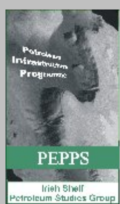
Cetaceans and Seabirds in Irish Waters: An integrated desktop study

Report prepared for the Irish Shelf Petroleum Studies Group (ISPSG)



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EXECUTIVE SUMMARY

The importance of Ireland's offshore area as an important habitat for cetaceans and seabirds, was highlighted by the *Cetaceans and Seabirds at Sea (CSS) Study*, 1999-2002 (Aguilar *et al.,* 2004; Mackey *et al.,* 2004; O' Cadhla *et al.,* 2004). Prior to that, research into the distribution and abundance of these animals was limited and undertaken in an ad-hoc manner. The CSS study provided an important opportunity to build national research capacity in this field. While this work has contributed significantly to our understanding of the distribution of cetaceans and seabirds off the coast of Ireland, limited information is available on the link between these distributions and environmental variables. This desktop study, funded by the Irish Shelf Petroleum Study Group (ISPSG), aimed to address this issue by investigating the potential for adding value to the existing CSS dataset through coupled physical and biological modelling techniques.

A literature review, a data review and a model review were undertaken as part of the investigation. Furthermore, a statistical modelling approach was implemented as part of a feasibility analysis. The literature review showed that modelling provides insights into the role of factors such as physiographic and hydrographic characteristics on cetacean and seabird populations. However, coupled modelling is a relatively recent advancement. As a result, there are a limited number of sophisticated 3D hydrodynamic and ecosystem models in existence and even fewer examples of the application of coupled models to seabird and cetacean studies. During the course of the study, it became apparent that there is a lack of capacity in this field in Ireland. In order to address this issue and to better fulfil the study objectives, Dr. Simon Ingram participated in a modelling training course in the Portugal in May 2005. This allowed the team to test the application of relevant statistical techniques to the CSS data, in combination with physical datasets.

The outcome of the process was a better insight into the key challenges associated with advancing such modelling methods in the future. Apart from the capacity issues the key-limiting factor, is the limited geographical coverage of the CSS data. At present, the level of coverage of the biological data is sufficient to test the model employed but still inhibits the production of fully robust statistical analysis. Conversely, there is a wealth of physical data available, most notably the high quality Irish National Seabed Survey (INSS) data, - the value of which could be unlocked if efforts were made to fill the gaps in the CSS dataset.

Significant opportunities could be derived from the development of a further CSS study, including a methodology for integrated modelling, to enable the identification of sensitive areas. This would facilitate the development of appropriate mitigation measures for the industry sector in order to afford protection to vulnerable marine species. This would also secure the continuity of Ireland's seabird and cetacean research community and help to achieve the future sustainable development of offshore resources.

SECTION 1 - INTRODUCTION

1.1 Objectives and approach

The PAD/RSG/PSG “Cetaceans & Seabirds at Sea” (CSS) research programme, undertaken by the Coastal and Marine Resources Centre of University College Cork, ran from 1999 to 2001. This study provided much needed information on the distribution and density of cetaceans and seabirds in Ireland’s Atlantic Margin (Figure 1). Nevertheless, it is still unclear as to why cetaceans and seabirds occur in certain locations. An integrated approach is required to understand the links between the physical and biological components of Ireland’s Atlantic Margin. This understanding is vital in order to help manage and protect this marine environment effectively.

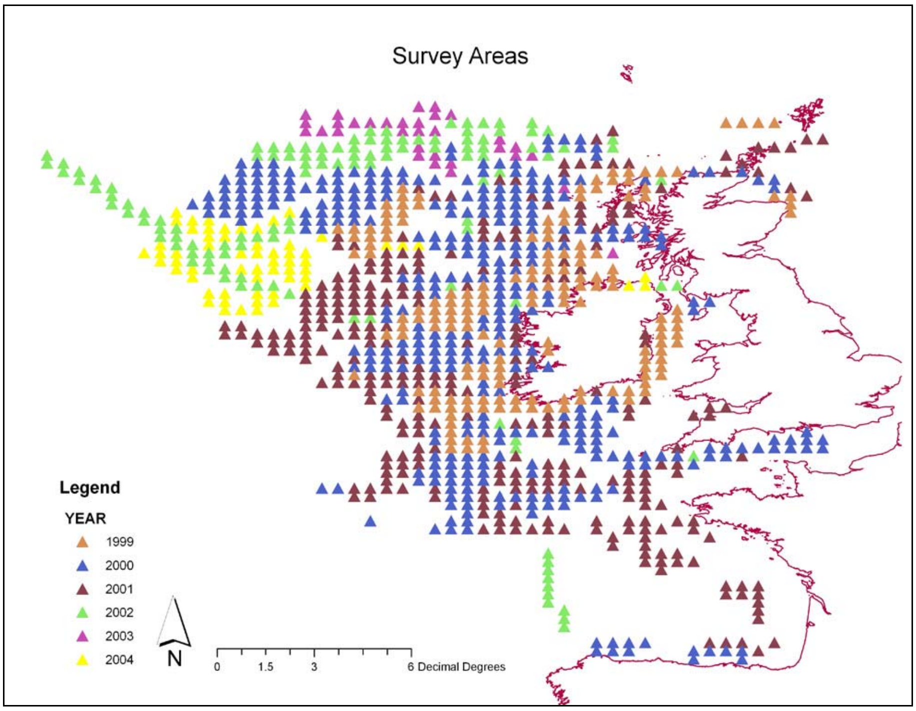

Figure 1. Areas where CSS surveys took place from 1999 to 2004

This study aims to examine if the dataset generated by the CSS study contains the potential for significant additional research to be performed with this data, in order to integrate it with relevant physical and oceanographic data. This report provides information on how this integration may be achieved with the use of available datasets as inputs for oceanographic and ecological models to model where cetaceans and seabirds occur in relation to natural environmental variability.

The objectives of this desktop study are to:

1. Review existing work and literature on the integration of physical and oceanographic data with cetacean and seabird survey datasets to help understand distribution patterns.
2. Investigate the availability of suitable physical, ecological and oceanographic datasets as well as their cost, quality and spatial scales.
3. Investigate the availability of suitable models.

The approach adopted involved a review of the literature and a data acquisition and modelling phase. The study went beyond the original objectives to test the appropriateness of statistical Modelling techniques within a predictive framework, where information on animal distributions can be predicted in time or over geographic areas. A number of steps were involved in the processing of relevant baseline data for incorporation into the model before it could be run. The approach, which focused on cetacean data, revealed the potential of integrated statistical modelling and challenges with data availability (Chapter 3). Training in relation to the statistical approach used in the study, was undertaken by Dr. Simon Ingram, who attended a course in Multivariate Analysis in Portugal in May 2005. The methods employed in this study were presented in a paper, prepared by Dr Ingram, at the 16th Biennial Conference on the Biology of Marine Mammals in San Diego between the 12th-16th of December (Ingram *et al.,* 2005).

This report presents the outcomes of investigations into each of the three objectives in separate chapters below. Section 2 describes the context for integrating physical and biological data to improve understanding of cetacean and seabird distribution and abundance. Section 3 presents an overview of relevant datasets, outlines potential models and tests the Generalised Additive Modelling (GAM) approach. Section 4 provides conclusions and recommendations for future work.

SECTION 2 - LITERATURE REVIEW

This section reviews existing work and literature on the integration of physical and oceanographic data with cetacean and seabird survey datasets to help understand distribution patterns.

2.1 Cetaceans and seabirds in Irish waters

At least 24 species of cetacean have been recorded in Irish waters either through sightings reports or strandings data (Berrow and Rogan, 1997; Berrow *et al.,* 2002). Until recently very little research effort had been directed at recording at-sea cetaceans and seabirds in Irelands offshore waters (Pollack *et al*., 1997; Evans & Scanlan, 1989). However, research effort has increased in recent years, in tandem with increased petrochemical survey effort in Irish shelf waters, for example the "Cetaceans and Seabirds at Sea" research programme (O' Cadhla *et al*., 2004). Related survey effort provided information on the distribution and density of 37 seabird species from five different surveys of seabirds in Irish waters (Mackey *et al*., 2004). This represents perhaps the largest single research effort focusing on cetacean and seabirds in Irish waters.

Although this work has contributed significantly to our understanding of the distribution of cetaceans and seabirds off the west-coast of Ireland, limited information is available on the link between these distributions and environmental variables. Many studies of marine mammals and seabirds in other sea areas have attempted to understand distribution, movements and activities in the context of physical and biological oceanographic variables (Ainley *et al*., 2005; Hastie *et al*, 2005; MacLeod *et al*., 2004, Ersts & Rosenbaum, 2003; Benson *et al*., 2002; Jaquet & Gendron, 2002; Mendes *et al*., 2002; Baumgartner *et al*, 2001; Davis *et al*., 1998; Baumgartner, 1997; Jaquet & Whitehead, 1996; Gowans & Whitehead, 1995; Griffen, 1993). These studies have usually been rather restricted however, due to the limited availability of useful oceanographic data sets.

Recent advances in complex environmental modelling and satellite imaging have enabled powerful predictive data sequencing. Together with sophisticated statistics these models can provide an increasingly effective insight into the processes governing cetacean and seabird distribution and habitat use. This study will evaluate the availability and suitability of oceanographic models able to provide data useful for explaining cetacean and seabird distributions off Ireland's west coast. It is likely that such data will include, sea depth, gradient, sediment type, currents, SST, and chlorophyll-a distribution.

2.2 Study area

There is a need for better understanding of marine mammal and seabird distributions and habitat use in European waters but at present there is little information on cetacean and seabird numbers in the waters off western Ireland (O'Cadhla *et al*., 2004; Mackey *et al*., 2004). All cetacean species occurring in European waters are now protected as Annex IV species under the EU Habitats Directive and under domestic Irish legislation (for example, 1976 and 2000 Wildlife Acts). The main research objectives for cetacean and seabird sighting surveys in the Irish Atlantic Margin were firstly, to identify major areas of concentration for cetaceans and seabirds in these waters and evaluate seasonal trends and distribution, and secondly, to estimate, where possible, the abundance of key cetacean species inhabiting western Irish waters.

