EVALUATING THE “FERRYBOX” AS AN APPROPRIATE MONITORING SYSTEM FOR THE MARINE ENVIRONMENT: USING THE WRECK OF THE MV ECE IN THE ENGLISH CHANNEL AS A TEST CASE

(Measuring phosphoric acid concentrations in the vicinity of the wreck of the MV Ece in March 2006: leakage, fate, ecosystem response and prediction)

(Contract Project Code: ME3208)

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31st March 2006

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ACKNOWLEDGEMENTS

This work has benefited greatly from the help and service of the following people: Jon Campbell for technical skills in setting up and maintenance of the FerryBox system, Jose Gonzales and Stephen Boswell for help on the calibration crossings, and the staff of P & O European Ferries Ltd. In particular, I would like to thank Captains Alastair Mcfadyen and Philip Hill for their full support and cooperation. The infrastructure for this work is supported by the George Deacon Division core strategic programme - BICEP (Biophysical Interactions and Carbon Export Production) - funded by the Natural Environment Research Council. We are grateful to Defra (and its predecessor, DETR) for financial support in helping to set up an early prototype Ferrybox system for use in Southampton Water under the SONUS project (SOuthern NUtrient Study Phase 2, contract no. CWO 805). The Met Office work has been funded under the UK National Meteorological Programme. We thank the BBC for permission to use the map showing the location of the wreck on the front cover.
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EXECUTIVE SUMMARY

- This study evaluates the use of the ship-of-opportunity (Ferrybox) concept for monitoring UK shelf sea waters. The sinking of a chemical tanker in the English Channel is used as a specific test case for the concept.

- An effective marine management strategy requires accurate knowledge of both specific incidents and background conditions preceding such incidents. Accurate data is also critical to know both the natural variability of those background conditions and the drivers behind the variability. Only then, through appropriate monitoring, can changes in marine states due to specific pollution incidents be properly managed.

- The Ferrybox system used in this study meets the demand for such accurate data.

- The Ferrybox system is an autonomous suite of electronic sensors installed on board P&O European Ferries Ltd ship, the Pride of Bilbao, operating year-round between Portsmouth (UK) and Bilbao (Spain) since April 2002. Data are collected every second along the route. The ship crosses within 1 mile of the shipwreck (the edge of the exclusion zone) every 12 hours to 3.5 days. The system provides data within five minutes of collection via a satellite link and additional data are collected on monthly manned crossings. Additional water samples were collected in this study to measure phosphate and other nutrients (on 28th-2nd March 2006 and 14th – 17th March 2006)

- The specific incident (test case) is the sinking of the chemical tanker - M.V. Ece -with a cargo of 10,000 tonnes of phosphoric acid. The ship sank in 70 metres of water, 30 miles northwest of Guernsey in the western English Channel on 1st February 2006.

- Phosphoric acid (phosphate) is an essential nutrient for phytoplankton (microscopic marine algae on which the entire marine food chain relies). Release of “additional” phosphate into the sea may intensify blooms of toxic phytoplankton species and/or lead to oxygen loss from the seawater, both of which are lethal to marine organisms.

- This report reviews the possible spill from the tanker on the basis of 1) new data collected by the NOC Ferrybox close to the wreck area, 2) detailed data around this area collected by the Ferrybox since 2003, 3) longer term (1929-1987) single site data from the Marine Biological Association’s station E1, located 20 miles from the coast of Plymouth (UK) and 4) numerical modelling work being carried out by the Met Office using an ecosystem model capable of describing eutrophication effects over UK shelf seas.

- The state-of-the-art computer model (MRCS-POLCOMS-ERSEM, from hereon MRCS), is used as an operational forecasting tool by the UK Metereological Office.

The main findings:

- The Ferrybox system has proved capable of identifying phosphate leakage from the wreck of the MV Ece. A single sample, from a total of 70 samples taken, contained a concentration four times higher than background levels, one nautical mile from the wreck site. The leak occurred between 3rd March and 17th March 2006.
• Measured nitrate to phosphate ratios in Ferrybox samples suggest that phytoplankton growth will be limited by nitrate rather than phosphate. Consequently, the phosphate leak is unlikely to enhance phytoplankton growth at the present time.

• The continuous record of measurements of phytoplankton chlorophyll-fluorescence from the Ferrybox show that phytoplankton growth close to the wreck site did occur in March 2006. However, similar growth occurred at the same time in 2005.

• Hence, the Ferrybox demonstrates its effectiveness as a decision support system, in this instance providing evidence for the view of British and French authorities that released phosphate is unlikely to pose a significant threat.

• These Ferrybox data (nutrients, nutrient ratios and phytoplankton) illustrate the highly variable nature of these coastal waters both in time (days to years) and space (few kilometres). This natural variability highlights the need for continuous monitoring to put new measurements into context, particularly regarding assessment of pollution transport and impacts.

• The annual cycle of changing concentrations of phosphate are similar at the MBA long term (1929-1987) time series station E1 and the wreck site. Hence, these two areas of the western English Channel (northern site E1 and central wreck site) show the same seasonal dynamics. Wreck site concentrations are significantly lower than the mean at E1 in winter, but are similar to concentrations in the 1960’s, highlighting the importance of long-term data sets.

• The MRCS model shows promise in determining chlorophyll concentrations and in particular, sea surface temperature. The model requires further work on phosphate and salinity. Salinity levels are low in the model, potentially affecting its ability to accurately determine the intensity of stratification in English Channel. Predicted phosphate concentrations are up to a factor of four higher than the Ferrybox observations.

• The MRCS model shows the potential to provide useful three-dimensional and temporally varying process insight for both physical and biogeochemical systems. Most significantly it provides full coverage of the North-West European shelf seas that could be valuable in the case of future spills, that one might expect to occur away from in-situ observations.

The scope for future work/implications:

• This study demonstrates that the NOCS Ferrybox system is an appropriate platform for monitoring the marine environment with considerable potential for improving our understanding of UK shelf seas (and their interaction with the Atlantic Ocean).

• The variability shown in the Ferrybox data from 2003-2006 suggests that the OSPAR recommendation of sampling only every three years in “non-problem areas” is likely to provide statistically inadequate data. Ferrybox data shows that off-shelf concentrations of nutrients varied by 50% between 2004 and 2005 due to deeper mixing of water off-shelf in early 2005.

• The NOCS Ferrybox is a highly cost effective way of 1) determining the natural background state of the sea and its variability, 2) putting new measurements into historical context and 3) making evidence based judgements on cause and effect between
ecosystem impacts (e.g. phytoplankton growth) and pollution incidents (e.g. phosphate release from the MV Ece).

- The Ferrybox operates unabated by the weather giving near continuous (near real-time monitoring) of plankton growth. This is in contrast to satellite observations which are severely limited in UK coastal waters due to cloud cover. The Ferrybox is therefore invaluable as an early warning system for pollution incidents.

- The western English Channel (including the wreck area) is typical of UK waters: it is highly heterogeneous in space and time. Continuous Ferrybox sampling captures this heterogeneity, unlike one-off spot sampling.

- The MRCS model has the potential to provide important three-dimensional information on the physical and biological conditions. Further work is required, and in progress, to improve representation of certain physical and biological parameters in the model.

