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Floating debris in the Ligurian Sea, north-western Mediterranean

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Abstract

Results from visual sightings of large floating debris are presented, taken in the Ligurian Sea, a sub-basin of the north-western Mediterranean Sea which belongs to the recently stated "Cetacean Sanctuary". Data have been collected during three oceanographic cruises, during the summer of 1997 and 2000. Results for the 1997 data suggest a debris density of the order of 15–25 objects km^{-2}, while for the 2000 data, a lower density of the order of 3–1.5 objects km^{-2} is found. The difference between the two results appears statistically significant using simple tests. Possible reasons for the observed variability are discussed, including meteorological forcing, marine currents and debris input variability.

Keywords: Marine debris; Plastic; Pollution; Mediterranean sea; Monitoring; Meteorological forcing

1. Introduction

Since coastal population has risen and society has turned from degradable natural materials to synthetic ones, the problem of non-degradable waste in the ocean has gotten worse. At the beginning, it has been ignored for a long time, e.g. Fergusson (1974) stated that plastic "causes no harm to the environment except for eyesore", but more recently the threat of marine debris has been proposed as one of the major problems in the marine environment (Prouter, 1987; Stefatos et al., 1999).

Besides looking ugly, floating debris is a problem for a number of reasons (Laist, 1987; Derrail, 2002): debris can snare boat propellers or clog cooling water intakes, causing substantial damage to boat motors; pieces of glass and metal can cut beachgoers and wildlife; sewage and medical wastes can contaminate beach waters and sicken swimmers; marine animals can become caught in discarded fishing nets and lines, grocery bags, six-pack rings, ribbons, and other floating debris even at remote sites (Hucke-Gaete et al., 1997); some animals mistakenly eat the man-made materials (Tomás et al., 2002). Endangered sea turtles (Gramentz, 1988) consume floating trash bags and balloons, likely mistaking them for jellyfish. Several seabird species have been found to swallow plastic pieces and cigarette butts (Ryan, 1988) and these materials can damage the animal's digestive systems. In addition, animals may stop eating because their stomachs feel full and starve to death. Tourists may not visit shore areas that have debris on the beaches and in the water, causing economic hardship. The threat to the marine environment caused by plastic also include less evident and less obvious debris as plastic "scrubbers" or small pellets (Derrail, 2002). The transport of alien species which may affect biodiversity is enhanced by floating objects (Barnes, 2002; Aliani and Molcard, 2003).

The most important legislation addressing the problem of marine pollution is probably the 1978 Protocol to the International Convention for the Prevention of Pollution from ships (MARPOL). Annex V of MARPOL is the key international authority for controlling sources of marine debris and it refers to some "special areas" including, among others, the Mediterranean Sea (Lentz, 1987).

Literature on the problem of marine litter in the Mediterranean ranges from studies about beach litter (Gabrielides et al., 1991; Golik and Gertner, 1992; Shiber, 1982) to studies on the accumulation of debris on the sea floor by fishing trawls and submarine dives

