Self-similar distribution of oil spills in European coastal waters

Jose M Redondo and Alexei K Platonov

Departament de Fisica Aplicada, Universitat Politècnica de Catalunya C/ J G Salgado s/n, Campus Nord, Modul B-4, E-08034, Barcelona, Spain
E-mail: redondo@fa.upc.es

Received 9 October 2008
Accepted for publication 30 December 2008
Published 19 February 2009
Online at stacks.iop.org/ERL/4/014008

Abstract

Marine pollution has been highlighted thanks to the advances in detection techniques as well as increasing coverage of catastrophes (e.g. the oil tankers Amoco Cadiz, Exxon Valdez, Erika, and Prestige) and of smaller oil spills from ships. The new satellite based sensors SAR and ASAR and new methods of oil spill detection and analysis coupled with self-similar statistical techniques allow surveys of environmental pollution monitoring large areas of the ocean. We present a statistical analysis of more than 700 SAR images obtained during 1996–2000, also comparing the detected small pollution events with the historical databases of great marine accidents during 1966–2004 in European coastal waters. We show that the statistical distribution of the number of oil spills as a function of their size corresponds to Zipf’s law, and that the common small spills are comparable to the large accidents due to the high frequency of the smaller pollution events. Marine pollution from tankers and ships, which has been detected as oil spills between 0.01 and 100 km², follows the marine transit routes. Multi-fractal methods are used to distinguish between natural slicks and spills, in order to estimate the oil spill index in European coastal waters, and in particular, the north-western Mediterranean Sea, which, due to the influence of local winds, shows optimal conditions for oil spill detection.

Keywords: marine pollution detection, SAR images, oil spills, oil pollution index, remote sensing, turbulence, Zipf’s law

1. Introduction

Information about the pollution of marine and coastal waters is very important for civil protection. Compared with other sources of pollution in the oceans, the risk of crude oil spillage to the sea presents the major threat for the marine ecology. Every year between 5 and 30 millions tons of oil are spilled in the ocean (Vladimirov et al 1991, Kirlenko 1994), with a large amount resulting from common operations of maritime transport and ballast cleaning.

The European littoral is subject to a wide range of oil spill sizes: small spills of less than 10 tons are registered on average daily, spills with mass between 10 and 1000 tons occur three or four times a year, and larger tanker related catastrophic spills seem to happen every few years, like the Erika (18 000 tons of crude oil in 1999 in French coastal waters) and Prestige (60 000 tons of heavy fuel oil near Galicia). Crude oil is a dangerous, toxic substance that pollutes the environment. Large shipwrecks such as that of the tanker Erika are not the only source of ocean pollution. The small but frequent oil spills have been shown to be much more dangerous in the long run but there is much less public awareness of their importance. They are mostly caused by ballast cleaning of ships’ tanks in the open sea, by harbour and refinery activities, by oil platforms, etc.

After a spill in the ocean, the crude oil or hydrocarbon products of similar origin, due to buoyancy, spread on the water surface and form a thin surface film (oil spill) of variable thickness as a function of the concentration and the diffusion coefficient. Immediately at the surface there begins a process of chemical transformation and emulsification of the petrochemical substances. After this initial spread the ambient turbulence disperses the spill further in an intermittent natural process. Finally, the spill also sediments towards the seabed,
and evaporates towards the atmosphere. In the first 12 h, about 25% of the light parts of crude oil evaporates. With a water temperature 15 °C all the hydrocarbons, up to C15, evaporate in less than 10 days. When all gaseous constituents are eliminated and dissolved, the remaining crude oil transforms into a viscous substance of the ‘chocolate mousse’ type. In time the viscosity of the ‘mousse’ increases and it begins to transform into oil pellets of different diameters (1 mm–10 cm). The high viscosity substances (‘mousse’ and oil pellets) can remain on the marine surface for a long time; they are also advected and dispersed by marine currents, and either sediment or are washed ashore (Oil in The sea III, NERC 2003, SEASAR 2006, SEASAR 2008).

