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The effect of the "*Prestige*" oil spill on the plankton of the N–NW Spanish coast

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Abstract

Chlorophyll, primary production, zooplankton biomass and the species composition of phytoplankton and zooplankton were studied in 2003, after the *Prestige* shipwreck. The information obtained was compared to previous data series available for the area affected by the spill. A large data series on plankton variables for the N–NW Spanish coast existed, and therefore a realistic evaluation of the effects by comparison with the range of natural variability could be carried out. We emphasized the evaluation of impact during the spring bloom, the first important biological event after the spill. Some minor changes were observed occasionally, but they did not show any clear pattern and were more related to the natural variability of the ecosystem than to effect of the spill. Plankton community structure did not undergo any changes. Only a few species were more abundant during spring 2003 than in previous years. No significant changes were detected in the planktonic community during productive periods, such as the spring bloom and the summer blooms related to intrusions of East North Atlantic Central Waters. The lack of evidence of the effects of the spill on planktonic communities is discussed in terms of the characteristics of the fuel, the high dynamics of the water masses, the biological mechanisms through which the fuel from the surface waters is transferred to the sea floor and, particularly, the influence of the natural variability by means of large and meso-scale hydrographic processes in the area under study. At the present time it is not possible to determine any minor effects the spill may have had on the plankton owing to the great variability of the planktonic cycles and the short-term impact of the oil from the *Prestige* on the pelagic system.

Keywords: Chlorophyll; Primary production; Zooplankton; Phytoplankton; Species composition; Oil spill; *Prestige* oil tanker; Galicia; NW Spain

1. Introduction

Oil tanker accidents have occurred frequently along the Galician coast. Over the course of the last 30 years, there have been three major oil spills: the *Urquiola* in 1976, the *Aegean Sea* in 1992 and finally the *Prestige* in November 2002. The first two affected a localized area of the coast off A Coruña (Fig. 1), while the last spill had a wider area of influence, extending from northern Portugal to the southern French coast (García-Soto, 2004).

Over the last 30 years, numerous studies on the influence of oil on plankton communities have been carried out. In

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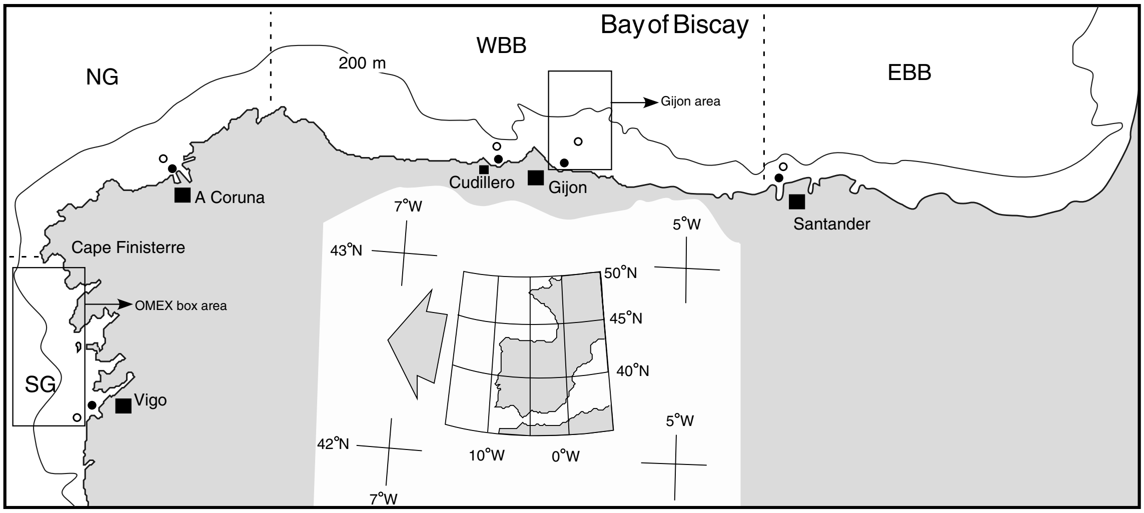

Fig. 1. Map of the study area showing the sampling locations from the IEO Core Project *Studies on Time Series of Oceanographic Data*, and the zone covered by *Pelacus* cruises from 1999 to 2003. SG: South Galicia; NG: North Galicia. WBB: West Bay of Biscay; EBB: East Bay of Biscay. Open circles: Shelf stations (around 100 m depth). Filled circles: Coastal stations (around 20 m depth). Rectangles delimit the areas where satellite information is available: OMEX box area (primary production), between Cape Finisterre and Vigo; and the area in front of Gijón (chlorophyll).

general, three main approaches have been used: cultures of single species, mesocosms with natural phytoplankton assemblages, and studies undertaken in natural or in situ conditions. The first two approaches provide a good idea of the potential toxicity on planktonic species (Lännergren, 1978; Vargo et al., 1982; Gin et al., 2001), the differential toxicity depending on the type of crude (Doerffer, 1992), the species-specific response (Bate and Crafford, 1985; Ostgaard et al., 1984), and the capability of plankton to metabolize hydrocarbons (Corner, 1975; Walters, 1982). However, the conclusions are often inconsistent and therefore difficult to extrapolate to the natural environment (Spooner and Corkett, 1979; Mahoney and Haskin, 1980; Davenport, 1982). Mesocosms have also been largely used for the evaluation of oil spill impact (Lee et al., 1978a; Gearing et al., 1979; Thomas et al., 1981; Scholten et al., 1987; Ohwada et al., 2003). Natural assemblages can be used but there are alterations stemming from enclosure as compared to the natural environment. Natural plankton communities are the final result of complex synergies or antagonisms among organisms and the influence of hydrographic conditions which are limited or absent in cultures and mesocosms.

Therefore, the most realistic approach seems to be the in situ study. However, a complete assessment of the effects of the oil spill on plankton communities through this approach is often difficult because many factors are involved. The effects are largely dependent not only on the original components of the crude (Davenport, 1982; Shailaja, 1988; Bate and Crafford, 1985; Doerffer, 1992; Gin et al., 2001), but also on the products resulting from degradation which can be more toxic than the original fuel (Lacaze and Villedon de Naïde, 1976). The effect of oil is also largely dependent on the structure of planktonic communities. The response of plankton to fuel is not only species specific, with a great variability in sensitivity (Thomas et al., 1981; Throndsen, 1982; Ostgaard et al., 1984), but also clone-specific (Mahoney and Haskin, 1980). The effect is also dependent on the natural environmental conditions. The inhibition of growth rate caused by oil is highly temperature-dependent (de la Cruz, 1982).

In addition, relationships among organisms in the pelagic system may conceal the possible effects of contaminants. Some studies reported an increase in primary productivity, but it was not clearly demonstrated whether this was caused by a stimulation of photosynthesis or a decrease in zooplankton grazing caused by oil (Lännergren, 1978; Johansson et al., 1980).

Finally, natural variability is probably the main obstacle standing in the way of being able to accurately determine the effects of oil spills on planktonic organisms. The natural seasonal variation in the marine ecosystems, the mobility of water masses, the patchiness in spatial and temporal distribution of planktonic organisms make it difficult to carry out quantitative sampling and to identify the effects of pollution (Dicks, 1982; Varela et al., 1996).

Natural variability is especially marked in the N–NW Iberian Peninsula where phytoplankton blooms show great fluctuations (Varela, 1992; Bode et al., 2002), depending on the intensity of meso and large-scale oceanographic events affecting the area such as the Iberian Poleward Current during spring (Frouin et al., 1990; Álvarez-Salgado et al., 2003), and coastal upwelling of Eastern North Atlantic Central Waters (ENACW) during the summer (Fraga, 1981; Blanton et al., 1984, 1987; Álvarez-Salgado et al., 1993). The spatial and temporal variability of the marine ecosystem under study strongly limits our ability to differentiate the anthropogenic effects from those that occur naturally. A good knowledge of the range of the natural variability of plankton is therefore essential for a correct evaluation of the impact caused by oil.

The natural variability is related to the season of year. The effects would be lessened if the spill were to occur during the winter in temperate latitudes when plankton biomass is comparatively low. However, spills occurring during the spring phytoplankton bloom or summer upwelling blooms in N–NW Spain would produce a more serious impact on plankton and, as a result, on the pelagic food web. Therefore, the study of the effect of oil spills must include an appropriate temporal scope to cover the most important biological periods defined for the N–NW Spanish coast, such as the spring bloom and the summer blooms related to the upwelling of ENACW (Campos and Mariño, 1984; Varela, 1992; Bode et al., 1996; Casas et al., 1997, 1999; Varela et al., 2001).

It should be pointed out that one of major limitations for the in situ evaluation of the impact of oil on the marine ecosystem is the lack of adequate monitoring carried out before a spill as well as the inadequate or insufficient historical data for consistent assessment. In 1989 the Spanish Institute of Oceanography (IEO) implemented the research core project *Studies on Time Series of Oceanographic Data*, the backbone and objectives of which, as well as the spatial and temporal coverage, is detailed in Valdés et al. (2002). The broad data set obtained over the last few years, has allowed for the precise quantification of the effects caused by the *Prestige* oil spill-in the form of relevant information with the appropriate temporal and spatial coverage-, on the variability of the natural ecosystem in the affected area.

The objective of this paper is to determine whether the *Prestige* oil spill has affected the planktonic communities in the North-Western shelf of the Iberian Peninsula. The information obtained after the accident, up to the year 2003, was compared with the historical data available for the purpose of answering the following questions: Have there been any changes in plankton biomass? Has the primary production changed? Have we observed any changes in the main taxonomic groups? Has there been a shift in the dominance of the characteristic plankton species? Even though we have made a comparison for all of 2003 covering the main oceanographic periods described for the area, a major effort was dedicated to investigating the effects on the planktonic spring bloom. The spring bloom was the first important production period occurring on an annual scale just after the accident and the effects of the oil spill on plankton, if any, would be first observed during this event. The spring bloom coincides with the spawning of many species of great commercial interest (mainly sardine, anchovy and mussel), so that any catastrophic impact on the first links of the pelagic food web would result in failed or reduced recruitment.