Irelands Atlantic Margin has a number of physical, climatic and oceanographic features, which combine to produce one of the most biologically productive areas of the eastern North

Atlantic Drift. As a result of complex interactions between shelf and oceanic water bodies, the seasonal climatic, sea temperature and salinity conditions as well as regional upwelling of deep, nutrient rich oceanic water, there are areas of seasonally high productivity along the Atlantic Margin (O'Cadhla *et al*., 2004). The area has high species richness for cetaceans with over a quarter of all global species represented here. However the distribution of these predators is never uniform in space and time, and prey movement patterns and the dynamic physical and oceanographic features add to this heterogeneous seabed environment. Such features occur on a range of scales, from large-scale processes (oceanic circulation routes) to small-scale local systems. Because of the diversity of these influences, a modelling approach is needed to continue this research.

There is a need to attempt the integration of observed species data from the "Cetaceans and Seabirds at Sea" programme with physical and oceanographic information, available for the Atlantic Margin over the 1999-2001 research period. This integration may be done by using existing datasets of the physical and biological oceanographic environment (from in-situ measurements or satellite data) as inputs for physical oceanographic models, perhaps coupled with ecological models. This would be the first time this approach has been taken to study cetaceans and seabirds in this region. Up to now ship based "platform of opportunity (POP)" surveys have provided excellent opportunities for researchers to survey for marine mammals and sea birds at sea but these surveys are not without limitations. There are inherent limitations with regard to survey design and control and these may lead to sampling biases and non-standardised survey coverage, as the researchers have no control over location. If more accurate predictions could be made of where the cetaceans and seabirds may be abundant, then survey effort must be increased.

Biological oceanographers have studied the pelagic dispersion and habitats of marine birds and mammals for decades (Yen *et al*., 2004). While previous studies have revealed that these upper trophic level marine predators associate with specific physical and biological processes at distinct spatial and temporal scales, the predictability of wildlife habitat associations and the underlying biophysical coupling mechanisms remain, for the most part, poorly understood. This gap in knowledge provides the incentive for this study.

2.3 Factors influencing cetacean and seabird distribution

There are many factors that influence the spatial and temporal distribution of cetaceans and seabirds. These factors include, physiographic and hydrographic characteristics, prey distribution, breeding and calving areas and predation (Davies *et al*., 2002; Benson *et al*., 2002). Variability in physical features can be seasonal, interannual or decadal. Such perturbations bring changes in nutrient upwelling, primary productivity, and zooplankton biomass within coastal upwelling systems (Benson *et al*., 2002).

<u>Feeding ecology</u>

The distribution patterns of cetaceans and seabirds are influenced by migration patterns, breeding behaviour and foraging ecology. The majority of studies on cetacean diet in North Atlantic waters have been based on the stomach analysis of stranded cetaceans (Clarke and Pascoe, 1985; Santos *et al*., 1999), those caught accidentally by fisheries (Gannon *et al*., 1997), and, for some species (such as the minke whale in Norway and the long-finned pilot whale in the Faroe Islands), from whaling operations (Nordøy and Blix, 1992; Haug *et al*., 1995; Lindstrøm *et al*., 1997). Diet is therefore understood in much more detail for those animals caught in large numbers as by-catch (e.g. harbour porpoises and common dolphins) and as part of whaling operations (e.g. minke whale and long-finned pilot whale) than for other species. Although it should be noted that by-caught cetaceans are likely to provide a biased estimate of diet, since only those groups feeding in the fisheries catchment area are likely to be caught. Cetaceans can be categorised by their diet: specialist species that consume predominantly plankton, squid or fish; and generalist species, that are able to feed on a wide range of prey.

Specialist plankton feeders include sei and fin whales, which feed predominantly on copepods and euphausiids respectively (Jonsgård and Darling, 1977; Sigurjónsson, 1995). In the North Atlantic, the copepod *Calanus finmarchius* appears to be the main component of the sei whale diet (Jonsgård and Darling, 1977). Evidence suggests that the fin whale feeds primarily on the euphausiid *Meganyctiphanes novegica*, although it is known to feed on a variety of fish such as herring, capelin, sandeel, mackerel and blue whiting, and some cephalopods (Christensen *et al*., 1992; Sigurjónsson, 1995; Sigurjónsson and Víkingsson, 1997).

Sperm whales, Risso's dolphins, and long-finned pilot whales are predominantly specialist squid-feeders, the main species eaten off Irish coasts including *Gonatus* spp., *Todarodes sagittatus*, and *Loligo forbesi* (Clarke and Pascoe, 1985; Wurtz *et al*., 1992; Desportes and Mouritsen, 1993; Santos *et al*., 1995; Pierce and Santos, 1996; Santos *et al*., 1999). Stomach analysis of animals from the North Atlantic also suggests that sperm whales and long-finned pilot whales also supplement their diet with small amounts of fish such as saithe, mackerel and blue whiting (Gannon *et al*., 1997; Santos *et al*., 1999).

The majority of the remaining cetaceans are primarily piscivorous, including the minke whale, which in addition to eating euphausiids, is known to feed on a wide range of fish species including herring, cod, haddock, saithe, sandeel and sprat (Nordøy and Blix, 1992; Haug *et al*., 1995; Lindstrøm *et al*., 1997). Off-shelf predators have been shown to eat mainly pelagic schooling species of fish, such as blue whiting and mackerel (Santos *et al*., 1995). On-shelf species such as the white-beaked dolphin and harbour porpoise include species such as herring, mackerel, sprat and sandeel in their diets, along with some squid species such as *Loligo forbesi* and octopus *Eledone cirrhosa* (Rae, 1973; Santos *et al*., 1995; Kinze *et al*., 1997). On- and off-shelf species, such as bottlenose dolphins and common dolphins, are generalist feeders taking a wide range of benthic and pelagic fish, as well as cephalopods and shellfish (Pascoe, 1986; Young and Cockcroft, 1994; Santos *et al*., 1995). The killer whale is the most widely feeding of all the cetacean species in Irish waters, taking a wide variety of prey from fish, squid, birds, turtles, seals and other cetaceans.

The primary influence on the distribution of high trophic-level predators, such as cetaceans, is the location of their prey species. A number of studies have been able to link cetacean distributions to that of their prey (Whitehead and Carscadden, 1985; Payne *et al*., 1986; Payne *et al*., 1990; Reijnders, 1992; Palka, 1995; Beardsley *et al*., 1996; Kenney *et al*., 1996; Woodley and Gaskin, 1996; Macleod, 2001). Methods of analysis will vary, for example Beardsley *et al*., (1996) sampled zooplankton in the area near a feeding right whale in the Gulf of Maine, and Palka, (1995) carried out trawls in order to determine the density of harbour porpoise prey in the Bay of Fundy, finding that porpoises associated with a small area containing intermediate fish densities.

Active acoustics (echosounder) methods used by Woodley and Gaskin, (1996) found that herring and euphausiids were abundant in areas where fin whales were present. In a study on the foraging ecology of marine birds and mammals, Croll *et al*., (1998) found that blue whales concentrated their foraging efforts on dense aggregations of euphausiids, found at discrete depths in the water column. They found these localised areas of high euphausiid densities to be predictable and sustained by enhanced levels of primary productivity in the regions, which are located downstream from coastal upwelling centres. Topographic breaks in the continental shelf located downstream from these upwelling centres, worked together with this euphausiid behaviour to collect and maintain large concentrations of euphausiid swarms. Thus mesoscale oceanographic features may affect cetacean distributions because these processes are driving prey movement patterns. Macleod, (2001) used fisheries catch data, comparing the encounter rates of harbour porpoises with herring and *L. forbesi* catches,and found that the geographic range of porpoise distribution corresponded with the distribution of *L. forbesi* catches in Scottish waters, However, these data are often difficult or impossible to collect at sea since as independent sampling of prey is often impractical, expensive or prohibited due to the opportunistic nature of survey platforms.

Assessing species distribution in relation to both bathymetric and hydrographic habitats is essential to obtain a more complete understanding of the dispersion of upper-trophic marine predators and the nature and location of habitat "hotspots" and preferred sea areas where particular species are more likely to occur.

<u>Relating cetaceans to oceanographic/physiographic variables</u>

Previous studies have demonstrated correlations of cetacean distribution with physiographic features such as ocean depth and seafloor slope (Davies *et al*., 2002). Some studies have also demonstrated correlations between cetacean distribution and hydrographic characteristics that may secondarily affect prey distribution. Piniped, cetacean and seabird distribution patterns have been shown to be closely related to oceanographic phenomena such as, thermoclines, fronts (convergence and divergence zones), upwelling plumes, Langmuir cells, eddies and large scale patterns in temperature, productivity and prey (Croll *et al*., 1998). Physiographic and hydrographic features alone may not fully explain cetacean distribution. Instead the distribution of cetaceans may be better explained by prey availability, which is secondarily influenced by hydrographic features, which act indirectly to influence the distribution of cetaceans through the aggregation of prey (Beardsley *et al*., 1996; Davis *et al*., 2002). Variable topography, such as that found on continental shelf edges and around islands, can induce upwellings of nutrients, thus increasing primary and secondary productivity (plankton) and ultimately higher trophic predators such as fish and cetaceans (Mann and Lazier, 1991).

Foraging seabirds and cetaceans are also associated with a variety of bathymetric features, including shallow banks and continental shelf-slope regions. In particular, continental shelf-breaks and slopes appear to be highly productive habitats, which frequently support high densities of marine predators. Bottlenose dolphins using the outer Shannon estuary have been shown to use deeper areas of their habitat and areas with steep benthic slopes (Ingram and Rogan, 2002). It is likely that dolphins use the tidal fronts associated with these benthic features to aid prey capture (Mendez, 2003). Risso's dolphins have also been found to demonstrate a strong preference for areas of high seabed slope, (Baumgartner, 1997). Steep topography has been shown in many other studies to be an important predictor of cetacean distribution, including fin whales (Woodley and Gaskin, 1996), sperm whales (Jaquet and Whitehead, 1996), Risso's dolphins and short-finned pilot whales (Davis *et al*., 1998).

