The Distribution and Habitat Preference of the North Atlantic Minke Whale (*Balaenoptera acutorostrata acutorostrata)* in the Southern Outer Moray Firth, NE Scotland

By

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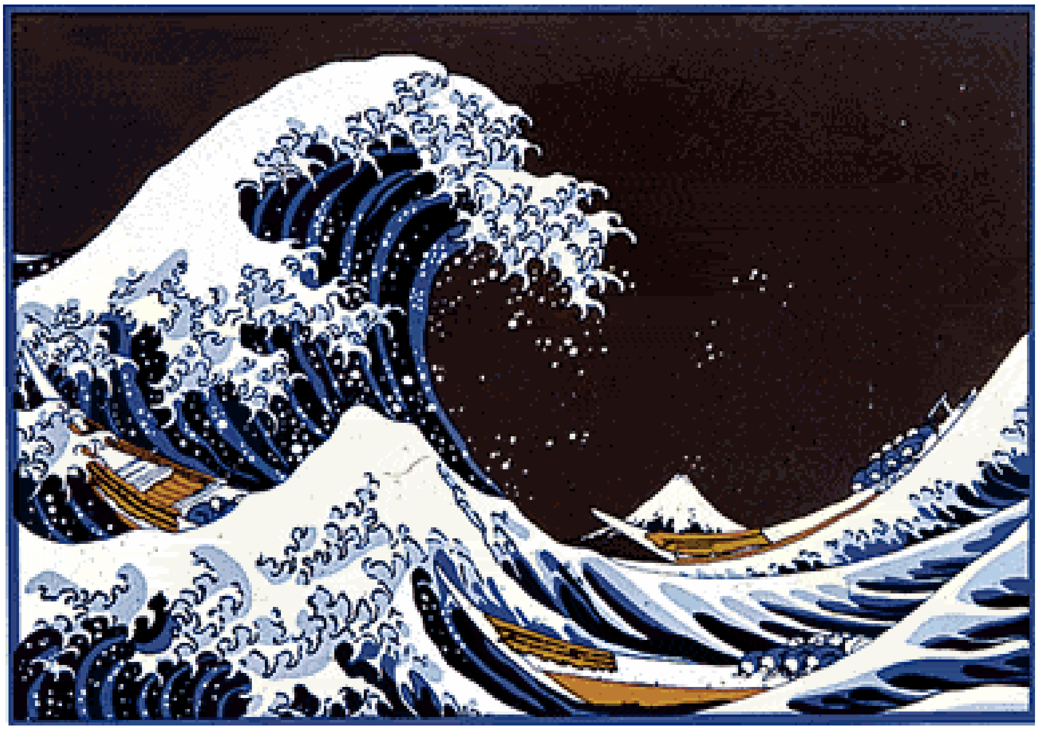

- The Great Wave
Katsushika Hokusai

"Would'st thou," so the helmsman answered, "learn the secret of the sea? Only those who brave its dangers comprehend its mystery!"

- The Secret of the Sea
Henry Wadsworth Longfellow

Abstract

Many studies have attempted to show correlations between the distribution of marine mammals and the surrounding environment. Sightings have been reported of minke whales (*Balaenoptera acutorostrata,* Lacepede 1804) occurring in the Moray Firth, a large embayment in the north east of Scotland. No detailed studies have been published on the presence of these animals in this region, nor has any research on their distribution in these coastal waters during the summer and autumnal months been conducted. A study was carried out to investigate if any significant patterns were observed between the distributions of minke whales and environmental variables in the southern outer Moray Firth. The study used a range of techniques and methods including behavioural observations, geographical information systems and remote sensing to determine environmental effects on the species spatio-temporal distribution. Results showed that the strongest correlations between whale distribution and encounter frequency were with fixed variables such as bathymetry and sediment type. A number of interesting observations were made between the distribution of whales and two important oceanographic features, a cold water current and a warm water plume, which dominate the Moray Firth system. These were thought to affect non-fixed variables such as temperature and primary productivity within the embayment, both of which are primarily associated with providing suitable habitat for the minke whales primary prey species, the sandeel (*Ammodytes marinus*). Therefore, these environmental variables promote productivity associated with higher densities of available prey. Lastly, detailed observations showed that distribution with regard to age class and behaviour were correlated with significant variations in the surrounding environment. These findings support the supposition that this area is important to the whales for foraging and further indicates the possible presence of habitat partitioning in this species. The information from the study not only adds to our understanding of minke whale ecology but also raises questions on the possible impacts to the species from anthropogenic activities such as increasing vessel traffic and demersal fishing techniques. Finally, the advantages of this method, in relation to uses in ecological modelling and the formation of new marine protected areas for the conservation and management of this and other marine mammal species, are also discussed.

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1. Introduction

1 Introduction

1.1 The Minke Whale

1.1.1 Taxonomy

The minke whale *Balaenoptera acutorostrata* Lacepede 1804 is the smallest species of whale in the family Balaenopteridae, also known as the rorqual whales (Gill, 1994). Other species in this family include the blue whale *Balaenoptera musculus,* fin whale *Balaenoptera physalus*, sei whale *Balaenoptera borealis*, brydes whale *Balaenoptera edeni* and the humpbacked whale *Megaptera novaeangliae* (Bannister, 2002). The Balaenopteridae belong to the larger sub order Mysticeti. This includes all those whales with plates of baleen instead of teeth, incorporating the families Balaenopteridae (rorqual whales), Eschrichtiidae (gray whale), Balaenidae (right and bowhead whales) and the Neobalaenidae (pygmy right whale) (Bannister, 2002). See **Figure 1.1** for a diagram of the members of these families. The Mysticeti are of the order Cetacea which also includes the Odontoceti, those species which have teeth instead of plates of baleen.

Until recently the minke whale was considered to be only one species *Balaenoptera acutorostrata*. However, in recent years, through morphological and genetic studies, it has been accepted that many geographically distinct subspecies occur (Christensen *et al.,* 1990; Martinez & Pastene, 1999; Born *et al.,* 2003). Minke whales which occur in the northern hemisphere, also referred to as the common minke whale, have been divided into two subspecies. These include the North Atlantic minke whale *Balaenoptera acutorostrata acutorostrata* and the North Pacific minke whale *Balaenoptera acutorostrata scammoni* (Perrin *et al.,* 2002). The primary morphological difference between the two subspecies are the extent of the white pigmentation or ‘spot’ on the pectoral flipper, the ‘spot’ having a greater coverage in *B. a. acutorostrata* than in *B. a. scammoni* (Gill, 1994). Although both species grow to a similar size (7-9 metres) the morphology of the skull appears to differ, those animals from the Atlantic having longer rostrums than those from the Pacific (Gill, 1994; Perrin *et al.,* 2002). Recently within the southern hemisphere more divisions have been made to minke whale taxonomy. A new species, the

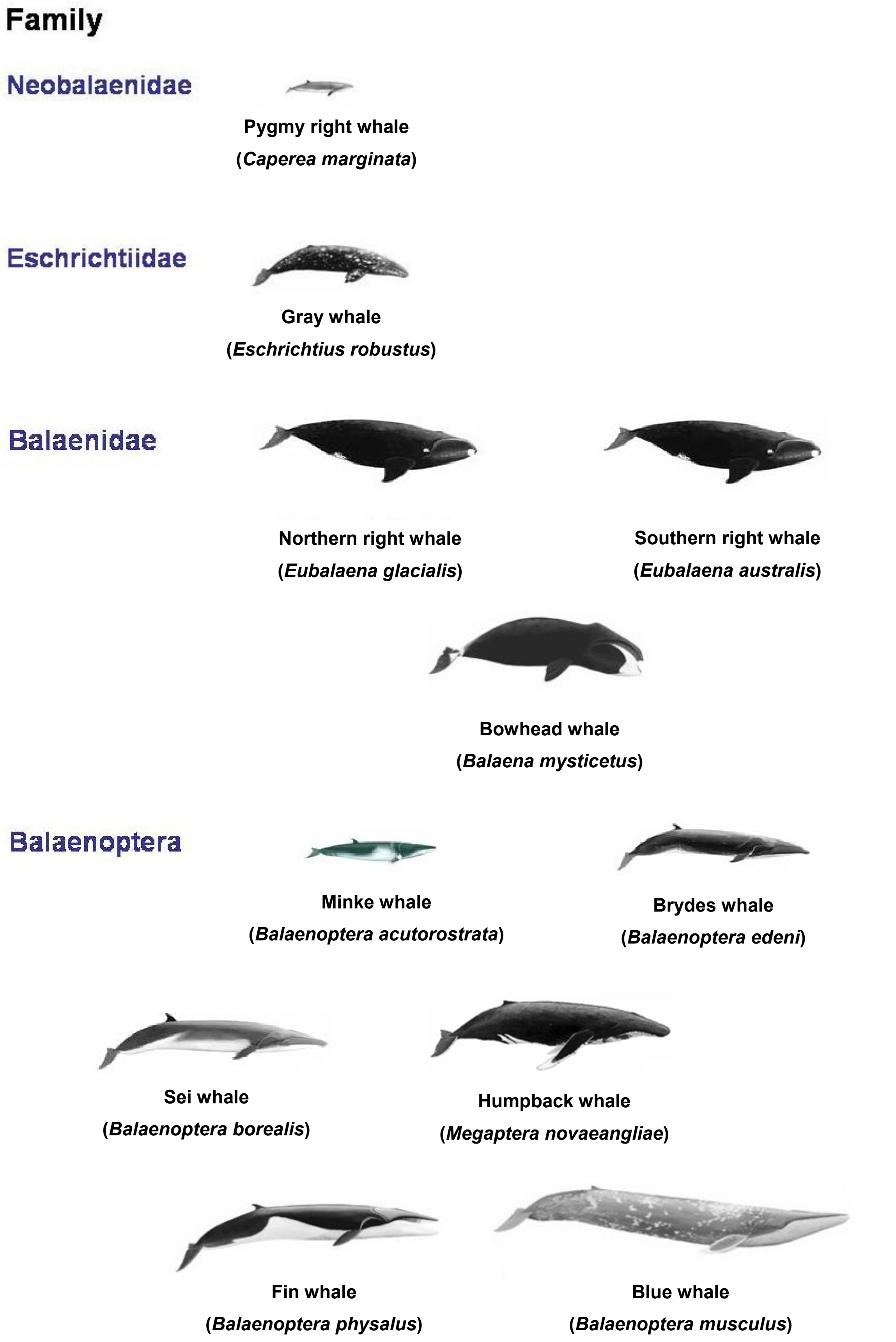


Figure 1.1 Diagram of the current members of the Mysticete families (adapted from Jefferson *et al.,* 2003).

Antarctic minke whale *Balaenoptera bonaerensis,* has been acknowledged (Perrin *et al.,* 2002). This species usually lacks the pronounced white patch on the pectoral fin. It is believed that individuals of the species *B. acutorostrata*, share a distribution in the southern hemisphere with *B. bonaerensis,* also considered to be a subspecies of the common minke, however they have yet to be named. These animals appear to be similar in appearance to the common species due to a white patch on the flipper (also extending up and over the shoulder). Also, as evident by their commonly used name, the dwarf minke whale, attain much smaller sizes, only reaching approximately 7 metres in length when adult (Perrin *et al.,* 2002).

For the remainder of this thesis any following biological or ecological characteristics described will be for the common North Atlantic subspecies *Balaenoptera acutorostrata acutorostrata.*

1.1.2 *Distribution*

The minke whale has a large and cosmopolitan distribution, being found in all the worlds' oceans (Perrin *et al.,* 2002). A distribution map can be found in **Figure 1.2**. However, the species is considered to be more frequently distributed in near-shore areas than with the open ocean. Minke whales are most commonly associated with coastal habitats or ice edge areas (Kasamatsu *et al.,* 2002). The occurrence of minke whales is also variable throughout the year as the species make seasonal migrations between polar feeding grounds and lower latitude breeding and calving sites (Perrin *et al.,* 2002). In North Atlantic minke whales, animals are frequently observed feeding in Baffin Bay in the Canadian arctic, Svalbard in the Greenland Sea, the Gulf of St Lawrence, Iceland and Norway (Christensen *et al.,* 1990). Minke whales also migrate into the coastal waters of the British Isles. Previous studies have documented the presence of minke whales in and around the Hebridean Islands on the west coast of Scotland (Gill, 1994; Gill *et al.,* 2000; Stockin *et al.,* 2001; Macleod *et al.,* 2004). In the North Atlantic the lower latitude breeding grounds for the species are poorly understood but are believed to be within the Caribbean in the west and around the straits of Gibraltar in the east (Christensen *et al.,* 1990).

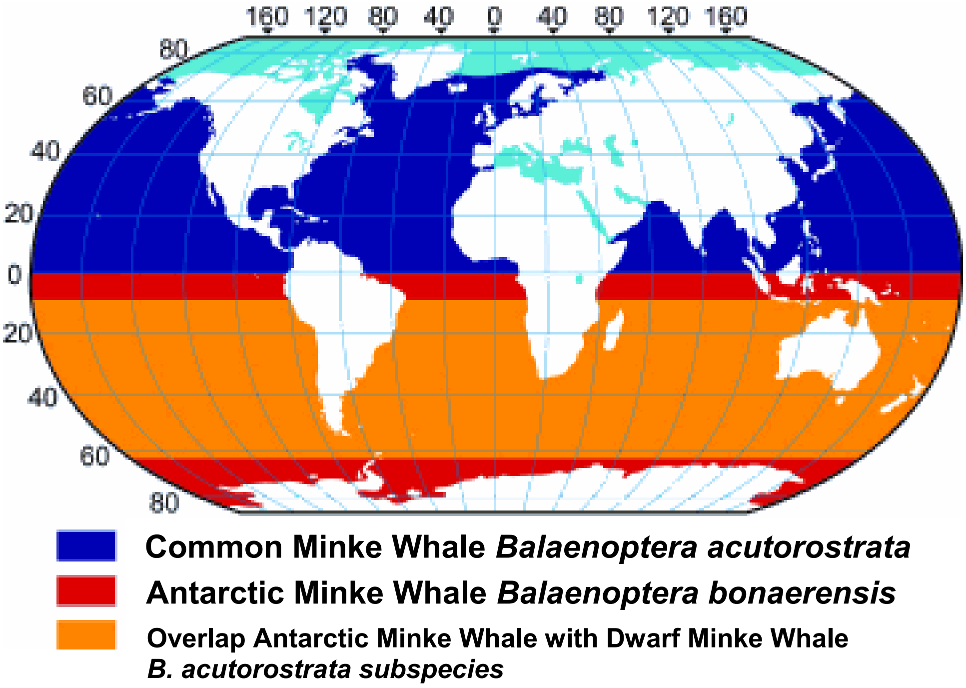


Figure 1.2 Map of the distribution of the three minke whale species / subspecies. These include the common minke whale *Balaenoptera acutorostrata*, the Antarctic minke whale *Balaenoptera bonaerensis* and the dwarf minke whale (unnamed *B. acutorostrata* subspecies). (ACS online 2004)

1.1.3 Morphology

The minke whale, like other members of the family Balaenopteridae, has a fusiform body shape, two pectoral fins, a caudal fluke and a falcate dorsal fin located two thirds of the way back along the body (Gill, 1994; Perrin *et al.,* 2002). An illustration of the morphology of the minke whale can be found in **Figure 1.3**. The species also has a particularly pointed rostrum with a single head ridge leading back towards a pair of blow holes. Approximately 50 to 70 throat grooves are found on the ventral side of the animal and extend backwards towards the naval (Christensen *et al.,* 1990). Approximately 230-360 baleen plates, hair-like panels comprised of keratin, hang from each side of the roof of the mouth. These plates have a length of around 25 cm with a width of approximately 12 cm at their base (Christensen *et al.,* 1990; Perrin *et al.,* 2002). The average length of a minke whale has been estimated as 8.5 – 8.8 metres in females and 7.8 – 8.2 metres in males (Christensen *et al.,* 1990).

Minke whales are predominantly grey in colouration with lighter areas of pigmentation observed on the lateral sides. These often unique markings are known as chevrons and have proven useful for purposes of photo identification (Dorsey, 1983; Dorsey, 1990). The most distinctive pattern of pigmentation which distinguishes the minke whale from the rest of the Balaenopteridae is the white pigmentation or 'spot' found on the pectoral fin (Christensen *et al.,* 1990; Gill, 1994).

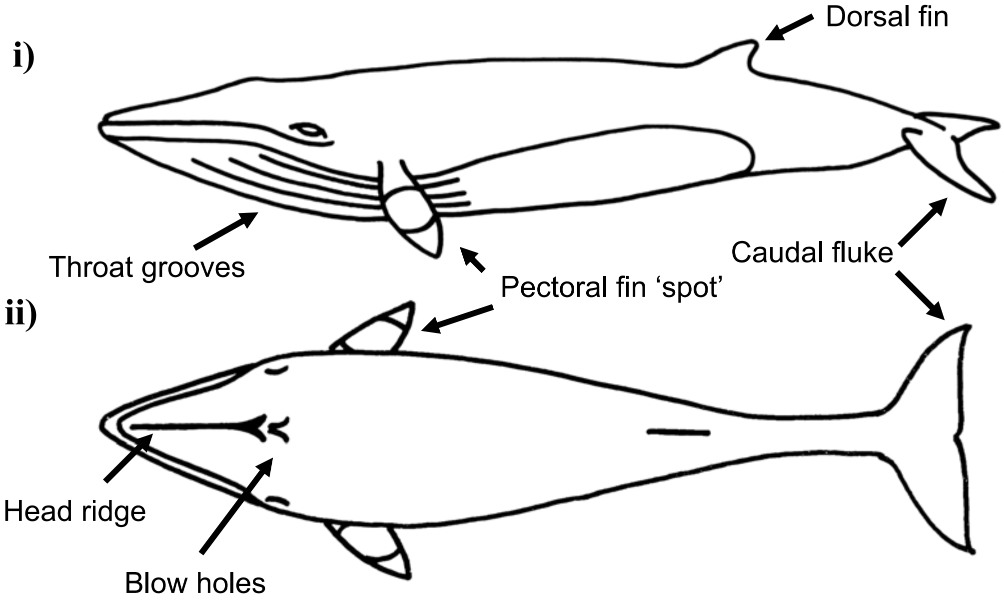


Figure 1.3 Illustration of the morphology of the minke whale *Balaenoptera acutorostrata* **i)** lateral view **ii)** dorsal view.

1.1.4 Feeding Ecology

The minke whale is a member of the mysticete whales. Their feeding strategies revolve around the use of baleen, plates constructed from keratin which hang from the roof of the mouth in place of teeth (Bowen *et al.,* 2002). Mysticete whales are grouped into three main types on the way in which the baleen plates are utilised. These are the swallowers which actively engulf compacted aggregations of prey, skimmers which passively entrap prey whilst swimming through the water column and swallowers and skimmers which use both strategies (Bowen *et al.,* 2002; Bannister, 2002). Minke whales are classified as swallowers and skimmers due to observations confirming the use of both strategies (Hoelzel *et al.,* 1989; Gill, 1994).

Swallowing strategies are the most frequently observed strategy used by minke whales within British waters. Like all Balaenopterid whales *Balaenoptera acutorostrata* feed by engulfing large quantities of water containing high densities of prey e.g. fish. Special grooves in the throat allow expansion of the throat to contain the prey laden water (Perrin *et al.,* 2002; Lambertsen & Hintz, 2004). The water is expelled from the mouth through the baleen plates, which act like a filter, and prevent the escape of prey. Once all the water has been removed the prey is then swallowed (Hoelzel *et al.,* 1989; Bowen *et al.,* 2002).

A number of different feeding techniques have been observed in minke whales. These include techniques which are used to aggregate prey together to then be engulfed, such as bubble blowing and lunging (Hoelzel *et al.,* 1989). Minke whales have been observed feeding in association with a number of other species. These include other marine mammals such as the harbour porpoise *Phocoena phocoena*, and non-prey fish such as the mackerel *Scomber scombrus.* However, the most well documented case of interspecific interaction is that between minke whales and seabirds (Gill *et al.,* 2000). Commonly when minke whales are observed to be feeding a number of bird species are often present. This has been phrased as 'bird associated feeding'. Some of the species which are frequently observed during bird associated feeding include the gannet *Morus bassanus*, kittiwake *Rissa tridactyla*, herring gull *Larus argentatus*, guillemot *Uria aalge* and razor bill *Alca torda*. It has also been hypothesised that individual minke whales tend to specialise in one of these feeding techniques, i.e. bird associated feeding or by aggregating prey together using lunging and bubble blowing (Hoelzel *et al.,* 1989).

The diet of the minke whale contains a range of different species including fish, crustaceans and cephalopods. However, due to the minke whales' cosmopolitan distribution the composition of an individual minke whales' diet may vary greatly between different regions. It is well documented that those whales occurring in the southern hemisphere feed nearly exclusively on Euphausiids, such as the Antarctic krill *Euphausia superba*, whilst those animals in the northern hemisphere feed on a much wider range of prey (Martensson *et al.,* 1996; Skaug *et al.,* 1997). However, it has been shown that minke whales only select and feed on single prey species aggregations (Tamura & Fujise, 2002). In the north east Atlantic and those waters surrounding the British Isles the primary prey species identified were the sandeel *Ammodytes marinus*, sprat *Sprattus sprattus* and the herring *Clupea harengus* (Haug *et al.,* 1997; Lindstrom *et al.,* 2002) (see **Figure 1.4**). Dietary analysis from the stomach contents of stranded animals found around the north of Scotland found that sandeels comprised the most significant part of the contents, whilst sprat and herring comprised the next most important parts (pers.comm. Begoña Santos). Finally, it has been shown that minke whale distribution also changes with time during the foraging season. It is believed that this may be due to animals following the migrations of certain species, such as spawning herring, or changing between prey species which become more abundant than one another during the time spent at foraging sites (Macleod *et al.,* 2004).

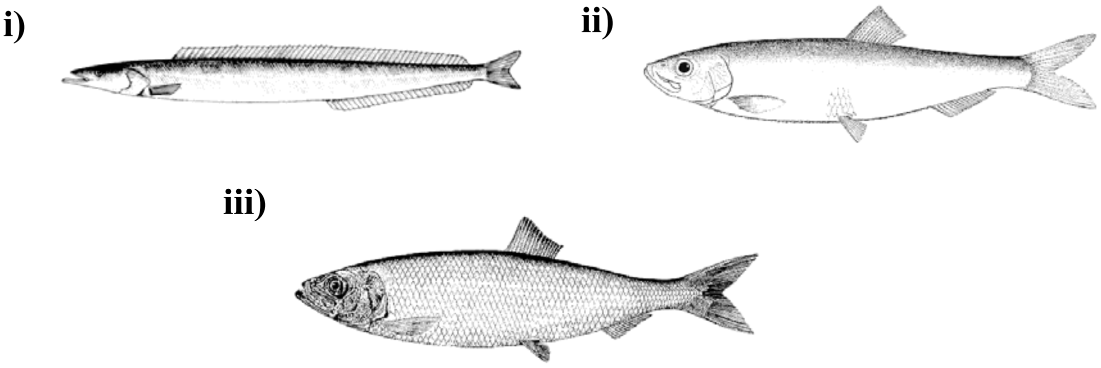


Figure 1.4 Main prey species of minke whale (*Balaenoptera acutorostrata*) in the British Isles **i)** sandeel *Ammodytes marinus* **ii)** sprat *Sprattus sprattus* **iii)** herring *Clupea harengus*. (Adapted from Fishbase, 2004)

1.2 Cetaceans and the Environment

In recent years many studies have attempted to show if correlations exist between the distributions of marine mammals and the surrounding environment. Those activities which have either utilised these species as a resource (Jaquet *et al.,* 1996), or more recently those who have studied the animals for management and conservation (Hooker & Gerber, 2004), have known that marine mammals are not evenly distributed throughout the world oceans, seas and rivers, and that they favour and concentrate in certain areas (Yen *et al.,* 2004). These species are logistically hard to access and as such research is often difficult. Some insights have been made although further research will be invaluable.

The following sections will review some of the recent research conducted in this field and what insights have been made.

1.2.1 *Bathymetry*

The marine environment is often thought by many to be a flat and homogeneous area (Cox & Moore, 1994). However, it has formed through many of the same geological processes which have shaped the terrestrial environment, so shares many similarities. On land there are steep mountain chains, expanses of plains and deep valleys and gorges. These are also present under the world's seas and oceans, concealed under vast quantities of sea water. These include great mid oceanic ridges which run the lengths of the world's major ocean basins, chains of sea mounts pushed up to the surface by volcanic activity and deep canyons and trenches plunging down to depths of almost 11,000 feet (Nybakken, 2000). These are formed by large scale geological events and as such are rare and isolated. However, even on a finer local scale there are differences in the bathymetry or underwater topography between different areas (Croll *et al.,* 1998). This can not only effect the oceanography of the area, i.e. mixing of water masses, circulation of nutrients (Kimura *et al.,* 1997) but also those species which are located within this habitat.

Many species rely on particular conditions of sediment type and bathymetry when selecting habitats. The distribution of these species is not uniform so aggregations are often present in particular sites of optimal habitat (Worm *et al.,* 2003). In marine mammals, especially the cetaceans, the two primary reasons for selecting a certain habitat are either related to foraging (areas of high prey density) or reproduction (favourable for courtship and giving birth to young). It has been shown that correlations exist between cetacean distributions and physiographic features, such as ocean depth and sea floor slope, as well as hydrographic characteristics which may affect animals directly (Baumgartner, 1997). However, it is believed that these environmental factors mostly effect cetacean distribution secondarily, through their effects on the distribution of cetacean prey (Davis *et al.,* 2002). Complex bathymetries, such as submarine canyons, deep basins, and steep slopes, can influence the surrounding seawater and produce important oceanographic features such as fronts and eddies (Kimura *et al.,* 1997; Yen *et al.,* 2004). These features act to aggregate weakly swimming organisms (e.g. plankton) and bring them closer to the surface, allowing greater access to diving predators (Croll *et al.,* 1998). This process of anchoring important oceanographic features in areas with specific bathymetric characteristics has been important in understanding the persistent presence of top marine predators within certain areas (Yen *et al.,* 2004).

Examples of studies which have found correlations between the distributions of marine mammals and bathymetric features, such as ocean depth and sea floor slope, include the presence of northern bottlenose whales (*Hyperoodon ampullatus*) in the Gully, a submarine canyon off Nova Scotia, Canada (Hooker, 1999). This study highlighted the importance of the Gully to this species, due to the way in which the canyon acted to aggregate squid, such as *Gonatus spp* which forms a primary component of the whale's diet (Hooker *et al.,* 2002). Baumgartner (1997) found that the distribution of risso's dolphins (*Grampus griseus*) in the Gulf of Mexico was not uniformly distributed with depth or slope. The species was closely associated with steep sections of the upper continental slope in the northern regions of the Gulf. This was also suggested to be the case when cetacean distribution was secondarily effected by the distribution of particular prey in these areas. Lastly, Hastie (2004) related the surface behaviours of bottlenose dolphins (*Tursiops truncatus*) to areas of certain bathymetry associated with higher abundances of bottlenose dolphin prey. Due to the use of this behavioural data Hastie was able to show that the distribution of animals over certain areas does not reveal the underlying function of that habitat to a species.