2. Material and methods

The area of study extended from Northern Portugal to Santander, in the Southern Bay of Biscay (Fig. 1). The localities of Vigo, A Coruña, Cudillero, Gijón and Santander were selected because reference data were available for phytoplankton, zooplankton or both. At these locations, there are coastal laboratories belonging to the Spanish Institute of Oceanography (IEO) integrated into the framework of the Core project *Studies on Time Series of Oceanographic Data*. Standard transects of several stations were sampled monthly. Two types of stations were selected: a coastal station around 30 m depth and a shelf station at approximately 100 m depth. In some cases and for some variables there is information available for only one station. This is the case of phytoplankton taxonomy in A Coruña and Cudillero, and primary production in Cudillero (Fig. 1). The sampling of plankton and the analytical procedures of different variables were carried out following the recommendations of JGOFS protocols (Unesco, 1994). The methods are described in detail in several papers taken from studies carried out on the Galician and Cantabrian coasts (Fernández et al., 1991; Varela, 1996; Casas et al., 1997, 1999; Bode and Varela, 1998; Varela et al., 2001; Varela and Prego, 2003). Chlorophyll-*a* (Chl-*a*) concentrations were measured by fluorimetry, using acetone extracts after filtration through Whatman GF/F filters (Unesco, 1994). Primary production was estimated by the C-14 method, using 2 h simulated in situ conditions as described in Bode et al. (1994). Samples for microscopic examination were preserved in Lugol's solution and kept cool and dark until they were ready to be examined following Utermöhl's technique. Only two main phytoplankton groups—dinoflagellates and diatoms—were considered for this study. Mesozooplankton samples were collected by vertical hauls with a 200 μm mesh size Bongo net. Processing of samples for the estimation of biomass (dry weight), counting and identification of species are detailed in Bode et al. (2003).

Additional information available from opportunistic cruises conducted on the shelves of the Galician and Southern Bay of Biscay, covering the area affected by the *Prestige* oil spill, was also used. *Pelacus* cruises are core surveys of the IEO which have been carried out every spring since 1987. The main objective of these cruises is the acoustic determination of biomass stock and the distribution of pelagic fisheries. Since 1999, plankton studies have been implemented into the cruises in the framework of several EU research projects (*Pelasses*, *Sardyn*). During the *Pelacus* cruises chlorophyll-*a* was measured as explained above for other areas. Phytoplankton samples were obtained using 20 μm mesh Bongo nets and vertical hauls from 100 m depth to the surface. As in the other areas of study, only dinoflagellates and diatoms were included in the study of the impact of oil. The wide spatial coverage of the area affected by the *Prestige* accident and the fact that the survey periods coincided with the season of spring bloom have made this information invaluable to the aim of the present study.

Sea WiFS-derived chlorophyll concentrations for the period 1998–2003, were calculated along the IEO standard section near Gijón (Fig. 1) at 5.29°W for shelf (43.25°N to 43.69°N) and oceanic waters (44.03°N to 44.56°N). The temporal resolution was 8 days with a spatial resolution of 9 km. Sea WiFS-derived primary production rates were calculated for shelf (depth < 200 m) and oceanic adjacent waters of the OMEX Box area (41°30′N to 43°00′N and 9°00′W to 10°30′W), between Cape Finisterre and Ria de Vigo (Fig. 1). Composite data with 9 km resolution were obtained from the Goddard GES distributed Active Archive Centre at daily, 8-day and monthly resolutions. Estimates of primary production, using satellite data as inputs, were computed following essentially the same method as in Joint et al. (2002). The available data cover the period between 1998 and 2004.

The evaluation of the effects was carried out comparing the values of the above-mentioned variables for each month of the year 2003, after the *Prestige* accident, with mean values of these variables for the same months in previous years.

3. Results

3.1. Chlorophyll and primary production

Data series chlorophyll in the stations off A Coruña showed a great year-to-year variability for the period 1989–2002 as deduced from large standard deviations (Fig. 2). Higher values (mean concentrations of around 100 mg Chl-*a* m^{-2} with maximum values of more than 200 mg Chl-*a* m^{-2}) were measured during spring and summer, the latter related to intrusions of ENACW. The same large variability was observed in the data from Cudillero for the 1992–2002 period. However, a clear variability between zones was observed. In Cudillero, higher values were recorded in spring. However, chlorophyll concentrations in summer were significantly lower (mean and maximum values of 35 and 60 mg Chl-*a* m^{-2} respectively), due to reduced upwelling intensity as compared to Galician waters (Fig. 3). Similar results were observed for primary production.

The water column integrated Chl-*a* for the different zones in Galicia and the Bay of Biscay sampled during *Pelacus* cruises is shown in Fig. 4. Data for the 2000–2002 period exhibited a great inter-annual variability. The Northern Galician and Western Bay of Biscay consistently showed higher values of chlorophyll in all cruises as compared to Southern Galicia and the Eastern Bay of Biscay. Slightly lower values were found in all zones in spring 2003 with respect to values from previous years.

SeaWiFS chlorophyll derived data for the area near Gijón (Fig. 1) showed a clear inter-annual and intra-annual variability for both shelf and ocean waters. Chl-*a* concentrations were around 0.4 mg m^{-3} and 0.7 mg m^{-3} for the ocean and shelf respectively. Ocean waters showed higher values in 1999, while shelf waters exhibited large concentrations in 2002. Both maxima are associated with greater variability as indicated by standard deviations of the data (Fig. 4). The derived primary production estimated for the OMEX box area from satellite data (Fig. 4) showed a slight year-to-year variation. Maximum production rates were observed for the shelf in 2001 and for oceanic waters

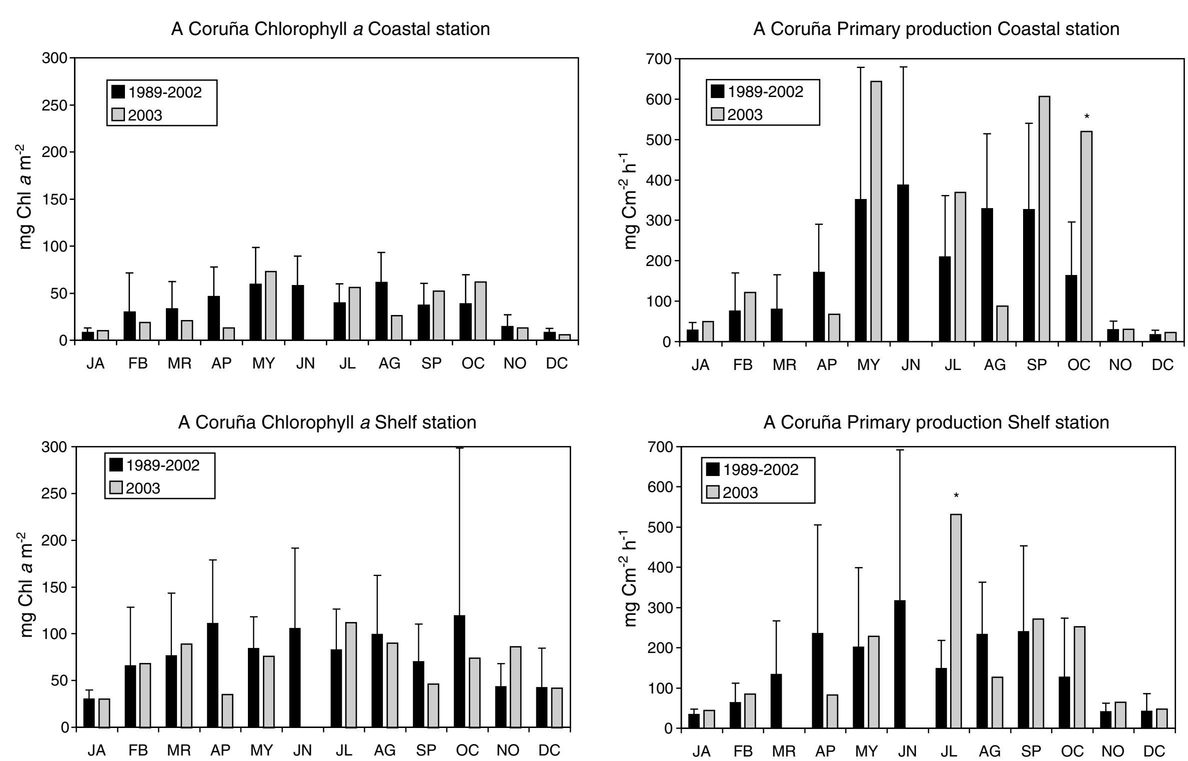

Fig. 2. Monthly integrated chlorophyll and primary production during 2003 compared to pre-spill data in coastal and shelf stations on the coast off A Coruña. Asterisk denotes significant differences ($p \geqslant 0.5$).