Horizontal gradients in water density and the degree of vertical stratification promote the aggregation of weakly swimming prey at discontinuities, which in turn provides enhanced feeding opportunities for many marine predators. Furthermore, many continental shelves are characterized by complex bathymetries, including submarine canyons, deep basins, and shallow banks. These structures influence water flow and give rise to secondary circulation features such as fronts and eddies, which often aggregate zooplankton, thereby making prey available close to the surface to diving predators (Yen *et al*., 2004). Another mechanism involves entrapment of vertically migrating prey advected over shallow-water topographies by sub-surface frontal systems. In particular, topographic features shallower than the nocturnal depth occupied by vertically migrating species are sites especially suited for prey entrapment.

Seabed depth is frequently found to be a significant factor influencing cetacean distributions. In the Gulf of Mexico for example, benthic depth was found to represent the main variable differentiating the distribution of several species found in the area (Davis *et al*., 1998). Water depth can also partition social groups within a single species, for example segregating mother-calf pairs of humpback whales using shallow waters from their conspecifics (Ersts and Rosenbaum, 2003). Within Scottish waters, Macleod, (2001) encountered white-sided dolphins most frequently in water greater than 500m, and statistical analysis (logistical regression) confirmed that depth was a significant predictor variable of the species' distribution. However, since some species use a range of habitats with varying depths (for example, killer whales use both inshore and offshore waters), depth is not always a good predictor of distribution.

Substrate type has also been shown to be a good predictor for species that feed on benthic prey with preferences for certain substrate types such as sand eels for example (Payne *et al*., 1986; MacLeod et al, 2004). The sand/gravel sediments preferred by sandeels, was found to be the most influential environmental variable predicting the spring distribution of minke whales around the Isle of Mull, Scotland (MacLeod et al., 2004). Sediment type can therefore prove to be a useful predictor variable in shelf habitats, though it is likely to be of lesser importance in deep water habitats where cetaceans prey on organisms that live suspended in the water column.

Oceanographic fronts are areas of high productivity (Mann and Lazier, 1991). At a thermal front where two water masses meet (such as at river plumes and around islands), nutrient-rich mixed waters meet stratified nutrient-limited waters, and the nutrient leakage across the boundary supports a sustained level of primary productivity and thus concentrates higher trophic level predators such as cetaceans and seabirds (Mann and Lazier, 1991). These fronts are characterised by differences in sea surface temperature (SST), temperature gradient within the water column, salinity, high concentrations of productivity, and aggregations of prey (Mann and Lazier, 1991).

Sea surface temperature (SST) has been shown to be a good predictor variable for a number of species. SST variation was linked by Hoydal and Lastein, (1993) to between-year differences in catches of long-finned pilot whales in the Faroe Islands. Also, Selzer and Payne, (1988) used SST and salinity to explain the apparent niche partitioning between common and white-sided dolphins in northwest Atlantic waters. Moses and Finn (1997) were able to use bathymetry and SST to predict North Atlantic right whale (*Eubalaena glacialis*) distribution in the northwest Atlantic using a GIS-based model, and used it to predict right whale summering grounds. A similar approach was adopted by Gregr and Trites, (2001), using bathymetry, SST, and salinity, as explanatory variables on which to model whale catches off British Colombia. They used this model to predict critical habitats for sei, fin and male sperm whales. In UK waters, Goold, (1998) used satellite-derived SST measures to identify frontal areas, and found that the offshore movement of common dolphins in the autumn was associated with the break-up of the Celtic Sea front. Similarly, bottlenose dolphins in the Gulf of Mexico were sighted more frequently in regions of the high surface temperature variability associated with ocean fronts (Baumgartner *et al*., 2001).

Primary and secondary productivity measures can be used to identify productive areas such as those associated with fronts. For example, zooplankton was sampled along with conductivity, temperature and depth (CTD) during a comprehensive study of sperm whales in Georges Bank (Griffin, 1999). The sighting rate of sperm whales in the vicinity of the thermal front was five times higher than in the remainder of the survey. Griffin (1999) did find, however, that the front was associated with low zooplankton densities, perhaps due to a lag between primary and secondary productivity such as observed by Jaquet *et al*., (1996). In Griffin's study (1999), phytoplankton pigment was used to explain the distribution of sperm whales caught in the temperate and tropical Pacific during the 19th century. Sperm whales were associated with chlorophyll-a at all spatial scales, and confirmed the existence of a space and time lag between a peak in chlorophyll concentration and a peak in sperm whale density. Chlorophyll-a was also used to explain the distribution of cetaceans off the Californian coast (Smith *et al*., 1986). Odontocetes were highly correlated with chlorophyll-a concentration, with common dolphins widely distributed in variable medium-chlorophyll waters, and Risso's dolphins associating with only a narrow range of chlorophyll waters. Secondary production measured from zooplankton trawls during a survey of sperm whales in the South Pacific, was correlated along with steep underwater to sperm whale density in the South Pacific (Jaquet and Whitehead, 1996).

Tidal effects

Ocean currents and tides can also act to aggregate prey. Tidally induced internal waves ('slicks') have been associated with high densities of plankton and fish (Watkins and Shevill, 1979). Silber and Smultea, (1990) observed harbour porpoises milling (foraging) and travelling in an area with surface slicks, and found that they spent significantly more time feeding in the slicks than in other area. In the Shannon estuary, bottlenose dolphin behaviour and school sizes are influenced by the tidal cycle (Ingram, 2000) and in the Moray Firth bottlenose dolphins aggregate near a tidal intrusion front (Mendes *et al*., 2002). In the Bay of Fundy fin whales and minke whales associate with tidal wakes which form around islands (Ingram *et al*., 2003, Johnston *et al*., 2006)

Anthropogenic threats to cetaceans

Cetaceans using Irish waters are vulnerable to a wide range of anthropogenic threats including physical disturbance, bycatch (incidental entanglement in fishing gear) and habitat degradation (chemical pollution, increased ambient noise, prey depletion, direct habitat loss). For example, the levels of harbour porpoises caught as bycatch in bottom-set gillnets is high enough to cause concern about the ability of the populations to recover (Jefferson and Curry, 1994). There is also increasing concern about the impact of active acoustic seismic survey activities used in oil and gas exploration and risks associated with industrial activities such as petrochemical extraction (Harwood and Wilson, 2000), and the construction of offshore windfarms (Tougaard *et al*., 2003). However, in order to be able to understand the potential impacts of anthropogenic threats it is necessary to have a good understanding of their abundance and distribution.

A summary of the studies, which examined the link between cetaceans and environmental variables is provided in Table 1.

Table 1. Summary of studies which examined cetaceans and environmental variables

Species	Environmental variables	References
Minke whale	Topography Topography, SST, season SST, frontal zone, sea ice	MacLeod et al., 2004 Hooker et al. (1999) Kasamatsu et al. (2000)
Sei whale	Topography, SST, salinity	Gregr and Trites (2001)
Fin whale	Topography, frontal zone, prey Topography, SST, salinity	Woodley and Gaskin (1996) Gregr and Trites (2001)
Sperm whale	Topography, temperature gradient, primary & secondary productivity Chlorophyll-a SST Topography Hydrographic structure, frontal zone, zooplankton, SST Topography, SST, depth of 15°C isotherm, chlorophyll, zooplankton Topography	Jaquet and Whitehead (1996) Jaquet et al. (1996) Whitehead (1997) Davis et al. (1998) Griffin (1999) Baumgartner et al. (2001) Cañadas et al. (2002)
Bottlenose dolphin	Topography (slope and depth) Topography Topography, SST, depth of 15°C isotherm, chlorophyll, zooplankton Topography Tidal cycle, tidal intrusion front	Ingram and Rogan (2002) Davis et al. (1998) Baumgartner et al. (2001) Cañadas et al. (2002) Mendes et al. (2002)
Common dolphin	Topography Topography, SST, salinity, latitude Topography, SST, month SST Topography	Hui (1979) Selzer and Payne (1988) Gowans and Whitehead (1995) Goold (1998) Cañadas et al. (2002)
White-beaked dolphin	Fisheries catches, chlorophyll-a	Macleod (2001)
White-sided dolphin	Topography, SST, salinity, latitude Topography, SST, month Topography, depth	Selzer and Payne (1988) Gowans and Whitehead (1995) Macleod (2001)
Risso's dolphin	Topography Topography Topography, SST, depth of 15°C isotherm, chlorophyll, zooplankton Chlorophyll-a Topography	Baumgartner (1997) Davis et al. (1998) Baumgartner et al. (2001) Macleod (2001) Cañadas et al. (2002)
Long-finned pilot whale	Topography SST Topography, SST, month Topography	Hoydal and Lastein (1993) Gowans and Whitehead (1995) Cañadas et al. (2002)
Harbour porpoise	Substrate Tidally-induced internal waves Fisheries catches, chlorophyll-a	Smith and Gaskin (1983) Silber and Smultea (1990) Macleod (2001)
Cetaceans – general	Chlorophyll Zooplankton (right whales) Bathymetry, SST (right whales) Topography, distance from shore (humpbacks)	Smith et al. (1986) Beardsley et al. (1996) Moses and Finn (1997) Ersts and Rosenbaum (2003)

2.4 Environmental modelling

The development of computing power has in the present decade has allowed for the coupling of models of biological processes with increasingly realistic three-dimensional physical models (Tett *et al*., 2000). Recently developed ecological models can have great complexity, reflecting the complexity of the real ecosystem (James, 2002). Multidisciplinary modelling is coming of age, and moving to the stage where it is feasible to contemplate running a model operationally to provide real-time predictions. Only in the last few years have high-resolution hydrodynamic models and complex ecosystem ecological models been combined. The effectiveness of such deterministic models for making useful predictions about the ecosystem is not yet completely proven and can still be controversial; some still prefer the more traditional empirical approach (James, 2002). Historically, the forcing of global ocean models with cyclical climatological fields has precluded studies of interannual variability. A new generation of numerical ocean models, however, used time-variant surface fluxes, thereby introducing realistic temporal oceanographic variability into the model output. These simulations permit investigation of temporal variability on a variety of timescales in areas where hydrographic data are sparse and allow examination of the potential impacts of this physical variability, for example on the local ecosystem (Thorpe *et al*., 2004).