The oily film changes the intensity and the spectral composition of the solar light and of the electromagnetic waves penetrating into the sea. A 30–40 μm oil capping of the sea surface completely absorbs the infrared radiation (Vladimirov et al. 1991). It also eliminates the capillary waves on the water surface, reducing the small waves considerably, and decreases the marine surface coefficient of roughness up to 2–3 times. These surface effects may be detected with active spatial sensors like synthetic aperture radar (SAR). Figure 1 shows examples of detected oil spills. The quality of the SAR images is independent of solar lighting conditions and cloud coverage; nevertheless, it strongly depends on the wind speed (Gade and Alpers 1999). When the wind speed is between 2–3 m s⁻¹ and 10–11 m s⁻¹ the conditions for spill detection by SAR are optimal. The SAR devices on board satellites such as SEASAT, RADARSAT, Okean-O, ERS-1/2, and ENVISAT have increased the possibility of detecting oil spills. The periodicity of SAR images obtained from ERS-1/2 is 35 days; their spatial resolution was between 12 and 200 m/pixel depending on the type of sensor and on the imaging processing technique. In order to evaluate the contribution of the small spills with respect to the recorded major accidental spills within European coastal waters, we used the statistical results of the Clean Seas project together with the historical data of shipwrecks and large oil accidents. 709 SAR ERS-1/2 images obtained during 1996–1998 on three separate test areas in the north-western (NW) Mediterranean, the North Sea, and the Baltic Sea were analysed (Platonov 2002). In section 2 we present the joint statistical analysis of all the oil spills detected by SAR, and evaluate the oil spill or pollution index in section 3. After discussing the size effects, how the self-similarity of the spills may be used to trace their natural or human origin, and discussing the influence of the wind on detection, we present in section 6 statistics on large accidents and compare the role of large and small oil spills in the total marine surface pollution. The distribution of oil pollution as a function of size is shown to agree with Zipf’s law discussed in section 8. Finally we discuss the topological aspects, frequency, and detectability of oil spills and slicks, and present our conclusions.

2. Oil spills in European coastal waters: detection statistics

The North Sea (81.441 × 10³ km²), the Baltic Sea (100.828 × 10³ km²), and the NW Mediterranean (106.782 × 10³ km²) test zones were chosen for continued monitoring by SAR because they seem typical and have evident risks of marine pollution due to high maritime traffic.

Figure 2 shows the positions and size of the oil spills detected by SAR images in the test zone during 1996–1998 in the NW Mediterranean Sea.

The total marine area covered by all ERS-1/2 frames amounts to almost 290,000 km². This would correspond to 29 frames, although the total number was slightly higher due to the detection of inland regions. A total of 709 correct SAR scenes were taken every 35 days, providing a large enough oil spill dataset.

The largest number of spills was detected in the Gulf of Lyons area (318 cases), which might indicate that this maritime zone is the most contaminated. Nevertheless, it is necessary to consider the environmental conditions for spill detection presented in this zone (the wind and the waves, all year round, are generally more moderate than in the other two zones). In the North Sea and Baltic Sea zones strong winds (with speeds
greater than 10 m s\(^{-1}\)) are frequent in winter. This hampers the detection of the oil films and decreases the capability of their detection by SAR systems (Gade and Alpers 1999).

The strong hydro-meteorological conditions in both the North and Baltic Seas (especially from September until April) could explain that fewer spills were detected in these areas during that time than in the NW Mediterranean area. On the other hand, the largest number of spills was detected in the North Sea and in the Baltic Sea during the summer months, when the winds are not so strong but are still more than 2 m s\(^{-1}\).

In the North Sea and Baltic Sea test zones, 194 and 197 spills were detected, respectively. Most of the detected spills were a few square kilometres in size.

Figures 3(a)–(c) show different aspects of the relative frequency of the geometrical characteristics of the detected spills in 1996–1998 in the NW Mediterranean (width, length and area). The longitudinal sizes of the majority of the detected oil spills vary between 5 and 20 km, the widths vary between 0.1 and 1.1 km, and the distribution of areas is hyperbolic, with most of them being less than 10 km\(^2\). As for the recent elongated oil spills from ships, considering those with a small fractal dimension of less than 1.1 (see below), 72 cases were detected in the NW Mediterranean alone. Their average geometrical characteristics show an average length of 25 km and a width of 400 m.

3. Oil pollution index

It is interesting to evaluate the degree of pollution and compare the three studied areas in Europe with other areas with different maritime traffic and environmental conditions. In a first analysis, just evaluating the number of spills detected, or their number per unit area of observation, we could conclude that the NW Mediterranean is more polluted than either the Baltic Sea or the North Sea; we will show that this is not the case. A convenient way in which to compare different areas used by Lu (2003) is to evaluate the average number of oil spills detected per 10,000 km\(^2\) of observations; this has to take into account the fraction of images that do not cover the desired area under study \(f_i\) and the surface fraction of the sea \(S_i\) for the \(i\)th scene or SAR image of a fixed spatial frame. Evaluating \(N_f\) as the number of detected oil spills in a determinate area, we may calculate the average spill number per frame as

\[
I_{\text{ave}} = \frac{\sum_i N_f}{\sum_i f_i S_i}.
\]  

This average oil pollution index may also be presented in terms of the worst cases as the maximum number of detected spills in a certain area:

\[
I_{\text{max}} = \frac{N}{f S}.
\]

We propose a further global estimate of a wider area of total surface \(A_T\) as

\[
I_p = \frac{\sum_i N_i}{A_T} \times 10^4.
\]

This also reflects the number of observations (scenes) of a determined position (frame) during the whole observation period \(T\): this period was two years for the Clean Seas project and three years for the south-east Asia observations by Lu (2003).

