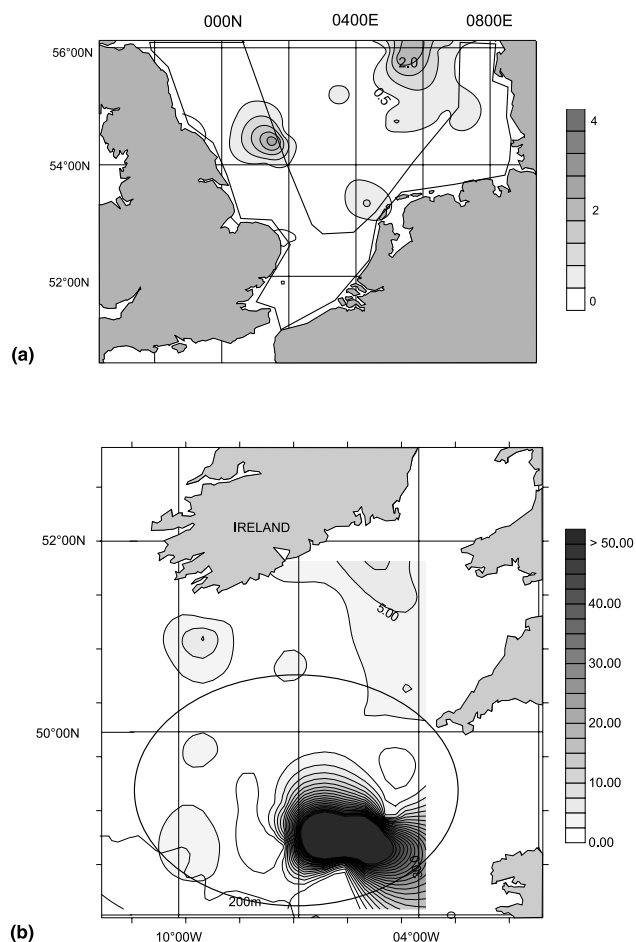


Fig. 7 Isoconcentration curves for debris from fishing in the North Sea (a) and the Celtic Sea (b). Results were obtained after kriging data from the cruise IBTS98 (a) and EVHOE (b) (see Materials and Methods) and are expressed in items per hectare. Circled areas indicates the localization of developed fishing activities.

First of all, densities were quite variable between zones and even within the same zone. Along European coasts, the greatest densities were found in the Mediterranean, which gave values comparable to those reported for the Sicily Channel (4.01 pd/ha according to Cannizarro, 1995). The high densities found during the METROMED cruise (more than 19 pd/ha) were related to frequent sampling operations near large metropolitan areas. The overall densities (1.4–3.78 pd/ha) were concordant with the quantities of floating debris (4.98 pd/ha) determined for this zone (data not shown; Morris, 1980) and the Sicily Channel.

Some accumulation zones in the Atlantic Seas and the Mediterranean Sea showed very high debris densities. Along the coast, these densities could exceed 1000 pd/ha at some points, particularly near large cities (e.g. in the south-east French Mediterranean coast) as well as in offshore canyons (e.g. Cape Breton in the southern Bay of Biscay). These densities are in no case representative of special accumulation zones such as those around