Ecological modelling must describe the interactions between all elements of the ecosystem in either a deterministic or an empirical manner (James, 2002). Models of biological-physical interactions in the sea must take into account physical transports (which conserve the total quantity of transported variables) and of non-conservative biological processes (which converts one variable to another) (Tett *et al*., 2000). Models of marine pelagic ecosystems have sought to compress the diversity of the system into a small number of compartments, which may represent higher-level taxa (such as diatoms) or trophic groups (e.g. zooplankton). Marine pelagic ecosystems contain many hundreds of species and very large numbers of individuals. Although the life of each individual and the dynamics of each population, can, in many cases, be described by a small set of rules, marine ecologists have achieved no consensus about a way to model system dynamics, according to Tett *et al*., (2000). There is no ecological equivalent of the physical oceanographer's basic hydrodynamic equations. It is also difficult to test for marine microorganisms because of the lack of observational data sets of sufficient resolution to reveal the dynamics of individual components of the system.

As argued by some modellers, it is neither possible, nor desirable, to capture the entire complexity of marine pelagic ecosystems in a model. In addition to computational limitations, uncertainty in parameter values would propagate through simulations, making the results unreliable. A variety of simplified approaches have been used e.g. Lagrangian simulation of ensembles, representations of higher-level taxa, or simulation of trophic groups, or both (Tett *et al*., 2000).

Many models aggregate biological components and abstract them into functional groups or compartments. These functional groups represent the main functional roles of production, consumption and decomposition. Individual organisms within a functional group are assumed to be identical and physiological processes and population dynamics are described in terms of fluxes of carbon and nutrients between functional groups and between organic and inorganic material, e.g. simulation of phytoplankton cycling. Functional groups may be subdivided into size classes to create a food web. However functional groups have limitations when it comes to representing the larger, long-lived organisms in the higher trophic levels, as biomass increase here may be growth of individuals, rather than by increased numbers of identically sized organisms (James, 2002; Baretta *et al*., 1995). This may pose problems for the modelling of the distribution of cetaceans but there is no doubt that these ecological models provide a valuable tool in determining the extent and spatial organisation of productivity within the desired sea area, which provide information as to where prey may occur at certain times, thus leading to potential cetacean sightings. There are of course also population models and individual-based models. Structured population models are appropriate for considering cohorts of particular species with multi-stage development, and can be coupled with spatially resolved models. Individual-based models track individuals through time and consider their interaction with the environment. These individual-based models have not been applied to species as far up the trophic ladder as cetaceans, but the technique has been used with animals such as wading birds by Wolf, (1994).

In shelf seas, a key component of ecological modelling has been the linking with physical models. The relative importance of diffusion, horizontal advection and local forcing can vary with the location and scales of the processes concerned. A three-dimensional model is necessary where horizontal advection is significant and inputs are non-local. Several of the biological models have now been linked to three-dimensional models, or at least have included estimates of horizontal transports, with horizontal resolution of varying scales (e.g. COHERENS [See Section 3 - Model Types]). The Princeton Ocean Model provides the physical module for NORWECOM (the Norwegian Ecological Model System).

A deliberately more complex ecosystem model in terms of the numbers of variables is ERSEM (the European Regional Seas Ecosystem Model), which attempts to include all significant processes necessary to produce a realistic representation of the cycling of carbon and nutrients in the European shelf seas (See Section 3 - Model Types). ERSEM includes several kinds of phytoplankton, a microbial loop and explicit mesozooplankton. An essential feature of aquatic ecosystem models is the combination of biology and physics, which cannot completely be separated, but a rough separation is possible. The biological dynamics of the functional groups are described in terms of physiological processes (growth, migration and mortality) with trophic interactions defined in the food web structure. The physical processes affecting the biological constituents are advection and dispersion in the horizontal, and sedimentation and dispersion in the vertical, with the horizontal processes operating on scales of tens of kilometres and the vertical processes on tens of metres (Baretta *et al*., 1995). It incorporates a benthic submodel, which describes the complex processes within the seabed including bioturbation: these have an important effect on the exchange of nutrients between the seabed and the water column (James, 2002). It has also been used in models of fish populations in combination with structured population models, including a larval stage.

The dependence of the physical model on boundary forcing means there is a requirement for boundary data from meteorological models and wider-area ocean models, and there is a need for understanding of air-sea interaction processes. The availability of open boundary data from larger area models are critical requirements. The area of interest may be small relative to the whole system, which determines flows there, and may need to be treated at high resolution. Therefore, a nested system is often required, from a relatively coarse ocean model to a fine-grid coastal model, or a system with variable grid size within the same model. A curvilinear coordinate system can also be used to place high resolution in an area of interest.

Good meteorological data is required for the surface boundary condition, which drives the currents through wind stress and changes the temperature through heat fluxes and the salinity through precipitation and evaporation. Where wave effects are important, in the surface layer and in shallow water, a wave prediction model may also be a requirement at least to derive increased mixing due to breaking waves, improved representation of surface fluxes and wave-induced enhancement of bed stress.

If there are enough observations, data assimilation may be used to bring the model results nearer to reality. Assimilation in an operational model can provide a method of combining models and observations in an optimal way, with regular updates, to give the best possible initial conditions, or representation of the field of state variables, for the beginning of each forecast period.

In the case of coastal-ocean modelling, a desirable attribute of such a modelling system is that it should be easily transferable to different areas, since the high resolution needed for coastal applications means that each area of interest will either be nested within a larger model or be an area of increased resolution within a variable-grid model. To relocate a coastal model to a new area requires not only detailed bathymetry of the new area, but also all the necessary initial and boundary conditions to run it (James, 2002). Another desirable feature is a user interface that makes this relocation easy to accomplish without extensive reprogramming, and also a system that is easily relocatable to different machines.

Correlation of environmental features and zooplankton biomass with sighting data may improve our understanding of cetacean ecology and indicate which, if any, physical and biological oceanographic variables influences cetacean distribution.
Combining multiple datasets, especially when data is collected concurrently can be very beneficial. With the addition of concurrently collected data on the physical environment, a detailed examination can be performed of how biotic and abiotic environmental parameters can be used to predict the temporal and spatial distribution of pelagic predators (Croll *et al*., 1998).

2.5 Satellite data

The advent of air and space borne measurement techniques has opened up a rich source of information with high spatial and temporal resolution (Losch *et al*., 2004). Satellite remote sensing is an important element of operational observation systems as it provides rapid global and regional news of key variables (Lehner *et al*., 2002). Satellite Earth Observation techniques have matured over the last two decades and now produce quality outputs for ocean wind, waves, temperature, eddy and frontal location, propagation and water quality (chlorophyll concentration, suspended sediment) that can be routinely produced and are in general, easily accessible (Johannessen *et al*., 2000).

However, so far, the most frequent variables retrieved from satellite sensors used in national and international pre-operational and operational systems are wind, waves, temperature and ice-conditions. Polar orbiting satellites can monitor large, regional, and mesoscale weather and ocean features with sensors operating in a wide range of the electromagnetic spectrum. Microwave sensors acquire data independent of sunlight and clouds, and are used to monitor wind, waves, and ocean currents, oil spills and sea-ice. Visible and infrared sensors (e.g. NOAA/AVHRR, ERS-ATSR, IRS-P3-MOS, SeaWiFS) monitor sea-surface temperature, fronts, currents, eddies, and ocean colour. These mesoscale ocean features can be very important in determining the location of cetaceans.

The distribution of SST provides significant information related to a wide range of marine processes and phenomena such as ocean currents, fronts, mesoscale eddies and up-welling phenomena. This allows the use of satellite derived SST information in the mapping of ocean circulation, fisheries, algal blooms and in assimilation of SST data in physical circulation models. SST is observed from space by thermal infrared imagery, during cloud-free conditions. These instruments measure the SST distribution at a spatial resolution of 1km and an accuracy of 0.5^{o}C or better. This type of data can be used to validate the modelling of SST.

The mechanisms for driving ocean currents in northern European waters are wind forcing, density differences, sea-surface gradients and tidal forcing, and current patterns are usually modified by topographic features. Currents can be identified in thermal infrared images through gradients in SST and ocean pigment distribution due to the differences of water masses of different origin. In Synthetic Aperture Radar (SAR), images of currents are mapped due to changes in surface roughness across fronts. SAR is able to image the surface expressions of features, such as eddies, meanders, fronts and jets, thereby providing qualitative information on their structure and evolution (Johannessen *et al*., 2000). These products may be used to assess the correlation of previous cetacean sightings with these features.

Wind speed and direction over the global ocean can be determined from the radar scatterometer on the ENVISAT and ERS2 satellites. It is also possible to determine detailed patterns of wind speed, and sometimes direction, from SAR images, and, at a lower resolution, from real-aperture satellite side-looking radar data.

Significant wave height can also be determined using satellite altimeter measurements and such measurements have been used to validate numerical wave forecasting models. Wave direction and wavelength can be determined using ENVISAT and ERS-SAR, both in image mode and globally in “wave mode”, and also in the high-resolution modes of RADARSAT. The typical resolution of satellite SAR, about 30m, means that only waves with periods of about 5s or more can be resolved. Wave refraction by bottom topography and the resulting change in surface roughness monitored by SAR, may be used to monitor the evolution of sandbanks in shallow-water areas, as well as in charting bathymetry in poorly-surveyed regions.

Water quality is measured through a series of bio-geophysical parameters and processes at the sea surface or in the water column. Some of the key parameters are dissolved or suspended in the water column, such as chlorophyll concentration, suspended sediment, and dissolved organic matter and biological and chemical films at the sea surface. The light scattering and absorbing characteristics of phytoplankton and other water constituents is the basis for the use of ocean colour Earth observation sensors (optical sensors). One of the main reasons for surveying phytoplankton distribution and concentration is the operational monitoring of harmful algae blooms. Remote sensors can provide information on the photosynthetic pigment concentration for the upper 20% of the euphotic zone. Total and new oceanic production calculated from remotely sensed data on ocean colour, validated by ship observations, yield more representative estimates of the large scale average production than those calculated from ship data alone (Hidalgo-Gonzalez *et al*., 2004).