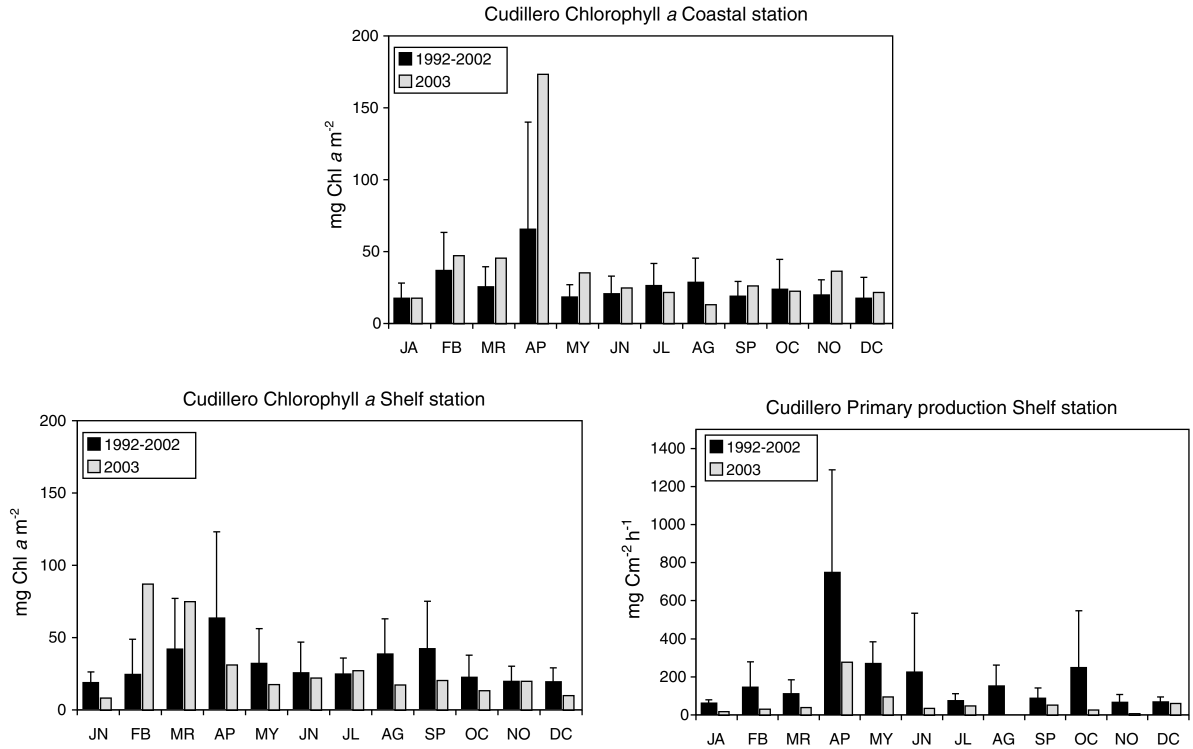

Fig. 3. Monthly integrated chlorophyll and primary production during 2003 compared to pre-spill data in coastal and shelf stations in the coast off Cudillero.

in 1999. Minimum values for both zones were recorded in 2004. Mean values of primary production were around 200 gC m^{-2} y and 350 g cm^{-2} y for ocean and shelf waters respectively. In general, satellite data showed less variability than field data, as the satellite is not able to detect the large vertical variations that tend to occur in the water column.

3.2. Phytoplankton community

Diatoms formed the bulk of the phytoplankton community in both Galicia (A Coruña) and the Southern Bay of Biscay (Cudillero, Asturias). Both diatoms and dinoflagellates exhibited large inter-annual and spatial variations as well. Dinoflagellates presented similar values in both zones even though they were comparatively more abundant in summer in Cudillero (Fig. 5). Diatoms showed similar abundances in both areas during spring, but in Galicia, higher concentrations were maintained throughout the summer until autumn. After spring, in contrast, values dropped significantly during summer in the Southern Bay of Biscay.

In both areas a great year-to-year variability was observed, especially for the more productive periods. Mean diatom values may reach 25000×10^6 cells m^{-2}, but maximum values can be up to four times higher. This high variability is related to the intensity of ENACW upwelling events during the summer in Galician waters (Campos and Mariño, 1984; Bode et al., 1994; Casas et al., 1997, 1999), and to meteorological and oceanographic conditions (influence of the Poleward current) prevailing during spring, which may or may not favour the development of a spring bloom (Casas et al., 1997; Fernández et al., 1991; Álvarez-Salgado et al., 2003).

During the spring bloom, diatoms dominated the phytoplankton community far above the others (Table 1). *Chaetoceros socialis* was the most abundant species in the study area with *Detonula pumila*, *Guinardia delicatula*, *Pseudo-nitzschia* cf. *pungens* and *Skeletonema costatum* as the main accompanying species. In contrast, dinoflagellates exhibited significantly lower abundances. As the standard deviations in Table 1 clearly show, the variations in abundance of all the species throughout the period covered by the data series are extremely high.

During the *Pelacus* cruises, diatoms clearly dominated the phytoplankton community for all areas and years (Table 2). *Detonula pumila*, *Pseudo-nitzschia* cf *pungens*, *Cerataulina pelagica* and *Guinardia delicatula* were the most representative species. Only occasionally did some species of large dinoflagellates, mainly *Ceratium furca*, appear in remarkable quantities.

3.3. Zooplankton biomass and community

Zooplankton biomass showed a clear inshore–offshore gradient with higher values inshore (Figs. 6–8). Biomass in the coastal stations showed similar values for all the locations (mean values of about 50 mg DW m^{-3} for the

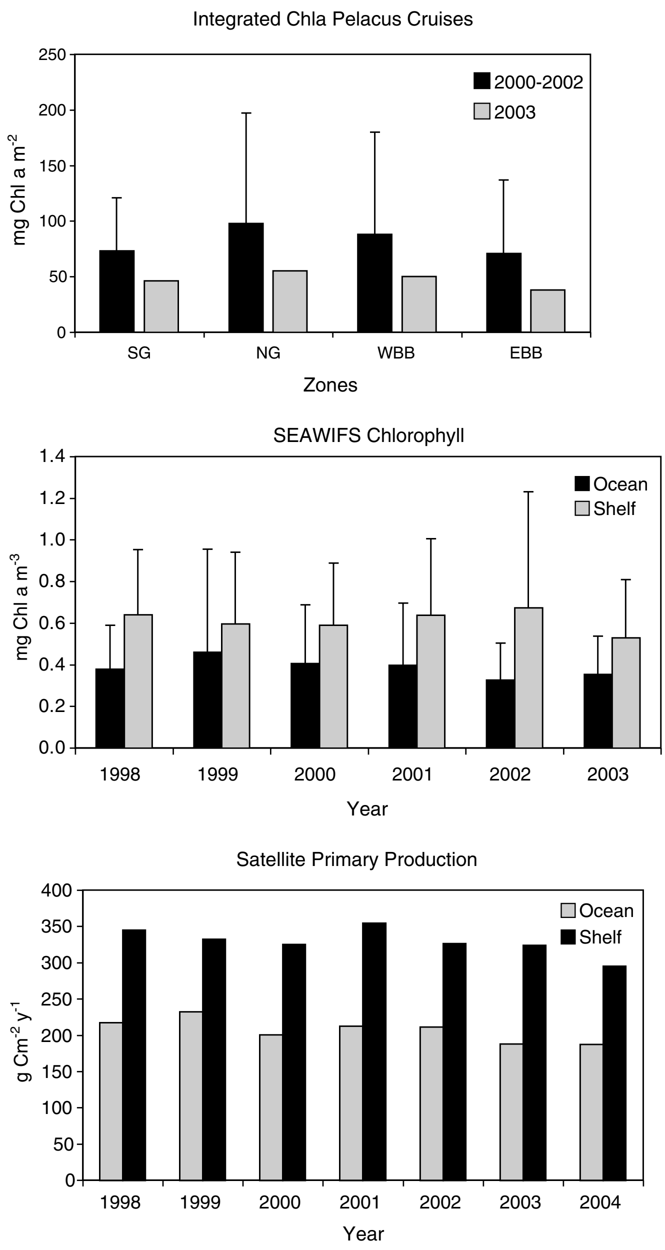

Fig. 4. Variation of integrated chlorophyll for 2003 compared to previous data series, in different areas of N–NW Spanish coast during *Pelacus* cruises. Data from. SG: South Galicia; NG: North Galicia. WBB: West Bay of Biscay; EBB: East Bay of Biscay. Yearly chlorophyll estimates from SeaWiFS for the area near Gijón from 1998 to 2003. Yearly primary production estimated from satellite images for the OMEX box area between Cape Finisterre and Ria de Vigo from 1998 to 2004.

more productive periods) except for Santander where values were lower (around 20 mg DW m^{-3} for the same periods, Fig. 8). In the shelf stations, a clear spatial gradient from Galicia to the Southern Bay of Biscay was observed. The highest biomass values were found on the shelf off Vigo in summer (between 50 and 60 mg DW m^{-3}), and the lowest in Santander (less than 20 mg DW m^{-3} in the same period). This is related to the influence of the upwelling of ENACW, which is more intense in Galician waters, especially off the Rias Bajas (Fraga, 1981).

The year-to-year variability of zooplankton data is lower than that of phytoplankton except for the shelf station in Vigo, where this variability is very high, especially in late spring and summer. This is probably related to inter-annual differences in upwelling intensity.

Calanoid copepods were by far the dominant species in the zooplankton community in these locations and the abundance of this group showed a similar pattern to that of biomass. The most representative calanoid species were *Acartia clausii*, *Calanus helgolandicus*, *Centropages chierchiae*, *Temora longicornis* and *Paracalanus parvus* (Table 3).

4. Discussion

4.1. Spatial and temporal coverage

This is probably one of the most complete studies carried out in the sea on the effects of oil spills on plankton communities owing to both the wide-ranging spatial and temporal coverage. Other complete studies (Johansson et al., 1980) did not extend beyond two months after the spill. This greatly limits the ability to evaluate possible changes in the trophic structure of pelagic system depending on the planktonic cycles in the area. In our case, we continued sampling one year after the spill to detect any possible effects of the spill on the main biological events in our area: the spring bloom and the summer blooms related to the upwelling of ENACW.

Most studies deal with a single or a few planktonic variables, mainly the abundance of a planktonic group or chlorophyll (Spooner, 1977; Scholten et al., 1987; Shailaja, 1988; Al-Yamani et al., 1993; Price et al., 1993; Al-Omran and Rao, 1999; Banks, 2003). In our case, however, we have included an important set of planktonic variables (zooplankton abundance and biomass, primary production, chlorophyll, phytoplankton and zooplankton species composition) to evaluate the effects from a broad perspective and for differential evaluation. Finally, this study benefits from the availability of a large set of historical reference data. Only a few studies have included such a vast amount of reference data and usually for only one variable (Reid, 1986; Batten et al., 1998; Banks, 2003). The lack of information on the spatial and temporal variability of the ecosystem is the main handicap for the natural approach of this kind of research when studying anthropogenic impacts (Dicks, 1982; Reid, 1986; Batten et al., 1998; Banks, 2003).

