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Temporal Variation in the Chlorophyll *a* Concentration of the Coastal Waters of Spain Following the Ship *Prestige* Oil Spill

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Time series changes in the chlorophyll *a* concentrations before and after the ship *Prestige* oil spill on 13 November 2002 were analyzed using NCEP wind data and ocean color data. Following the oil spill, southwesterly winds pushed the oil towards the Spanish coast. In addition, the daily chlorophyll *a* concentration decreased dramatically from the middle of November to the end of December 2002, with the minimum value being recorded in December. Additionally, the mean chlorophyll *a* concentration in November and December 2002 was lower than the average value recorded for the same months from 2000 to 2005; however, with the exception of 2000, the concentration was higher in October 2002 before the spill and in January-March 2003 after the spill during the same period from 2000 to 2005.

Key words: *Prestige* oil spill, Spanish coast, Chlorophyll *a*, Ocean color, Satellite,

Introduction

On 13 November 2002, the tanker *Prestige*, which was carrying more than 77,000 tonnes of heavy fuel oil, was reported to be in distress and to have started leaking crude oil due to severe oceanic and atomspheric conditions (Balseiro et al., 2003). On 17 November 2002, a large quantity of crude oil was spilled into the sea from the shipwrecked tanker. Six days after the accident, the tanker broke in two and sank in the southwestern portion of the south coast of Galicia (Albaiges et al., 2006; Fig. 1).

The heavy crude oil (M-100 type) in the *Prestige* had a viscosity of 100,000 cSt at 15℃, contained 2.28% sulphur, and had a chemical composition of 22% aliphatic hydrocarbons and 50% aromatic hydrocarbons (Albaiges et al., 2006). The oil widely affected the Galicia coastal area in the northwestern portion of Spain, which is a well-known high biological production area (Ruiz-Villarreal et al., 2006).

Oil spills due to shipping accidents have the potential to cause severe short/long term damage to marine ecosystems. Indeed, significant damage to coastal waters and open seas has been frequently documented following oil spills (Jackson et al., 1989; Houghton et al., 1991, Varela et al., 2006). However, the effects of spilled oil on marine ecosystems are largely dependent on the origin of the components of the oil (Davenport, 1982; Doerffer, 1992), as well as the products that result from degradation of the oil, which can be more toxic than those in the original oil (Lacaze and Villedon de Naide, 1976; Fig. 2, Fig. 3). The results of several studies have suggested that there is an increase in chlorophyll *a* concentrations following an oil spill; however, it is not known if such changes in the chlorophyll *a* concentration are caused by a stimulation of photosynthesis or by changes in zooplankton grazing caused by the oil spill (Lannergren, 1978; Johansson et al., 1980). One of the reasons that the influence of spilled oil on marine ecosystems is not well understood is because there is a lack of data. This is because it is difficult to predict where and when shipping accidents will occur, which has prevented the time series changes in environmental factors following an oil spill from being quantified. Although the effects of oil spills on marine ecosystems are primarily estimated through field observations and laboratory experiments, in some cases there is not enough data to allow an adequate comparison with the changes that occur in