There is generally a trade off between the spatial resolution of satellite data and their available temporal coverage. Geostationary meteorological satellites afford continuous, nearly global coverage, and coverage several times daily is available from the polar orbiting NOAA/AVHRR. Cloud cover significantly reduces the nominal coverage rate of optical and infrared sensor systems. Only regions under cloud-free conditions are available – a significant disadvantage for mid-latitude locations, which are subject to frequent poor weather. High latitude polar regions also suffer from limitations due to the winter darkness.

2.6 Statistical modelling

Recent advances in computing power have improved environmental modelling and statistical modelling. The advent of sophisticated statistical algorithms has initiated an increasing effort to correlate cetacean and seabird distributions with environmental data. Recently such modelling has included the use of Generalized Linear Models (GLMs) to examine linear relationships between a number of factors and biological datasets (see for example MacLeod *et al*., 2004). Non-linear relationships between environmental data and animal distributions are being developed using General Additive Modelling (GAM) and Generalised Non-linear Mixed Models (for example see Ainley *et al*., in press, Clarke *et al.*, 2003). These emerging methods are offering the possibility of generating predictive models, which will alert developers and managers to sensitive areas. A brief summary of the biological systems and the applied statistics are presented in Table 2.

Table 2. Summary of statistical analyses used on various cetacean data sets

Statistical methods	Species	Biological variables	Oceanographic variables	Literature
linear correlation multivariate - Canonical Correspondence Analysis (CCA) log likelihood Chi square General Additive Models	sperm whale dolphins general cetaceans	chlorophyll zooplankton squid catch records historical whaling records	Depth upwellings & benthic gradient CTD & flourescence Sea Surface Temp (SST) El Nino records salinity	Jaquet 1999 Jaquet & Gendron 2002 Reilly in press Hastie et al 2005 Ainley et al (2005)
linear regression	common dolphin		SST	Neumann 2001
Kolmogorov D+ chi Square χ^2 General Linear Models Logistic regression	bottlenose dolphin minke whales	sandeel data herring data	benthic gradient depth sediment	Ingram & Rogan 2002 MacLeod et al., 2004
descriptive stats student's t-test G-test	north atlantic right whale white-sided dolphin	Dinoflagellate zooplankton Krill	SST salinity benthic data	Durbin et al. 2002 Selzer and Payne 1988 Baumgartner et al, 2003
descriptive stats density estimates multi-linear regression	blue whale minke whale killer whale Antarctic fur seal	Plankton krill seabird distribution telemetry data diet chlorophyll	CDT SST ice cover depth bathymetry	Thiele and Gill 1999 Kasamatsu et al.2000 Murase et al., 2002

SECTION 3 – DATA AND MODELLING

3.1 Introduction

Integrating environmental information with biological data using statistical models has been a developing topic with the increase in the palette of techniques available and the rapid advances in computational power (Austin, 2002). Recently, sophisticated statistical modelling techniques have been used to fit cetacean distribution data to environmental variables (Hastie *et al* 2005, Macleod *et al* 2004, Macleod and Zuur 2005). These models enable scientists to examine distribution data collected from non-standardised surveys over large and complex marine habitats and the potential role of various environmental variables on animal habitat use movements and distribution patterns.

In order to identify the key challenges associated with adding value to existing biological datasets such as the CSS dataset, a statistical modelling approach was identified and implemented. The approach and findingsare described below.

3.2 Data review

As a first step, an investigation into the availability of suitable physical and oceanographic datasets was undertaken and where possible the cost, quality and spatial scales of the data were identified. This review provides a useful resource for researchers interested in this thematic area. The datasets that were reviewed are summarised in Annex 1. The datasets listed in Annex 1 are described in more detail in the Progress Report (February 2005).

The utilisation of datasets in the statistical modelling approach highlighted issues of data availability and quality. These issues are discussed in more detail in Section 3.5.

3.3 Model review

A review of available models was also conducted to obtain an overview of the range of models currently available, which could have some relevance to the analysis of the CSS data. For full descriptions of the models reviewed, see the Progress Report (February, 2005).

The model review showed that there are many physical models available, including an increasing number of 3D circulation models with various capabilities at a range of spatial scales and costs. In Ireland, the Marine Institute, the Department of Communications Marine and Natural Resources (DCMNR), universities and private companies, amongst others, use oceanographic models. The most significant advances in the marine sector have been in the application of high-resolution circulation models e.g. MIKE 3 and QUODDY.

As described in Section 2.4 the development of computing power has in the present decade allowed the coupling of models of biological processes with increasingly realistic three-dimensional physical models (Tett *et al*., 2000). However, there are relatively few ecologically coupled models currently available. Examples of the models reviewed included the coupled Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) / European Seas Regional Ecosystem Model (ESREM) and the Coupled Hydrodynamical Ecological Model for Regional Shelf Seas (COHERENS).

POLCOMS- Proudman Oceanographic Laboratory Coastal Ocean Modelling System
The core of this model is a sophisticated 3D hydrodynamic coastal and ocean model that provides realistic physical forcing to interact with environmental parameters. This model incorporates into the simulation, the effect of waves, tides, and meteorological forcing. It can be used to model sediment transport and resuspension, the movement of contaminants and

the movement of fish larvae (this could be extremely useful in assessing movement of potential food sources). POLCOMS includes the sophisticated European Seas Regional Ecosystem Model (ERSEM). ERSEM was designed as a generic model, and is one of the most complex lower trophic level marine ecosystem models currently in use. It describes both the pelagic and benthic ecosystems and the coupling between them in terms of the significant biogeochemical processes. It groups the biota into 'functional groups' according to their trophic status. When it is coupled with a hydrodynamic model it can compute the spatial distribution or movement of ecological fluxes during the different seasons of the year.

This model can be used to simulate processes in the deep ocean as well as the continental shelf at coastal to regional scales. It can be run on laptop computers as well as paralleled computer systems. It may also be nested to produce a finer grid for coastal areas and the shelf edge. The model code may be obtained by permission from the Proudman Oceanographic Laboratory.

COHERENS – Coupled Hydrodynamical Ecological Model for Regional Shelf Seas
COHERENS is a three-dimensional hydrodynamic multi-purpose model for coastal and shelf seas. A multinational group developed this model as part of a series of MAST projects, which were funded by the EU. It is coupled with a biological module, a resuspension module and a contaminant module. These modules may all be switched on or off as desired, thus allowing for flexibility in the use of the model. The hydrodynamic model produces outputs for variables such as currents, salinity and temperature. Based on the outputs from the hydrodynamic model, a biological model may be run to provide information on the cycling and transport of nutrients and microplankton. Outputs from the hydrodynamic model may also be input in a sediment transport model to produce data for deposition and erosion of sediments and also suspended particulate matter. Advection-diffusion equations are also present which may be used to model the movement of contaminants through the system.

This model is designed for coastal and shelf seas. It is free to obtain and can be ordered from the Internet. Once registration is complete a CD with the code, and model documentation are sent to the user. The model is written in Fortran code and so can be used in any Linux or Unix machine.

Figure 2 provides a graphical representation of a coupled physical and ecosystem model, which combines physical, benthic and pelagic parameters.

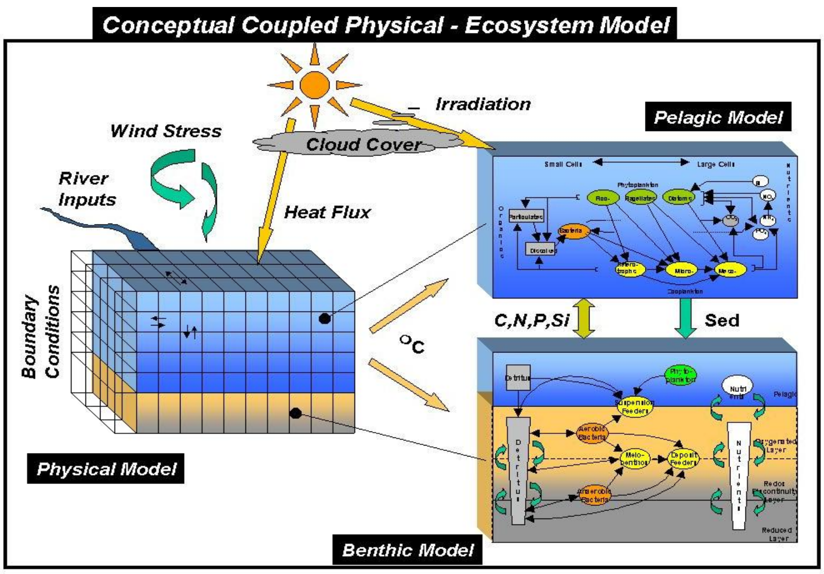

Figure 2. Graphical representation of coupled physical and ecological model. (Source: http://www.pol.ac.uk/home/research/polcoms/eco.html).

During the model review, it became apparent that there is a lack of national capacity in the application of such models to Irish marine biological data. In order to address the issue of capacity and to investigate the potential of coupled models further, a member of the project team, Dr. Simon Ingram, undertook a training course in "*Analysing Environmental and Biological Data Using Univariate Methods*", in the University of Algarve, Portugal, May 2005. Course participants were introduced to relevant statistical analysis techniques. Participants were also provided with the model software Brodgar, which is a custom written software package dedicated for use with biological and physical data. The background to the statistical modelling method applied using this software and the subsequent results are outlined below. The discussion in Section 3.5 describes the limiting factors, which influence the validity of the approach.

3.4 Statistical modelling methods

Traditional statistical methods were of limited benefit to ecologists studying the distribution of wild animals in complex habitats. Methods such as linear regression assume the data to be homogeneous and normally distributed. Furthermore linear methods allow for potential negative data values, an assumption incompatible with positive count data. Recently, Generalised Linear Models (GLMs), which fit a link function of explanatory variables to response variables, have proved useful for analysing animal distribution data (McCullagh & Nelder, 1983). Related non-parametric modelling techniques are able to deal with non-linear heterogeneous data sets. Generalised Additive Models (GAMs) use non-parametric smoothing functions to fit models to data without restrictions associated with linearity in generalised linear models and linear regression (Hastie & Tibshirani, 1990).

Generalised Additive Models are particularly useful in cases where limited environmental data are available and data are over dispersed as is the case with our offshore cetacean sightings data.

