ASSESSMENT OF METHODS USED TO INVESTIGATE THE IMPACT OF OFFSHORE WIND FARMS ON SEABIRDS

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CONTENTS

AUTHOR'S DECLARATION

I declare that the work presented in this thesis has been composed and undertaken by myself. No part of this work has been accepted in any previous application for a degree. All sources of information have been specifically acknowledged and all quotations have been distinguished by quotation marks. All assistance from others has been specifically acknowledged.

Kate Brookes, 2009

SUMMARY

Large increases in the capacity for producing renewable energy are necessary if the UK and EU are to meet their greenhouse gas emission targets. Much of this increased capacity will come from offshore wind farms. The installation of these structures may have impacts on marine wildlife, including seabirds, requiring robust environmental impact assessments to identify and mitigate against potential risks. The overall aim of this thesis was to assess whether remote radar technology could be used to collect ornithological data required for EIA for offshore wind farms. An S-band marine surveillance radar was installed on the Beatrice Alpha oil platform, 22 km offshore in the Moray Firth, Scotland and operated from June 2006. This was adjacent to the site of the EU DOWNVInD demonstrator project, which installed two 5 MW wind turbines at the most offshore deep water site yet developed. Commercially available software linked to the radar was used to automatically detect and track birds, but significant amounts of radar clutter were also recorded in this offshore environment. Bespoke filters were then developed to eliminate non-avian tracks from the dataset. The filtered data showed temporal patterns over scales of days to seasons that could be linked to existing knowledge of the use of the site by seabirds. Patterns in flight directions during the breeding season indicated that birds using the site were also attending colonies at the East Caithness cliffs SPA to the north west. Radar data were also used to assess the flight speed parameter used in the Band collision model, which calculates collision probability between birds and wind turbines. Collision risk was shown to increase with decreasing ground speed of the bird. The flight speed values used in most calculations of collision risk are the published mean airspeeds, which do not account for the effect of wind on flight speed. Ground speeds of radar tracks were highly variable and on average were 0.707 ms^{-1} slower than airspeeds, indicating that in many cases it is not appropriate to use airspeed as a proxy for ground speed. Radar was shown to be a useful tool for answering some questions relating to offshore wind turbine impacts on seabirds, but should be viewed as one technique within a suite available and may not be the most appropriate to answer every question.

The second aim of this thesis was to use visual boat-based surveys in the spring of 2006 and 2007 to assess the impact of the installation of the two wind turbines on seabird abundance and distribution at the site. No impact of turbine installation was detected, despite large differences in abundance between the years. However, environmental variation had a highly significant effect on the density of birds, demonstrating the difficulties in assessing impacts against the background variability inherent in marine environments.

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I dedicate this thesis to my grandfather, James Lawson, who turned 100 this year and is the best example of tenacity and determination I know.

Chapter one

General introduction

INTRODUCTION

Climate change has become a key policy issue for governments around the world. The period from 2011 to 2030 is predicted to be 0.64ºC to 0.69ºC warmer than the period from 1980 to 1999 (Meehl *et al.*, 2007). Previous inconsistencies in time series have been resolved, strengthening the case that this is the result of increased anthropogenic production of greenhouse gases (Thompson *et al.*, 2008). The consequences may include an increase in the frequency and intensity of storms (Meehl *et al.*, 2000) as well as rises in sea level as a result of melting polar ice (Meehl *et al.*, 2007).

Ecological responses to this warming are already evident in the form of range shifts (Devictor *et al.*, 2008), changes in phenology (Cleland *et al.*, 2007) and in community assemblages and trophic interactions (Doney, 2006; Walther *et al.*, 2002). Seabird breeding success has been shown to be linked to large scale climate events (e.g. Frederiksen *et al.*, 2004; le Bohec *et al.*, 2008; Thompson & Ollason, 2001), although for some species, the benefits of synchronous breeding may outweigh the benefits of individual responses to climate variation (Reed *et al.*, 2006). While phenology may be changing in relation to climate change, a meta-analysis of studies of 11 species showed that eight were mistimed in relation to peak food availability (Visser & Both, 2005) and Devictor *et al.* (2008) showed that the while the ranges of breeding birds in France were moving northwards, they were not keeping pace with temperature changes. For many species, these changes are additional to problems such as habitat loss and persecution. Crain *et al*. (2008) reviewed studies in the marine environment and demonstrated that in many cases, multiple stressors act in a synergistic or cumulative manner, increasing the stress on individual species.

Warming between the years 2011 and 2030 is already committed, meaning that this will occur even if greenhouse gases remain at year 2000 levels. However, predictions of warming for the middle of the 21st century show that only about a third is already committed and for the end of the century, only 20% is committed (Meehl *et al.*, 2007). This indicates that mitigation efforts have the potential to ameliorate the worst effects of future climate change. The economic case for taking action to reduce greenhouse gas emissions was made in the Stern review, which concluded that it will be cheaper do this now than to take action against the effects of climate change in the future (Stern, 2007). Consequently, the EU has targets to increase energy production from renewable sources to 20% by 2020, with the UK contributing an increase in production of renewable energy from 1.3% in 2005 to 15% by 2020 (EU Renewable Energy Directive, 2009; DECC, 2009).

Meeting these targets will require a large increase in the installed capacity of renewables, much of which is predicted to be from offshore wind sources. In the UK's Round 3 of offshore wind (figure 1.1a), The Crown Estate is aiming to facilitate the installation of 25 GW of power (The Crown Estate, 2009a), more than 28 times the capacity already installed or under construction. Applications have been taken for exclusivity agreements for this (The Crown Estate, 2009a) and have already been announced for a Scottish territorial waters round (waters within 12 NM) (The Crown Estate, 2009b) (figure 1.1b).

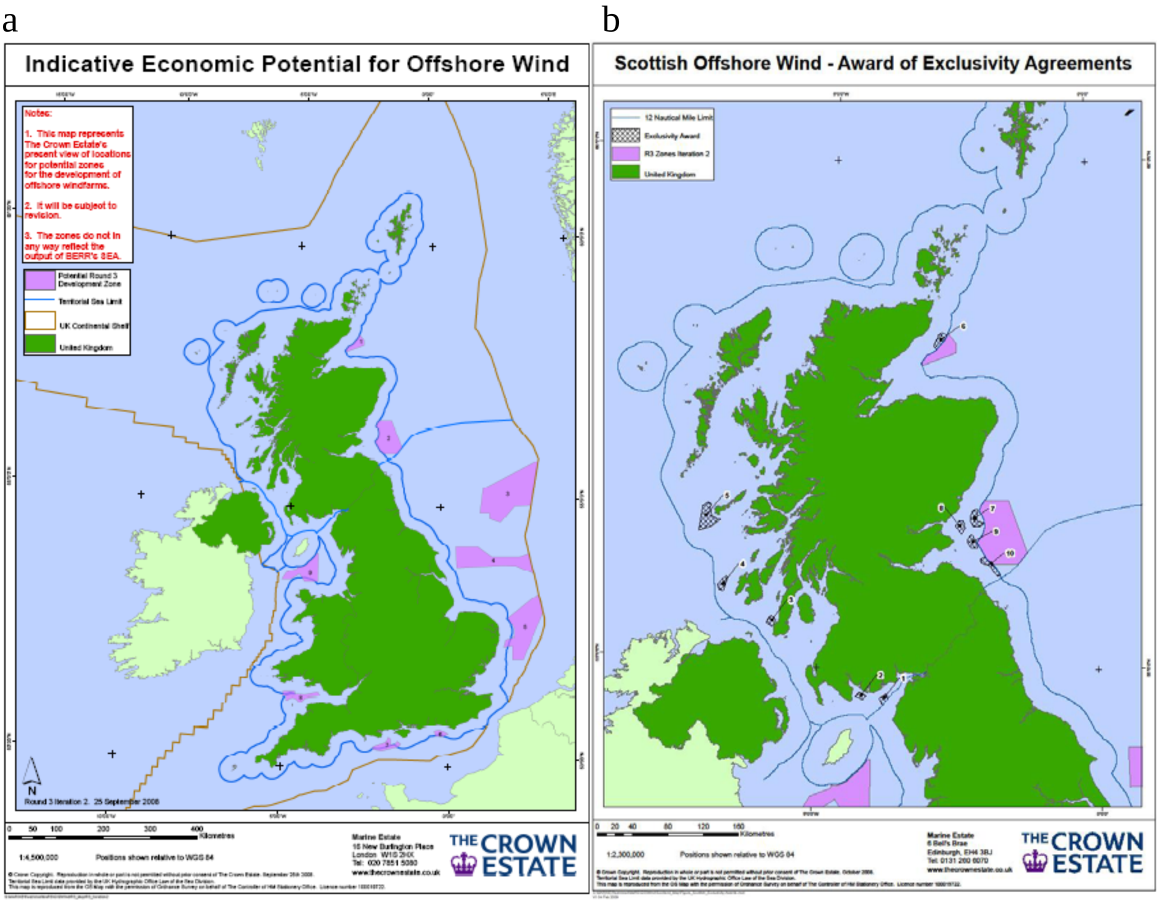

Figure 1.1. Maps showing The Crown Estate's proposed locations for (a) Round 3 of offshore wind in the UK (The Crown Estate, 2009a)and (b) the location of exclusivity agreements for wind farms in Scottish territorial waters (The Crown Estate, 2009b).

Sutherland *et al*. (2006) and Sutherland *et al*. (2008) identified the interaction between wildlife and renewable energy devices as a key ecological policy question in the UK. Mapping of onshore areas in Scotland containing bird species sensitive to wind turbines and sites that are protected showed that there was considerable overlap with turbine sites in some areas, particularly the Highlands and Islands (Bright *et al.*, 2008). However, spatial analyses of terrestrial sites in Germany have shown that despite restrictions placed on developments from nature conservation, there is still plenty of scope for increasing the number and capacity of wind farms (Krewitt & Nitsch, 2003). This study only considered protected sites as being sensitive to wind power developments. The results of studies addressing the risk to wildlife from renewable energy devices are beginning to become available (e.g. de Lucas *et al.*, 2004; Devereux *et al.*, 2008; Everaert & Stienen, 2007; Hoover & Morrison, 2005; Horn *et al.*, 2008; Johnson *et al.*, 2004; Larsen & Guillemette, 2007; Larsen & Madsen, 2000; Madsen *et al.*, 2006; Rabin *et al.*, 2006; Wilhelmsson *et al.*, 2006), but many questions remain and most studies, particularly in relation to birds, are not concerned with offshore wind farms. Additionally, Stewart *et al*. (2007) found that the quality of data in published reports and EIA was often not good enough to allow informed meta-analysis of potential effects. This was compounded by the use of confidentiality agreements by wind developers, preventing studies from being made available for such analyses.

The potential impacts of renewable energy devices can be categorised as those associated with the construction of the wind farm and those associated with its operation. Displacement from the site during construction is common, while habitat loss through disturbance is a potential problem during the operation phase. Examples of disturbances caused during the construction phase of offshore wind farms are the loud noises created as a result of pile driving activities, which may impact on marine mammals (Madsen *et al.*, 2006) and the presence of boats in the area, which Christensen *et al*. (2003) found to attract herring gulls *Larus argentatus* to the area, but may have displaced diver and Alcid species.