Comparing the oil pollution index of the European areas and those of south-east Asia gives 0.99 versus 4.8 for average values, indicating much higher pollution detected by Lu (2003). The sampling periods and areas of these studies are very different: 290,000 km\(^2\) for the Clean Seas project, and 657,000 km\(^2\) for the Pacific. Their ratio is 22. The number

![Figure 3](image-url)
of frames and scenes is also very different (709 scenes and 29 frames for the Clean Seas project versus 5029 scenes and 657 frames for the Pacific). The fact that only an average of 7.6 images per area was available in Lu (2003) compared with our 29 images per area allows the production of much better local statistics in spite of the shorter time span. Also, there was much stronger variation between the Pacific areas, their maritime traffic and environmental conditions than in European waters. The maximum oil pollution index corresponded to the South China Sea, 6.3, and the minimum one corresponded to the Gulf of Tonkin, 2.0. Another explanation of the higher values is that no attempt was made by Lu (2003) to discriminate spills and natural slicks.

The influence of maritime traffic is clearly appreciated, having generally higher concentrations of detected oil spills near harbours or straights with high traffic. It is also possible to judge the safety and environmental practices better by weighting the detected spills with the inverse of the local traffic. For example, doing that with traffic near Barcelona, Marseille, Rotterdam, and Stockholm (their respective traffic data for the year 2000 in millions tons being 30.2, 92.3, 322.0, and 121.1), calculating their respective oil pollution indices \( I_p \) in a region of \( 10^4 \) km\(^2\) near each city, we find 1.7, 1.3, 1.4, and 0.9. Thus, it is clear that there is less control in Barcelona than in the other major European harbours (Platonov and Redondo 2003). The Clean Seas test areas have slightly above average shipping traffic, but can be considered representative of European waters. It is perhaps more important to include the influence of the wind as it may hamper the possibility of oil spill detection, especially when comparing areas with different weather patterns, as described below.

4. Multi-fractal measurements and spill–slick discrimination

It is important to be able to discriminate between real oil spills and other features detected in the SAR images, and we have developed a technique that aids this process; we use the scale to scale variability of the spills that disperse and adapt their scaling to the environment in time. We use a topological method measuring the self-similarity of the images. In order to calculate the fractal dimension of the detected features in the SAR images, the box-counting method used produces a coverage of the object, and the simplest method is to characterize it with boxes of side \( \lambda \). For a plane these boxes will be squares and for an object in space they will be cubes. The distribution of the boxes is accomplished systematically. The intersection of these with the object gives us the number, \( N \), of boxes with a non-void intersection.

When we work with real images they do not have perfectly defined contours, as in black–white spots, but we often find a wide range of scalar intensity values to process. If we group the available data and describe them by a single large set and calculate the fractal dimension we then lose the corresponding information due to the intensity variation, which in an SAR image corresponds to the roughness of the surface.

It is also possible to accomplish a segmentation in many intervals that contain a well defined intensity range. For each one of these ranges we apply the usual fractal dimension calculation with the box-counting method and we obtain the corresponding fractal dimension for each intensity level. The result of the process is a complex set of fractal dimension values \( D(\rho) \) as a function of the intensity of the SAR image \( \rho \), and it may be calculated using

\[
D(\rho) = -\frac{\log N(\rho)}{\log \lambda}
\]

where \( N(\rho) \) is the number of boxes of size \( \lambda \) needed to cover the SAR contour of intensity \( \rho \).

The box-counting algorithm divides the embedding Euclidean plane into smaller and smaller boxes (e.g., by dividing the initial length \( \lambda_0 \) by \( n \), which is the recurrence level of the iteration). For each box of size \( \lambda_0/n \) it is then decided if the convoluted line, which is analysed, is intersecting that box. Finally, \( N \) is plotted versus \( \lambda_0/n \) (i.e., the size of the box) in a log–log plot, and the slope of that curve, within reasonable experimental limits, gives the fractal dimension. This method of box-counting is used in ImaCalc software Redondo et al (2008a, 2008b) that we applied to detect the self-similar characteristics for different SAR image grey intensity levels and to identify different sea surface dynamic processes. Each of the intensity values may reflect different physical processes and lead to a different value of its fractal dimension. This entity can be either fractal or not, but there is a range of values of \( D(\rho) \) of 0–2 for each SAR intensity. The purpose of the method is to compare the plots \( D(\rho) \) for oil spills and natural slicks, because the natural (e.g. plankton induced tension-activities) slicks are produced over a long time and distributed over a large surface, and they show the typical parabolic multi-fractal shape of a fully turbulent environment. Anthropogenic oil spills, in contrast, exhibit lower fractal values for the low SAR (smooth) backscatter values, as seen in the examples of figure 4. Eventually, if the oil spill has had enough time to disperse totally, its fractal signature would be similar to that of a natural slick, but this would need a very large persistence (more than 10–15 days in normal wind–wave conditions). Thanks to this method the identification of oil spills has been exhaustive with very few look-alike errors.