4.2. The effects on plankton

A few significant statistical differences (ANOVA post hoc tests $p \leqslant 0.5$) were found (Figs. 2–8). However, these differences do not follow a clear temporal pattern. In some areas these differences were found during the first months of 2003, while in others they appeared in summer and even in the winter immediately following the accident (Figs. 2, 5–8). This suggests that differences are more likely the

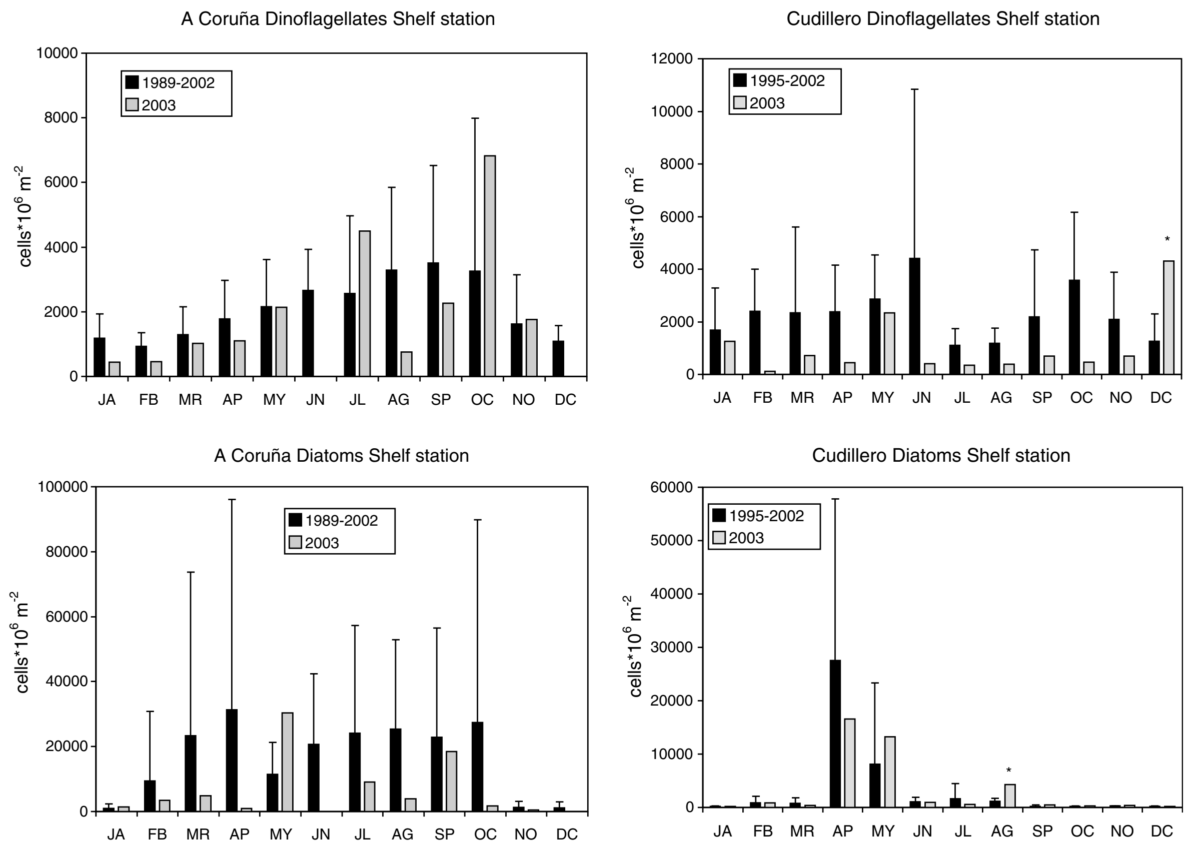

Fig. 5. Monthly integrated abundances of dinoflagellates and diatoms during 2003 compared to historical series in a shelf station on the coast off A Coruña and Cudillero. Asterisk denotes significant differences ($p \geqslant 0.5$).

result of the natural variability of the ecosystem rather than the direct effect of the fuel from the *Prestige*.

All the significant changes observed in phytoplankton and zooplankton species and zooplankton biomass involved increases in the values of these variables. This increase was usually observed between 4 and 8 months after the spill (Figs. 5–8). It is difficult to assume that the fuel had an effect after such a long time and that this effect was positive, as it consistently resulted in increased biomass or abundance. Even though a detailed analysis of the reasons for these increased values is beyond the scope of this paper, the peculiar hydrographic characteristics during the spring and summer of 2003 in the area studied, would provide a more consistent explanation than those related to the influence of the fuel (Ruiz-Villareal et al., this issue).

The spring bloom was the most important biological event occurring after the oil spill. The study of the effects during this period is relevant as the recruitment of many important shellfish and pelagic fishes depends on the normal development of this bloom. During the spring bloom no significant differences in phytoplankton biomass and primary production rates were detected. Nor were any changes in the dominance of the main phytoplankton groups observed. As expected for this time of the year, diatoms formed the bulk of the phytoplankton. No significant differences were found for either diatoms or dinoflagellates as compared with values reported before the spill. Similar results were found when a comparison was made at the species level. Only four species accounting for only 3% of the total species reported in the area during this period showed significantly higher values after the spill (Table 1). However, on the basis of these few changes, it is not possible to conclude that these differences are a consequence of the accident rather than a result of natural ecosystem variability, since most of the characteristic species of the spring phytoplankton bloom did not show statistically significant differences in abundance after the spill.

A data analysis of the whole N–NW Iberian Peninsula (*Pelacus* Cruises) did not reveal any significant differences between the 2000 and 2002 period and the year 2003. Values of Chl-*a* were low in all the areas during 2003 but fell within the variability range expected in this ecosystem (Fig. 4). The dominant phytoplankton species in the different study areas during 2000–2002 matched up well with those found in 2003 (Table 3). As expected, there was some variability among years, but most of the characteristic species were found again after the accident throughout the area of study. Similar results were obtained as regards the abundance of sardine eggs and larva (Porteiro, pers. commun.).

The available satellite information for chlorophyll and primary production, confirms the results obtained by field-

Table 1
Mean (cells/mL) and standard deviation of the more frequent phytoplankton species in a station off A Coruña and Cudillero, before and after the accident during the spring bloom period (February to May for A Coruña; April and May for Cudillero)

A Coruña	Before (1990–2002)			After (2003)		
Groups and species	%n	Mean	sd	%n	Mean	sd
Dinoflagellates						
Heterocapsa niei	39	2.0	3.9	75	0.9	0.6
Gyrodinium glaucum	22	0.1	0.2	75	0.4	0.3
Prorocentrum balticum	33	1.3	5.2	50	4.9	8.4
Scrippsiella trochoidea	24	0.5	2.1	25	0.1	0.1
Torodinium roubustum	33	0.2	0.3	50	0.3	0.3
Diatoms						
Asterionellopsis glacialis	33	1.7	4.5	25	0.2	0.3
Chaetoceros affinis	24	2.3	8.2	75	1.4	1.4
Chaetoceros compressus	16	12.9	70.5	25	0.9	1.5
Chaetoceros curvisetus	14	15.7	104.0	20	0.1	0.2
Chaetoceros didymus	29	5.1	15.8	50	0.9	1.4
Chaetoceros socialis	65	377.5	1138.1	75	31.6	44.0
Chaetoceros spp	47	4.3	14.2	75	16.5	21.0
Detonula pumila	43	13.3	26.3	20	0.1	0.1
Guinardia delicatula	51	13.7	52.3	100	2.9	2.0
Guinardia striata	14	0.3	1.6	25	0.5	0.9
Lauderia borealis	20	5.6	18.8	25	0.1	0.2
*Leptocylindrus danicus**	51	19.7	59.9	75	151.6	258.5
Leptocylindrus minimus	12	0.6	1.8	25	1.6	2.7
Nitzschia sp	14	1.5	4.9	50	0.7	0.9
Nitzschia longissima	51	1.3	2.5	75	2.0	2.2
Pseudo-nitzschia pungens	57	12.7	28.1	75	6.3	9.5
Pseudonitzschia delicatissima	10	0.6	2.5	50	0.8	1.2
Skeletonema costatum	39	13.8	46.2	25	0.1	0.1
Thalassionema nitzschoides	35	1.2	3.7	75	1.7	1.2
Thalassiosira fallax	22	0.9	2.8	50	1.1	1.6
Other phytoplankters						
Phaeocistis pouchetii	33	3.0	7.3	25	1.8	3.1
Solenicola setigera	22	9.4	46.9	75	10.6	17.6
Cudillero	Before (1995–2002)			After (2003)		
Groups and species	%n	Mean	sd	%n	Mean	sd
Dinoflagellates						
Heterocapsa niei	29	0.4	0.9	25	0.1	0.1
*Prorocentrum balticum**	14	0.1	0.4	100	3.2	2.6
Scrippsiella trochoidea	57	0.6	0.8	50	0.2	0.2
Diatoms						
Asterionellopsis glacialis	14	0.2	0.7	50	0.2	0.2
Bacteriastrum hyalinum	14	1.3	3.3	25	0.1	0.1
Cerataulina pelagica	21	0.3	1.1	25	0.1	0.2
*Chaetoceros curvisetus**	14	0.2	0.6	50	16.5	16.5
Chaetoceros danicus	29	0.4	0.9	25	0.1	0.1
Chaetoceros socialis	7	121.4	437.7	50	191.0	191.0
Detonula pumila	57	11.6	26.7	50	0.1	0.1
Guinardia delicatula	57	38.3	109.2	25	0.1	0.1
Leptocylindrus danicus	71	67.0	224.8	100	46.1	43.6
Leptocylindrus minimus	7	0.1	0.3	50	24.6	24.6
*Pseudo-nitzschia pungens**	93	3.1	5.3	100	93.2	93.1
Rhizosolenia setigera	36	0.4	1.1	25	0.1	0.1
Skeletonema costatum	14	23.9	86.0	50	12.4	12.4

n (before): percentage of species appearance for the total number of samples (49). *n* (after) the same for four samples. Asterisk denotes significant differences ($p \geqslant 0.5$).