Disturbance from the operation of wind turbines may be a significant impact on some species. California ground squirrels *Spermophilus beecheyi* exhibited elevated levels of vigilance in areas around wind farms compared with similar control areas (Kikuchi, 2008; Rabin *et al.*, 2006). Disturbance from wind turbines may also cause birds to avoid some areas and has been shown to cause a reduction in the area of available foraging habitat for pink-footed geese *Anser brachyrhynchus* by as much as 13% (Larsen & Madsen, 2000). The layout of the turbines was also found to have a strong influence; birds were found not to use the areas between clustered turbines at all. However, wintering farmland birds (except for common pheasant *Phasianus colchicus*) were equally likely to be found at all distances from wind turbines (Devereux *et al.*, 2008). In the marine environment, structures under the water may act as an artificial reef and cause aggregation of some fish species, although this is likely to be a fairly localised effect (Wilhelmsson *et al.*, 2006). Other studies have shown that noise may reduce the hearing range of some species of fish in close proximity to wind turbines (Wahlberg & Westerberg, 2005).

Birds and bats are also susceptible to mortality due to collision with turbine blades. The risk of collision is increased in comparison with other structures because the tips of turbine blades can move more quickly than any predator that birds or bats may have encountered. Studies of bird collisions are more numerous, largely due to this group being more conspicuous, but both migratory and resident bats are thought to be at risk of collision and this may be caused by them being caught in wind vortices around blades (Horn *et al.*, 2008; Johnson *et al.*, 2003; Johnson *et al.*, 2004). Birds are thought to be more likely to collide with turbine blades in low visibility conditions when they are less able to detect obstacles, and during migration because they are less familiar with the areas they fly through (Drewitt & Langston, 2008). Soaring birds were shown to decrease their flight altitude with increased cloud cover (Shamoun-Baranes *et al.*, 2006), which may bring them into the range of turbine heights.

There have been some high profile cases of collisions between wind turbines and birds, especially raptors and soaring birds. For example, in Altamont Pass, California, fatalities of raptors have been documented over the past two decades (Thelander & Smallwood, 2007). Studies in southern Spain showed that griffon vulture *Gyps fulvus* mortality was highest in the autumn when thermals were not available for soaring (Barrios & Rodriguez, 2004). Furthermore, the number of turbine related deaths was not related to the abundance of birds, but more closely to factors that reduced the availability of thermals (de Lucas *et al.*, 2008).

Wind turbines may present a barrier to migration for some bird species, although it seems likely that under most conditions, flocks will be able to avoid turbines. For example, migrating common eiders *Somateria mollissima* were shown to avoid flying through a wind farm area and in cases where they flew between turbines, they maximised the distance to rows of turbines (Desholm & Kahlert, 2005). Avoidance behaviour in eiders has been shown even when decoys were used to attract birds in to the wind farm area (Larsen & Guillemette, 2007). However, migrating birds will only be able to continue avoiding wind farms if there are other suitable areas for them to fly through, so the cumulative effect of increasing the number of wind farms must also be considered (Norman *et al.*, 2007; SNH, 2005).

Much of the work carried out on potential impacts of wind turbines on birds has been terrestrial, largely due to most wind farms being built onshore until recent years. Early studies aimed to use existing information to assess the sensitivity of different bird species to the effects of marine wind farms qualitatively (Garthe & Hüppop, 2004). Criteria such as sensitivity to disturbance, flight characteristics and conservation status were used. Black-throated diver *Gavia arctica* and red-throated diver *G. stellata* were found to be the most sensitive to the installation of marine turbines and the study found that the impact of wind turbine developments generally decreased with increasing distance from the coast. The impact that moving developments further offshore would have on different species was not discussed, although many of the species found to be most at risk are typically coastal (Stone *et al.*, 1995) and so will be less likely to encounter such installations.

During Round 2 of offshore wind in the UK, developers were required to contribute to a trust fund created by The Crown Estate, which financed research on the environmental effects of wind farms. The body created was COWRIE (Collaborative Offshore Wind Research Into the Environment) and has a steering group with members from interested parties such as wind farm developers, Natural England, Scottish Natural Heritage, Countryside Council for Wales, Joint Nature Conservation Committee, Department for Environment, Food and Rural Affairs, Centre for Environment, Fisheries and Aquaculture Science, Royal Society for the Protection of Birds, Department of Energy and Climate Change (formerly Department for Trade and Industry (DTI), then Business, Environment and Regulatory Reform (BERR)) and the British Wind Energy Association (The Crown Estate, 2009c). The research financed has concentrated on developing strategic methodological guidance for carrying out studies of impacts (e.g. Camphuysen *et al.*, 2004; Desholm *et al.*, 2005; Mellor *et al.*, 2007; Norman *et al.*, 2007; Walls *et al.*, 2009).

ENVIRONMENTAL IMPACT ASSESSMENTS FOR OFFSHORE WIND DEVELOPMENTS

There are currently five operational offshore wind farms in UK waters, with a further four under construction. While increasing renewable energy capacity is clearly important for mitigating the effects of climate change on humans and wildlife, it must be balanced against existing conservation objectives. As a result of these potential problems, Environmental Impact Assessments (EIA) have been required for all offshore wind farm developments in the UK to date. Part of this process requires the production of an Environmental Statement which describes the site, from literature already available and also presents the results of any further studies undertaken. The Environmental Statement is a public document and can be commented upon by any person or organisation. Comments are considered by the Department for Energy and Climate Change (DECC), before consent is granted for the development.

The key issue that must be addressed in relation to seabirds is the likelihood and population effect of collision with wind turbines. The questions that need to be answered to allow informed assessments of this can be split into generic questions and those that are site specific. Generic questions include: the flight height of birds in offshore locations; the flight speed of birds; mode of flight; the effect of wind on flight speeds, heights and mode; the identification of species disturbed by the presence of wind turbines; likelihood of flocking; and whether species can and will take action to avoid colliding with turbines. Site specific questions include the number and species of birds using the site, their use of the site (e.g. foraging, migration, roosting), the flight paths taken through the site and whether the birds using the site belong to protected colonies.

For the generic questions, strategic decisions must be taken about whether regulators can expect developers to collect the data at all sites, or whether this should be carried out thoroughly once and applied to all other sites. Questions relating to bird flight height, speed and mode in offshore locations lend themselves to the later approach and could theoretically be carried out at any suitable offshore site, irrespective of whether a wind farm is present. Studies on disturbance and avoidance behaviour must be carried out at post-construction wind farms and therefore will need to be carried out in collaboration with developers.

In all EIA for wind farm developments in the UK, some form of visual survey has been used to identify the species using the site and a desk based study of the proximity of protected areas has been used to determine whether special attention must be paid to particular species. The results of these studies have been used to determine whether further studies of potential impact are required for particular species, for example, using radar to track migration routes of wildfowl (Desholm & Kahlert, 2005), or radio tracking studies to determine the use of a site by birds from a particular colony (Perrow *et al.*, 2006). An assessment of the number of birds likely to collide with the turbines is also carried out and the results of the field studies are used to inform this (Band *et al.*, 2007).

Two main methods have been used in EIA to investigate the use of proposed offshore wind farm sites by birds; visual surveys and radar studies. Visual surveys have been carried out using one of three methods; boat-based surveys, aerial surveys or land based surveys. Guidance on the methods used in these surveys is based upon the well established European Seabirds at Sea protocols (Camphuysen *et al.*, 2004; Tasker *et al.*, 1984; Webb & Durinck, 1992). These methods use point or line transects and distance sampling (Buckland *et al.*, 2001) to determine which species use the site and to produce density estimates of these species at the site. Boat and land based surveys are usually carried out on a site by site basis, whereas aerial surveys have been conducted in a more strategic fashion, by the Wildfowl and Wetlands Trust (WWT) in England and Wales and the Joint Nature Conservation Committee (JNCC) in Scotland. This has been necessary because of limited numbers of trained aerial observers and suitable aircraft.

Visual surveys are useful in most cases because they give species specific information and robust estimates of densities of birds present. However, they are unable to give information about how birds move around the site, what movement occurs at night, or larger scale movements by migrants around the site. Such questions are within the scope of radar studies, but the technique is not widely used, despite being recommended by COWRIE (Desholm *et al.*, 2005). This is mostly due to a lack of understanding of how to employ the techniques, despite radar first being shown to be able to detect bird flocks in World War II (Eastwood, 1967). Moving wind farm developments further offshore increases the need for reliable remote techniques because of the increasingly complex logistics of carrying out visual surveys in such areas.

Three main types of radar have been used in ornithological research: long range surveillance radar (weather and air traffic control radar), military tracking radar, and low powered marine surveillance radar. The choice of radar depends on the type of study and the scale and resolution of observations required, although prices and availability must also be taken into consideration. All have the same major drawback, which is the lack of species discrimination, requiring additional visual observations to gather these data.

Long range surveillance radar such as weather radar have been used to make observations of movements of purple martins *Progne subis* in and out of roost sites in the USA (Russell & Gauthreaux, 1998) and combining images from across the network of weather radars has allowed patterns across continents to be studied (Russell *et al.*, 1998). Migration movements through areas have also been studied and radar has been shown to be a more effective tool for detecting migration than techniques such as call counting at night (Farnsworth *et al.*, 2004). The weather radars used in the studies often have Doppler capability, allowing very accurate speeds to be recorded, which can help to discriminate between birds and insects and in some cases between species of birds (Gauthreaux *et al.*, 2008). Much of the work has so far been carried out in the United States of America, largely due to the fact that the weather radars all belong to the same network, making comparisons easier. However, recent studies have demonstrated that weather radar data in the Netherlands could collect data on bird flight heights, speeds and direction that was comparable to those collected by a dedicated bird radar (van Gasteren *et al.*, 2008). Smaller Doppler radars are used in police speed guns and have been used effectively to gather data on bird flight speeds (Evans & Drickamer, 1994).

Military tracking radar have been used in many studies of migration, and are capable of tracking birds (individuals or flocks) in three dimensional space (Alerstam *et al.*, 2001; Alerstam *et al.*, 1993; Hedenström *et al.*, 2002; Komenda-Zehnder *et al.*, 2002; Shamoun-Baranes *et al.*, 2006). These radars are often high powered (e.g. 150 kW) X-band radars, with short wavelengths (2.5 cm to 3.75 cm), meaning that they are capable of discriminating small targets such as passerines (Schmaljohann *et al.*, 2007). Some studies have also been able to use frequency modulations to investigate wing beat frequencies, to give an indication of the species identity (Bruderer, 1997; Komenda-Zehnder *et al.*, 2002). However, it seems likely that it is only possible to separate groups of species with this method (Liechti, 1993).