5. Wind effects on oil spill detection

A detailed evaluation was performed for every detected spill in the Gulf of Lyons area, although some interpolation was necessary from the data of meteorological observatories and the numerical model HIRLAM from the Instituto Nacional de Meteorología. Wind speeds from Barcelona, Palma, Girona, and Marseille were used. Figure 5 shows as an example the average wind probability distribution near Barcelona. The observed and extrapolated winds during the 88 different dates within the 700 days of the Clean Seas project showed a similar, though coarser, wind distribution.

From the work of Gade and Alpers (1999), showing the diminished resolution of SAR images when the wind is strong, we can also correlate the probability of the different events for the different wind speeds; this is shown in figure 6, where we
consider as a function of local (measured or interpolated) wind speed whether oil spills and/or natural slicks are present.

The ability to detect oil spills as a function of wind magnitude was calculated for the 88 different days when the 318 oil spills were detected in the NW Mediterranean Sea. Four different categories were used: 1—no detected spills or other features, 2—detection of oil spills but no natural slicks, 3—detection of both oil spills and slicks, 4—detection of natural slicks but no oil spills. There were no cases of detections of natural slicks but not of oil spills, justifying the observation that the oil pollution index is close to 1. This means that when wind conditions are suitable for SAR observations of oil spills, these are generally detected.

Considering the low probability values of detecting oil spills in high winds ($v > 11 \text{ m s}^{-1}$) or in low winds ($v < 1 \text{ m s}^{-1}$), both because the persistence is much less in high winds and because the SAR reflectivity does not allow good contrast between the spill and the surrounding region in both cases, different regions should be evaluated with their local climatology and wind distributions. For the three Clean Seas study areas, the NW Mediterranean Sea had the best conditions for oil spill detection by SAR.

6. Statistics of the historical accidents in European seas during 1966–2004

We present a comparative statistical analysis of the historical data on oil tanker wrecks for 39 years in European coastal waters in parallel to the analysis of common, relatively small oil spills discussed earlier and detected by SAR. The statistics of the largest accidents in European coastal waters during 1966–2004 are based on the data of (National Research Council 2005, 2003, Environmental Technology Centre 2001, CUTTER ENVIRONMENT 1997, Marine Board 1991). The size distribution of the number of cases is as follows: 1 (for an oil spill of mass greater than $200 \times 10^6$ kg), The Amoco Cadiz, 4 (between $100 \times 10^6$ and $200 \times 10^6$ kg), 8 (between $50 \times 10^6$ and $100 \times 10^6$ kg), 6 (between $30 \times 10^6$ and $50 \times 10^6$ kg).
13 (between $10^6$ and $30 \times 10^6$ kg), 41 (between $3.5 \times 10^6$ and $15 \times 10^6$ kg); in total: 73 large accidents causing significant oil spills.

The statistical results of the detection of small spills (of up to 75 km$^2$) and their size distribution was obtained in three test areas. The different times of observation and the number of spills on the total European coastal seas.

In order to study the comparative role of the small but common spills in the global marine contamination versus the large accidental disasters, it was necessary to standardize the small spills data collected under the Clean Seas project (table 1) both in time and in space. This involved some approximations.

The total area of interest includes the Black Sea, the Mediterranean Sea, the North Sea, the Baltic Sea with the straits, and a part of the Atlantic Ocean (the 200 marine miles coastal waters near the Bay of Biscay, United Kingdom, Norway, and European part of Russia). This zone has an area of $6062 \times 10^9$ km$^2$. All great accidents took place in this marine space during 1966–2004 (39 year period). On the other hand, the total area of the three Clean Seas project study zones is just 289,051 km$^2$. The different times of observation and the fact that many small spills were not detected due to their small persistence had also to be taken into account statistically. Other factors discussed below are the ability to detect (detectability) due to the environmental conditions and the distribution of maritime traffic. For the small spills we elaborated the spatial, temporal, and lack of detection normalizing coefficients and introduced them in the following equation:

$$Nn = Ni \frac{N_{ft}}{Acs} N_{fr} \frac{1}{Na} \frac{35}{n}$$

where $Nn$ is the standard annual probable number of small spills on the total European coastal seas. $Ni$ is the total number of spills detected during the Clean Seas project in the three test areas. $Afr$ is the total area of the European coastal seas and $Acs$ is the total area monitored under the Clean Seas project. Thus, the relation factor between the two areas is 20.97. $N_{ft}$ is the total number of possible images (1000) i.e. the total number of images that were to be acquired theoretically during the Clean Seas project time period (700 days). $N_{fr}$ is the total number of real images obtained by the Clean Seas project (700) (Jolly et al 2000). Then, the ratio between $N_{ft}$ and $N_{fr}$ is a factor that compensates the lack of images for analysis (1.41). $Na$ is the time period of the Clean Seas project in years (1.92) and its inverse, 0.51, is a time factor that allows us to obtain the average number of the observations made in a year. The value of $n$ is the average number of days of persistence of a spill on the sea surface until it disappears.