- Ferrybox data should be used in validating model output, and may also prove informative in improving lateral nutrient boundary conditions for the model.
1. BACKGROUND

This work concerns the use of an established marine measurement platform and its effectiveness as a monitoring system for UK coastal waters. The measurement platform, known as Ferrybox, is a ship-of-opportunity operation on board P&O passenger ferry, the Pride of Bilbao sailing year-round between Portsmouth and Bilbao. The Ferrybox - installed in April 2002 and operated by the National Oceanography Centre, Southampton (NOCS) - provides continuous year-round measurements of marine environmental conditions. The ability of the Ferrybox system to provide appropriate monitoring is evaluated by using the recent sinking of a chemical tanker (M.V. Ece) in the western English Channel (49.73 °N - 3.25 °E, Fig. 1) as a test case.

The aim of this study is to evaluate the effectiveness and ability of the Ferrybox to monitor any leakage of the cargo of 10,000 tonnes of phosphoric acid from the M.V. Ece, the fate of any leakage, and assess the likely response of the marine ecosystem - in particular the phytoplankton. This evaluation study occurred in March 2006.

Figure 1. Ferry tracks completed between 21st February and 26th March 2006. Also shown are the locations of station E1 and the wreck of MV Ece. The circled portions of the track are used in the data analysis.

1.1 The Ferrybox concept

For the effective management of coastal and shelf sea ecosystems it is necessary to distinguish between the natural cycling from small and regional scale anthropogenic effects. In many aspects the north west European shelf is considered to be a well studied area. However it is evident from the data assembled during the NORWESP project (Radach et al., 1996), that data are lacking in many areas, particularly in the winter months when research ships have difficulty working. Research cruises allow extensive ranges of measurements to be made but the view is potentially highly aliased by the limited temporal coverage that is possible. Satellites potentially provide
global coverage but are limited to a few determinands and problems leading to aliasing such as cloud cover. The technologies of measuring devices, control systems, data logging and transmission are advancing rapidly. This means that one of the oldest ideas in oceanography - the use of ships of opportunity - has great potential to provide regular cost effective cover of a wide range of parameters in surface waters.

The "Ferrybox" concept is the installation of oceanographic instrumentation on ferries running regular routes to collect systematic data. In EuroGOOS planning it has been highlighted that over 800 ferries operate in European waters. Uses of systems have been reported in open seas – the Sea of Japan (Harashima et al., 1997), the North Sea (Swertz et al., 1999) the Baltic Sea (Leppanen, 2000), the English Channel/Bay of Biscay (Kelly-Gerreyn et al In press) - and in estuaries (e.g. Holley & Hydes 2002). The EU-Framework-5 project "FerryBox" has developed procedures for integrating the data from such systems. A key part of this work was the development of uniform quality controls. Furthermore, Ferrybox measurements are the cheapest effective way of collecting high-quality surface marine data (Jun She, EU FP5 project Optimal Design of Observational Networks - ODON)

1.2 The Pride of Bilbao Ferrybox

The “Ferrybox” system used in this evaluation study was installed in April 2002 on the P & O European Ferries Ltd ship “Pride of Bilbao” operating between Portsmouth (50.8° N, -1.1° E) and Bilbao (43.4° N, -3.0° E) (Fig 1). The ship is equipped with autonomous sensors making continuous (year - round), high frequency (every second) sea surface (5 metres depth) measurements of temperature, salinity (conductivity) and phytoplankton (chlorophyll - fluorescence). Monthly manned crossings measure algal nutrients (phosphate, nitrate and silicate) as well as calibration samples for the autonomous measurements (salinity and chlorophyll). For further details of the sampling see sections 2.1 and 2.2. The Pride of Bilbao is a 40,000 tonne ship which operates year-round (except during annual refit and maintenance in January), unabated by the weather conditions.

The ferry makes between Portsmouth and Bilbao every three days giving a repeat sampling rate of between 12 hours to 3.5 days in the western English Channel (the region focused on in this study). This high frequency, continuous monitoring means that the Pride of Bilbao Ferrybox can be used to determine both the natural state and variability of the sea and the impact of pollution incidents in its area of operation - it is particularly useful as an early warning system. These characteristics are tested in the context of the monitoring of the recent sinking of a chemical container ship, the M.V. Ece.

1.3 The sinking of the M.V. Ece

Two cargo ships collided in the English Channel 50 nautical miles west of the French port of Cherbourg (Fig.1) on the morning (0309 UTC) of Tuesday 31st January 2006. The collision was between the MV Ece (an 8000 tonne chemical tanker heading for Ghent, Belgium and owned by the Turkish operator Aksay Denizcilik), and the General Grot - Rowecki (a 26,000 tonne bulk carrier ship heading for Police, Poland and owned by the Polish Steamship Company Polska Zegluga Morska). The incident left the MV Ece with a 5 m by 2 m breach of its port cargo wing tank causing it to list at 25 degrees whereas the General Grot - Rowecki sustained no major damage. Within 24 hours of the collision, the Ece was being towed – by French rescue and salvage vessel Abeilles Liberte - towards the French port of Le Havre when it sank in 70 metre depth waters (49.73°N, -3.25°E, Fig. 1) at 0230 UTC on Wednesday 1st February. There were
no injuries reported and all crew (34 in all) were rescued by helicopter and lifeboat. Fishing and all nautical activities have since been prohibited within one nautical mile around the position of the wreck.

1.4 Phosphoric acid and environmental considerations in the aftermath of sinking

Phosphoric acid (phosphate) is used in the manufacture of cleaning agents and detergents and commonly applied as an agricultural fertiliser. Phosphate is classified as a category D chemical - the lowest category of MARPOL's Annex II prevention of Pollution By Chemicals Rating - and presents a hazard to both marine resources and human health.

The MV Ece cargo of 10,000 tonnes of phosphoric acid was stored in five internal containers. Initial reports from French divers and ROV (Remotely Operated Vehicle) deployments stated that the cargo of phosphoric acid was intact. However, recent assessments suggest that up to 50% of the phosphate has been released into the water (Maritime and Coastguard Agency – MCA, pers. comm., 24th March 2006). Further release of phosphate from the containers remains a possibility.

Following the sinking, official responses from British and French authorities were that any leaked acid from the MV Ece would not pose a significant threat (MCA and CEDRE, Times Online, http://www.timesonline.co.uk/article/0,,2-2018045,00.html) because 1) the buffering (neutralising) effect of the ocean - from the presence of carbonates dissolved within it - will cause negligible changes to the pH in the sea and 2) the effects of diffusion and dispersion will quickly dilute the phosphate concentrations. Furthermore, while phosphoric acid is also an essential fertiliser for marine algae (phytoplankton), winter conditions (low light levels) are not conducive for algal growth. Consequently, any leaks of phosphate in the immediate aftermath of the sinking were considered not to pose a significant impact on the marine ecosystem in the western English Channel. However, phosphate release towards the end of winter/early spring, when light levels are higher, may lead to enhanced levels of phytoplankton and subsequent impacts on the rest of the marine ecosystem (see section 1.5).

Determining the degree of threat from such a pollution incident can only be established with continuous monitoring. The Ferrybox operation provides this continuous monitoring and the high quality evidence base upon which appropriate management decisions can be supported.

1.5 Potential ecosystem responses to phosphate additions in the western English Channel

The addition of phosphate into the western English Channel, particularly in late winter (March) - early spring (April), has the potential to intensify phytoplankton growth (Table 1).

