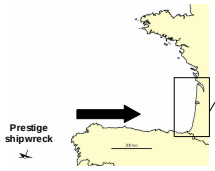
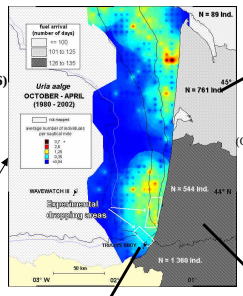
BILAN SYNTHETIQUE DE LA MAREE NOIRE DU PRESTIGE SUR LE LITTORAL AQUITAIN

Suivi des oiseaux marins en mer (depuis 1976)
(MNHN, LAPHY, UPPA, CMCB, Gardes Côtes)





Oiseaux échoués collectés
(Centres de soins, DIREN Aquitaine)

Arrivées d'hydrocarbures
(CEDRE)

Données de vent et de houle
(Tour des signaux, Météo France, Laboratoire des Sciences Appliquées aux Génies Civil et Côtier)



PROGRAMME REGIONAL
ENVIRONNEMENT ET RESSOURCES DES MILIEUX MARINS AQUITAINS

Le Programme régional « Environnement et ressources des milieux marins aquitains » constitue une démarche inter organismes et pluridisciplinaire comptant actuellement **dix participants principaux** :

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I – Le naufrage du *Prestige*

Figure 1: étapes du naufrage du *Prestige* entre le 13 et le 19 novembre 2002. De gauche à droite : la brèche dans la coque, brisure du navire et nappe d'hydrocarbures.
Photos © Douanes françaises.

Le 13 novembre 2002, le pétrolier *Prestige* battant pavillon des Bahamas et transportant plus de 77 000 tonnes de fioul lourd, émet un appel de détresse au large du Cap Finisterre (Galice, Espagne). Le navire, en avarie machine, dérive au gré des courants et perd déjà une partie de sa cargaison.

Le 14 novembre le Plan Biscaye (accord bilatéral de coopération entre la France et l'Espagne en matière de lutte contre les pollutions accidentelles dans le Golfe de Gascogne) est déclenché.

Le 16 novembre les premiers arrivages de pétrole sur les côtes espagnoles sont signalés.

Le 19 novembre, après plusieurs jours de remorquage, le pétrolier se casse en deux et coule à 270 Km au large de Vigo (Figure 1), la partie avant par 3 565 m de fond et la partie arrière à 3 830 m, provoquant la marée noire la plus importante (en durée et en étendue de côtes touchées) en atlantique nord-est.

Le fioul du *Prestige* a souillé les côtes atlantiques, du Portugal jusqu'au nord de l'Europe, de façon plus ou moins importante (Figure 2). La France n'a pas connu la même marée noire que la Galice : près de 26 000 tonnes de déchets, tout confondu, ont été récupérés à terre en France et environ 90 000 en Espagne.

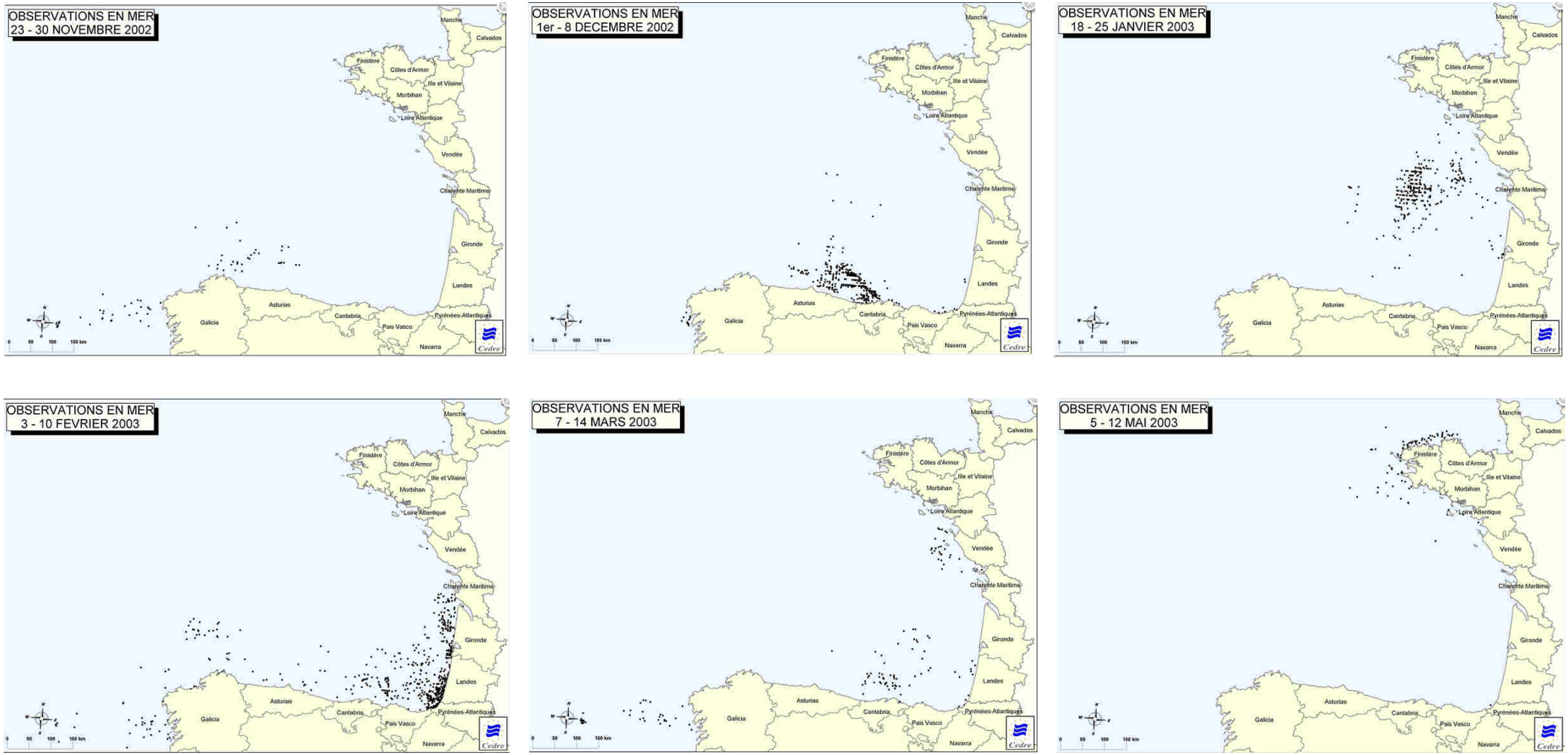

Figure 2 : Dérive des nappes d'hydrocarbures suite au naufrage du *Prestige* de novembre 2002 à mai 2003 (source : CEDRE).

En France c'est la Zone de Défense Sud Ouest qui a été la plus touchée, en Aquitaine, c'est le département des Landes qui a reçu le plus de polluants (Figure 3).

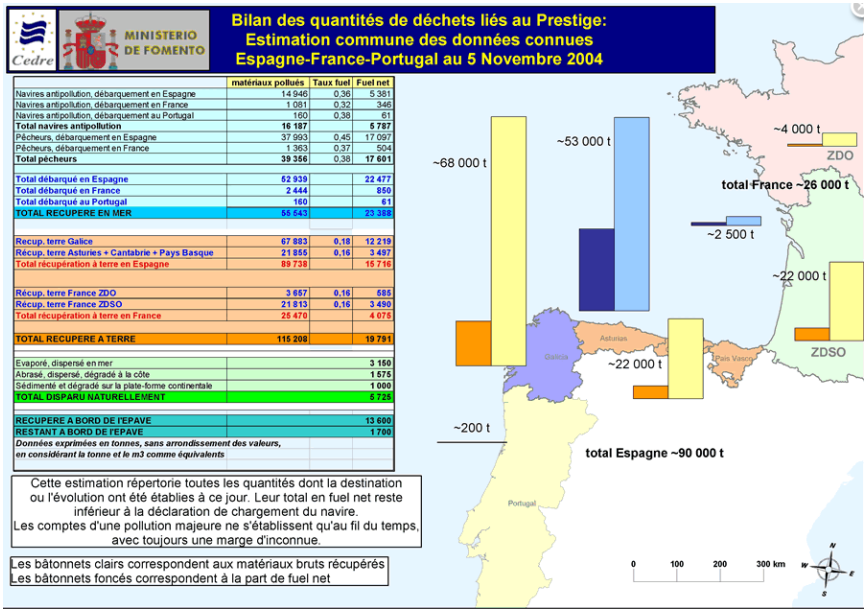

Figure 3 : Bilan des quantités de déchets liés au *Prestige* (en tonnes). Estimation commune Espagne-France-Portugal de novembre 2004 (source : CEDRE).

Le naufrage du *Prestige* constitue le 4ème accident pétrolier au large des côtes espagnoles depuis 1967 (Figure 4). Depuis cette date, près de 15 marées noires sont survenues dans les eaux du golfe du Gascogne dont 6 au large de la Bretagne. La marée noire du *Prestige* n'est pas la plus importante en termes de quantité de fioul déversé (le maximum de 227 000 tonnes concerne le naufrage de l'*Amoco Cadiz* en 1978 sur les côtes bretonnes), néanmoins les côtes aquitaines avaient récemment été touchées par la marée noire de *l'Erika* 3 ans auparavant. L'environnement avait donc déjà été fragilisé.

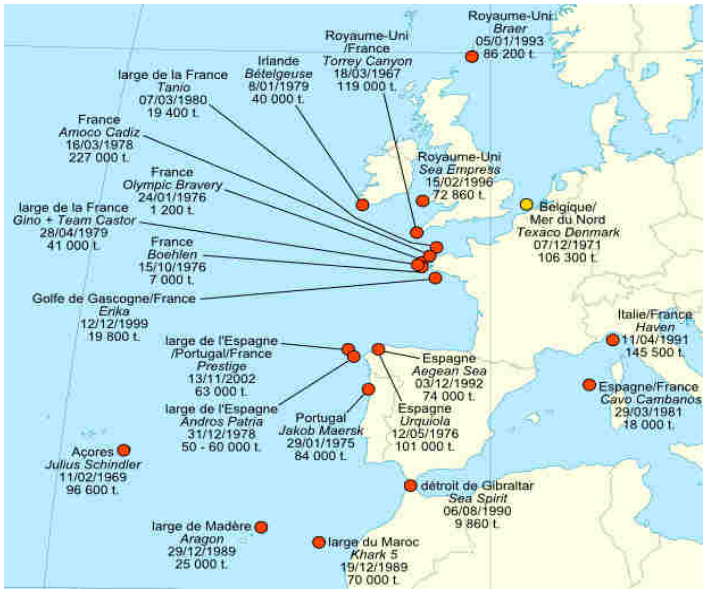

Figure 4 : Localisation des principaux accidents pétroliers survenus en Europe de 1967 à 2002, noms des pétroliers et quantité de fioul déversé (source : Eric Gaba).

II – Les moyens de gestion déployés

Dès la catastrophe, un comité technique s'est mis en place, regroupant des experts du CEDRE, de Météo-France, de l'IFREMER et du SHOM afin de prévoir les déplacements des nappe de pétrole et ainsi anticiper les actions de dépollution (Daniel *et al.*, 2004). Ce genre d'intervention a été réalisé avec l'aide du logiciel numérique MOTHY (Modèle Océanique de Transport d'Hydrocarbures). En liaison étroite avec les observateurs et modélisateurs portugais et espagnols, ce comité a produit tous les soirs une carte des observations du jour et des prévisions à trois jours (Figure 5).

Le 3 décembre, le plan POLMAR (Pollution Maritime) a été enclenché par le Préfet Maritime de l'Atlantique. Il s'agit de plans d'intervention en cas de pollution accidentelle des milieux marins, permettant la mobilisation et la coordination des moyens de lutte qui ont été dans le cas du *Prestige* :

- ✓ une surveillance des nappes à la fois aérienne par hélicoptère et maritime par des bateaux hauturiers ;
- ✓ une réquisition des chalutiers déjà en mer pour ramasser le pétrole en surface grâce à des filets spéciaux traînés entre deux bateaux ;
- ✓ la mise en place de barrages flottants à l'embouchure de la Gironde.

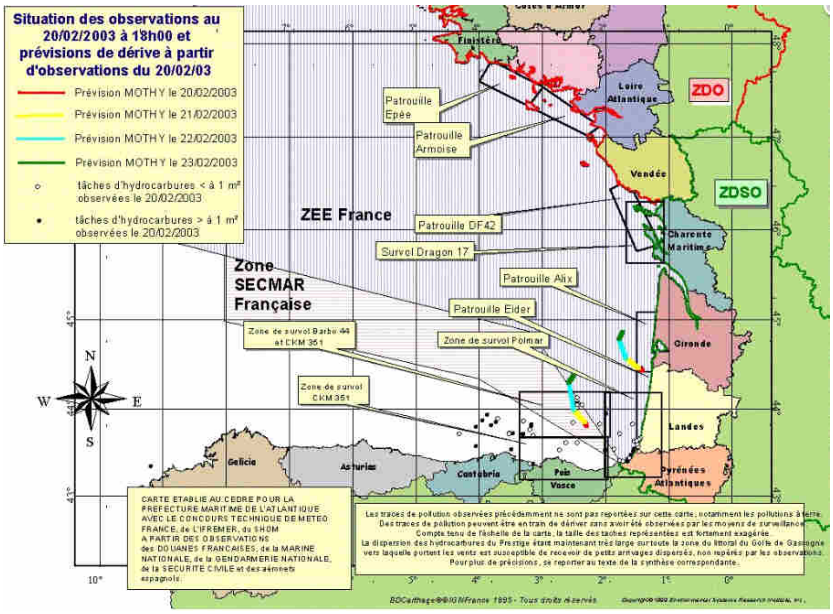

Figure 5 : exemple de cartes produites par le comité d'expert mis en place suite au naufrage du *Prestige.* Cette carte représente la situation des observations d'hydrocarbure en mer et des prévisions de dérive avec le logiciel MOTHY pour le 20 février 2003 (source : CEDRE).

Plusieurs mois plus tard, des bouées ont été mises à l'eau afin d'étudier la propagation des nappes de pétrole. Les mouvements de deux bouées larguées dans le front des nappes à la dérive dans le golfe de Gascogne ont montré comment la pollution a largement circulé à travers le golfe, venant toucher successivement la quasi-totalité du littoral. Les nappes se sont dirigées vers les côtes aquitaine et basque, y déposant des boulettes et galettes en février, avant de repartir vers le centre du golfe puis de faire des allers-retours devant la côte des Asturies.

Les bouées larguées au niveau de l'épave en février et mars 2003, sont toutes parties d'abord vers le large avant de revenir pratiquement à leur point de départ, puis d'entamer un long voyage vers le sud. Toutes donnent sous des formes différentes une même information : la pollution qui est arrivée sur le littoral français provient bien plus vraisemblablement du naufrage que de fuites depuis le navire postérieures à fin février 2003.

À l'époque, ces analyses avaient conclu que l'emprise géographique où des boulettes de pétrole étaient possiblement présentes couvrait un million de kilomètres carrés (source : CEDRE).

III – Etudes pluridisciplinaires : impacts sur la faune marine

Afin de réaliser une étude de grande ampleur sur les données collectées au moment de la marée noire du *Prestige* et de pouvoir en déterminer l'impact, l'ERMMA a multiplié les collaborations et les contacts avec les principaux organismes et acteurs au moment du *Prestige* : CEDRE, DREAL, principaux centres de soins (UMSOM, Hégalaldia), etc.

Les oiseaux marins, les cétacés et la faune benthique ont été particulièrement étudiés par le programme ERMMA pour appréhender l'impact de la marée noire sur les populations de ces différents maillons des chaînes alimentaires. Certains suivis ont été ponctuels juste après la catastrophe tandis que d'autres sont poursuivis actuellement afin de mieux comprendre les conséquences sur le long terme.

Impact sur les oiseaux marins

Les nombreuses collaborations à l'époque ont permis de regrouper puis analyser les données au sein de l'ERMMA. La première étude pluridisciplinaire a été réalisée sur une estimation de la mortalité des oiseaux marins en mer en relation avec la marée noire (Castège *et al.*, 2007).