The ratio between 35 days, which is the ERS-1/2 satellite observation time period, and $n$ days indicating the possible persistence of spills provides us with the approximate number of spills that could have been detected during this period if the satellite observations were carried out daily. The number of detected oil spills would have been greater due to the larger frequency of the acquisition, and some spills would have been detected even during several consecutive frames. This highly variable ratio depends strongly on the environmental factors, i.e. wind stress, wave activities, currents, etc, as well as on the spill size, so larger spills would exhibit more persistence (Richardson 1926, Ozmidov 1990).

Table 2 shows for the different areas the total number $Ni$ of the detected small oil spills during the Clean Seas project (column 2). Column 3 shows the standardized number of spills that could be detected theoretically in all European coastal waters during the same period. Column 4 shows the number of spills that could have been detected theoretically in all European coastal waters during the span of the Clean Seas project in terms of the compensating factor for the lack of images, including satellite error, transmission problems, etc.

For the great accidental spills we calculated the crude mass as a simple function of their marine surface areas, considering the following average conditions mentioned in (Vladimirov et al 1991, Nelson-Smith 1977) for well dispersed oil spills: the average thickness of the crude film is 0.305 µm and 0.352 m$^3$ of crude occupies 1 km$^2$ of marine surface. Considering that the average density of a spilt petrochemical product in the sea $\rho$ is 760 kg m$^{-3}$, a crude oil mass of 267 kg occupies an area of $1 \times 10^3$ km$^2$ or an oil spill area of 3.7 km$^2$ weighs one ton. For these large accidental spills the temporal factor of the analysis period (39 years) is normalized with a coefficient of 0.026 = 1/39, that applied to the data provides the annual probability of an accident of a certain magnitude. The ship Amoco Cadiz that spilt 233 500 tons of crude in 1978 in the French coastal waters near Bretagne was the largest accident, as indicated in table 3. For example, statistically, marine

### Table 1. Number of detected oil spills on the different test areas of the Clean Seas project.

| Limit of area (km$^2$) | Gulf of Lyons (NW Mediterranean) | North Sea | Baltic Sea | Total |
|------------------------|---------------------------------|-----------|------------|-------|
| $0.1 < S < 1$          | 110                             | 70        | 81         | 261   |
| $1 < S < 5$            | 147                             | 90        | 84         | 321   |
| $5 < S < 10$           | 39                              | 19        | 22         | 80    |
| $10 < S < 25$          | 13                              | 8         | 8          | 29    |
| $25 < S < 50$          | 7                               | 6         | 2          | 15    |
| $50 < S < 100$         | 2                               | 1         | 0          | 3     |
| Total                  | 318                             | 194       | 197        | 709   |

### Table 2. Calculation of the standard number of small spills based on the results of the Clean Seas project, affected by the different factors from equation (5).

| Average area (km$^2$) | $Ni$ total | $Ni$ $\frac{Afr}{Acs}$ $N_{fr}$ $\frac{1}{Na}$ $\frac{35}{n}$ |
|-----------------------|------------|---------------------------------------------------------------|
| 0.5                   | 261        | 5473                                                          |
| 3                     | 321        | 6731                                                          |
| 7.5                   | 80         | 1678                                                          |
| 17                    | 29         | 608                                                           |
| 37.5                  | 15         | 314                                                           |
| 75                    | 3          | 63                                                            |

J M Redondo and A K Platonov
Table 3. Statistics of the great oil spill accidents in European coast waters during 1966–2004.

| Mass range (10^6 kg) (example) | Possible average area (km^2) | Total case number N | N cases/year N/39 | Statistical period of occurrence (years) |
|-------------------------------|-----------------------------|---------------------|------------------|----------------------------------------|
| Smaller 3.5–15                | 34 644                      | 41                  | 1.05             | 1.0                                    |
| 15–50 (Erika)                 | 121 723                     | 19                  | 0.49             | 2.0                                    |
| 50–100 (Prestige)             | 280 899                     | 8                   | 0.20             | 4.9                                    |
| 100–200 (Torre Canyon)        | 561 798                     | 4                   | 0.10             | 9.8                                    |
| 200–250 (Amoco Cadiz)         | 842 697                     | 1                   | 0.03             | 39.0                                   |
| Total                         | 73                          |                      |                  | 0.5                                    |

Table 4. The exponent \(a\) and coefficient of determination \(R^2\) of equation (4) for the small spills considering different persistence times together with the large accidental spills of figure 7.

| Persistence of small oil spills (days) | \(-a\) | \(R^2\) |
|----------------------------------------|--------|--------|
| 2                                      | -1.078 | 0.989  |
| 3                                      | -1.041 | 0.989  |
| 4                                      | -1.015 | 0.989  |
| 5                                      | -0.994 | 0.989  |
| 6                                      | -0.977 | 0.988  |
| 7                                      | -0.963 | 0.988  |
| Variable persistence                   | -1.133 | 0.982  |

In our case \(f_i\) is the number of cases of the detection of the oil spills of a certain area rank and \(i\) is the rank or complexity or size of the event (in our case, it is the average area of the spills). The exponent \(a\) is a power, whose value is 1 if the described process is independent of the scale. Transforming equation (6) to a logarithmic scale, we obtain

\[
\log f_i = \log C - a \log(i)
\]

which is described as a line of slope \(a\) and intercept \(b\).

\[
y = b - ax
\]

where now \(x = \log(i)\), \(y = \log f_i\), and \(\log C\) is the constant \(b\).