1.2.2 *Water Temperature*

As stated earlier oceanographic variables can have important effects on the distributions of many species of marine mammal. One feature which can affect the physical and biological processes occurring in the sea is the temperature of the water (Selzer & Payne, 1988). Water temperature can effect the distribution of marine mammals in many ways. Firstly all marine mammals, cetaceans in particular, are greatly affected by heat loss by being immersed in water. Therefore, in order to survive, cetaceans have developed ways to maintain body heat and energy expended on thermoregulation to ensure an efficient energy budget (Hind & Gurney, 1997). Therefore, many species, once adapted to certain temperature regimes, can only occur in those areas. An example of this is the distribution of the harbour porpoise (*Phocoena phocoena*) in European waters (Bjorge & Tolley, 2002). Harbour porpoise are found in the North Atlantic and the Black Sea. However, no harbour porpoise are found in the Mediterranean Sea. It is currently hypothesised that the species distribution may have once stretched from the Atlantic through to the Black sea (Martin & Reeves, 2002). A changing climate was thought to have made temperatures in the Mediterranean Sea increase. Because of their adaptations to colder ambient water temperatures some harbour porpoise were trapped in the Black Sea over time. They now differ genetically from the Atlantic population (Bjorge & Tolley, 2002).

The primary way that temperature can effect the distribution of marine mammals is through the influence of physical and biological processes of the area affecting the abundance of prey (Wakefield, 2001). Water masses with different temperatures have different salinity and oxygen carrying capacities (Nybakken, 2000). When two water masses of different water temperatures collide, an area described as a front is formed (Horsburgh *et al.,* 1998). Many studies have shown these frontal zones to be sites of enhanced biomass (Franks, 1992). This occurs through a process of stratification in the water column, ensuring those organisms such as plankton remain in surface water for longer periods of time (Franks, 1992; Kimura *et al.,* 1997). Therefore, being able to identify those areas, such as fronts in sea surface temperature, can indicate those places set to have higher abundances of prey for marine mammals to forage (Benson *et al.,* 2002). Some larger species which act as prey for marine mammals can also be affected directly by temperature. The mackerel (*Scomber scombrus*) migrates large distances around the coasts of the UK. In a study by Reid (1997) it was shown that the migrating behaviour of mackerel was altered at different temperatures. Those animals subjected to colder water temperature would swim fast and cover large distances. However, if ambient temperatures were warm, mackerel migration slowed and they remained longer in areas of warm water (Reid *et al.,* 1997).

Many studies have used measurements of sea water temperature to find significant correlations occurring with cetacean distribution (Hamazaki, 2002). Temperature measurements have been used in researching changes in distribution across areas of similar bathymetry, i.e. depth and slope characteristics (Yen *et al.,* 2004). Examples of studies trying to relate the distribution of marine mammals with water temperature, or the presence of thermal fronts, include that on right whales (*Eubalaena glacialis*) in the great south channel of the North West Atlantic (Brown & Winn, 1989). This study found that whales were distributed non-randomly and were in close proximity to the 100m isobath and a thermal front. Goold (1998) and later by Wakefield (2001) found that common dolphins (*Delphinus delphis*) were strongly associated with a frontal system in the Celtic Sea and Irish Sea, known as the Celtic sea front. It was observed, using both visual and acoustic survey techniques, that common dolphins spend part of the year closer to the coast of Pembrokeshire, in south west Wales. However, later in the year their distribution shifts to offshore areas of the Irish and Celtic seas. This was explained using satellite derived imagery of sea surface temperature showing that the offshore migration of common dolphins coincided with the break up of the Celtic Sea front (Goold, 1998). Wakefield (2001) found that common dolphins correlated positively with sea surface temperatures, with those animals encountered being confined to temperatures warmer than 14.5°C south of the Celtic Sea front. Rendell (2004) found that foraging sperm whales *Physeter macrocephalus* foraging off the coast of Chile were closely associated with the cold water upwelling features of this productive marine ecosystem. This was done through comparing the defecation rate of animals, as a measure of foraging success, with sea surface temperature derived from satellite imagery. It was found that those animals located close to a cold upwelling feature off the Mejillones peninsula were higher than in other areas located to the south (Rendell *et al.,* 2004). This coastal upwelling was believed to make the higher productivity associated with the upwelling available to offshore pelagic predators.

1.2.3 *Primary productivity*

As stated previously the most important factor underlying the distribution of marine mammals is that of the distribution of their prey (Croll *et al.,* 2002). Previous studies relating marine mammal distribution to the environment have focused on showing correlations with physiographic or oceanographic features that promote productivity. As a result these support much higher biomass and organisms further up trophic chains and webs (Yen *et al.,* 2004). There are a few studies which have attempted to directly correlate the abundance of cetaceans with measurements of productivity. In the marine environment all ecosystems which derive energy from sunlight begin with that part of the plankton, tiny microscopic organisms, which are capable of photosynthesis. This is the process of using light to generate simple carbohydrates and sugars (Nybakken, 2000). These plant plankton or phytoplankton can only do this because of photosynthetic pigments called chlorophylls (Holligan & Groom, 1986). Phytoplankton abundance can change quickly and is highly dependable on many environmental factors such as the availability of nutrients, water temperature and water circulation (Franks, 1997; Joint & Groom, 2000). By being able to measure the concentration of phytoplankton, or alternatively the concentration of chlorophyll pigment in the water, it becomes possible to quantify the amount of primary productivity occurring at the base of the trophic system. Therefore, it is possible to ascertain the amount of biomass or organisms which can be supported higher up the food chain (Smith *et al.,* 1986; Littaye *et al.,* 2004).

Recent examples of studies using chlorophyll concentration, as a measure of primary productivity to understand marine mammal distribution, include the study of the distribution of sperm whales killed by Yankee whalers during the 18th and 19th century (Jaquet *et al.,* 1996). This study showed that there was a significant correlation between the distribution of whales caught by whalers and areas characterised by high concentrations of chlorophyll obtained from modern satellite imagery. Smith and others (1986) used satellite imagery of the concentrations of chlorophyll present off the coast of California to understand the distribution of marine mammals. Study showed that the distribution of animals was not randomly distributed with respect to chlorophyll concentrations and that cetaceans were more abundant in the productive coastal areas than in the offshore oceanic waters of the California current (Smith *et al.,* 1986). Finally, Littaye and others (2004) used chlorophyll concentration data from satellite images to try to explain the summer distributions of fin whales (*Balaenoptera physalus*) in the northwestern Mediterranean Sea. The study highlighted strong correlations between the distributions of whales and areas of high primary productivity and also made insights into the variability of fin whale distribution during the summer months. While food availability at a particular time and place was thought to be a function of environmental conditions occurring in previous months, the study provided evidence that the whales adapted their movements and group size directly to food availability rather than to instantaneous changes in environmental conditions (Littaye *et al.,* 2004).

Studies which have used chlorophyll concentration as a indication of primary productivity effects on marine mammal distribution have been useful. They support the hypothesis that the movement and habitat selection of cetacean species, such as sperm whales, fin whales and oceanic dolphins, may be related to the mesoscale features that are manifest in patterns of chlorophyll (Smith *et al.,* 1986; Kimura *et al.,* 1997). It is also suggested that satellite derived measurements of chlorophyll may be useful in the future as a habitat descriptor for a number of marine mammal species, as well as useful in the interpretation of observed distribution patterns and the estimation of their movements and abundance (Smith *et al.,* 1986; Littaye *et al.,* 2004).

1.3 The Moray Firth

The following section describes many of the important aspects of the biology, ecology and geology of the Moray Firth, north east Scotland.

1.3.1 *Location and Extent*

The Moray Firth is a large embayment in the north east of Scotland, bounded on two sides by land, the outer extremity of which is considered as an arc reaching from Duncansby Head to Kinnaird's Head near Fraserburgh (**Figure 1.5**). This triangular area of sea covers approximately 5230 km^2 (Wilson, 1995). It is the largest of its kind on the east coast of Scotland and contains within it three smaller Firths being the Dornoch Firth, Cromarty Firth and Inverness Firth (Eleftheriou *et al.,* 2004). The Moray Firth is divided into two parts, the first being the inner Moray Firth defined as a straight line drawn from Helmsdale to Lossiemouth and all water lying within this area extending back into the Cromarty and Inverness Firths

(Wright *et al.,* 1998). The outer Moray Firth is the area of water lying between the Helmsdale to Lossiemouth line extending outwards towards the line drawn between

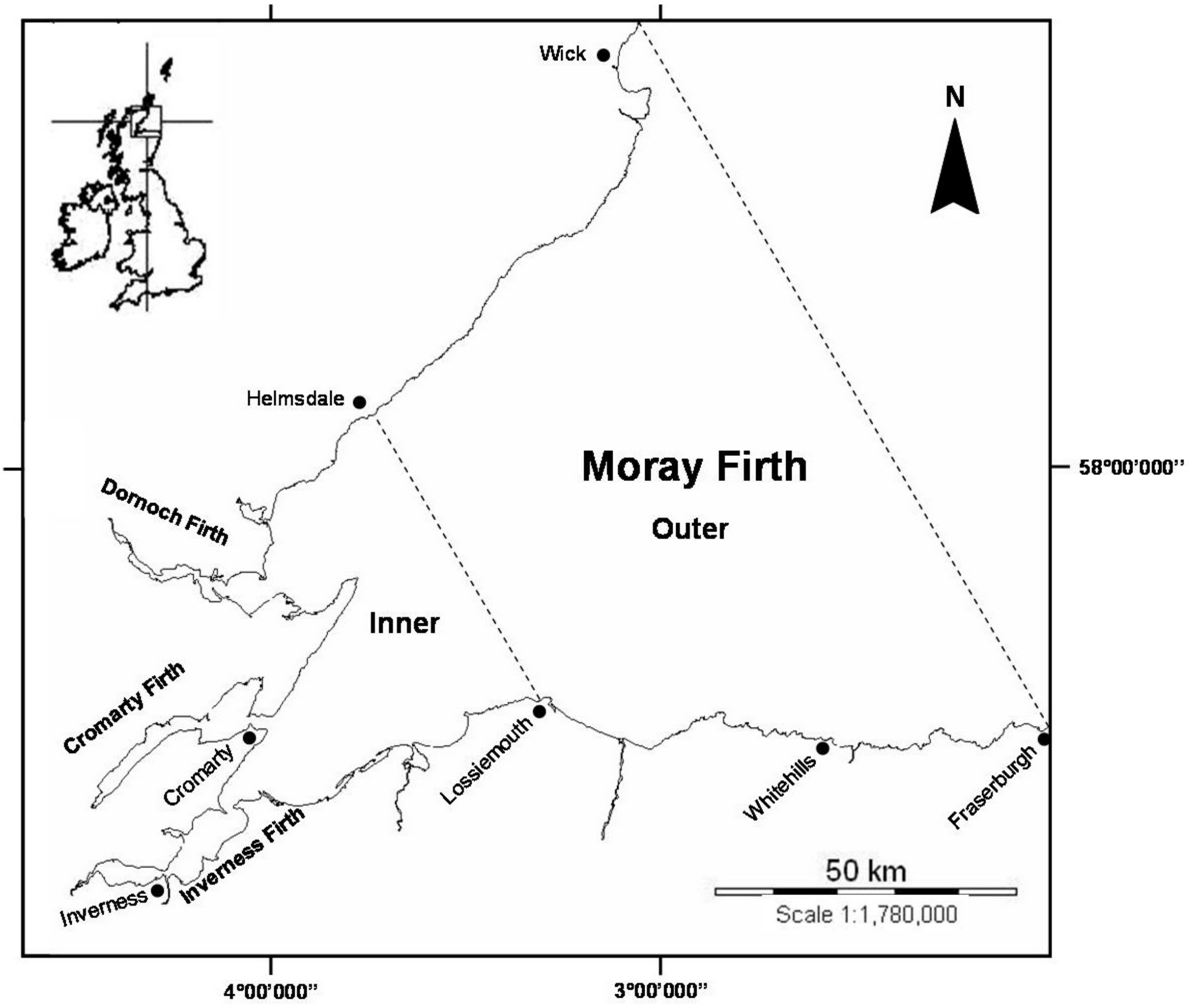


Figure 1.5 Map of the location and extent of the Moray Firth, north east Scotland. (re-plotted from JNCC coastal directories, 1999)

Duncansby Head and Kinnaird's Head. The Moray Firth is an 'open system' which forms an integral part of the wider North Sea basin and Atlantic beyond, sharing large scale environmental factors such as water circulation and climate patterns (Wright *et al.,* 1998; Eleftheriou *et al.,* 2004). It is an internationally recognised area of outstanding biological importance. However, it is under threat from many anthropogenic pressures, particularly from fishing pressure, oil and gas activities, industry and tourism (Wright *et al.,* 1998). Therefore, it is imperative for the conservation and management of this natural resource that detailed knowledge and data concerning its marine and coastal environments, and the species utilising them, be collected and analysed. Within the Moray Firth approximately 50% of the coastlines are covered by sites and areas designated for the conservation of the environment and the many species contained therein. These include 34 sites of special scientific interest (SSSI), one natural nature reserve (Nigg and Udale Bays), one national scenic area (Dornoch Firth) and the major area, the candidate special area of conservation (cSAC) in the inner Moray Firth (Eleftheriou *et al.,* 2004).

1.3.2 *Physiography and Oceanography*

The bathymetry characteristics of the Moray Firth vary greatly within in its extent. In the inner Moray Firth the seabed slopes gently from the coast to around 50 metres in depth, approximately 15 km from the coast. In contrast the outer Moray Firth more closely resembles the open North Sea with the seabed sharply sloping from the coast with the deepest extent being located within 26 km of its southern shore (Wilson, 1995). This deep region in the south western part of the outer Moray Firth is known as the Southern Trench, an enclosed seabed basin at least 250 metres deep (see **Figure 1.6**). The trench lies directly off the location of the Banff Fault, 10 km north of the Fraserburgh – Banff coastline (Holmes *et al.,* 2004). Conversely on the north western Helmsdale – Wick coastline, a large submarine embankment can be found where depths only reach a shallow 30 – 50 metres (Wright *et al.,* 1998). Sediment characteristics of the Moray Firth also vary dramatically within this large embayment, see **Figure 1.7** for a map of sediments found in the Moray Firth. Sediments are predominantly sandy, with a close inverse correlation between depth and grain size (Wilson, 1995). Those deepest areas within the Southern Trench vary slightly and are mostly comprised of mud (Holmes *et al.,* 2004). The waters of the Moray Firth are a combination of coastal and mixed waters. The main marine input is produced by the Dooley current which brings cold mixed waters down from the north, the current circulating this water in a clockwise direction within the Firth (Wilson, 1995). Of the twelve major rivers which discharge freshwater into the Moray Firth, ten discharge into the inner Firth, substantially reducing salinity (Wilson 1995; Holmes *et al.,* 2004). Changes in water temperature can be quite rapid between different regions of the Firth and can change radically. For example in the inner Moray Firth maximum summer temperature recorded at 12.5 °C, whilst during the winter the minimum temperature recorded was approximately 5.5 °C (Wilson, 1995).

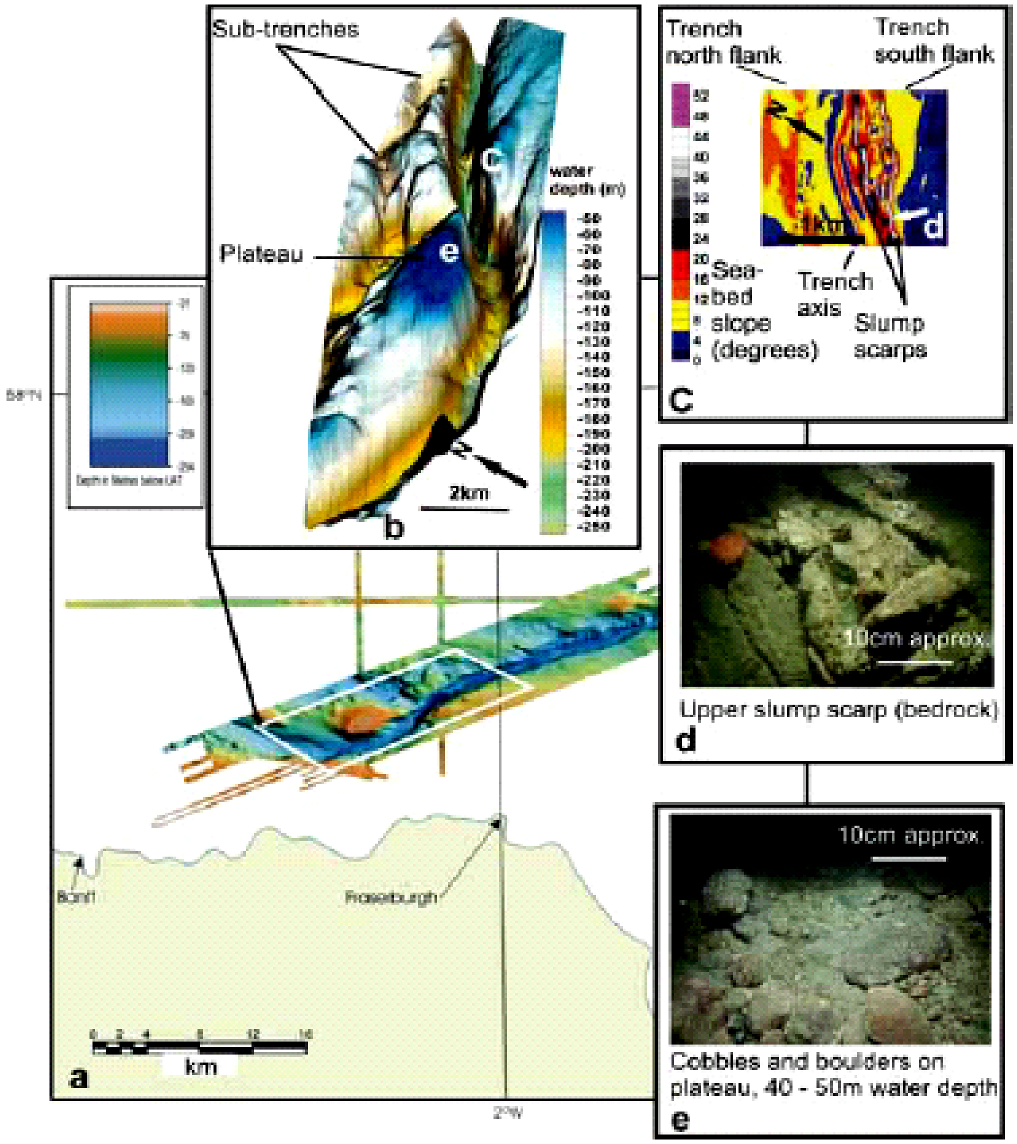


Figure 1.6 The physiography of the Southern Trench, north east Scotland. Insets show **a.** colour shaded topography **b.** seabed terrain **c.** seabed slope **d.** image of bedrock & **e.** image of seabed pebbles, cobbles and boulders (Holmes *et al.,* 2004)

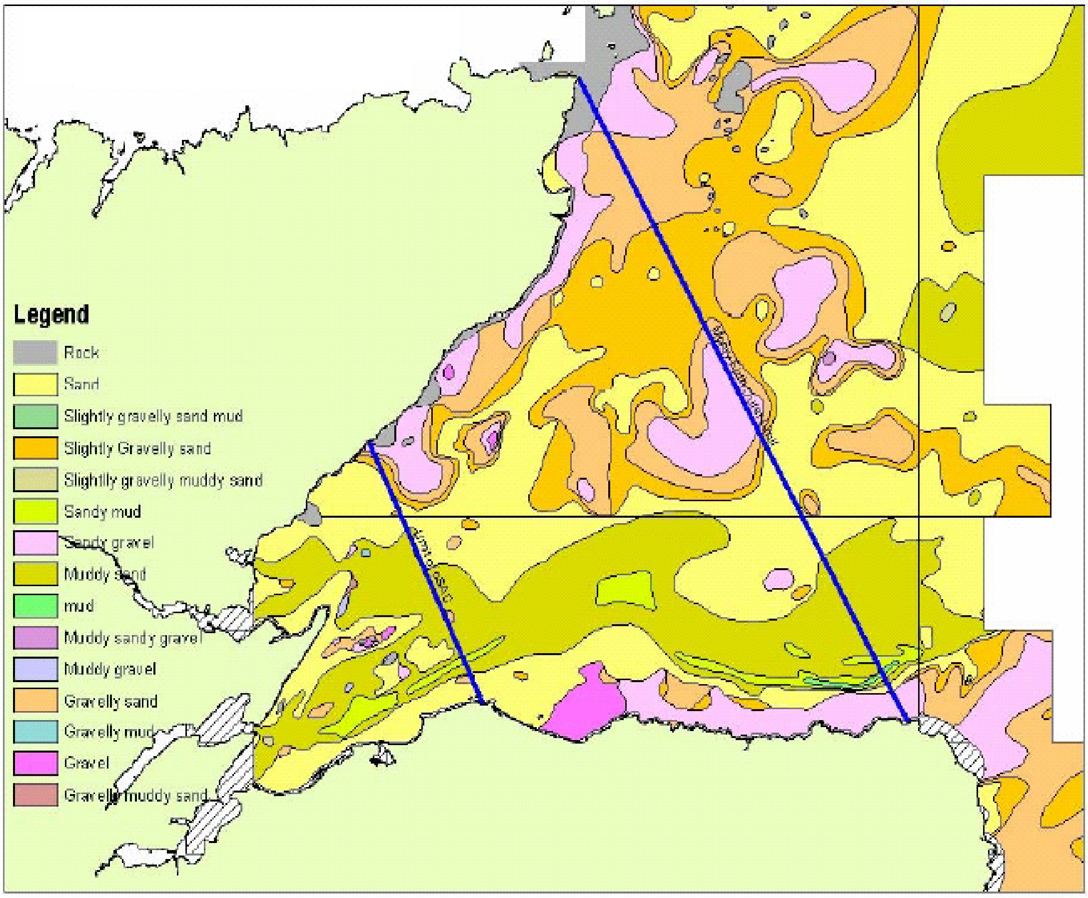


Figure 1.7 Map of seabed sediment types found in the Moray Firth, north east Scotland. (Eleftheriou *et al.,* 2004)

1.3.3 Species present

The Moray Firth is recognised internationally as an area of natural outstanding beauty and of high biological biodiversity and importance (Wright *et al.,* 1998). Species which can be found in the Moray Firth include fish such as herring (*Clupea harengus*) which as juveniles move into areas of the inner firth to over-winter in substantial quantities (Wilson, 1995). The Moray Firth is also an important site for over-wintering sprats (*Sprattus sprattus*) in the North Sea. Mackerel (*Scombrus sombre*) pass through the Moray Firth whilst on migration during the summer and autumn months, their stratified movement into the firth clearly observed (Reid *et al.,* 1997). This species supports a large portion of the Scottish fishing fleet and is the most economically important species in Scotland (FRS, 2004c). However, the most important and abundant species in the Moray Firth is the sandeel (*Ammodytes marinus*) and is responsible for the large diversity and abundance of seabirds found there (Hislop *et al.,* 1991, Ollason *et al.,* 1997; Wright & Begg 1997; FRS, 2004b). Other species present include the cod (*Gadus morhua*), whiting (*Merlangus merlangius*), haddock (*Melanogrammus aeglefinus*) and the Atlantic salmon (*Salmo salnar*) (Greenstreet *et al.,* 1998; Lusseau *et al.,* 2004).

This high abundance of fish species, primarily the sandeel, supports a large diversity of seabirds. This makes the Moray Firth one of the most important areas for birds in the UK and contains a significant part of Britain's seabird population (Wilson, 1995). Examples of these include the gannet (*Morus bassanus*), kittiwake (*Rissa tridactyla*), guillemot (*Uria aalge*), razor bill (*Alca torda*), puffin (*Fratercula arctica*) and shag (*Phalacrocorax aristotelis*) (Ollason *et al.,* 1997; Wanless *et al.,* 1997; Wright & Begg 1997; Garthe *et al.,* 2003).

Marine mammals such as pinnipeds and cetaceans play an important part of the ecology of the Moray Firth (Wilson, 1995). The firth is visited by and has had recorded sightings of almost all those cetaceans which have been recorded occurring in the waters surrounding the British Isles (see **Table 1.1**). However, the most commonly sighted cetacean species in the Firth include the bottlenose dolphin (*Tursiops truncatus*), harbour porpoise (*Phocoena phocoena*) and the minke whale (*Balaenoptera acutorostrata*) (**Figure 1.8**).

The Moray Firth supports a population of bottlenose dolphins, located at the most northerly part of the species distribution (Wilson, 1995). The species was found to be distributed coastally with the population extending from the inner (Hastie, 2004) and outer (Eisfeld, 2003) parts of the Moray Firth, to the eastern coasts of the UK as far south as Sunderland, Tyne & Wear. Also, high abundances of harbour porpoise have been recorded occurring within the coastal waters of the Moray Firth (Thompson *et al.,* 2004; Whaley, 2004). Finally, reported sightings have been made of minke whales occurring within the Moray Firth. So far no studies have been published on the presence of these animals in this region, nor has any in depth research on the reasons for their distribution in these coastal waters during the summer and autumnal months been conducted.

Table 1.1 Table of cetacean species which have been sighted around the coasts of the British Isles (adapted from Reid *et al.,* 2003).

Common Name	Scientific Name
Mysticetes	
Northern right whale	*Eubalaena glacialis*
Humpback whale	*Megaptera novaeangliae*
Blue whale	*Balaenoptera musculus*
Fin whale	*Balaenoptera physalus*
Sei whale	*Balaenoptera borealis*
Minke whale *	*Balaenoptera acutorostrata*
Odontocetes	
Sperm whale	*Physeter macrocephalus*
Pygmy sperm whale	*Kogia breviceps*
Cuvier's beaked whale	*Ziphius cavirostris*
Northern bottlenose whale	*Hyperoodon ampullatus*
Sowerby’s beaked whale	*Mesoplodon bidens*
Pilot whale	*Globicephala melas*
Killer whale	*Orcinus orca*
False killer whale	*Pseudorca crassidens*
Beluga whale	*Delphinapterus leucas*
Narwhal	*Monodon monoceros*
Risso’s dolphin	*Grampus griseus*
Bottlenose dolphin *	*Tursiops truncatus*
White-beaked dolphin	*Lagenorhynchus albirostris*
White-sided dolphin	*Lagenorhynchus acutus*
Common dolphin	*Delphinus delphis*
Striped dolphin	*Stenella coeruleoalba*
Fraser’s dolphin	*Lagenodelphis hosei*
Harbour porpoise *	*Phocoena phocoena*

* indicates those species most frequently sighted in the Moray Firth, Scotland.