Phytoplankton growth requires sufficient light levels and three main inorganic nutrients - dissolved inorganic nitrogen (DIN, mostly as nitrate, ammonium and nitrite), dissolved inorganic phosphorus (phosphate) and silicate. These nutrients are taken up by phytoplankton in a well-known ratio called the Redfield ratio (= 16 DIN to 1 DIP, shortened to 16, Redfield, 1934). If this ratio is higher than 16 then phytoplankton growth is restricted by the availability of DIP(phosphate). That is, phosphate concentrations run out before DIN can be taken up to yield the full DIN growth potential of the phytoplankton. Conversely, lower ratios mean that phytoplankton growth is limited by the availability of DIN. Any addition of phosphate in a
Table 1. Potential effect of phosphate release from the MV Ece on phytoplankton growth in the Channel Island area (Fig. 1), assuming favourable light conditions.

<table>
<thead>
<tr>
<th></th>
<th>DIN input ( (t^1) )</th>
<th>DIP input ( (t) )</th>
<th>DIN:DIP input ratio</th>
<th>Limiting nutrient</th>
<th>Phytoplankton growth ( (t \text{ OC}^2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rivers(^\d)</td>
<td>9300</td>
<td>133</td>
<td>70</td>
<td>DIP</td>
<td>14000(^\d)</td>
</tr>
<tr>
<td>Rivers + Ece % increase</td>
<td>9300</td>
<td>3133(^\circ)</td>
<td>3</td>
<td>DIN</td>
<td>62000(^\d)</td>
</tr>
</tbody>
</table>

PARCOM inputs survey (1990); DIN = dissolved inorganic nitrogen; DIP = dissolved inorganic phosphorus
\(^\d\)Selune, Couesnon, Rance.
\(^\circ\)10,000 t \( \text{PO}_4 \) = ~3,000 t DIP
\(^\d\)t = tonnes
\(^\circ\)OC = organic carbon
\(^\d\)assuming Redfield ratio of 106 units of organic carbon produced from 1 unit of DIP
\(^\d\)assuming Redfield ratio of 6.6 units of organic carbon produced from 1 unit of DIN

phosphate limited region will enhance the growth of phytoplankton during the main growth season (from late winter/early spring onwards) when sufficient light (normal for this time of year) is available.

Figure 2. Mean winter nitrate to phosphate ratios from Ferrybox data in the region (ferry track section 49 \(^\circ\)N - 50 \(^\circ\)N circled in Fig. 1) of the MV Ece wreck in the western English Channel in 2003, 2004 and 2005.

The area around the Channel Islands where the Ece sank (Fig. 1) can be phosphorus limited (N:P ratios of up to 33 just prior to the onset of the phytoplankton bloom, Fig. 2). This may be due to DIN and DIP inputs from the main source of nutrients to this region - the rivers Selune,
Couesnon, Rance (Table 1). Note that other sources of nutrients (e.g. the river Seine and oceanic inputs) may influence the DIN:DIP ratios in this region. However, the river Seine outflow is transported towards the North Sea and has no direct contact with the western English Channel (Brylinski et al, 1996). Another nutrient source may be the low salinity water derived from French Atlantic Rivers (Loire and Gironde) which intrudes into the western English Channel (Kelly-Gerreyn et al In press). NOC Ferrybox observations clearly show a discontinuity in concentrations across the shelf break (see Figure 13 section 4.2), suggesting that the shelf break acts as a barrier to oceanic-shelf sea exchange as it induces a current which flows along it rather than across it (see Hydes et al., 2004 and references there in). Estimates of cross shelf exchange into the greater North Sea area that are required to balance the denitrification (the microbiologically mediated loss of nitrogen from the water to the atmosphere) suggest water exchange across the whole oceanic margin is only of the order of $0.6 \times 10^6$ km$^3$ per year (Hydes et al., 1999). An ongoing task in interpretation of the NOC Ferrybox data is discover if the changes in ocean concentrations influence on shelf concentrations (section 4.2). The shelf ocean margin is an area in which existing numerical models are at there most unreliable. Consequently, reliable estimates of oceanic inputs of nutrients to the western English Channel are yet to be established.

Table 1 shows that there is the potential for a more than 400% increase in phytoplankton growth in this region if all the phosphate is released into the water column during the algal growth season (late winter/early spring onwards). Such an increase in growth has the potential to lead to oxygen depletion in the water column caused by the bacterial decay of phytoplankton biomass, inducing mortality in animals living on the seabed. This would occur where the detritus from the bloom collected on the seabed in a limited area and was not dispersed. Furthermore, the increase in phosphate inputs from the leak could intensify the blooms of toxic and nuisance phytoplankton such as Karenia mikimotoi (formerly Gyrodinium aureolum) and Phaeocystis sp. which regularly occur in this region of the western English Channel (Partensky and Sournia, 1989; Kelly-Gerreyn et al, 2006). Such phytoplankton blooms are known to cause mortality in a number of marine organisms such as fish and shellfish.

1.6 Aims and objectives of this study

This study evaluates the ability of the Pride of Bilbao Ferrybox system to effectively monitor the waters around the wreck site by

1. Making new measurements of sea surface (5m depth) concentrations of phosphate in the area of the wreck to detect for the presence of leakage from the MV Ece
2. Monitoring sea surface (5m depth) concentrations of phytoplankton in the area of the wreck to detect for an ecosystem response to phosphate leakage
3. Comparing these measurements to historical phosphate and phytoplankton data in the context of interannual variability in the western English Channel.

In addition, this study illustrates the importance of the Ferrybox data with respect to assessing state-of-the-art numerical models. In particular,

4. validation of the UK Met Office operational numerical ecosystem model of the western English Channel. This will evaluate its use in predicting leakage fate and ecosystem response.

The working assumption is that any leakage of phosphate from the MV Ece will reach the sea surface within hours on account of the well mixed water column in which the ship sank.
2. METHODS AND APPROACHES

The approach adopted here relies on our many years of experience and expertise in collecting data along the track of the P&O passenger ferry, The Pride of Bilbao (Fig. 1). A summary of the sampling approach is given in Table 2.

Table 2. Suite of measurements made on the Pride of Bilbao Ferrybox

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Method</th>
<th>Standard Frequency</th>
<th>Dates of new measurements</th>
<th>New samples frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manual collection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphate</td>
<td>Wet chemical analysis(^1)</td>
<td>Monthly (30 min)</td>
<td>28/02/06 - 03/03/06</td>
<td>15(^\circ) min</td>
</tr>
<tr>
<td>Nitrate</td>
<td>Wet chemical analysis(^1)</td>
<td>Monthly (30 min)</td>
<td>14/03/06 – 17/03/06(^a)</td>
<td>15 min</td>
</tr>
<tr>
<td>Silicate</td>
<td>Wet chemical analysis(^1)</td>
<td>Monthly (30 min)</td>
<td>As above</td>
<td>15 min</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>Acetone extractio(^3)</td>
<td>Monthly (60 min)</td>
<td>28/02/06 - 03/03/06</td>
<td>30 min</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>Winkler titration</td>
<td>Monthly (60 min)</td>
<td>ND</td>
<td></td>
</tr>
<tr>
<td>Salinity</td>
<td>Salinometer</td>
<td>Monthly (120 min)</td>
<td>28/02/06 - 03/03/06</td>
<td>120 min</td>
</tr>
<tr>
<td><strong>Autonomous collection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorophyll-fluorescence</td>
<td>CTD - F MINIPack(^3,4)</td>
<td>1 Hz (1 sec)</td>
<td>24/02/06 – 26/03/06</td>
<td>1 sec</td>
</tr>
<tr>
<td>Temperature</td>
<td>CTD - F MINIPack</td>
<td>1 Hz</td>
<td>As above</td>
<td>1 sec</td>
</tr>
<tr>
<td>Salinity</td>
<td>CTD - F MINIPack</td>
<td>1 Hz</td>
<td>As above</td>
<td>1 sec</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>Aanderaa Optode</td>
<td>0.03 Hz (30 sec)</td>
<td>As above</td>
<td>30 sec</td>
</tr>
<tr>
<td>CO2</td>
<td>LiCOR</td>
<td>0.03 Hz</td>
<td>ND</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)Hydes (1984)  
\(^2\)Jeffrey & Humphrey (1975)  
\(^3\)Conductivity, Temperature, Fluorescence unit - Chelsea Technology Group MINIPack  
\(^4\)Welschmeyer (1994)  
ND = not determined during this study  
\(^a\)only taken on the return leg (Bilbao to Portsmouth due to personnel illness)  
\(^\circ\) 15 minutes = 4 kilometres between samples