Figure 7 shows the average annual number of small spills (more than 0.1 km^2 and less than 75 km^2) for different persistence on the sea surface and at the same time the average annual probability of great spills of more than 35 000 km^2. The data are plotted as a function of their respective areas, for both small and large oil spills occurring in European coastal waters according to table 3. Also in figure 4(a) spatial- temporal normalization of the data sets with different scales was considered. The oil spill persistence time period is related to many environmental factors, such as surge, wind, and dominant current structure. Therefore the probability of detecting the real number of spills with just one observation every 35 days will strongly depend on the environmental conditions, and a low persistence will hamper the possibility of detection.

According to table 4, the coefficient \(a\) varies between 1.08 (2 days’ persistence of spills) and 0.96 (7 days’ persistence). The best fit for both small and large spills corresponds to a 5 day average persistence, as seen in figure 7, which adjusts better to the Zipf’s law distribution (coefficient \(a = 0.994\), i.e. close to 1).

accidents with tankers such as Erika (1999) or Prestige (2002) occur approximately every 2 and 5 years in accordance with the statistics of the past 40 years.

8. Application of Zipf’s law

The comparative statistical analysis of the 39 year span of known tanker shipwrecks in European coastal waters and the relatively small but common spills shows a power relation between the number of spills and their respective sizes over a seven decade interval. In the logarithmic scale this relation shows a good approximation to Zipf’s law (law of increasing entropy) (Zipf 1949). This basic law is simply described as \(i f_i = C\), where \(i\) is the event rank, \(f_i\) is the frequency of its occurrence, and \(C\) is a constant (Laherrère 1996), or

\[
f_i \approx Ci^{-a}.
\]
9. Discussion

Although we have no statistical data for the detection of either the very small (from a few square metres up to 0.1 km$^2$) or the middle size oil spills (between 100 and 35,000 km$^2$) due to lack of visibility of the very small oil spills, and to the relatively low occurrence of the middle size spills and even their absence in the official records of oil spills in minor accidents, our hypothesis is that the overall distribution of spills should agree with Zipf’s distribution (figure 7) even considering the uncertainty in detection due to wind and other factors. It is then possible to estimate the annual expected number of very small and middle size spills by extrapolating the unexplored ranges in figure 7. For example, the annual expected occurrence of oil spills of size about 500 km$^2$ is 80, which would correspond to an unreported accident of a much larger size (40,000 km$^2$ or $11 \times 10^6$ kg). The reason for the lack of detection of spills in this middle range by the Clean Seas project is that the area and time of observation were too small and the lack of official records is probably due to small accidents that are not reported and go unnoticed. There is also a further possibility that needs further investigation of longer sets of SAR images: that due to the higher cost of an oil spill larger than several tons, the recovery procedures before ballast dumping are more stringent and there could be a discontinuity in the application of Zipf’s law.

The possible prolongation of the fit shown in figure 7 to include the very small oil spills (less than 0.1 km$^2$) is also useful in order to evaluate the undetected pollution produced by the many small vessels and fishing boats that transit European coastal areas. The extrapolation towards other sizes may be also used to predict their annual estimated occurrence. Of course, the largest areas of spills cannot be attained for the very large accidents the black tides are much thicker. Due to the use of a constant oil spill thickness, the power laws are the same with respect to oil spill area and mass. Considering an oil spill thickness that is a function of size and of expected persistence then both effects cancel out, and Zipf’s law and its generalization by Mandelbrot are recovered so that on average $a = 1$ and $D = D_c$. The existence of small and middle size spills must be also considered in a global analysis of the annual total mass of petroleum spilt in the sea. We can estimate both the expected annual area and mass of the different size ranges of oil spills using the observation that 267 kg of oil occupies 1 km$^2$ of the marine surface following experiments by (Vladimirov et al 1991, Nelson-Smith 1977).

The percentage of the detected small spills of size ranging from 0.1 to 100 km$^2$ is about 38% of the total estimated pollution, and they have been detected by the monitoring by SAR images from ERS-1/2. In the range of middle sized spills comprising areas between 100 km$^2$ and $34 \times 10^3$ km$^2$, the provision of oil pollution of these undetected spills amounts to 32% of the total. Finally, it is important to point out that the well advertized and alarming great accidental spills of size larger than $34 \times 10^3$ km$^2$ than correspond yearly to more than $39 \times 10^6$ kg amount to only 17% of the total pollution.