Low powered surveillance radar has been the most commonly used radar for wind farm environmental assessments (Desholm & Kahlert, 2005; Harmata *et al.*, 1998; Harmata *et al.*, 1999). The units are more commonly used as marine radar, on boats, which increases their availability and reduces cost (Kunz *et al.*, 2007). The power ranges from around 5 kW to around 30 kW. The most common type of marine surveillance radar is X-band, which gives high resolution of targets, particularly when used at low range (e.g. Williams *et al.*, 2001). However, such high resolution also means that X-band radars detect rain very easily and displays can become saturated with rain clutter. Using S-band radar can ameliorate this effect since the wavelength is considerably longer (7.5 cm to 15 cm) and will often be larger than the radar cross section of rain, reducing its detection (Cooper, 1995). At sea, there is the additional problem of sea clutter, which occurs when the radar tracks waves and is worse in high sea states. Using S-band radar ameliorates the effect of sea clutter to a lesser extent than rain clutter, because wave targets are considerably bigger than rain targets.

Surveillance radars used for wind farm impact assessments have generally been used to monitor migration through the study site (Christensen *et al.*, 2004; Cooper *et al.*, 1991; Desholm & Kahlert, 2005; Harmata *et al.*, 2003; Krijgsveld *et al.*, 2005). The first deployment of radar offshore for ornithological purposes was at the Horns Rev wind farm development in Denmark (Christensen *et al.*, 2004; Desholm & Kahlert, 2005), where the radar was situated on a meteorological mast installed as part of the wind farm development, to monitor wind conditions at the site. The study aimed to monitor the movement and collision risk to migrating common eiders at the site. Several researchers have gathered data on flight altitudes by modifying the antenna of X-band radar to spin in the vertical plane (Cooper *et al.*, 1991; Harmata *et al.*, 2003; Krijgsveld *et al.*, 2005; Parnell *et al.*, 2006; Walls *et al.*, 2007).

During Rounds 1 and 2 of offshore wind in the UK (figure 1.2), applications for consent were made for 23 offshore wind farms (The Crown Estate, 2009d). A further five are expected to submit applications before the end of 2009. Copies of all 23 Environmental

Statements were requested from DECC. They were able to provide 11 of these and a further two were made available by the developers (table 1.1). Of this sample, six used some form of radar study, and these fell into two categories: boat-based marine surveillance radars and the avian laboratory style radar used by the Central Science Laboratory (CSL), supplied by DeTect (Inc), Florida. Horizontal and vertical scanning boat-based marine surveillance radars were used to monitor migratory movements of wildfowl through the site, and to aid visual detection of birds.

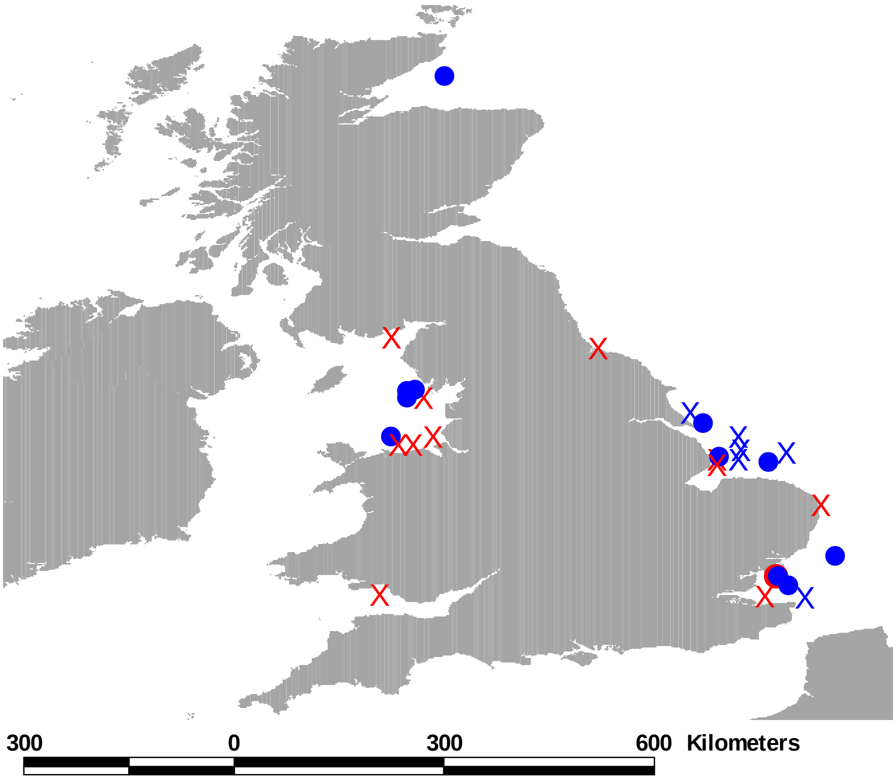

Figure 1.2. Map showing the locations of Round 1 (red symbols) and Round 2 (blue symbols) offshore wind farms in UK waters (The Crown Estate, 2009d). Dots indicate sites for which the Environmental Statement was made available by DECC or the developer, and crosses indicate those for which it was not available.

Table 1.1. List of 13 UK offshore wind farm developments for which the Environmental Statement was available. The use of a radar study and the method used for this is included. CSL radar is a mobile radar system used by the Central Science Laboratory. *The Beatrice radar study was not included in the Environmental Statement. Environmental Statements made available by DECC, Talisman Energy (UK) Ltd and npower renewables.

Wind farm	Region	Radar study	Type of radar study
Beatrice	Highland	Yes*	Academic
Cirrus Array (Shell Flats)	Northwest England	No	-
Greater Gabbard	Thames Estuary	No	-
Gunfleet Sands I	East of England	No	-
Gunfleet Sands II	East of England	No	-
Gwynt y Môr	North Wales	Yes	Boat-based radar
Humber Gateway	Yorkshire and Humber	No	-
Lincs	Greater Wash	Yes	CSL radar
London Array	Thames Estuary	No	-
Ormonde	Northwest England	No	-
Sheringham Shoal	East of England	Yes	CSL radar
Walney	Northwest England	Yes	Boat-based radar
West of Duddon Sands	Northwest England	Yes	Boat-based radar

The radar system used by CSL is mobile, being towed on a trailer and consists of a horizontally scanning S-band radar and a vertically scanning X-band radar to give altitude profiles of bird flight. Both radars are linked to automatic detection and tracking software, but the two data sets are not linked, so the position and height of an individual bird or flock is not known. Radar observations have tended to be made at sites where migrating birds are a cause for concern during relatively short periods, usually of up to six weeks, to provide information on the number of flocks moving through the site and the typical flight paths travelled (Parnell *et al.*, 2006; Walls *et al.*, 2007). The system has not been used from boats, but is believed not to be capable of accounting for the pitch and roll of a vessel. The radar system used in the Beatrice study is similar to the CSL radar, using the same automatic detection and tracking software, but uses only horizontally scanning S-band radar.

Collision risk modelling

A collision risk assessment is required for species shown to be using the site for transit or foraging. In the UK, this is usually based on the Band model (Band *et al.*, 2007), developed by Scottish Natural Heritage (SNH). A spreadsheet containing the calculations is available (SNH, 2000) to allow standardised calculation of the collision risk for use in EIA. The model has two stages; the first calculates the number of birds likely to fly through a risk area per year and the second calculates the probability of collision. When combined, these two factors allow an estimation of the numbers of birds that might collide with turbines per year. The number of birds passing through the risk area per year has two cases; birds making transit flights through the area and birds using the area for foraging or perhaps breeding. The first case simply requires knowledge of the number of birds passing through the area, whereas the second case requires more detailed knowledge of the behaviour of specific birds at the site throughout the year. This sort of information is usually gathered using vantage point visual surveys to monitor the number of flights through different areas of the site (e.g. Walker *et al.*, 2005), but radar may prove a useful alternative technique in some cases, particularly in offshore locations, where suitable vantage points may be difficult to access.

Parameters relating to bird length, wing span and flight speed are input by the user for the species of interest. Generalised average values for bird length and wing span are useful where species do not exhibit large amounts of sexual dimorphism, but flight speeds may vary considerably with wind speed (see chapter five). The model also does not include any parameter on the flight height of birds at offshore locations. McAdam (2005) modified the Band model and showed that it underestimates collision probability at flight heights around the hub height (64.5 m to 111.5 m, on a turbine with hub height of 88 m), but overestimates it at all other heights. At the heights with the highest risk, McAdam’s model showed that flying with a strong headwind could increase collision probability by 14.3%, compared to flying with a weak tailwind.

Cumulative impacts

The cumulative impacts that building many wind farms may have on seabirds have been given little consideration to date, largely due to the complex nature of the question. Other impacts on seabirds, such as fishing and reduced breeding success (Wanless *et al.*, 2005) must also be taken into consideration since the installation of a wind farm may exacerbate these impacts. Impacts potentially exist for both migratory and breeding species. For migratory species, the additional energy expenditure required to avoid a single wind farm is negligible (Speakman *et al*. 2009), but diverting flights to avoid several wind farms over large stretches of coast line may increase the energetic demands of long distance flight. Speakman *et al*. (2009) also showed that increased foraging ranges for breeding birds may increase their daily energetic requirements by as much as 6%, based on daily increases in flight distance of 15 km. The relationship between energy demand and increase in foraging distance was linear, with increases in distance of 1 km resulting in an increased energy expenditure of between 0.3% and 0.4% for divers and terns. Many breeding birds, for example, guillemots, forage on sand banks for sandeels *Ammodytes marinus* to feed chicks (Wright & Begg, 1997) and some are capable of flying up to 80 km per trip during the chick rearing period (Cairns *et al.*, 1987). If birds are found to be susceptible to displacement from sand banks by wind turbines, construction of wind farms on several sand banks within this foraging range may have a serious impact on the birds' ability to find food.

No guidance exists to date on how developers should assess cumulative impacts, although a workshop on the subject was held by COWRIE (Norman *et al.*, 2007). The key outcome from this was to draw attention to a lack of accord on a definition of cumulative impacts. It was agreed that impacts could occur over different timescales and that some of the impacts, for example climate change, are yet to manifest themselves fully. It was also agreed that impacts could come from several different sources, some of which will be related to wind farm activities and will therefore require consent, while others, such as fishing and boat traffic will not require specific consent. The workshop also agreed that there should be more discussion between interested parties during the consenting process and more openness about the lack of knowledge surrounding cumulative impacts.

The workshop on cumulative impacts (Norman *et al.*, 2007) identified population viability analysis (PVA) as being of critical importance as a currency for measuring impacts. These analyses use demographic parameters to estimate the probability that a population will persist for a given number of years, given stochastic variability (Brook *et al.*, 2000). Brook *et al*. (2000) assessed the use of PVA for 21 species and found that it could be a useful tool for conservation. However, Coulson *et al*. (2001) was critical of the conclusions drawn in Brook *et al*.'s (2001) study because the analyses can only be robust where high quality long term demographic data are available for the species, and where there is an expectation that the population demographics will be similar in the future. Maclean *et al*. (2007) determined that the quality of demographic data on seabird populations around the UK was good enough to enable PVA in relation to wind farms to be carried out for most species. However, the assumption that demographic parameters will remain the same in the future is unlikely to hold true. Seabird species around the UK and

Ireland generally showed range expansions and increases in abundance throughout the 20th century (Grandgeorge *et al.*, 2008), but have had poor breeding seasons since 2004 (Mavor *et al.*, 2008; Wanless *et al.*, 2005). This indicates that demographic parameters are unlikely to remain constant in the future, limiting the use of PVA to determine potential impacts of offshore wind farms.