Figure 1.8 Most frequently encountered cetacean species in the Moray Firth, north east Scotland **i)** bottlenose dolphin *Tursiops truncatus* **ii)** harbour porpoise *Phocoena phocoena* **iii)** minke whale *Balaenoptera acutorostrata.*(all photographs courtesy of Kevin Robinson, CRRU)

1.4 Aims of the study

The central aim of this project is to investigate and ascertain if any significant patterns can be seen between the distributions of north Atlantic minke whales (*Balaenoptera acutorostrata acutorostrata*) and the surrounding environmental factors which are present in the southern outer Moray Firth. The present study intends to use a range of techniques and methods to determine which different environmental variables may affect a species spatio-temporal distribution, using an integrated multi-discipline (behavioural observation, GIS and remote sensing) approach. It is also hoped that the methods used in the study can show how the application of a multi-discipline approach can provide useful information for the future construction of spatio-temporal models used in the prediction of the distribution of cetacean species. Application of the method as an aid to conservationists and policy makers, with regards to the conservation and management of the minke whale, and the establishment of more effective marine protected areas will be discussed with the use of case studies and contemporary research.

Summary of aims:

1. To investigate and describe the presence of significant patterns and correlations between the distribution / behavioural ecology of minke whales in the Moray Firth and the following environmental variables;

   a) Bathymetry (*depth, slope* and *aspect*)

   b) Sediment type

   c) Water temperature (*sea surface temperature*)

   d) Primary productivity (*chlorophyll-a concentration*)

2. Discuss the advantages of this multi-discipline method in relation to uses in ecological modelling. The formation of new marine protected areas for the conservation and management of this and other marine mammal species will also be discussed.

2. Methods

2 Methods

2.1 Survey Methods

All data used in the present study was collected during the months of May to September 2000 – 2004, from a 880 km^2 area within the southern outer Moray Firth, north east Scotland (**Figure 2.1**). The area was divided into four routes, each approximately 45 minutes apart in latitude. These included three dedicated minke whale routes (inner, middle and outer) and a route dedicated for bottlenose dolphin surveys (BND). These were divided into a further four sub routes. This allowed surveys to be carried out from the centrally located point of Whitehills in either an easterly or westerly direction. Surveys consisted of travelling between a number of way points.

All surveys were conducted using one of the Cetacean Research & Rescue Units (CRRU) two fully equipped *Avon Searider* ridged inflatable boats (RIB) (**Figure 2.2**). Each vessel was propelled by a 90 horse power two stroke outboard engine and fitted with Lowrance GPS unit with sonar and thermistor probe. Surveys were conducted at a speed of 10-18 km per hour with a crew of between 3 to 7 observers. Surveys were also carried out at sea states of 3 or less in good light conditions. If the sea state increased beyond 3 or the weather deteriorated the survey was either halted temporarily until conditions improved or was terminated. To assist observations a pair of Compass 7 x 50 122mm waterproof binoculars were used whilst on surveys.

Cues used to locate minke whales whilst surveying included the presence of bird feeding rafts, often a sign of the presence of marine mammals, or direct observation of animals from their long dark backs and falcate dorsal fins when surfacing (**Figure 2.3**). When animals were sighted, the speed of the vessel was reduced and the direction maintained in an attempt to make the movements of the boat as predictable as possible. The boat was never directly driven towards animals but once in the vicinity of a whale the engine was reduced to an idle speed or shut down to minimise any disturbance whilst a number of recordings could be made. In addition to the time and GPS position of the animals encountered, notes on their age, gender (where possible) and behaviour of the subject were recorded (see **Table 2.1**). Other information was recorded including the presence or absence of

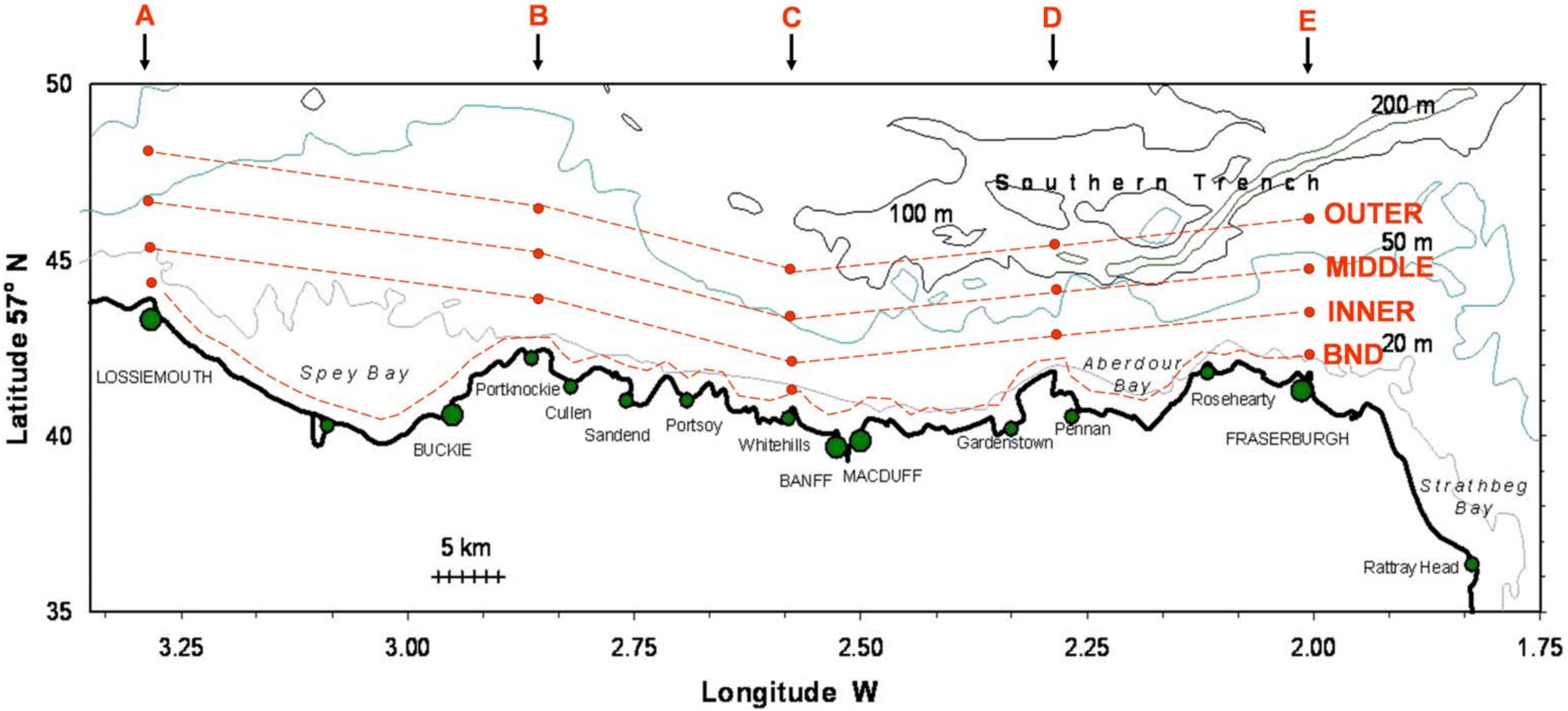


Figure 2.1 Map of line transect route types used to survey the study area. These included dedicated minke whale routes (**INNER**, **MIDDLE** and **OUTER**) and an additional innermost route typically used during bottlenose dolphin survey work (**BND**). The division of each route into four sub routes is indicated by the five waypoints labelled (from east to west) **A**, **B**, **C**, **D** and **E**.

Figure 2.2 One of CRRU's *Avon Searider* RIBs used for surveys in the present study. (Photograph courtesy of Kevin Robinson, CRRU)

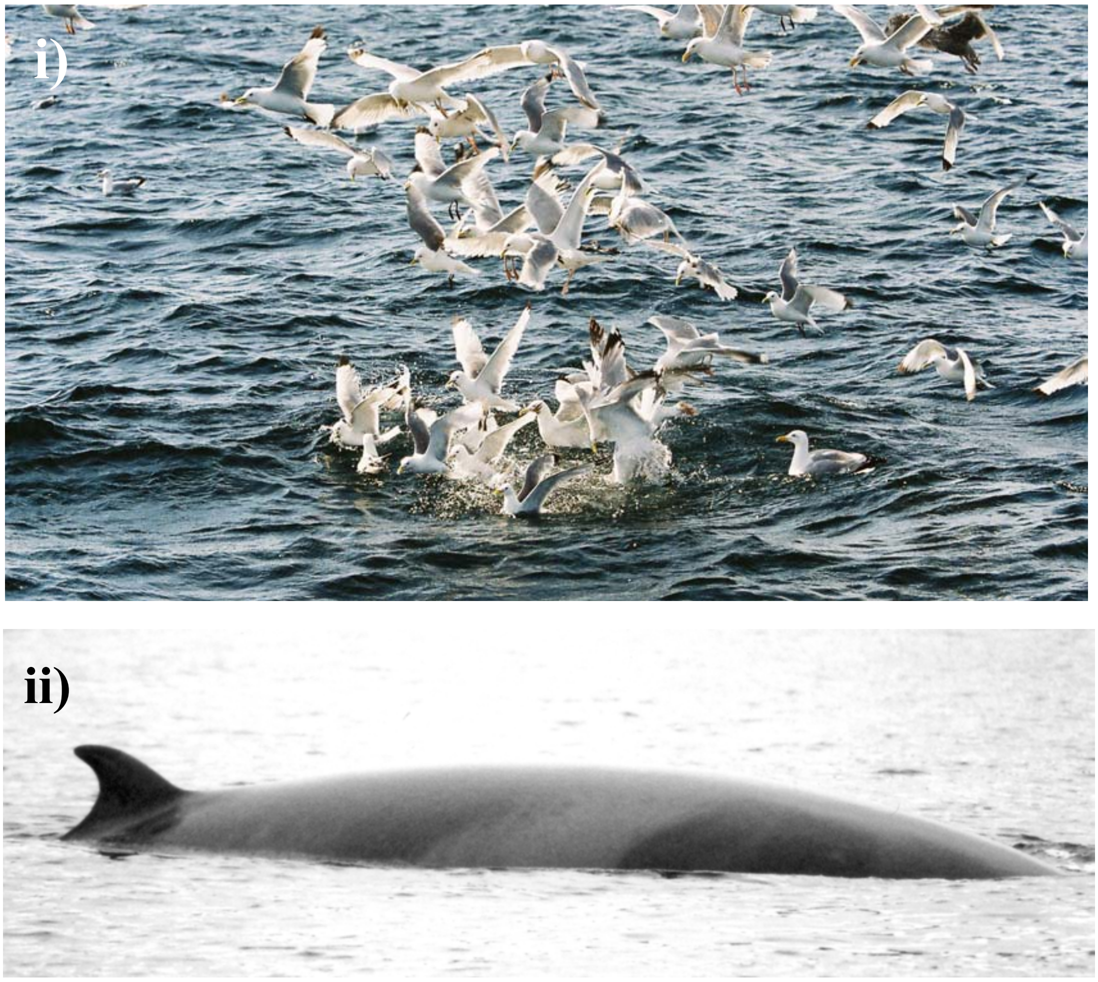


Figure 2.3 **i)** The activity of feeding seabirds, indicating presence of minke whale prey **ii)** Minke whale observed during surfacing. (Photographs courtesy of Kevin Robinson, CRRU)

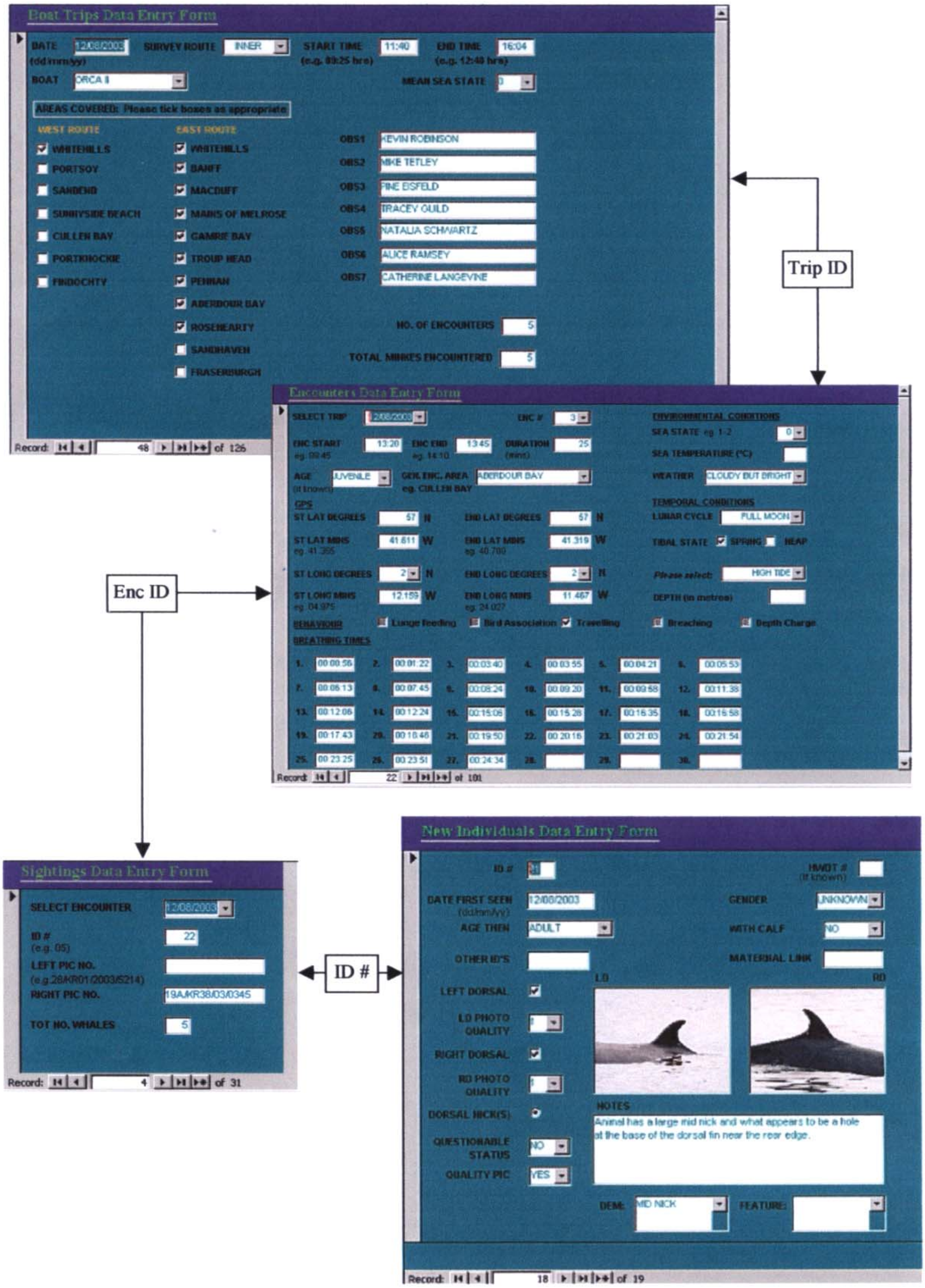
Table 2.1 Definitions used to determine the age class (adults & juveniles) and behavioural activity (travelling & foraging) of minke whales recorded during encounters.

Category	Definition
Age:	
Adults	Dark colouration, tall falcate fins, many dorsal edge marks
Juveniles	Light colouration, small triangular fins, few dorsal edge marks
Behaviour:	
Travelling	Travelling in straight direction with little alteration in course
Foraging	Either observed circling an area or directly feeding

associated bird species and bird feeding activity. In addition environmental data was collected such as the depth, water temperature, weather conditions and sea state. Where possible the whales' surfacing intervals were also recorded using a digital stopwatch.

Whilst on surveys and during encounters with animals all information was recorded onto A4 laminated survey logs using water resistant chinagraph pencils. On completion of each survey trip, back on the shore, all the recorded information was transcribed to a generic hard copy form. Examples of the forms used during surveys and on shore can be found in **Appendices A, B, C & D**.

Survey and encounter information was subsequently entered into an inter-relational database created in Microsoft Access. This could be used to allow the extraction of information required from simultaneous files using the databases "Queries" mode. Please see **Figure 2.4** for an example of the database design.



Boat Trips Data Entry Form

DATE (dd/mm/yy): 12/08/2003
SURVEY ROUTE: INNER
START TIME (e.g. 09:25 hrs): 11:40
END TIME (e.g. 12:48 hrs): 16:04
BOAT: ORCA II
MEAN SEA STATE: 0

AREAS COVERED: Please tick boxes as appropriate

WEST ROUTE
☑ WHITEHILLS
☐ PORTSOY
☐ SANDEND
☐ SUNNYSIDE BEACH
☐ CULLEN BAY
☐ PORTKNOCKIE
☐ FINDOCHTY

EAST ROUTE
☑ WHITEHILLS
☑ BANFF
☑ MACDUFF
☑ MAINS OF MELROSE
☑ GAMRIE BAY
☑ TROUP HEAD
☑ PENNAN
☑ ABERDOUR BAY
☑ ROSEHEARTY
☐ SANDHAVEN
☐ FRASERBURGH

OBS1: KEVIN ROBINSON
OBS2: MIKE TETLEY
OBS3: FINE EISFELD
OBS4: TRACEY GUILD
OBS5: NATALIA SCHWARTZ
OBS6: ALICE RAMSEY
OBS7: CATHERINE LANGEVINE

NO. OF ENCOUNTERS: 5
TOTAL MINKES ENCOUNTERED: 5

Record: 48 of 126

Encounters Data Entry Form

SELECT TRIP: 12/08/2003
ENC #: 3
ENC START (eg. 09:45): 13:20
ENC END (eg. 14:10): 13:45
DURATION (mins): 25
AGE (if known): JUVENILE
GEN. ENC. AREA (eg. CULLEN BAY): ABERDOUR BAY

GPS
ST LAT DEGREES: 57 N
END LAT DEGREES: 57 N
ST LAT MINS (eg. 41.395): 41.611 W
END LAT MINS (eg. 40.700): 41.319 W
ST LONG DEGREES: 2 N
END LONG DEGREES: 2 N
ST LONG MINS (eg. 04.975): 12.159 W
END LONG MINS (eg. 24.027): 11.467 W

ENVIRONMENTAL CONDITIONS
SEA STATE eg. 1-2: 0
SEA TEMPERATURE (°C):
WEATHER: CLOUDY BUT BRIGHT

TEMPORAL CONDITIONS
LUNAR CYCLE: FULL MOON
TIDAL STATE: ☑ SPRING ☐ NEAP
Please select: HIGH TIDE
DEPTH (in metres):

BEHAVIOUR: ☐ Lunge feeding ☐ Bird Association ☑ Travelling ☐ Breaching ☐ Depth Charge

BREATHING TIMES
1. 00:00:56 2. 00:01:22 3. 00:03:40 4. 00:03:55 5. 00:04:21 6. 00:05:53
7. 00:06:13 8. 00:07:45 9. 00:08:24 10. 00:09:20 11. 00:09:58 12. 00:11:38
13. 00:12:06 14. 00:12:24 15. 00:15:06 16. 00:15:28 17. 00:16:35 18. 00:16:58
19. 00:17:43 20. 00:18:46 21. 00:19:50 22. 00:20:16 23. 00:21:03 24. 00:21:54
25. 00:23:25 26. 00:23:51 27. 00:24:34 28. 29. 30.

Record: 22 of 101

Sightings Data Entry Form

SELECT ENCOUNTER: 12/08/2003
ID # (e.g. 05): 22
LEFT PIC NO. (e.g.28/KR01/2003/5214):
RIGHT PIC NO.: 19A/KR38/03/0345
TOT NO. WHALES: 5

Record: 4 of 31

New Individuals Data Entry Form

ID #: 21
HWDT # (if known):
DATE FIRST SEEN (dd/mm/yy): 12/08/2003
GENDER: UNKNOWN
AGE THEN: ADULT
WITH CALF: NO
OTHER ID'S:
MATERIAL LINK:
LEFT DORSAL: ☑
LD PHOTO QUALITY: 1
RIGHT DORSAL: ☑
RD PHOTO QUALITY: 1
DORSAL NICK(S): ●
QUESTIONABLE STATUS: NO
QUALITY PIC: YES
LD
RD
NOTES: Animal has a large mid nick and what appears to be a hole at the base of the dorsal fin near the rear edge.
DEM: MID NICK
FEATURE:

Record: 18 of 19

Figure 2.4 Schematic diagram depicting the data entry forms from the CRRU's minke whale database created in Microsoft Access (designed by Robinson & Benda). Each of the boxes below shows the fields for the "Trips", "Encounters", "Sightings" and "Individuals" tables respectively. The information entered into each table is interrelated by a number of common fields or identities (indicated by arrows) that allow the extraction of information required from simultaneous files using the databases "Queries" mode.

2.2 Geographical information system (GIS)

Information concerning the physical environment (fixed variables) was obtained to compare with minke whale distributions as well as to be able to generate additional environmental data. A geographical information system or GIS was used to process each parameter used and described in the following sections.

2.2.1 *Bathymetry*

Data for the depth of the research area was obtained using Admiralty charts of the Moray Firth, from which depth contours were digitised using a digitising tablet. Subsequently, the study area (11 x 80 km^2) was divided into 1 km blocks, and data for minimum, maximum and mean depth determined. This information was then saved into a Dbase* IV file and imported into a GIS.

The program ArcView 3.3 was used to create and manipulate the GIS so that depth data could be converted from an event theme to a grid theme and finally converted to a Mercator map projection. A land mask was applied to show the position of the coastline, extending from Lossiemouth to Fraserburgh.

The slope or gradient between different adjacent cells in the map projection was generated directly from the depth data using a slope modelling function available in ArcView 3.3.

Finally the aspect (i.e. direction of the determined slopes) between adjacent grid cells within the survey area face (North & Southwest) was generated directly from the slope data using the aspect modelling function within ArcView 3.3.

2.2.2 *Sediment type*

The distribution of sediment type within the study area was obtained from British Geological Survey maps of the Moray Firth. Once again, the maps were divided into 1 km^2 blocks and the respective sediment type was determined for each block. The information was then entered into a Dbase* IV file and imported into ArcView 3.3 and converted to a Mercator map projection.

Please see **Figure 2.5** for a flow chart of the GIS process used in the study.

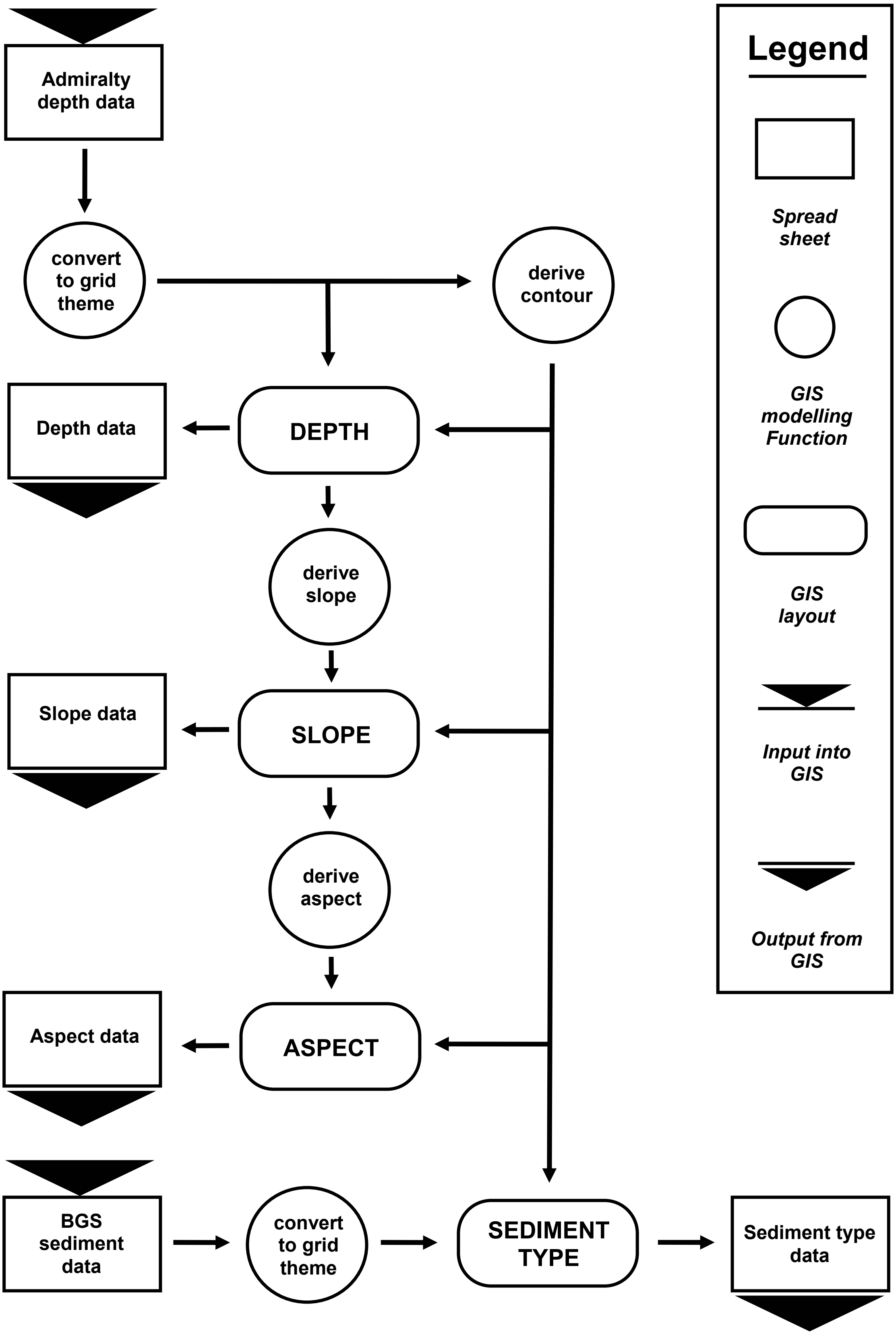


Figure 2.5 Flow diagram illustrating the process by which the environmental data set was derived from Admiralty and British Geological Survey charts using GIS and spatial modelling functions available with ArcView 3.3 and the grid and spatial analyst extension packages.

2.3 Remote Sensing

The sea surface temperature and chlorophyll-a concentration were obtained using the AVHRR and SeaWiFS satellite sensors respectively for application to the data set used in the present study. The use of imagery is outlined below.

2.3.1 AVHRR

Sea surface temperatures (SST) used in the study were determined from NOAA advanced very high resolution radiometer or AVHRR satellite imagery. Images were downloaded from the Remote Sensing Data Analysis Service (RSDAS) website for the months of May through to September from 2001 to 2004 inclusive. The AVHRR data had an image resolution of 1.1 km^2 and were converted to a Mercator map projection using standardised scales for SST.