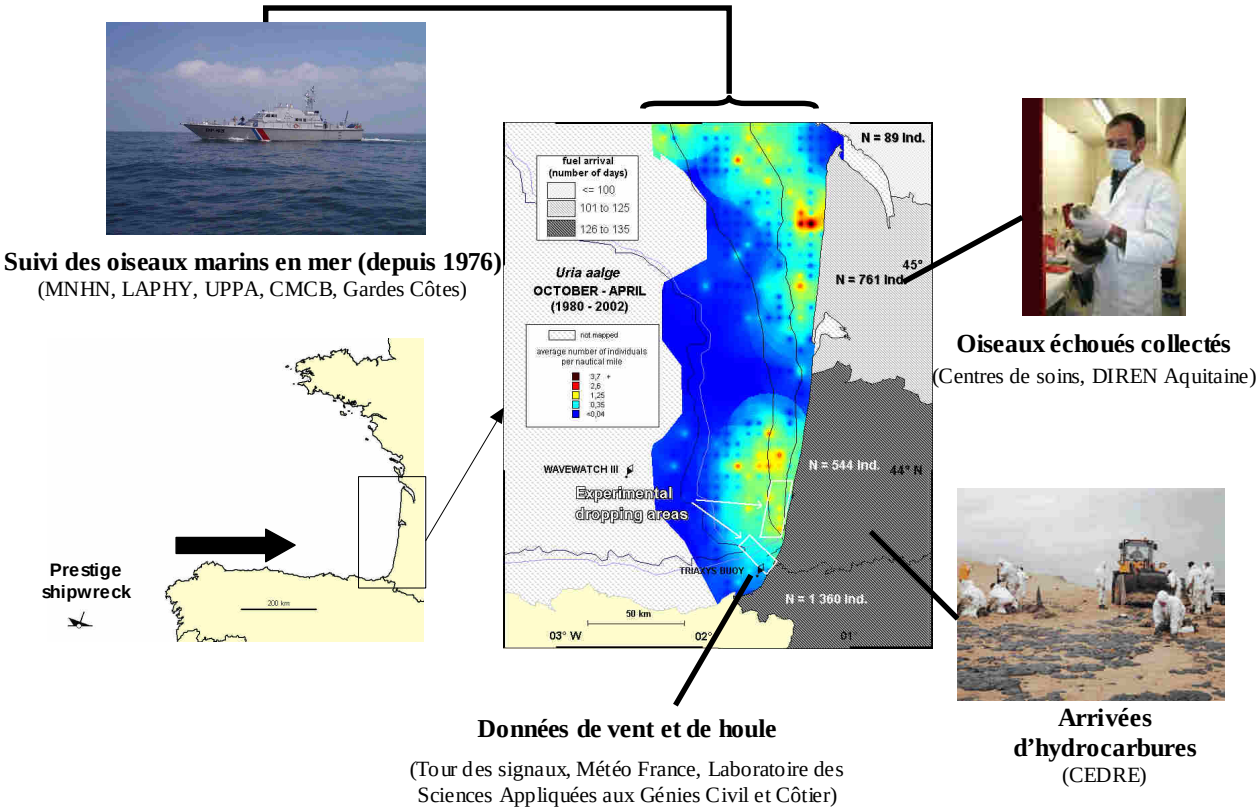

Figure 6 : Nature et provenance des données regroupées lors de l'étude pluridisciplinaire sur les arrivées d'hydrocarbures du *Prestige* et leurs impacts sur l'avifaune marine.

La dérive en mer et donc l'arrivée sur le littoral de matériaux flottant en surface tels que des bois, déchets ou hydrocarbures dépendent étroitement de la direction et la vitesse du vent. À partir des données météorologiques et de houles (Météo France, Tour des signaux, LASAGEC), des quantités d'hydrocarbures ramassées dans les différents chantiers (CEDRE), des dénombrements d'oiseaux marins échoués (UMSOM, DREAL, Hégalaldia) et de la connaissance des zones d'hivernage en mer (MNHN-LAPHY-UPPA), ont été étudiées conjointement la dérive des animaux touchés et celles des hydrocarbures au large de l'Aquitaine lors de la pollution du *Prestige*. Cette étude a donc mis en œuvre la collaboration d'une douzaine d'organismes (Figure 6).

Il apparaît que les échouages d'oiseaux sont fortement corrélés avec les conditions de vent offshore (venant du large) du jour même, alors que les arrivées de pétrole sont corrélées avec 8 jours de décalage. Ces résultats confirment le fait que les oiseaux échoués peuvent être considérés comme indicateurs de l'arrivée prochaine de pollution par hydrocarbure (avec un délai de 8 jours dans le cas du *Prestige*) (Figure 7).

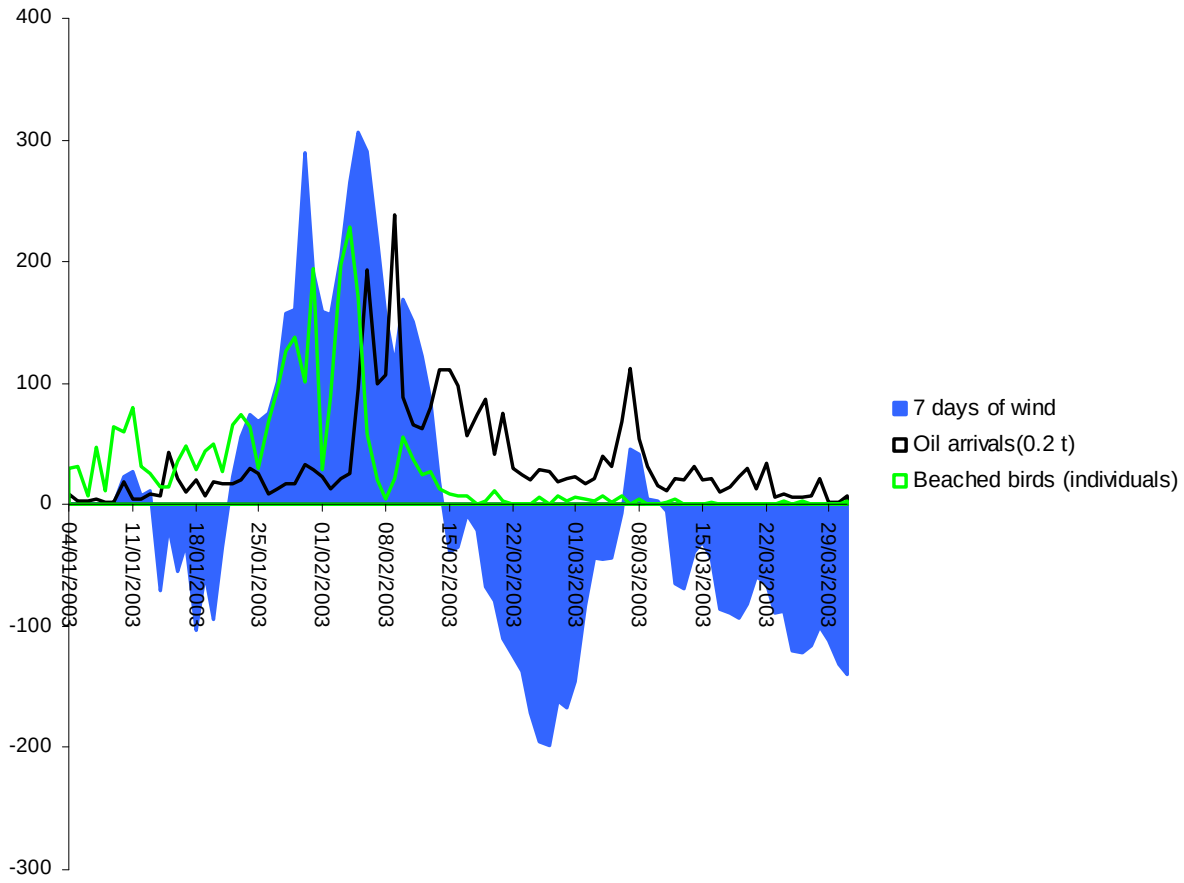

Figure 7 : Variations journalières des échouages d'oiseaux (en individus par jour ; en vert), d'arrivées de pétrole (x 0.2 tonnes par jour ; en noir) et conditions de vent (cumul de 7 jours de vent ; en bleu) durant la période de crise du *Prestige*.

Simultanément une première expérience de remise en mer au large de la côte basco-landaise de 121 cadavres de Guillemots *Uria aalge* bagués (Figure 8) a permis d'estimer par capture-recapture le taux de découverte des individus à la côte et donc d'apprécier la mortalité totale des populations d'oiseaux.

Suite à une expérience de flottaison de cadavre réalisée dans les aquariums d'eau de mer du Musée de la Mer de Biarritz, le temps de flottaison maximum d'un cadavre d'oiseaux en mer a été estimé à 30 jours.

La combinaison du modèle de dérive des corps relargués en mer et de la méthode de capture-recapture a permis d'estimer la mortalité totale des populations à 30 240 oiseaux soit 11 fois plus que le nombre total d'oiseaux réellement retrouvés sur les plages.

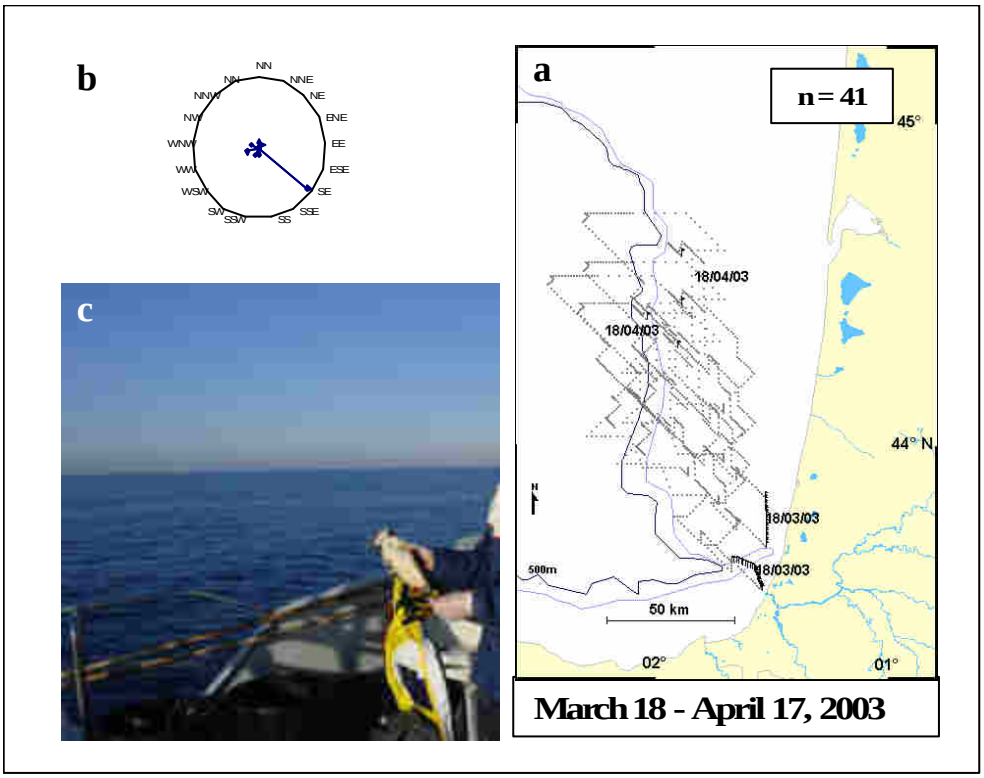

Figure 8: a : Modèle de dérive des corps en mer : la route théorique pour chaque oiseaux est représentée du point de relargage en mer jusqu'à la disparition, dérive du 18 mars au 17 avril (les modèles de dérive des oiseaux relargués aux mois de février et mars ne sont pas représentés n total = 121 corps).
b : direction du vent (nombre de jours) durant la période de dérive.
c : Guillemot de Troïl (*Uria aalge*) bagué et géoréférencé relargué en mer.

Cette sous estimation de la mortalité (si l'on ne considère que les individus réellement retrouvés sur les plages) s'explique principalement par les conditions de vent. En effet, Les conditions de vent majoritairement offshore (venant de terre) durant le *Prestige* auraient fait dériver les individus touchés vers le large, masquant ainsi l'impact réel du *Prestige*.

Ces résultats ont été ensuite comparés à la répartition spatio-temporelle en mer des espèces (Figure 9).

L'importance de l'impact du *Prestige* mis en évidence par l'expérience de relargage de corps en mer est compatible avec la diminution de l'abondance du Guillemot observée en mer. La

diminution de cette espèce, la plus touchée en nombre d'individus lors des marées noires de *l'Erika* et du *Prestige*, peut s'expliquer par un impact différé de *l'Erika* (déficit de reproducteurs 4 ans après l'accident dû à une maturité sexuelle différée) ou par un effet combiné avec la pollution du *Prestige*.

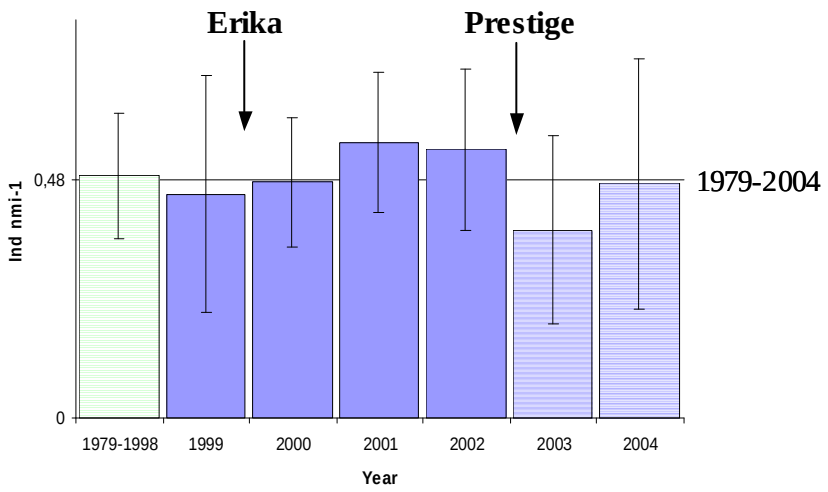

Figure 9 : Variation en mer de l'abondance du Guillemot de Troïl en Aquitaine (1979 – 2004). (nombre moyen d'individus par milles nautiques, barres verticales représentant l'erreur standard).

Les résultats de ces travaux ont été validés et publiés dans la revue internationale : « ARDEOLA ». L'article intitulé « Estimating actual seabirds mortality at sea and relationship with oil arrival: lesson from the "*Prestige*" oilspill in Aquitaine (France)» a paru dans l'édition 2007 de la revue (Annexe).

Au delà de la mesure de l'impact du *Prestige*, ce travail a soulevé la nécessité de mise en commun de données de nature et d'origines différentes pour appréhender l'impact de pollutions telles que celles de *l'Erika* et du *Prestige*, sur les populations animales et plus généralement pour la conservation de la biodiversité marine.

Impact sur les cétacés

En ce qui concerne les cétacés, les données d'échouages de ces animaux sont collectées par le RNE (Réseau National d'Echouage) sur les côtes de France. Ce réseau est constant et permet le suivi des échouages au fil des mois et des années.

Suite à la pollution de *l'Erika* (décembre 1999) aucune augmentation des échouages traduisant une mortalité accrue n'avait été constatée. **Les années suivant l'accident pétrolier du *Prestige* ne montrent également aucun accroissement des échouages en Aquitaine** (Figure 10).