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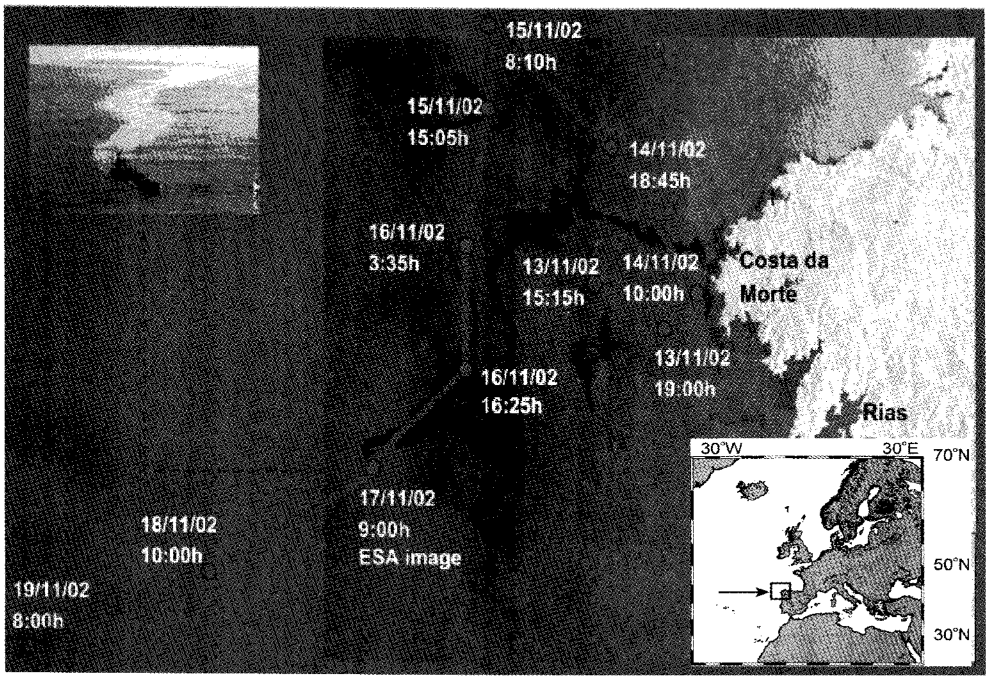

Fig. 1. Towing track of the tanker Prestige from 13 to 19 November 2002 and satellite image of the spill (ESA) on 17 November 2002 (Alabiges et al., 2006)

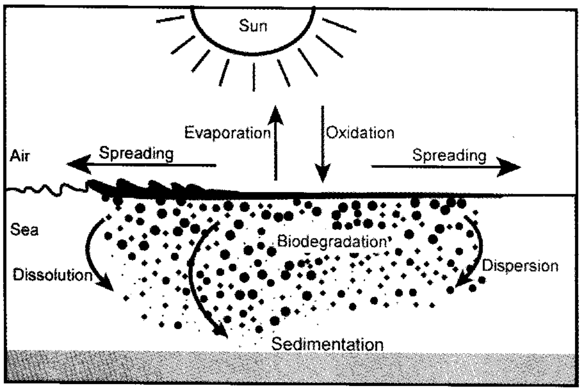

Fig. 2. The rate of removal of oil from the sea surface according to type (from http://www.itopf.com).

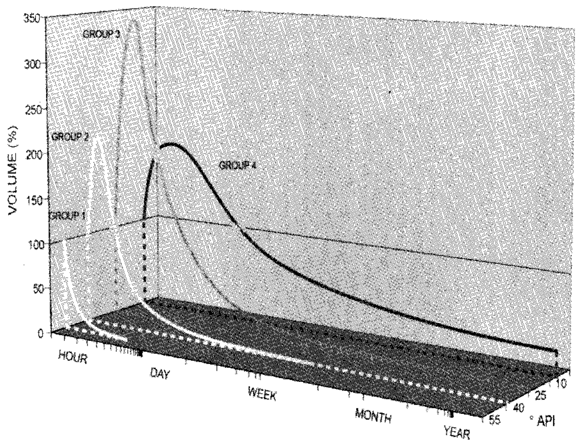

Fig. 3. The rate of removal of oil from the sea surface according to type (from http://www.itopf.com). The heavy crude oil that spilled from the tanker, *Prestige*, belongs to group 4.

the marine environment before and after an oil spill. That is, *in-situ* data before an oil spill sometimes does not exist because the in-situ observations are limited by time and space.

However, variation in ocean color detected by satellite images may be useful for evaluating differences in chlorophyll *a* concentrations before and after an oil spill, thereby providing a clear, quantifiable measure of the changes caused by an oil-spill.

Therefore, this paper was conducted to evaluate changes in the chlorophyll *a* concentration off the coast of Spain before and after the *Prestige* oil spill through the use of satellite ocean color data to determine the influence of spilled oil on the marine ecosystem.