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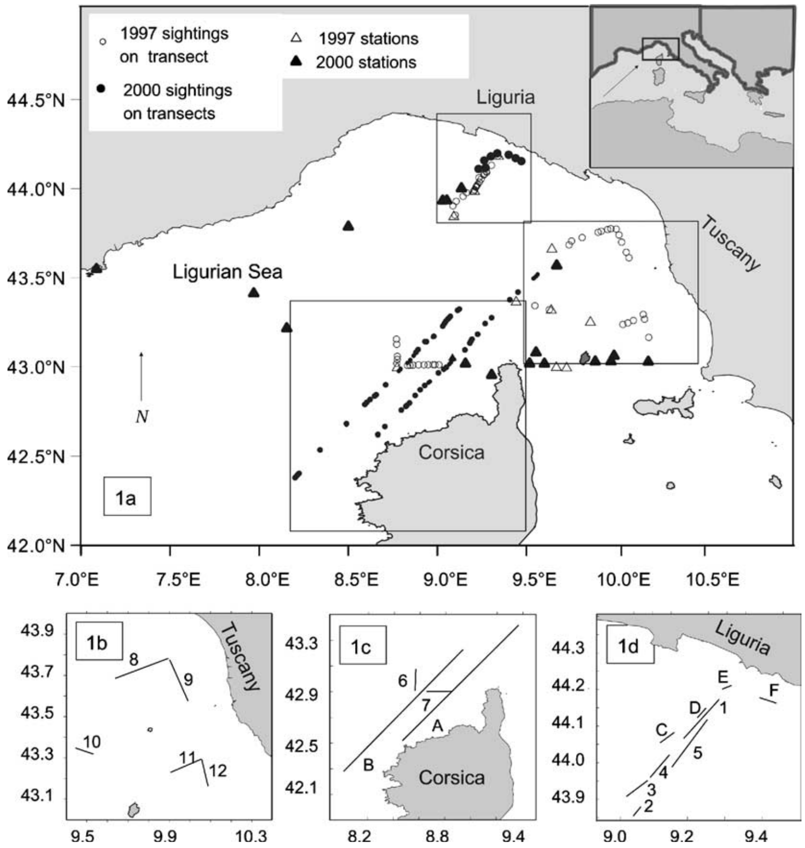

Fig. 1. (a) Map of the Ligurian Sea showing the locations of debris sightings during transects and the locations of the fixed stations for the 1997 and 2000 cruises. Sightings (stations) are indicated as dots (triangles), white for 1997 and filled for 2000. For 1997 only one dot per three sightings is shown, due to the high sighting density; (b)–(d) show the magnified regions framed in (a), indicating the transect structure. Numbers (letters) indicate 1997 (2000) transects.

(Galgani et al., 1995; Galgani et al., 2000). Floating debris received less attention. Some observations were made offshore during oceanographic cruises in the central and eastern Mediterranean (Morris, 1980; McCoy, 1988; Kornilios et al., 1998).

In this paper we report data from sightings of large debris floating offshore on the north-western Mediterranean sea. Observations were made in two years (1997 and 2000) during three oceanographic cruises. The main goal of this work is to extract statistical informations from the observations about spatial and temporal variability of the floating debris in the area of interest.

The study area is in the Ligurian Sea, within the recently stated ''Cetaceans Sanctuary'' where the number of cetaceans is at least twice as high as anywhere else in the Mediterranean (Ambrose, 1999). The Ligurian sea (Fig. 1) is situated to the north east border of the Western Mediterranean and is connected to the southern basin (Tyrrhenian Sea) across the Corsica Channel. The eastern and northern borders are the Tuscany and Liguria coasts and the western border is open toward the western basin (Provençal region and Gulf of Lions). The major large scale feature of the water dynamic of the Ligurian Sea is a cyclonic circulation active all year round, more intense in winter than in summer, which interests deep and surface layers. Climatic forcing can greatly change intensity of fluxes but the general pattern can be considered permanent (Astraldi and Gasparini, 1992). Southern waters filling the Ligurian sea occur in two main currents running along each side of Northern Corsica. The West Corsica Current (WCC) runs along the western side of Corsica while the warm and salty Tyrrhenian current (TC) goes trough the Corsica Channel (Artale et al., 1994). The two waters merge to the north of Corsica and they flow together along the Ligurian coast toward the Gulf of Lions (Astraldi et al., 1995).

2. Methods

Data were collected during three cruises: one cruise during the summer 1997 (10–16 July) aboard the R/V Urania, and two cruises during the summer of 2000 with the R/V Alliance (22–23 August) and the R/V Magnaghi (7–14 September), respectively. The 1997 cruise was part of a program focused on the study of plankton communities, while the two 2000 cruises were part of the

"Sirena" program (www.solmar.saclantc.nato.int/research) for the study of marine mammals and acoustic risk mitigation.