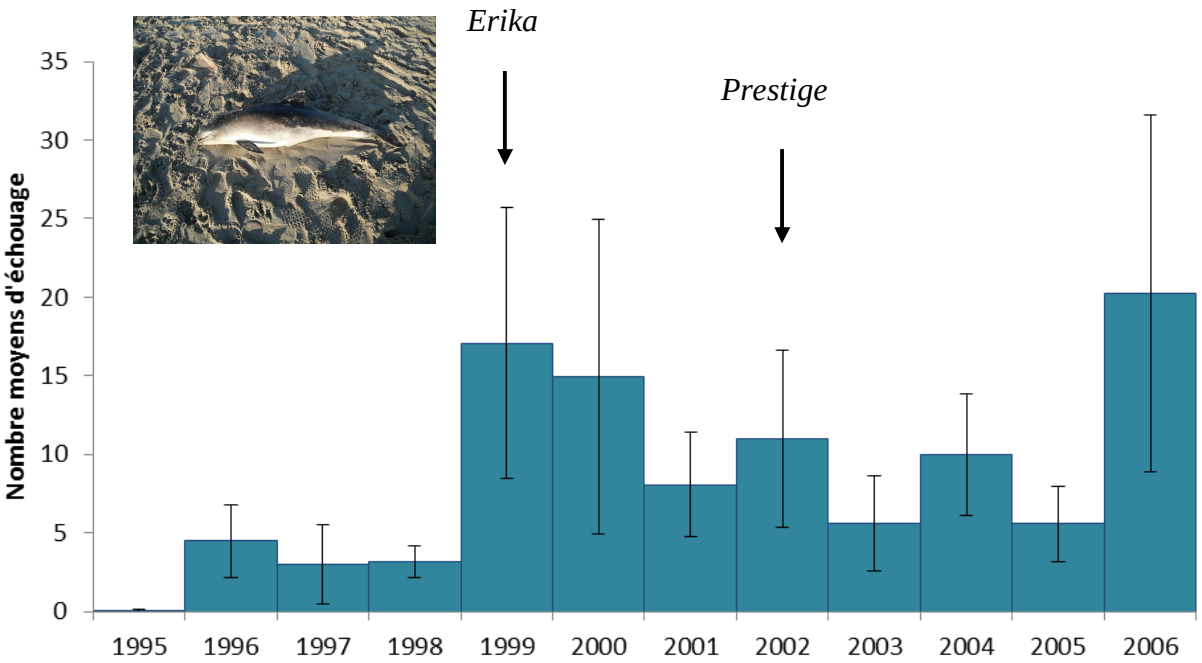

Figure 10 : Evolution de l'abondance des échouages des cétacés en Aquitaine de 1995 à 2006. Aucune augmentation significative des échouages n'est observée suite à la pollution du *Prestige*.

Ces résultats semblent indiquer que les cétacés éviteraient les nappes d'hydrocarbures ce qui limiterait l'impact direct sur ces animaux. D'après une étude de Ridoux *et al.* (2004), aucun effet mesurable de la marée noire de *l'Erika* n'a été trouvé chez les dauphins communs et les phoques gris.

Impact sur les biocénoses benthiques

Le cantonnement de pêche de Guéthary (département 64) fait l'objet d'un suivi scientifique depuis 2002 (Figure 11). La méthode d'observation standardisée d'une vingtaine de quadrats répartis sur les différents étages de l'estran permet la comparaison d'une année sur l'autre. Ce site possède une biodiversité remarquable et présente l'avantage de bénéficier d'une protection (cantonnement de pêche) limitant certaines activités anthropiques. Ainsi, ce secteur constitue une bonne station de référence pour la mesure des pollutions et changements globaux pouvant influencer les biocénoses benthiques.

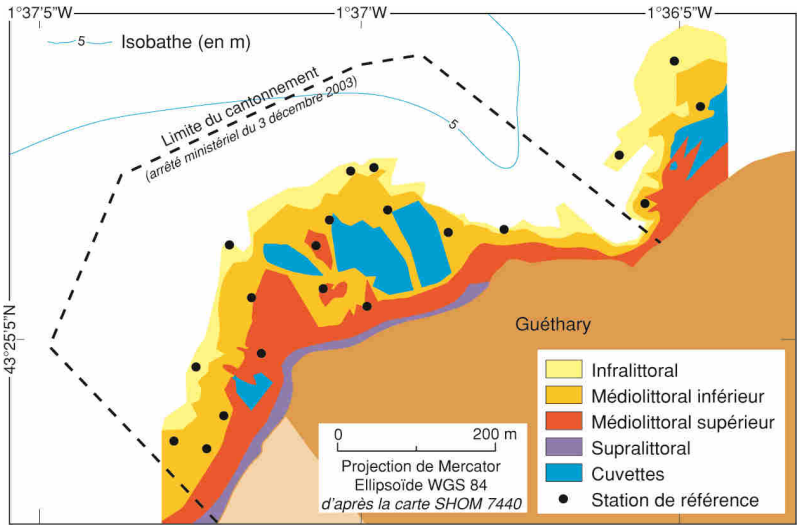

Figure 11 : localisation des stations sur l'estran rocheux de Guéthary, photographie d'un quadrat et deux exemples d'espèces benthiques régulièrement échantillonnées : l'oursin violet *Paracentrotus lividus* et l'anémone fraise *Actinia fragacea*

L'impact du naufrage du *Prestige* s'est traduit en premier lieu par une diminution de la richesse taxonomique (ramenés à l'échelle taxonomique la plus grande) sur le secteur de Guéthary dans les années suivant la pollution (Figure 12). Depuis 2005, le nombre de taxon semble revenu à un niveau comparable à la situation antérieure à la pollution du *Prestige*.

Une étude plus approfondie a permis de mettre en évidence des différences dans les structures des populations avec des espèces qui ne sont jamais réapparues *(Hymeniacidon perlevis*), et d'autres qui sont revenues deux ou trois ans plus tard (Ophiure écailleuse, *Amphipholis squamata ;* Botrille étoilé, *Botryllus schlosseri ;* Calliostome, *Calliostoma zizyphinum ;* Oursin globuleux, *Echinus esculentus*).

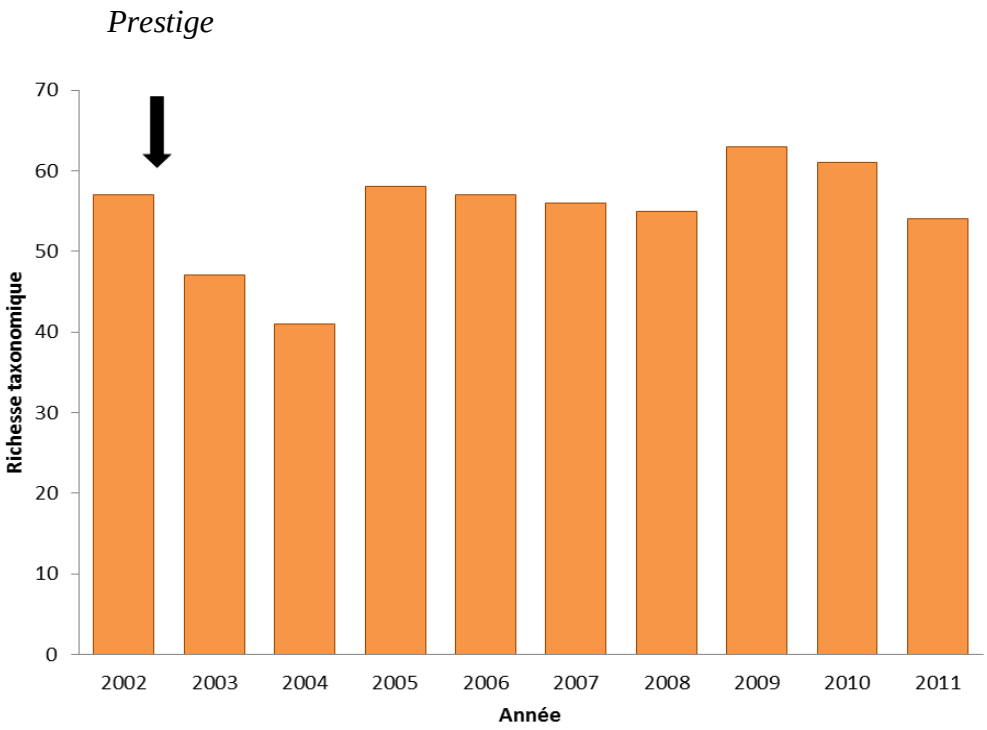

Figure 12 : Evolution de la richesse taxonomique des biocénoses benthiques sur la station de référence de l'estran de Guéthary.

Les étapes de la résilience ont été étudiées grâce au recul temporel du suivi et ont également montré une **forte augmentation temporaire des abondances des brouteurs traduisant un bouleversement des écosystèmes** (par exemple : Oursin violet, *Paracentrotus lividus ;* Oursin globuleux, *Echinus esculentus ;* Gibbules, *Gibbula sp.*, Bigorneau, *Littorina littorea ;* Patelles, *Patella sp.*). Ces espèces ont connu un pic d'abondance en 2004 (Figure 13).

D'après les publications qui ont suivi de précédentes marées noires dans le monde, le schéma correspond à une disparition des herbivores au moment de la pollution qui entraîne une explosion des algues qui elle-même va encourager la prolifération de nouveaux brouteurs. Le retour à des abondances normales les années suivantes laisse à penser un retour à l'équilibre de l'écosystème.

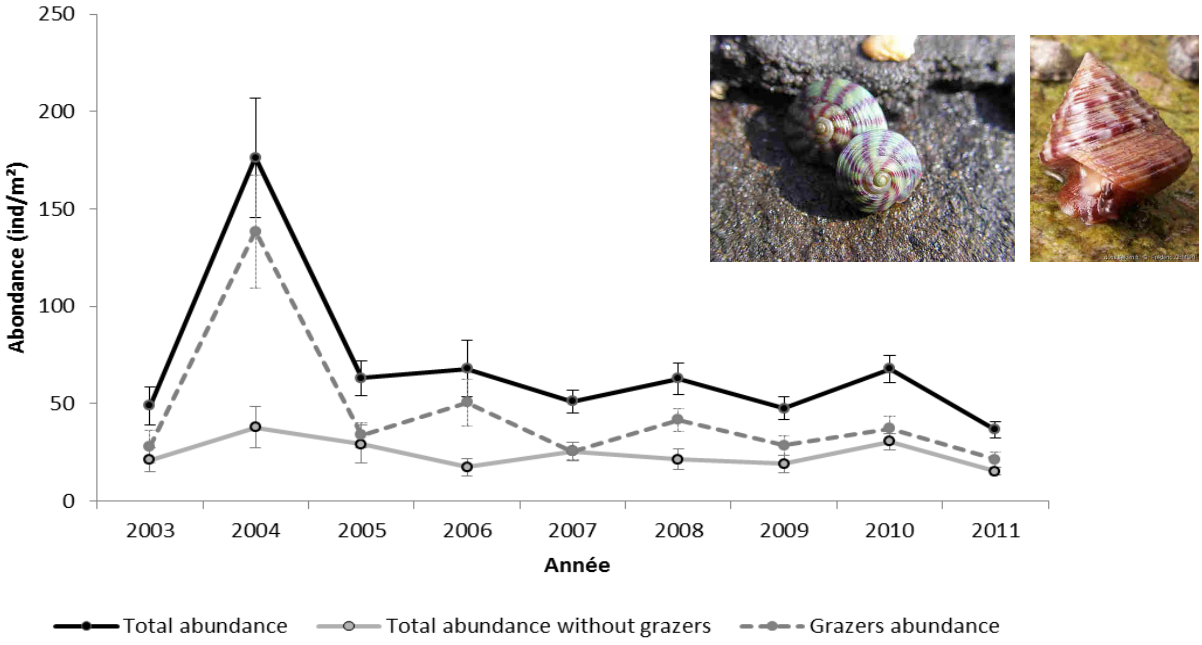

Figure 13 : Evolution de l'abondance moyenne totale (toutes espèces confondues ; seulement les brouteurs et sans les brouteurs). Les barres verticales représentent l'erreur standard. En photo deux exemples de brouteurs : à gauche Gibbule ombiliquée *Gibbula umbilicalis* et à droite Calliostome, *Calliostoma zizyphinum.*

Une partie des résultats est en cours de publication (Castège *et al.*, submitted) et apporte des éléments sur la réponse des écosystèmes de l'estran rocheux de Guéthary face à la pollution du *Prestige*.

Bilan de l'impact de la pollution du *Prestige*

L'évaluation de l'impact du *Prestige*, qui a sombré en novembre 2002, a été étudiée dans le cadre du programme ERMMA et a abouti à un certain nombre de publications scientifiques dans des revues internationales. Plusieurs compartiments biologiques ont été appréhendés : les prédateurs supérieurs que sont les oiseaux marins et les cétacés, ainsi que la macrofaune benthique.

Ainsi l'impact sur les **oiseaux marins** est estimé au final à **30 240 individus** en Aquitaine. Cette étude pluridisciplinaire prend également en compte une estimation des individus touchés mais non collectés par les centres de soin. Elle souligne l'importance des conditions de vent majoritairement offshore (venant de terre) durant le *Prestige* qui auraient fait dériver les individus touchés vers le large, masquant ainsi l'impact réel sur ces populations.

Concernant les **cétacés** aucun effet notable direct n'apparaît. En effet, les années suivant l'accident pétrolier du *Prestige* ne montrent aucun accroissement des échouages en Aquitaine.

Le suivi scientifique sur l'estran de Guéthary a mis en évidence un **effet à long terme sur la macrofaune benthique**. Un premier effet est la diminution de la richesse taxonomique les deux années qui ont suivi la catastrophe. Une autre perturbation immédiate concerne les brouteurs dont l'abondance a connu un pic important en 2004. Près de cinq ans après la pollution, l'écosystème semble avoir **retrouvé un équilibre**, bien que sensiblement différent du précédent.

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Annexes

Annexe I : Article intitulé « Estimating actual seabirds mortality at sea and relationship with oil arrival: lesson from the "*Prestige*" oilspill in Aquitaine (France)» publié dans la **revue internationale « ARDEOLA** » (2007).

Annexe II : Poster présentant les travaux du programme ERMMA dans le cadre du suivi scientifique de l'estran rocheux de Guéthary, exposé lors des **colloques internationaux** de Biarritz en 2011 sur la « Vulnérabilité des écosystèmes côtiers au changement global et aux évènements extrêmes » et **ISOBAY XII** à Santander en 2012 sur l'océanographie du golfe de Gascogne.

Le poster est intitulé : Vulnerability of benthic macrofauna of the Guthary's forehsore (E. Atlantic, France) after the *Prestige* oil spill.

Annexe III : Article intitulé « Response of benthic macrofauna to an oil pollution: lessons from the "*Prestige*" oil spill in the South of the Bay of Biscay (France).» Soumis pour publication en 2012.

Annexe I : Article intitulé « Estimating actual seabirds mortality at sea and relationship with oil arrival: lesson from the "*Prestige*" oilspill in Aquitaine (France)» publié dans la **revue internationale « ARDEOLA** » (2007).

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ESTIMATING ACTUAL SEABIRDS MORTALITY AT SEA AND RELATIONSHIP WITH OIL SPILLS: LESSON FROM THE "PRESTIGE" OIL SPILL IN AQUITAINE (FRANCE)

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SUMMARY.—*Estimating actual seabirds mortality at sea and relationship with oil spills: lesson from the "Prestige" oilspill in Aquitaine (France).*

Aims: Estimations were made of seabirds mortality at sea and drift in relationship with oil arrival during the "Prestige" oilspill.

Location: South Bay of Biscay (Aquitaine), South-West France.

Methods: meteorological data (Météo France), the amount of hydrocarbons collected along the coast line (CEDRE), number of beached seabirds (UMSOM, DIREN) and their distribution and abundance on wintering areas at sea (MNHN-LAPHY), to assess the joint drift of oiled animals and of hydrocarbons in the south Bay of Biscay (Aquitaine) during the "Prestige" oilspill. For the first time at the time of an oil slick, we experimentally dropped into the open sea (off the French basco-landaise coast) ringed corpses of guillemots *Uria aalge* in order to estimate by capture-recaptures approach the rate of reported bodies (1 over 121) at the coast and thus to appreciate the total mortality of the populations of seabirds (UPPA-MNHN).

Results: It is estimated that seabirds mortality was eleven times the amount of beached birds collected on the Aquitaine coasts. That result was in accordance with the decrease in the number of guillemots (the most beached species) observed at sea after the "Prestige" shipwreck.

Conclusions: It is demonstrated that the pooling of databases of different natures and origins was necessary to assess the impact of oil spill pollutions, such as those of "Erika" and "Prestige", on the animal populations and more generally for marine biodiversity conservation.

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Key words: Oil spill, "Prestige", impact, seabirds, mortality estimate, drift experiment, capture-recapture.

RESUMEN.—*Estimación de la mortalidad de aves marinas en altamar y su relación con los vertidos de petróleo: caso de la marea negra del "Prestige" en Aquitania (Francia).*

Objetivos: Estudiamos la mortalidad y la deriva de las aves marinas en mar abierto en relación con la llegada de petróleo durante de la marea negra del "Prestige".

Localidad: Sur del Golfo de Vizcaya (Aquitania), Suroeste de Francia.