STUDY AIMS

In the UK, most EIA for offshore wind farms have used boat-based or land-based visual observations for ornithological data collection, while rather few have used radar techniques. No study has used radar to monitor local or fine scale movements of birds. This is probably due to two factors: limited expertise in radar ornithology within the UK and the cost of contracting such work for longer periods. The overall aim of this study is to compare the feasibility, efficiency, quality and applicability of data produced by both radar and visual methods in offshore locations. To achieve this overall aim, three specific aims were identified:

Assess the feasibility of installing and running an automated radar tracking system on an offshore platform, without a human observer present
Where radar has been used in EIA, an observer has always been present, and in the UK, most deployments have been from land. As wind farms move further offshore, radar range will not be sufficient to monitor such sites and the logistics of having an observer present at all times will become very difficult. Therefore the study aimed to assess the use of a radar system run automatically from an offshore platform, with minimal intervention by personnel. The data retrieved were assessed for quality and applicability to questions about bird use of the site and in assessments of the impact of wind turbines.

Use radar data to improve estimates of the flight speed parameter in the Band collision model
Using a species' generalised airspeed as the flight speed parameter in the Band model may not represent the speed at which birds actually encounter wind turbines. Radar will be used to gather fine scale experimental data on the speeds that birds actually fly through the study area.

Assess the extent to which impacts on birds can be detected using visual surveys
Environmental impacts can be difficult to distinguish due to background natural variation in bird numbers and movements. Boat-based visual surveys accompanied by measurement of environmental variables will be used to establish the extent to which the abundance of birds at the site is due to the installation of wind turbines.

Many of these questions are addressed in more than one chapter. Chapter two describes the background and context of the study and reviews the biological setting of the study site. Chapter three describes the process of installing a radar unit onto an offshore oil platform, and assesses the data collected. This chapter also lays the foundations for the filtering of data required to ensure quality. In chapter four, the spatial patterns in the use of the site by birds, recorded by radar are investigated and the detection capability of the system is assessed. Chapter five looks more closely at the flight speed component of the Band collision model, to determine whether variability in flight speed is likely to affect the rate of collision between birds and wind turbines. An assessment of the impact of turbine installation on bird abundance at the study site is undertaken in chapter six and is compared with the influence of natural environmental variation on abundance of birds. Chapter seven discusses the results presented in the thesis and puts them into the context of advice to developers on assessing the impact of wind farm developments on seabirds.

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Chapter two

Project background and study area

THE DOWNVInD PROJECT

The work carried out in this thesis is part of the DOWNVInD (Distant Offshore Windfarms with No Visual Impact in Deepwater) project, which is a collaboration between industry and research organisations with the aim of furthering techniques and technologies for developing wind power in deep water. It forms part of an EU Framework 6 project. This demonstrator project will last for five years from turbine installation to assess the feasibility and limitations of offshore wind power. The main partners in the project are Talisman Energy (UK) Ltd. and Scottish and Southern Energy. The project centred on the installation of two 5 MW wind turbines in the Moray Firth, to provide power to the Beatrice Alpha oil platform. These turbines are the largest in offshore waters and are installed in the deepest water and furthest offshore of any wind turbines to date.

The environment group of the DOWNVInD project consists of members from three European universities, and one consultancy, researching the impacts of wind turbine installation and operation on birds, marine mammals and fish as well as visual impacts from land. The work presented in this thesis, as part of the environment group, aims to consider impacts on birds and techniques for assessing these.

STUDY SITE

The study site is in the Moray Firth, in the north of Scotland, within the Beatrice oil field area (figure 2.1). The site is 22 km from the closest point to land, at Berriedale. Three oil platforms (Alpha, Bravo and Charlie) have been in place for more than 20 years and, during this study, were operated by Talisman Energy (UK) Ltd. The largest platform and the only one that is permanently manned is the Beatrice Alpha.

The two wind turbines were installed 1.2 km and 1.8 km from the Beatrice Alpha oil platform (figure 2.1). WTG1 (wind turbine 1) was fully installed in July and August 2006, but was not fully operational until May 2007 due to technical problems. The jacket, on which WTG2 stands, was installed in July 2006, but weather constraints prevented turbine installation from being completed until July 2007.

Each turbine is capable of producing 5 MW of power and is functional at wind speeds between 3.5 ms^{-1} (12.6 kph or Beaufort 3) and 30 ms^{-1} (108 kph or Beaufort 11). The rotors are 63 m long and the hub stands at 88 m above the water (http://www.repower.de/fileadmin/download/produkte/5m_uk.pdf).

The oil platforms and turbines both lie on the Smith Bank in the Moray Firth (figure 2.1). This is a large, sandy area with water depth of approximately 40 m (BGS, 2003). Extensive seabird surveys of the Moray Firth were undertaken from 1980 to 1983, during the early stages of the operation of the Beatrice oil field. The data show seasonal variation in the numbers and species of birds present, with a general trend to increased numbers in the spring and summer and likely dispersal during the autumn and winter (Mudge *et al.*, 1984; Stone *et al.*, 1995). This suggests that the site is an important feeding area for breeding birds. In August and September of 1982 and 1983, Mudge *et al*. (1984) found concentrations of up to 276,000 moulting, post-breeding adult common guillemots *Uria aalge* and chicks in the offshore waters around the Smith Bank. The main fishery in the Moray Firth is for *Nephrops*, although there have been recent increases in the squid fishery (ICES, 2007). The sandeel *Ammodytes marinus* stock is not monitored in the Moray Firth and landings data are not recorded at a fine enough scale to allow conclusions to be drawn about the stock locally. The Moray Firth was historically a commercially important fishing

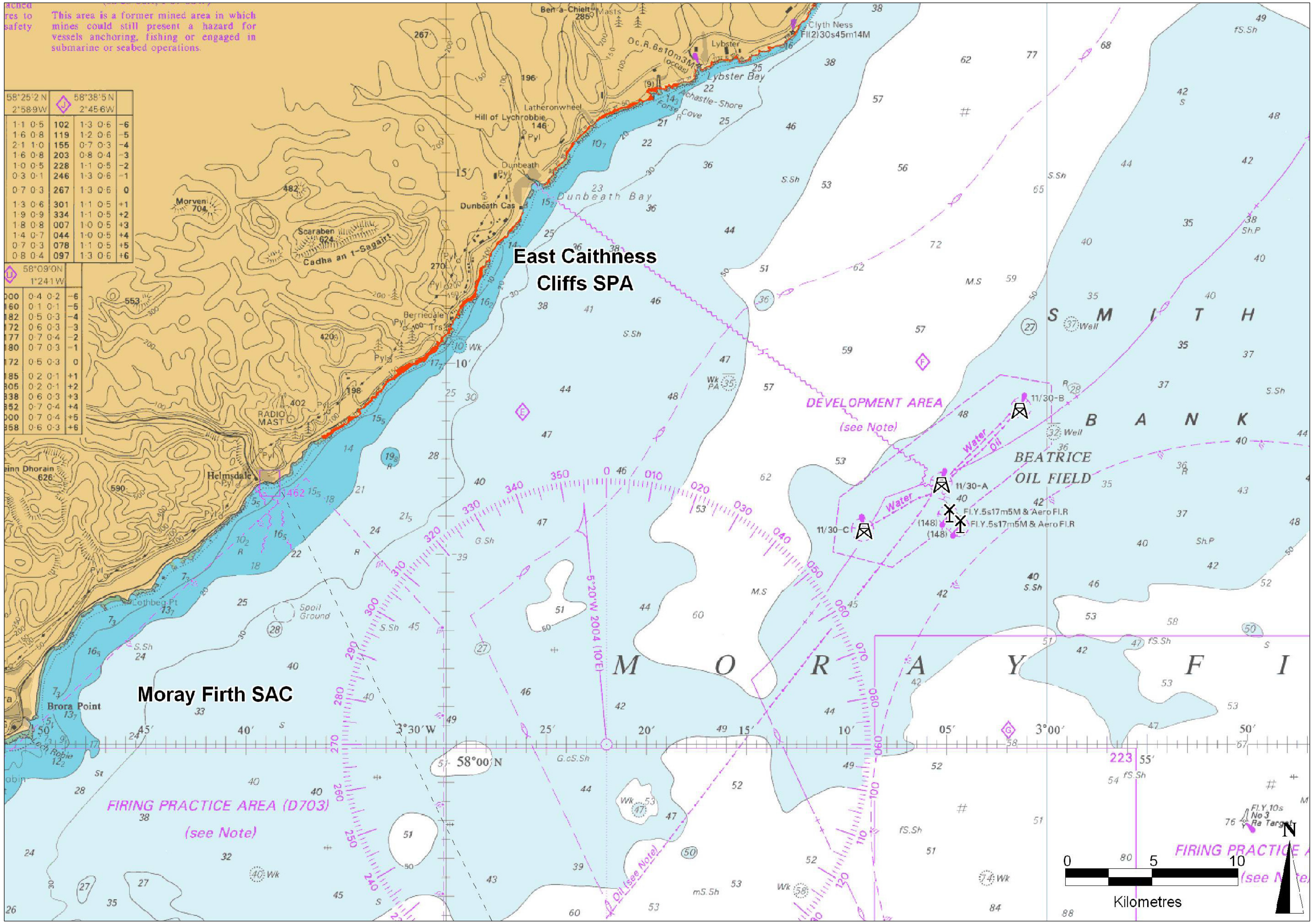


Figure 2.1. Chart showing the north of the Moray First, Scotland, with the locations of the Smith Bank, East Caithness Cliffs SPA (shown in red) and Moray Firth SAC. The Beatrice oil field, with Alpha, Bravo and Charlie platforms and WTG1 and WTG2 (to the south of the platforms) are also shown. © Crown Copyright and/or database rights. Reproduced by permission of the Controller of Her Majesty's Stationary Office and the UK Hydrographic Office (www.ukho.gov.uk). Licence number 13599.

area, with haddock *Melanogrammus aeglefinus,* cod *Gadus morhua*, whiting *Merlangius merlangus*, plaice *Pleuronectes platessa* and lemon sole *Microstomus kitt* being exploited (Hopkins, 1986). The firth was also an important nursery area for herring *Clupea harengus* and was the most important spawning ground for plaice in the North Sea (Hopkins, 1986).

To the north of the site the East Caithness cliffs Special Protection Area (SPA) is designated for its internationally important breeding seabird assemblage (JNCC, 2001). The site also hosts internationally important breeding numbers of common guillemot, razorbill *Alca torde,* shag *Phalacrocorax aristotelis,* black-legged kittiwake *Rissa tridactyla* and herring gull *Larus argentatus* (table 2.1).

Table 2.1. Breeding species for which the East Caithness cliffs are designated an SPA, with total numbers of birds counted and the percentage of the national and biogeographic populations that this accounts for (JNCC, 2001).