Visual surveys of large debris were conducted during the three cruises following the same procedure. Two types of observations were conducted during the cruises; along transects with the ship in motion, and at fixed stations with the ship at rest. In both cases, the survey was made by an observer standing on the top deck and recording the GPS position for each sighting. Information on sea state and light conditions were also recorded, and only data taken in good visibility condition have been retained and analyzed. It can be estimated that transects observations have an effective range of approximately 50 m at each side of the ship (Dufault and Whitehead, 1994), while observations at fixed stations cover approximately a 200 m radius away from the ship (McCoy, 1988). These estimates are only indicative, and they will be further discussed. During the 1997 cruise, debris at fixed stations was also brought on board for detailed identification and for analysis of benthic invertebrates living on it (Aliani and Molcard, 2003). Most of the observed and collected debris consisted of plastic bags and other plastic objects.

Sampling and sightings for the three cruises are shown in Fig. 1a. The circles indicate transect sightings, while the triangle indicate station positions. White and filled marks indicate 1997 and 2000 cruises respectively. The transect structure is shown in some details in the three magnified boxes, corresponding, respectively, to (i) the eastern area in front of the Tuscany coast (Fig. 1b), (ii) the western area close to Corsica (Fig. 1c) and (iii) the northern area close to the Ligurian coast (Fig. 1d) (numbers and letters indicate 1997 and 2000 transects, respectively).

As it can be seen, the sampling is inhomogeneous in space and it has a different coverage in the two years. On the other hand, both years show observations in all three boxes, suggesting a certain degree of compatibility between the two data sets despite the different sampling strategy.

3. Results

3.1. Transects

Specific information on each transect are given in Table 1. The length L_t and the number of sightings for each transect, n_t, are provided, as well as an estimate of the average distance between consecutive sightings (in the transect direction), $r_t = L_t/n_t$. As it can be seen from the length of the transects, for the 2000 data set most of the transect measurements have been conducted during the Alliance cruise (22–23 August), since transects C–F (Magnaghi) are very short. Furthermore, data collected during year 1997 have a better spatial coverage than the ones collected during 2000: data collected in 1997 are spread out over the whole domain, while for the 2000, transect data in the Ligurian region (Fig. 1d) are available from the Magnaghi only (7–14 September) and in the Corsica region (Fig. 1c) from the Alliance

Table 1
Transect charactersitics (see Fig. 1)

Transect	date	time (h)	Start long	Start lat	Stop long	Stop lat	L_t (km)	# sight.	r_t (km)
1997 Urania									
1	July 10	12:00–13:15	9.329	44.166	9.233	44.061	13.8	26	0.53
2	July 10	16:25–16:40	9.117	43.875	9.100	43.851	3.1	3	1.03
3	July 11	16:45–17:30	9.137	43.947	9.080	43.903	6.3	10	0.63
4	July 13	10:32–11:30	9.144	43.956	9.199	44.016	8.0	8	1.00
5	July 13	14:40–17:10	9.298	44.116	9.203	43.983	16.6	56	0.30
6	July 14	10:00–13:00	8.770	43.168	8.770	43.008	17.8	30	0.59
7	July 14	15:33–18:09	8.832	43.006	9.029	43.010	16.0	49	0.33
8	July 15	11:24–14:12	9.738	43.684	9.995	43.780	23.2	37	0.63
9	July 15	14:20–15:35	10.003	43.773	10.090	43.578	22.8	30	0.76
10	July 16	9:18–9:58	9.485	43.360	9.628	43.320	12.4	10	1.24
11	July 16	13:15–14:00	10.008	43.230	10.155	43.293	13.8	15	0.92
12	July 16	14:00–15:25	10.155	43.293	10.186	43.164	22.1	7	3.15
2000 Alliance									
A	Aug. 22	7:00–18:00	9.562	43.518	8.666	42.619	123.0	33	3.73
B	Aug. 23	6:46–18:00	8.203	42.379	9.123	43.325	129.0	41	3.15
2000 Magnaghi									
F	Sept. 11	14:45–15:00	9.484	44.157	9.439	44.172	4.0	8	0.49
E	Sept. 11	15:32–15:45	9.360	44.206	9.337	44.195	2.1	5	0.43
D	Sept. 11	16:08–16:23	9.292	44.142	9.272	44.119	3.0	2	1.50
C	Sept. 11	17:00–17:15	9.209	44.075	9.170	44.051	4.1	0	>4

L_t indicates the transect length, and r_t the average distance between consecutive sightings along the transect.