<u>Data selection</u>
Cetacean data
Data collected in the offshore field project was distributed over five hundred thousand square kilometres, yet despite the intensive field effort, many species are poorly represented and due to the large area surveyed all species are statistically over dispersed producing statistical challenges. In order to investigate statistical modelling approaches two cetacean data sets were selected for preliminary analysis. Patterns evident from the distribution plots were used to identify the most data rich groups of species. Firstly delphinids with the exclusion of killer whales and pilot whales were selected. This selection was due to the large number of sightings (246) in the database. Secondly, pilot whale sightings were selected due to the relatively high number of sightings of this species (79) and the apparent concentrations around the region of the shelf edge (Mackey *et al*., 2004). In order to standardise the sightings data and to remove biases associated with over sampling effects the sightings data were corrected for effort. The survey distances travelled in each ¼ ICES grid cell were measured and these values were used to correct the sightings data for each cell.

Environmental data
Whilst marine mammal distribution patterns may be governed by complex oceanographic processes and indirect influences on factors such as prey distribution and movements, simple benthic descriptors were selected for the preliminary analyses. At present, the cetacean sightings data available are insufficient to support a complex modelling procedure. Latitude, longitude (these provide useful geographic measures) charted depths and benthic slope (providing basic oceanographic descriptors) were selected. These data will be key to many of the ocean processes affecting animal movements.

In accordance with the sightings database we divided the study area into ¼ ICES squares measuring 0.5 degrees latitude by 0.5 degrees longitude. Benthic depth and a calculated index of benthic slope were derived from the readily available GEBCO dataset using a Geographic Information System (GIS) (Figure 3).

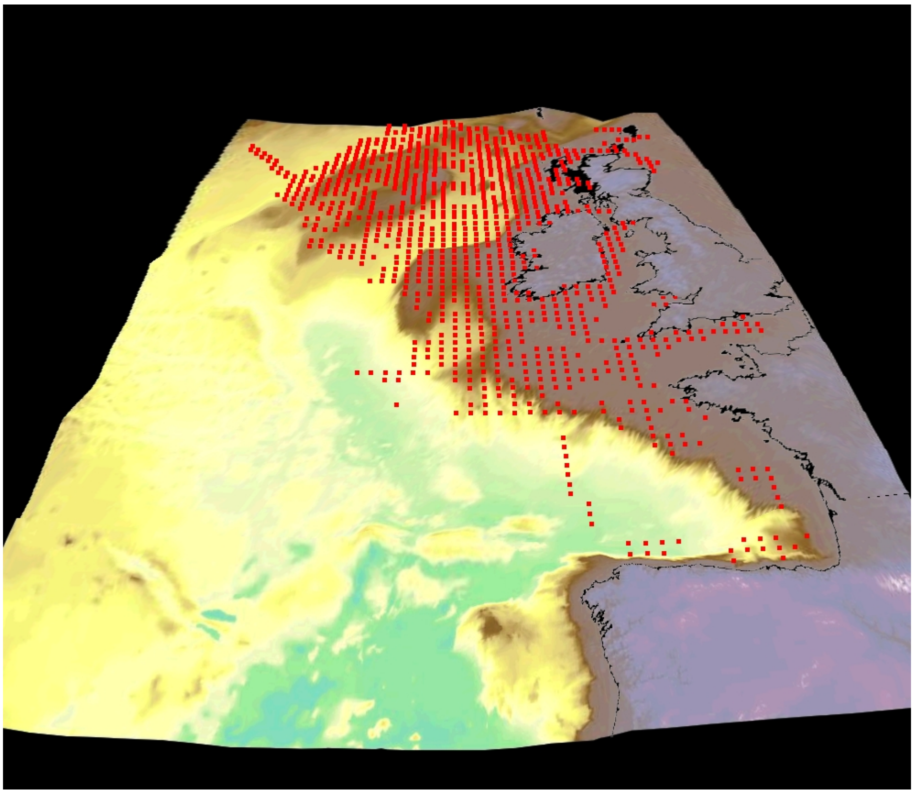

Figure 3. Areas of survey effort overlaid on GEBCO bathymetry

Benthic slope was calculated as the change in charted depth over the width of each ¼ ICES grid cell. Rather than representing actual slopes within each cell this measure provided an index of slope approximated over the whole cell.

<u>Statistical analyses</u>
The effort corrected sightings data corresponding to each cell and the benthic descriptors associated with each cell were compiled into an Excel spreadsheet. These data were then imported into the analysis package Brodgar (Zuur pers. com.). Brodgar is a custom written software package dedicated for use with biological data.

<u>Modelling results</u>
The model outputs for analysis of the delphinid data and pilot whale data are presented in Table 3.

Table 3. Summary of the GAM modelling results for dolphins and pilot whales

Variable	Delphinids	Pilot whales
Latitude	p>0.01	p>0.05
Longitude	Not significant	p>0.001
Min depth	p>0.05	
Average depth	Not significant	Not signifcant (p=0.06)
Benthic slope	Not significant	p>0.01
Deviance explained	9.72 %	30.7 %

Delphinids

Latitude and depth were found to have a significant non-linear effect on the numbers of dolphins sighted in each ¼ ICES cell (see Table 4). There was no significant relationship found between the density of dolphin sightings and longitude or benthic slope.

Table 4. Generalised Additive model results for delphinid data

Smoother terms	edf	F value	p-value
S Latitude	4	4.179	<0.001
S minimum depth	4	2.446	<0.05

Dolphin sightings were found to decrease slightly with depth (Figure 4a) with more sightings in the shallower shelf waters than the deep off-shelf waters. Additionally, more dolphins were sighted at the more southern lower latitudes of the survey area than in the high latitude northern areas (Figure 4b), and they were bi-modally distributed preferring latitudes from around 49-53°N and 56-58°N.

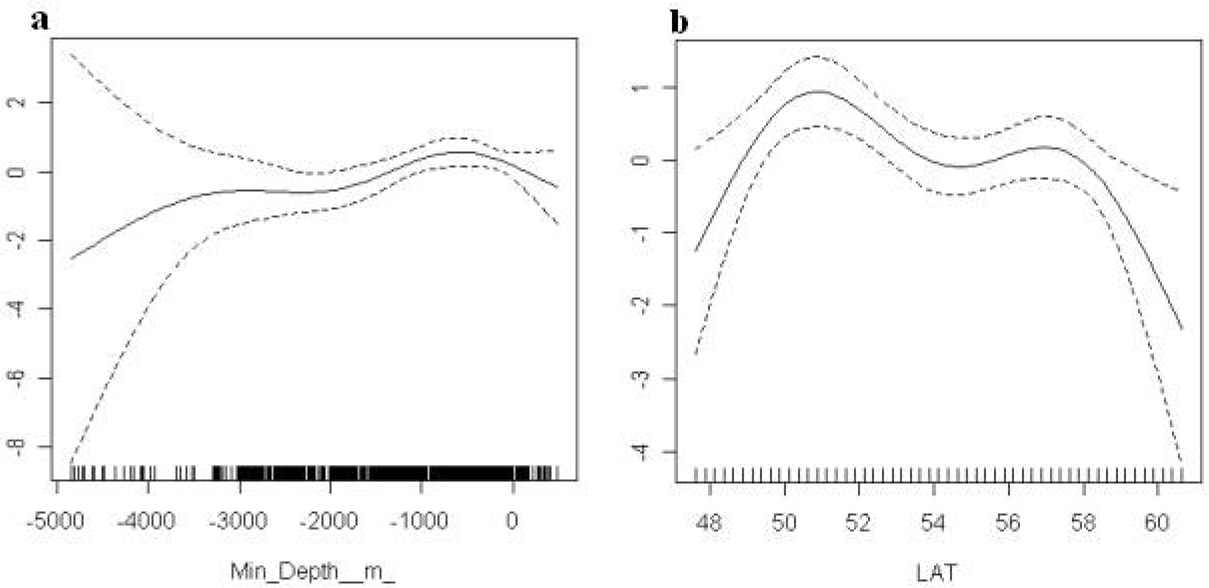

Figure 4. Smoothing curves for delphinid sighting frequency and a) latitude and b)minimum depths of each ¼ ICES grid cell.

Pilot whales

Latitude, longitude and benthic gradient were all found to have a significant non-linear effect on the numbers of dolphins sighted in each ¼ ICES cell (see Table 5, and Figure 2). Additionally, average depth was found to have a p value of 0.06 suggesting this variable to have an important influence (but not quite statistically significant) on the probability of sighting pilot whales.

Table 5. Generalised Additive model results for pilot whale data

Smoother terms	edf	F value	p-value
S Latitude	4	3.264	<0.05
S longitude	4	7.053	<0.001
S average depth	4	2.261	= 0.06
S slope	4	3.896	<0.01