Material and Methods

To illustrate the differences in the chlorophyll *a* concentration before and after an oil spill, the ocean color data of the SeaWiFS (resolution: 9 km) images collected from January 2000 to June 2002 and of Aqua-MODIS (resolution: 4 km) images collected from July 2002 to December 2005 were used. The Aqua-MODIS images, which had a relatively higher resolution, were used for the period after July 2002. Both sources of data were level-3 standard mapped images and are available at the ocean color website (http://oceancolor.gsfc.nasa.gov).

In addition, the daily chlorophyll *a* concentrations for the period between 1 November 2002 and 31 December 2002 and the monthly mean chlorophyll *a* concentrations reordered from October to March during 2000 to 2005 at two stations (Fig. 2) that were affected by the oil spill were calculated, after which the time series changes in the daily and monthly values before and after the oil spill were compared.

During the early stages of an oil spill, the oil drifts with the currents and sea winds. Therefore, we utilized daily wind fields provided by the NOAA National Center for Environmental Prediction (NCEP, http://www.cdc.noaa.gov/) to identify the spread of oil along the Spanish coast (Fig. 4).

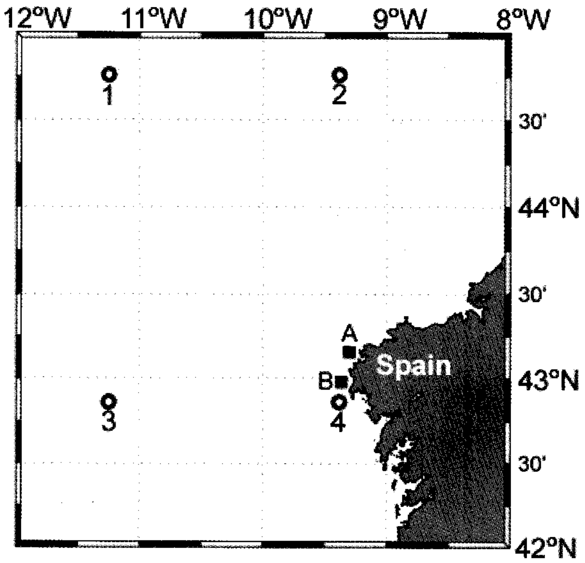

Fig. 4. Clear circles mark stations from which the time series of NCEP wind data were obtained and filled rectangles indicate areas affected by the oil spill. SeaWiFS and Aqua-Modis ocean color data were collected at stations A and B.

Results

Change in wind field

Southwesterly winds prevailed over a very wide area, including the area affected by the oil spill; however, northwesterly winds also occurred frequently (Fig. 5 and Fig. 6). As mentioned in the introduction, the tanker began leaking crude oil on 13 November 2002, and a large quantity of the crude spilled into the sea on 17 November 2002, after which the tanker broke in two and sank. The oil continued to leak into the ocean until December 2002. Northwesterly and northerly winds prevailed in the area of the spill from 13 November to 17 November, after which southwesterly winds prevailed. These southwesterly winds pushed the oil towards the coast. In addition, the tanker moved from the Spanish coast to the northwestern portion of the coast, after which it began to drift towards the southwest, apparently in response to the wind. Indeed, wind transportation of spilled oil towards the coast is considered to be one of the primary factors responsible for the presence of marine pollutants in coastal waters.

Changes in chlorophyll *a* concentration

A large quantity of the crude oil was spilled into the sea when the *Prestige* sank. This oil spread towards the coast with the wind. After 17 November 2002, the crude oil drifted over a wide area, while continuing to drift towards the coast.