Due to the nature of the sensor, however, no information could be obtained through cloud cover. As such, only a small fraction of this time period available for each month could be used for AVHRR imagery and so composite images for each month were created thus avoiding the problems of low statistical power due to small samples sizes as experienced by Macleod (2003) and Wakefield (2001). The images were geometrically corrected and their colour attributes altered subsequently to allow accurate representation of SST, using the program ERDAS Imagine.

The images obtained from RSDAS were subsetted to provide two smaller scales of coverage as shown in **Figure 2.6**. The first encompassing the whole Moray Firth, the second detailing the area covered by surveys in the present study.

The composite images for each period were used to determine the corresponding SST for each minke whale encounter using the following formulas:

X position of whale

$$X = (cols - 1) \times \left[\frac{(lon - \min lon)}{(\max lon - \min lon)} \right]$$

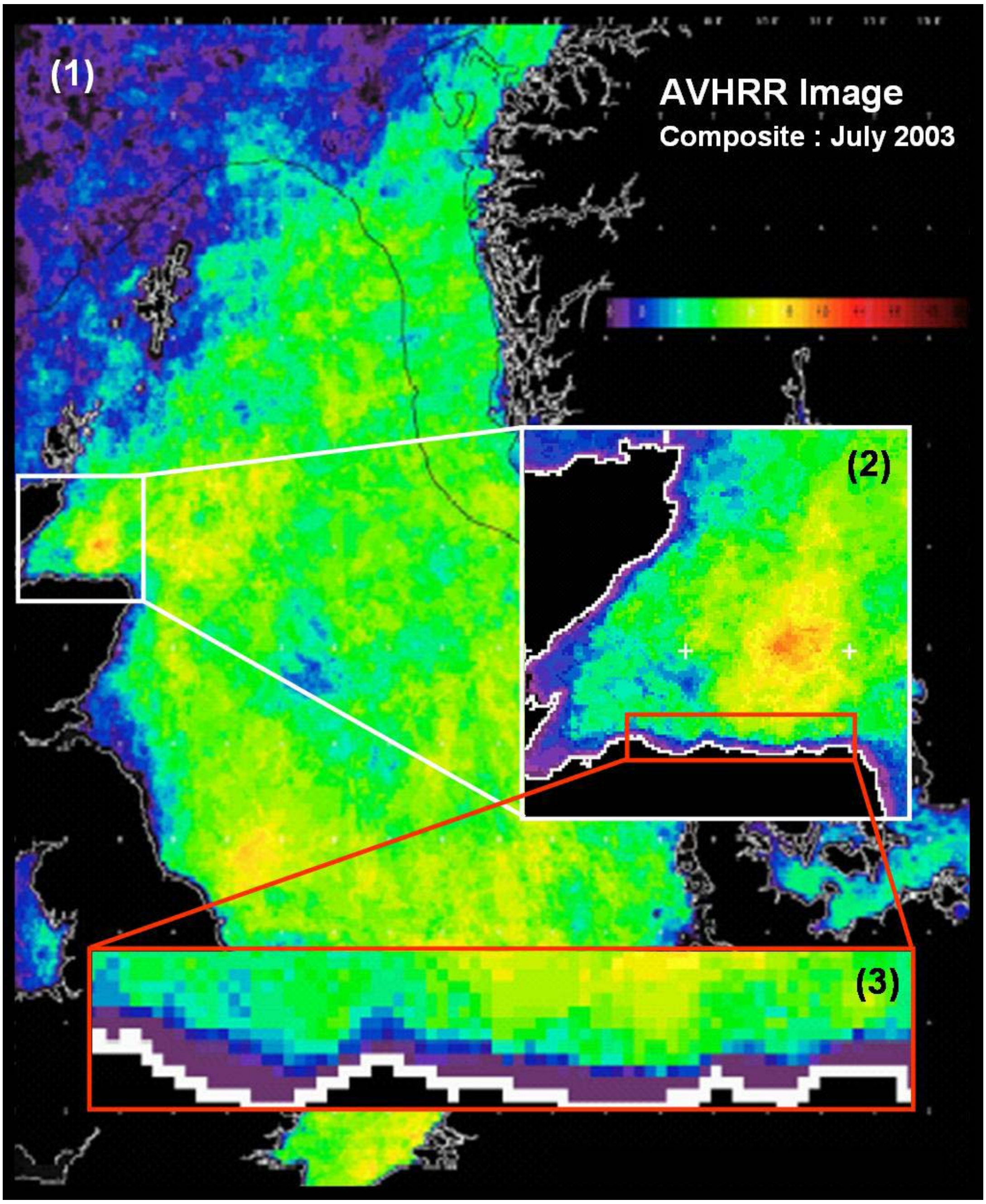


Figure 2.6 AVHRR composite image for SST showing the subsetting applied to the present data set. This example image shows a composite image processed for the month July 2003. Images were processed at three scales of coverage. These include all the area provided by RSDAS [***North Sea***] (**1**), all of the Moray Firth area [***Moray Firth***] (**2**) and the area in which surveys were conducted [***survey area***] (**3**).

Y position of whale

$$Y = (rows - 1) \times \left[1.0 - \left(\frac{(Y\,\text{int} - Y\,\text{min})}{(Y\,\text{max} - Y\,\text{min})} \right) \right]$$

$$Y\,\text{int} = \ln(\tan(DEGtoRAD \times (45.0 + (lat/2.0))))$$

$$Y\,\text{min} = \ln(\tan(DEGtoRAD \times (45.0 + (\text{min}\,lat/2.0))))$$

$$Y\,\text{max} = \ln(\tan(DEGtoRAD \times (45.0 + (\text{max}\,lat/2.0))))$$

Where

rows	=	number of rows in image
cols	=	number of columns in image
min *lon* / max *lon*	=	minimum / maximum longitude of image (in decimal degress)
min *lat* / max *lat*	=	minimum / maximum latitude of image (in decimal degress)
DEGtoRAD	=	conversion from degrees to radians (PI/180.0)
ln	=	natural log

The SST values (in °C) for each encounter were then obtained using the following formula provided by RSDAS:

$$SST = DN \times (0.1 - 0.3)$$

Where

DN = Digital number or the value of each pixel

The composite images were also used in visual analysis to ascertain if the presence of oceanographic feature such as fronts and upwellings had an effect on the distribution and frequency of minke whale sightings.

2.3.2 SeaWiFS

Concentrations of chlorophyll-a ($\mu g1^{-1}$) throughout the study area were determined using NASA satellite imagery from the Sea-viewing Wide Field-of-view ocean colour sensor or SeaWiFS. Once again images with a resolution of $1.1km^2$ were downloaded from the RSDAS website for the months of May through to September from 2001 to 2004.

To overcome the problem associated with cloud masking as before, composite images were created for each month surveyed. These images too were geometrically rectified and had the colour attributes altered to allow an accurate representation of chlorophyll-a concentration using the program ERDAS Imagine.

The monthly composites were subsequently used to determine the corresponding chlorophyll-a concentration for each minke whale encounter.

The values of chlorophyll at each position were obtained using the following formula provided by RSDAS:

$$CHL = 10\hat{}\,[DN \times (0.015 - 2.0)]$$

Where

CHL = Chlorophyll-a ($\mu g1^{-1}$)
DN = Digital number or the value of each pixel

Once again, the composite images were used to ascertain visually if the presence of areas with higher primary productivity (chlorophyll-a) had an effect on the distribution and frequency of whale sightings.

Ground truthing and corrections for chlorophyll-a concentration were carried out by sampling methods. Between May and September 2004 a total of forty 1 litre samples were taken from an array of set sampling sites. The sample bottles were simply placed below the surface of the water column to fill and then sealed. These samples related to specific days and times associated with corresponding SeaWiFS images. The samples were then returned to the laboratory and filtered using Whatmann 47mm glass micro fibre filter paper and a Millipore 100 Kilo Pascal vacuum pump. The resulting filtrate was then stored in darkness in a freezer compartment.

The subsequent analysis was carried out thanks to the support of the chlorophyll laboratory at the Fisheries Research Services, Aberdeen. Chlorophyll was extracted from the filtered samples in a fume cupboard. Filter paper was placed in a homogeniser tube and packed down using a glass rod. For the 10/15ml extract approximately 5/10ml of 90% acetone was added to the tube, while another 5ml was measured to clean the centrifuge tube. The samples were then ground for less than 1 minute and the resulting acetone/filter paper solution was poured into a centrifuge tube. The volume of the extract was noted prior to spinning the samples in a 1EC centrifuge at a speed of 1500 rpm for just 1 minute. The samples were then removed and inverted to mix the contents before spinning again at 3000 rpm for a further 10 minutes. The final measurements of chlorophyll-a concentration were made using a 10 AU fluorometer.

2.4 Statistical analysis

A number of statistical tests were applied to the data to determine the presence of any significant differences, trends and correlations. These included Kolmogorov-Smirnov tests for normality, t-tests for use in analysis of variance and Pearson’s statistic for the detection of correlations.

All statistical tests were conducted using the statistical package MiniTab 13.30.

3. Results

3 Results

For a summary table of all the data used during this project see **Appendix E**.

3.1 Survey Effort

The survey effort of the study is shown in **Table 3.1**. Survey effort was broken down to show effort for the four ways in which minke whales were encountered. These include the three minke whale survey routes (Inner, Middle & Outer) and the times when animals were encountered on other routes and at times off surveys (Opportunistic). Survey effort was expressed in minutes. The results show that the survey effort was variable over the study period. The highest amount of survey effort was concentrated along the inner survey route, the effort decreasing rapidly with increasing distance from shore, i.e. inner and outer survey routes. Also, across the five year study period, survey effort was lowest in 2000 and 2001 compared with the effort for 2002 onwards. Effort decreases steadily between 2002 and 2004. This is shown in **Figure 3.1**.

Table 3.1 Survey effort by route type for the years 2000 to 2004. These include the three minke whale survey routes (inner, middle & outer) and those times when animals were encountered on other routes and at times off surveys (opportunistic).

Year	Survey effort by route type (minutes)				
	INNER	MIDDLE	OUTER	OPPORTUNISTIC	All Types
2000	165	145	0	0	310
2001	340	705	0	98	1143
2002	4555	1990	1338	134	8017
2003	2412	1127	859	181	4579
2004	1148	770	618	0	2536
Total	8620	4737	1477	413	15247

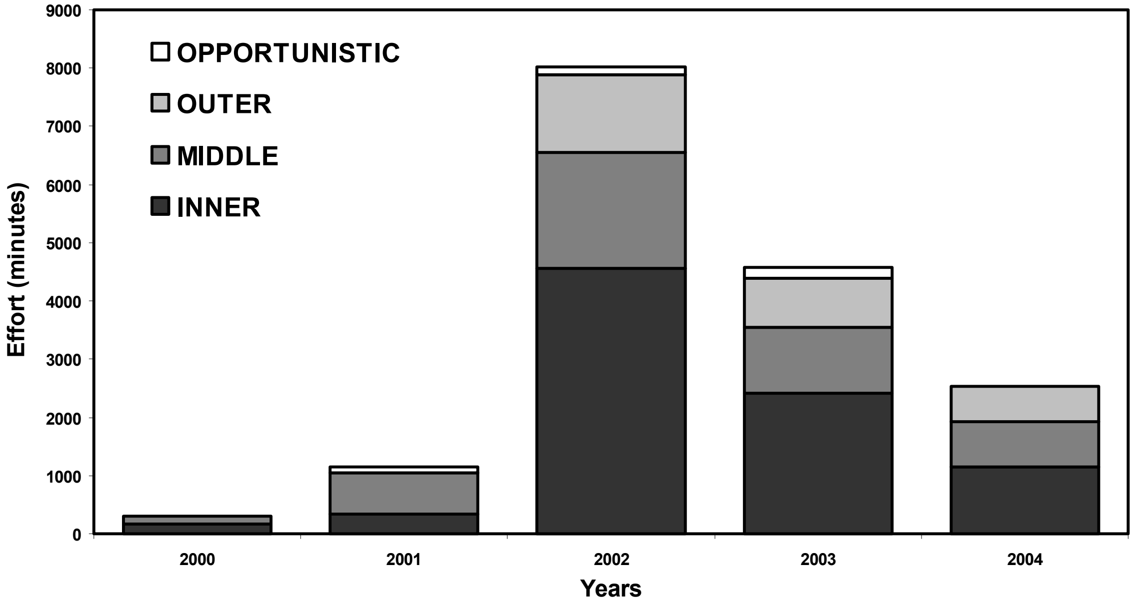


Figure 3.1 Stacked column bar chart of survey effort in minutes, for the ways in which minke whales were encountered, during the years 2000 - 2004. These include the three minke whale survey routes (Inner, Middle & Outer) and those times when animals were encountered on other routes and at times off surveys (Opportunistic).

3.2 Distribution of encounters

The number of minke whales encountered during the study can be seen in **Table 3.2**. Results show that whales were encountered within the survey area in the years 2000 to 2003. No minke whales were encountered in 2004. Results also show that the number of encounters was variable between the different years and months of the study.

Table 3.2 Number of minke whale encountered during the study for the months May to September between 2000 and 2004.

Year	Encounters by month				
	May	June	July	August	September
2000	0	0	0	0	4
2001	0	1	7	7	2
2002	0	0	0	9	36
2003	0	1	28	12	14
2004	0	0	0	0	0

In 2000 and 2002 the highest sightings frequency of minke whale encounters occurred in September. In 2001 most minke whales were seen in the months of July and August. In the year 2003 minke whale encounters were highest during the month of July whilst encounters halved during August and September. Encounter frequency slowly increased during the years 2001 to 2003. No minke whales were encountered in May during the entire study. This is shown in **Figure 3.2**.

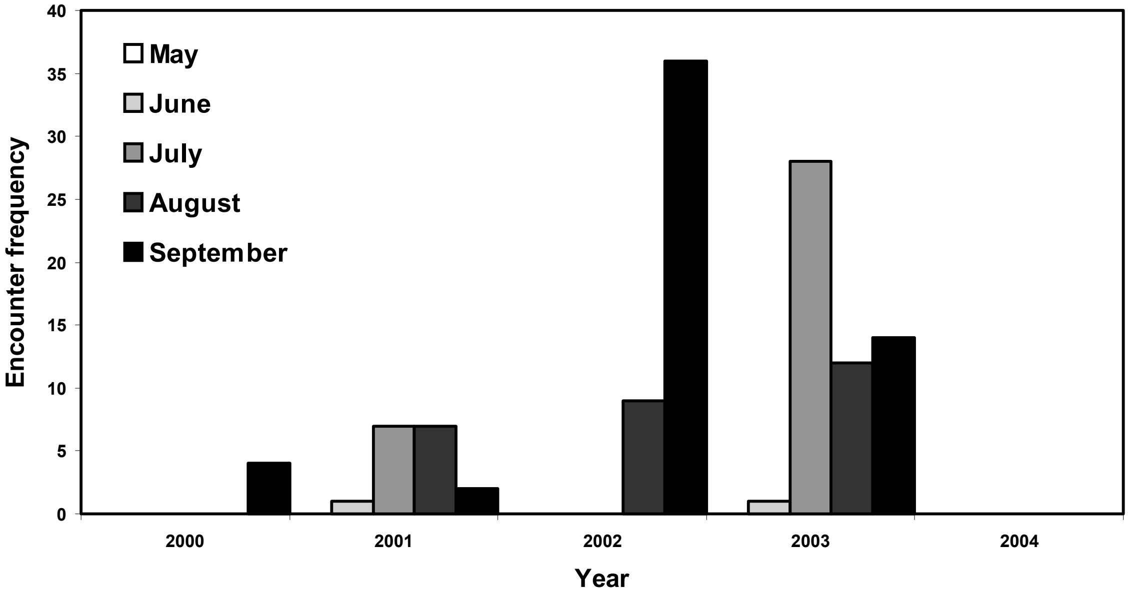


Figure 3.2 Frequency histogram of minke whale encounter frequency during the months May to September between 2000-2004.

The distribution of minke whales between Lossiemouth and Fraserburgh is shown in **Figure 3.3**. The majority of minke whales were encountered close to the coast with encounter frequency decreasing with distance from the shore. Two areas in particular seemed to have high numbers of minke whale encounters. The first was a strip of the coastline lying between Portknockie and Whitehills. The other area of high encounter frequency was found in Aberdour Bay, located between Gardenstown and Rosehearty. No minke whales were encountered in the area west of Portknockie, a large and shallow embayment named Spey Bay. The frequency of minke whale encounters, divided up to compare distribution between different years, can be found in **Figure 3.4**. The location of these areas can be found in **Figure 2.1** located in the previous Methods section.

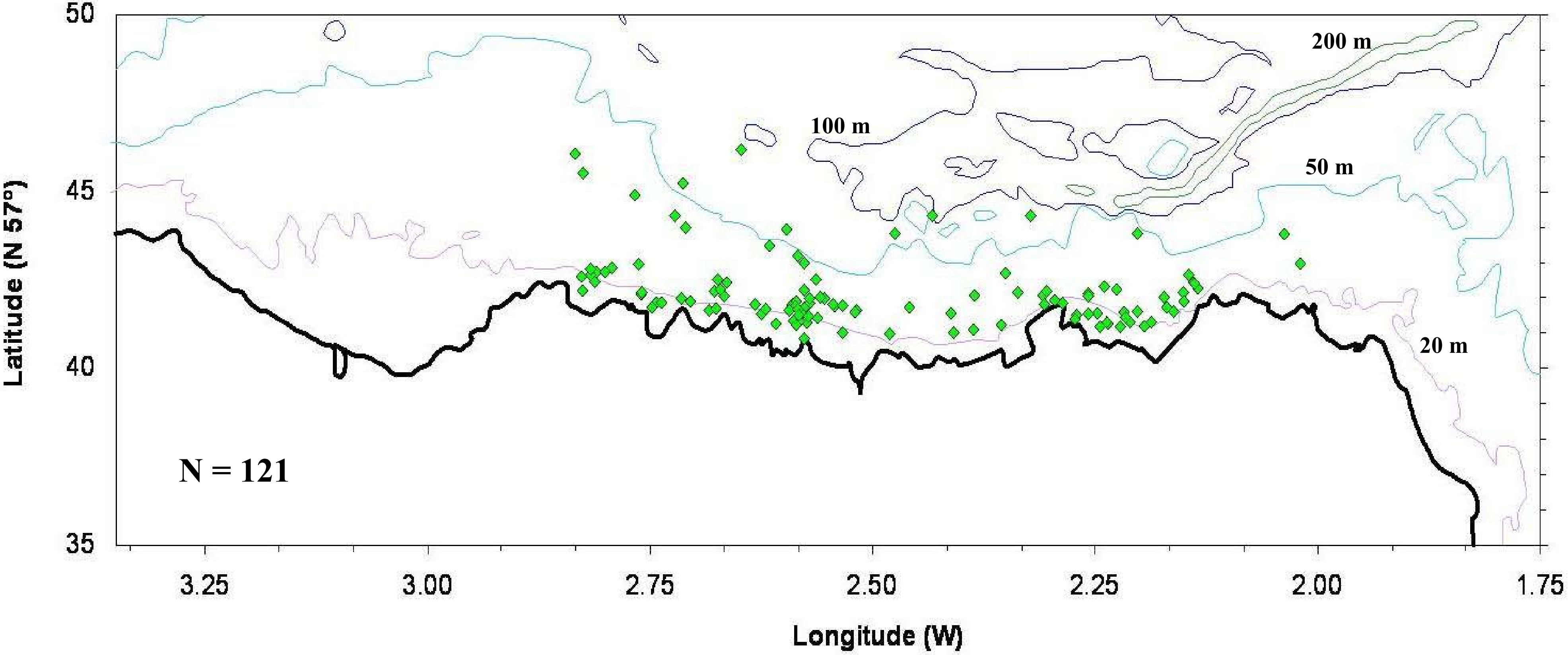


Figure 3.3 Map showing the distribution of minke whales along the southern outer Moray Firth recorded between 2000 and 2003. No minke whales were encountered during 2004. 121 minke whales were encountered. Depth contours for 20, 50, 100 and 200 metres are shown.

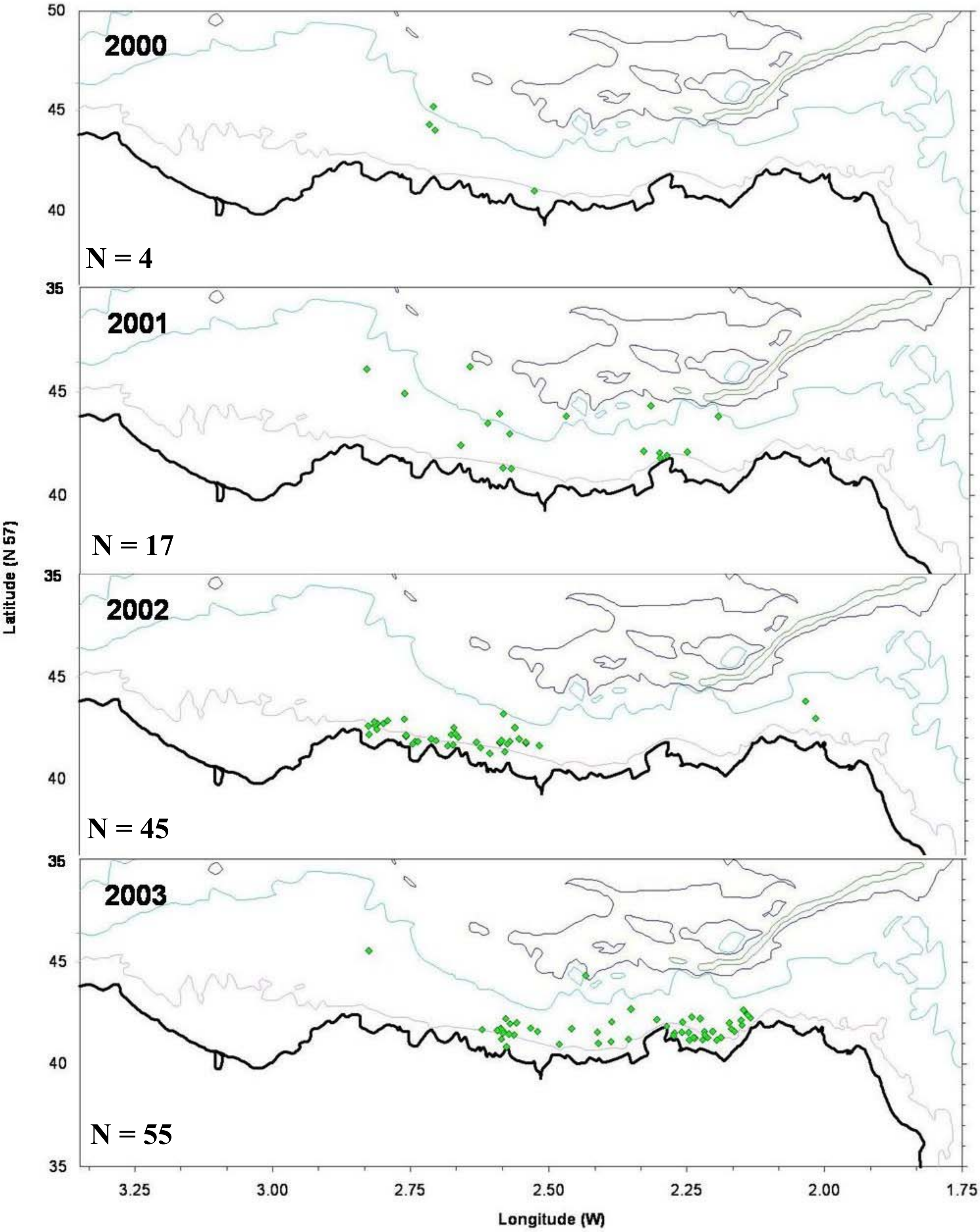


Figure 3.4 Maps showing the annual occurrence of minke whales along the southern outer Moray Firth recorded between 2000 and 2003. Note: 2004 not shown as no whales were encountered during this year. Number of encounters are shown for each year. Depth contours for 20, 50, 100 and 200 metres are shown.

Distribution maps showed that minke whale distribution during 2000 – 2003 was highly variable. Many changes in the distribution of whales were observed along the coastline as well as with increasing distance from the shore. During the years 2000 and 2001 the number of minke whale encounters was low and those individuals which were encountered were distributed further offshore, in proximity to the 50 metre depth contour line. In the years 2002 to 2003 minke whale encounter frequency was higher than in the previous two years and distributed more coastally, distribution occurring around the 20 metre depth line.

A noticeable shift in distribution of minke whale encounters occurs between the years 2002 and 2003. In 2002 animals were primarily located on the strip of the coastline lying between the towns of Portknockie and Whitehills. This changed in 2003 with encounters occurring in two main patches. These two areas were off Whitehills and the area of Aberdour Bay. A few encounters occurred between these two areas on the stretch of coastline incorporating Banff, Macduff and Gardenstown. Therefore, it was observed that though the majority of sightings occurred along a certain depth, changes in minke whale distribution occurred within those depths.

3.3 GIS

GIS layouts for minke whale density and the environmental variables associated with bathymetry (depth, slope & aspect) and sediment type can be found in **Figure 3.5**. The GIS layout for minke whale density showed that the areas which were most frequently visited by minke whales were the areas off Cullen Bay, Whitehills and Aberdour Bay. Through the use of GIS it was possible to say that all these areas which harbour the highest densities of minke whale distribution were characterised by very similar categories of environmental variables associated with bathymetry. All three areas were defined as having shallow depths, high slope values and northerly facing slopes. Also, the areas of Cullen Bay, Whitehills and Aberdour Bay were all associated with sandy gravel sediment types.