2.1 Autonomous measurements

The electronic sensors are installed in the engine room of the Pride of Bilbao. The sampled water is taken from the ship’s cooling water supply which has an intake at a depth of 5 metres. The flow rate in the system is 15 - 20 litres per minute giving a residence time of 3 - 4 seconds before the water reaches the sensors. The sensors are cleaned on a weekly basis when the ship is in port (Portsmouth).

Data are logged at a rate of 1 Hz on a NOCS designed and built logging and control system. The 1 Hz data are downloaded weekly when the ferry is in port. The logger unit sends a sample of the data at 5 minute intervals to an ORBCOMM satellite data transmission and receiving unit on the bridge deck. On shore data are taken from the ORBCOMM e-mail message that arrives at NOCS and is entered into an SQL database. The database is attached to a public web page which displays the current data.
readings and position of the ship. This web facility allows both the functioning of the system and state of the sea to be checked remotely. Public domain Matlab routines (http://marine.csiro.au/~morgan/seawater) provide the calculations for salinity (from the conductivity and temperature measurements) based on the standard UNESCO (1983) algorithms.

2.2 Water samples and calibration of sensors

Manned crossings occurred twice - 28th February – 3rd March 2006 (from hereon crossing 1) and 14th - 17th March 2006 (from hereon crossing 2) (Table 2). Water samples were collected from a spur tap at the point where water is diverted from the ships cooling water supply to the FerryBox sensors. Sample collection was maintained round the clock in both directions by two people to determine: a) concentrations of phytoplankton nutrients - phosphate, nitrate and silicate and b) salinity to calibrate the MiniPack derived salinity. Unfortunately, staff illness meant that water sample collection in the western English Channel only occurred on the return trip of the second manned crossing.

Samples for the determination of nutrients were collected every 15 minutes in sterile 30 ml vials. These were stored in the dark at 4°C until they were analysed on shore 1 - 4 days after collection. Analysis follows the procedures described in Hydes (1984).

Duplicate water samples for chlorophyll $a$ analysis were collected every hour on crossing 1. Samples (250 ml) were immediately filtered through 25 mm diameter glass fibre filters, (Whatman GF/F) under low vacuum. Both filters were stored in acetone at - 30 ºC for analysis on shore. Chlorophyll $a$ analysis is based on the Jeffery & Humphrey (1975) and Welschmeyer (1994).

Salinity samples were collected in 250 ml containers at intervals of 2 hours during the crossings. On return to the laboratory the salinity of the samples was measured on a Guildline™ salinometer standardised with OSI Standard Seawater. The salinity samples are used to calibrate the conductivity derived salinity measurements from the autonomous sensors.

Quality assessments for temperature are made by comparisons with a Seabird 48 temperature sensor placed on the inside of the ship's hull as part of a complimentary project on board the ferry (the Defra funded ISAR project - Infrared Sea surface temperature Autonomous Radiometer).

2.3 Historical data

To put the new measurements into historical context (the context of interannual variability), Ferrybox data from 2003 to 2005 are used. Longer term historical data comes from station E1 (50.03 °N, -4.65 °E, Fig. 1) in the western English Channel, which dates from 1930 to 1987 for phosphate and from 1973 to 1987 for chlorophyll. The E1 data set has been collected and maintained by the Marine Biological Association. Analysis of the E1 data and its comparison to the Ferrybox data enables the quantification of the degree of similarity between different parts of the western English Channel. The question posed is whether the E1 data can be used as a proxy for what is happening in the central western English Channel (the region of the MV Ece wreck).
2.4 Numerical model

Modelling should be an integral part of the support provided for effective management of the marine environment. It is therefore critical for numerical models to be as accurate as possible if they are to be used in the event of aiding the management of pollution events. Models have the unique ability of integrating and assimilating sparse data sets collected at different times and at different places with the purpose of understanding and predicting natural phenomena.

The model used here is POLCOMS (Proudman Oceanographic Laboratory Coastal Ocean Modelling System) on a 7 km Medium-Resolution Continental Shelf domain coupled with the European Regional Seas Ecosystem Model (MRCS-ERSEM2004). This model has been implemented within an operational framework giving the capability for near-real time and forecast simulations, details of which can be found in Siddorn et al. (In Press) and results from which are freely available at http://www.metoffice.gov.uk/research/ncof/mrcs/browser.html. The physical framework is provided by the POLCOMS system. The ecosystem model, ERSEM, is developed at Plymouth Marine Laboratories and is one of the most complex lower trophic-level marine ecosystem models currently in use. Its philosophy is to include all those processes which significantly influence ecosystem dynamics, including several functional groups. It consists of coupled pelagic and benthic modules. Blackford et al, (2004) gives a full description of the ERSEM2004 model and the parameterisations used. From hereon the combined model is referred to as MRCS.

3. RESULTS

The Ferrybox results focus on the portion of the ferry track between latitudes 49 °N and 51 °N (Fig. N1). The rationale is that any leakage of phosphate from the MV Ece wreck location (49.73 °N) will surface and head in an eastwards direction - the predominant direction of water transport in the English Channel (Pingree 1980, Leonard et al 1992, Kelly - Gerreyen et al, In Press, and also suggested in section 3.4.2 from model results). Hence, the portion of the ferry track considered here may allow for the contrast in phosphate and phytoplankton concentrations south - westwards of the wreck (< 49.5 °N) and south - eastwards of the wreck (> 49.5 °N), particularly with respect to picking up enhanced concentrations of both phosphate and phytoplankton in the event of a leak. It should be noted, that advection over a tidal cycle for a source at a fixed geographic location might spread the plume over an area of up to 20 km in diameter (for tidal currents of up to ~1 m s^{-1}, MRCS model for an average tide). This is in addition to any subsequent spreading by diffusion. This adveective spreading which would occur over one tidal cycle, is considerably larger than the 1 nautical mile exclusion zone.

3.1 New measurements

3.1.1 Phosphate

The new measurements of phosphate concentrations for the two manned crossings in February and March 2006 (Table 2) are shown in figure 3a - b. Concentrations of phosphate are between 0.33 mmol m^{-3} and 0.55 mmol m^{-3} on crossing 1 (28th February - 3rd March, Fig. 3a), with mean values of 0.38 ± 0.05 (standard deviation) mmol m^{-3} between latitudes 49 - 49.5 °N and 0.45 ± 0.03 mmol m^{-3} for latitudes 49.5 - 50 °N. These means are significantly different (p<0.001). Phosphate concentrations on crossing 2 (14th - 17th March, Fig. 3b) are between 0.31 and 1.54 mmol m^{-3}. Mean phosphate values are 0.36 ± 0.06 mmol m^{-3} for latitudes 49 - 49.5 °N and 0.59 ± 0.32 mmol m^{-3} for latitudes 49.5 - 50 °N (again these are significantly different,
p<0.001). The maximum value on crossing 2 occurs at 49.68 °N, -3.29 °E (Fig. 3b), which is an increase in concentration by a factor of 4 in this region compared to crossing 1 (Fig. 3a).