Species	**Number breeding**	**% of national population**	**% of biogeographic population**
Guillemot *Uria aalge*	71,509	10.2	3.2
Razorbill *Alca torda*	9,259	9.3	1.6
Shag *Phalacrocorax aristotelis*	2,345	6.3	1.9
Kittiwake *Rissa tridactyla*	31,930	6.5	1.0
Herring gull *Larus argentatus*	9,370	5.9	1.0

As part of the EIA for the wind turbine development, monthly visits were made to the Beatrice Alpha platform from January 2005 to June 2008, by an ornithologist, who recorded birds present. The methods used were refined in March 2006, to include hourly scan samples of a 90° arc from the platform out to 2 km. The ornithologist stood at the same position on the platform for every scan, at a height of approximately 50 m above the water and scanned the arc in one direction with the aid of binoculars. All birds in the arc were identified to species level whenever possible and counted. The distance from the platform was estimated by eye, in distance bands of 0-250 m, 250-500 m, 500-1000 m, 1000-2000 m and over 2000 m. Bird height was estimated and recorded in bands of 0-

20 m, 20-150 m and above 150 m. Environmental data such as wind speed and direction, sea state, visibility and precipitation were also gathered for each scan. Scans were carried out over a 10 minute period and efforts were made to avoid counting individual birds more than once. In total, 370 scans were made, and a total of 12,152 birds were recorded.

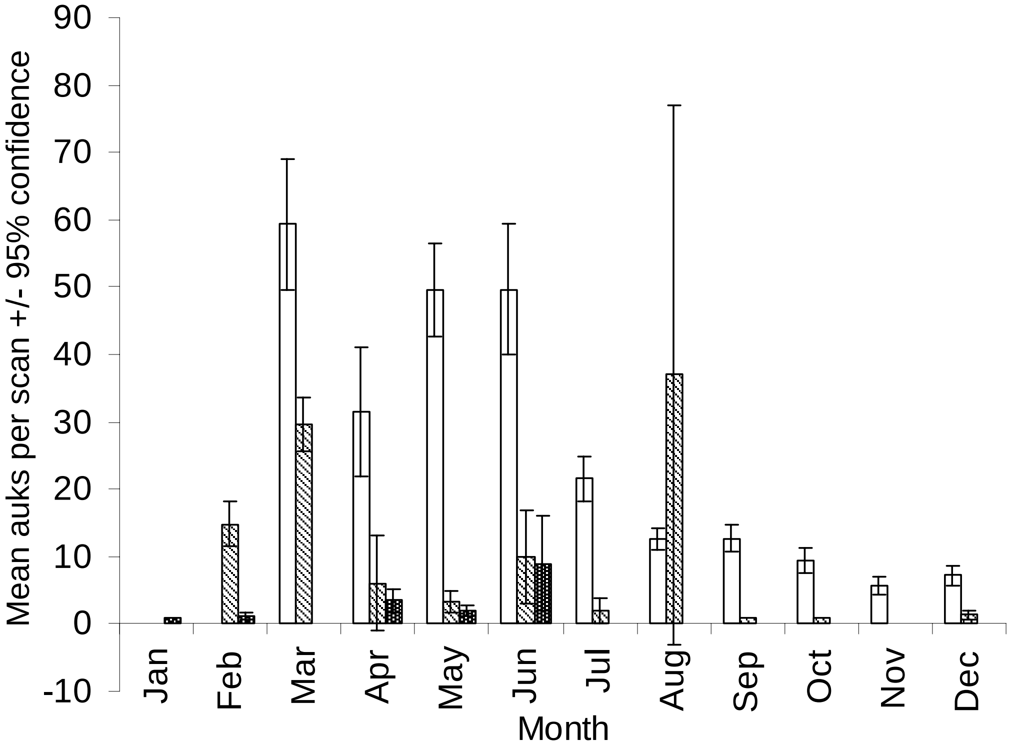
The species composition at the site was found to be of offshore seabirds (table 2.2). Many observations of auks were not to species level, but of those that were, 94% were common guillemot, indicating that as in the early 1980s (Mudge *et al.*, 1984), the area was still important for this species despite changes in fish species composition (Hopkins, 1986; ICES, 2007). Very few coastal birds, such as diving ducks or terns were observed, demonstrating the offshore nature of this site.

Species composition varies with season and year. Numbers of both auks and gulls were higher in 2006 than 2007 or 2008 (figure 2.2). In general, auks were more abundant between March and August, in all years, indicating that they are using the area for foraging during the breeding season, but dispersing outside of this. This seasonal pattern is consistent with records from 1982 and 1983 (Mudge *et al.*, 1984). Gull abundance shows less variability with season, but these numbers may be influenced by the rafts of gulls roosting of the water close the platform (personal observation). Considerable interannual variation is evident in the abundance of gulls.

Table 2.2. List of species recorded in scan samples from the Beatrice Alpha oil platform, between March 2006 and June 2008. The number of each species and the percentage of total sightings are given.

Species	**Total number recorded**	**% of all birds recorded**
All auks	**6151**	**50.62**
Auk	4695	38.64
Guillemot	1362	11.21
Razorbill	53	0.44
Puffin *Fratercula arctica*	34	0.28
Black guillemot *Cepphus grille*	4	0.03
Little auk *Alle alle*	3	0.02
All gulls	**3704**	**30.48**
Kittiwake	2506	20.62
Great black backed gull *Larus marinus*	822	6.76
Herring gull	320	2.63
Gull *Laridae* spp.	36	0.30
Common gull *L. canus*	11	0.09
Lesser black backed gull *L. fuscus*	5	0.04
Black headed gull *L. ridibundus*	4	0.03
Fulmar *Fulmarus glacialis*	**974**	**8.02**
Gannet *Morus bassanus*	**920**	**7.57**
All wildfowl and waterbirds	**295**	**2.43**
Pink footed goose *Anser brachyrhynchus*	247	2.03
Goose *Anser* spp.	34	0.28
Oystercatcher *Haematopus ostralegus*	5	0.04
Eider *Somateria mollissima*	4	0.03
Knot *Calidris canutus*	2	0.02
Velvet scoter *Melanitta fusca*	2	0.02
Redshank *Tringa tetanus*	1	0.01
Diver *Gavia* sp.	1	0.01
All cormorants	**41**	**0.34**
Shag	39	0.32
Cormorant *Phalacrocorax carbo*	2	0.02
All skuas	**35**	**0.29**
Great skua *Catharacta skua*	33	0.27
Arctic skua *Stercorarius parasiticus*	2	0.02
All terns	**10**	**0.09**
Common or arctic tern *Sterna* spp.	8	0.07
Sandwich tern *S. sandvicensis*	2	0.02
Manx shearwater *Puffinus puffinus*	**4**	**0.03**
All passerines	**18**	**0.15**
Starling *Sturnus vulgaris*	12	0.10
Meadow pipit *Anthus pratensis*	2	0.02
Redwing *Turdus iliacus*	2	0.02
Passerine	1	0.01

a



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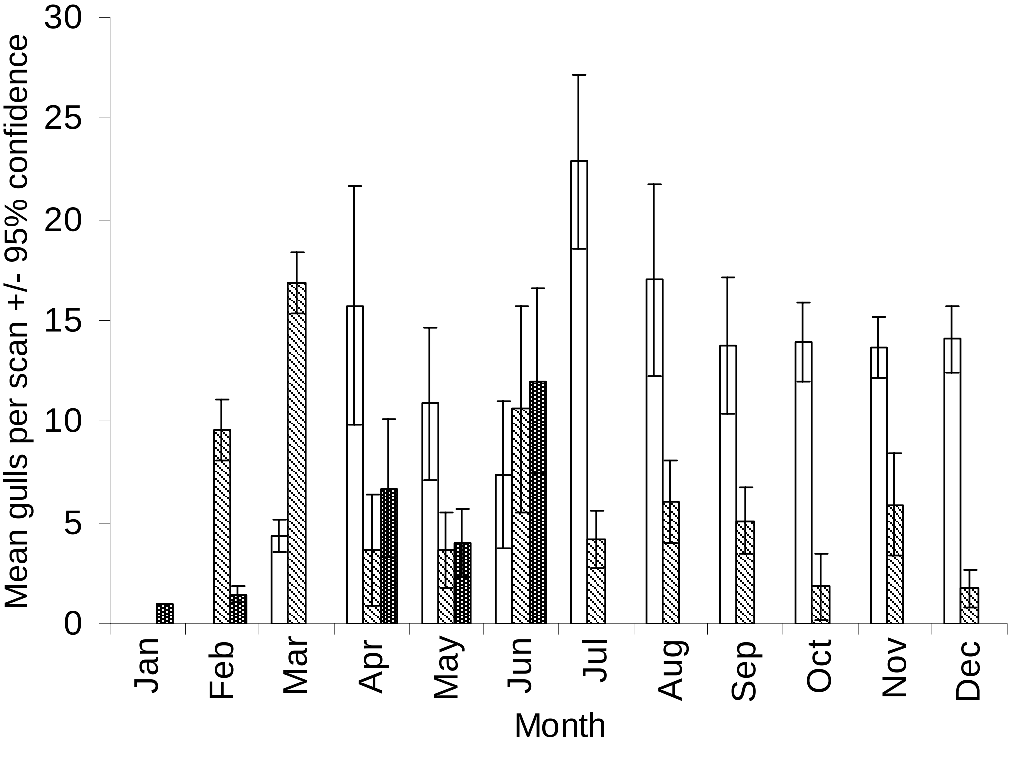

Figure 2.2. Mean number of (a) auks and (b) gulls per month recorded in scan samples, in 2006 (empty bars), 2007 (hatched bars) and 2008 (dotted bars).

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Chapter three

Offshore marine surveillance radar installation and methods for ensuring data quality

INTRODUCTION

Areas suitable for offshore wind developments are, by their nature, relatively inaccessible. It can therefore be difficult to reach sites to make direct visual observations for use in EIA, particularly in high sea states, and no observations can be made during periods of darkness or poor visibility. As future developments move further offshore in Round 3 of offshore wind and the Scottish territorial waters round (see figure 1.1), these problems will become more pronounced. Turbines will be placed in less sheltered waters, with increased travel time to sites.

Surveillance radar was first proposed as a tool for making observations around wind turbine installations in the 1990s (Cooper, 1995; Harmata *et al.*, 1998a). It has generally been used to monitor the movement of avian migrants through study sites (e.g. Christensen *et al.*, 2004; Harmata *et al.*, 1999; Krijgsveld *et al.*, 2005; Parnell *et al.*, 2006; Walls *et al.*, 2007). Data collection methods in most radar studies involve some form of manual detection and tracking of targets. Three main methods have been used: tracing movements on screen onto acetates (Christensen *et al.*, 2004; Desholm & Kahlert, 2005), recording the screen for processing at a later date, either by filming (Pettersson, 2005) or taking stills with time lapse cameras (Lilliendahl *et al.*, 2003), and recording bearings and distances either on maps and data sheets or on Dictaphones (Harmata *et al.*, 1999; Harper *et al.*, 2004; Williams *et al.*, 2001). These methods limit data collection to periods when it is possible to have an operator present. Since the radar must be installed on a platform or boat in the vicinity of the turbine locations, data collection opportunities may be influenced by weather patterns and the availability of vessels that can be used to transport operators and radar equipment to the site. In a high clutter environment, it may be difficult for an observer to determine genuine bird targets. There is also the possibility for inaccuracies to be introduced into the data during the processes of transcription and manual digitisation.