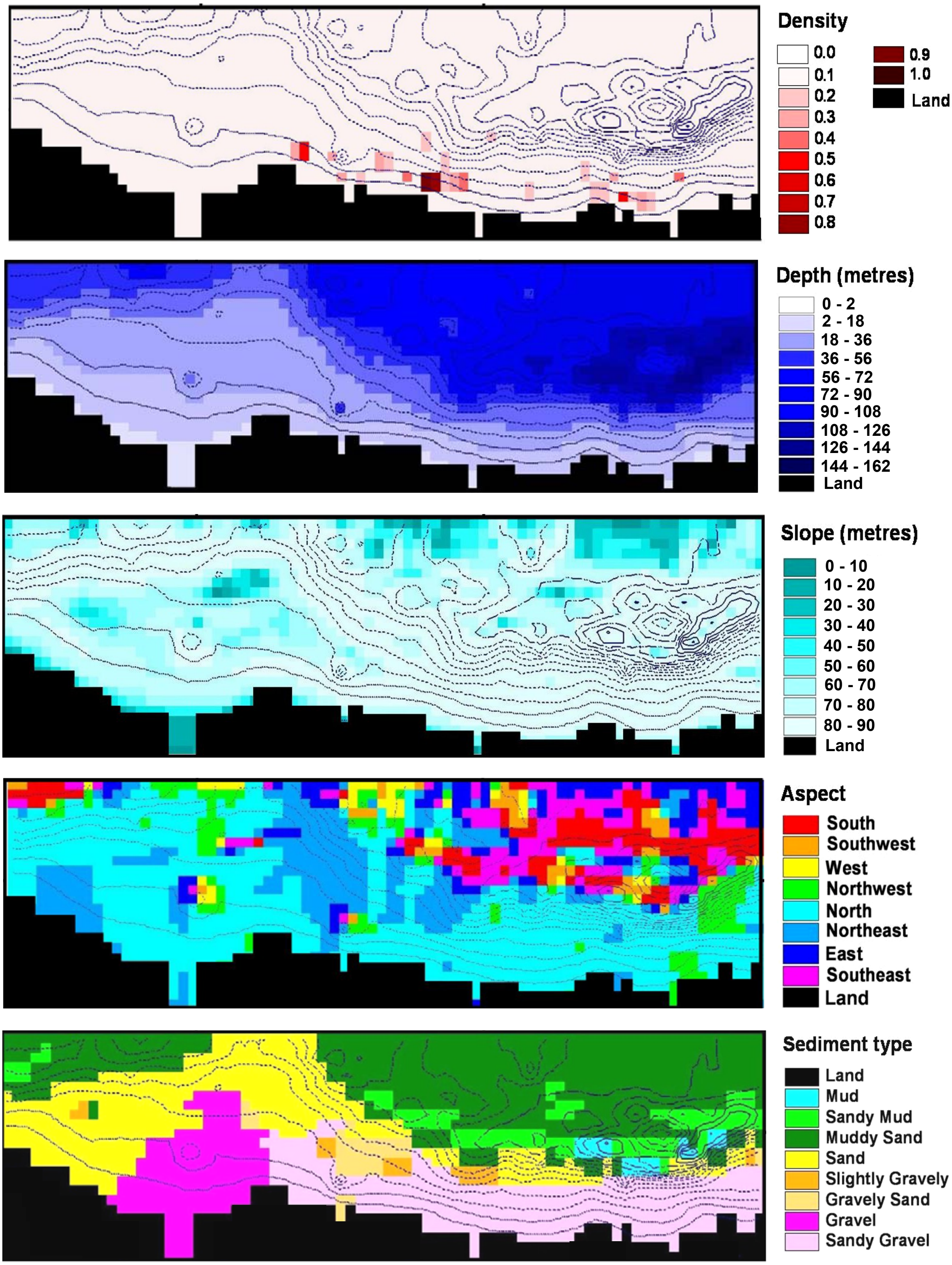


Figure 3.5 GIS layouts of minke whale density and environmental variables associated with bathymetry (depth, slope & aspect) and sediment type. Coast line extends from Lossiemouth to Fraserburgh. Contours for depth are shown. (created using ArcView 3.3)

3.4 Remote sensing

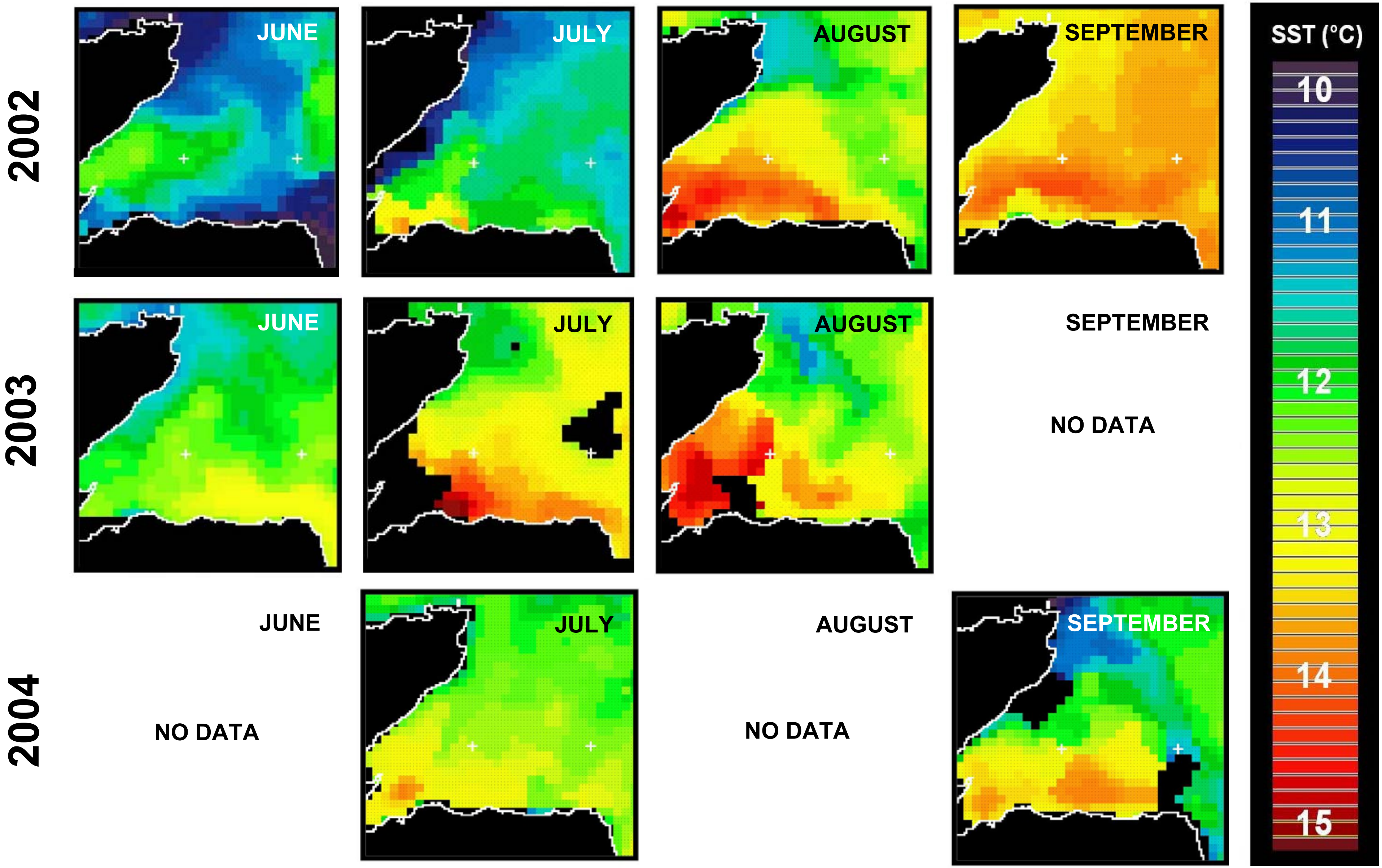
3.4.1 *Sea surface temperature*

The dynamic changes and variability in SST within the Moray Firth can be seen in **Figure 3.6**. Images show that SST within the Moray Firth is highly variable both spatially and temporally. Composites show that SST increases between June and September in all years of the study. Also, sea surface temperatures are higher in the inner firth than the outer part of the embayment and the North Sea. Minke whales were seen in the outer southern part of the Moray Firth during the months with warmer SST. Minke whales were not observed until August in 2002 whilst in 2003 animals were encountered in June. The months of highest minke whale encounter frequency during the study occurred in those months of highest sea surface temperatures, e.g. September 2002 and July 2003. No minke whales were encountered during 2004.

In the composite images two oceanographic features can be seen. These include a current of colder water running across the mouth of the Moray Firth which can be seen clearest in June 2002 and September 2004. Secondly, a plume of warmer water can be seen extending out of the inner part of the Moray Firth into the outer embayment and wider North Sea. This feature can be seen clearest in September 2002. Minke whale sightings frequency was observed to be higher during periods when the warm water plume was more evident in composites and smaller during those months when the cold water current is more clearly visible.

Figure 3.6 AVHRR monthly composite images showing the sea surface temperatures (SST °C) for the Moray Firth in June, July, August and September during 2002 to 2004. No data was available for the months of September 2003, June & August 2004. (created using ERDAS Imagine).

See over page for **Figure 3.6**


2002
JUNE
JULY
AUGUST
SEPTEMBER
2003
JUNE
JULY
AUGUST
SEPTEMBER
NO DATA
2004
JUNE
NO DATA
JULY
AUGUST
NO DATA
SEPTEMBER
SST (°C)
10
11
12
13
14
15

3.4.2 Chlorophyll-a concentration

Composite images of the changes in chlorophyll-a concentration across the study area between 2002 and 2004 can be found in **Figure 3.7**. Images show that chlorophyll-a concentration was highly variable both in time and across the survey area. It was observed that concentrations of chlorophyll-a increase between June and September. Also, it was observed that chlorophyll-a concentration decreases with distance from the shore, i.e. with increasing depth. The extent to which the higher chlorophyll-a concentrations extend out from the shore increases between June and September. Minke whale encounter frequency was highest in both those areas and times when concentrations of chlorophyll-a were also high. Minke whale encounter frequencies decreased with distance from the shore with decreasing chlorophyll-a levels. No minke whales were observed during 2004.

In 2002 animal encounter frequencies were highest during the month of September whilst in 2003 more minke whale encounters occurred in July. Also, a shift in the distribution of animals is visible between 2002 and 2003. In 2002 minke whale encounters occurred to the west within the area between Portknockie and Whitehills. However, in 2003 encounters occurred more often to the east between Whitehills and Rosehearty. During 2003 chlorophyll-a concentrations were on average much lower within the area between Portknockie and Whitehills than in the previous year. To the east of Whitehills to Rosehearty, concentrations of chlorophyll-a were much higher than to the west to Portknockie.

During 2003 a shift is observed in the distribution of minke whale encounters between July and August. In July minke whale encounters were highest in the area off Whitehills. In August the frequency of minke whale encounters move further east into the waters of Aberdour Bay. Also, it was observed that in July concentrations of chlorophyll-a were highest in the area between Whitehills and MacDuff. Then during August, a change is observed with higher relative concentrations of chlorophyll-a being found further east in the region of Aberdour Bay, particulary off Rosehearty.

A

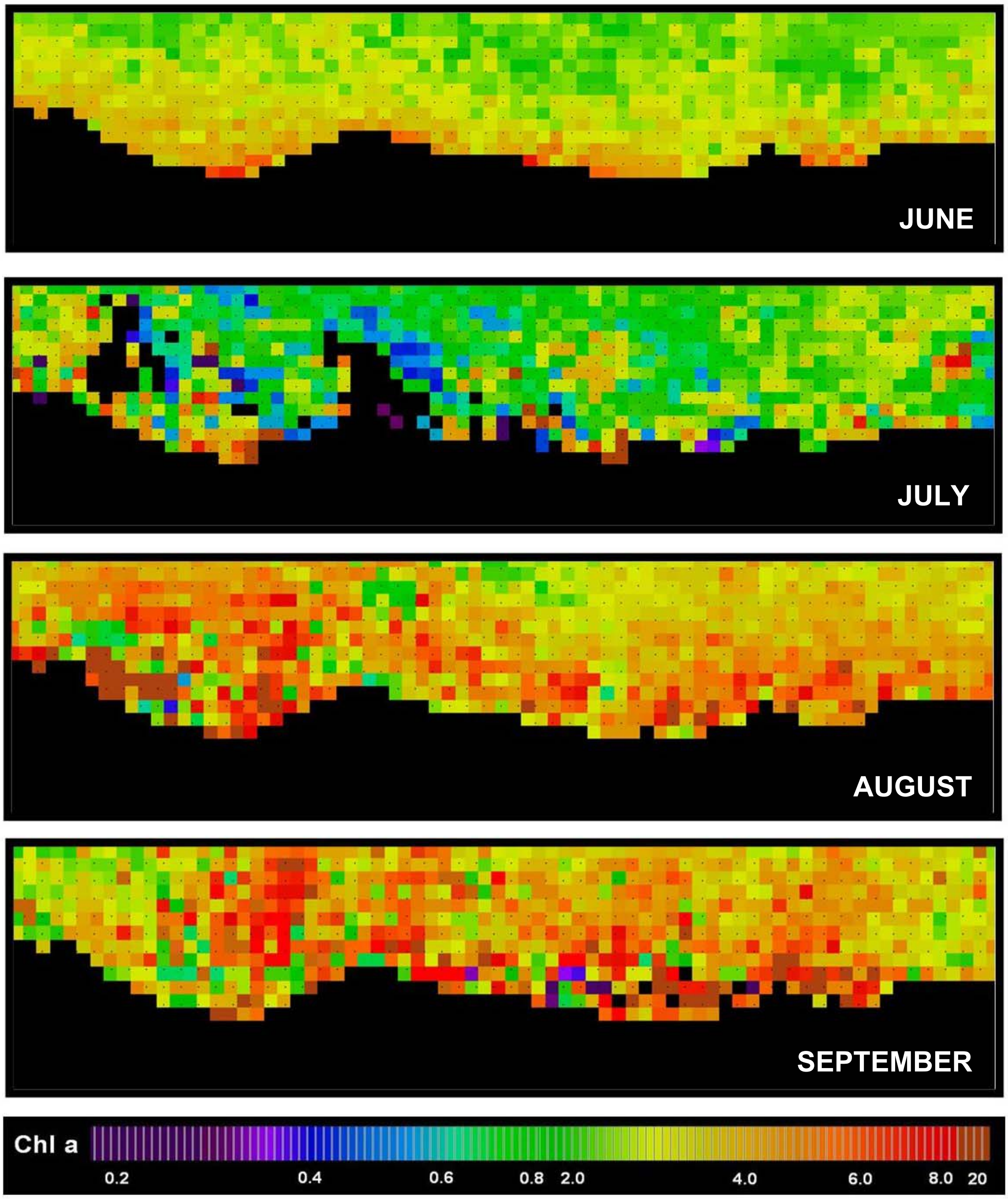


Figure 3.7 SeaWiFS composite images showing the mean monthly chlorophyll-a concentration (Chl a µg1^{-1}) for the study area in June, July, August & September during **A** 2002 **B** 2003 and **C** 2004. Coastline extends from Lossiemouth to Fraserburgh. (created using ERDAS Imagine)

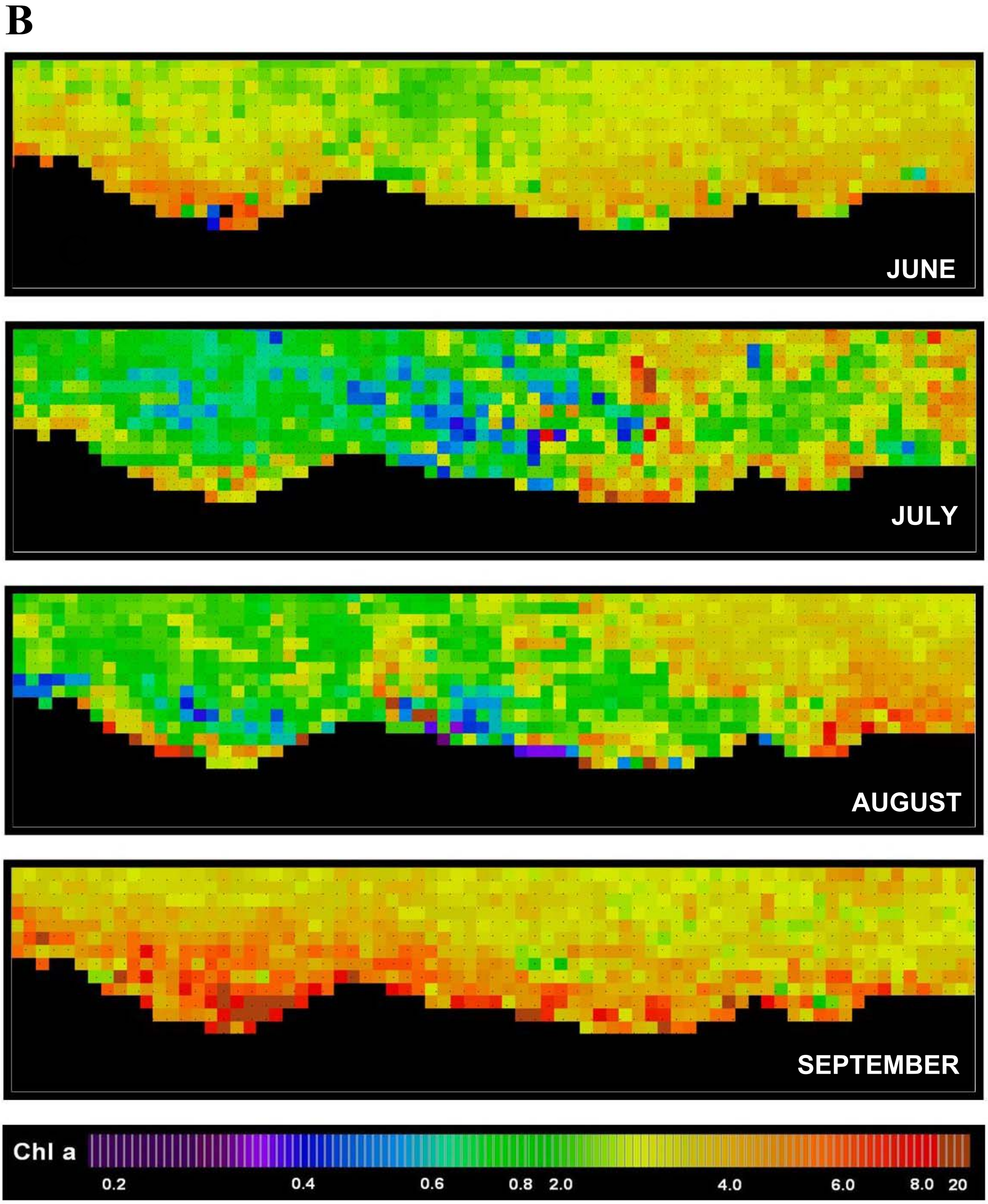


Figure 3.7 See previous page.

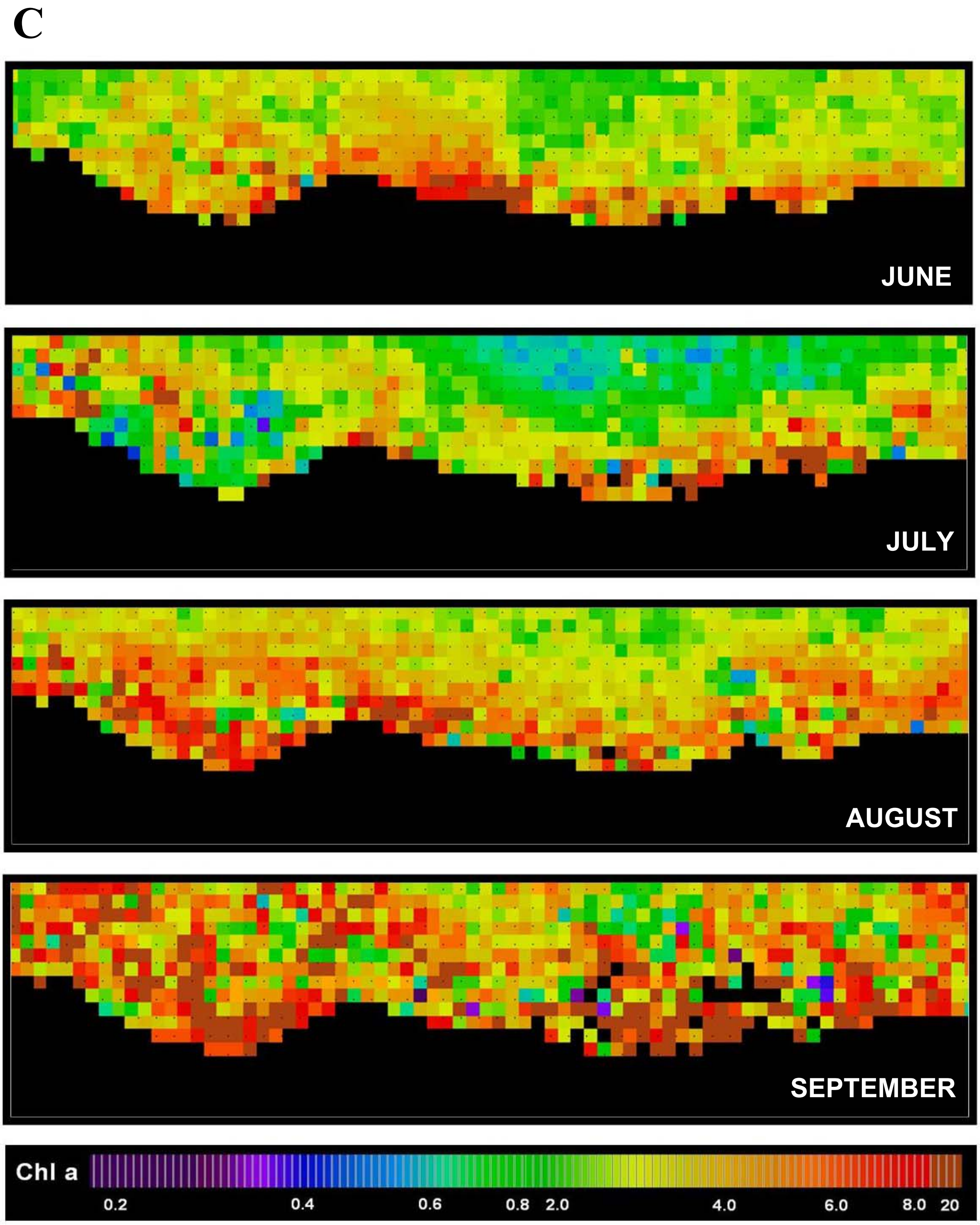


Figure 3.7 See previous page.

Results of ground truth sampling during 2004 can be found in **Table 3.3**. Results show that no significant difference was observed between chlorophyll-a concentrations obtained by direct sampling and those obtained through the use of the SeaWiFS sensor (t-test t = -0.34 p = 0.736).

Table 3.3 Results of ground truth sampling of chlorophyll-a concentration (µg1^{-1}) during 2004. No significant difference was found between the ground truth samples and the concentrations of chlorophyll-a obtained using the SeaWiFS sensor (t-test t = -0.34 p = 0.736).

Sample no.	**Chlorophyll-a (µg1^{-1})**				**Date**	**Time**	**GPS**		**SeaWiFS (µg1^{-1})**
	1	**2**	**3**	**Mean**			**N**	**W**	
1	0.24	0.33	0.32	0.30	03/08/2004	12:45	57.43.000	002.35.000	0.28
2	0.49	0.51	1.03	0.68	08/08/2004	19:30	57.43.000	002.35.000	0.76
3	0.84	0.95	0.60	0.80	08/08/2004	19:50	57.42.000	002.35.000	0.62
4	1.49	1.39	1.21	1.36	11/08/2004	12:30	57.43.096	002.35.595	1.41
5	1.11	1.09	1.07	1.09	11/08/2004	15:30	57.43.090	002.21.493	1.13
6	0.83	-	-	0.83	04/09/2004	16:20	57.41.733	002.10.507	0.90
7	0.65	-	-	0.65	04/09/2004	16:28	57.42.070	002.08.593	0.62
8	0.78	-	-	0.78	04/09/2004	19:00	57.42.455	002.17.161	0.73
9	0.86	-	-	0.86	04/09/2004	19:06	57.42.262	002.20.614	0.79
10	0.84	-	-	0.84	04/09/2004	19:10	57.42.867	002.21.657	0.82
11	0.79	-	-	0.79	04/09/2004	19:15	57.42.839	002.22.881	0.82
12	0.69	-	-	0.69	04/09/2004	19:19	57.42.122	002.24.007	0.72
13	0.67	-	-	0.67	04/09/2004	19:22	57.42.633	002.24.881	0.61
14	0.89	-	-	0.89	04/09/2004	19:26	57.42.403	002.26.295	0.88
15	0.72	-	-	0.72	04/09/2004	19:30	57.42.299	002.27.566	0.67
16	0.76	-	-	0.76	04/09/2004	19:36	57.42.416	002.27.996	0.79
17	0.54	-	-	0.54	04/09/2004	19:40	57.42.407	002.28.670	0.63
18	0.50	-	-	0.50	04/09/2004	19:45	57.42.365	002.29.304	0.49
19	0.05	-	-	0.05	04/09/2004	19:49	57.42.305	002.30.867	0.53
20	0.76	-	-	0.76	04/09/2004	19:51	57.42.261	002.31.999	0.82
21	0.62	-	-	0.62	04/09/2004	19:54	57.42.020	002.32.622	0.67
22	0.83	-	-	0.83	04/09/2004	20:00	57.42.967	002.33.680	0.84
23	0.50	-	-	0.50	04/09/2004	20:03	57.41.886	002.34.766	0.45
24	0.76	-	-	0.76	04/09/2004	20:06	57.41.633	002.34.788	0.73
25	0.65	-	-	0.65	04/09/2004	20:10	57.41.304	002.34.836	0.67
26	0.43	-	-	0.43	29/09/2004	03:30	57.42.721	002.56.121	0.54
27	0.95	-	-	0.95	29/09/2004	03:30	57.42.009	002.34.700	1.05
28	1.03	-	-	1.03	29/09/2004	03:30	57.42.617	002.34.450	1.09
29	0.84	-	-	0.84	29/09/2004	03:30	57.42.383	002.35.633	0.88
30	1.50	-	-	1.50	29/09/2004	03:30	57.41.970	002.35.935	1.43
Control	0.03	0.02	0.02	0.03	04/09/2004	n/a	n/a	n/a	n/a

3.5 Adults and juveniles

Minke whale encounters were separated to show if any differences were detectable between animals of different age class (adults and juveniles) and their distribution in relation to the environment. These distributions with environmental variables can be seen in **Figure 3.8**. Results show that both adult and juvenile minke whales were similar in their distribution with respect to the underlying environment. All whale encounters were highest with variables of shallow depth, high slope value, northerly facing aspects, sandy gravel sediment types, warm temperatures and high chlorophyll-a concentration.

The environmental data set was tested for normality using a Kolmogorov-Smirnov statistic. A summary of these results can be found in **Table 3.4**. Tests showed that the environmental data recorded during minke whale encounters was found to be normally distributed. Therefore, parametric statistics could be used to determine if any further trends or patterns occurred between minke whales and the environment.

Table 3.4. Results of Kolmogorov-Smirnov tests (statistic and probability values) used to determine if environmental data set associated with minke whale encounters was normally distributed.