Métodos: Hemos relacionado informaciones meteorológicas (Météo France), las cantidades de petróleo colectadas sobre las costas (CEDRE), las cantidades de aves varadas (UMSOM, DIREN) y sus distribuciones o abundancias en los lugares de invernada en altamar (MNHN-LAPHY), para estimar la deriva combinada de las aves y del petróleo en el sur del golfo de Vizcaya durante la marea negra del "Prestige". Por primera vez, durante una marea negra se anillaron cadáveres de arao común *Uria aalge* en altamar para estimar la tasa de cuerpos recobrados por medio del método de captura-recaptura (1 sobre 121) en la costa. Así se pudo estimar la mortalidad total de las poblaciones de aves marinas en Aquitania debidas a la marea negra del "Prestige" (UFR-MNHN).

Resultados: Estimamos que la mortalidad de los aves marinas fue once veces mayor que el número de aves recolectadas en las costas de Aquitania. Este resultado está de acuerdo con la disminución del número de araos comunes (la especie que más se encontró en las playas) observada en el mar después del naufragio del Prestige.

Conclusiones: Demostramos que el cruce de base de datos de distinta naturaleza y origen es necesario para estimar el impacto de una marea negra por petróleo (como la del "Erika" o "Prestige") sobre las poblaciones de aves marinas y de forma más general sobre la conservación de la biodiversidad marina.

Palabras clave: marea negra, "Prestige", impacto, aves marinas, estimación de mortalidad, experimentación de deriva, captura-recaptura.

INTRODUCTION

Every year, in world's oceans and seas, oil spills from ships (either illicitly and deliberately or at the time of shipwrecks) are responsible for the death of a large number of seabirds (Camphuysen, 1998; Camphuysen *et al.*, 2001; Clark; 1992, Heubeck *et al.*, 2003; Wiese *et al.*, 2003). Around the world, most public and research attention has been given to the effects of large catastrophic spills created by accidents such as the "Exxon Valdez" in Alaska, "Torrey Canyon" in British Coast, "Braer" in Shetland Islands, "Sea Empress" in Wales or "Amoco Cadix" in France -where 30 000 to 37 0000 seabirds were killed and collected on the coastline- (Bourne, 1979; Holme, 1969; Ford *et al.*, 1996; Edwards and White, 1999; Piatt *et al.*, 1990).

In France, in the Bay of Biscay, after the "Erika" shipwreck (12 December 1999), which poured 20 000 tons out of its cargo of 30 000 tons of heavy fuel and soiled the French coast, overall 74 000 oiled birds (among them 32 000 and 42 000 seabirds and seaducks, alive and dead respectively; see Cadiou *et al.*, 2003, 2004) were collected on the coast including 80 % oiled Guillemot, the most frequently beached species. More recently, 23180 killed birds (6 120 alive and 17 061 dead) including 90 species were collected in Spain, Portugal and France (including 2 831 killed birds from 29 species only for France) at the time of the oil slick which followed the "Prestige" shipwreck (13 November 2002) near to the Finistere Cape in Galicia (Spain) with 77 000 tons of fuel on board spilling some 63 000 tons at sea (Garcia *et al.*, 2003; CEDRE & Diren Aquitaine, *pers. com.*).

Obviously, any impact of oil surface pollution on seabirds neither depends only on the quality of the fuel nor the total amount poured at the time of the shipwreck (the same is true for illicit discharge in the marine environment) but also varies considerably with the geographic location of the spill, the season during which it occurs, environmental weather conditions as wind and streams (Wiese *et al.*, 2003) and the ecology of the species affected (Reid *et al.*, 2001). Indeed, the drift and dispersal at sea over large distance and thus the subsequent arrival on the coast of floating material such as waste or hydrocarbons, corpses of birds died at sea, depend closely on the direction and the speed of the wind (Wiese *et al.*, 2003; Hope Jones *et al.*, 1968). Moreover, the impact of any oil slick is likely to have an important effect when it occurs during winter (non breeding period) when more species and higher numbers of marine birds are present. It is especially true in the south of the Bay of Biscay given that it is a major wintering zone for many birds species (Hémery, 1985; Castège *et al.*, 2004).

The impact of oil pollution on seabirds is well documented and in many parts of the world, systematic surveys of beached corpses of birds (Beached Bird Surveys) have been used (Camphuysen and Heubeck, 2001; Seys *et al.*, 2002; Wiese *et al.*, 2003). However, if both absolute and relative abundance of dead and live seabirds species found oiled along coastline (so called "beached birds") are usually considered indicators of oil pollution events over time and space, very little is known about the real impact of such contamination on these species at sea. Obviously, after oil spills, only one fraction of these live and dead oiled individuals can be found on the beach. The remnant is made up of oiled specimens dying and disappearing at sea following sinking, decomposition or predation and also of individuals actually beached at inaccessible sites and thus not found (Tanis and Mozer-Bruyns, 1968; Hope-Jones *et al.*, 1970; Flint *et al.*, 1999). As a major consequence, those birds are not taken into account in "oiled bird census".

This study had three aims. The first was to study the relationship between oiled beached birds abundance and arrivals of hydrocarbons along Aquitaine coast using environmental data, bird abundance distribution data at wintering zones at sea and data on oiled seabirds and total amount of hydrocarbons collected at various beaches. The second, very original in the sense that it was carried out for the first time exactly at the time of the oil slick, was to launch an original release experiment of corpses of guillemots at sea off the coast which received most impact ("basque and landesaise" coast) in order to estimate the fraction of the oiled individuals which died and were not found subsequently on the coast following the "Prestige" oilspill. Guillemot corpses were ringed so that capture-recapture (CMR) estimates provided the rate of discovery of individuals at the coast and thus enable to appreciate the total mortality of seabirds. Eventually those results were compared with the spatio-temporal distribution at sea of species in the absence of pollution.

MATERIAL AND METHODS

The study area is located along the Aquitaine coast (Fig. 1) where almost all oiled beached birds were collected and oil arrivals recorded in France. Data for oiled beached birds were collected from the 1 January 2003 (when the first oiled birds were discovered and collected by various rehabilitation centres along the Aquitaine coast) and the 31 March 2003 (when the main wildlife rehabilitation centres closed). Data relative to oil arrivals were collected from 1 January 2003 (when the first oil arrivals on the beaches were noted) and 15 May 2003. Data of the national long-term data base (1980 - 2004) standardized monitoring study of abundance at sea of seabirds and cetaceans were used (Hémery *et al.*, 1985; Castège *et al.*, 2004).

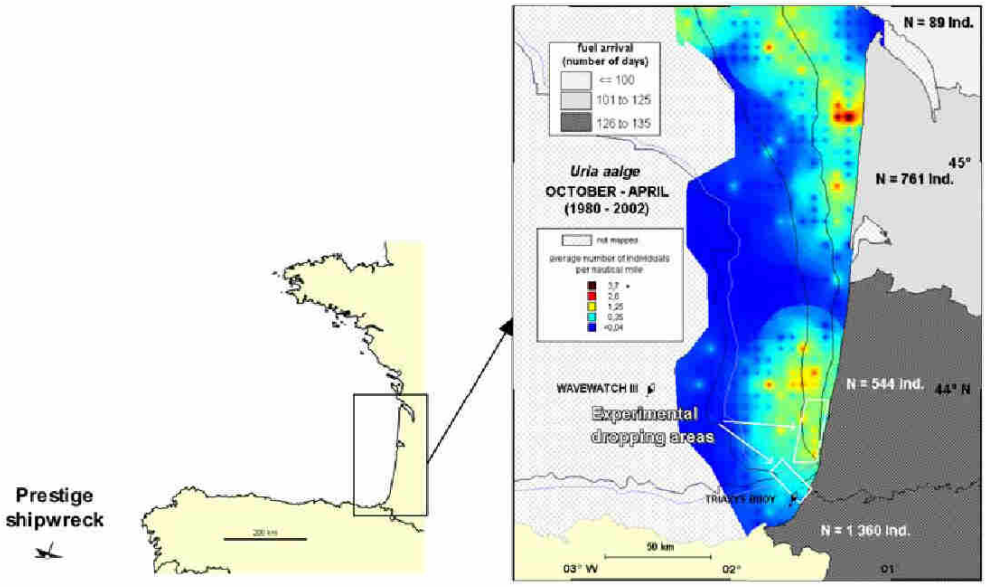

FIG. 1.—Left: location of the "Prestige" shipwreck and the study area. Right: geographical distribution of guillemot abundance at sea in winter (October - April 1980 - 2002, abundance expressed as the average number of individuals per nautical mile); experimental dropping areas ; location of WAVEWATCH III and Triaxys buoy; number of beached birds and days of oil arrivals on the coast represented by administrative regions (Pyrénées-Atlantiques, Landes, Gironde, Charentes-Maritimes).
[Izquierda: localización del hundimiento del "Prestige" y de las áreas de estudio. Derecha: distribución y abundancia de las araos en alta mar durante el invierno (octubre-– abril 1980 - 2002; abundancia expresada por el número medio de individuos por milla náutica); zonas experimentales donde se depositaron los cadáveres; localización del WAVEWATCH III; número de aves varadas en la plaza y días de la llegada de petróleo a la costa de las distintas regiones administrativas.]

Data collection

Weather data

Use was made of environmental conditions known to affect the number of oiled birds (dead or alive) found on the beach (Wiese *et al.*, 2003) such as wind direction, speed and frequency. Weather information (wind speed and direction) and sea state were obtained from "La Tour des Signaux" station based on the Adour estuary (3 measurements per day at 9 a.m., 11 a.m., 17 p.m.) and the Météo France station located in Biarritz city. Off-shore wind data (i.e. coming from coast and transporting ashore floating waste) and on-shore wind data were respectively coded –1 and +1 and multiplied by the wind speed. Data for swell (height, mean period and direction) were measured in situ by a Triaxis directional wave buoy ashore off Bayonne (location: 43°31' N, 1°36.8' W; Abadie *et al.*, 2005; Fig. 1). This TRIAXIS wave buoy (Axys Technology) performs hourly measurements and proceeds to the computation of statistical and spectral wave parameters for the measurement period. These parameters were sent every hour to the coastal station located at the Adour river mouth.

A second data set composed by WAVEWATCH III (Tolman, 1991; 1999) was used to complete the TRIAXIS dataset. WAVEWATCH III is a third generation spectral model used for instance by the U.S. Navy to give simulations of sea states every three hours (*http://www.fnmoc.navy.mil*; location 44°N, 2°30'W).

Beached birds data

Daily data of oiled seabirds (alive or dead) were collected by various wildlife rehabilitation centres [Hegalaldia, Biarritz (64) ; Union Française des Centres de Sauvegarde de la faune sauvage (UFCS) - Unité Mobile de Soins pour Oiseaux Mazoutés (UMSOM), Pouydesseaux (40); LPO-Certe (33)] along the Aquitaine coast (Fig. 1) between January and March 2003. This data set was made available to us by the "DIREN Aquitaine" (Bordeaux).

Oil arrivals data

Daily quantities of hydrocarbons were collected at various beaches along the Aquitaine coast by the Centre of Documentation, Research and Experimentation on Accidental Water Pollution (CEDRE) which was responsible for the activity of depolluting sites.

Total mortality estimate for seabirds

Experimental release of corpses

An estimation of the rate of discovered beached individuals is required to assess the total mortality of the populations of birds. Using a CMR approach (Graham Bell, 1974; Seber, 1982), we experimentally released at sea 121 ringed corpses of guillemots, the most collected species in term of number of individuals collected on the coast after the "Erika" and "Prestige" oil spill (Cadiou *et al.*, 2004). The chosen released zones corresponded both to the coast line which received most impact from the "Prestige" pollution and to sectors used by wintering guillemots (Fig. 1). The corpses of freshly dead oiled guillemots collected in different rehabilitation centres were used and marked with combinations of standard metallic MNHN rings and an additional band made of a large (3 x 5cm) orange plastic flag. The experiment was replicated on three dates (February 18, March 18 and April 18, 2003), releasing corpses from coastguard vessels following a line transect methodology. For each experiment, two samples were used: the first on a South-east - North-west transect along the Basque Coast and the second along a South-North transect along the Landesaise Coast (Fig. 1). Each corpse was released every 800 m along the transect, their geographical coordinates being systematically recorded using a Global Positioning System.

Assessment of floating time

An additional *ex situ* experiment (aquariums at the Biarritz "Sea Museum") was carried out to estimate the floating time of the specimens at sea before sinking naturally. This parameter is required in the drift model for corpses (see below). At the same time, a sub-sample (from the sample of dead birds used in the release experiment at sea) made of 8 oiled corpses of guillemots recovered from the rescue centres was plunged in salt water aquariums pumped directly at sea and constantly renewed to mimic natural conditions (air and sea temperature, salinity, microbial communities...).

Corpses drift modelling

Time vectors of the corpses drift were obtained using wind direction and intensity measured 3 times a day (9 am, 11 am, 5 pm) multiplied by a drift coefficient at sea (see Appendix

1 for details). This coefficient is estimated for corpses of guillemot on average to 2.5 % of the wind speed (Hope Jones *et al.*, 1970; Wiese and Jones, 2001). In the study area, the surface current was considered negligible (SHOM, 1973) and thus was not integrated into the drift model. Eventually, modelling drifting guillemot corpses along the Aquitaine coast was performed using Statistical Analysis System (SAS institute).

Total mortality estimation

Estimates for the total mortality of the populations of seabirds (including in particular the oiled individuals which died at sea or were beached but not found on the coast) were derived from the average impacted birds number using mark-recapture method during the release experiment (18 February - April). Asymptotic Standard Error (ASE) was calculated by SAS software (SAS Institute Inc, Cary, NC, USA, release 8.2). Because wind speed and direction strongly influenced the number of beached birds, a wind coefficient (W) was calculated for each period using the wind on-shore rate.

$W = \Sigma$ on-shore wind velocity / Σ wind velocity

The estimated impacted bird number obtained during the release experiment (February - April) was extrapolated to the beginning of the disturbance event (04 January - February) knowing the wind coefficient for the two periods (see § 3.2).

Statistical analysis

Principal Component Analysis (PCA) was used to investigate linear correlations between weather parameters (wind speed an direction), swell (height, mean period and direction), oiled beached birds arrivals and hydrocarbons arrivals (Stabox V. 6.3). The PCA matrix related to 15 explanatory variables [wind (measures per day and added by step of one day time), swell (height, mean period and direction), state of the sea] and 12 variables to explain (additional) [oiled beached birds (alive, dead and total) day per day and shifted by step of one day time, arrivals of hydrocarbons on Aquitaine coast] and on 72 statistical units (January 19 at March 31, 2003). Prior to analysis each variable was normalized. Correlation analysis between hydrocarbons arrivals, beached birds arrivals and weather data was performed using non parametric Kendall test (SAS institute V.8).

RESULTS

Total mortality estimate of the marine bird populations

The *ex situ* experiment with floating corpses in salted water aquariums indicated that all the individuals were already steadily decomposed when 20 days old and sank between 25 and 30 days, respectively. A maximum floating time of 30 days was logically retained and it was assumed that beyond 30 days at sea, all guillemots corpses have disappeared. Thus, no simulation was carried out beyond 30 days in the drift model.