Figure 3. Phosphate concentrations in the western English Channel close to the wreck of the MV Ece on crossings 1 and 2. (The red dot next to the MV Ece location in panel b) is a concentration of 1.54 mmol PO$_4^-$ m$^{-3}$; note that phosphate measurements only taken on the return leg of crossing 2).
3.1.2 Phytoplankton

The chlorophyll - fluorescence data from 24th February (day 55) to 26th March (day 85) 2006 is shown in figure 4. Note that these values have not been calibrated. Hence, the changes in these measurements must be considered as qualitative. Chlorophyll - fluorescence is lower at the start of the data series than later on along the entire portion of the ferry track shown in figure 4 (more blue colours prior to day 65 - 6th March - than afterwards). Interestingly, the chlorophyll - fluorescence signal increases (the onset of browns and reds) after day 70 - 11th March - just north of 49.7 °N (the region of the MV Ece wreck). Note that the increase in chlorophyll - fluorescence in the region of the MV Ece starts between crossing 1 and crossing 2, the period in which the high phosphate concentration was measured (Fig. 3b).

3.3 Historical data

3.3.1 Ferrybox : phosphate

Winter phosphate concentrations for 2003 to 2005 in the vicinity of the MV Ece are shown in figure 5a. The range in values is 0.07 mmol PO₄⁻ m⁻³ to 0.51 mmol PO₄⁻ m⁻³. The lowest winter concentrations of phosphate occurred in 2004 and the highest in 2005 (Table 3). Phosphate concentrations in 2006 are significantly higher than for other years in the western English Channel (Fig. 5b, Table 3). If the high value of 1.54 mmol PO₄⁻ m⁻³ is removed from the 2006 data, then there is no significant difference between winter phosphate concentrations in 2005 and 2006 (Table 3).

Table 3. Mean winter (February + March) phosphate concentrations (mmol m⁻³) along two sections of the ferry track in 2003 to 2006. The two sections are regions to the south (49 °N - 49.5 °N) and the region covering the wreck site (49.5 °N - 50 °N).

<table>
<thead>
<tr>
<th></th>
<th>49°N - 49.5°N</th>
<th>49.5°N - 50°N</th>
<th>Significantly different 5% level</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>0.30 ± 0.05*</td>
<td>0.39 ± 0.06</td>
<td>Yes</td>
</tr>
<tr>
<td>2004</td>
<td>0.22 ± 0.05</td>
<td>0.26 ± 0.06</td>
<td>Yes</td>
</tr>
<tr>
<td>2005</td>
<td>0.39 ± 0.04</td>
<td>0.41 ± 0.06</td>
<td>Yes</td>
</tr>
<tr>
<td>2006</td>
<td>0.38 ± 0.05</td>
<td>0.50 ± 0.21/0.48 ± 0.07*</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*standard deviation; †significant difference of 2006 (5% significance level) compared to each year; *value with highest concentration (1.54 mmol m⁻³) removed; †2006 is significantly different from 2004 and 2003 - 2004 has significantly lower phosphate concentrations than all other years.

3.3.2 Ferrybox : phytoplankton (chlorophyll a water samples)

Winter chlorophyll a concentrations for 2003 to 2005 in the vicinity of the MV Ece are shown in figure 6a. The range in values is 0.02 mg Chl a m⁻³ to 1.52 mg Chl a m⁻³. The lowest winter concentrations of chlorophyll occurred in 2003 and the highest in 2004 (Table 4). The mean winter chlorophyll concentration in this region for the years 2003 - 2005 is 0.70 ± 0.36 mg Chl a m⁻³. Chlorophyll concentrations in 2006 (February) are significantly different (lower by up to an order of magnitude) from other years in the western English Channel (Fig. 6b, Table 4).
Figure 4. Chlorophyll-fluorescence measurements from 24th February (day 55) to 26th March (day 85) 2006 in the western English Channel, including crossings 1 and 2. (Black dot is the location of the MV Ece; units of the colour scale are mg Chl a m$^{-3}$ - factory calibration values).
Figure 5. Winter (February, March) phosphate concentrations in the latitude range 49-50 °N in a) 2003-2005 and b) 2003-2006.
Table 4. Mean winter (February + March) chlorophyll \(a\) concentrations (mg m\(^{-3}\)) along two sections of the ferry track in 2003 to 2006. The two sections are regions to the south (49 \(^\circ\)N - 49.5 \(^\circ\)N) and the region covering the wreck site (49.5 \(^\circ\)N - 50 \(^\circ\)N).

<table>
<thead>
<tr>
<th>Year</th>
<th>49(^\circ)N - 49.5(^\circ)N</th>
<th>49.5(^\circ)N - 50(^\circ)N</th>
<th>Significantly different 5% level</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>0.38 ± 0.34 (^*)</td>
<td>0.57 ± 0.49</td>
<td>No</td>
</tr>
<tr>
<td>2004</td>
<td>0.88 ± 0.32</td>
<td>0.89 ± 0.28</td>
<td>No</td>
</tr>
<tr>
<td>2005</td>
<td>0.60 ± 0.13</td>
<td>0.82 ± 0.21</td>
<td>Yes</td>
</tr>
<tr>
<td>2006(^1)</td>
<td>0.49 ± 0.05</td>
<td>0.64 ± 0.12</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\(^*\)standard deviation; \(^1\)significant difference (5% significance level) of 2006 compared to each year; \(^1\)only February data available

Figure 6. Winter (February, March) chlorophyll \(a\) concentrations in the latitude range 49-50 \(^\circ\)N in 2003-2006. (Only February data for 2006).

**3.3.3 Comparisons of E1 and Ferrybox data**

A comparison of the annual mean seasonal cycles of phosphate between station E1 and all Ferrybox data (2003 - 2005) collected between latitudes 49 \(^\circ\)N and 50 \(^\circ\)N is shown in figure 6a. Average concentrations of phosphate vary between 0.5 mmol m\(^{-3}\) in winter to 0.1 mmol m\(^{-3}\) in summer at station E1 (Fig. 7a). This compares with winter high values of 0.34 mmol PO\(_4\)\(^{-3}\) m\(^{-3}\) and summer lows of 0.07 mmol PO\(_4\)\(^{-3}\) m\(^{-3}\) in the Ferrybox - MV Ece region. Phosphate concentrations are higher in winter, spring and early summer - by between 0.15 mmol m\(^{-3}\) in winter and <0.01 mmol m\(^{-3}\) in summer - at station E1 compared to the Ferrybox - MV Ece region.
Figure 7. Comparison of seasonal cycles of a) phosphate, b) chlorophyll at full range and c) chlorophyll at reduced range at station E1 (monthly means 1930-1987) and the Ferrybox data (monthly means 2003-2005, latitudes 49°N-50°N). (error bars = standard error; black circles indicate where there is no statistical significant difference (5% significance level) between E1 and Ferrybox data)
Phosphate concentrations are higher in the Ferrybox region by 0.03 mmol m$^{-3}$ and 0.09 mmol m$^{-3}$ in late summer (June - September). The monthly differences between the seasonal cycles are significantly different ($p < 0.0001$) except in May, July and November (Fig. 7a). Regressing station E1 data against the Ferrybox data yields a slope of 0.85 (Ferrybox phosphate = 0.85*E1 phosphate) and a significant fit ($r^2 = 0.76$, $p < 0.01$).