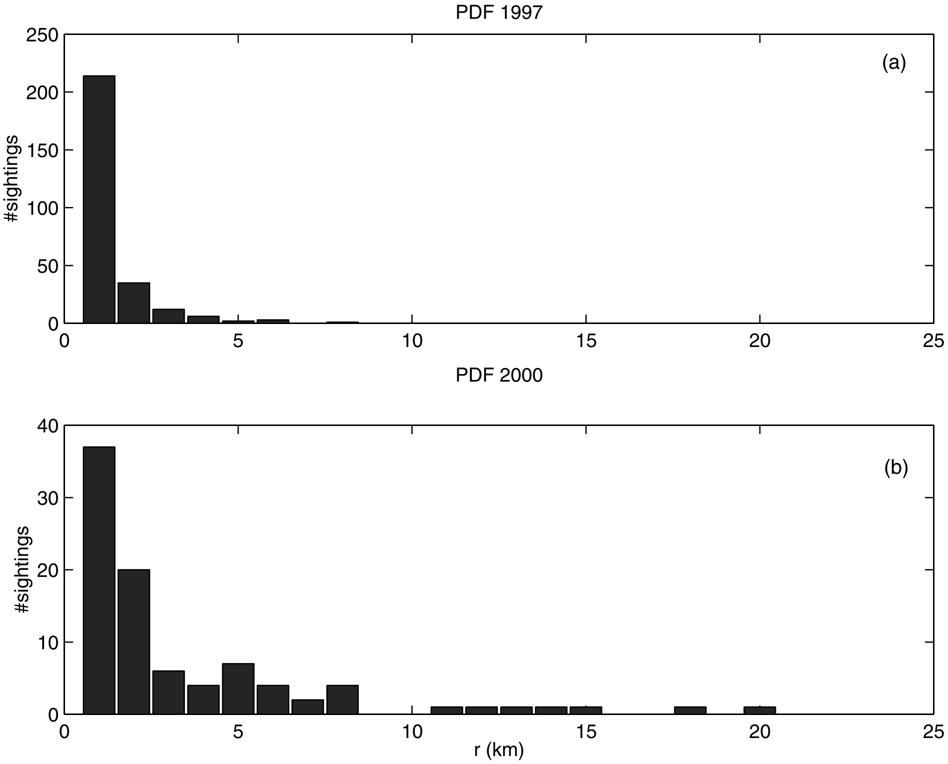

Fig. 2. Probability density function (pdf) of distance between consecutive sightings, *r*, divided in classes of 1 km: (a) 1997 data; (b) 2000 data.

only (22–23 August). In the Tuscany region (Fig. 1b), only station data (Magnaghi) are available in 2000.

Given the high variability in transect lengths, the average density values, r_t, cannot be quantitatively compared. Nevertheless, they provide a first, qualitative description of the variability in the sighting distribution. The r_t values in 1997 vary within a small range going from 0.3 to 1.2 km (excluding the "out-of-range" transect 12). The 2000 transects, instead, show higher values and higher variability, with r_t varying from 0.4 to 3.7 km.

In order to perform a more quantitative analysis, all the distances r_i of consecutive sightings have been computed from the recorded positions and they have been grouped in two data sets, corresponding to the 1997 and 2000 observations, respectively. For each data set, the average distance $\hat{r}$ and the standard deviation S.D. have been computed (Table 3),

$$\hat{r} = \sum r_i/N, \quad \text{S.D.} = \sum (r_i - \hat{r})/N \tag{1}$$

where $N + 1$ is the total number of sighting for each data set.

For 1997, $\hat{r} = 0.7$ km with S.D. $= 1.7$ km, while for 2000 the average is approximately four times larger, $\hat{r} = 2.9$ km with S.D. $= 3.9$ km. The difference between the two averages has been tested and it appears significant using a simple statistical test (Comincioli, 1992). It has been found that the null hypothesis that the two distributions have the same mean can be rejected at the 99% confidence level using the standardized variable $z = (\hat{r}_1 - \hat{r}_2)/\sqrt{(\sigma_1/N_1 + \sigma_2/N_2)}$, where the suffices 1,2 indicate the 1997 and 2000 variables, respectively, and σ is the standard deviation, approximated with the sampling S.D. (1). The obtained value of z is $z = 6.1$, while the critical value for the 99% confidence level is $z = 2.58$.