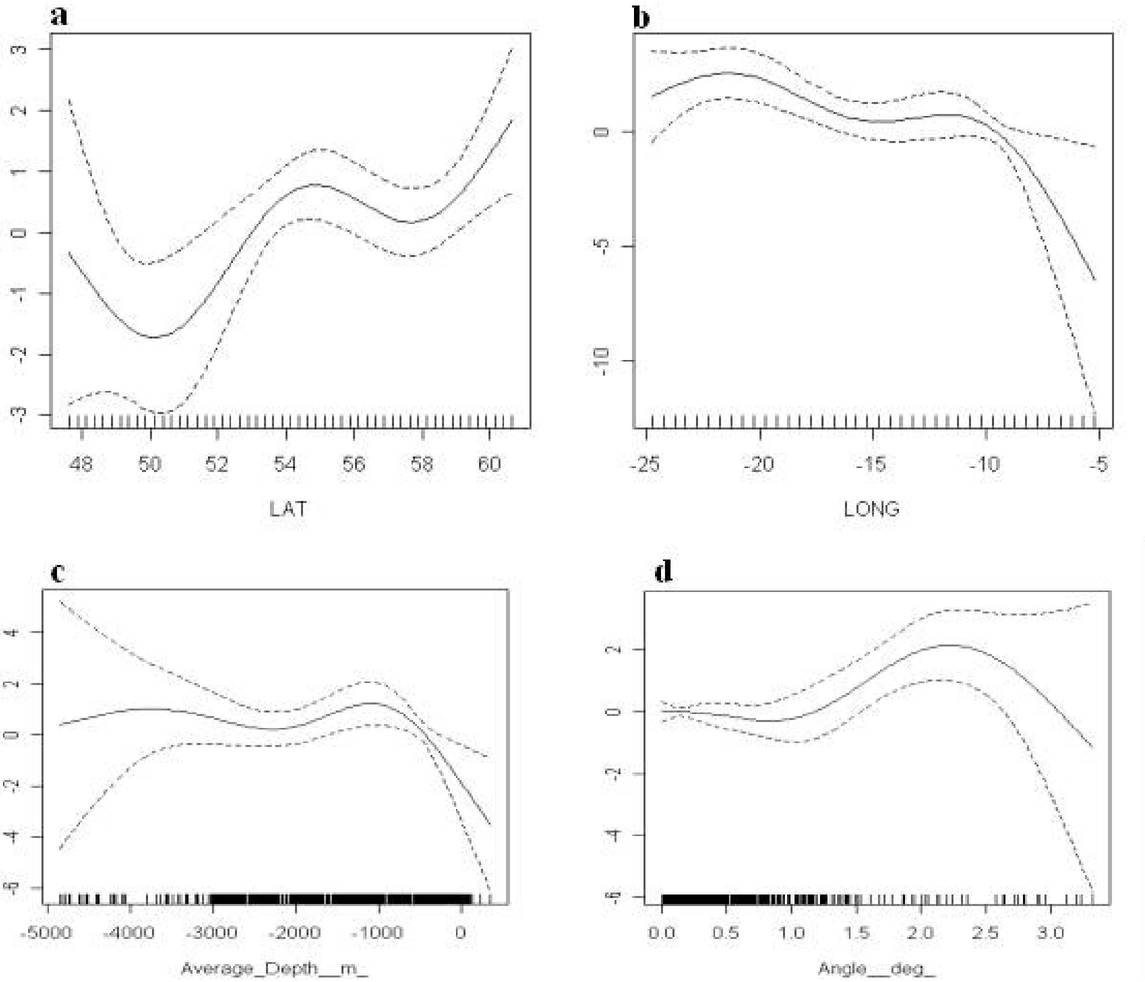

Figure 5. Smoothing curves for the variables a) latitude b) longitude c) depth and d0 benthic gradient and the effects on the sightings of pilot whales in the study area.

Pilot whale sightings were found to increase with northern latitudes (Figure 5a) and to increase with increasing westerly longitudes (Figure 5b). Although not statistically significant pilot whale sightings increased with increasing depth (Figure 5c). There was also a significant non-linear link between increasing benthic gradient and sighting frequency of pilot whales.

3.5 Discussion

From the existing data set an attempt was made to demonstrate the significance of simple benthic descriptors in the distribution of dolphins and pilot whales. Pooled dolphin sightings will include many oceanic species such as white-sided dolphins, striped dolphins and common dolphins but will also include common coastal species such as bottlenose dolphins. The GAM models showed a significant link with dolphin sightings and latitude with more sightings in the more southerly latitudes of the area surveyed. Furthermore, the model showed a significant link between sea depth and sightings with an increase in sightings in shallower waters. These results indicate that dolphins are more likely to be encountered in shallower southern latitude waters within Ireland's Exclusive Economic Zone (EEZ) than northern offshore areas. Conversely pilot whale sightings were found to increase with increasing latitude, longitude, depth and slope. This indicates that pilot whales prefer the deeper offshore waters in the northern areas of Ireland's EEZ.

These findings support the distribution plots presented by and O Cadhla *et al.,* (2004) and show that different species (or groups of species) have differing habitat preferences. Pilot whales tend to feed on cephalopods such as squid and probably prefer steep deep ocean areas where upwelling currents concentrate preferred prey species. Dolphins feed on many varieties of fish species and tend to follow migrating or spawning aggregations as they migrate inshore. These results illustrate interesting differences between surveyed species and they reveal perhaps how coupled models can identify patterns of habitat use with respect to simple environment variables.

In terms of the statistical approach used, it was shown that Generalised Additive Modelling could be used when linear regression and GLM models do not suit the data well enough. It has been shown that there is potential to apply GAM techniques within a predictive framework for modelling marine mammal distributions in the ocean. While the modelling approach was focused on selected cetacean species, there is no reason to assume that meaningful results could not be achieved with a combination of CSS seabird data with relevant environmental variables.

Nevertheless, the validity of the results must be viewed with caution, in particular in context of the quality of the input data, which warrants consideration here. The approach has used simple environmental data (e.g. the derived benthic slope). The low deviance explained values (see Table 1) correctly show that there is a lot of variability left unexplained by such simple models. The availability of high quality baseline datasets (e.g. GEBCO and Irish National Seabed Survey [INSS] data) is less of an issue than the methodology used to extract the relevant parameter (e.g. the simplified treatment of the calculation of benthic slope in this instance). The need to understand the consequences of the treatment of both biological and physical datasets in the data processing stage highlights the importance of involving of a multidisciplinary team in such work. A multidisciplinary approach would ensure the appropriate treatment of basic and additional variables such as salinity, temperature, depth and prey distributions.

As discussed, the model predictions rely on various environmental variables from measured data; the data review (Annex 1) demonstrated that a wide range of data is available from a variety of sensors including ship and satellite based sensors. In this simple test case, data availability was not an issue in order to map the physical parameters used. This makes the exploration of depth and cetacean distribution easily accessible. In a more complex modelling approach (e.g. 3D hydrodynamic model and ecosystem models), data acquisition is likely to be more challenging. However, it appears that a greater challenge exists with access to good coverage biological data, than with access to data relating to oceanographic or benthic parameters. Furthermore, the desire for a more complex coupled physical/ecological approach to modelling would have to be considered, given certain doubts that exist over the value of coupled models in determining complex ecological trends and the relevance of applying these techniques to animals higher up on the trophic chain.

The aim of this exercise was to investigate the potential of working with coupled physical and biological models. However it became apparent that the reliability of the model output and therefore the whole research effort would be hampered by the extent of the CSS dataset. Thus, the key limitations highlighted during the preliminary modeling procedure were primarily associated with modelling capacity and with the insufficient coverage of the CSS data. It is strongly advised that the valuable data analysed here are enhanced and augmented by further offshore sightings effort.

The 0.5 million km^2 covered during surveys is an unprecedented effort but such a large sea area requires further survey effort to yield maximal use from this work. At present of the 913 ¼ ICES cells surveyed, pilot whales (a relatively common species) were only found in 79 cells, this represents less than 10% distribution throughout the total survey area. In order, to secure a more statistically robust outcome, increased effort is needed to ascertain whether this represents their true distribution (unlikely) or whether this limited distribution is an artifact of the limited survey coverage. With more data it would be possible to examine such effects in less frequently sighted and more rare vulnerable species such as large baleen whales and beaked whales.

Originally, the study team intended to model the CSS data with more environmental parameters than the basic parameters selected. For example, a second finer scale grid concentrating on sighting “hotspots” was to be developed and it was hoped to utilise the high resolution data from the INSS to produce more precise values for the physical parameters for each of these cells. This approach warrants future merit, as a way of adding value to the INSS datasets. However, the issue of the level of coverage of CSS data has to be addressed in the first instance to ensure the identification of a true picture of animal ‘hotspots’.

The CSS project represented a milestone in the acquisition of fundamental baseline data to improve our understanding of cetaceans and seabirds in the Irish offshore area. It also provided an opportunity to build national capacity and expertise among the Marine Mammal Observers (MMOs) and scientists that participated in the study. This current desktop study has also opened doors to the scientific team involved, by providing an opportunity to apply new statistical modelling techniques to the CSS data. The UCC team is keenly interested in pursuing this line of research further. Significant national investment would be required to advance our knowledge to the level of development in coupled modelling that is underway, for example in POL and PML in the UK. However, there are many other steps towards progress that could be made with a reasonable amount of support from funding bodies. Clearly, there is an opportunity to add value to the initial investment in the CSS research by funding a new CSS project. It would be important to include in such a project a methodology to analyse the data by building on the statistical modelling approach commenced here, including approaches to further strengthen links between the Irish oceanographic modelling and marine biological communities.

It is timely to consider a new CSS project as a critical instrument in maintaining capacity among the CSS team in UCC. This team is unique in the country in terms of its skill set, scientific integrity and its expertise in relation to the operation of acoustic monitoring equipment (e.g. hydrophones) available in the CMRC. Industry can play a vital role in contributing to the ongoing stability of the research group, which is 100% dependent on research grant income, especially as current sources of funding, such as HEA funding, draw to an end. As requirements for MMOs on board seismic and other vessels becomes more desirable, industry support for a new CSS project will ensure the availability of an MMO resource in support of the requirements of the hydrocarbon sector, whilst also achieving the required data necessary for ensuring the sustainable management of marine resources.

To conclude, more sophisticated models will enable researchers to produce predictive plots to highlight potentially sensitive areas based on the findings of sightings at sea. These models will be useful for mapping sensitive areas and advising the timing of industrial activities, which may be of potential threat to marine mammals at sea.

SECTION 4 – CONCLUSIONS AND RECOMMENDATIONS

Literature review

1. The literature review showed that modelling has an important role to play in improving our understanding of the distribution and abundance of cetaceans and seabirds. Although, complex coupled hydrodynamic and ecosystem models offer exciting analytical prospects, these techniques have only recently been advanced and significant research needs to be undertaken to bring about widespread confidence in these approaches.

Data review

2. For the purpose of this study oceanographic data were more readily available than the requisite biological datasets. Opportunities exist for adding value to high quality physical datasets such as the INSS data, if issues pertaining to the availability of CSS data are addressed.

3. The limited shipboard effort dispersed over a large geographic coverage poses difficulties for obtaining an enhanced understanding of cetacean and seabird activities at sea through coupled modelling approaches. It is timely to consider the development of a new CSS project to acquire additional data. This will make modelling approaches more viable whilst also ensuring the availability of a ready pool of skilled MMOs to meet the needs of the hydrocarbon and other marine industries.