work. No significant differences were observed for 2003 and 2004 as compared to the previous years (Fig. 4). During 2003 only one single bloom extended from the coast to the oceanic Bay of Biscay near Gijón as opposed to two blooms in the mean distribution (1998–2002). However, the inter-annual standard deviation of the second bloom is comparable to the mean so its absence in 2003 may be considered as included in the natural year-to-year

Table 2
Main phytoplankton species ranked by order of relative abundance during the 2000–2002 period before the accident and for year 2003, after the accident from *Pelacus* Cruises

Zone	Year before			Year after
	2000	2001	2002	2003
SG	*Leptocylindrus danicus* *Pseudo-nitzschia cf pungens* *Guinardia delicatula*	*Skeletonema costatum* *Detonula pumila* ***Ceratium furca***	*Asterionellopsis glacialis* *Thalassiosira rotula* *Chaetoceros decipiens* *Detonula pumila*	***Ceratium furca*** *Detonula pumila*
NG	*Chaetoceros socialis* *Pseudo-nitzschia cf pungens* *Guinardia delicatula*	*Bacteriastrum delicatulum* *Skeletonema costatum* *Detonula pumila* *Guinardia flaccida*	*Thalassiosira rotula* *Detonula pumila* *Thalassionema nitzschioides* *Chaetoceros curvisetus*	*Guinardia delicatula* *Detonula pumila* *Chaetoceros curvisetus* *Chaetoceros decipiens* *Thalassionema nitzschioides*
WBB	*Guinardia delicatula* *Detonula pumila* *Pseudo-nitzschia cf pungens*	*Guinardia flaccida* *Detonula pumila* *Cerataulina pelagica*	*Detonula pumila* *Asterionellopsis glacialis* ***Ceratium furca*** *Cerataulina pelagica* *Pseudo-nitzschia cf pungens* *Thalassionema nitzschioides*	*Pseudo-nitzschia cf pungens* *Proboscia alata* ***Ceratium furca*** *Detonula pumila*
EBB	*Guinardia delicatula* *Pseudo-nitzschia cf pungens*	*Cerataulina pelagica* *Detonula pumila* ***Ceratium furca*** *Leptocylindrus danicus* *Pseudo-nitzschia cf pungens*	*Detonula pumila* ***Ceratium furca*** *Pseudo-nitzschia cf pungens* *Cerataulina pelagica*	*Pseudo-nitzschia cf pungens* *Proboscia alata* *Leptocylindrus danicus* *Detonula pumila*

SG: Southern Galicia; NG: Northern Galicia; WBB: Western Bay of Biscay; EBB: Eastern Bay of Biscay. Names in lightface print: diatoms; names in boldface print: dinoflagellates.

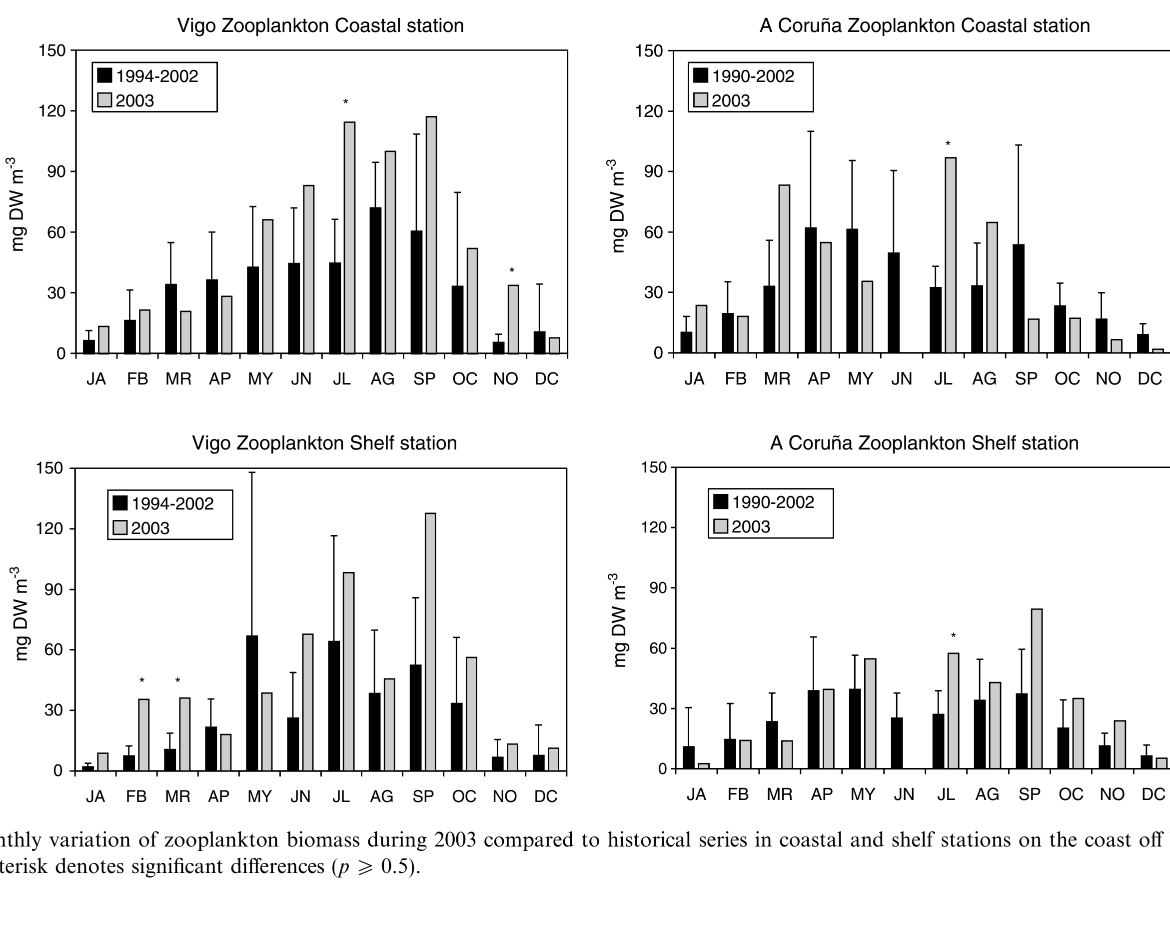

Fig. 6. Monthly variation of zooplankton biomass during 2003 compared to historical series in coastal and shelf stations on the coast off Vigo and A Coruña. Asterisk denotes significant differences ($p \geqslant 0.5$).

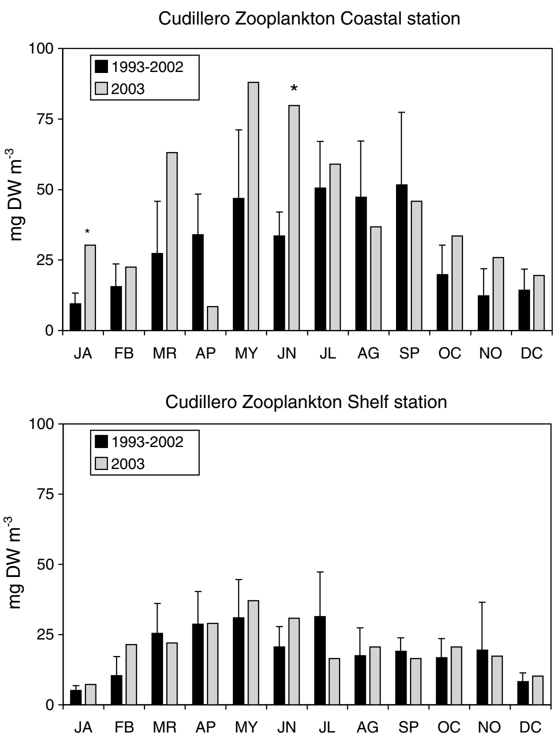

Fig. 7. Monthly variation of zooplankton biomass during 2003 compared to historical series in coastal and shelf stations on the coast off Cudillero. Asterisk denotes significant differences ($p \geqslant 0.5$).

variability of this ecosystem. Values of satellite derived primary production showed no differences in 2003 as compared to previous years in the OMEX Box area in front of the Rias Bajas (Fig. 4). Since most of yearly primary production occurs during the spring and summer upwelling blooms, it may be concluded that these events were similar in intensity from 1998 to 2004.

The data on zooplankton do not reveal any significant shifts in biomass after the spill during the spring bloom. As in previous years, calanoid copepods were the dominant group of zooplankton in 2003. Statistical tests for the main calanoid copepods during this period did not exhibit any changes in abundance except for one species in the Ria de Vigo (Table 3). As in the case of phytoplankton species, this is probably related to natural variability. Similar results were obtained when other holoplanktonic (cladocera, tintinids) or meroplanktonic (crustacea, briozoa or equinoderm larva) groups were considered.