A further comparison between the two data sets has been performed considering the probability density function (pdf) of the r values. The pdf have been estimated considering the two complete data sets for 1997 and 2000 and using classes of 1 km values (Fig. 2). The distribution appears different in the two years, with the 1997 showing a much more pronounced peak for the first class, $0 < r < 1$ km. This is due to the presence of clusters in the debris distribution, which are much more common in 1997 than in 2000.

3.2. Stations

Information on the station positions and sightings are given in Table 2. For the 2000 data, all the station measurements were performed during the Magnaghi cruise (7–14 September). Also, during the 1997 cruise some stations were repeated more than once at different times, so that possible effects related to biases due to the time of measurement or to diurnal fluctuations can be evaluated. These effects do not appear relevant.

Table 2
Fixed station charactersitics

Date	Time	Latitude	Longitude	# sight.
1997 Urania				
09/07/97	8:30	43.001	9.725	5
09/07/97	17:20	43.004	9.667	5
10/07/97	10:40	44.191	9.341	2
10/07/97	13:40	43.992	9.209	5
10/07/97	16:30	43.851	9.092	4
11/07/97	13:15	44.191	9.341	2
11/07/97	9:30	43.992	9.209	2
11/07/97	15:30	43.991	9.210	2
12/07/97	8:30	43.859	9.093	5
12/07/97	12:00	43.860	9.095	2
13/07/97	12:30	44.191	9.341	5
14/07/97	14:00	43.002	8.774	2
15/07/97	9:40	43.668	9.643	2
16/07/97	8:20	43.371	9.442	2
16/07/97	10:20	43.325	9.639	2
16/07/97	12:10	43.258	9.859	2
2000 Magnaghi				
07/09/00	12:10	43.086	9.554	0
07/09/00	13:25	43.023	9.518	0
07/09/00	14:20	43.023	9.601	0
08/09/00	14:47	43.035	9.974	0
08/09/00	15:42	43.067	9.992	0
08/09/00	18:31	43.034	10.184	1
09/09/00	8:15	43.575	9.670	0
11/09/00	15:45	44.007	9.135	0
11/09/00	16:30	43.940	9.054	2
12/09/00	9:57	43.055	9.085	0
12/09/00	10:23	43.023	9.158	0
12/09/00	12:47	42.960	9.304	0
13/09/00	10:34	43.222	8.155	0
13/09/00	13:53	43.418	7.968	0
13/09/00	14:30	43.554	7.087	1
14/09/00	7:04	43.792	8.501	0

For 1997, the values of the number of sightings per station, n_s, vary between 2 and 5 over all the stations. In Table 3, the average and standard deviation computed over all the values are shown, $\hat{n}_s = 3.0$ and S.D. = 1.43. The 2000 records show lower values of sightings per station n_s, varying between 0 and 1, except for 1 station very close to the french coast on the western side of the domain. The average and standard deviation are $\hat{n}_s = 0.2$ and S.D. = 0.5. These values appear to be significantly different from the 1997 values on the basis of the same test as for the variable r.

Table 3
Statistics computed from transect and station sightings based on: the whole 1997 data set; the whole 2000 data set; the Alliance data set only (2000)

	$\tilde{r}$	D_t (# sight./km^2)	$\tilde{n}$ (# sight./station)	$D_{\bar{s}}$ (# sight./km^2)
1997	0.7 (S.D. 1.7)	14.2	3 (S.D. 1.43)	25
2000	2.9 (S.D. 3.9)	3.4	0.2 (S.D. 0.5)	1.6
2000 Allianc	3.29 (S.D. 4.18)	2.9		

$\hat{r}$ indicates the average distance between consecutive sightings along transects; $\hat{n}_s$ indicates the average number of sightings at fixed stations; D_t and D_s indicate the average densities estimated from transect and station data, respectively.