Environmental variable	**D**	**p**
SST	0.136	<0.01 **
Chlorophyll-a	0.123	<0.01 **
Depth	0.186	<0.01 **
Slope	0.229	<0.01 **
Sediment type	0.084	0.043 *
Aspect	0.259	<0.01 **

* indicates results which are significant (p = <0.05)

** indicates results which are very significant (p = <0.01)

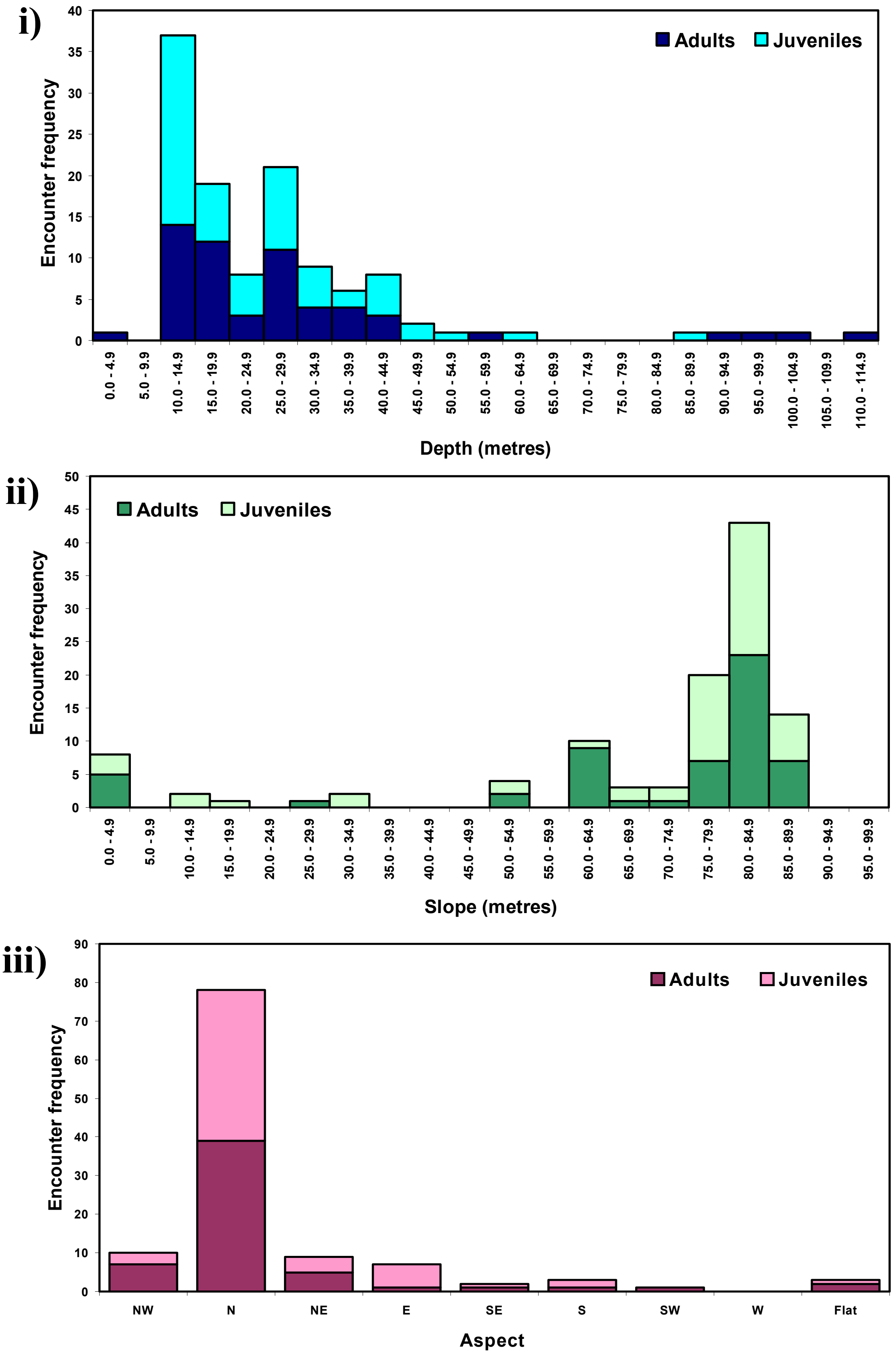
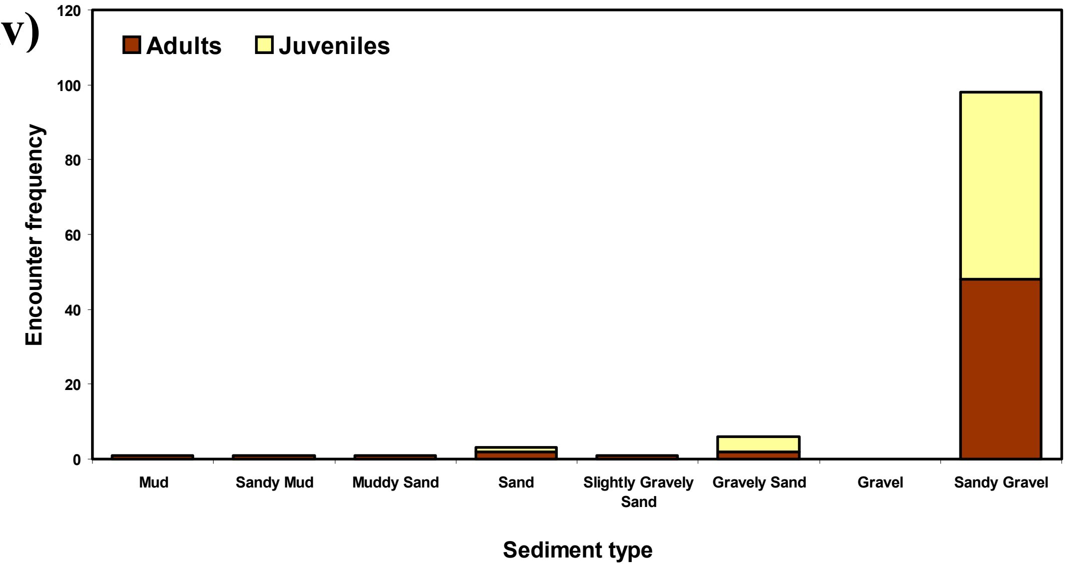
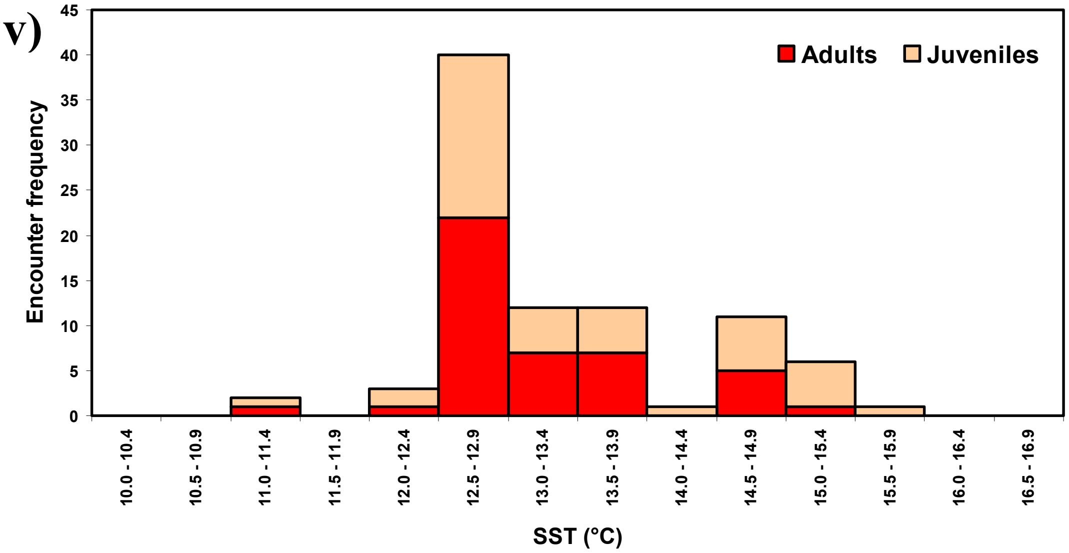


Figure 3.8 Stacked histograms of minke whale encounter frequency, for adult and juvenile animals, across the range of environmental variables associated with their distribution. These include **i)** depth **ii)** slope **iii)** aspect **iv)** sediment type **v)** SST and **vi)** chlorophyll-a.

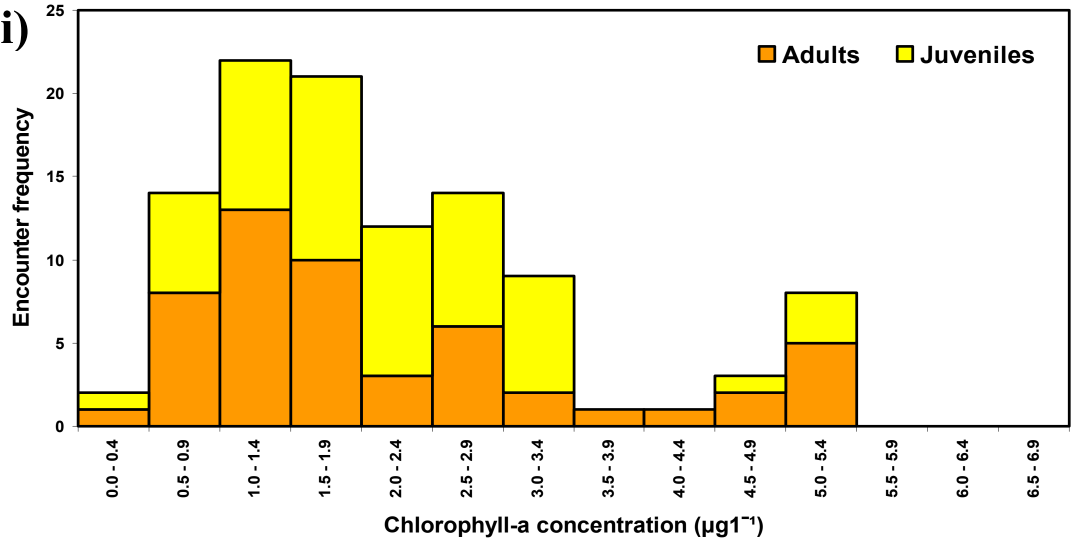
See over the page for the rest of **Figure 3.8** iv)


Adults
Juveniles
Encounter frequency
0
20
40
60
80
100
120
Mud
Sandy Mud
Muddy Sand
Sand
Slightly Gravely Sand
Gravely Sand
Gravel
Sandy Gravel
Sediment type

v)


Adults
Juveniles
Encounter frequency
0
5
10
15
20
25
30
35
40
45
10.0 - 10.4
10.5 - 10.9
11.0 - 11.4
11.5 - 11.9
12.0 - 12.4
12.5 - 12.9
13.0 - 13.4
13.5 - 13.9
14.0 - 14.4
14.5 - 14.9
15.0 - 15.4
15.5 - 15.9
16.0 - 16.4
16.5 - 16.9
SST (°C)

vi)


Adults
Juveniles
Encounter frequency
0
5
10
15
20
25
0.0 - 0.4
0.5 - 0.9
1.0 - 1.4
1.5 - 1.9
2.0 - 2.4
2.5 - 2.9
3.0 - 3.4
3.5 - 3.9
4.0 - 4.4
4.5 - 4.9
5.0 - 5.4
5.5 - 5.9
6.0 - 6.4
6.5 - 6.9
Chlorophyll-a concentration (µg1⁻¹)

t-tests were used to see if any significant differences occurred between the distribution of adult and juvenile whales in relation to the surrounding environment. A summary of these results can be found in **Table 3.5**.

Table 3.5 Results of t-tests (statistic and probability values) used to determine differences occurring in the distribution of adult and juvenile minke whales in relation to environmental variables.

Variable	t	p
SST	-1.65	0.103
Chlorophyll-a	0.25	0.804
Depth	1.08	0.285
Slope	-0.29	0.769
Sediment type	-6.98	<0.001 ***
Aspect	0.24	0.810

*** indicates results which are highly significant (p = <0.001)

Results show that adult and juvenile minke whales were significantly different in their distribution across different sediment types (t = -6.98 p = <0.001). Therefore, it was assumed that adult and juvenile whales differed in their range of sediment type selection. No significant difference was observed between adult and juvenile whales in relation to their distribution across the other environmental variables tested. Therefore, it was assumed that adult and juvenile animals had the same distribution across sea surface temperature, chlorophyll-a concentration, depth, slope and aspect.

Dive durations recorded for animals were divided into those sampled from adult and juvenile animals and examined using a t-test. No significant difference was found between the dive durations of adult and juvenile animals (t = -1.23 p = 0.218). Therefore it was assumed that diving behaviour was the same for adult and juvenile whales.

3.6 Travelling and foraging

In the previous section encounters with minke whales were divided into adult and juvenile animals. In this section encounters were separated by different behavioural class, i.e. between those animals which were deemed to be travelling and those which were foraging. These behaviour classes were then plotted against data concerning the environment and can be found in **Figure 3.9**. Results show that both travelling and foraging minke whales were similar in their distribution with respect to the underlying environment. As in the previous section on age classes, whale encounters were highest with variables of shallow depth, high slope value, northerly facing aspects, sandy gravel sediment types, warm temperatures and high chlorophyll-a concentration.

Environmental data set was previously tested for normality and found to be normally distributed. Therefore, please refer to that section for further information.

t-tests were used to see if any significant differences occurred between the distribution of travelling and foraging whales in relation to the surrounding environment. A summary of these results can be found in **Table 3.6**.

Table 3.6 Results of t-tests (statistic and probability values) used to determine differences occurring in the distribution of travelling and foraging minke whales in relation to environmental variables.

Variable	**t**	**p**
SST	-0.51	0.610
Chlorophyll-a	2.39	0.020 *
Depth	-1.67	0.101
Slope	1.25	0.216
Sediment type	2.30	0.026 *
Aspect	0.89	0.378

* indicates results which are significant (p = <0.05)

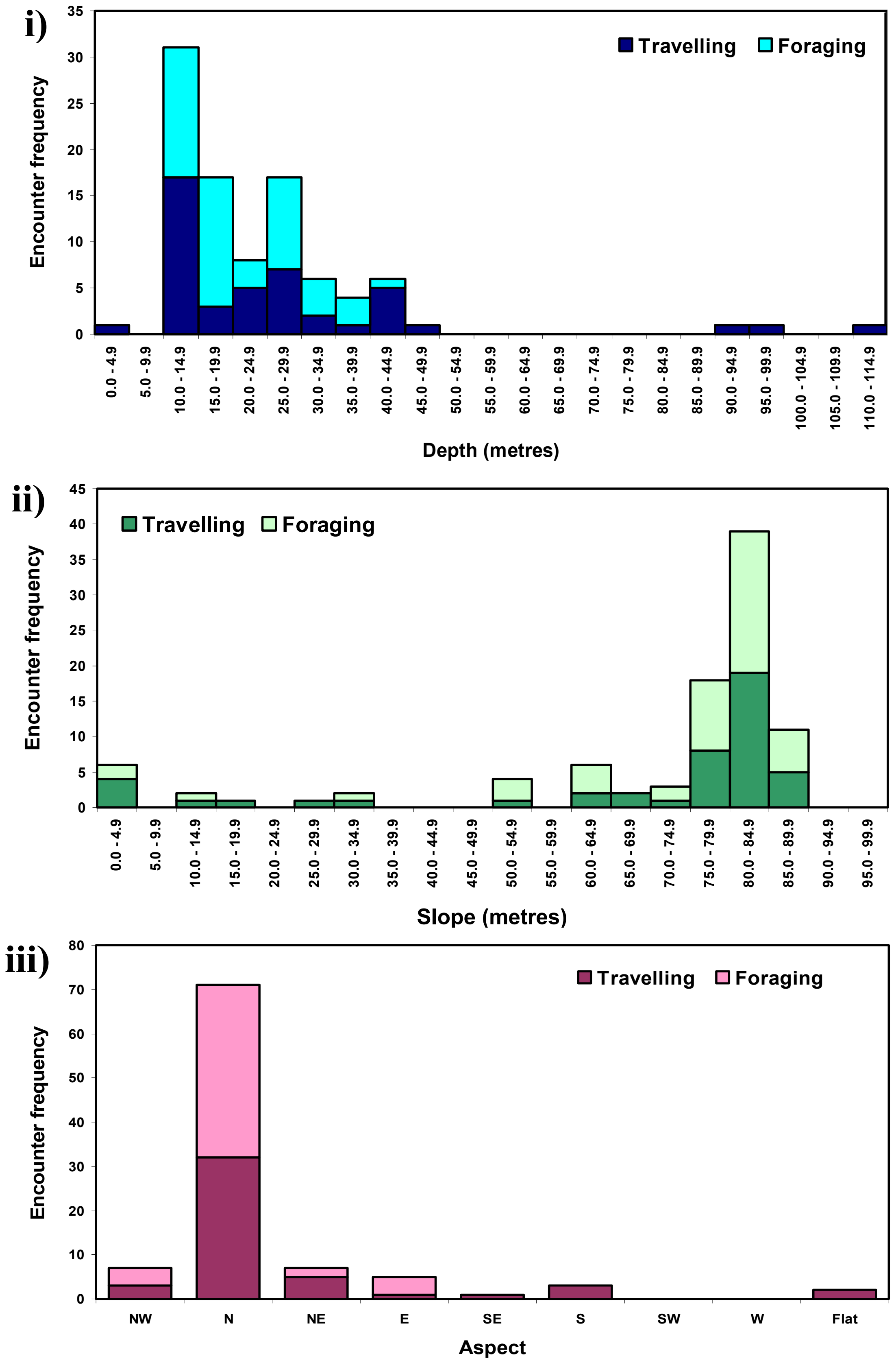
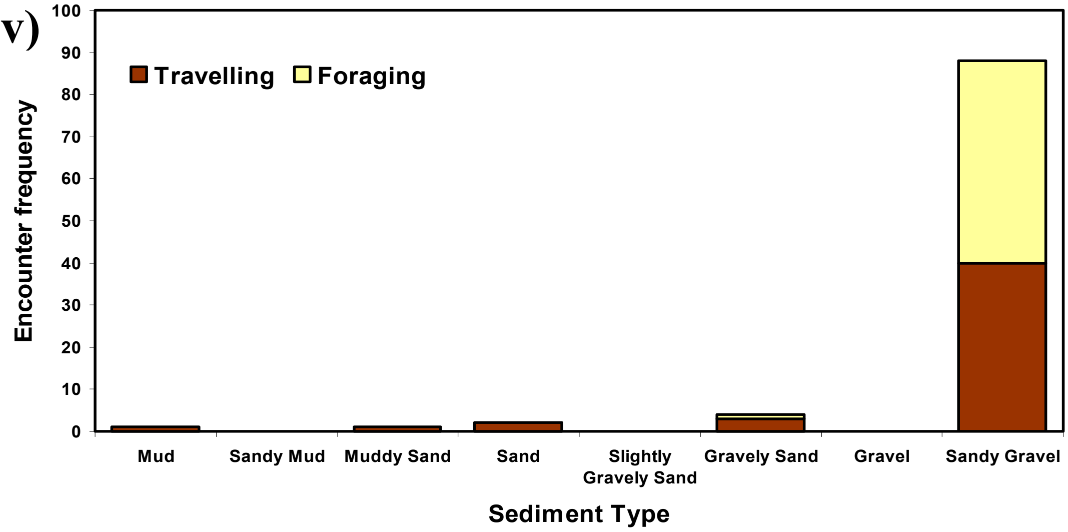
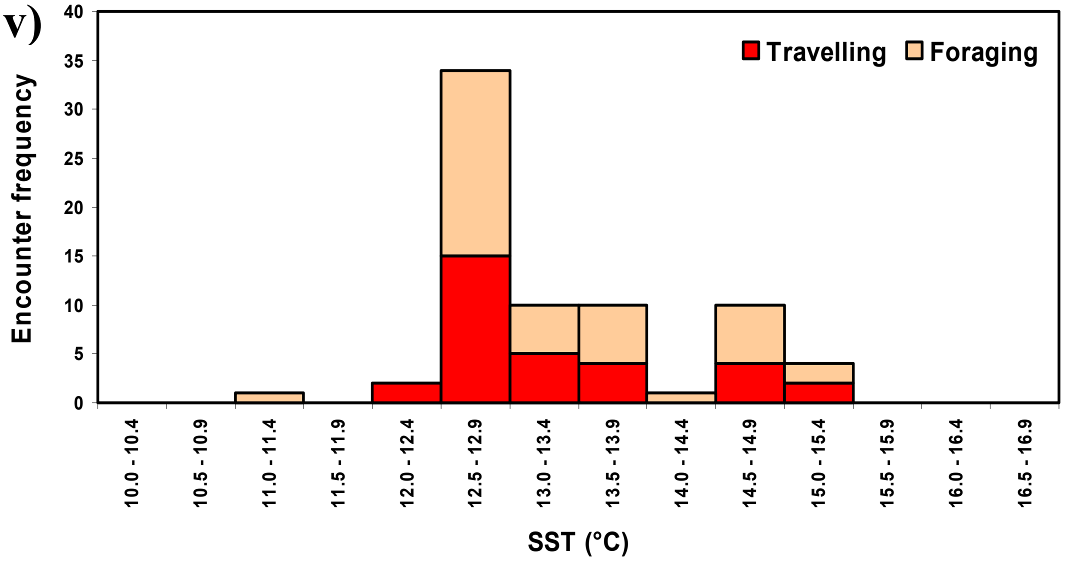


Figure 3.9 Stacked histograms of minke whale encounter frequency, for travelling and foraging animals, across the range of environmental variables associated with their distribution. These include **i)** depth **ii)** slope **iii)** aspect **iv)** sediment type **v)** SST and **vi)** chlorophyll-a.

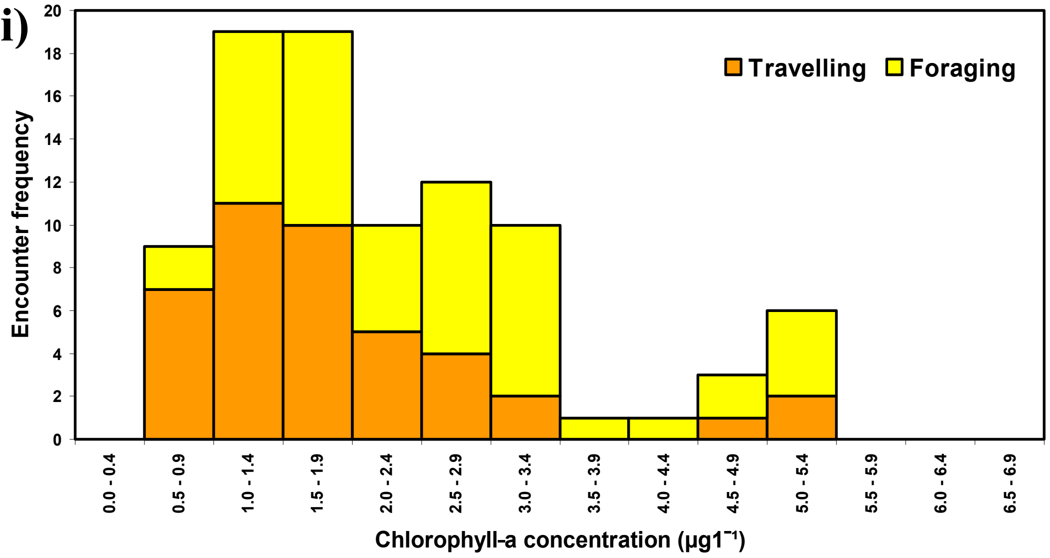
See over the page for the rest of **Figure 3.9** iv)


Encounter frequency
100
90
80
70
60
50
40
30
20
10
0
Travelling
Foraging
Mud
Sandy Mud
Muddy Sand
Sand
Slightly Gravely Sand
Gravely Sand
Gravel
Sandy Gravel
Sediment Type

v)


Encounter frequency
40
35
30
25
20
15
10
5
0
Travelling
Foraging
10.0 - 10.4
10.5 - 10.9
11.0 - 11.4
11.5 - 11.9
12.0 - 12.4
12.5 - 12.9
13.0 - 13.4
13.5 - 13.9
14.0 - 14.4
14.5 - 14.9
15.0 - 15.4
15.5 - 15.9
16.0 - 16.4
16.5 - 16.9
SST (°C)

vi)


Encounter frequency
20
18
16
14
12
10
8
6
4
2
0
Travelling
Foraging
0.0 - 0.4
0.5 - 0.9
1.0 - 1.4
1.5 - 1.9
2.0 - 2.4
2.5 - 2.9
3.0 - 3.4
3.5 - 3.9
4.0 - 4.4
4.5 - 4.9
5.0 - 5.4
5.5 - 5.9
6.0 - 6.4
6.5 - 6.9
Chlorophyll-a concentration (μg1⁻¹)

Results show that travelling and foraging minke whales were significantly different in their distribution across different sediment types (t = 2.30 p = 0.026). Therefore, it was assumed that travelling and foraging whales differed in their distribution across the range of different sediment types. It was also observed that travelling and foraging minke whales were significantly different in their distribution across different concentrations of chlorophyll-a concentration (t = 2.39 p = 0.020). It was concluded that travelling and foraging whales were different in their distribution across the range of differing chlorophyll-a concentrations. No significant difference was observed between travelling and foraging whales in relation to their distribution across the other environmental variables tested. Therefore, it was assumed that travelling and foraging animals had the same distribution across varying sea surface temperature, depth, slope and aspect.

Dive durations recorded for animals were divided into those sampled from whales deemed to be travelling and those classed as foraging. A t-test was used to investigate the presence of any differences between minke whales separated by behavioural activity. A significant difference was found between the dive durations of travelling and foraging animals (t = 2.18 p = 0.030). Therefore, it was assumed that the surface diving behaviour was different between those animals which were travelling and those which were foraging.

3.7 Multivariate analysis

Pearson's correlation tests were used to determine if any correlations were present between different combinations of environmental variables and their effect on the distribution of minke whales. A summary of the results of these tests can be found in **Table 3.7**. Tests showed that minke whale distributions were highly correlated with certain variables and not correlated with others.

Table 3.7 Summary of probability values obtained form Pearson's correlation tests used to determine correlations between variables SST, Chlorophyll-a, Depth & Slope, associated with the distribution of minke whales.

Variable	**Age**		**Behaviour**		**All whales**
	Adults	**Juveniles**	**Foraging**	**Travelling**	
Chlorophyll-a & SST	0.023 *	0.285	0.433	0.098	0.029 *
Chlorophyll-a & Depth	0.099	0.009 **	0.088	0.674	0.005 **
Chlorophyll-a & Slope	0.935	0.620	0.617	0.815	0.801
SST & Depth	0.480	0.318	0.681	0.280	0.849
SST & Slope	0.015 *	0.039 *	0.005 **	0.175	0.002 **
Depth & Slope	0.829	0.669	0.467	0.865	0.937

* indicates results which are significant (P = <0.05)

** indicates results which are very significant (P = <0.01)

Results showed that a significant correlation was observed between chlorophyll-a concentration and sea surface temperature in relation to the distribution of minke whales (p = 0.029). However, in terms of age classes only the distributions of adult animals followed this pattern (p = 0.023) whilst no significant correlation was observed in the distribution of juvenile animals (p = 0.285). Scatter plots of the trend between chlorophyll-a concentration and sea surface temperature for both adult and juvenile animals can be found in **Figure 3.10**.