Using the simple drift model (Appendix 1), theoretical routes were mapped for each of the 121 released birds (Fig. 2). During this simulation period of bird corpses drift, wind conditions were almost offshore (61 % with 44.5 % of south-eastern) carrying away (*i.e.* ashore) all floating material including bird corpses (Fig. 2). It appeared that a majority of dropped birds (n = 84) would have disappeared at sea after 30 days. Among the 121 corpses of oiled ringed guillemots released at sea, the model indicated that 37 birds should have been beached along Pays Basque and Landes coast (Fig. 2). However, only one guillemot (FU0991) was recaptured on 19 April, 2003 on the beach of Anglet

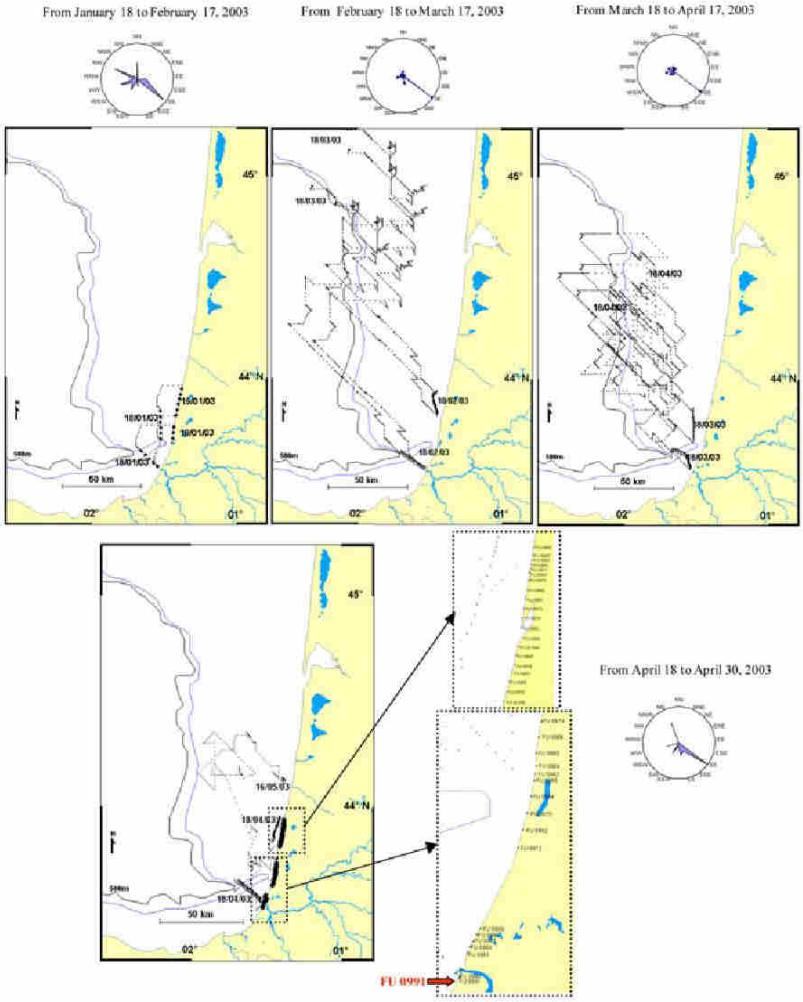

FIG. 2.—Drift model of guillemots corpses at sea : theoretical route for each bird is represented from the dropping point till disappearance or beach arrival; **b)** *n* = 40 corpses, drift from February 18 to March 17; **c)** *n* = 41corpses, drift from March 18 to April 17; **d)** *n* = 40 corpses, drift from April 18 to April 30. The recaptured corpse (FU 0991) the April 19, 2003 is represented. **a)** drift simulation from 18 January to 17 February of a virtual sampling from the same dropping area (*n* = 11 corpses). Wind direction (number of days) is also represented for each drift simulation period.

[Modelo de deriva de los cadáveres de las araos en el mar: ruta teórica de cada aves representada desde el punto desde el cual se arrojo al mar hasta su desaparición o llegada a la playa; ***b****)* n = *40 cadáveres, derivas desde el 18 de febrero al 17 de marzo;* ***c****)* n = *41 cadáveres, derivas desde el 18 de marzo al 17 de abril;* ***d****)* n = *40 cadáveres, derivas desde el 18 al 30 de abril. La recaptura del cadáver (FU 0991) del 19 de abril de 2003 se representa: a) como la simulación de la deriva desde el 18 de enero al 17 de febrero de una muestra virtual de la misma área donde se arrojaron las aves (*n *= 11). La dirección del viento (número de días) se representa también para cada periodo de simulación de derivas.]*

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TABLE 1

Compared estimates of birds impacted in the study area during the "Prestige" oil spill: A) mortality estimate from beached bird census (data collected by various rehabilitation centres); B) total mortality estimate from CMR modelling, the recapture probability was estimated during the second period (P2, released corpses at sea experiment). Then, the estimated impacted bird number of the second period was extrapolated to the first one knowing the wind conditions (see text).
[Comparación de las estimas de aves afectadas por el vertido del "Prestige" en el área de estudio: A) mortalidad estimada por censo de las aves varadas en las playas (datos obtenidos por varios centros de rehabilitación); B) mortalidad estimada a partir de los modelos de captura-recaptura (CMR), la probabilidad de recaptura se estimó para el segundo periodo (P2, cadáveres arrojados al mar de forma experimental). Conociendo éstas y las condiciones de viento, se pudo extrapolar el número de aves afectadas en el primer periodo (P1; ver texto).]

Period	**Beached bird number**	**Wind coefficient (*W*)**	**estimated impacted bird number (*n*)**	**Asymptotic Standard Error**		**recapture probability (*P*)**
				n	***p***	
January 04 - February 17 (P1)	2 612	0.6483	18 739	18 807	-	-
February 18 - April 30 (P2)	95	0.3979	11 501	11 543	0.00823	0.00826
TOTAL	2 707	1.04	30 240	22 067	-	-

(Fig. 2). It is important to note that this unique catch was made exactly at the time and at the location where the simulation model indicated it (Fig. 2d).

Capture Marking Recapture modelling provided an estimation of the value for total mortality equal to 30 240 killed birds in Aquitaine area (Table 1). This estimate was eleven times the amount of beached birds collected despite a large Asymptotic Standard Error (ASE).

Correlation between arrivals of oiled beached birds, hydrocarbons and environmental conditions

The two dimensional plan provided by PCA explained 75 % of the total variance (Fig. 3). The active variables, apart from the period and the direction of the swell, were very well represented and correlated positively. The explanatory variables describing wind strongly contributed to the formation of the PC1, the maximum contribution being for 7 days of cumulated wind. The state of the sea, the height and the period of the swell contributed to the formation of the PC1 and PC2 and were strongly correlated. The number of beached birds (alive, dead and total) and oil arrivals were well represented on the correlations circle of the PC1 x PC2 plan and expressed as a gradient along the PC1. The number of beached birds (alive, dead and total) were strongly correlated but not synchronised directly with arrivals of hydrocarbons.

Beached birds were strongly correlated with the wind measured the very same day ($P < 0.05$, Kendall test; January - February included when all the rehabilitation centres were operational). The oil arrivals were strongly and significantly correlated with birds beached 8 days before ($P < 0.05$; January - February included; Fig. 4). Oil arrivals were strongly correlated with the variables described by 7 days of cumulated wind ($P < 0.05$, Kendall test; January - March included). The state of the sea (strong-

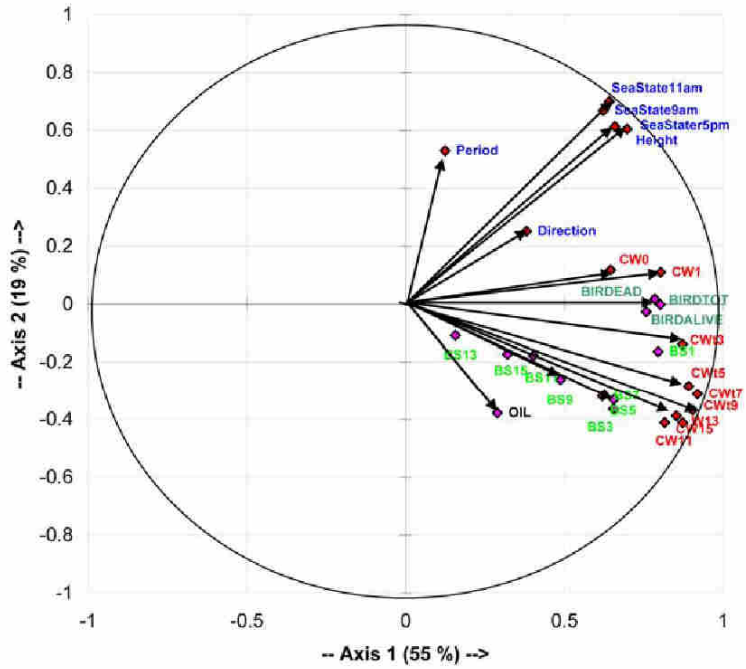

FIG. 3.—Correlation circle within the PC1-PC2 plan of the Principal Component Analysis (PCA). The fraction of the variance captured by the PC's is indicated on the axis. Abbreviations used: **CW** = wind cumulated (added by step of one day time), **Height, Period and Direction** = Swell, **BirdDead, BirdAlive** and **BirdTotal** = Beached birds collected, **BS** = Beached birds shifted by step of one day time, **Sea state** (measured 3 times a day) and **Oil** = arrivals of hydrocarbons .
[Representación circular de las correlaciones de los componentes principales (PC1-PC2) obtenidos del Análisis de Componentes Principales (PCA). La fracción de la varianza capturada por cada PC se indica en el eje.]

ly correlated with wind intensity), height, period and direction of the swell were not strongly correlated with beached birds (alive and/or died) and the oil arrivals.

DISCUSSION

Total mortality estimate of the marine bird populations

As several other authors have done, here too it is pointed out that after other spills offshore winds versus onshore winds can be an explanation of the decreasing number of birds drifting ashore in one period (Stowe, 1982, in Camphuysen *et al.*, 2001). During the "Prestige" crisis, weather conditions have strongly influenced the number of beached birds. This explained the poor rate of simulated beached corpses (only 37 individuals over 121 released at sea could have been found on the beaches according to our drift model), due to frequent offshore winds (61 %) moving ashore corpses which disappeared at sea (Fig.2), a result in accordance with previous studies using wood-

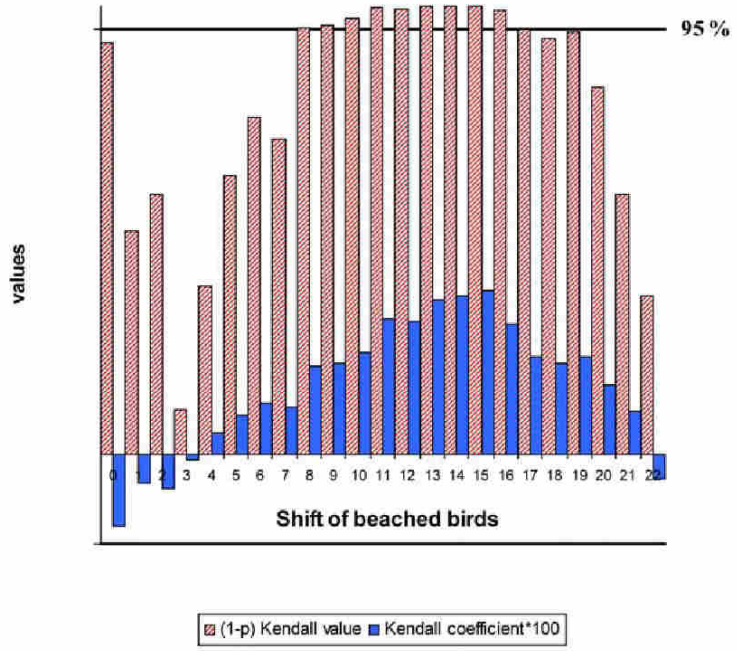

FIG. 4.—Correlation Kendall test between oil arrivals and beached birds shifted by step of one day time (between 0 and 22 days). The black line indicates the significant value [(1 - *P*) > 95]. The Kendall rate is presented.
[Prueba de la correlación de Kendall entre las llegadas de petróleo y de las aves a la playa con un cambio de un día por cada intervalo (entre 0 y 22 días). La línea negra indica el valor de significación [(1 – P) > 95].]

en blocks (Flint and Fowler, 1998). Disappearance was attested by the *ex situ* experiment revealing a maximum floating time of 30 days. Given the wind conditions during the crisis, if the maximum floating time provided by Wiese (2003) had been used, the same number of simulated beached birds woiuld have been found (Fig. 2). This time afloat was likely to be less if sea state (accelerating decomposition process) and predation was added. Indeed, Wiese (2003) found that 70% of floating individuals *Uria* spp. sank within 5 days whilst other sank before 20 days. The present modelling approach proved to be of great help in understanding or predicting patterns of corpses drift. The simple drift model designed on other models previously tested (Hope Jones *et al.*, 1968) was quite efficient as the only individual found (FU 0991, "Cavalier" beach (Anglet) the 19 April 2003, Fig.2) was collected exactly at the date and location expected by the drift model.

The major lesson drawn from this study was that the impact of the "Prestige" would be strongly underestimated if only collected beached birds were considered. The CMR experiment showed that the mortality during the release experiment averaged 11 500 birds corresponding to an extrapolated whole amount of 30 240 birds directly killed in Aquitaine waters by the "Prestige" oilspill; it is approximately eleven times the amount of beached birds collected. The wide ASE associated to this

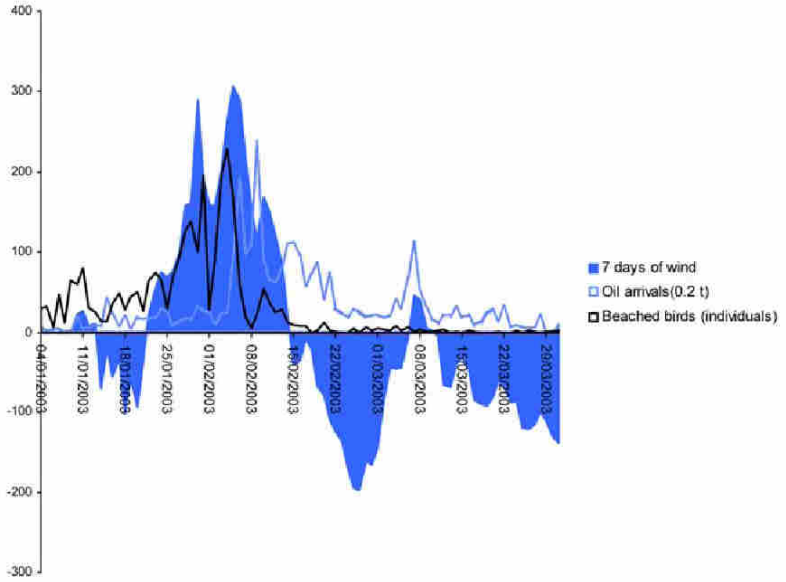

FIG. 5.—Daily variation in beached birds abundance (expressed as individual numbers day^{-1}), oil arrivals (x 0.2 tons day^{-1}) and wind (7 days of additional data.day^{-1}) during the study period.
[Variación diaria de la abundancia de aves varadas (expresada como número de individuos x día^{-1}), llegada de petróleo (x 0,2 toneladas x día^{-1}) y viento (7 días de datos adicionales x día^{-1}) durante el periodo de estudio.]

estimate is largely explained by the very low recapture rate. This low recapture rate is not a pitfall as a useful estimate of population size can be obtained even when no individuals have been recaptured (Graham Bell, 1974). One may also consider that the release experiment from the 18 January to the 17 February (P1; Fig. 2) was not carried out because of delayed administrative authorisation whilst the number of beached birds was maximum (Fig. 5); note that at that time, the drift model simulated virtually an important number of beached corpses (Fig. 2). Certainly, if these data could have been incorporated, the final estimation would have been more precise. Nevertheless, because wind conditions and beached birds are strongly correlated, it was decided to extrapolate the estimated impacted bird number of the second period (CMR experiment) to the first period.

During the CMR experiment (18 February - 30 April; P2), if the recapture number would have been more important, the estimated impacted bird number would have been decreasing and stabilizing quickly. The simulation (Fig. 6) indicated that the estimated impacted bird number strongly would have decreased if two extra birds had been recaptured: 11 501 (± 11 543) to 3 832 (± 6 738) respectively for 1 to 3 recaptured birds. Then the estimation decreased slowly from 4 recaptured birds. Because the estimated impacted bird number depend on the recapture number, it would be interesting to standardize the frequency and the travelled distance of beached birds survey in order to maintain a strong and continuous recapture probability.