Notice that the difference between the two years appear even more evident for the station data (a factor 10 in the averages) than for the transect data (a factor 4). We will come back on this point in the discussion.

3.3. Estimates of areal density

The results from transects and stations are used to provide some simple estimates of debris density D per given area, using the "strip transect estimator" (Lecke-Mitchell and Mullin, 1992, 1997). Areal density estimates are useful because they provide a bulk estimate of debris coverage and they can be easily compared with other values obtained in the literature. On the other hand, it is important to keep in mind that they are only indicative of the real density values, since they are based on some higly simplifying assumptions. In particular in the "strip transect" estimates performed here it is assumed that effective observations are made consistently over a certain size area, so that the density is obtained simply dividing the number of sightings over the specified area. In reality, of course, the sighting effectiveness decreases with distance, and therefore the effective area should be computed and corrected as function of distance from the vessel. Appropriate correction factors can be computed (e.g. Thomas et al., 2002; Loya, 1978) when information on the relative positions of the sightings with respect to the vessel are available. In our case, these information are not available and therefore a fixed area has been considered. In the case of transect sightings, the area is assumed to correspond to a strip of width $d = 100$ m across the transect, while in the case of stations it corresponds to a circle of radius $R = 200$ m around the ship. Similar values have been previously used for similar estimates in the literature (e.g. Dufault and Whitehead, 1994; McCoy, 1988).

The density computed from transects, D_t, is then:

$$D_t = \frac{N}{Ld} = \frac{1}{\hat{r}}\frac{1}{d},$$

where L is the total length of the transects, and L/N corresponds to $\hat{r}$ as it can be seen from (1).

The density from stations, D_s instead, is computed as

$$D_s = \frac{N}{A} = \frac{N}{\sum \pi R^2}$$

where A is the total area of observation computed as a sum $\sum$ over all the stations.

The values of D_t and D_s for both years are given in Table 3. For 1997, $D_t \approx 14.2$ km^{-2} and $D_s \approx 25.0$ km^{-2}. The difference between the two values can be due to the imprecision in the areal estimates. For 2000, the densities are consistently lower, $D_t \approx 3.4$ km^{-2} and $D_s \approx 1.6$ km^{-2}. Again, the difference between the two estimates D_t and D_s can be due to the imprecisions of the method, even though it is interesting to notice that in this case D_s is lower than D_t, while the opposite occurs for 1997. We will come back on this point in Section 4.

The values in Table 3 are in the range of other debris density values recently reported in the literature in other regions of the world ocean. For example, densities in the Gulf of Mexico are reported to be of order 1 km^{-2} (Lecke-Mitchell and Mullin, 1992, 1997), while values on the coast of Nova Scotia are approximately 10–30 km^{-2} (Dufault and Whitehead, 1994). On the other hand, earlier values in the Mediterranean Sea reported much higher values, up to 2000 km^{-2} (Morris, 1980). These estimates appear to be in a completely different range with respect to the present ones. There could be many reasons for this difference. Morris (1980) observations have been made at one location only, 40 miles SW of Malta, and they consist of 60 periods of observations of 1 min each, so that they are not necessarily representative of the concentration in the area. Also, the observations were taken in 1980, and it is possible (and likely) that the debris input had indeed decreased in the following 20 years.

4. Discussion and conclusions

In summary, the results show that

(a) for 1997, the average distance between sightings (in the transect direction) is $\hat{r} = 0.7$ km, while the areal debris density is estimated of the order of 14–25 km^{-2}.
(b) for 2000, the sighting distance is higher, and the density is lower: $\hat{r} = 2.9$ km, and the density is of the order of 1.5–3 km^{-2}.
(c) the variability observed between the 1997 and 2000 data sets appears to be statistically significant using simple tests.

The important question to be addressed at this point is what is the reason for the observed variability. Many aspects are expected to play a role. First of all, some differences might be due to the different sampling strategies followed in the two years. On the other hand we do not expect this to be the only reason, since both data sets cover the same three main regions (Fig. 1) and the statistical differences appear noticeable in all the regions and records. This indicates the existence of an actual difference in the debris density in the Ligurian water.