4.3. Comparison with other studies

A comparison with other spills is difficult because each one has its own characteristics with various types of oils, environmental conditions and planktonic communities involved. Despite these limitations, our results were similar to those reported in other studies. In fact, the investigations carried out on different spills have not been able to demonstrate important effects on pelagic organisms (Michael, 1977; Sandborn, 1977; Spooner, 1977). It was not possible to demonstrate any major effects on the phytoplankton community after the *Torrey Canyon* (Nelson-Smith, 1970), the *Santa Barbara* (Straughan, 1972), the *Argo Merchant* (Kühnhold, 1978), the *Tsesis* (Linden et al., 1979; Johansson et al., 1980) or the *Aegean Sea* (Varela et al.,

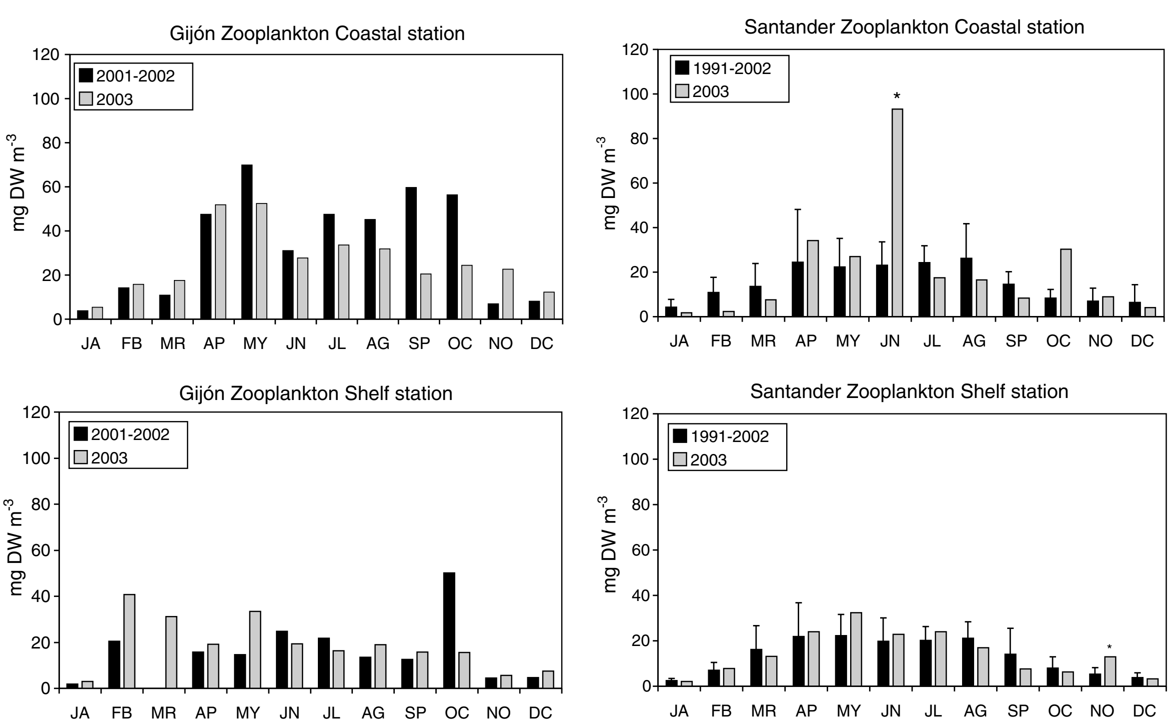

Fig. 8. Monthly variation of zooplankton biomass during 2003 compared to historical series in coastal and shelf stations on the coast off Gijón and Santander. Asterisk denotes significant differences ($p \geqslant 0.5$).

Table 3
Mean (abundance/m^3) and standard deviation of selected copepods species during the spring bloom in different areas before and after *Prestige* oil spill

	Vigo		Coruña		Cudillero		Santander	
	Before	After	Before	After	Before	After	Before	After
Coastal stations								
Acartia clausi	1572 ± 1365	695 ± 120	2630 ± 2248	4054 ± 1555				
Calanus helgolandicus	143 ± 111	125 ± 192	61 ± 159	253 ± 10				
Centropages chierchiae	73 ± 100	12 ± 15	35 ± 87	127 ± 27				
Paracalanus parvus	193 ± 144	641 ± 75*	341 ± 307	111 ± 42				
Temora longicornis	236 ± 185	206 ± 102	366 ± 461	133 ± 38	52 ± 87	14 ± 23		
Shelf stations								
Acartia clausi	2363 ± 5159	290 ± 32	724 ± 635	390 ± 131			200 ± 236	362 ± 293
Calanus helgolandicus	2086 ± 5868	136 ± 30	25 ± 24	10 ± 8			95 ± 159	69 ± 117
Centropages chierchiae	53 ± 71	18 ± 19	62 ± 83	32 ± 14			15 ± 62	17 ± 24
Paracalanus parvus	478 ± 1113	161 ± 78	458 ± 443	127 ± 35			277 ± 255	279 ± 161
Temora longicornis	158 ± 193	11 ± 15	87 ± 102	19 ± 13	7 ± 10	4 ± 7	28 ± 45	6 ± 7

Asterisk denotes statistical significant differences ($p \leqslant 0.5$).

1996). One of the drawbacks of most of the above studies is the short duration of the research after the spill and the lack of previous information for comparisons. However, our results are comparable with those reported by Reid (1986) in the area of North Sea oil platforms or Batten et al. (1998) after the *Empress* oil spill, using long data series.

4.4. The reasons for reduced or no effects

The main question arising from the results obtained is: why were clear effects not observed in spite of the large amount of fuel released into the pelagic system? Several reasons can be pointed out. The first is related to the type of fuel. The solubility of this fuel was very low so measurements of the water-soluble fraction indicated hydrocarbon concentrations slightly over the background values (González et al., this issue). In addition, the *Prestige* oil was a high-density fuel with an elevated tendency to sink (Serrano et al., this issue).

The high dynamics of water in the area of the accident favoured not only the dispersion of oil and the eventual decrease in the effects on plankton, but also the recovery of the potential losses. Some papers (Spooner, 1977) reported a quick improvement in the water quality, related to the mixing of water masses carrying new plankton forms from unaltered areas.

The season of the year may also be considered an important factor to take into account when explaining the lack of relevant effects. The *Prestige* spill occurred during the winter when plankton biomass is low, therefore resulting in limited effects. Extremely adverse weather conditions such as those prevailing at the time of the accident helped to spread the fuel and clean the water column.

The low concentrations of hydrocarbons in the water and consequently, their reduced effects may be related to the active role of bacteria in the degradation processes of oil. Under optimal conditions bacteria can degrade up to 60–80% of crude oil (Gutnick and Rosenberg, 1977). No historical data on bacteria were available in the area affected by the *Prestige* spill. However, the rates of bacterial production measured in December and January 2003 off A Coruña were slightly higher than the values measured for the area in previous years (Valencia et al., 2003), indicating the presence of oil and the importance of these microorganisms in the degradation processes and the low hydrocarbon concentrations measured (González et al., this issue). The presence of hydrocarbons in shelf waters off A Coruña was confirmed by the recovery of haul nets with fuel particles and the observation of fuel adhered to the bodies of copepods.

Several studies carried out over the last few years have demonstrated the existence of an important mechanism involving oil sedimentation on the sea floor by means of planktonic organisms. Zooplankton is able to feed on oil particles (Johansson et al., 1980; Sleeter and Butler, 1982), which are incorporated to faecal pellets. The high sinking rates of pellets could accelerate sedimentation, especially at low water temperatures (Honjo and Roman, 1978). Up to 30% of surface hydrocarbons could be removed from surface waters through zooplankton pellets (Sleeter and Butler, 1982). This mechanism might have operated after the *Prestige* spill. Oil was frequently observed in the gut contents of copepods in a station off A Coruña in December and January 2003. Previous studies on the vertical flux of organic matter showed a significant amount of zooplankton faecal pellets recovered in sediment moored off A Coruña (Bode et al., 1998), supporting the idea of the important role of zooplankton in the short-term removal of fuel particle residues from surface waters. The possible accumulation of toxic hydrocarbons by phytoplankton and eventual predation of zooplankton as a removal mechanism must be taken into account as well. In any case, this process might only be important in the case of microzooplankton (Bode et al., 2003).

The vertical transport of a large soluble fraction of oil to the bottom may take place after adsorption to suspended amorphous matter (detritus) and living diatoms (Ohwada et al., 2003). Both diatoms and detritus (as well as zooplankton pellets), represent an important part of the material recovered in sediment traps in Galician coastal waters (Bode et al., 1998; Varela et al., 2004) and diatoms are the dominant phytoplankton group in the area (Varela et al., 2001). This would suggest a potentially important flux of the soluble fraction to the bottom by means of diatoms and detritus in Galician waters. The joint action of zooplankton diatoms and detritus could explain the high percentage of oil transported to the bottom in the days immediately following a spill, ranging between 15% and 39% as reported in some studies (Lee et al., 1978b; Gearing et al., 1979; Johansson et al., 1980).

The reduced impact on the pelagic system is also the result of the capability of both phytoplankton and zooplankton to metabolize hydrocarbons (Walters, 1982). Many studies have demonstrated limited effects and fast recovery of growth rates after a short lag period following exposition to fuel, even at concentrations of one order of magnitude higher than those reported for the *Prestige* spill (Herbert and Poulet, 1980; Thomas et al., 1981). This ability of the plankton would result in an additional decrease in the concentration of hydrocarbons in the water.

The available information points to the efficiency of physico-chemical, physiological, and biological mechanisms in particular, in the dispersion or removal of petroleum components from ocean waters and their transport to the sea bottom. These processes could explain the reduced effect on the planktonic system and the more important effects on bottom communities as reported in other studies on spills (Davies et al., 1981; López-Jamar et al., 1996; Varela et al., 1996).

4.5. The importance of natural variability

Some authors reported variations in planktonic systems after spills in some areas, but according to historical data, the magnitude of these changes were within the range of ecosystem variability. Price et al. (1993) pointed out that the decrease in the abundance of some larvae in the Arabian Gulf was more related to natural environmental changes than to the enormous spill resulting from the Gulf War. The minor shift in species composition observed after the *Empress* oil spill (Batten et al., 1998) may be attributed to other factors related to the natural variability of the ecosystem rather than to the oil spill. Banks (2003) showed that the variance observed in phytoplankton biomass following the *Jessica* oil spill in the Galapagos Islands was not significant in comparison to the normally high variability between years caused by variations in the intensity of El Niño. The minor changes observed in the planktonic community off A Coruña after the accident of the *Aegean Sea* in 1992 were due more to the marked variability of the ecosystem in the near shelf, associated to the upwelling of ENACW, than to the oil spill (Varela et al., 1996).