The experimental release in April was continued because i) there were still wintering

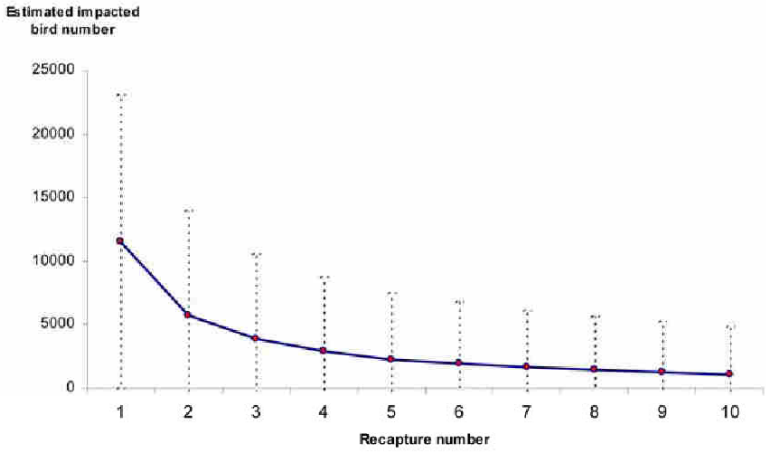

FIG. 6.—Estimated impacted bird number in relation to the number of recapture birds during the CMR experiment. Vertical bars indicate the Asymptotic Standard Error.
[Número estimado de aves afectadas en relación al número de recapturas durante el experimento de captura-recaptura (CMR). Las barras verticales indican el error estándar asintótico.]

seabirds (particularly guillemots; Fig. 7) at sea and also ii) even if most wildlife rehabilitation centres were closed some of them were not. Apart from this apparent weakness in the present study, many results were in agreement to greatly emphasize that the true impact of the "Prestige" on marine birds was far beyond the number of birds collected on the coastline. The important decrease of collected beached birds in February and March did not indicate a decrease of the mortality of seabirds at sea but on the contrary, these two months revealed a maximum abundance of seabird populations and mainly those of the Common Guillemot which was the most impacted species (Fig. 7; Castège *et al.*, 2004). Thus, the impact of the "Prestige" would have been strongly underestimated if only beached birds were accounted for, particularly during this period, because as we highlighted above, birds dead at sea drifted ashore with highly frequent off- shore winds at this time (Ruiz-Villareal *et al*, 2006).

This is not the first time that this severe underestimation has been pointed out. In Europe, if each oil spill event have been characterized by an estimate of bird mortality relying only on beached bird number, by contrast, few have tried to assess whether this estimate was reliable or not. For example, in their drift experiments, Bibby and Lloyd (1977) showed that between 11 and 59 % of ringed corpses were found on the coast (Table 2). Hope Jones *et al.* (1970) recaptured only 20 %. In 1966, after the shipwreck of the Liberian tanker "South America", the Hydrobiological Delta Institute calculated that the number of birds perished at sea was between 8 to 11 times more important than what could be counted on the coast line (*in* Tanis and Bruyns, 1968). In Alaska, after the shipwreck of the "Exxon Valdez" in 1989, using extrapolation of the number of dead birds recovered on the coastline and observations from aerial and ship-based surveys, Piatt *et al.* (1990) also estimated that the total mortality from oil pollution was 3 to 10 times more important. After the "Prestige" shipwreck, the underestimation of mortality varied from 5 to 13 times according

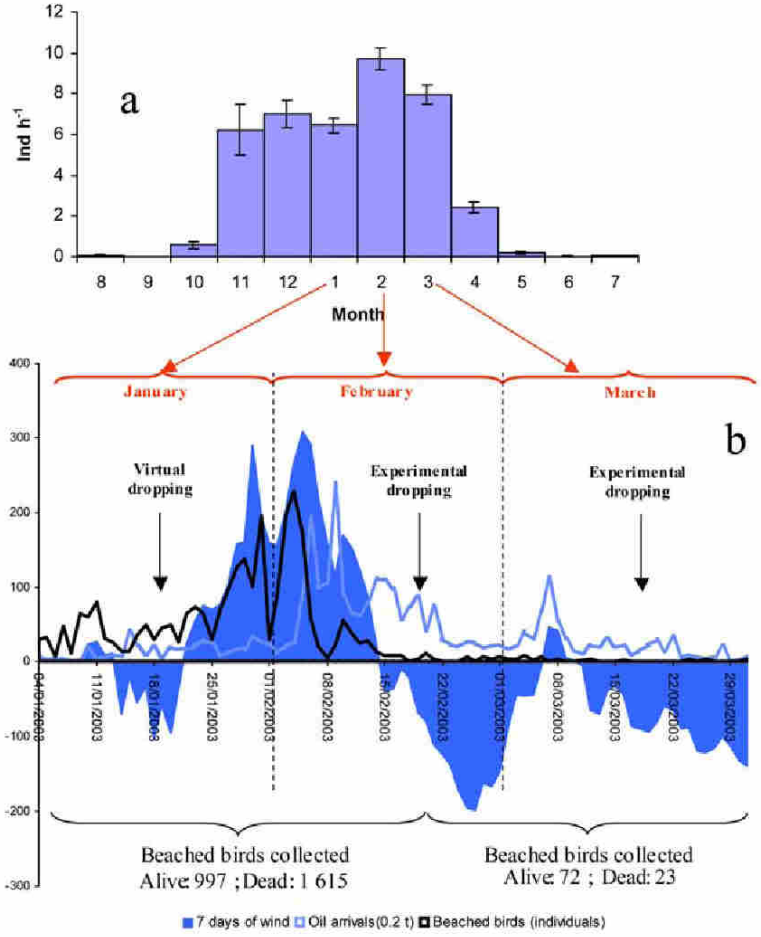

FIG. 7.—a) Seasonal variation in guillemot abundance at sea expressed by the average number of individuals per hour (1980 - 2002); b) evolution of beached birds and oil arrivals during the period of the study. *[a) Variación estacional de la abundancia de araos en el mar expresado por el número medio de individuos por hora (1980 - 2002); b) evolución de las aves varadas y de la llegada de petróleo durante el periodo de estudio.]*

to the studies (Table 2). Arcos *et al.* (2004) estimated this underestimation between 6.5 to 10.8 times more important using drift blocks experiment.

Our CMR-based study is in accordance with those results despite revealing a slightly higher underestimation (x 11) than many other studies above. This could be explained by the fact that our work used standardized methodology combining simultaneously and at the exact time of oilspill *in situ* release and *ex situ* floating corpse's experiments to match perfectly the intrinsic characteristic of the oil spill. However, caution is required before comparing any results with other estimates describing other oil spill events. Indeed, each

TABLE 2

Some total mortality estimate of marine birds (all species) quoted in literature.
[Algunas estimas de mortalidad de aves marinas obtenidas de la literatura.]

Topic	Year	Location	Beached birds collected	Estimate of total mortality death toll	Estimate Methods	Source
Experiment	1966		-	(x 8 to 11)	?	Tanis and Bruyns (1968)
Drift carcasses experiment	1973-1974	Irish Sea	-	11 % to 59 % (x 1.7 to 9)	CMR	Bibby and Lloyd (1977)
Drift carcasses experiment	1969	Irish Sea	-	20 % **(x 5)**	CMR	Hope Jones *et al.* (1970)
Exxon Valdez	1989	Alaska	30 000	100 000-300 000 **(x 3 to 10)**	Aerial and ship-based survey	Piatt *et al.* (1990)
Erika	1999	France (Britain)	74 000	80 000- 150 000 **(x 1.1 to 2)**	Empirical	Cadiou *et al.* (2003)
Prestige	2002	Spain (Galice)	23 181	250 000-300 000 **(x 10.8 to 13)**	Empirical	Dominguez *et al.* (2003)
Prestige	2002	Spain (Galice)	23 181	115 000-230 000 **(x 5 to 10)**	Empirical	Garcia *et al.* 2003
Drift blocks experiment (Prestige)	2002	Spain (Galice)	23 181	150 000-250 000 **(x 6.5 to 10.8)**	CMR	Arcos *et al.* (2004)
Drift carcasses experiment (Prestige)	2003	France (Aquitaine)	2 707	30 240 **(x 11)**	CMR	Our study

oil spill is different and presents its own particular characteristics [(geographic location of the spill, season during which it occurs, ecology of species affected (abundance, breeders, winterers…) and environmental weather conditions such as wind].

Aside from the main trends described above, this study also revealed subtle patterns. For example, even if the estimate of the total mortality of marine birds presented an important ASE (due to a poor rate of recaptured corpses), this was in accordance with the decrease in numbers of guillemots (the most affected species) observed at sea (Fig. 8). During the three years following the "Erika" oil spill, no significant decrease in the abundance

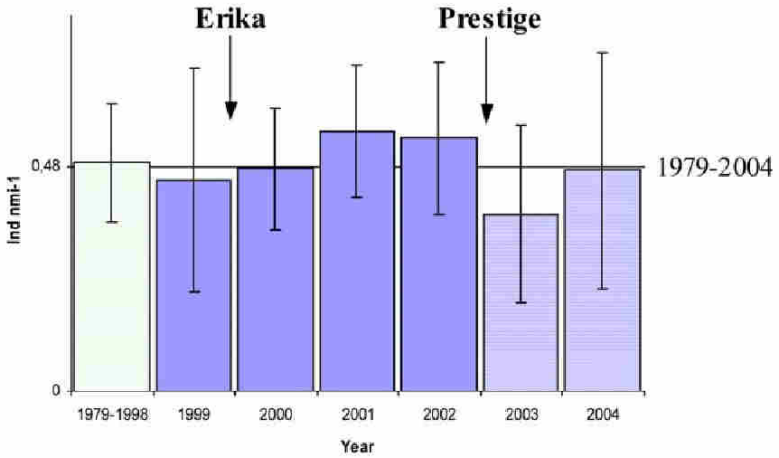

FIG. 8.—Variation of guillemots abundance (mean number of individuals per nautical mile) in the south of the Bay of Biscay (1979-2004). Verticals bars represent standard errors obtained under standardized conditions (Castège *et al.*, 2004).
[Variación en la abundancia (número medio de individuos por milla náutica) de araos en el sur del Golfo de Vizcaya (1979 - 2004). Las barras verticales representan un error estándar (Castège et al. *(2004).]*

of guillemots at sea was observed while a decrease was noted despite not significant ($P > 0.05$) after the "Prestige". This decrease could be explained by the combined effect of both oil spills. Indeed, most of the individuals present in the Bay of Biscay were young birds (< 2 years old). As they grow older and especially as they initiate breeding (at 3 - 5 years old), guillemots do not winter any more the Bay of Biscay but stay in northern areas (Cramp and Simmons, 1983). Thus, those surviving individuals from the cohorts affected by the "Erika" were likely to be not observed in the Bay of Biscay during the subsequent years. However, a low rate of juveniles production, resulting in fewer individuals being observed in the Bay of Biscay in winter, occurred three to five years after the catastrophe when these birds recruited into the breeding population. Eventually, it appeared that both the long term impacts of "Erika" and the underestimated gross mortality caused by the "Prestige" were likely to explain the decrease in the number of guillemots observed in the south of the Bay of Biscay.

The applied issue is that, because seabirds have a late sexual maturity (Schreiber and Burger, 2002), it is crucial to monitor the seabird's abundance affected by oil spills at least five years after the accident.

Correlation between arrivals of oiled beached birds and hydrocarbons

It has been demonstrated here that beached birds patterns were strongly correlated with wind measured the same day ($P < 0.05$). This suggests that birds beached on the Aquitaine coast came from a population that wintered in coastal waters where their abundance is maximum (Fig. 1), and in particular Aquitaine and near Spanish areas. It is unlikely that beached birds may have come from remote areas such

as Galicia because of limited floating time and rapidity of the response.

Moreover oil arrivals were strongly correlated with the variables described by 7 days of cumulated wind ($P < 0.05$). This result is not surprising as the shipwreck occurred in a remote place and the oil drifted slowly and with complex patterns before reaching French coastal waters and soiled the Aquitaine coast (CEDRE, 2005). Oil arrivals were strongly and significantly correlated ($P < 0.05$) with birds beached 8 days before (Fig.4). This suggests that once oiled, birds reach the nearest coast mainly because of impermeability loss (Hémery *et al.*, 2005). This phenomenon can explain the early arrival of birds on the coast before the oil as this is often observed during pollution by hydrocarbons (Camphuysen and Heubeck, 2001).

The applied issue is clearly that the beached birds precede (about 8 - days advance in the case of "Prestige") the arrivals of hydrocarbons on the beaches.

Conclusion

This study showed that in the case of "Prestige", oil arrivals on Aquitaine coast were strongly and significantly correlated with birds beached 8 days before. As quoted in literature for others oil spill, this further confirm that beached birds can be used as indicators of oil pollution.

The originality and novelty in this approach was to assess real total mortality through *in situ* and *ex situ* experiments carried out exactly at the time of oil spills. The derived parameters (i.e. floating time, expected proportion and location of beached corpses, mortality estimate and confidence interval) matched perfectly the intrinsic characteristics of the oil spill, thus giving the best 'warranty' in term of estimate reliability. Furthermore, the combination of a simple drift model to a CMR experiment proved to be a powerful strategy. However, because each oil spill is different in nature and presents its particular characteristics (geographic location of the spill, season during which it occurs, ecology of species affected, environmental weather conditions…) any estimate of mortality calculated after an oil spill may not be extrapolated to others.

Broadly speaking, the main question in assessing the real impacts of any oil spill on seabirds population is to know if the number of birds recovered on beaches after the spill is true or represents only a fraction of the real mortality. In this study, it is demonstrated how the impact of the "Prestige" oil spill was strongly underestimated by the sole consideration of beached bird collection. In particular, it was obvious that off-shore wind masked the real mortality whilst bird abundance at sea was maximum (February - Mars). This leads to advocating the use of drift models, even as simple as the one proposed in this paper, either to simulate expected location of beached corpses either to assess true mortality using CMR method for example. Using such an approach, the total mortality of marine birds was demonstrated to be about eleven times the amount of beached birds collected on the Aquitaine coast.

This result is in accordance with those provided by the ongoing standardised monitoring of seabirds abundance at sea. This further explains why guillemots declined recently in the south of the Bay of Biscay; indeed, it is hypothesised that the differed impact of the "Erika" shipwreck, expected between 3 or 4 years after the catastrophe, added to the mortality caused by the "Prestige".

Because of their complexity, in particular effects delayed in time, true assessment of oil spill impact needs further monitoring of marine ecosystems on a long term basis, at least five years after the accident. More generally, the pooling of databases of different nature and origins proves to be necessary to apprehend the impact of pollutions, such as those of "Erika" and "Prestige", on the animal populations and more generally for the conservation of the marine biodiversity.

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APPENDIX 1 *[APÉNDICE 1]*

Simple model for corpses drift (see § 2.3.3)

$$\begin{bmatrix} D_d \\ D_i \end{bmatrix}_{t,t+1} = \delta \times \begin{bmatrix} W_d \\ W_i \end{bmatrix}_{t,t+1}$$

where:
D_d and D_i represent drift direction an drift intensity for corpses;
W_d and W_i represent wind direction (degree) and wind intensity (km per hour);
δ is the drift coefficient (in this study we assume that δ= 2.5 % for Guillemot corpses - Hope Jones *et al.*, 1970; Bibby and Loyd, 1977).

Annexe II : Poster présentant les travaux du programme ERMMA dans le cadre du suivi scientifique de l'estran rocheux de Guéthary, exposé lors des **colloques internationaux** de Biarritz en 2011 sur la « Vulnérabilité des écosystèmes côtiers au changement global et aux évènements extrêmes » et **ISOBAY XII** à Santander en 2012 sur l'océanographie du golfe de Gascogne.

VULNERABILITY OF BENTHIC MACROFAUNA OF THE GUETHARY'S FORESHORE (E. ATLANTIC, FRANCE) AFTER THE "PRESTIGE" OIL SPILL

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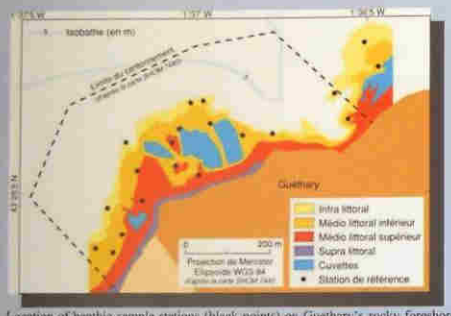
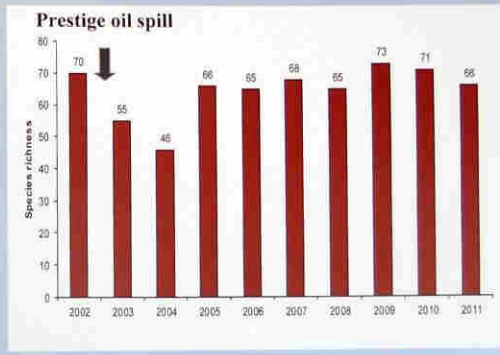
Participants ERMMA

Context:

On 13th November 2002 the "Prestige" sunk near to the Finistere Cape in Galicia (Spain) with 77 000 tons of fuel on board spilling some 63 000 tons at sea. The oil slick which followed the shipwreck impact the Guethary's foreshore in early 2003. The effects of this pollution on the **littoral benthic community** have been studied during **nine years** following the spill.