The debris density in a basin is, in first approximation, influenced by two main factors: (a) debris inputs, (coming mostly from urban discharges, river outflows and ship discharges) and (b) mechanisms of transport in the marine environment. Since the present study involves sightings of large debris at the sea surface or in the first meter of water, the transport mechanisms are expected to involve the action of the marine currents as well as the action of wind and waves. The component of transport due to marine currents is characterized by relatively long time scales. In Aliani and Molcard (2003), estimates of these time scales in the Ligurian Sea have been obtained based on numerical simulations and on a qualitative comparison with drifter data. It appears that the spreading time for particles launched on the southern side of the Ligurian Sea, in the Corsica Channel, is of the order of months. By contrast, the time scales related to the wind action can be much faster and impulsive, as they are related to specific meteorological events. The presence of strong winds, in fact, can cause a consistent transport of surface debris, with possible beaching. Also, vertical mixing due to wave activities can alter the vertical distribution of the debris.

In order to verify whether or not the meteorological conditions were similar for the 1997 and 2000 measurements, wind time series from the European Centre for Medium-Range Weather Forecasts (Reading, UK; www.ecmwf.int) in the Ligurian Sea have been considered. These data have a coarse spatial resolution (0.56°) and they tend to underestimate the wind magnitude (Bozzano et al., 2002), nevertheless they can provide a valid general picture of the meteorological regimes. In Fig. 3, the wind time series at a central location representative of the Ligurian Sea (43°N, 9°E) are shown (a similar pattern is found in the other points of the basin). As it can be seen, the conditions in the periods before and during the 1997 cruise and the first 2000 cruise (Alliance) were relatively similar and characterized by light winds. On the other hand, the conditions for the second 2000 cruise (Magnaghi) were distinctively different. Before the cruise, a stormy period occurred, with strong winds from the south. Even during the cruise, the winds maintained sustained (allowing for measurements only in the calm days). The wind effects could be responsible for the particularly low density recorded by the Magnaghi measurements in the open sea stations

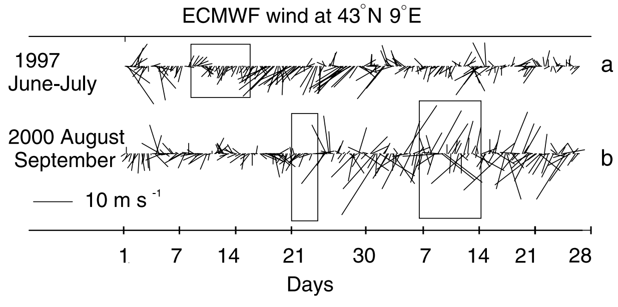

Fig. 3. Time series of ECMWF wind speed (stick diagram) at 43°N, 9°E for (a) June–July 1997; (b) August–September 2000.

(see Tables 2 and 3), and could also be consistent with the strong gradient of density toward the coast, suggested by the Magnaghi data in the north Ligurian transects (see Fig. 1 and Table 1).

The impact of the different meteorological conditions in the 1997 and 2000 results has been tested by recomputing the transect statistics for 2000 discarding the data of the second period (Magnaghi) and keeping only the data of the first period (Alliance). The results, in terms of $\hat{r}$, S.D. and D_t are shown in Table 3. As it can be seen, the values do not change significantly (since most of the transect data have been taken by the Alliance), maintaining higher $\hat{r}$ and lower D_t with respect to 1997. Also, the difference between the 1997 and 2000 statistics are significant at the 99% confidence level ($z = 7.4$). This result suggests that there are other reasons for the variability between the 1997 and 2000 data, in addition to the meteorological differences shown by Fig. 3. One possibility is that the lower density in 2000 is due to an earlier meteorological event, still influencing the distribution. Other possibilities are related to variability in the marine currents or in the debris input. This, in turn, can be a function of the meteological conditions, for example in terms of magnitude of river discharge.

In conclusion, the present results indicate the existence of a significant time variability in the debris concentration in the basin. In order to understand the mechanisms and the time scales of this variability, it is necessary to improve our knowledge on debris distribution and concentration and to relate them to the meteorological and marine conditions.

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