A good knowledge of the year-to-year variability of the ecosystems affected by oil spills is essential to be able to evaluate the impact on the environment. Otherwise it will not be possible to conclude whether or not the results observed are a consequence of the effects of the oil or if they fall within the range of ecosystem variability. Therefore long data series are essential to make an assessment of any anthropogenic impact. In the present study the data supplied by the IEO Core Project, *Studies on time Series of Oceanographic Data*, provided sound information on the natural variability of the pelagic ecosystem at different levels of the planktonic component, allowing for a realistic evaluation of oil effects.

The results of this study have showed, on the one hand, the great natural variability of the pelagic ecosystem of the N–NW Spanish coast, and on the other, the lack of detectable effects of *Prestige* oil on planktonic communities. However we cannot ascertain whether or not there are, in fact, effects. In this ecosystem, influenced by large and meso-scale hydrological phenomena as well as a marked seasonality in the development of biological processes, the great variability of planktonic cycles will probably conceal any low intensity effect.

In our case it is unlikely that *Prestige* shipwreck had any relevant effect even in the short-term. Not only were the concentrations of oil measured during the study period low, but also the fuel observed was not always related to the wreck (González et al., this issue). The few significant changes observed in phytoplankton species composition and zooplankton biomass may be explained by changes in environmental conditions over the course of the year 2003. The phytoplankton species showing significantly higher values in spring (Table 1), are typical of upwelling conditions, which are predominant during the summer in this area (Casas et al., 1999). Upwelling events started earlier in 2003—in March and April in the Galician and Southern Bay of Biscay (Ruiz-Villareal et al., this issue). This advance in the upwelling season could explain the higher biomass of these phytoplankton species. The higher zooplankton biomass found occasionally in summer months (Figs. 6–8) may be related to the unusually warm temperatures during the summer of 2003. These temperatures coincided with reduced upwelling intensity (Ruiz-Villareal et al., this issue), but it was still strong enough to maintain relatively high values of chlorophyll (Figs. 2 and 3) to support an large zooplankton biomass with increasing growth rates favoured by warmer waters. Therefore, the few variations found in plankton may be explained by natural changes in the environmental conditions of the ecosystem of the area of study and not by effects caused by the *Prestige* oil spill.

5. Conclusions

No relevant effects on the pelagic system were observed in the study area. There were not any noticeable changes in phytoplankton primary production and no alterations in either phytoplankton or zooplankton biomass were detected as compared to previous years. The phytoplankton and zooplankton community structure did not exhibit any significant differences before and after the spill. Despite the fact that zooplankton copepods were found to be contaminated with oil—externally as well as internally—no harmful effects were observed to cause changes in the biomass or community structure.

Only a few, occasional variations were observed in plankton communities, but they were related to variations on a temporal scale of oceanographic processes typical of this ecosystem, mainly upwelling of ENACW, and not to the effect of the oil.

Through field studies, we are unable to ascertain whether or not oil has affected plankton, especially in the short-term, because meso and large-scale hydrographic processes can cause extreme variability in plankton, masking any effect of the oil, especially when, as in this case, the effect is reduced or short-lived.

In the case of new spills, the studies of the effects on plankton must be extended until the next important biological period, such as, in our case, the phytoplankton spring bloom, with special emphasis on plankton community structure. In areas where the probability of oil spills is high and no previous information exists, monitoring programs should be implemented to obtain information on the year-to-year variability of the ecosystem.

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References

Al-Omran, L.A., Rao, C.V.N., 1999. The distribution and sources of hydrocarbons in the regional sea area of the Arabian Gulf. Kuwait Journal of Science and Engineering 26 (2), 301–314.

Álvarez-Salgado, X.A., Rosón, G., Pérez, F.F., Pazos, Y., 1993. Hydrographic variability off the Rias Baixas (NW Spain) during the upwelling season. Journal of Geophysical Research 98, 14447–14455.

Álvarez-Salgado, X.A., Figueiras, F.G., Pérez, F.F., Groom, S., Nogueira, E., Borges, A., Chou, L., Castro, C.G., Moncoiffé, G., Ríos, A.F., Miller, A.E.J., Frankignoulle, M., Savidge, G., Wollast, R., 2003. The Portugal Coastal Counter Current off NW Spain: new insights on its biogeochemical variability. Progress in Oceanography 56, 281–321.

Al-Yamani, F., Al-Rifaie, K., Ismail, W., 1993. Post-spill zooplankton distribution in the NW Gulf. Marine Pollution Bulletin 27, 239–243.

Banks, S., 2003. SeaWiFS satellite monitoring of oil spill impact on primary production in the Galapagos Marine Reserve. Marine Pollution Bulletin 47 (7–8), 325–330.

Bate, G.C., Crafford, S.D., 1985. Inhibition of phytoplankton photosynthesis by the WSF of used lubricating oil. Marine Pollution Bulletin 16 (10), 401–404.

Batten, S.D., Allen, R.J.S., Wotton, C.O.M., 1998. The effects of the Sea Empress oil spill on the plankton of the southern Irish Sea. Marine Pollution Bulletin 36 (10), 764–774.

Blanton, J.O., Atkinson, L.P., Fernandez, F., Lavin, A., 1984. Coastal upwelling off the Rias Bajas, Galicia, Northwest Spain I: Hydrographic studies. Réunion Conseil internationalle Exploration de la Mer 183, 79–90.

Blanton, J.O., Tenore, K.R., Castillejo, F., Atkinson, L.P., Schwing, F.B., Lavin, A., 1987. The relationship of upwelling to mussel production in the rias on the western coast of Spain. Journal of Marine Research 45, 497–511.

Bode, A., Varela, M., 1998. Primary production and phytoplankton in three Galician Rias Altas (NW Spain): seasonal and spatial variability. Scientia Marina 62 (4), 319–330.

Bode, A., Casas, B., Varela, M., 1994. Size-fractionated primary productivity and biomass in the Galician shelf (NW Spain): Netplankton versus nanoplankton dominance. Scientia Marina 58 (1–2), 131–141.

Bode, A., Casas, B., Fernández, E., Marañón, E., Serret, P., Varela, M., 1996. Variability of phytoplankton biomass and primary productivity in the shelf waters of the upwelling area of N–NW Spain. Hydrobiologia 341, 225–234.

Bode, A., Varela, M., Barquero, S., Alvarez-Ossorio, Ma.T., González, N., 1998. Preliminary studies on the export of organic matter during phytoplankton blooms off La Coruña (North-western Spain). Journal of Marine Biological Association UK 78, 1–15.

Bode, A., Varela, M., Casas, B., González, N., 2002. Intrusions of eastern North Atlantic central waters and phytoplankton in the northwestern Iberian shelf during spring. Journal of Marine Systems 36, 197–218.

Bode, A., Alvarez-Ossorio, M.T., Barquero, S., Lorenzo, J., Louro, A., Varela, M., 2003. Seasonal variations in upwelling and in the grazing impact of copepods on phytoplankton off A Coruña (Galicia, NW Spain). Journal of Experimental Marine Biology and Ecology 297, 85–105.

Campos, M.J., Mariño, J., 1984. El ciclo anual del fitoplancton en la ría de Arosa (1978–1979). Boletín del Instituto Español de Oceanografía 1 (2), 20–30.

Casas, B., Varela, M., Canle, M., Gónzalez, N., Bode, A., 1997. Seasonal variations of nutrients, seston and phytoplankton, and upwelling intensity off La Coruña (NW Spain). Estuarine, Coastal and Shelf Science 44, 767–778.

Casas, B., Varela, M., Bode, A., 1999. Seasonal succession of phytoplankton species in the coast of La Coruña (Galicia, NW of Spain). Boletín del Instituto Español de Oceanografía 15 (1–4), 413–429.

Corner, E.D.S., 1975. The fate of fossil fuel hydrocarbons in marine animals. Proceedings of the Royal Society B 189, 391–413.

Davenport, J., 1982. Oil and planktonic ecosystems. Philosophical Transactions of the Royal Society of London Series B 297 (1087), 369–384.

Davies, J., Hardy, R., McIntyre, A., 1981. Environmental effects of North Sea oil operations. Marine Pollution Bulletin 12 (12), 412–416.

de la Cruz, A., 1982. Effects of oil on phytoplankton metabolism in natural and experimental estuarine ponds. Marine Environmental Research 7 (4), 257–264.

Dicks, B., 1982. Monitoring the biological effects of North Sea platforms. Marine Pollution Bulletin 13 (7), 221–227.

Doerffer, J., 1992. Oil Spill Response in the Marine Environment. BPCC Wheatons Ltd., Great Britain, UK, pp. 125–135.

Fernández, E., Bode, A., Botas, A., Anadón, R., 1991. Microplankton assemblages associated with saline fronts during a spring bloom in the central Cantabrian Sea: differences in trophic structure between water bodies. Journal of Plankton Research 13 (6), 1239–1256.

Fraga, F., 1981. Upwelling off the Galician Coast, Northwest Spain. In: Richards, F.A. (Ed.), Coastal Upwelling. American Geophysical Union, Washington, DC, pp. 176–182.

Frouin, R., Fiúza, A.F.G., Ambar, I., 1990. Observations of a poleward surface current off the coasts of Portugal and Spain during winter. Journal of Geophysical Research 95, 679–691.

García-Soto, C., 2004. "Prestige" oil spill and Navidad flow. Journal of Marine Biological Association UK 84, 4534, 1–4.

Gearing, J.N., Gearing, P.J., Wade, T., Quinn, J.G., McCarthy, H.B., Farrington, J., Lee, R.F., 1979. The rates of transport and fates of petroleum hydrocarbons in a controlled marine ecosystems, and a note on analytical variability. In: Proceedings 1979 Oil Spill Conference (Prevention, Behaviour, Control, Cleanup), 19–22 March, Los Angeles, California.

Gin, K.Y.H., Huda, M.D.K., Lim, W.K., Tkalich, P., 2001. An oil spill-food interaction model for coastal waters. Marine Pollution Bulletin 42 (7), 590–597.