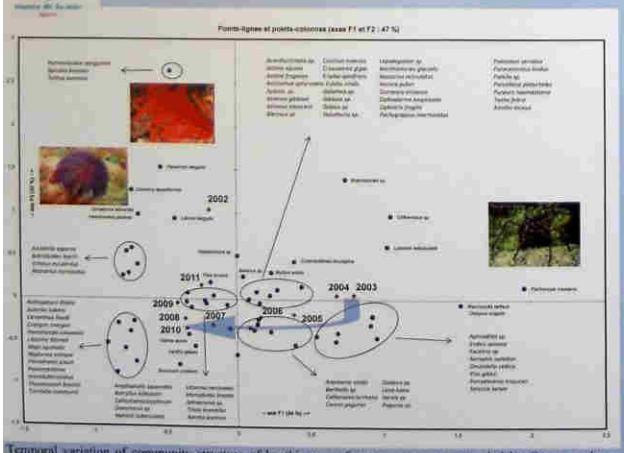
Location of benthic sample stations (black points) on Guethary's rocky foreshore. Quadrats (see photo) are located from the supralittoral to the infralittoral



Variation in species richness on Guethary's rocky foreshore from 2002 to 2011. The vertical arrow indicates the oil slick following the Prestige shipwreck.

Area and method:

The Guethary's foreshore is located to the Northeast Atlantic ocean, on the French coast Bay of Biscay. The standardized and quantitative monitoring method presents counts 20 geographically referenced quadrats spread on 3 littoral zones of the Guethary's rocky foreshore: the supralittoral, the mediolittoral and the infralittoral zone.



Temporal variation of community structure of benthic macrofauna among years revealed by Correspondence Analysis (matrix 10 years * 99 species (presence/absence)). Axis 1 and axis 2 plan.

Statistical approach:

Non parametric Spearman test

Multivariate statistical technique : *correspondence analysis*

Results:

Two years after the "Prestige" oil spill, **species richness decreased** in the studied area with a loss of 24 species: from 70 in 2002 (before the shipwreck) to 46 species in 2004. Mediolittoral zones were the most impacted. The following years, species richness increased significantly ($p = 0.0336$) up to a level observed prior to the oilspill.

A detailed analysis showed some **change in the population structure**. Polluo-sensitive species disappeared after 2002 but reappeared two or three years later (e.g.: *Echinus esculentus, Botryllus schlosseri*…). On overall aspect, the benthic community seems to show resilience of this ecosystem since 2007 although a new composition of macrofauna populations is observed.

Our analysis pointed out the **complexity of the environmental response in front of pollution**. They also showed that a temporal point of view and **a regularly updated baseline are needed** in order to assess the impact of an oil spill on benthic communities.

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<u>Annexe III</u> : Article intitulé « Response of benthic macrofauna to an oil pollution: lessons from the “Prestige” oil spill in the South of the Bay of Biscay (France).» Soumis pour publication en 2012.

Response of benthic macrofauna to an oil pollution: lessons from the "Prestige" oil spill in the South of the Bay of Biscay (France).

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Abstract:

The "Erika" oil spill which impacted the Bay of Biscay ecosystem in December 1999 confirmed that reference state of ecosystems was needed in order to assess the impact of an oil spill especially on benthic communities. Thus, the benthic community on the rocky foreshore of Guéthary (France) is monitored since 2002. The standardized and quantitative monitoring method counts twenty geographically referenced quadrats spread on three littoral zones: upper mediolittoral, lower mediolittoral and infralittoral zone. The year of the setting up of these monitoring, the "Prestige" sunk near to the Finistere Cape in Galicia (Spain). The oil slick following the shipwreck impacted the foreshore of Guéthary in early 2003.

After the "Prestige" oil spill, the specific richness decreased in the studied area with a loss of 16 species from 57 in 2002 (before the shipwreck) to 41 species in 2004. In the following years, taxonomic richness increased to a level observed prior to the oil spill.

Temporal variations in community structure of benthic macrofauna among years are revealed by detailed analysis. Some polluo-sensitive species disappeared after 2002 and have not reappeared yet (*e.g.*: *Hymeniacidon perlevis*). Some others reappeared two or three years after the spill or even later (*e.g.*: *Amphipholis squamata, Botryllus schlosseri, Calliostoma zizyphinum, Echinus esculentus*…). Noteworthy changes were found in 2004 driven by the sudden increase in abundance of grazers. Following years these abundances went back to a stable level. The benthic community seems to recover almost five years later although a new composition of macrofauna populations is observed.

On overall aspect, the complexity of the benthic ecosystem response to oil spills confirms the need of regularly updated baselines to assess the impact of pollutions and more generally for the conservation of the marine biodiversity.

Keywords: Oil spills, Benthos, Rocky shores, Taxonomic richness, Abundance, Recovery, Bay of Biscay

1. Introduction:

Over the last three decades, Bay of Biscay coast has experienced many oil spills such as "*Torrey Canyon*" (1967), "*Urquiola*" (1976), "*Amoco Cadiz*" (1978), "*Aegan Sea*" (1992) or "*Erika*" (1999). In 2002 a new oil spill following the "Prestige" shipwreck impacted French coast.
The "*Prestige*" was an oil tanker that been broken in two parts about 130 nautical miles off the west Spanish coast, near Galicia, on November 19 2002. Of the 77,000 tons of heavy fuel carried by the tanker, 63,000 spilled. Since the accident, fuel has spread along the north coast of Spain and reached the French and Portuguese shores. According to the rough weather conditions of that winter, the oil might also have been mixed until a certain depth within the water column, where sensitive organisms may have been exposed and affected (Sánchez *et al.*, 2006). Finally, such a spill involves the deposition of oil, in particulate and aggregate forms, on the sea floor, where it can also affect the benthic ecosystem.

The "Prestige" accident represents one of the largest environmental catastrophes in the history of European navigation. Due to its expansion, magnitude and temporal persistence, the "Prestige" oil spill (POS) is considered as the most important environmental disaster on the northern coast of Spain and one of the most relevant on a worldwide scale (Puente *et al.*, 2009). More than 1000 km of coastline and a huge variety of habitats were affected, ranging from supralittoral, intertidal and sublittoral levels to oceanic and bathyal environments (Penela-Arenaz *et al.*, 2009).

Effects of POS on different marine ecosystems have been well studied during years following the oil spill, including seabirds (Camphuysen *et al.*, 2002; Velando *et al.*, 2005; Alonso-Alvarez *et al*, 2007; Castège *et al.*, 2007), plankton (Varela *et al.*, 2006), microfauna (Pascual *et al.*, 2008), fishes (Sánchez *et al.*, 2006; Martínez-Gómez *et al.*, 2009) and benthic communities (Sánchez *et al.*, 2006; Puente *et al.*, 2009…).

Most benthic communities studies following the POS have been carried out in Spain: in deep shelf (Sánchez *et al.*, 2006; Serrano *et al.*, 2006), on estuaries (Puente *et al.*, 2009) or sandy beaches (de la Huz *et al.*, 2005; Junoy *et al.*, 2005). None monitored only dedicated on rocky shore affected by POS has been brought to our attention.

Assessing the impact of pollution on rocky shores is greatly complicated by a high level of spatial and temporal diversity. According to Hartnoll and Hawkins (1980), changes in the overall composition of the community may be seasonal, due to more or less regular annual changes as a result of mortality, recruitment, growth and behavior patterns. Furthermore rocky shore organisms are subject to several natural stresses such as tidal amplitude or wave action (see Raffaelli and Hawkins, 1996; Thompson *et al.*, 2002 for reviews), thus many of them must be tolerant to a wide range of stresses. Rocky shores are also subject to a variety of human impacts on a

wide range of spatial and temporal scales (see Crowe *et al.*, 2000; Thompson *et al.*, 2002 for reviews): pollution (*e.g.* oil spills, eutrophication and toxic alga blooms, endocrine disrupter…); food gathering; introduced species; global change (*e.g.* Mieszkowska *et al.*, 2006); modification of coastal processes.

Thereby, the need of long-term monitoring is highlighted by many authors to study polluted areas or variability of natural systems in general (Southward, 1995; Peterson, 2001; Hawkins *et al.*, 2002; Puente *et al.*, 2009). Indeed, recovery after acute events may take several years and can only be studied properly over long periods of time. The length of the period needed would depend on the nature of the habitat, the degree of shore cleaning as well as the recolonization. The latter depends on the time of year, the availability of recolonizing forms, the biological interactions, and climatic and other factors (Crowe *et al.*, 2000; Kingston, 2002).

In the Bay of Biscay, the "Erika" oil spill also confirmed that reference state was needed in order to assess the impact of an oil spill in particular on benthic communities (Laubier *et al.*, 2004). Due to this, benthic community is monitored since 2002 on the rocky foreshore of Guéthary (France).

In this paper we investigate the temporal change of benthic communities after the "Prestige" oil spill on the rocky shore of Guéthary using a ten-year data set, including one sample prior the oil spill. We focus more particularly on three changes 1) global taxonomic richness 2) temporal variations of community structure and 3) variations in species abundance.

2. Materials and Methods:

2.1 Study area

The study area is located on the rocky shore of Guéthary (France) on the Aquitaine coast in the southern part of the Bay of Biscay. This area was chosen before the POS because of its singularities. Firstly, this is a protected area where most of fishing activities or human impacts is prohibited. Secondly, this rocky shore is listed as a ZNIEFF (Zone Naturelle d'Intérêt Ecologique, Faunistique et Floristique), a natural area considered for its noteworthy ecology, fauna and flora according to a national French inventory.

The standardized monitoring method counts twenty geographically referenced quadrats spread on three littoral zones: upper mediolittoral, lower mediolittoral and infralittoral zone. Four of them were placed outside the protected area (Fig.1). The quadrats are located between latitude from 43.4297 N to 43.4227 N and longitude from -1.6082 W to - 1.6214 W.

2.2 Field sampling

All field work was conducted on the rocky shore of Guéthary between march and may of each year since 2002. The sampling method is standardized, the twenty quadrats location were randomly chosen in the three littoral zones and are permanent since 2002. Each of them was sampled between two and four

time a year depending on the tidal predictions: quadrats located on infralittoral zones can only be sampled during low spring tide (which appears one or two time by month).

Quadrat size was set to 16m² (4x4m) in order to cover a large area. Peterson *et al.* (2001) pointed out, without giving a size, that a larger area of coverage by sample can achieve better representation by spreading the sample out a larger range of any natural gradient or across spatial heterogeneity.

In each quadrat, all individuals of each macrofauna species were counted and identified at the lowest possible taxonomic level. The abundance of six taxa (*Balanomorpha*, *Botrylloides leachi*, *Botryllus schlosseri*, *Janua pagenstecheri*, *Mytilus sp.* and *Spirobranchus triqueter*), chosen because of their high density, is estimated. However, abundances were not collected during the first year so only presence/absence data is available for 2002.

2.3 Data Analysis

Temporal variation of the benthic community was assessed using three major analyses. Firstly the taxonomic richness was calculated for each year from 2002 to 2011 (ten years of data). The Spearman non-parametric test was applied to calculate significant variations in the number of species before the POS. All analyses were made with the Statistical Analysis System (CORR procedure), and MapInfo® Software.

To avoid problems with the correct determination of some species, analyses were conducted for data aggregated to a mixed taxonomic level (*e.g.* Smith and Simpson, 1995; Junoy *et al.*, 2005). The validity of this approach is supported by studies suggesting that effects of pollution are detectable at taxonomic levels higher than species (Gray *et al.*, 1990; Smith and Simpson, 1993; Gomez Gesteira *et al.*, 2003).

Secondly we performed a multivariate analysis in order to compare community structure of benthic macrofauna before and after the oil spill. We used a correspondence analysis based on the presence/absence of taxa (matrix 10 years X 110 taxa) and conducted by Statbox software (6.4 version).

Thirdly we investigated the temporal changes in the abundance of benthic macrofauna from 2003 to 2011. Sampling fluctuations around the mean abundances were described by their standard error SE = SD / √n-1 (with SD: standard deviation and n: sample size). The analysis is then focused on the most abundant trophic level: the grazers. Indeed, this group alone represents 53 % of the abundance of benthic macrofauna on the rocky shore of Guéthary. For grazers, common taxa of sea urchins are considered (*Paracentrotus lividus*, *Echinus esculentus* and *Sphaerechinus granularis*), as well as mollusks (*Aplysia sp.*, *Calliostoma zizyphinum*, *Diodora sp.*, *Gibbula sp.*, *Haliotis tuberculata*, *Littorina littorea*, *Littorina neritoides*, *Monodonta lineata*, *Neoloricata*, *Patella vulgata*) and sea slug *Onchidella celtica*.

A lot of temporal variations due to rocky shore natural diversity, such as seasonality, disappeared since our samples were monitored during the same period each year within three months. All the same, spatial variations are eliminated in using permanent quadrats (Hartnoll and Hawkins, 1980).

3. Results:

3.1 Changes in the taxonomic richness

Through the ten years of monitoring, 110 taxa were identified on the rocky shore of Guéthary. The benthic community is dominated by Mollusca (32.7%), Arthropoda (27.3%) and Echinodermata (10.9%). Regarding trophic group, 42% of taxa are mainly predators, 18% are suspension feeders and 13% are grazers.

Before the oil spill, a total of 57 species was sampled. The "*Prestige*" oil spill began the 13th of November 2002 but our study area was hit the 31st of December (Daniel *et al.*, 2004). Thus, the following year, when sampling started, the area was already polluted since three months. Taxonomic richness decreased significantly ($p < 0.001$) until it reaching the lowest value of 41 species in 2004 (Fig. 2). The following years, the number of species gets back to the level (around 58 species) observed prior to the oil spill. Since 2005, taxonomic richness showed no significant variations ($p = 0.7599$) and stabilized despite some inter-annual variations.

3.2 Temporal variation of the community structure

The Correspondence Analysis (axis 1 and axis 2 explained 39 % of the total variance) shows in detail the changes among the community structure of benthic macrofauna (Fig. 3). There was a community structure in 2002 with taxa clearly specific to this year, such as *Hymeciadon perlevis* or *Tethya sp.* Then structure changed through years with an important loss of taxonomic richness (Fig. 2). After 2006, specific richness was close to prior the oil spill but a quite new composition of macrofauna population appeared.

A further look in data pointed out four kinds of groups: 1) taxa sampled every year (*e.g. Actinia equina, Anemonia viridis, Asterina gibbosa, Athanas nitescens, Carcinus maenas, Eriphia spinifrons, Galathea squamifera, Gibbula sp., Holothuria sp.*) 2) "rare" taxa sampled from time to time (*e.g. Clavelina lepadiformis, Doriopsilla areolata, Lepidonotus squamatus, Rostanga rubra, Onchidella celtica)* 3) taxa who disappeared after the oil spill and reappeared 2-5 years later (*e.g. Amphipholis squamata, Botryllus schlosseri, Calliostoma zizyphinum, Echinus esculentus, Littorina littorea Psammechinus miliaris), and* 4) taxa who never reappeared after 2002 (*e.g. Hymeniacidon perlevis,Tethya sp.*).

3.3 Changes in the abundance of some trophic groups

Notably, total mean abundance increased in 2004 with a sharp peak (176 ± 30 ind.m^{-2}). Next year total mean abundance strongly decreased until a value of 63 ± 30 ind.m^{-2} which remained above abundance measured in 2003. During the following years, total mean abundance presents no significant variations ($p = 0.2152$) and stayed stable between 68 ± 14 ind.m^{-2} (2006) and 36 ± 4 ind.m^{-2} (2011).
Figure 4 shows that total mean abundance is mainly explained by grazers especially in 2004 (138 ± 28 ind.m^{-2} that is 78% of the total abundance). There was a bloom of grazers this year: densities increased 3.6 times. Total mean abundance and grazers mean abundance are strongly correlated ($p = 0.0016$) whereas relation between total abundance and abundance of other species (*i.e.* excepted grazers) is no congruent ($p = 0.0671$). It should be noted that total mean abundance without grazers seemed relatively stable from 2003 to 2011 with no significant trend ($p = 0.3807$).