The annual mean seasonal cycles of chlorophyll $a$ at station E1 and the Ferrybox - MV Ece region are shown in figure 7b - c. Chlorophyll concentrations at station E1 vary between 0.17 mg Chl $a$ m$^{-3}$ in winter (January) and 1.49 mg Chl $a$ m$^{-3}$ in spring (May) while in the Ferrybox - MV Ece region, the variation is between 0.30 mg Chl $a$ m$^{-3}$ in early winter (December) and 18.12 mg Chl $a$ m$^{-3}$ in summer (July). The latter value results from the regularly occurring summer bloom of the toxic algae, *Karenia mikimotoi* in the western English Channel (Kelly - Gerreyn et al, In prep.). Chlorophyll $a$ concentrations are higher in the first seven months of the year in the Ferrybox - MV Ece region of the western English Channel - by a factor of 2 in spring and a factor of 90 in summer. The monthly values in the two seasonal cycles are significantly different ($p<0.001$) except on two occasions: in August and November. Hence, chlorophyll concentrations are significantly lower at station E1 between February and July and significantly higher in part of autumn and early winter compared to the region of the MV Ece wreck. A regression of the two sets of chlorophyll concentrations is not significant (even with the large *K. Mikimotoi* blooms removed from the analysis), indicating that the seasonal cycles are different at the two locations.

### 3.4 MRCS model assessments

#### 3.4.1 Comparisons with Ferrybox data : 2003 - 2006

Three consecutive annual cycles of phosphate, chlorophyll, salinity and temperature from the MRCS model are compared with Ferrybox data for the latitudes 49°N - 50°N in figure 8a - d. Note that the model nutrients were re-initialised at the end of 2003, on account of drift in the model. This caused the observed jump in modelled concentrations seen in figure 8a. The model was not adjusted at the end of 2004. The simulated seasonal cycle of phosphate is higher than the observations - by up to a factor of 4 - except on one occasion when the model matches the observation (day 980, Fig. 8a). Modelled concentrations are particularly high in winter when differences of approximately 0.8 mmol PO$_4$ m$^{-3}$ occur in each year.

The simulated temporal evolution in the concentrations of chlorophyll shows high frequency cycling (Fig. 8b). The model chlorophyll concentrations are similar to the observations (chlorophyll $a$ water samples, see section 2.2), both in terms of seasonal dynamics and absolute values. The one exception is in the summer of 2003 (day 190) when an exceptionally large bloom (reaching levels close to 100 mg Chl $a$ m$^{-3}$; in both the water sample chlorophyll and the chlorophyll - fluorescence data, the mean for the latitude range shown in Fig. 8b is 33 mg Chl $a$ m$^{-3}$) of the toxic dinoflagellate *Karenia mikimotoi* occurred in the western English Channel. As the model does not explicitly account for this particular phytoplankton, the model cannot be expected to reproduce this particular phenomenon.
Simulated salinity values are lower than the observations at all times by between 0.1 and 0.5 units (Fig. 8c). Model salinity values are all below 35, with the exception of the beginning of
2006 (> day 1095). The observations show the seasonal cycle in salinity with highest values (maximum mean = 35.40) in winter and lowest values (minimum mean = 34.96) in summer in all years. This seasonal cycle is the result of a combination of river inputs, oceanic inputs and the balance between evaporation and precipitation. The model also shows a seasonal cycle with higher salinity in winter (maximum mean = 35.04) and lower in the summer (minimum mean = 34.80). The observations show that there has been a dampening in the amplitude of the seasonal cycle between 2003 and 2006. This is not reflected in the model output.

The modelled time series of temperature compares favourably with the Ferrybox observations (Fig. 8d). Both the seasonal cycle and the absolute values are close to the observations. The model temperatures are close to the observations (values match by < 0.1 °C) during spring and summer but cooler by up to 1 °C during autumn and winter.

Table 5. Regression analysis of MRCS model and Ferrybox data

<table>
<thead>
<tr>
<th></th>
<th>Equation (y=mx+c)</th>
<th>R²</th>
<th>Significance (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphate</td>
<td>2.13x + 0.16</td>
<td>0.49</td>
<td>Yes (&lt;0.1)</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>1.15x + 1.02</td>
<td>0.32</td>
<td>No</td>
</tr>
<tr>
<td>Salinity</td>
<td>0.22x + 27.32</td>
<td>0.24</td>
<td>No</td>
</tr>
<tr>
<td>Temperature</td>
<td>1.01x + 0.76</td>
<td>0.88</td>
<td>Yes (&lt;0.001)</td>
</tr>
</tbody>
</table>

*y= model output, x= Ferrybox observations, m= slope of regression, c= intercept on the y - axis

Regression analysis of modelled and observed data (Table 5) reveals that there is some correspondence between the model and the observations with respect to the dynamics of the seasonal cycle of phosphate and temperature (i.e. the regressions for the two parameters are significant)

3.4.2 Complementary model results - subsurface and areal information

The key potential benefit of using model data in conjunction with the in situ data from the Ferrybox and the surface data available from satellite is that models give 3-D temporally varying information that may assist in gaining process insight, in addition to that which can be obtained from the surface data obtained from Ferryboxes and satellite data. This may be valuable even where the absolute values from the model differ from observations. Examples of this are shown in the next two figures.

Figure 9 shows the surface currents, phosphate concentrations and temperatures for day 86 (27th March), demonstrating the level of horizontal heterogeneity in both the physical and biological systems. The site is close to a frontal system, and there are large spatial gradients in both temperature and phosphate. Figure 10 shows that the system was vertically well mixed at the time of the sinking but by day 86 became stratified in some areas. Information on the extent of stratification, the current directions and the residence times of bottom waters can all be used to determine the eventual fate and potential impact of a release from the wreck. Figure 9 shows the tidal mean currents for day 86 and indicate that the predominant direction of net displacement is south-east around the wreck site. Instantaneous currents for the wreck site on this day (mid-way between springs and neaps) taken from the model are a maximum of 2 knots at the surface and 1 knot in the bottom waters, suggesting horizontal tidal displacements of water by up to 20 km over each tidal cycle. This would spread a point source pollutant over an area of up to ~20km diameter over each tidal cycle in addition to any subsequent dispersion.
4. DISCUSSION

The earliest studies in the English Channel date back to the 18th and 19th century (Rennell, 1793, Dickson, 1891). It is a well studied region owing to its many interesting oceanographic features which have been reviewed by Pingree (1980) and recently by Southward et al, (2005). However the complex hydrographic regime of the English Channel means that a coherent understanding of all of its features has yet to be fully achieved. Understanding of the controls on winter nutrient concentrations (e.g. the importance of the Atlantic Ocean as a source of nutrients to the English Channel versus rivers and internal cycling) has not been properly established even with the long - term data series at station E1 from which much has been learnt (Southward et al, 2005). The cost effective long term monitoring that is being done with NOCS Ferrybox is opening up an understanding of how conditions change in winter both on shelf and in the Atlantic Ocean and how the two areas are interconnected. The study undertaken here is possible because that monitoring effort is now in place, providing reliable base line information against which specific incidents can be compared.
4.1 The high phosphate concentration and phytoplankton response in March 2006