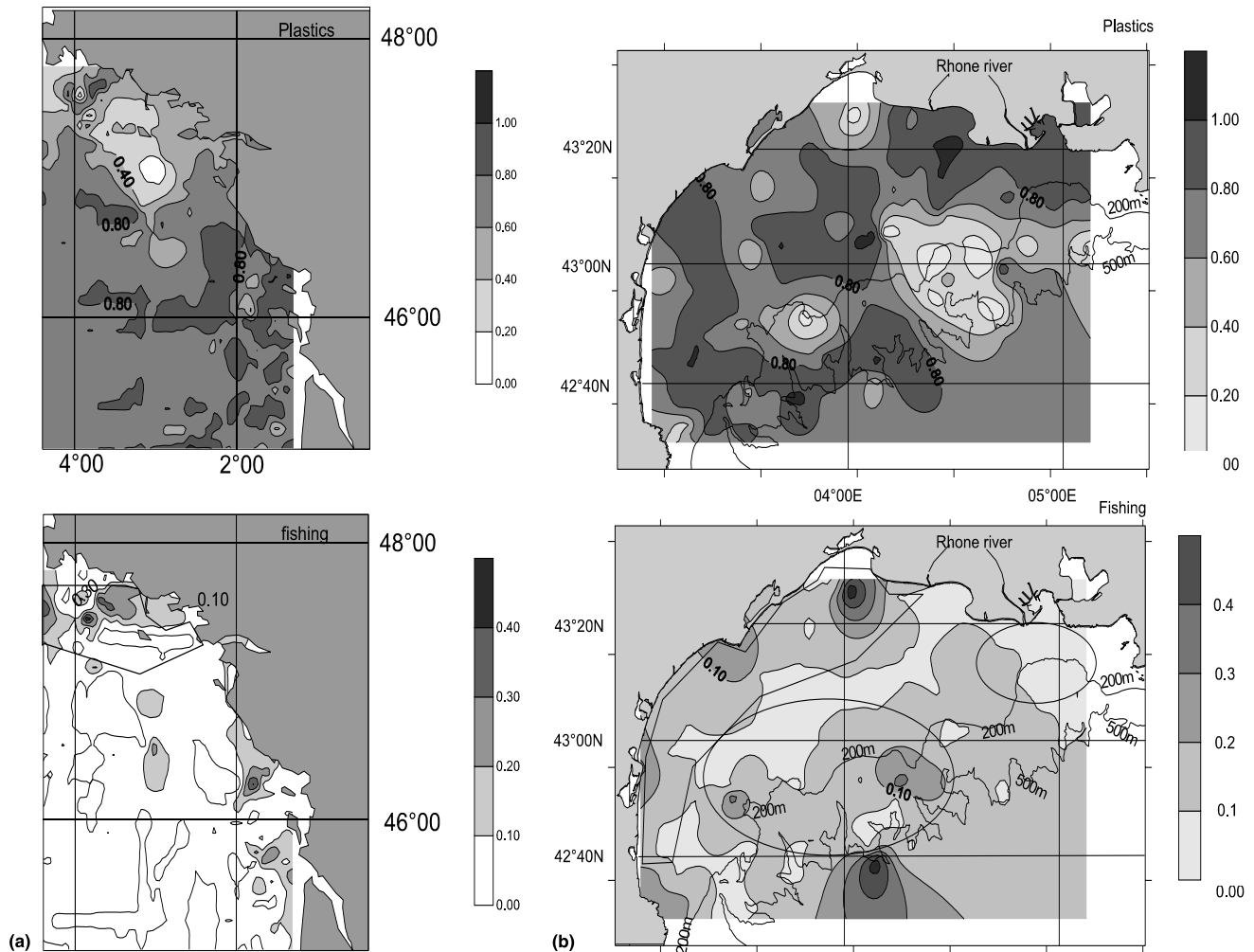


Fig. 8 Distribution of percentages for plastic items (a) and fishing gears (b) in relation to total debris in the Bay of Biscaye and Gulf of Lion. Results were obtained after kriging the percentage values for each station from the cruises RESS-GASC92-98 and MEDITS 94-97 (see Materials and Methods). Sampling strategy was the same for each cruise in a given area, some tows being invalid for technical reasons. Circled areas indicates the localization of developed fishing activities.

rocks and wrecks or in depressions or channels (Galvani *et al.*, 1996), but relate to normal situations on flat bottoms where trawling can be conducted. This situation is due to massive inputs of waste trapped in zones with high sedimentation rates, which is the case for the Adour River whose low residual flow rate does not allow debris to be transported out into the open sea. Conversely, other areas near the coast showed very low densities.

Accumulation zones in the open sea can be found far from waste sources (e.g. off the Gironde Estuary) or even very far out to sea (200 miles from the coast of Denmark) and maybe a result of the influence of hydrodynamics. For this situation, the influence of rivers seems to be slight in comparison with that of general water movements. In the North Sea, Delhez and Martin (1992) not only described an area of eddies in the centre

of the basin but also noted that high residual water movements probably producing considerable south-north transport within the eastern part of the basin, which could be responsible for the transportation of debris from west Denmark to the northern area. The spread of this zone toward the north will have to be studied since fine sediments accumulate in this zone (Tappin *et al.*, 1997) and the transport of cesium-137 from La Hague (France) and the northern English coasts follows this course of water movements in the North Sea at certain periods of the year (Breton and Salomon, 1995; Maff, 1991).