Analysis of the time series change in chlorophyll *a* concentration clearly revealed a change in the concentration after 17 November 2002 (Fig. 7). Specifically, the chlorophyll *a* concentration decreased by approximately 0.1 mg/m^3 following the oil spill, and this pattern continued until December, at which time the minimum concentration was recorded. This change was also observed in the monthly chlorophyll *a* concentration measurements that were collected from 2000 to 2005 (Fig. 8). Specifically, the mean chlorophyll *a* concentration in October 2002, prior to the oil spill, was similar to those observed in October from 2000 to 2005, with the exception of 2003. However, the chlorophyll *a* concentration in November and December 2002 was lower than the concentration observed in November and December of the other years included in this study. This indicates that the chlorophyll *a* concentration decreased immediately after the spill, but began to increase two months later. It is interesting to note that, from January-March 2003 after the oil spill, the chlorophyll *a* concentration was approximately 5-45% higher than that of the other months, with the exception of February and March 2000.

Discussion

The natural variability of the ecosystem and direct/indirect effects of the crude oil that spilled from the *Prestige* may have been a primary factor in the change in chlorophyll *a* concentration that was observed in the area affected by the oil spill. Although this paper deals with the change in chlorophyll *a* concentration before and after the oil spill, the chan-

Fig. 5. Daily change in wind field from 1 to 30 November 2002.

ges shown in Fig. 7 and Fig. 8 may be the result of natural variability in the ecosystem rather than a direct effect of the spill. Therefore, the results of this study do not provide a solid foundation to claim that the time series change in chlorophyll *a* concentration was caused by the oil spill. In addition, the sea/weather conditions before and after the oil spill were severe (Balseiro et al., 2003), which may have had a negative impact on the ecosystem that lead to the decrease in chlorophyll *a* concentration.

In this study, we did not consider the role of current, including tidal current, on the drift of the oil. According to the results of a study conducted by Cheong (2008), oil spills drifts at a speed approximately 60% of those of the current and at 3-4% of the wind speed. The daily wind (Fig. 5 and Fig. 6) and current field (Ruiz-Villareal, 2006; Caballero et al., 2007) clearly demonstrate that the spilled oil spread towards the Spanish coast. According to results of studies conducted by Ruiz-Villareal (2006) and Caballero et al. (2007), northeastward and northward flows prevail along the Spanish coast. This correlates closely with time series change in chlorophyll *a* that was observed in the study area following the oil spill. The drift of spilled oil towards the coast is considered to be an important factor that is often responsible for the change in marine environments. Cheong (2008) suggested that oil spills have both short- and long-term negative effects on the structure of marine ecosystems. Conversely, we cannot rule out the large amount of organic matter that was released by the weathering process and a decrease in predators such as zooplankton as primary factors responsible for the increase of phytoplankton. However, serious