A single sample containing an phosphate concentration 4 times higher than normal winter background levels was collected above the wreck during sampling in March 2006 (Fig. 3b). The concentration of phosphate in samples collected 4km either side of this maxima is < 0.5 mmol m$^{-3}$. Evidence for elevated concentrations of phosphate in other samples and a plume emanating from the wreck site is ambiguous. A group of three high phosphate values - 0.5 - 0.7 mmol m$^{-3}$ occurred just northeast of the wreck site, Fig. 3b), but the data for silicate and nitrate also has a group of three higher values (not shown) in the same location. The variability (both in time and space) in the nutrient concentrations along the ferry track close to the wreck site highlights the
heterogeneous nature of the waters in the western English Channel and the influence of different processes (tidal effects) and different nutrient sources (rivers). This study’s evidence shows that leakage from the MV Ece occurred between crossing 1 (28th February - 3rd March 2006) and crossing 2 (14th - 17th March 2006).
Model simulations of phosphate leakage in this area show that enhanced phosphate levels may remain for up to six weeks (NCOF model phosphate leakage scenarios). This time period is well within the timing of the main spring bloom of phytoplankton in this region. Consequently, the phosphate may intensify the magnitude of the spring bloom.

The measurements of the nitrate to phosphate ratio (10 - 18) do not support the idea that this area is currently phosphate limited. This suggests that future plankton growth in much of the area will be limited by the availability of nitrate rather than phosphate. Consequently, the influence of the high phosphate concentrations recently measured (Fig. 3b) may have little impact phytoplankton activity.

The timing of the phosphate leak coincides with the onset of growth in phytoplankton (as evidenced from the chlorophyll - fluorescence data, Fig. 4) in the vicinity of the wreck site. This may indicate a cause and effect but a similar growth scenario occurred in late winter 2005 in the same region (Fig. 11). Such phytoplankton growth did not occur in 2003 and 2004 (not shown), all of which highlights once more the challenge of understanding this complex hydrographic regime. If the growth in phytoplankton is, in part, being caused by the phosphate leakage, then continuing monitoring in this area may establish a clearer link between cause and effect.

Corroborative evidence based on satellite imagery showing the temporal and spatial evolution of enhanced levels of phytoplankton activity in the region of the wreck site is not available. The only single clear satellite image available for this region during this study (from all satellites - SeaWifs, MERIS and MODIS, Peter Millar, pers. comm) was collected on the 28th March 2006 (Fig. 12). The image shows some indication of higher chlorophyll levels in the region of the MV Ece (see green trail encircled in Fig. 12), but it is not conclusive evidence. The stormy nature of the English Channel at this time of year results in high levels of suspended sediment. The algorithms used to derive concentration data from the satellite image are limited in their ability to distinguish between suspended sediment and chlorophyll (this is not an issue with the Ferrybox chlorophyll - fluorescence sensor). Consequently, the green trail in figure 12 may be suspended sediment rather than chlorophyll. The problem of clouds in the satellite data for the period covered by the Ferrybox chlorophyll - fluorescence time series (Fig. 4), highlights an important advantage of the Ferrybox system over satellite data for use in operational monitoring. The Pride of Bilbao operates year round enabling the collection of data regardless of the weather.

4.2 Interannual variability - the historical context

Winter nutrient levels determine the overall growth potential of phytoplankton and therefore the flow of energy through the entire food chain. A critical step towards understanding the complex hydrography and biogeochemistry of UK coastal waters is the ability to put new measurements into historical context. This can be achieved because the long - term dataset from station E1 can be compared against the continuous year - round measurements from the Ferrybox system. This greatly enhances our ability to link cause and effect by providing wide geographical cover (e.g Kelly - Gerreyn et al, In Press).

The interannual variability in winter concentrations of both phosphate and chlorophyll captured by the Ferrybox system (Figs. 5, Table 3 and Fig. 6, Table 4, respectively) put the new measurements made in this study into context. Apart from the leakage derived maximum value of phosphate recorded in crossing 2 (Fig 3b, 5), phosphate concentrations in 2006 are similar to 2005 (Table 3). Phosphate concentrations are anomalously low in 2004 (Table 3). The data also
Figure 12. Satellite image (the Moderate Resolution Imaging Spectroradiometer- MODIS) showing sea surface chlorophyll levels on 28th March 2006 (this is the first clear image in March 2006). Courtesy of the Remote Sensing Data Analysis Service (Plymouth, UK). (Note that red and brown areas close to the coast and around islands are most likely suspended sediment; the dotted red circle indicates the region of the MV Ece wreck).

suggests that there is an increasing gradient in phosphate concentrations along the ship's track heading towards Portsmouth (Fig 3a,b, Table 3 - the same is true for silicate and nitrate). Hence, one-off point measurements that compare phosphate concentrations at specific locations in a grid around the MV Ece wreck site must take this variability into account - spatial differences are not a reliable way of detecting phosphate leakage.

The differences in phosphate concentrations between station E1 and the Ferrybox data (Fig. 7a) may be due to natural interannual variability. One characteristic that has been recognised in the E1 data is the variability over periods extending for several years (the so-called “Russell” cycle, Southward, 1980). This variability was also highlighted in the Defra-funded SONUS (Southern Nutrient Study) programme (Joint et al, 1997; Jordan and Joint, 1998). The values currently being observed in 2003-2006 are similar to the lower values recorded in the E1 dataset in the 1960s. So the difference in concentrations observed between the Ferrybox and average E1 data may be due to the state we are currently in as part of these natural variations in the English Channel.

Differences in chlorophyll concentrations between the two data sets (E1 and Ferrybox, Fig. 7b,c) are greater than what would be expected compared to the differences in winter nutrient concentrations between the two locations. The reason for this remains unclear, again reflecting the heterogeneous nature of the western English Channel. (Note that considerable effort has been employed in the NOC FerryBox programme to ensure that samples for the determination of chlorophyll a are well preserved between the time of collection and the time of measurement, Qurban et al, 2004).
The OSPAR document “Ecological Quality Objectives for the Greater North Sea with Regard to Nutrients and Eutrophication Effects” (OSPAR Commission, 2005) suggests that monitoring of “Non Problem Areas” like the Western Approaches need only be carried out every three years. Consideration of the E1 data suggests that this would produce a statistically weak data set for the identification of trends. Furthermore, there is a critical need to understand the causes in the variability picked up by both the E1 and Ferrybox data. While the single site sampling at station E1 has significantly contributed to the understanding of seasonal cycling in nutrients by biological production and decay, it is limited to this understanding. An aim of the Ferrybox project is to provide data sets which will enable us to overcome this limitation and improve our understanding of other causes for the inter-annual variability in nutrients in UK shelf seas. The Ferrybox data set is now large enough to be able to identify changes in winter conditions off the shelf and to explain the causes. Concentrations of nutrients observed in 2003 and 2004 were low south of the shelf break relative to concentrations observed in the EU-FP4-OMEX project in 1994 and 1995 (Hydes et al., 2001).

Figure 13 shows that in 2005 observed concentration of nitrate south of 47 °N and the shelf break were about 50% higher than in the two proceeding winters and were similar to concentrations observed during the OMEX sampling. The extent of the data available from the Ferrybox enables this increase in concentration to be attributed to deeper mixing of waters off the shelf in 2005 relative to 2004. Figure 14 shows that the waters off shelf are not only richer in nitrate in 2005 but also colder as a result of deeper mixing bringing cold nutrient rich water to the surface from depth (Henson et al 2003).
4.3 Prediction capabilities: concentrations and leakage fate

The ability of the MRCS model to accurately simulate biological and physical properties in the western English Channel is variable.