An increasing number of studies use automatic detection and tracking software with low powered surveillance radar (e.g. Krijgsveld *et al.*, 2005; van Belle *et al.*, 2007). Automatic detection and tracking software has the advantage of acquiring targets in a standardised manner and plotting them at the same level of accuracy as the radar, without the need for transcription. These systems were initially designed for use at both commercial and military airfields to inform air traffic controllers of the risk of bird strike to aircraft. They have been used in wind farm EIA and impact studies in the UK and Europe, to track migrant movements through study sites (e.g. Krijgsveld *et al.*, 2005; Parnell *et al.*, 2006; Walls *et al.*, 2007), but no peer reviewed studies have been published. The first deployment of automatic detection and tracking systems offshore was in the Netherlands (Krijgsveld *et al.*, 2005), where the radar was based on a meteorological monitoring platform 9 km from land. Krijgsveld *et al*. (2005) aimed to monitor the movement of migrant birds through the area, but found that high levels of sea clutter limited the use of the horizontal S-band radar. Instead, more emphasis was placed on the vertically scanning X-band radar, which provided data on the altitude profiles of birds as well as giving quantitative data on the rate of target movement through the study area.

Automatic detection and tracking software has been developed by two companies in the United States of America; Merlin, from DeTect Inc and MARS from GeoMarine. Both work in a similar manner and have the potential to allow data collection 24 hours a day and at times when an operator is not present. The software processes the raw radar data and uses standardised algorithms to detect targets, reducing the possibility for observer bias. Both systems track targets that have been identified by the algorithms as birds, and record their locations at regular (several seconds) intervals.

There have been some criticisms of the methods used for automatic tracking, for example the fact that a single bird track may be split into two separate tracks if it passes behind a structure such as a wind turbine, whereas a human radar operator might chose to join the tracks (Desholm *et al.*, 2005). However, such a decision is subjective and may be incorrect under some circumstances. Other authors have argued that a human observer must be present in all radar studies in order to allow accurate counts of birds (Schmaljohann *et al.*, 2008), but there are cases where the absolute quantification of bird numbers is not the objective of the study. However, the absence of a human observer does mean that no species information can be gathered to relate to the radar tracks.

In contrast with visual observation methods, there is currently little guidance about the most appropriate radar systems to use or the data that should be collected. The COWRIE report into remote techniques (Desholm *et al.*, 2005) describes the required specification for a dedicated bird tracking radar, but this is hypothetical since this radar has not been developed yet. The automatic detection and tracking systems available are discussed, but few details of how such systems could be used are given. Their report focuses on data collection and storage methods for manual detection and tracking.

Aims

Most of the applications of these automated systems have been on land and therefore there is little information available on how well they work in offshore locations. Where they have been used at sea, this has mostly been coastal (Krijgsveld *et al.*, 2005). Clearly, there is a need for an assessment of the feasibility of using an automated radar system for tracking birds in offshore environments. This should answer questions about the reliability of the system, the range of conditions under which it can be used and the post-processing that must be carried out on the data. The radar data should be compared with data obtained through visual surveys in order to determine the likelihood that radar tracks are genuine bird targets. Radar data should also be investigated to determine whether observed patterns can be explained through the ecology of birds at the site. Finally, an assessment must be made of whether the technique gives us useful information about how birds move around offshore sites that could not be gained through alternative techniques.

METHODS

The use of radar for detecting and tracking birds was trialled at the Beatrice oil field, in the Moray Firth, Scotland, which is the site of the DOWNVInD demonstrator project. The site is 22 km from land and has 40 m depth of water (see figure 2.1), making it the furthest offshore and the deepest water that any turbines are installed to date. The oil field has three fixed platforms, the largest of which, and the only manned platform, is the Beatrice Alpha. Two 5 MW wind turbines (WTG) were installed in the summers of 2006 and 2007.

Radar installation

A S-band marine surveillance radar (FAR-2137S, Furuno, Japan), was installed on the Beatrice Alpha platform in June 2005 for the purpose of recording fine-scale bird movements through the proposed wind turbine area. The radar has a peak output of 30 kW, with a 10 cm wavelength, a horizontal beamwidth of 1.8°, a vertical beamwidth of 25° and a frequency of 3050 MHz ± 30 MHz. A short pulse length of 0.07 µs was used to give high resolution data. S-band radar was chosen over the more common X-band because it has a longer wavelength and therefore is less affected by rain clutter (Eastwood, 1967). The radar was located approximately 35 m above sea level (figure 3.1), at the only suitable site on the oil platform that allowed a view over the wind turbine site. The radar scans an area with a 1.5 NM radius, in an arc of 240°. The remaining 120° is obscured by the Beatrice Alpha platform (figure 3.2). The combination of this radius and the short pulse length was chosen to allow the greatest discrimination between targets in order to investigate fine scale movement patterns. A position for a target can be obtained every 2.3 seconds, since the radar antenna rotates at 26 rpm.

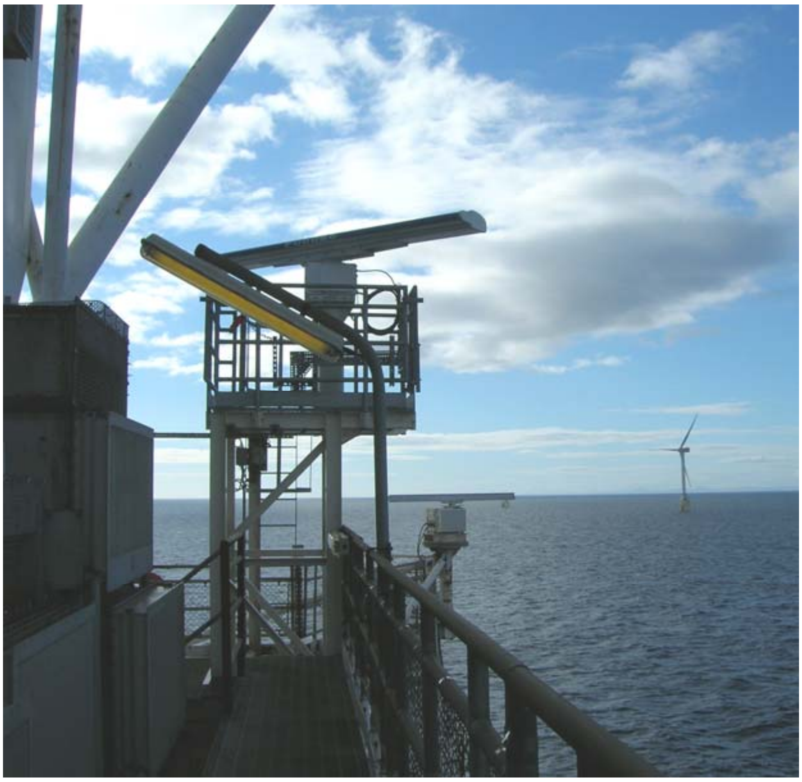

Figure 3.1. The large radar antenna in the centre of the photograph is the S-band radar used in this study. The smaller radar is an X-band used by the platform for monitoring vessel movements. WTG1 is shown.

Initial setup

The radar was initially furnished with off-the-shelf boat tracking software (MaxSea Professional version 10.3.5) which was intended to be able to track birds automatically. Targets could be selected either manually or automatically, using algorithms in the radar unit itself. This involved setting a “guard zone” which was an area that the radar would check for potential targets. A maximum of 100 targets could be tracked automatically at one time. Targets were only recognised after they were detected in five out of ten scans and could be lost if at any time they were not detected in this number of consecutive scans. No information was available from the manufacturer on the criteria used to define a target. Targets could be manually selected, but the radar would then only track the target if it met the criteria and would regularly lose targets selected this way within three or four scans.

Once the radar recognised the targets, the plotting software began recording the track. Targets that were recognised and recorded by the plotting software were only available as visual tracks and exports of these did not include any time or date information. The radar had anti-clutter algorithms which removed the influence of wave movement (sea clutter) and atmospheric moisture (rain clutter). These could also be controlled either manually or automatically. Automatic clutter settings removed almost all of the clutter from the radar display, and along with this, most of the potential bird targets.

Merlin radar system

Given the difficulty with exporting data from the plotting software and the lack of faith in the automatic tracking and automatic clutter removal settings, it was decided that the system was not fit for purpose. Two companies in the USA produce bird tracking radar systems (DeTect Inc., Florida and Geo-Marine Inc., Texas) and both were asked to tender to provide a system. The system produced by DeTect Inc. is used by several research groups in Europe and was offered with a discounted academic licence and so was selected. The Merlin radar system was installed in March 2006. Preliminary data were collected and processed by DeTect to determine the optimal software settings. Changes were made to the settings in June 2006 and the data used in this study were collected from this point on.

The software analyses the raw radar data in a 1024 x 1024 pixel grid. Target position is calculated using pixels on the screen. Since the radar is in the central pixel, the size of each pixel is $\frac{Range}{512}$, and given that the range of the radar in this instance is 1.5 NM (2.78 km), each pixel is 5.43 m long. If a target occurs over more than one pixel, the centroid mean pixel is given. The manufacturer’s stated accuracy is the position ± 1 pixel.

The original radar hardware was retained, but was modified to run the raw data through the Merlin processing system. The raw video data displayed on the original radar is four bit (eight levels of signal intensity); the Merlin system digitises the video data into 12 bit data, giving 4096 levels of signal intensity. On a clear and calm day, the system was run to collect baseline data on weather and clutter, in order to produce a map of baseline signal intensity. Two criteria were then set by DeTect staff to reduce the amount of clutter detected by the software. A minimum level of signal intensity of 500 above the baseline was set, and a clear air threshold of signal intensity of 500 was also set. Overall, this meant that a pixel must have had a signal intensity of 1000 above the baseline before a potential target could have been identified. These values were selected based upon DeTect’s experience of operating the radar system offshore in the Netherlands (Krijgsveld *et al.*, 2005), although this was in considerably more sheltered waters. Once a target was detected, it was referred to as a “plot”. To become a “track” a target had to continue to meet intensity criteria in three out of four consecutive scans of the radar. Additionally, targets were required to meet size, speed and movement criteria:

- The minimum target size was 8 pixels and the maximum was 450 pixels. These criteria helped to remove large objects such as boats and helicopters. A minimum size of 8 pixels allowed individual birds to be tracked under good conditions. There were two mechanisms for this, the first acted to lengthen the target, in terms of its distance from the radar and the second acted to make the target wider. Targets were lengthened because the short pulse length radar waves travel approximately 25 m. This meant that the target would have been reflecting back to the radar receiver for the entire length of the pulse. Individual targets cannot be resolved at less than half of this distance, so even very small targets could have appeared to be 12.5 m long. Similarly, targets were wider, because the horizontal beam width was 1.8°, so the target would have been reflecting a signal back to the receiver for the entire width of the beam. The radar cannot resolve targets at less than half of the beam width. Therefore targets would have appeared to be 0.9° wide and increased in width with greater distance from the radar.
- Targets were not recognised if they changed direction by more than 30° between consecutive scans. This was achieved by limiting the pixels surrounding the target that the software searched in the following scan. This means that highly mobile foraging birds may have been lost from the dataset.
- The ground speed of a target was restricted to a maximum of 35 ms^{-1}. This was also achieved by limiting the number of pixels searched for the target in the following scan. The value ensured that the software did not track fast objects such as aeroplanes or helicopters. It is also possible that genuine bird targets, with high ground speeds as a result of flying with a tail wind, may have been lost from the dataset.