As far as the larger size spills are concerned, we recognize that their expected areas of detection are excessive in our
estimation since commonly they cannot extend completely due to their drift by local currents, and they deposit on the coast in a short time period; their thickness is also much larger, and sinking and evaporation are also more important than in smaller oil spills.

Both in situ hydro-meteorological conditions and oil spill size determine the persistence time period of a spill on the sea surface. Spills disappear more quickly due to strong environmental stress conditions, such as high waves and winds. Correlations with wind velocity non-Gaussian distributions and evaluation of the turbulent diffusivity show a dependence of persistence on oil spill size. The statistically average oil spill persistence of a 10 km² oil spill, in agreement with the Richardson law (Richardson 1926) and Okubo’s experiments (Okubo 1971, Okubo and Ozmidov 1980), is 4 days, although 5 days’ average persistence agrees better with Zipf’s law for all sizes; the deviations observed from the linear fit seem to be due to under-sampling in both small size (a few pixels in the SAR images) and large size (because of the small period of the studies and the small area of the image analysis monitoring).

With a limited range of oil spill sizes it is difficult to obtain a good hyperbolic fit, as seen in figure 6, but if we compare the logarithmic fits from Lu (2003) and our data, both are close to Zipf’s law (0.8 and 0.95) in spite of the small range of the Lu (2003) data. This seems to be due to the different hydro-meteorological conditions in the Mediterranean Sea and the south-western Pacific that prevented observation of long spills due to strong dispersion. It would be interesting also to evaluate large accidents in other parts of the world in order to compare them with the results in European coastal waters (Jolly et al 2000) and to consider the evolution in time of the oil spill distribution (Redondo and Platonov 2001, 2006).

10. Conclusions

The oil spills detected by satellite that correspond to small offshore accidents, runoff, and wash-waters of ships’ tanks and ballast in open sea are part of a self-similar trend that includes the largest environmental disasters.

Comparing the oil pollution index of the 709 SAR images in European waters with the 5029 ERS-1/2 images between the Indian and Pacific Oceans analysed by Lu (2003), shows that European waters are less polluted than those in south-east Asia; nevertheless, the inclusion of look-alike natural slicks and the low repeatability, i.e., 7.6 images at each location over three years, would partly explain the higher average oil pollution index (2.0–6.3) in Lu (2003) data compared with (0.9–1.13) for the different study areas.

It cannot be said that the area of the NW Mediterranean is more contaminated than that of the Baltic Sea or the North Sea, even if more oil spills have actually been detected. The in situ environmental conditions in these three test zones are sufficiently different to allow us to evaluate the influence of the wind. The percentage of winds either higher than 11.3 m s⁻¹ or lower than 1 m s⁻¹ have to be taken into account locally, and also when comparing different study sites. For example, the higher winds and waves in the North Sea zone and the distribution of local winds (the average annual wind speed is 5.7 m s⁻¹ with a strong skewness) compared with the NW Mediterranean area (the average annual wind speed is 4.6 m s⁻¹) show that in the NW Mediterranean conditions are more favourable for oil spill detection by SAR.

The statistical distribution of the number of oil spills corresponds roughly to Zipf’s law, i.e. the number of spills depends on their size in a hyperbolic fashion over a very large range and is not affected by the local distribution of winds. We foresee that with more environmental control it will be possible to reduce the value of the intercept b in equation (8), but human behaviour will make it more difficult to change the slope a. The overall distribution is not affected significantly by local environmental conditions.

The non-detected and non-registered small and middle size oil spills, which do not enter into the official statistics and do not draw the attention of the public, also have an important role in pollution statistics in accordance with Zipf’s law. When evaluating global pollution, even when their impact is not so visible, the small and undetected spills have to be taken seriously because they may be much more important in the long run. A longer period of detection by SAR and higher frequency of SAR images, as well as using the ENVISAT satellite, would give a chance of detecting spills of larger size, and an increase in resolution of the SAR and ASAR sensors would also allow the detection of some of the very small oil spills.

Acknowledgments

We would like to acknowledge the financial support from the Ministerio de Educación y Ciencia of Spain (RYC-2003-005700, FTN-2001-2220, ESP2005-07551) and grant 2001-SGR00221. We thank the CLEAN SEAS (ENV4-CT96-0334) European Union Project and the European Space Agency (Project ESA-AO-C1P.2240) for the SAR images provided. Dr Diogo Bolster and the referees have helped in improving this paper.