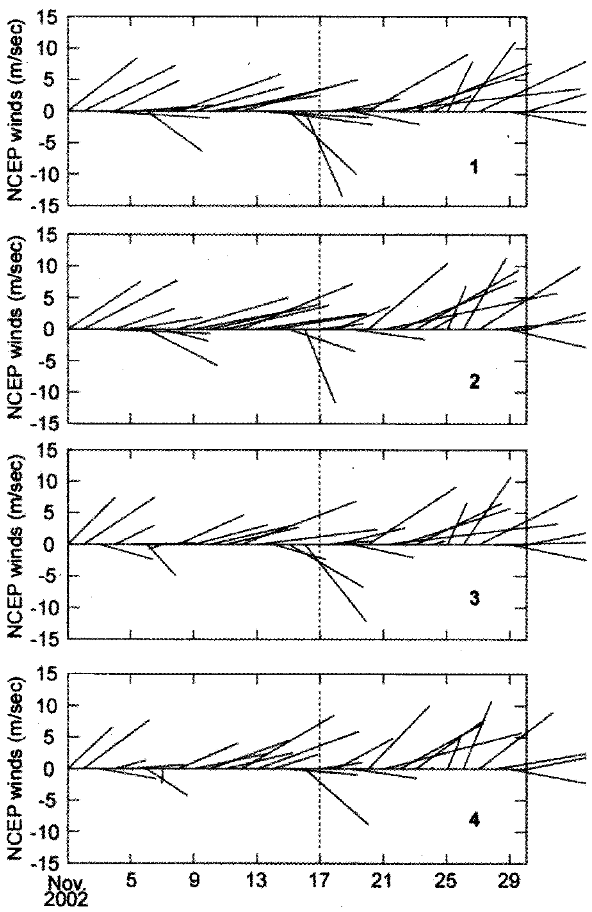

Fig. 6. Time series of wind stick vectors during November 2002 at sts. 1-4 shown in Fig. 4. The vertical dotted line represents 17 November 2002, which was when a large quantity of crude oil spilled into the sea.

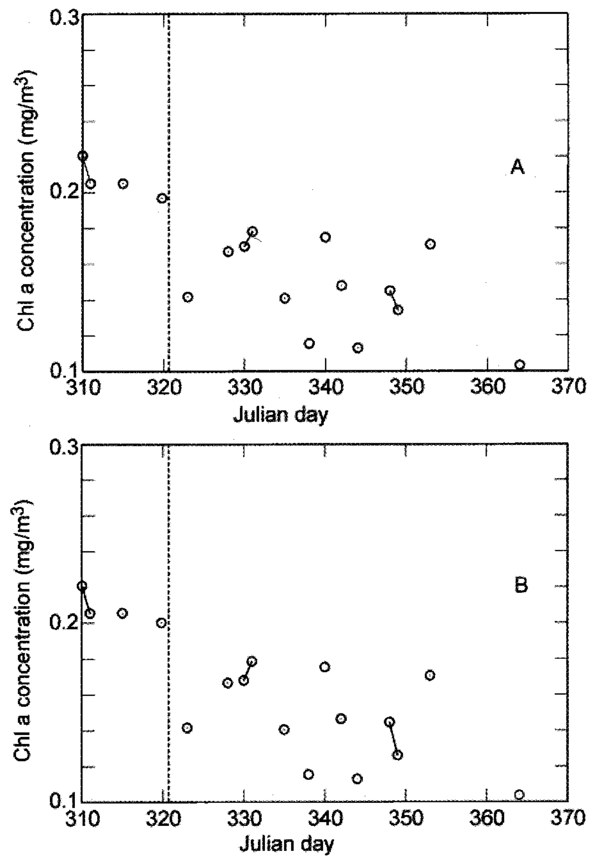

Fig. 7. Daily variation in chlorophyll *a* concentration during 2002 at Sts. A and B. The vertical dotted line represents 17 November 2002, which was when a large quantity of crude oil spilled into the sea.

consideration must be given to the potential influence of oil spills on changes in chlorophyll *a* concentrations since some of the spilled oil can remain for more than 1 year (Fig. 3). In this paper, the chlorophyll *a* concentrations were lower from November 2002 to December 2002, and higher from January 2003 to March 2003 when compared to concentrations observed in the other periods.

Changes in chlorophyll *a* concentration before and after several oil spill accidents have often been reported. Based on the ocean color data obtained using SeaWiFS, Bank (2003) reported that there was a change in phytoplankton primary production in affectted coastal sites, but that the spill had no obvious influence on primary production. Furthermore, Ruiz-Villarreal et al. (2006) used in situ data to demonstrate that there was an increase in chlorophyll *a* and primary production following an oil spill. Additionally, Lee and Kim (2008) showed that, although the chlorophyll *a* concentration decreased by approximately 50% in the area affected by an oil spill from the *Hebei Spirit*, over time, the chlorophyll *a* concentration increased greatly when compared to that of a normal year. Specifically, a higher chlorophyll *a* concentration was reordered at both the surface and the bottom layer in the winter following the spill from the *Hebei Spirit* (personal communication). Both the *Prestige* and *Hebei* incidents occurred in early winter at middle latitudes, where higher chlorophyll *a* concentrations are recorded during winter. In addition, according to the results of a study conducted by Varela et al. (2006), the chlorophyll *a* concentration in the Spanish coast gradually increases from winter to spring. However, the change in chlorophyll *a* concentration observed in the present study differs from the concentrations that were reported in the study conducted by Varela et al. (2006). This indicates that the change in chlorophyll *a* concentration was affected by natural variability in the marine ecosystem, as well as by direct/indirect effects of the oil spill from the *Prestige*.