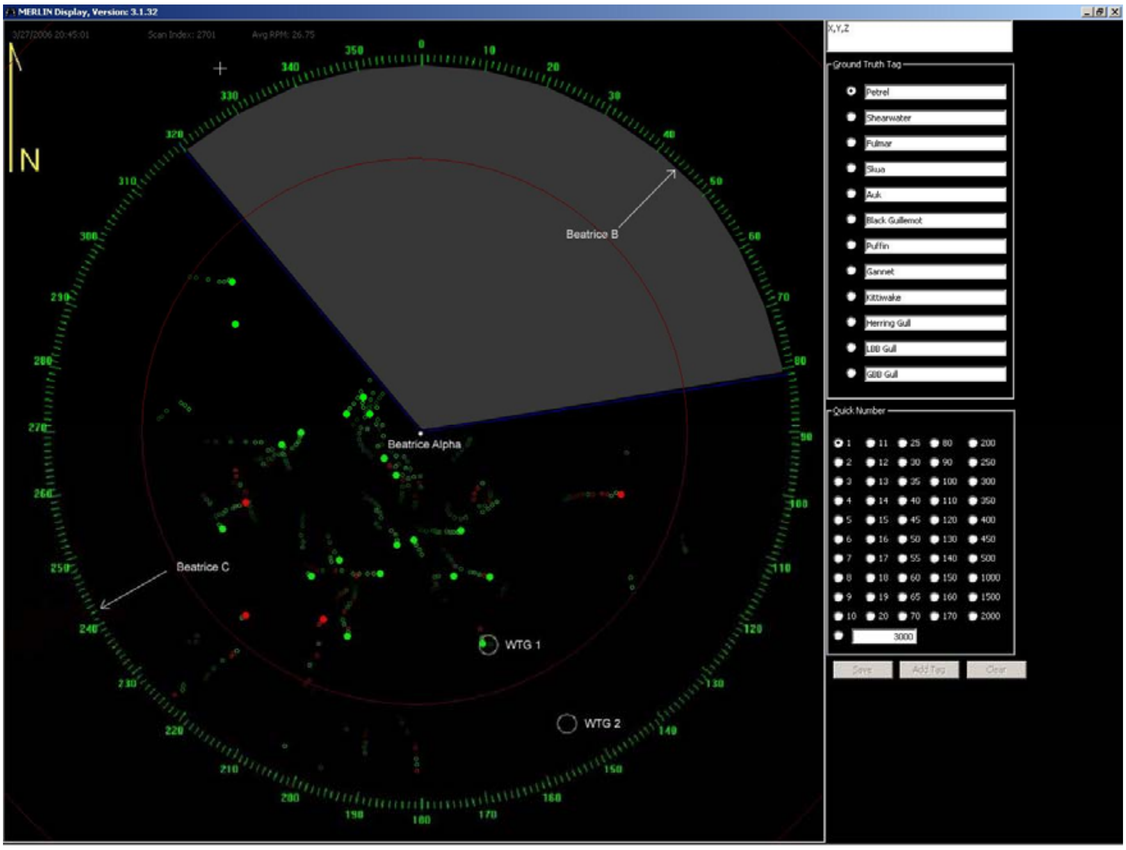

Figure 3.2. Example of Merlin radar display, indicating the positions of the three oil platforms and the two wind turbines. The green dots with trails are targets that the software has identified as birds.

Tracks were displayed in plotting software (figure 3.2) and were recorded into a Microsoft Access database. A unique track identifier was defined for every target and remained the same for every position recorded in the track. The time (precise to milliseconds) was recorded, along with range and bearing from the radar, speed, heading, predicted heading, distance travelled since the last detection and the position in pixels. This was also converted to latitude and longitude. Many other characteristics of the target were recorded; most refer to different definitions of size, shape and reflectivity.

In common with other radar studies of seabirds at sea (Krijgsveld *et al.*, 2005), sea clutter was identified as a serious problem in the data. Sea clutter tracks tend to be short and move in random directions and are more likely to be produced under rough sea conditions. To ameliorate the effects of sea clutter, a clutter shield was installed on the radar in April 2007. This was an aluminium tray fitted to the underside of the antenna, to reduce the size of the sector that the radar beam covered on its lower side. In effect this meant that the beam reached the water at a greater distance than without the shield and so wave movements were less readily detected. This seemed to reduce the extent of the clutter somewhat, but the effect was not quantified and a great deal still remains in the data. Radar engineers from both Furuno and DeTect suggested that the installation of the radar 35 m above sea level was too high and that this contributed to the extent of the sea clutter. Unfortunately, no alternative location was available on a lower level of the platform to relocate the unit.

Remote management

System management was initially carried out either by travelling out to the platform, which required a two night stay due to the availability of helicopter flights, or by requesting telecoms personnel on the platform to check the PC and make changes. Telecoms personnel were often engaged in other duties on the platform and it could take several days for them to have the time to check on the radar and PC. In November 2006, a remote link was established between the radar PC and the Talisman server on Beatrice Alpha. This allowed remote access to the radar PC, via the Talisman intranet, using VNC viewer. Talisman, the Lighthouse Field Station (University of Aberdeen), and DeTect all had access to the system, which allowed all further system management to be carried out in this way.

Wind speed data were collected and recorded automatically (Pace, version 1.0.13.0, Muir Matheson), once a minute on the Beatrice Alpha platform. Wind speed was measured in knots and the manufacturer’s stated accuracy was ± 1 knot.

Data filtering

Sea clutter was a very significant problem. This occurred when the radar tracked waves and was often recorded along with bird tracks into the database. The situation was exacerbated by high sea states and generally resulted in many short tracks, with more scattered patterns of movement. It is possible for tracks to have been made entirely by bird movement, entirely by wave motion, or a combination of the two. This is because targets must have met intensity criteria to have been tracked. Radar energy is principally reflected by the breast muscle (Eastwood, 1967), so birds that flew with their head or tail to the radar had much lower signal intensity than birds flying across the radar beam. If the direction of flight changed, so that a bird no longer reflected a strong signal to the radar receiver, the software may have started to track clutter in the area where it next expected the bird to be present. In order to remove these tracks from the dataset, three filters were developed. The first of these was based upon wind speed, with data collected on days with an average wind speed greater than 15 knots, equivalent to sea state 4, being removed.

On 273 days out of the 442 days between 16th June 2006 and 31st August 2007, on which we aimed to collect data, the wind speed was greater than 15 knots, removing data collected on 61.76% of days from the dataset. Notably, all data collected in January and February 2007 were removed by the wind speed constraint, because every day with data collected during this period had an average wind speed greater than 15 knots. Additionally, the radar system either suffered power loss or some form of malfunction on 211 of the 442 days. Power loss and malfunctions sometimes co-occurred with high wind speeds, but on many occasions did not, resulting in additional data loss. In total, useful data were collected on 90 out of a potential 442 days between June 2006 and August 2007.

The second and third filters were developed on data collected in June 2006, when visual line transect surveys showed a high density of birds at the site (see chapter 6) and then applied to the whole dataset.

The second filter used was for track length (figure 3.3). Forty percent of all tracks had only one position associated with them. The natural log of the frequency distribution of positions within a track showed a largely linear decline, indicating that this decline was exponential (figure 3.3b). However, the evident curve at small track length values indicated that the decline was greater than exponential for these short tracks. Such tracks gave little or no information about bird movements through the area, due to their short duration. Given that it is possible to acquire a location for a target every 2.3 seconds, a track with four positions will last for at least 9 seconds, which is the minimum that we consider to be useful for analysis. All tracks with fewer locations than this were removed.

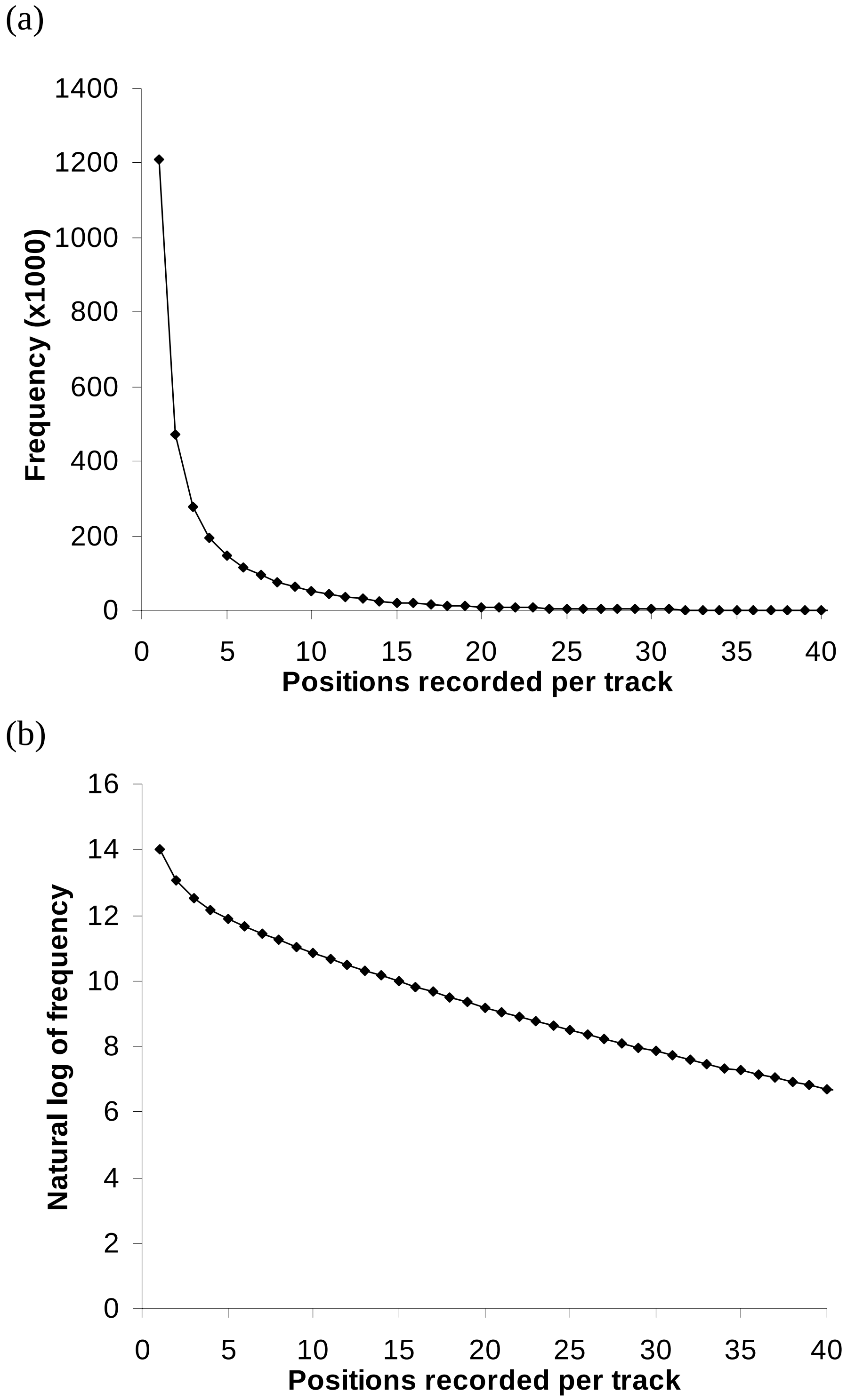

Figure 3.3. Frequency distribution of the number of positions in tracks (a) and natural log transformed frequency distribution of the number of positions in tracks (b), recorded using automated radar software from June 2006.