References

Breslau L, Cao P, Fan L, Phillips G and Shenker S 2000 Web caching and Zipf-like distributions: evidence and implications Proc. INFOCOM ’99 (Piscataway, NJ: IEEE)
Camacho J and Sole R V 2001 Scaling in ecological size spectra Europhys. Lett. 55 774–80
CUTTER ENVIRONMENT 1997 Oil Spill Intelligence Report’s (White Paper Series vol 1) Cutter Information Corp. No 6
Environmental Technology Centre 2001 Spill Technology Databases, Canada. http://www.etcentre.org
Gabaix X 1999 Zipf’s law for cities: an explanation Q. J. Econ. 114 739–67
Gade M and Alpers W 1999 Using ERS-2 SAR images for routine observation of marine pollution in European coastal waters Sci. Total Environ. 237/238 441–8
Gade M and Redondo J M 1999 Marine pollution in European coastal waters monitored by the ERS-2 SAR: a comprehensive statistical analysis IGARSS’99 (Hamburg) pp 1375–7
Jolly G W et al 2000 The Clean Seas Project (ENV4-CT96-0334) Final Report http://www.satobsys.co.uk/CSeas/report.html DG XII/D, Bruselas pp 1–75
Kirilenko V P 1994 Ocean Ecology and International Law (Ecologia okeana i mejdanutvodnoe pravo) (Saint Petersburg: Gidrometeoizdat) p 8 (in Russian)
Laherrère J 1996 Parabolic fractal distributions in Nature. C. R. Acad. Sci. Ila 322 535–41

Lu J 2003 Marine oil spill detection, statistics and mapping with ERS SAR imagery in south-east Asia. Int. J. Remote Sens. 24 3013–32

Mandelbrot B 1977 *The Fractal Geometry of Nature* (New York: Freeman)

Marine Board 1991 Tanker Spills: Prevention by Design (MB Commission on Engineering and Technical Systems (CETS))

National Research Council 2003 *Oil in The Sea III Ocean Studies Board*

National Research Council 2005 *Oil Spill Dispersants: Efficacy and Effects Committee on Understanding Oil Spill Dispersants Ocean Studies Board*

Nelson-Smith A 1977 *Oil and Marine Ecology (Neft I Morskaya Ekologiya)* (Moscow: Progress) (in Russian)

Okubo A 1971 Oceanic diffusion diagrams Deep-Sea Res. 18 789–802

Okubo A and Ozmidov R V 1980 An empirical relationship between the horizontal eddy diffusivity in the ocean and the scale of the phenomenon (Empiricheskaya zavisimost' gorizontal'noy diffuzii v okeane i mashinab uvelenya) Atmos. Ocean. Phys. 6 534–6 (in Russian)

Ozmidov R V 1990 Diffusion of Contaminants in the Ocean Oceanographic Sciences Library from 1986

Platonov A K 2002 SAR satellite images applications to both sea contamination and dynamic studies in the NW Mediterranean PhD Thesis UPC Official Catalogue TDC@t http://www.tdcat.cesca.es/TDCat-0905102-135541/ (in Spanish)

Platonov A K and Redondo J M 2003 Surface pollution of the north-western Mediterranean Sea: detection of the oil spills Ing. Agua 10 149–62

Popov A 1998 An effective method of the search of information into the World Wide Web J. Internet 2 7–13 (in Russian)

Redondo J M and Platonov A K 2001 Aplicación de las imágenes SAR en el estudio de la dinámica de las aguas y de la polución del mar Mediterráneo cerca de Barcelona Ing. Agua 8 15–23

Redondo J M and Platonov A K 2006 Oil Spill Detection and Prediction in the Northwest Mediterranean Sea, SEASAR06 Conf. ESA http://earth.esa.int/workshops/SEASAR2006/proceedings/participants/360/paper_redondo.pdf

Redondo J M, Platonov A K, Grau J and Garzon G 2008a Multifractal analysis of self-similar processes: satellite images and baroclinic instabilities Rev. Int. Methods Numer. Calc. Diseno Ing. 24 25–48

Redondo J M, Platonov A K and Tarquis A 2008b Detection and prediction from SAR multiscale analysis http://earth.esa.int/ workshops/seasar2008/participants/21/pres_21_redondo.pdf

Reed B 2002 On the rank-size distribution for human settlements J. Reg. Sci. 41 1–17

Richardson L F 1926 Atmospheric diffusion shown on a distance-neighbour graph Proc. R. Soc. A 110 709

SEASAR 2006 http://earth.esa.int/workshops/seasar2006/ programme.html

SEASAR 2008 http://earth.esa.int/workshops/seasar2008/ programme.html

Sornette D, Knopoff L, Kagan Y Y and Vanneste C 1996 Rank-ordering statistics of extreme events: application to the distribution of large earthquakes J. Geophys. Res. 101 13883–94

Vladimirov A M, Lyakhin Y I, Matveev L T and Orlov V G 1991 Protection of the environment Gidrometeoizdat (Okhrana okrujayushey sredi) Leningrado URSS p 268 (in Russian)

Weather Base Center 2004 http://www.weatherbase.com/weather

Zimpf G K 1949 *Human Behaviour and the Principle of Least Effort* 2nd edn (New York: Hafner Publishing) reprinted 1972