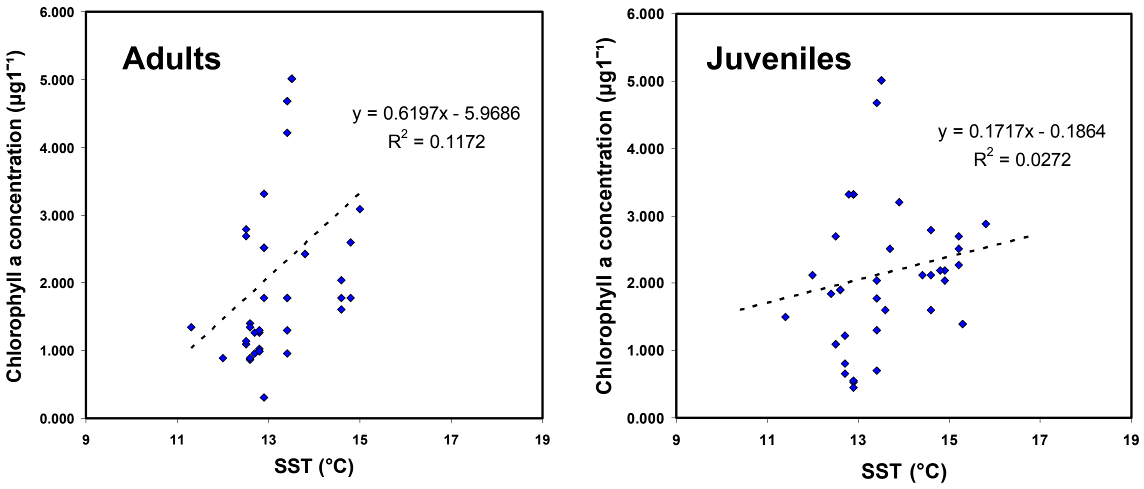


Figure 3.10 Scatter plots of chlorophyll-a concentration (μgl^{-1}) and sea surface temperature (SST °C) for the distributions of adult and juvenile minke whales. The trend line equation and R-squared values are shown on each plot.

It was observed from the Pearson's correlation statistic that a significant correlation was found between chlorophyll-a concentration and depth in relation to the distribution of minke whales ($p = 0.005$). However, a difference was once again observed between the distribution of adult and juvenile animals. A significant correlation was observed between chlorophyll-a concentration and depth in relation to the distribution of juvenile whales ($p = 0.009$), whilst no correlation was observed between variables in the distribution of adult animals ($p = 0.099$). Scatter plots of the correlation between chlorophyll-a concentration and depth for both adult and juvenile minke whales can be found in **Figure 3.11**.

Results from multivariate analysis showed that a significant correlation was observed between sea surface temperature and slope with regards to the distribution of minke whales ($p = 0.002$). This correlation was also evident in the distributions of adult ($p = 0.015$) and juvenile ($p = 0.039$) whales. However, when animals were separated by behaviour class a difference was observed. Those animals which were identified as foraging showed significant correlations between sea surface

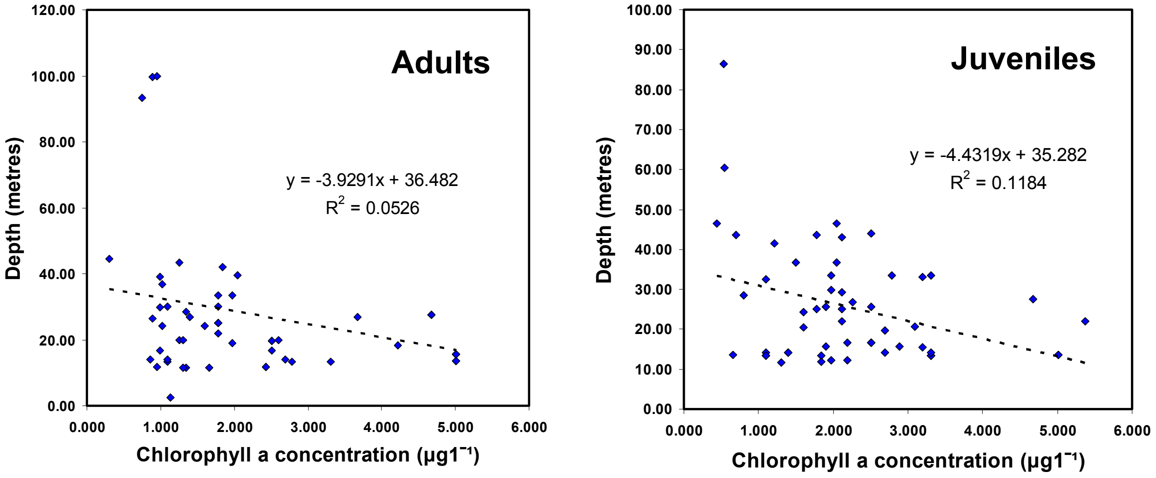


Figure 3.11 Scatter plots of depth (metres) and chlorophyll-a concentration (µg1⁻¹) for the distributions of adult and juvenile minke whales. The trend line equation and R-squared values are shown on each plot.

temperature and slope in relation to the distribution of the animals (p = 0.005). The distribution of those whales which were deemed to be travelling, however, showed no significant correlation with environmental variables (p = 0.175). Scatter plots of the trends between sea surface temperature and slope for both adult and juvenile minke whales can be found in **Figure 3.12**.

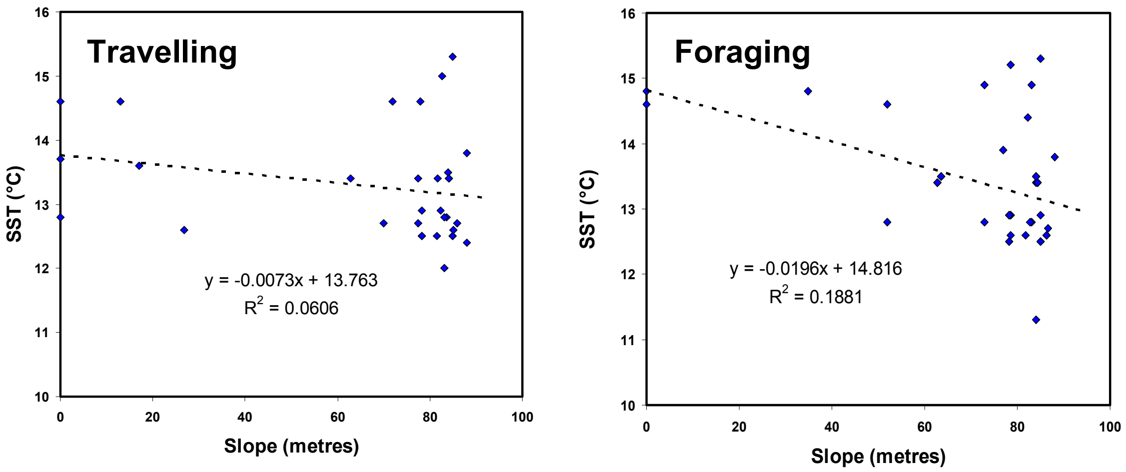


Figure 3.12 Scatter plots of sea surface temperature (SST °C) and slope (metres) for the distributions of travelling and foraging minke whales. The trend line equation and R-squared values are shown on each plot.

3.8 Summary

A number of observations, patterns and correlations were found to be significant from the results of the study. These have been summarised below:

- Minke whales were encountered in the Moray Firth, north east Scotland.
- Minke whale distribution and encounter frequency were highly variable both spatially and temporally within the survey area.
- No minke whales were encountered in the year 2004.
- The highest frequencies of whales were encountered during the months of July, August and September across the years of the study.
- Areas of highest minke whale encounter frequency occurred in regions which were characterised by shallow depths, steep slopes, northerly facing aspects and sandy gravel sediment types.
- Significant differences were observed between the distribution of adult and juvenile minke whales with respect to sediment type.
- Significant differences were observed between the distribution of whales deemed to be travelling and foraging with respect to sediment type.
- It was observed that minke whale encounter frequencies were highest during the months with highest values of sea surface temperature.
- Change in minke whale distribution across the survey area may be due to the influence of changing levels of primary productivity, represented by variations in the measurements of chlorophyll-a concentration.

- Significant differences were observed between the distribution of animals deemed to be travelling and foraging in respect to changes in chlorophyll-a concentration.

- Significant correlations were found for adult and juvenile minke whale distribution and the interactions of the environmental variables of depth, sea surface temperature and chlorophyll-a concentration.

- Significant correlations were found for the distribution of those minke whales deemed to be foraging and the interactions of the environmental variables of slope and sea surface temperature.

- The distribution of animals deemed to be travelling showed no correlations with the interactions of any of the environmental variables associated with their position.

- A significant difference was observed between the dive durations of those minke whales deemed to be travelling and those classed as foraging. Therefore, it was assumed that the diving behaviour was different between those animals which were travelling and those which were foraging.

4. Discussion

4 Discussion

Interpretation of results

From the results of the study the most significant observations made were between the distributions of encounters associated with the fixed environmental variables. Primarily it was observed that whales were most frequently encountered in areas of shallow depth, steep slope, northerly facing aspect and sandy gravel sediment type. However, of these variables it was the sediment type parameter which had the strongest association with the distribution of minke whales. It is assumed from behavioural observation that the main focus of habitat selection occurring in this region was associated with the acquisition of prey. It was found from stomach contents analysis that the primary constituent of the diet of minke whales occurring around Scotland, including the Moray Firth, was the sandeel *Ammodytes marinus* (pers.comm. Begoña Santos). The distribution of sandeels is highly dependent upon the presence of suitable substrate in which to bury themselves (FRS, 2004b). The most preferred type of sediment for sandeels in which to do this are those of sandy gravels.

Other studies of minke whales have also found strong correlations between animal distribution and underlying sediment. Naud and others (2003) observed that minke whales in the St Lawrence Estuary, Canada, were most often sighted in areas with sandy substrate types. It was speculated in the study that these areas were of suitable habitat for sandeels which required it for shelter. This information was used to explain why, although there were many areas of similar bathymetry (depth and slope), the distribution of animals across these features was discontinuous (Naud *et al.,* 2003). For minke whales located around the Hebrides in Scotland, sediment type, as an indicator of underlying prey, was used to explain the seasonal progression of the species distribution moving northward throughout the summer months (Macleod *et al.,* 2004). In the earlier part of the summer minke whales were found at their highest abundance over sediments which are favoured by sandeels for sheltering. As the summer moved on however the distribution of animals changed to areas with underlying sediments which favoured herring spawning. The positions of the sediment types match the northward progression of minke whale distribution. It was therefore assumed that minke whales are primarily located in areas with an active food source. It is then assumed that minke whale sightings frequency was highest in the areas represented by sandy gravels because this is the area of highest sandeel occurrence (Macleod *et al.,* 2004).

Minke whale associations with other fixed environmental parameters such as depth, slope and aspect can be secondarily explained due to the presence of the predominant parameter for distribution, sediment type. Aspect is thought not to be an important factor of minke whale distribution because those areas of sandeel preferred sediment were generally categorised by northerly facing slopes. Therefore, if the coastline had been the reverse and slopes faced south but had still been characterised by sandy gravel sediments, then it is hypothesised that minke whale distribution would still have been the same. This area was also predominantly associated with shallow depths and steep slopes. These factors may contribute to making the area more productive (upwelling of nutrients) and provide the population of sandeels with a greater supply of resources on which to sustain themselves (Croll *et al.,* 1998). Also, steep slopes have been found to actively aggregate prey together and assist predators in foraging effectively so are selected more often because of this feature (Yen *et al.,* 2004). The interactions of these variables may then help to explain why the distribution of minke whales, and the sandeels on which they depend, is discontinuous across this area of similar sediment type.

Several interesting observations were made on the distribution of minke whales in association with those environmental variables which were not fixed, i.e. water temperature and primary productivity. From AVHRR satellite imagery of sea surface temperature, two important oceanographic features appear to dominant the Moray Firth embayment. These include a cold water current moving into the area form the north and a plume of warmer water emerging from the inner Firth. These features are thought to be the Dooley Current which transports cold water from the Atlantic into the northern North Sea. The plume feature is believed to be due to the warming of water within the shallow inner firth. This is then transported out into the wider embayment and North Sea by the outflow from the many smaller firths and rivers which discharge into the Moray Firth. This is in turn fed by runoff from the surrounding Scottish highlands. The interaction of these two features appears to have significant effects upon the temperature regime of the Moray Firth embayment. In relation to the encounter frequency of minke whales, encounters were predominantly higher later in the research season, i.e. steadily building across the months of July, August and September. This was related to increasing sea surface temperatures which also followed a similar pattern, i.e. steadily building across the months of July, August and September. Therefore, sea temperature is thought to be one of the primary variables affecting the presence of animals within the Moray Firth. More importantly though it is hypothesised that it is the interactions between the Dooley Current and warm water plume which determine the presence of whales because of their effect on the distribution and variability of temperature within the embayment.

Many studies have attempted to show correlations between the distributions of minke whales *Balaenoptera acutorostrata* and sea water temperature. However, no study has been able to show strong correlations between sea water temperature and the distribution of minke whales. Macleod (2003) used satellite images of sea surface temperature to try to explain the northward movement of animals through the summer over areas of similar depth and slope characteristics. Unfortunately, due to problems with low sample sizes of animals directly associated with satellite images and low coverage in those images used due to cloud masking, no significant patterns were observed between distribution and sea surface temperature (Macleod, 2003). Kasamatsu and others (2000) managed to show strong correlations between the presence of minke whales and ice edge areas in the Bellinghausen and Amundsen Seas in the Antarctic. Although no significant correlations were found between minke whale density and sea surface temperature, it was observed that densities appeared to be higher during the surveys conducted during 1982/1983 when the region was experiencing intrusions of colder water. Later in surveys conducted during 1989/1990 when the areas experienced a large warm water intrusion from the north, minke whale density appeared to be much lower. It was assumed in the paper that sea surface temperature by itself does not well explain the density of minke whales in both periods of study and the simple observed correlation may be caused by other underlying factors (Kasamatsu *et al.,* 2000).

Interesting observations were made with the use of satellite imagery to note changes in primary productivity levels within the survey area and the distribution of minke whales. Overall, whales were found in those months and areas with the highest concentrations of chlorophyll-a, an indicator of primary production. Also, it was observed that changes in minke whale distribution during the year 2003 could have been due to observed shifts in the distributions of primary productivity. Sandeels spend the majority of their time buried in the sediment, only venturing into the water column to spawn during the winter and to feed on plankton during the summer months (FRS, 2004b). Thus, it is believed that sandeels will only be available to predators such as minke whales in areas with higher concentrations of sandeel prey, predominantly phytoplankton. Therefore, the observed shift of encounters with minke whales from one area of high productivity to another could be related to animals finding areas in which sandeels are more likely to be encountered. This is then due to the withdrawal of sandeels from the protection of the seabed sediment, to feed on plankton in the water column.

During the study a few differences were observed between the distribution of adult and juvenile minke whales in relation to the interaction of environmental parameters. Whilst both age classes were associated with the interaction of sea surface temperature and slope variables, this interaction was considered as a product from the oceanographic processes which leads to increased primary productivity. Steep slopes stimulate upwelling of nutrients and temperature limits/promotes productivity through alteration of the physical and chemical properties of water column (Franks, 1992). However, while the distribution of adults was observed to be correlated with the interactions of chlorophyll concentration and sea surface temperature, juveniles were observed to be correlated with the interactions of chlorophyll concentration and depth. Therefore, as chlorophyll-a concentrations are thought to be indicators of increased primary productivity (occurrence of prey) and is common in both age classes, then it could be hypothesised that adult and juvenile animals may be partitioning this selected foraging habitat by associating with different environmental variables. Juveniles may select their distribution based upon the relative depth of the water as the most productive areas are often located in areas of shallow depth. Adults, however, may use a different strategy when selecting areas for foraging based on the ambient temperature of the water, as productivity in the area is often observed to be higher when sea surface temperatures were predominantly warmer.

Habitat partitioning in ecosystems is an important mechanism by which a group of organisms within a system reduce competition and make the most of what little and patchy resources are available (Kerbs & Davies, 2003). This mechanism is most commonly observed between different species co-occurring within the same habitat, each species finding its own niche in which to specialise. However, this partitioning of habitat can also occur in an intraspecific manner, within the individuals of the same species (Cox & Moore, 1997). Though the majority of examples of differences in habitat selection in a species is predominantly between the different sexes, examples do exist between animals of different age class. Werner & Hayes (2004) found that apparent habitat partitioning existed between adult and juvenile lake sturgeon (*Acipenser fulvescerns*) in the St. Lawrence River (USA) and that differences in preferred prey types and densities between the age classes could account for this. This was done through benthic evaluation to determine prey densities and substrate types found in areas were the different age classes were most frequently encountered. Study found that the selection of habitat was predominantly based on the underlying sediment type. It was observed that adults were found in areas with river bed substrate being classed as boulder (51.5%) and juveniles were located in areas with river bed substrate being classed as silt (65.4%). These two differing substrates support different prey types and densities which were then in turn preferred by each of the different age classes of lake sturgeon. Other examples of ontogenic variation in habitat utilisation, i.e. between individuals of differing age class can be found in the habitat selection of northern diamond backed terrapins (*Malaclerys terrapin terrapin*) (Mohrman & Wood, 2003), prey selection and habitat use of the Oregon garter snake (*Thannophis atratus hydrophilus*) (Lind *et al*., 1994) and the habitat uses and selection of adult and juvenile kiwi (*Aptaryx australis mantelli*) (Gibbs & Clout, 2003). Observations have been made of ontogenic habitat partitioning in various species of marine mammal. In many species of diving pinnipeds, dives by younger seals and sea lions are often constrained by physiological development and therefore only able to make shorter and shallower dives than adult animals. It has been observed in elephant seal (*Mirounga angustirostris*) pups, which on their first trips to the sea, make a transition from short, shallow dives to a pattern similar to that of adult animals, with longer deeper dives that show diel fluctuations (Heithaus & Dill, 2002). It was stated that this change appeared to be related to changes in physiology of the younger animals and possible differences in prey distribution. Lastly, it was found that sea otters (*Enhydra lutris*) show differences between animals of different age class in relation to their distribution and prey selection, juvenile adults being found to forage further offshore and making longer dives than other sex and age classes (Heithaus & Dill, 2002). Therefore, from these previous examples of interspecific habitat partitioning amongst age classes, it becomes possible to suggest and hypothesize that this may be occurring within the distribution of minke whales encountered in the southern outer Moray Firth. However, unlike terrestrial systems where interactions between a species and the surrounding environment are more clearly visible, marine mammal relationships to these variables may be more subtle and harder to observe and interpret.

During the study, differences were observed between the distributions of travelling and foraging animals in relation to environmental variables. Those animals which were identified as foraging were closely associated with the environmental variables which determine both the presence of the minke whales main prey, the sandeel, but also with areas where their abundance is stimulated and made more available to the feeding strategies employed by the whales. Those animals deemed to be travelling were found not to show any strong correlations associated with the environmental parameters which identify areas of highest sandeel occurrence. Also, it was observed that dive durations between travelling and foraging animals were significantly different. This observation helps reinforce the definitions used to separate animals based on behavioural activity but also to show that different regimes of energetic expenditure are employed for the different behaviours (Hoelzel *et al.,* 1989; Hind & Gurney, 1998). Therefore, it is assumed because they are not actively in the pursuit or acquisition of prey, then the distribution of travelling whales should not be effected by those parameters which are associated with the activity of foraging.

During the present study it was observed that no minke whales were encountered during surveys in 2004. The findings of the study have lead to the hypothesis that the overriding reason for minke whales to select the study area is due to its suitability for foraging behaviour, and that foraging is centred upon the presence of sandeels. The lack of minke whale encounters during the summer of 2004 can then be hypothesised to be due to a lack of sandeels. This absence of available prey could occur in either of two ways. First, due to a suite of unsuitable environmental variables occurring in 2004, sandeels may have remained hidden within the sediment and did not venture into the water column in large enough numbers to provide suitable foraging for the area to be selected. However, the study showed that no difference was observed between 2004 and the previous years of high minke whale sightings frequency. Therefore, it is assumed that conditions present were suitable, unless other more subtle differences between years were not apparent. The second reason may be because of a direct lack of sandeels, because the population may have become much smaller and fewer sandeels are present in the area. Incidental evidence from other areas and studies has indicated that sandeel numbers have plummeted around the coasts of the UK (FRS, 2004a). This has been made evident by the high mortality of sea birds occurring around Scottish coastlines in previous years (Ollason *et al.,* 1997; FRS 2004a).

Incidental sightings have shown that though minke whales were not encountered on research surveys, minkes were observed in the area. However, of the few sightings reports which were made, those animals which were sighted were believed to be travelling (pers.comm. Mark Ellington). Also, minke whales were observed to be foraging elsewhere in the north east of Scotland. Sightings were recorded incidentally on the northern coast of the Moray Firth, near Duncansby Head and Caithness (pers.comm. Ian McDonald). Whales were also recorded actively foraging off the North Sea coastline of Aberdeenshire, near Aberdeen, Montrose and Cruden Bay (pers.comm. Elaine Roft). An explanation of this radical shift in minke whale distribution could be due to prey resource utilisation. The areas off the coasts of Duncansby Head and Caithness have sandy gravel sediment types, providing suitable habitat for sandeels. Also, the seabed off Aberdeen, Montrose and Cruden Bay are typified as having sediment types which are closely associated with the spawning of herring. Minke whales have been shown to shift distribution between areas suitable for sandeels to those suitable for spawning herring (Macleod *et al.* 2004). Therefore, it is hypothesised that a combination of low sandeel abundance and higher numbers of sandeels and spawning herring in other areas may have shifted the distribution of actively foraging minke whales. It has been highlighted, both in this and previous studies, that the primary reason for habitat selection in the north east of Scotland is for foraging. It then seems acceptable that minke whales would shift distribution to areas of highest prey availability.

Another reason why minke whales may have shifted distribution could be due to the increasing pressure of disturbance from boats using coastal areas suitable for the optimal foraging of sandeels. There has been an increase in the number of whale and dolphin watching boats in the outer southern Moray Firth since 2002 (pers.observation). Previous studies looking at the effects of whale watching activities on cetaceans have shown that many negative and even deleterious impacts can be caused (Bejder & Samuels, 2004). These studies include impacts on killer whales in British Columbia (Williams *et al*., 2002), Risso's dolphins in the central Mediterranean (Miragliuolo *et al*., 2001) and bottlenose dolphins near Panama Beach, Florida (Samuels & Bejder, 2004). Also, fishing vessels using demersal trawling techniques have increased in abundance using this strip of the Firth's southern coastline. Usually these fishing vessels are displaced further out to sea, fishing for pelagic fish such as mackerel. However, a large abundance of squid found along the coast in the months of August and September during 2003 encouraged more vessels to trawl for squid (pers.comm. Kevin Robinson). Minke whales were seen to be breaching in the presence of trawlers on two occasions, this behaviour being thought of as a display of aggression and avoidance (pers.observation). In 2004 trawling activity in the area started in the month of May and continued until the later part of the summer.

It is thought that an increase in trawling for squid, using demersal methods and gears, within this coastal area may have impacted directly upon the sandeel population. This could be done either through a process of bycatch upon the sandeels themselves or through the disruption or modification of the seabed making it no longer suitable as an ideal sandeel habitat. Recently, intensive trawling and dredging has raised great concern about the extent by which these activities might cause long-term and large-scale changes in the diversity and composition of benthic marine species assemblages (Lindgarth *et al.,* 2000). It has been recognised that demersal trawling causes one of the most widespread physical and biological changes to shallow and shelf sedimentary habitats (Rosenberg *et al.,* 2003). Demersal trawling methods and gears (otter boards, nets & weights) can cause damage to the seabed through scarring and ploughing deep furrows into the surface sediments (Sanchez *et al.,* 2000). This can significantly impact marine benthic habitats through the alteration of sediment biochemistry and faunal composition (Nilsson & Rosenberg, 2003). Lindgarth and others (2000) showed that this process can also occur over small periods of time. In their study, experimental trawls were undertaken in Gullmarsfjorden, Sweden, a fjord which had been protected from trawling activities for eight years. After 8-12 months of experimental trawling it was shown that species assemblages were significantly different between trawled and untrawled sites. Also, it was observed that large temporal and spatial changes in the composition of benthic fauna occurred in trawled areas (Lindgarth *et al.,* 2000). Therefore, in the present study it is hypothesised that sandeels may have shifted in distribution to areas with more optimal and less disturbed sandeel habitat and sediments.

Applications of the study

The identification of habitat has become a crucial part in the conservation and management of many species which, because of anthropogenic effects and impacts, have become threatened (Hamazaki, 2002; Hooker & Gerber, 2004). A way in which those areas important for a species, terrestrial and marine, can be identified is through the use of ecological modelling. Through the use of information concerning those factors which have an effect on the distribution of a species, such as environmental variables, it then becomes possible to not only model where those species will occur but also in other areas were no species information has been gathered (Zaniewski *et al.,* 2002; Schweder, 2003). This has proved particularly useful in the identification of important areas or hotspots for top level predator diversity and the establishment of marine protected areas (Worm *et al.,* 2003). Also, relatively smaller resources are required for the prediction and subsequent direction of research, conservation and management activities to particular areas efficiently. The development of models therefore has become a recognised priority for this area of research (Schweder, 2003). However, the ability of these spatial models to predict the distribution of species is dependent upon the information of species interaction with the surrounding environment (Hamazaki, 2004).

A number of studies in recent years have attempted to model the distribution of marine mammals to aid understanding their interactions with the environment and help in their conservation and management. These include two separate studies conducted by the authors Gregr and Hamazaki. Gregr & Trites (2001) attempted to model the distribution of critical habitats for a number of cetacean species in the waters of coastal British Columbia. Historical records of whale takes from commercial whaling were used to model the distribution of five whale species including the sperm whale, Sei whale, fin whale, humpback whale, and blue whale. These data were used in relation to oceanographic information on bathymetry, temperature and salinity. The habitat predictions from the models supported recent hypotheses about sperm whales breeding off British Columbia and identified humpback whale habitat in sheltered bays and straits throughout the coast (Gregr & Trites, 2001). Hamazaki (2002) conducted a similar study, using cetacean sightings data from dedicated surveys of the mid-western north Atlantic. The study used this information to produce predictive habitat maps of 13 cetacean species and related this to oceanographic variables (sea surface temperature) as well as topographic variables (depth and slope). The results of the modelling techniques used in the study predicted habitat locations which matched current and historical cetacean distribution (Hamazaki, 2002). Also, models were capable of predicting shifts in distribution for select species due to oceanographic changes.