Sedimentologic factors also need to be taken into account. A good example is also given with the accumulation of debris in the northern part of the channel (Fig. 3a) that corresponds not only to the zone of very low turbulence as described previously (Jegou and

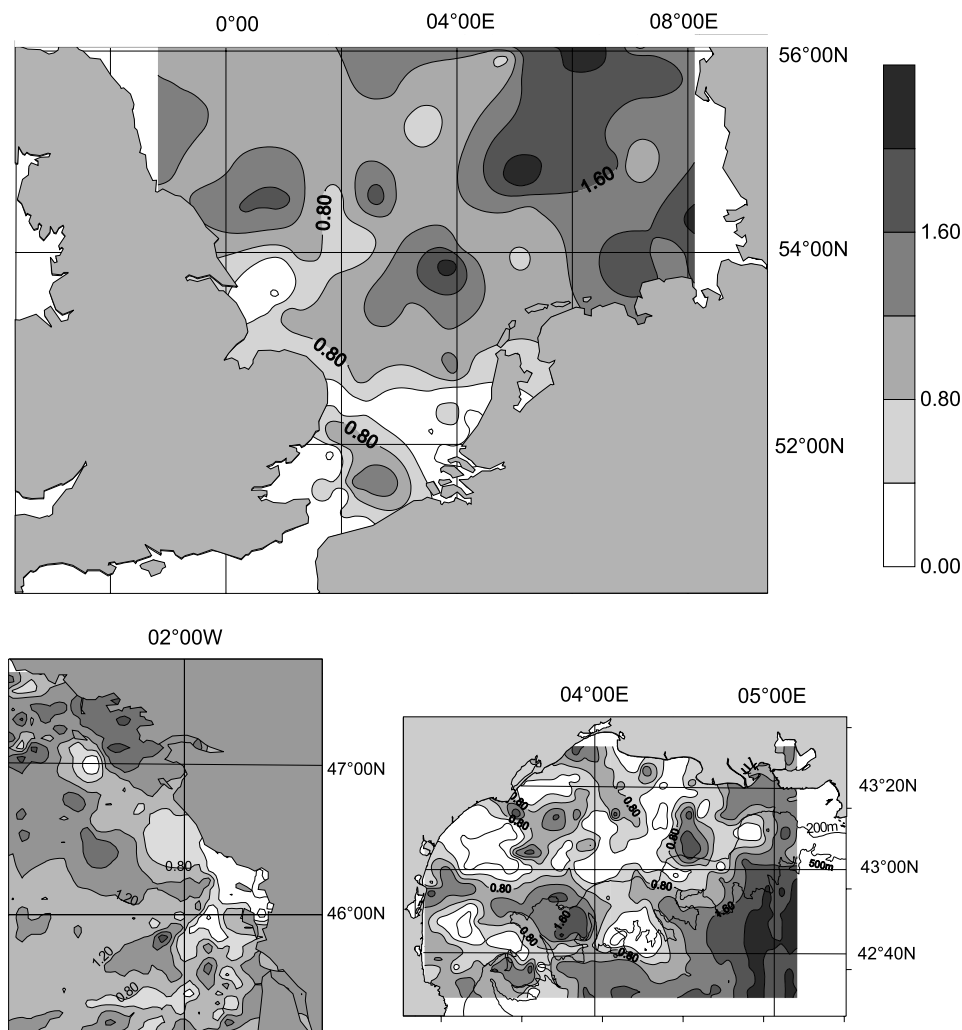


Fig. 9 Isoconcentration curves for the diversity index (Shannon index) of debris. Results were obtained after kriging the Shannon index for each station from the cruises IBTS98, RESSGASC92-98 and MEDITS 94-97 (see Materials and Methods).