Phosphate concentrations are too high in the model at all times in the year (Fig. 8a). The correspondence between the seasonal cycles of the model and the observations has an $r^2$ value of 0.49 (Table 5), but the increase in model phosphate concentrations at the end of summer in each year is too high (Fig. 8a). The cause of this overestimation of phosphate in the model is not clear, but many source and sink terms are poorly defined. Validation with the Ferrybox data contributes to understanding model error and would be expected to lead to future model improvements.

The chlorophyll levels simulated by the model are similar to the observations gathered from the monthly chlorophyll values (Fig. 8b). The high frequency (weekly) cycling of chlorophyll in the model cannot be substantiated by the monthly chlorophyll measurements extracted from the water samples (Fig. 8b). However, the chlorophyll-fluorescence data collected from the Ferrybox system gives support to the existence of high frequency cycling (Fig. 15). A common cause of high frequency phytoplankton cycles is strong predator-prey interactions between zooplankton and phytoplankton. However, chlorophyll-fluorescence data is known to be highly variable owing to the fact that the signal varies as a function of both phytoplankton physiological state and phytoplankton species. The model's ability to capture both chlorophyll levels and the high frequency cycling gives some confidence in it's ability to predict changes in phytoplankton.
The MRCS model underestimates salinity by up to approximately 0.5 psu in the Western English Channel (Fig. 8c). The seasonal salinity cycle in this region results from a combination of river inputs, oceanic inputs and the balance between evaporation and precipitation. In the model, salinity is influenced by river inputs which are not accurately represented due to the use of climatological values as real time data are not available. Furthermore, the reduction in the amplitude of the observed seasonal salinity cycle between 2003 and 2006 (Fig. 8c) is most likely due both to lower rain fall over France in the last two winters and changes in the differences in the wind field that control the flow of fresh waters from the French Atlantic coast into the English Channel (Kelly - Gerreyn et al, In Press). There is the potential for the low salinity values to adversely affect the degree of stratification that takes place in the western English Channel but, fortunately, temperature, which is well modelled (Fig. 8d) is the dominant factor determining the vertical stratification in English Channel (Pingree, 1980; Kelly - Gerreyn et al, In Press). The fact that the model is shown to reproduce temperature reasonably suggests the surface heat fluxes and the tidally dominated advection/mixing processes are well represented. However, changes in surface salinity brought about by freshwater intrusions derived from French Atlantic rivers (as described by Kelly - Gerreyn et al, In Press) can have a considerable influence on the vertical density profile (Kelly - Gerreyn et al, 2006). Accurate predictions of the degree of stratification are critical to correctly modelling the intensity of phytoplankton blooms. Therefore, work is needed to improve the modelled salinity. Model upgrades being tested at the moment are expected to go some way in achieving this, but the lack of real-time river flow data continues to be a limitation.

Within the remit of this study there has not been the scope for detailed or extensive modelling analysis of the system, but a tracer release experiment using near-real time forcing data has been undertaken by NCOF partners at PML (funded by the MCA). This further demonstrates the benefits that modelling within the NCOF partnership can bring to operational responses to events such as these.

Figure 15. Comparison of modelled chlorophyll (black) and chlorophyll-fluorescence (blue)
5. CONCLUSIONS

• The Ferrybox system has proved capable of identifying phosphate leakage from the wreck of the MV Ece. A single sample, from a total of 70 samples taken, contained a concentration four times higher than background levels, one nautical mile from the wreck site. The leak occurred between 3rd March and 17th March 2006.

• Measured nitrate to phosphate ratios in Ferrybox samples suggest that phytoplankton growth will be limited by nitrate rather than phosphate. Consequently, the phosphate leak is unlikely to enhance phytoplankton growth at the present time.

• The continuous record of measurements of phytoplankton chlorophyll-fluorescence from the Ferrybox show that phytoplankton growth close to the wreck site did occur in March 2006. However, similar growth occurred at the same time in 2005.

• Hence, the Ferrybox demonstrates its effectiveness as a decision support system, in this instance providing evidence for the view of British and French authorities that released phosphate is unlikely to pose a significant threat.

• These Ferrybox data (nutrients, nutrient ratios and phytoplankton) illustrate the highly variable nature of these coastal waters both in time (days to years) and space (few kilometres). This natural variability highlights the need for continuous monitoring to put new measurements into context, particularly regarding assessment of pollution transport and impacts.

• The annual cycle of changing concentrations of phosphate are similar at the MBA long term (1929-1987) time series station E1 and the wreck site. Wreck site concentrations are significantly lower than the mean at E1 in winter, but are similar to concentrations in the 1960’s, highlighting the importance of long-term data sets.

• The MRCS model shows promise in determining chlorophyll concentrations and sea surface temperature, but salinity levels are low in the model, potentially affecting its ability to accurately determine the intensity of stratification in English Channel.

• Estimates in the modelled distribution of phosphate concentrations are too high by a factor of up to 4.

6. SCOPE FOR FUTURE WORK

• This study demonstrates that the NOCS Ferrybox system is an appropriate platform for monitoring the marine environment with considerable potential for improving our understanding of UK shelf seas (and their interaction with the Atlantic Ocean).

• The variability shown in the Ferrybox data from 2003-2006 suggests that the OSPAR recommendation of sampling only every three years in “non-problem areas” is likely to provide statistically inadequate data. Ferrybox data shows that off-shelf concentrations of nutrients varied by 50% between 2004 and 2005 due to deeper mixing of water off-shelf in early 2005.

• The NOCS Ferrybox is a highly cost effective way of 1) determining the natural background state of the sea and its variability, 2) putting new measurements into historical context and 3) making evidence based judgements on cause and effect between
ecosystem impacts (e.g. phytoplankton growth) and pollution incidents (e.g. phosphate release from the MV Ece).

- The Ferrybox operates unabated by the weather giving near continuous (near real-time monitoring) of plankton growth. This is in contrast to satellite observations which are severely limited in UK coastal waters due to cloud cover. The Ferrybox is therefore invaluable as an early warning system for pollution incidents.

- The western English Channel (including the wreck area) is typical of UK waters: it is highly heterogeneous in space and time. Continuous Ferrybox sampling captures this heterogeneity, unlike one-off spot sampling.

- The MRCS model has the potential to provide important three-dimensional information on the physical and biological conditions. Further work is required, and in progress, to improve representation of certain physical and biological parameters in the model.

- Ferrybox data should be used in validating model output, and may also prove informative in improving lateral nutrient boundary conditions for the model.
7. KNOWLEDGE TRANSFER

A passenger display monitor has been installed in the main reception area of the Pride of Bilbao (Fig. 16). This display, which is still under development, is used to raise awareness of the scientific and monitoring work undertaken on board the ferry to the 100,000 passengers who travel on the ship each year of

Figure 16. Passenger display monitor on board the Pride of Bilbao showing detailed information on a poster and one example of the display on the monitor

The passenger display also includes a large A0 size poster giving greater detail of the Ferrybox operation. The poster has a section on the current monitoring of the Ece site (to the left of the monitor in Fig. 16). The actual display on the monitor shows the moving track of the ship as it
sails between Portsmouth and Bilbao (Fig. 16). In addition, data on the current state of the sea is displayed using the Ferrybox data: temperature, salinity, chlorophyll - fluorescence and carbon dioxide.

8. REFERENCES


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