Later in 2004 both Gregr and Hamazaki discussed the applications of these modelling techniques and disadvantages associated with them, as well as ways to improve their reliability (Gregr, 2004; Hamazaki, 2004). Gregr’s (2004) comment on Hamazaki’s (2002) paper raised important issues concerning the use of modelling techniques, which are still in development, and that those using these methods should be cautious in their interpretation. Also, it is stated that the way in which the reliability of the models accuracy are tested must be urgently improved (Gregr, 2004). However, in Hamazaki’s (2004) response on Gregr’s comments he states that when constructing spatial models it is in designing and implementing sampling procedures which match the research objectives of the study which should be considered first. Only through the development of this first step can our understanding marine mammals and production of meaningful descriptions of their habitat selection and interaction be achieved (Hamazaki, 2004).

In support of their arguments both authors use the quote “because we are so clever at devising explanations of what we see, we may think we understand the system when we have not even observed it correctly” (Wiens, 1989). Therefore, it is interpreted that we must first understand the ways in which species interact with their surrounding environment and the reasons why species select certain habitats. Those models which are currently used to predict animal distributions merely use information of environmental variables which occur during sightings (Gregr & Trites, 2001; Hamazaki, 2002). It therefore seems appropriate that greater detail should be gained when observing and understanding the ways in which marine mammals select and interact with their surrounding environment, before attempting to predict a species distribution.

Understanding the ways in which cetaceans interact with the surrounding environment is now becoming a key tool in their subsequent conservation and management. In the terrestrial environment it has been shown that the protection of a species or population is far easier in a managed environment, e.g. either in a captive facility (zoo) or in a controlled area of natural habitat (protected area) (Barlow, 2002). These protected areas are useful tools for conservation and management because the concept is so, simple i.e. easy to enforce and understand (Barlow, 2002). Now the procedures used in planning and constructing terrestrial reserves are being used to create marine reserves to protect many species of threatened and endangered marine flora and fauna (Gerber *et al.,* 1999). Due to their high trophic status and vulnerability to anthropogenic effects marine mammals such as cetaceans are ideally suited to act as indicator species of ecosystem change (Hooker & Gerber, 2004). Also, whales, dolphins and porpoise can act as flagship species because of their charismatic nature to stimulate interest and subsequent protection of the marine environment and other equally endangered but less appealing species (Hooker & Gerber, 2004). Therefore, many marine protected areas are centred on the conservation of marine mammals. An example of marine protected areas established around marine mammals include the Gully marine reserve, an underwater canyon of the coast of Nova Scotia, which has been shown to be a vital foraging area for the northern bottlenose whale *Hyperoodon ampullatus* (Hooker *et al.,* 2002). Within the Moray Firth a candidate special area of conservation (cSAC) has recently been established for the protection of the isolated population of bottlenose dolphins at the most northern extent of its range (Wilson, 1995; Hooker & Gerber, 2004).

When constructing a protected area on land it is easy to be able to identify the factors which make it suitable for the species present. Also, terrestrial habitats remain static or change at very slow rates (Cox & Moore, 1994). However, in the marine environment the factors which dictate the distribution of many marine species including cetaceans are often highly variable spatially and temporally (Forney, 2000). Currently the boundaries or extents of already established marine protected areas are either chosen arbitrarily with concern to the environment, i.e. being based solely on high sighting frequencies (Hamazaki, 2002) or with respect to those features of habitats which do not change or vary at extremely low rates. These features are commonly referred to as fixed environmental variables and examples include bathymetric characteristics (depth, gradient, aspect) and sediment types (Naud *et al.,* 2003; Yen *et al.,* 2004). An intrinsic feature and problem of marine reserves established using either of the procedures is that their boundaries become permanently fixed (Hamazaki, 2002). However, as stated previously, cetacean distributions may change i.e. shift around or outside of designated protective zones, due to oceanographic changes of non-fixed environmental parameters (e.g. sea surface temperature, salinity, productivity). an example being the higher density of sperm whale *Physeter macrocephalus* associated with warm core rings in the north Atlantic (Griffin, 1999). To accommodate non stationary cetacean habitats, it could be more effective to shift the location and extent of protective zones if required because of seasonal variation or climate change, based on the results of habitat prediction models incorporating more accurate information and data regarding fixed and non-fixed environmental variables (Hamazaki, 2002; Gregr, 2004; Hamazaki, 2004).

Limitations of the study and future research

It is acknowledged that the present study has a number of limitations which could introduce errors into results and subsequent interpretations. Firstly, patterns observed in this study could be explained in part by survey effort. Due to the distances required for travel on surveys and the variable nature of weather and sea conditions occurring in the north of Scotland, many of the surveys took place within the area of predicted sandeel habitat, i.e. inner survey routes from Roseharty to Port Knockie. This would therefore make any sighting of minke whales entirely self selecting in terms of the environmental variables associated with encounters, e.g. sandy gravel sediments, shallow depths and steep slopes. Also, it was observed that in those years when survey effort was low, minke whale sightings frequency was low. In those years when survey effort was high, minke whale sightings frequency was high. Therefore, the relative amount of survey effort is a key part to why minke whales may be more abundant. Varying levels of survey effort can make the presence of minke whales, once again, self selecting. Weather and sea state is also an important factor. If sea states are high then the probability of sighting animals, even though survey effort may be high, is greatly reduced and incomparable to previous years with the same effort but calmer seas.

Though this project has made a series of interesting observations regarding the interactions between the spatio-temporal distributions of minke whales in relation to the environment, it is difficult to relate these findings directly to minke whale distributions in other locations. The minke whale is a cosmopolitan species and therefore must cope with a wide range of different habitats and prey species throughout its extensive range. In response minke whales from different areas have developed differing strategies and behaviours to utilise these areas and resources. Therefore, observations made of whales within the present study area may differ slightly from the behaviours of whales observed elsewhere in the UK and differ entirely to whales observed further a field, e.g. Norway, Canada & Antarctica.

Lastly, all animals encountered during the analysis of this master's project were considered to be different. However, this does not take into account that some encounters may have been the same whales sampled multiple times. The CRRU research activities do have a photo-identification project. This has established a catalogue of animals which have occurred and been recaptured during the time scale of the project. However, this information was not included within this MSc because it was considered to be too much information with regard to the scope of the thesis.

Future research which could be conducted can overcome the limitations of the present study as well as introduce new techniques to add greater detail and application of information from research activities. These are listed below:

- Increased survey effort to ensure that the survey area is evenly studied to reduce bias induced from effort focused in particular areas.

- More focal observations should be made on the behaviours observed by whales and their interaction with other species such as sea birds, fish and other marine mammals. This information will add greater detail into the methods used in this study, providing a greater picture of what processes and interactions are occurring between the whales, the community and the environment.

- The application of a photo-identification method to discern to what extent animals are encountered multiple times. This method would also allow insight into the site fidelity of minke whales selecting the area and therefore, how crucial this part of the British Isles is for this portion of the species population.

- Predictive modelling techniques should be conducted to ascertain whether the patterns and correlations observed in this study have applications to predicting the species future distribution. This should first be done within the Moray Firth to ascertain if the patterns and interactions observed between minke whales and the surrounding environment during the study were typical for the species distribution and subsequent habitat selection. If minke whale distribution and relative encounter frequency can be predicted successfully then this process can be expanded to include other areas around the UK and then elsewhere in the north Atlantic.

- The project should be expanded in scale to collect information on the distributions of minke whales in relation to co-occurring environmental parameters in other locations. Currently the study can only represent patterns observable for the species in this part of the survey area. Therefore, the collection of data from areas where the environment differs slightly in terms of nature, i.e. coastal areas and ice edges, and in terms of primary prey selection, e.g. sandeels in UK and Euphausiids around Svalbard, should be considered a priority. Only until we correctly observe all the influences the environment has upon the habitat selection of this cosmopolitan and highly adaptable species can we begin to predict its distribution and adequately manage and conserve it.

- As shown in this study the encounter locations of animals can be directly compared to surrounding environmental conditions such as bathymetry, sediment type, water temperature and productivity remotely through the use of GIS and remote sensing. Therefore, through communication with other similar organisations, compare and contrast collaborations could provide additional sightings information for a range of different areas including the west coast of Scotland (Hebridean Whale and Dolphin Trust), St Lawrence Estuary, Canada (Foundation for Marine Environment Research) and Andøya, Norway (Andenes Whale Centre). This additional information would allow a more complete picture to be observed on the interactions of the species and its varying adaptations to a wide range of environmental conditions.

5. Conclusion

5 Conclusion

This study has shown that though minke whales were encountered in the southern outer Moray Firth their distribution in space and time was highly variable. Through the use of GIS and remote sensing techniques a number of observations were made and the subsequent hypothesises of why this variability occurs made possible. The strongest correlations between minke whale distribution and encounter frequency were for those variables which were fixed such as bathymetry (depth, slope & aspect) and sediment type. All these variables were associated primarily with providing suitable habitat for the minke whales primary prey species, the sandeel, promoting productivity associated with higher densities of available prey. Also, a number of interesting observations were made between the distribution of whales and the existence of two important oceanographic features, a cold water current and a warm water plume, which dominant the Moray Firth system. These are thought to effect the distribution of non-fixed variables such as temperature and primary productivity within the embayment. Finally, detailed observations showed that distribution with regard to age class and behaviour were correlated with significant variations in the surrounding environment. These findings support the supposition that this area is important to the whales for foraging, and further indicates the possible presence of habitat partitioning in this species.

This information and the further questions raised from the study not only add to our understanding of minke whale ecology but also to the further development of the methods with which we observe this and other species. This is crucial not only for our ability to understand the ecology of these animals but to enhance the ways in which we conserve, manage and protect them. It is considered a priority in this action therefore to accurately identify and understand why these animals choose and interact with certain areas and not others. This will direct conservation and research effort to areas which require protection and management quickly and efficiently. Time and cost are identified as the two primary restrictions effecting any future conservation or research endeavour relating to any threatened species, especially the marine mammals.

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6 Acknowledgements

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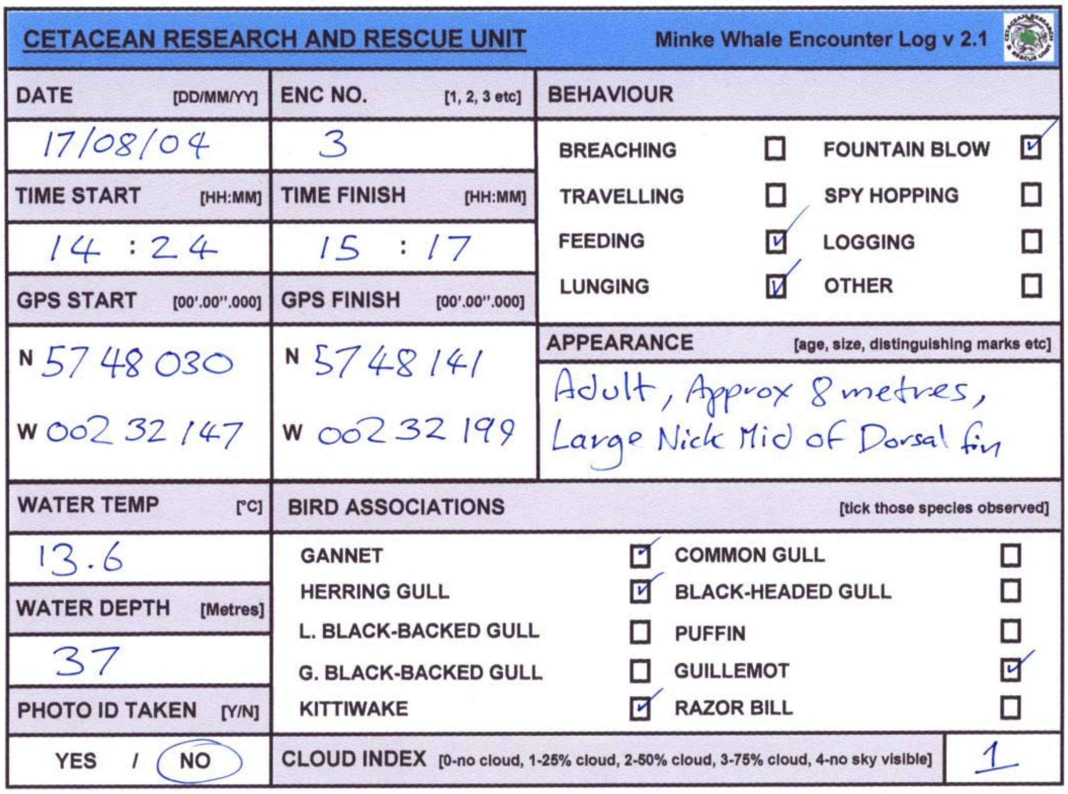
8. Appendices

Appendix A. Example of minke whale encounter log which was laminated and used to record information using a chinagraph pencil.



CETACEAN RESEARCH AND RESCUE UNIT Minke Whale Encounter Log v 2.1

DATE [DD/MM/YY]: 17/08/04

ENC NO. [1, 2, 3 etc]: 3

TIME START [HH:MM]: 14 : 24

TIME FINISH [HH:MM]: 15 : 17

GPS START [00'.00''.000]: N 57 48 030 W 002 32 147

GPS FINISH [00'.00''.000]: N 57 48 141 W 002 32 199

BEHAVIOUR

BREACHING	☐	FOUNTAIN BLOW	☑
TRAVELLING	☐	SPY HOPPING	☐
FEEDING	☑	LOGGING	☐
LUNGING	☑	OTHER	☐

APPEARANCE [age, size, distinguishing marks etc]: Adult, Approx 8 metres, Large Nick Mid of Dorsal fin

WATER TEMP [°C]: 13.6

WATER DEPTH [Metres]: 37

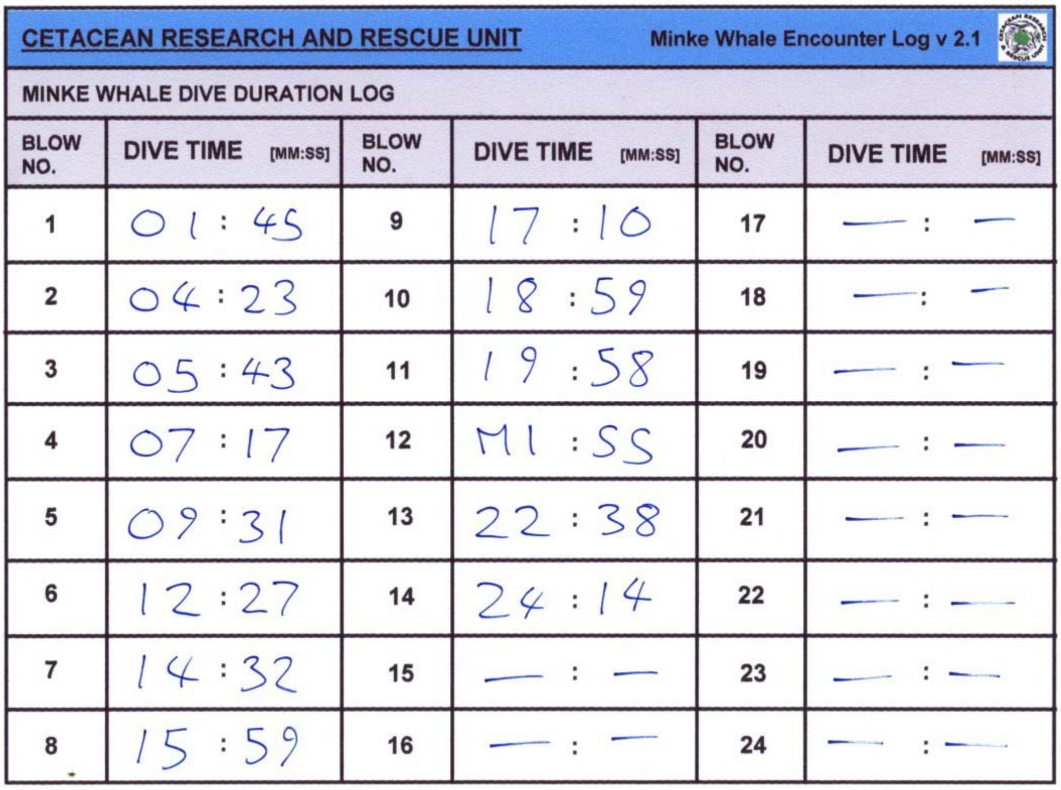
PHOTO ID TAKEN [Y/N]: YES / [✓ NO]

BIRD ASSOCIATIONS [tick those species observed]

GANNET	☑	COMMON GULL	☐
HERRING GULL	☑	BLACK-HEADED GULL	☐
L. BLACK-BACKED GULL	☐	PUFFIN	☐
G. BLACK-BACKED GULL	☐	GUILLEMOT	☑
KITTIWAKE	☑	RAZOR BILL	☐

CLOUD INDEX [0-no cloud, 1-25% cloud, 2-50% cloud, 3-75% cloud, 4-no sky visible]: 1

Appendix B. Example of minke whale dive duration log which was laminated and used to record information using a chinagraph pencil.

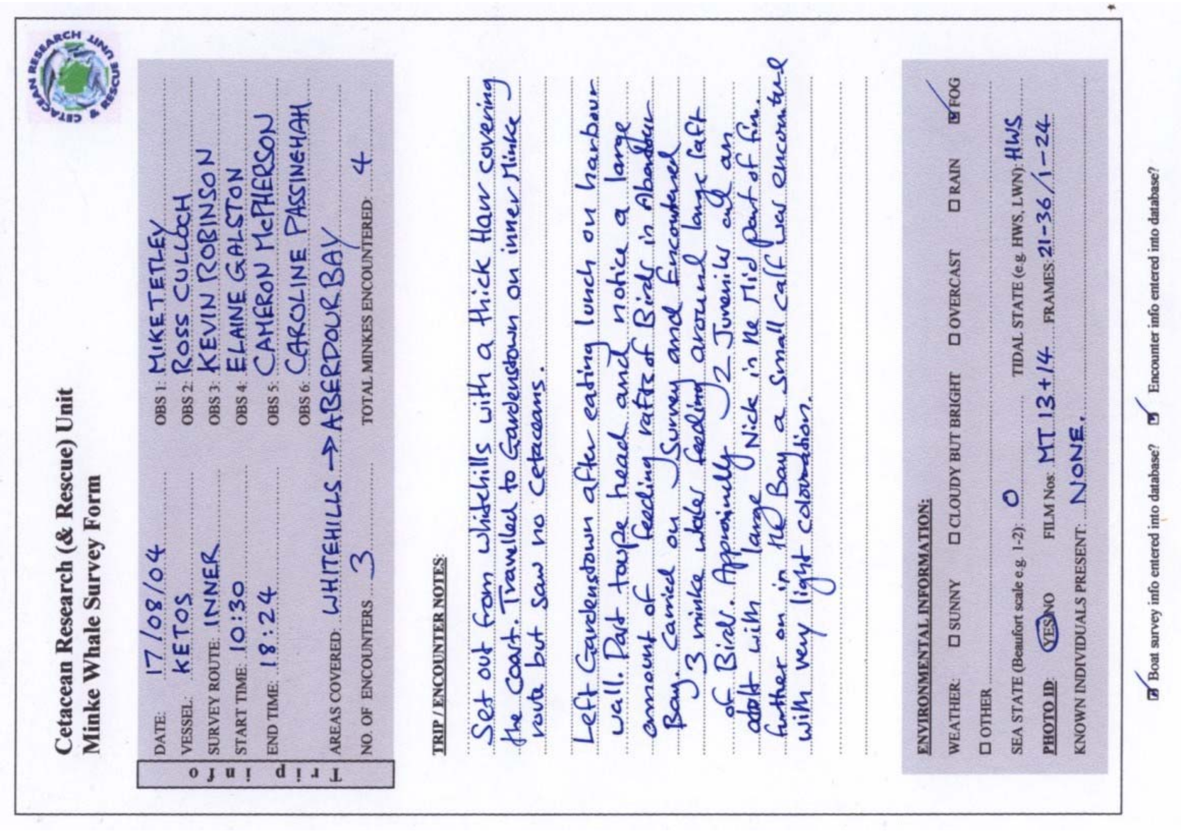


CETACEAN RESEARCH AND RESCUE UNIT Minke Whale Encounter Log v 2.1

MINKE WHALE DIVE DURATION LOG

BLOW NO.	DIVE TIME [MM:SS]	BLOW NO.	DIVE TIME [MM:SS]	BLOW NO.	DIVE TIME [MM:SS]
1	01 : 45	9	17 : 10	17	— : —
2	04 : 23	10	18 : 59	18	— : —
3	05 : 43	11	19 : 58	19	— : —
4	07 : 17	12	MI : SS	20	— : —
5	09 : 31	13	22 : 38	21	— : —
6	12 : 27	14	24 : 14	22	— : —
7	14 : 32	15	— : —	23	— : —
8	15 : 59	16	— : —	24	— : —

Appendix C. Example of minke whale survey form which was used as a hard copy for storage of survey trip and encounter information.



Cetacean Research (& Rescue) Unit
Minke Whale Survey Form

Trip info

DATE: 17/08/04
VESSEL: KETOS
SURVEY ROUTE: INNER
START TIME: 10:30
END TIME: 18:24
OBS 1: MIKE TETLEY
OBS 2: ROSS CULLOCH
OBS 3: KEVIN ROBINSON
OBS 4: ELAINE GALSTON
OBS 5: CAMERON McPHERSON
OBS 6: CAROLINE PASSINEHAH
AREAS COVERED: WHITEHILLS → ABERDOUR BAY
NO. OF ENCOUNTERS 3
TOTAL MINKES ENCOUNTERED: 4

TRIP / ENCOUNTER NOTES:

Set out from whitehills with a thick Haar covering the coast. Travelled to Gardenstown on inner Minke route but saw no Cetaceans.

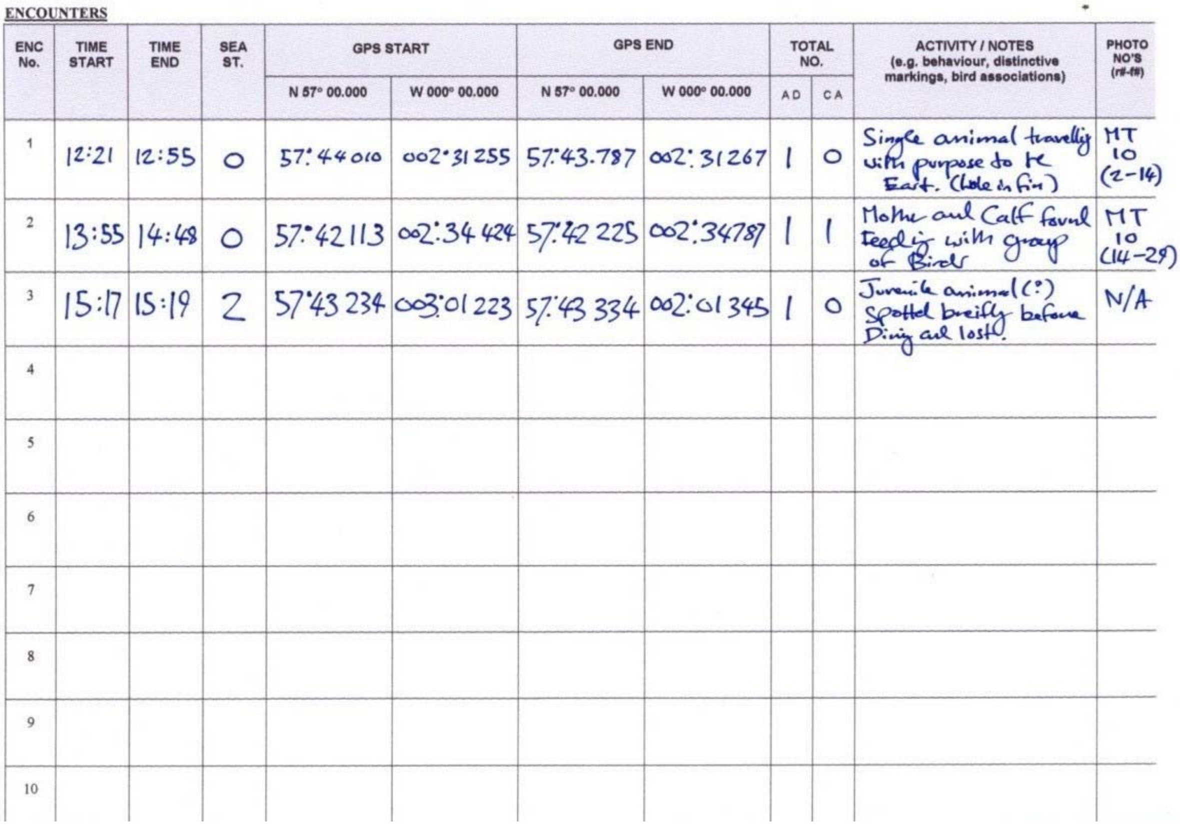
Left Gardenstown after eating lunch on harbour wall. Past toupe head and notice a large amount of feeding rafts of Birds in Aberdour Bay. Carried on Survey and Encountered 3 minke whales feeding around large raft of Birds. Approximately 2 Juveniles and an adult with large Nick in the Mid part of fin. further on in the Bay a Small calf was encountered with very light colouration.

ENVIRONMENTAL INFORMATION:

WEATHER: ☐ SUNNY ☐ CLOUDY BUT BRIGHT ☐ OVERCAST ☐ RAIN ☒ FOG
☐ OTHER
SEA STATE (Beaufort scale e.g. 1-2): 0
TIDAL STATE (e.g. HWS, LWN): HWS
PHOTO ID: [✓ YES] NO
FILM Nos: MT 13+14
FRAMES: 21-36/1-24
KNOWN INDIVIDUALS PRESENT: NONE.

☒ Boat survey info entered into database? ☒ Encounter info entered into database?

Appendix D. Example of minke whale survey form which was used as a hard copy for storage of encounter information.



ENCOUNTERS

ENC No.	TIME START	TIME END	SEA ST.	GPS START		GPS END		TOTAL NO.		ACTIVITY / NOTES (e.g. behaviour, distinctive markings, bird associations)	PHOTO NO'S (r#-f#)
				N 57° 00.000	W 000° 00.000	N 57° 00.000	W 000° 00.000	AD	CA		
1	12:21	12:55	0	57°.44010	002°.31255	57°.43.787	002°.31267	1	0	Single animal travelling with purpose to the East. (Hole in fin)	MT 10 (2-14)
2	13:55	14:48	0	57°.42113	002°.34424	57°.42 225	002°.34787	1	1	Mother and Calf found feeding with group of Birds	MT 10 (14-29)
3	15:17	15:19	2	57°43 234	003°01 223	57°43 334	002°01 345	1	0	Juvenile animal (?) Spotted briefly before Diving and lost.	N/A
4											
5											
6											
7											
8											
9											
10											

Appendix E. CD rom containing encounter data used during the study. Includes encounter locations, details (age & behaviour classes) and environmental variables associated with each encounter.

This Box

Should Contain

A Data CD Rom