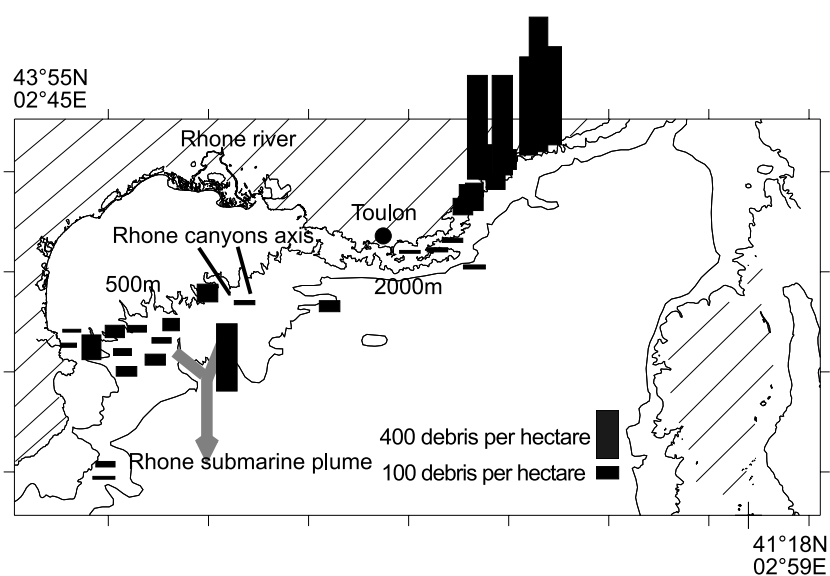


Fig. 10 Total debris collected from Pole trawling experiments along the south east part of France and in deep canyons of the French Mediterranean coast.

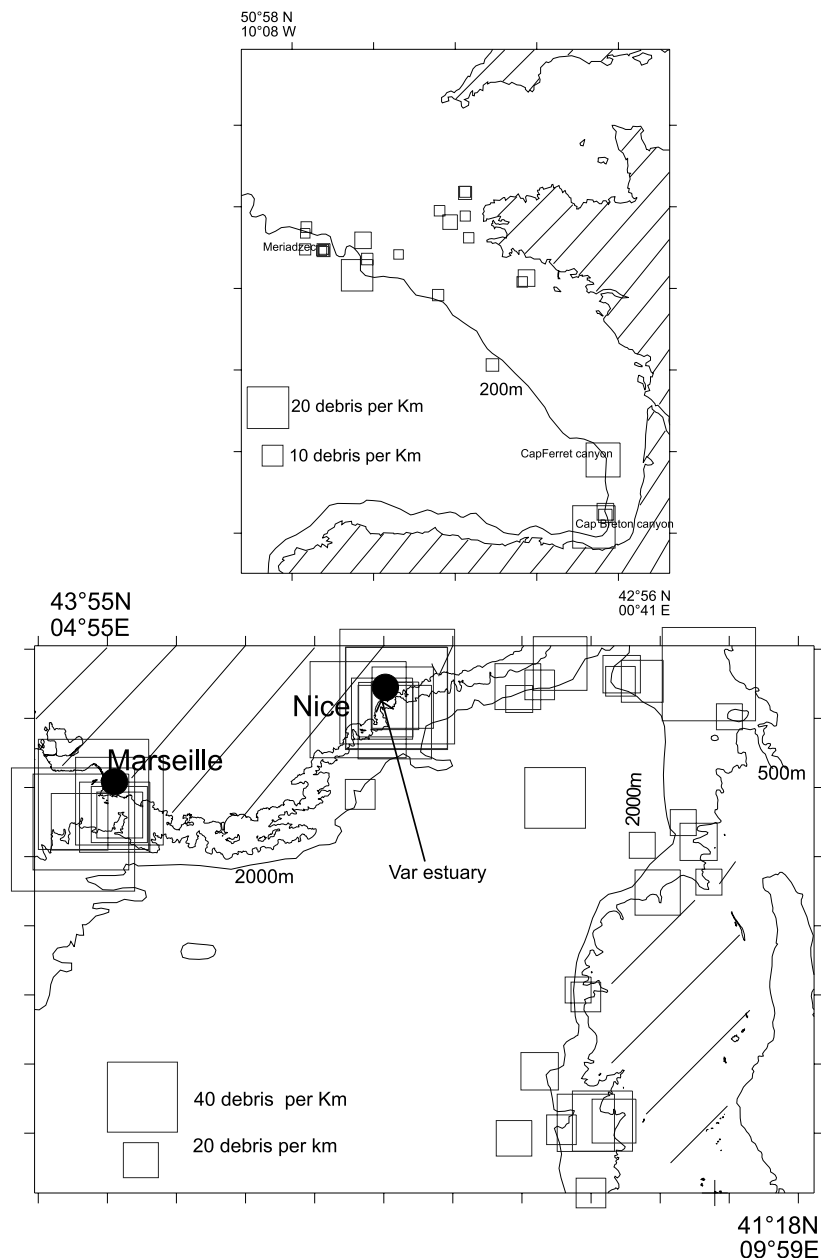


Fig. 11 Debris observed (debris per km dive) during dives performed with the manned submersibles Cyana and Nautille (see Materials and Methods) in the Bay of Biscaye and the north-western Mediterranean Sea. Note the different scales between the two areas.