4. A multidisciplinary approach to data processing and modelling is to be recommended, bringing together biologists and oceanographers and other relevant disciplines.

Model Review

5. Modelling approaches range from relatively simple statistical modelling techniques, which focus on a limited number of physical and biological parameters, to highly complex coupled 3D hydrodynamic and ecosystem models. The approach tested in this study (GAM) has the potential to be further developed as a valuable new methodology in the analysis of CSS data to:
    - Determine the importance of different environmental variables to the distribution of cetacean and bird species off the west coast of Ireland.
    - Help identify critical cetacean and seabird habitat within Ireland's waters as an aid to advising future management of these areas.

6. There is a need to build capacity for implementing coupled physical and biological models in Ireland to add value to the significant investment already undertaken in the acquisition of the CSS data. This study provided an opportunity to make some progress in this field of research.

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Annex 1
Dataset Information

For details on the individual datasets, see the Progress Report (February, 2005).

Table 1 - Data sources and websites

No.	Source/Company/Institute	Website
1	Petroleum Infrastructure Programme DI	
2	Petroleum Affairs Division DI Output from Research Cruises 1998-2005	www.informatic.ie/paddi/paddi.asp www.pip.ie/page/89
3	Marine Institute	www.marine.ie
4	GSI Ireland	www.gsiseabed.ie
5	British Oceanographic Data Centre	www.bodc.ac.uk
6	UK National databank of CTD/STD profiles	www.bodc.ac.uk/data/online_request/ctd/
7	EDMED/Ifremer/CTD-Data	www.ifremer.fr:582/sismer/catal/base/edmed
8	IDM/SISMER - Scientific information systems for the sea	http://www.ifremer.fr/sismer/
9	The Marine life information network for Britain and Ireland	http://www.marlin.ac.uk/index.htm
10	European Sea Level Service	www.eseas.org
11	LOIS SES (shelf edge study)	http://www.bodc.ac.uk/
12	OMEX-1 dataset (ocean-margin exchange experiment)	http://www.bodc.ac.uk/
13	OMEX-2 dataset (ocean-margin exchange experiment)	http://www.bodc.ac.uk/
14	European Directory of Initial Ocean Observing System (EDIOS)	http://www.edios-project.de
15	UK Met Office - Shelf seas model data and products	http://www.metoffice.gov.uk
16	NOAA / Argo	www.ifremer.fr/coriolis/cdc/argo.htm
17	PO.DAAC	http://podaac.jpl.nasa.gov/index.html
18	Earth Observing system data Gateway	http://delenn.gsfc.nasa.gov/~imswww/pub/imswelcome/
19	National geophysical data center	http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html
20	NOAA / World Ocean Database 2001	www.nodc.noaa.gov/osc/wod01/data2001.html
21	ICES Oceanographic Database&Services	http://octopus.ices.dk/ocean/
22	Online ROSCOP database	http://www.ices.dk/ocean/roscop/
23	ACACIA Regional climate data access system	http://dataserver.ucar.edu/arcas.main.html
24	AOML Near-Real time wind data	http://ioc.unesco.org/iocweb/index.php
25	Aquarius/SAC-D Project data server	http://aquarius.gsfc.nasa.gov:8080/las/servlets/dataset
26	GTSPP Best copy datasets	www.nodc.noaa.gov/GTSPP/access.data/gtspp-bc.html
27	Near Real-time 1/12 deg Atlantic HYCOM nowcast/forecast system	http://hycom.rsmas.miami.edu/os2006.html
28	Ocean surface current analysis-Real-time OSCAR	www.oscar.noaa.gov/
29	World Data Centre for Marine Environmental Data	www.wdc-mare.org/info.html
30	Ocean and Sea Ice SAF	www.meteorologie.eu.org/safo

Table 2 - Spatial extent of selected data sources

No:	Source/Company/Institute	Location
1	Petroleum Infrastructure Programme DI	
2	Petroleum Affairs Division DI	Atlantic
3	Marine Institute	Irish Territorial waters
4	GSI Ireland	Irish continental shelf
5	British Oceanographic Data Centre	UK +
6	UK National databank of CTD/STD profiles	UK +
7	EDMED/Ifremer/CTD-Data	World wide
8	IDM/SISMER - Scientific information systems for the sea	France +
9	The Marine life information network for Britain and Ireland	Britain and Ireland
10	European Sea Level Service	European region
11	LOIS SES (shelf edge study)	Hebridean Slope
12	OMEX-1 dataset (ocean-margin exchange experiment)	NW European Continental Shelf
13	OMEX-2 dataset (ocean-margin exchange experiment)	NW European Continental Shelf
14	European Directory of Initial Ocean Observing System (EDIOS)	European Region
15	UK Met Office - Shelf seas model data and products	NW European Continental Shelf
16	NOAA / Argo	Top 2km of world ocean
17	PO.DAAC	Global
18	Earth Observing system data Gateway	Global
19	National geophysical data center	Global
20	NOAA / World Ocean Database 2001	Global gridded at 10 degree intervals
21	ICES Oceanographic Database & Services	International
22	Online ROSCOP database	North Atlantic Research cruises
23	ACACIA Regional climate data access system	Global
24	AOML Near-Real time wind data	Global
25	Aquarius/SAC-D Project data server	Global
26	GTSPP Best copy datasets	Global
27	Near Real-time 1/12 deg Atlantic HYCOM nowcast/forecast system	Global
28	Ocean surface current analysis-Real-time OSCAR	Tropical Atlantic
29	World Data Centre for Marine Environmental Data	Global
30	Ocean and Sea Ice SAF	NE Atlantic and global

Table 3 - Details of parameters and time-series available from selected data sources

No:	Source/Company/Institute	Parameters	Time Series
1	Petroleum Infrastructure Programme DI		
2	Petroleum Affairs Division DI	Oceanographic	Cruise dates
3	Marine Institute	P,T(s),T(a),Wd,WSp,T(w),Hs,Hum Oceanographic/compilation of metadata Spatial+temporal oceanographIc	Real-time (after 24hrs) 1970-2000 1994-present
4	GSI Ireland	Bathymetric/geological/CTD/SVP	
5	British Oceanographic Data Centre		
6	UK National databank of CTD/STD profiles	Oceanographic/CTD	1975 onwards
7	EDMED/Ifremer/CTD-Data	P,T,Con,DisO,flour	1971 onwards
8	IDM/SISMER - Scientific information systems for the sea	Oceanographic	1968 onwards
9	The Marine life information network for Britain and Ireland	Marine life	
10	European Sea Level Service	Tidal and sea levels	Real-time
11	LOIS SES (shelf edge study)	Phys, chem., bio, geo	1995-1996
12	OMEX-1 dataset (ocean-margin exchange experiment)	Phys, chem., bio	1993-1995
13	OMEX-2 dataset (ocean-margin exchange experiment)	Phys, chem., bio, geo	1997-2000
14	European Directory of Initial Ocean Observing System (EDIOS)	All	
15	UK Met Office - Shelf seas model data and products	Temp,sal,currents,SSL	Real-time and forecasts
16	NOAA / Argo	IR,LH,R,Sal,SST,ST,WS	Real-time (after 24hrs)
17	PO.DAAC	SST, sea-ice, Wd, etc	Depends on satellite
18	Earth Observing system data Gateway	Atmos/ocean/land/cryosphere/solar	
19	National geophysical data center	Elevation/bathymetry	
20	NOAA / World Ocean Database 2001	Oceanographic,CTD,nutrients	
21	ICES Oceanographic Database & Services	Oceanographic	
22	Online ROSCOP database	Oceanographic	1960s onwards
23	ACACIA Regional climate data access system	Atmospheric	1980-present, 6hr intervals
24	AOML Near-Real time wind data	Wind speed	Real-time, hourly (1day lag)
25	Aquarius/SAC-D Project data server	Sea surface salinity	
26	GTSPP Best copy datasets	Ocean temperature and salinity	Real-time (3 day lag)
27	Near Real-time 1/12 deg Atlantic HYCOM nowcast/forecast system	SSH,SST,surface currents,SST,SSS	
28	Ocean surface current analysis-Real-time OSCAR	Ocean surface vel.Fields/vector wind data	5 day mean/monthly mean
29	World Data Centre for Marine Environmental Data	All	Older datasets mainly
30	Ocean and Sea Ice SAF	SST, sea-ice, Wd,IR	2002-onwards

Table 4 – Examples of live access servers

Server Name	URL	Server description
NVODS	http://www.ferret.noaa.gov/nvods	National Virtual Ocean data system – data available via OPeNDAP (DODS)
WODB	http://www.ferret.noaa.gov/wodb	In-situ data server providing access to NODC's World Ocean Data Base
GODAE Modellers	http://www.ferret.noaa.gov/godae	Cooperative modelling umbrella site linking distributed Live Access Servers
Geophysical Fluid Dynamics Lab	http://www.data1.gfdl.noaa.gov/las4/	Ocean data from IRI/ARCS
Goddard Space Flight Centre	http://daac.gsfc.nasa.gov/las/	MODIS and SeaWifs data
Goddard Space Flight Centre	http://aquarius1.gsfc.nasa.gov:8080/las/servlets/dataset	Aquarius/SAC-D
Naval Oceanographic Offices	http://pdas.navo.navy.mil/las/	Real-time WAMS, SWAFS, MCSST model output
USGODAE	http://usgodae1.usgodae.org/las/servlets/dataset	US component of the Global Ocean Assimilation Experiment – providing data streams needed for operational modelling research.
Estimating the Circulation and Climate of the Ocean (ECCO)	http://www.ecco-group.org:8080/lasxml-org/servlets/dataset	Ocean model output
HYCOM	http://hycom.rsmas.miami.edu/dataserver/	HYCOM/MICOM model data
National Environmental Research Council	http://www.nerc-essc.ac.uk/las/	Environmental Systems Science Centre – Met office model data
AVISO	http://las.aviso.oceanobs.com/las/servlets/dataset	Satellite altimetry
MERCATOR	http://las.mercator-ocean.fr	Serving MERCATOR model outputs
MERSEA	http://las.Mersea.eu.org	Serving European model outputs + AVISO satellite altimeter data + Coriolis in situ data.