4. Discussion:

Results obtained in the present work suggest that macrofauna population on rocky shore of Guéthary was impacted by the "Prestige" oil spill. This impact was expressed by a global decrease in taxonomic richness with a loss of 16 species between 2002 (prior the spill) and 2004. Increase of number of taxa in following years reveals a process of recovery of the ecosystem. Ten years after the oil spill, taxonomic richness seems to remain stable. It took three years to reach a taxonomic richness similar to the reference value of 58 taxa obtained before the oil spill.

Noteworthy differences in the community structure were revealed by the multivariate analysis. Some species never reappeared on the shore since the POS (*e.g.* Sponges *Hymeciadon perlevis* and *Tethya sp)*, while others are present all along the monitoring. More interesting, some species disappeared just after the spill and reappeared few years later (mostly between 2-5 years). This last group gathers species known for their sensibility to pollution, such as *Amphipolis squamata*, *Calliostoma zizyphinum* and *Psammechinus miliaris* (Grall and Glémarec, 1997; Borja *et al.*, 2000; Barillé-Boyer *et al.*, 2004). The first axis scans the temporal gradient, highlighted by the arrow, suggesting a recovery of the ecosystem (Fig. 3).

Although taxonomic richness went back to "normal" in 2005 with 58 species, multivariate analysis indicated that recovery process is more complex because benthic communities vary among time. Indeed, the recovery process seems to take longer (almost five years) before reaching a composition of macrofauna up to the level observed prior the spill. Finally recovery measurement remains difficult, as highlighted by Crowe *et al.* (2000), moreover different survey design could lead to varying interpretations of the time-scale of recovery (Peterson *et al.*, 2001).

Our results were in accordance with previous studies on the impact of oil spills on worldwide rocky shores which reported a recovery of initial communities around three or four years after the event (Kingston, 1999;

Crowe *et al.*, 2000; Kingston, 2002; Barillé-Boyer *et al.*, 2004; Penela-Arenaz *et al.*, 2009). Sell *et al.* (1995) reviewed 27 oil spill cases in which studies on the recovery rate of rocky shores have been made and found that only four cases showed a recovery delayed beyond three years. Their study also showed that recovery times are ranging from 3 to 4 years for an rocky shore exposed to wave action to over 12 years for a sheltered shore.

Nevertheless the recovery can be delayed by the cleanup. The rocky shore of Guéthary was partially cleaned using high pressure hot water washing. In Sell *et al.* review (1995), cleanup appears to have delayed re-establishment of the biota and also the recovery process. Such detrimental effects presumably arise because the cleaning operations sterilize the substratum by removing or killing any biota that have survived the initial effect of oiling. For example, as a result of the *Torrey Canyon* oil spill in Cornwall, the major damage was not caused by the tons of oil which came ashore, but by excessive treatment with over 10 000 tons of dispersants (Smith, 1968). These were later shown to be very toxic to marine life (Corner *et al.*, 1968). The dispersants killed the grazer *Patella vulgata*, and, to a lesser extent, other herbivores such as *Monodonta lineata* and *Littorina* spp. The negative effects of high pressure or hot water to clean on rocky shore ecosystems have also been shown too (Broman *et al.*, 1983; Peterson, 2001; Le Hir and Hily, 2002). Both oil slick and cleanup effects could explain that some sensitive species attached on the rocks never reappeared (*e.g.Hymeciadon perlevis* and *Tethya sp.*).

Despite some inter-annual variation, total mean abundance pointed out very interesting data about response of this ecosystem. Three month after the POS total mean abundance was 49 ± 9 ind.m^{-2} but one year later (2004) value reached a peak of 176 ± 30 ind.m^{-2}. Following years, abundance stabilized around a value of 60 ind.m^{-2}. As grazers alone represent 53% of the total abundance, we focused our analysis on this trophic group. It appears that most of total mean abundance is explained by densities of grazers.

From this perspective we can link this phenomenon with study of Barillé-Boyer *et al.* (2004) also located in the Bay of Biscay. Authors emphasized the importance of changes in percent cover of the two species of macrophytes, *Ulva sp.* and *Grateloupia doryphora* after the "Erika" oil slick. The significant correlation between the decrease in algal cover and the rise in herbivore density illustrated the pressure of grazing exerted by the return of the herbivores in the area. Even if we did not measure algual cover, following literature, we can suggest that the maximum of herbivore density could illustrate a variation of the algal abundance. Indeed, the proliferation of macrophytes, caused by the immediate death of the herbivores after an oil spill, is well described in studies of oil tanker accidents (Marchand, 1981; Newey and Seed, 1995; Crump *et al.*, 1999; Barillé-Boyer *et al.*, 2004). Three years after the POS (2005), the density of grazers in the studied area decreased and then seemed to stabilize. This could show balance between herbivore and algal communities after a period of perturbation.

The effects of the "Prestige" oil spill on marine ecosystem were studied from plankton to seabirds. Despite varied results, most of the studies have showed impacts on the populations, for example: a decrease in the species richness and abundance of the macroinfauna in sandy beaches with disappearance of rare species (de la Huz *et al.*, 2005; Junoy *et al.*, 2005); reduction in the abundance of shrimp, lobster and megrim in deep shelf (Sánchez *et al.*, 2006); indirect impact for European shags through a reduction on the availability of preys (Velando *et al.*, 2005). Generally these studies indicated a strong initial impact during first year after the spill, mainly on intertidal communities and fishing resources, with recovery by 2004 (Penela-Arenaz *et al.*, 2009). Peterson *et al.* (2003) revealed that cascades of indirect effects can be as important as direct trophic interactions in structuring communities. In the present study, we also measured a strong initial impact (loss of taxonomic richness, changes in community structure, proliferation of grazers). The recovery took between 3 (if we only considered the number of taxa) and almost 5 years (according to community structure).

Definition of "recovery" can vary following literature (*e.g.* Ganning *et al.* 1984; Sell *et.al* 1995) because processes may take many forms depending on the nature of the oil spill damage under consideration. Kingston (2002) in his review shares this possible definition of recovery: "Recovery of an ecosystem is characterized by the re-establishment of a biological community in which plants and animals characteristic of that community are present and functioning normally". Thereby, the multivariate analysis which revealed community structure seems to be the more suitable.

We agree with Elmgren *et al.* (1983) who consider that whole systems are better indicators of oil pollution than single species even if several orders seem to be in some cases polluo-sensitive, *e.g.* the Amphipoda (Bellan-Santini, 1980; Gomez Gesteira and Dauvin, 2000; de-la-Ossa-Carretero *et al.*, 2012). Our study suggests considering species richness, abundances and multivariate analysis to define recovery of this ecosystem.

Conclusion:

The "Prestige" oil spill impacted taxonomic richness, community structure and abundance of benthic macrofauna on the rocky shore of Guéthary.

Even if taxonomic richness went back to "normal" in 2005 (3 years after the spill), multivariate analysis indicates that recovery processes are more complex because benthic communities vary among time. Indeed, the recovery processes seem to take more time (almost five years) before reaching a composition comparable to the macrofauna observed prior to the spill. Moreover, the proliferation of grazers suggests a perturbation of the benthic ecosystem.

These results confirm the complexity of recovery of impacted ecosystems and that true assessment of oil spill impact needs reference state monitoring, at least five years after the accident. Globally, long-term study of marine

biodiversity proves to be necessary for the understanding and the conservation of the marine ecosystems. From this perspective, the monitoring of the area will be extended to observe the next steps in the ecological successions.

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CAPTIONS FOR FIGURES

Fig. 1:
Location of study area and benthic sample stations (black points) on the rocky foreshore of Guéthary. Quadrats are located from the mediolittoral (orange) to the infralittoral (yellow). Dotted lines represent the protected zone.

Fig. 2:
Variation in taxonomic richness on rocky foreshore of Guéthary from 2002 to 2011. The vertical arrow indicates the oil slick following the Prestige shipwreck.

Fig. 3:
Temporal variation of community structure of benthic macrofauna among years revealed by Correspondence Analysis (matrix 10 years X 110 taxa (presence/absence)). Axis 1 and axis 2 plan.

Fig. 4:
Mean variation in total abundance (all species), grazers abundance and total abundance without grazers on intertidal rock at Guéthary from 2003 to 2010. Vertical bars represent standard errors.

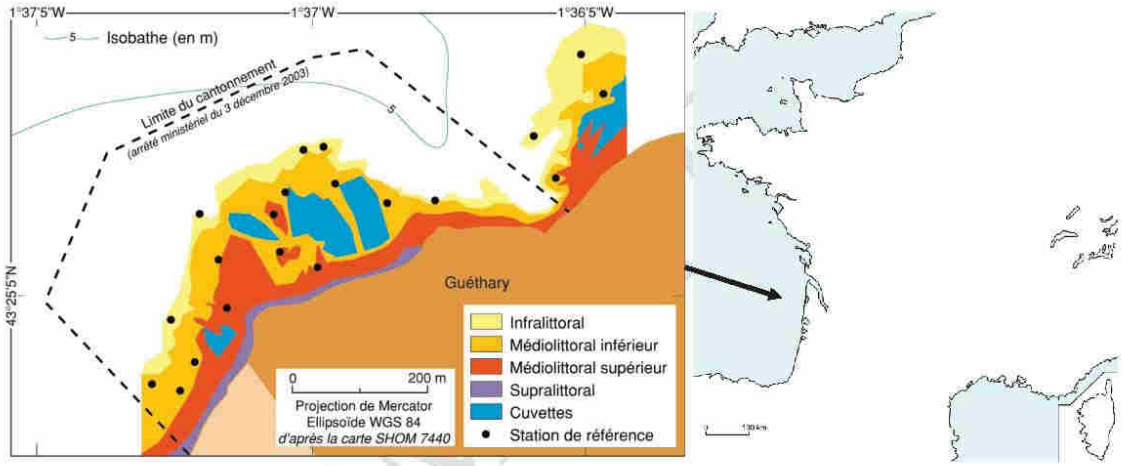
1°37'5"W
1°37'W
1°36'5"W
43°25'5"N
5
Isobathe (en m)
Limite du cantonnement
(arrêté ministériel du 3 décembre 2003)
Guéthary
Infralittoral
Médiolittoral inférieur
Médiolittoral supérieur
Supralittoral
Cuvettes
Station de référence
0
200 m
Projection de Mercator
Ellipsoïde WGS 84
d'après la carte SHOM 7440

Fig. 1

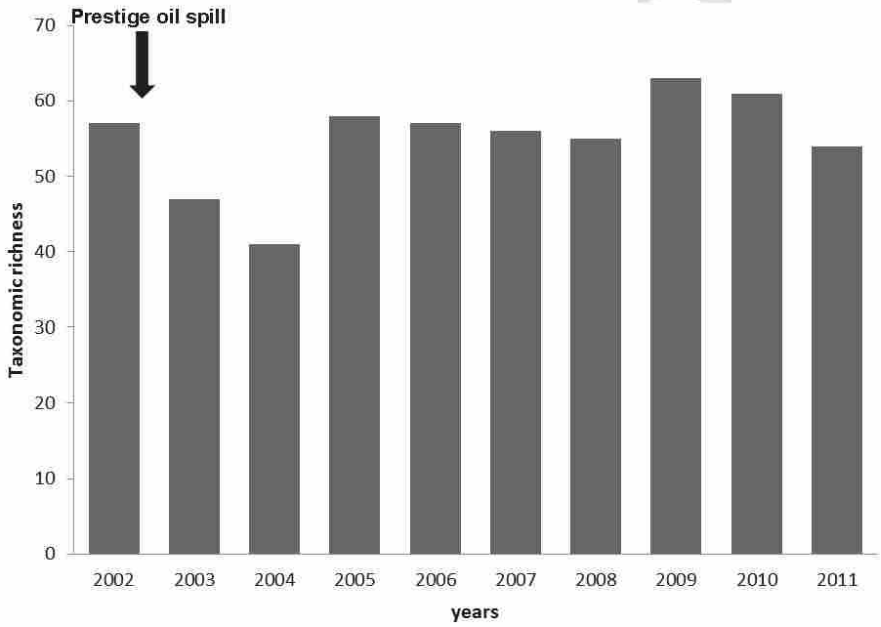
Prestige oil spill
Taxonomic richness
70
60
50
40
30
20
10
0
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
years

Fig. 2:

16

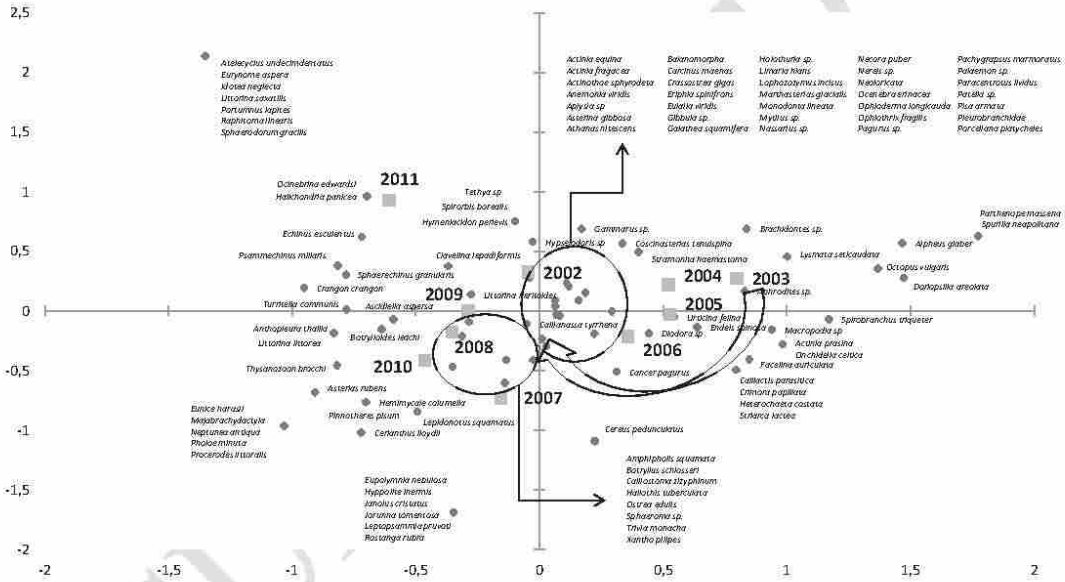
2,5
2
1,5
1
0,5
0
-0,5
-1
-1,5
-2
-2
-1,5
-1
-0,5
0
0,5
1
1,5
2
2011
2002
2009
2004
2003
2005
2008
2006
2010
2007

Fig. 3:

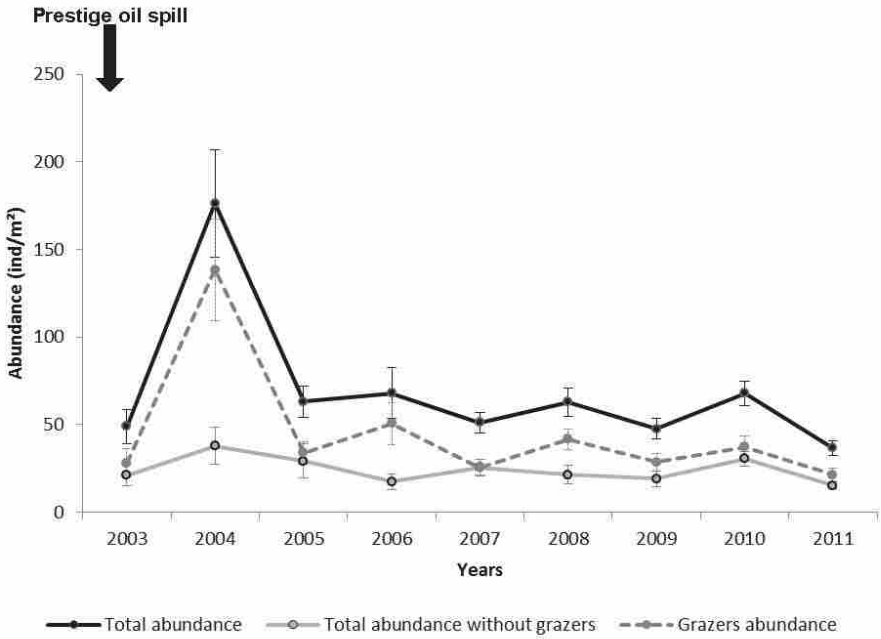
Prestige oil spill
250
200
150
100
50
0
Abundance (ind/m²)
2003
2004
2005
2006
2007
2008
2009
2010
2011
Years
Total abundance
Total abundance without grazers
Grazers abundance

Fig. 4:

18