González, J.J., Viñas, L., Franco, M.A., Fumega, J., Soriano, J.A., Grueiro, G., Muniategui, S., López-Mahía, P., Prada, D., Bayona, J.M., Alzaga, R., Albaigés, J., this issue. Spatial and temporal distribution of dissolved/dispersed aromatic hydrocarbons in seawater in the area affected by the Prestige oil spill. Marine Pollution Bulletin.

Gutnick, D., Rosenberg, E., 1977. Oil tankers and pollution: a microbiological approach. Annual Review Microbiology 31, 379–396.

Hebert, R., Poulet, S.A., 1980. Effect of particle size of emulsions of Venezuelan crude oil on feeding, survival and growth of marine zooplankton. Marine Environmental Research 4 (2), 121–134.

Honjo, S., Roman, M.R., 1978. Marine copepods fecal pellets: production, preservation and sedimentation. Journal of Marine Research 36 (1), 45–57.

Johansson, S., Larsson, U., Boehm, P., 1980. The Tsesis oil spill. Impact on the pelagic ecosystem. Marine Pollution Bulletin 11 (10), 284–293.

Joint, I., Groom, S., Wollast, R., Chou, L., Tilstone, G.H., Figueiras, F.G., Loijens, M., Smyth, T.J., 2002. The response of phytoplankton production to periodic upwelling and relaxation events at the Iberian shelf break: estimates by the 14C method and by satellite remote sensing. Journal of Marine Systems 32, 219–238.

Kühnhold, W.W., 1978. Impact of the *Argo Merchant* oil spill on macrobenthic and pelagic organisms. Paper presented at the AIBS Conference Assessment of Ecological Impact of Oil Spill, 14–17 June 1975, Keystone, Colorado, USA.

Lacaze, J.C., Villedon de Naïde, O., 1976. Influence of illumination on phytoxicity of crude oil. Marine Pollution Bulletin 7 (4), 73–76.

Lännergren, C., 1978. Net- and nanoplankton: effects of an oil spill in the North Sea. Botanica Marina 21, 353–356.

Lee, R.F., Takahashi, M., Beers, J., 1978a. Short term effects of oil on plankton in controlled ecosystems. In: Conference Assessement of Ecological Impacts of Oil Spills, 14–17 June 1978, Keystone, Colorado, American Institute of Biological Sciences.

Lee, R.F., Gardner, W.S., Anderson, J.W., Blaylock, J.W., Barwell-Clarke, J., 1978b. Fate of polycyclic aromatic hydrocarbons in controlled ecosystem enclosures. Environmental Science Technology 12, 832–838.

Linden, O., Elmgren, R., Boehm, P., 1979. The Tsesis oil spill: its impact on the coastal ecosystem of the Baltic Sea. Ambio 8 (6), 244–253.

López-Jamar, E., Bode, A., Parra, S., Vázquez, A., 1996. Consecuencias del vertido de crudo del Aegean Sea sobre la macrofauna bentónica submareal. In: Seguimiento de la contaminación producida por el accidente del buque Aegean Sea, Ministerio de Medio Ambiente (Ed.), pp. 67–106.

Mahoney, B.M., Haskin, H.H., 1980. The effects of petroleum hydrocarbons on the growth of phytoplankton recognised as food forms for the eastern oyster, Crassostrea virginica Gmelin. Environmental Pollution 22A (2), 123–132.

Michael, A.D., 1977. The effects of petroleum hydrocarbons on marine populations and communities. In: Wolfe, D.A. (Ed.), Fate and Effects of Petroleum Hydrocarbons in Marine Ecosystems and Organisms. Pergamon Press, Oxford, pp. 129–137.

Nelson-Smith, A., 1970. The problem of oil pollution of the Sea. In: Russel, F.S., Yonge, M. (Eds.), Advances in Marine Biology, vol. 8. Academic Press, London and New York, pp. 215–306.

Ohwada, K., Nishimura, M., Wada, M., Nomura, H., Shibata, A., Okamoto, K., Toyoda, K., Yoshida, A., Takada, H., Yamada, M., 2003. Study of the effect of water-soluble fractions of heavy-oil on coastal marine organisms using enclosed ecosystems, mesocosms. Marine Pollution Bulletin 47, 78–84.

Ostgaard, K., Eide, I., Jensen, A., 1984. Exposure of phytoplankton to Ekofish crude oil. Marine Environmental Research 11 (3), 183–200.

Price, A., Mathews, C., Ingle, R., Al-Rasheed, K., 1993. Abundance of zooplankton and penaeid larvae in the western Gulf: analysis of pre-war and post-war data. Marine Pollution Bulletin 27, 273–278.

Reid, P.C., 1986. The importance of the planktonic ecosystem of the North Sea in the context of oil and gas development. Philosophical Transactions of the Royal Society of London Series B 316 (1181), 587–602.

Ruiz-Villareal, M., González-Pola, C., Díaz del Río, G., Lavín, A., Piedracoba, S., Otero, P., Cabanas, J.M., this issue. Oceanographic conditions in Galicia and the Southern Bay of Biscay and their influence on the Prestige oil spill. Marine Pollution Bulletin.

Sandborn, H.R., 1977. Effects of petroleum on ecosystems. In: Malins, D.C. (Ed.), Effects of Petroleum on Arctic and Subarctic Marine Environments and Organisms. Academic Press, New York, pp. 337–357.

Scholten, M., Kuiper, J., Groenewoud, H., Hoornsman, G., Vlies, E., 1987. The effects of oil and chemically dispersed oil on natural phytoplankton communities. Fate and effects of oil in marine ecosystems. In: Proceedings of the Conference on oil pollution organized under the auspices of the (AWWPRC), pp. 173–185.

Serrano, A., Sánchez, F., Preciado, I., Parra, S., Frutos, I., this issue. Spatial and temporal changes in benthic communities of the Galician Continental Shelf after the *Prestige* oil spill. Marine Pollution Bulletin.

Shailaja, M., 1988. The influenced of dissolved petroleum hydrocarbons residues on natural phytoplankton biomass. Marine Environmental Research 25 (4), 315–324.

Sleeter, T.D., Butler, J.N., 1982. Petroleum hydrocarbons in zooplankton faecal pellets from the Sargasso Sea. Marine Pollution Bulletin 13 (2), 54–56.

Spooner, M., 1977. Oil spill in Hong Kong. Marine Pollution Bulletin 8 (3), 62–65.

Spooner, M., Corkett, C., 1979. Effects of Kuwait oils on feeding rates of copepods. Marine Pollution Bulletin 10 (7), 197–202.

Straughan, D., 1972. Biological effects of oil pollution in the Santa Barbara Channel. In: Ruivo, M. (Ed.), Marine Pollution and Sea Life. Fishing News Books Ltd., London, pp. 355–359.

Thomas, W.H., Rossi, S.S., Seibert, D.L.R., 1981. Effects of some representative petroleum refinery effluent compounds of photosynthesis and growth of natural marine phytoplankton assemblages. Marine Environmental Research 4 (3), 203–215.

Throndsen, J., 1982. Oil pollution and plankton dynamics.III. Effects on flagellate communities in controlled ecosystem experiments in Lindaspollene, Norway, June 1980 and 1981. Sarsia 67 (3), 163–169.

Unesco, 1994. Protocols for the Joint Global Ocean Flux Study (JGOFS) core measurements. Manuals and Guides 29, 1–70.

Valdés, L., Lavín, A., Puelles, M.L.F.D., Varela, M., Anadón, R., Miranda, A., Camiñas, J., Mas, J., 2002. Spanish Ocean Observation System. IEO Core Project: studies on time series of oceanographic data. In: Flemming, N.C., Vallerga, S., Pinardi, N., et al. (Eds.), Operational Oceanography: Implementation at the European and regional Scales. Elsevier Science BV, pp. 99–105.

Valencia, J., Abalde, J., Bode, A., Cid, A., Fernández, E., González, N., Lorenzo, J., Teira, E., Varela, M., 2003. Variations in planktonic bacterial biomass and production, and phytoplankton blooms off A Coruña (NW Spain). Scientia Marina 67 (2), 143–157.

Varela, M., 1992. Upwelling and phytoplankton ecology in Galician (NW Spain) rías and shelf waters. Boletín del Instituto Español de Oceanografía 8 (1), 57–74.

Varela, M., 1996. Phytoplankton ecology in the Bay of Biscay. Scientia Marina 60 (2), 45–53.

Varela, M., Prego, R., 2003. Hydrography and phytoplankton in an isolated and non-pristine ria area: The A Coruña Harbour (NW Spain). Acta Oecologica 24, 113–124.

Varela, M., Bode, A., Alvarez-Ossorio, M.T., Prego, R., Canle, M., Casas, B., Lorenzo, J., Mariño, D., González, I., Carballo, R., Vilas, M., 1996b. Seguimiento de la contaminación producida por el accidente del buque Aegean Sea. Sistema Pelágico. In: Seguimiento de la contaminación producida por el accidente del buque Aegean Sea. Ministerio de Medio Ambiente (Ed.), pp. 15–63.

Varela, M., Prego, R., Belzunce, M.J., Martín-Salas, F., 2001. Inshore–offshore differences in seasonal variations of phytoplankton assemblages: the case of a Galician Ria Alta (A Coruña Ria) and its adjacent shelf (NW Spain). Continental Shelf Research 21, 1815–1838.

Varela, M., Prego, R., Pazos, Y., 2004. Vertical biogenic particle flux in a western Galician Ria (NW Iberian Peninsula). Marine Ecology Progress Series 269, 17–32.

Vargo, G.A., Hutchins, M., Almquist, G., 1982. The effect of low, chronic levels of no. 2 fuel oil on natural phytoplankton assemblages in microcosms: 1. Species composition and seasonal succession. Marine Environmental Research 6 (4), 245–264.

Walters, J.M., 1982. Fate of petroleum hydrocarbons in marine zooplankton. University of Kent, 189pp.