Salomon, 1991) but also to the convergence zone of seabed sediment movements (Open university, 1993). The areas where circulation is low such as the western part of the channel where begins the Celtic shelf must also be considered (Salomon and Breton, 1991). Debris is accumulating at this site, where also begins the shipping routes for the channel.

The seasonal variations of these contributing factors are affecting the seasonal distribution of debris, particularly in the West Gironde area where debris accumulated in winter, whereas inter-annual variations of the geographical distribution in the Gulf of Lion

were very slight, showing a close similarity of debris between 1994 and 1997. The different factors involved in the distribution of debris also need to be considered. In particular, hydrodynamic factors play an important role in the case of large rivers. The accumulation off the Gironde estuary is related to the high flow rate of this river, although it is difficult to distinguish between waste input from the river or debris transported onto the continental shelf by the plume of the river and general north-south water movements in the winter related to the Portugal current (Frouin *et al.*, 1990).

In general, large rivers appear to be responsible for inputs at sites around estuaries (Williams and Simon, 1997). However, they also transport waste out to sea because of their high flow rate and the presence of bottom currents. In that case, debris transportation should be relevant to that of the river sediment's load, as in the case of the nontidal Rhone river which deposits only small amounts of debris immediately along the coast. With smaller coastal rivers, such as the Adour, the displacement is slight, and waste can be found in zones adjacent to estuaries. Moreover, the deep submarine extensions of coastal rivers are also a contributing factor. In the case of the nontidal Rhone, the greatest densities were found 100 km south of the gulf, corresponding to the deep bed of this river (D'heilly *et al.*, 1988; Bellaiche *et al.*, 1980) in which local water movements can transport waste from the estuary and accumulate it in zones of high sedimentation. In these conditions, the distal deltas of rivers can fan out in deeper waters (Piper and Savoye, 1993), creating an area of high accumulation.

The accumulation of debris in coastal canyons of the Bay of Biscay or Mediterranean Sea may be related to strong currents occurring in the upper part of the canyons with decreased water movements, deeper areas resulting from the confinement of the sites. Accordingly, the mapping of debris distribution shows a more stable situation over time. Moreover, an inevitable effect of this type of situation is the presence of greater amounts of waste in deeper waters than in coastal waters. With the exception of the south-eastern Mediterranean in which anthropic inputs are considerable, the greatest densities occur in coastal canyons or in submarine extensions of river's plumes. For the Gulf of Lion, waste is transported onto the continental shelf by three currents: The Rhone River plume (north-south), coastal upwelling currents (north-west and north to the south, Millot and Wald, 1980; Millot, 1987; Millot *et al.*, 1994) and the general water movements created by the Ligurian current (east-west in the gulf then to the south in the western part of the gulf). The displacement occurs in a north-south direction, and accumulation is observed in the canyons of the gulf, except in the central part where the Rhone River plume induces transport toward the south. This was confirmed by the low percentage of plastics in the central and southern part of the continental shelf where most of the debris consisted of heavy objects such as glass or metal.

In these conditions, typological analysis revealed the effect of certain factors. In all cases, human factors were quite influential. The best example concerns fishing gear debris, even though this category is not necessarily preponderant (Kanehiro *et al.*, 1996). In our study, this type of debris was found in zones of high fishing activity, particularly in the north and south-west of the Gulf of Lion and in the South Brittany region. It can also be subject to displacement by currents, as in the North Sea

where the spatial distribution of activities related to fishing (ICES, 1994) does not correspond exclusively to areas of waste accumulation (Fig. 7a). Activities related to tourism and the presence of large metropolitan areas are also influential factors for the abundance and distribution of waste.

Conclusions

The study of the abundance and distribution of debris of anthropic origin on the continental shelves and slopes was performed for certain European coastal areas. To our knowledge, this is the first study on a large scale of the distribution of debris in the oceanic environment. The results indicate that large quantitative variations occur and that geographical distribution could be affected by hydrodynamics, geomorphology and human factors. Moreover, notable seasonal variations exist in some zones such as the Bay of Biscay and in areas of accumulation and concentration along the coast and in the open sea as well as in the depths. The data presented here should contribute to the elucidation of the mechanisms regulating the transport of solid waste and the evaluation of the complex problems involved in the functioning of marine ecosystems.

The authors are grateful to all participants in cruises for their assistance in collecting data and to James Gray for translation.

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