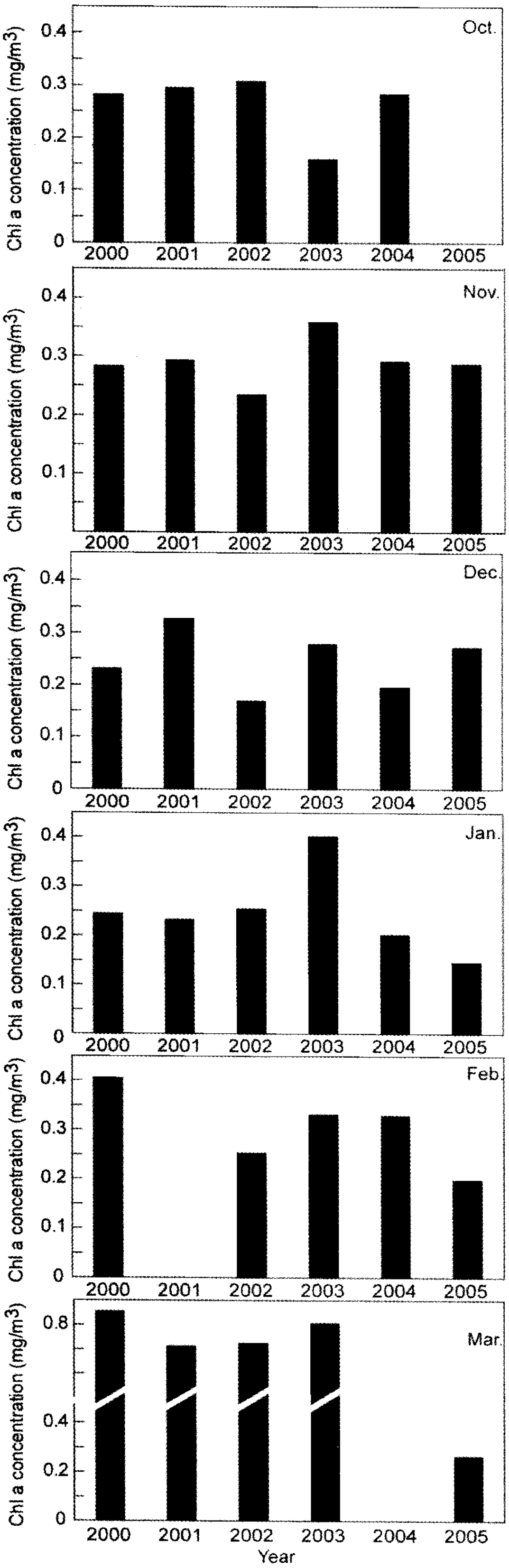

Fig. 8. Yearly variation in chlorophyll *a* concentration in October – March from 2000 to 2005.

As mentioned in the introduction, marine ecosystems may be affected by the components of the oil as well as the products resulting from its degradation, which can be more toxic than the original crude oil. In addition, a stimulation of photosynthesis (Fig. 2) or a change in zooplankton grazing caused by an oil spill may lead to changes in the concentration of chlorophyll *a*.

The results of this study clearly demonstrate that it is difficult to establish a quantitative estimate of the changes in chlorophyll *a* concentration due to oil spills using ocean color and *in situ* data. Furthermore, based on the data reviewed for this study, it was not possible to determine whether natural variability or the effects of the oil spill had a greater effect on the chlorophyll *a* concentration in the study area. However, the effects of the oil spill could not be ruled out entirely, and the oil spill clearly played a role in the changes that were observed in the chlorophyll *a* concentration.

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