The third filter used was for the angular deviation (*s*) of the mean track heading. Angular deviation is used as a measure of dispersion for circular data (Zar, 1998), where it is not appropriate to use linear measures, such as the mean or standard deviation. It is given as:

$$s = \frac{180°}{\Pi}\sqrt{2(1-r)}$$

where $r = \sqrt{\left(\frac{\sum \sin a_i}{n}\right)^2 + \left(\frac{\sum \cos a_i}{n}\right)^2}$

and a_i = angle in degrees.

Angular deviation can take values between 0° and 81.03° (Zar, 1998). Tracks with a low angular deviation typically showed a consistent heading and a straighter pattern, whereas tracks with a high angular deviation showed much more variability in heading, with location points more randomly scattered (figure 3.4).

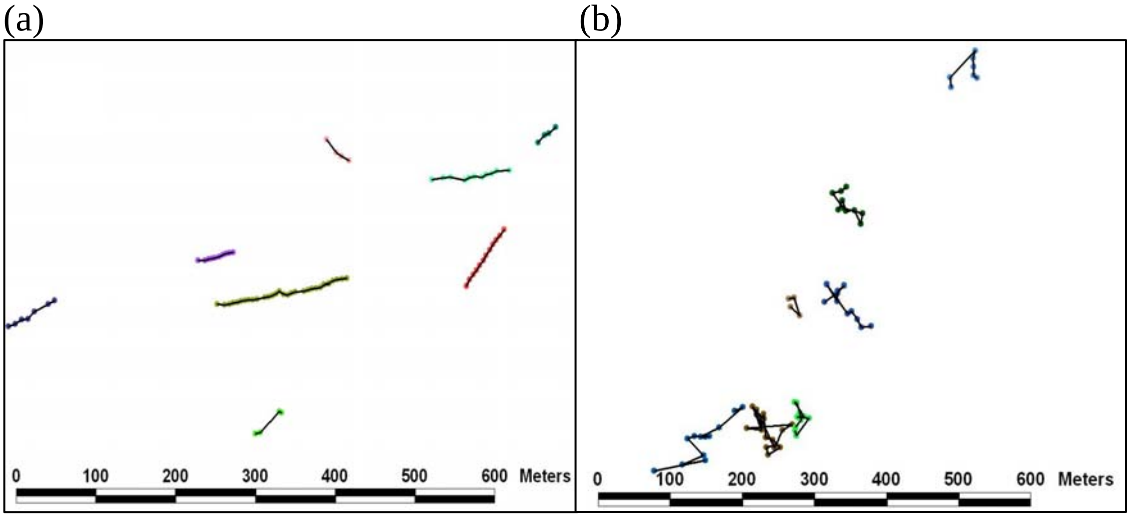

Figure 3.4. Examples of tracks with: (a) low angular deviations and (b) high angular deviations. Tracks with high angular deviations were filtered out of the dataset.

Angular deviation was calculated for every track and plotted as a frequency distribution (figure 3.5). Data from June 2006 showed a bimodal distribution, with a first, low peak between 0° and 20° and a second much larger peak between 45° and 81°. A comparison was then made between data from June 2006 and December 2006. Visual observations made from the oil platform (see chapter two for methods) showed contrasting numbers of birds in the area in the two months. In June 2006, the mean number of birds recorded per hour of observation was 70.52, with a standard deviation of 16.52, while the mean number of birds recorded per hour in December 2006 was 22.91, with a standard deviation of 4.59. The frequency distribution of track angular deviation in December 2006 showed only one peak, at the higher end of the scale. From this, we reason that tracks with low angular deviation are more likely to represent birds and therefore retain in the dataset only tracks with angular deviation values of less than 20°.

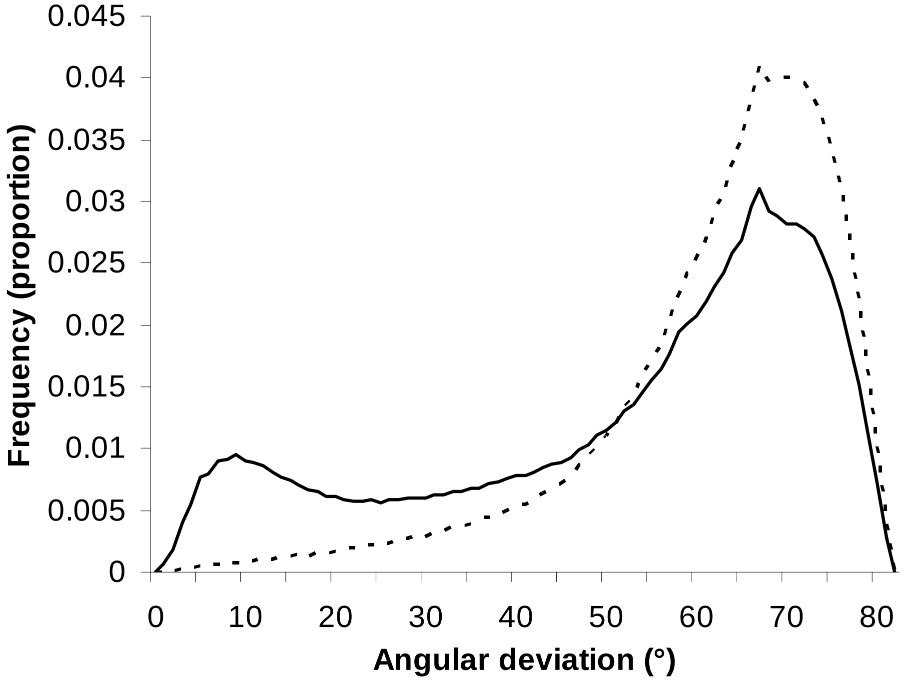

Figure 3.5. Frequency distributions of angular deviation of the heading of radar tracks recorded in June 2006 (solid line) and December 2006 (dashed line). Values are displayed as the proportion of all tracks recorded in that month (1,314,233 in June 2006 and 2,214,921 in December 2006).

Overall, the second and third filters removed 95.96% of tracks from the low wind speed June 2006 dataset. These filters were subsequently applied to all data collected in wind speeds of less than 15 knots, from June 2006 to August 2007 and removed 98.75% of tracks. This process is highly conservative, and aimed to provide high confidence in the tracks that remain. Despite this, the final dataset contained 475,932 tracks from 2059 hours of observations, over 90 days, which gives high power to detect patterns when using statistical analyses.

Further investigations into the effect of these filters were carried out, specifically focussing on relationships between angular deviation and track length. For data collected in June 2006, the correlation between angular deviation and track length was calculated. To determine the empirical relationship between track length and angular deviation, simulated tracks of different length were generated, each with a fixed change in heading throughout the track. Tracks of length 4, 10 15, 20, 30 and 50 positions were created, and each was tested thirty times, with an incremental change in heading of all values between +1° and +30° between positions within the track. For example, the headings for a track of length 4, with an incremental change of 1° would have been 0°, 1°, 2°, 3°, while for a track of the same length, with an incremental change of 5°, the headings would have been 0°, 5°, 10°, 15°.

As a first step in producing a null model for the angular deviation of tracks, 1000 simulated tracks, of length 30 positions were created, with randomly selected changes in heading between each position. These were constrained between -30° and +30°, because the Merlin software's criteria for continuing to track a target stipulated that the target could not change heading by more than 30° between moves. The angular deviation was calculated for each of these tracks and plotted as a frequency distribution alongside the distributions from June 2006 and December 2006.

RESULTS

Data filtering

The correlation between track length (number of positions within the track) and angular deviation (figure 3.6) for tracks recorded in June 2006 was very weak, but statistically significant (r=0.028, t=28.43, d.f.=1037813, p<0.001). Correlation analysis is very sensitive to large sample sizes, and this dataset has 1,037,815 tracks, which could easily lead to type I errors. This analysis used all tracks with at least four positions recorded. Considering only the longest tracks, with a minimum of 40 positions (sample size 8344), makes little difference to the strength of the correlation, but the relationship becomes negative (r=-0.047, t=-4.32, d.f.=8342, p<0.001); as track length increases, angular deviation decreases.

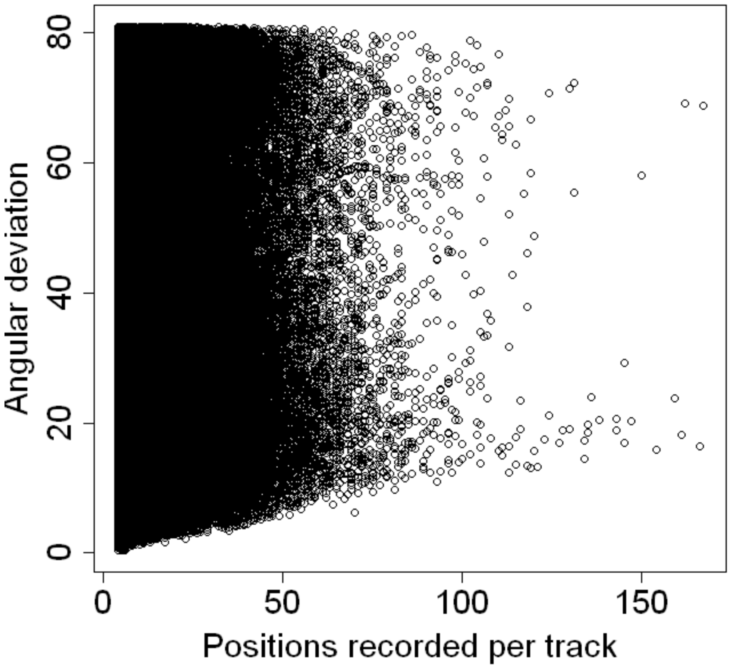

Figure 3.6. Plot of the number of positions recorded in a track against the angular deviation of the track, from 1,037,815 tracks recorded in June 2006.

Tracks with 4, 10, 15, 20, 30 and 50 positions were created to test the effect of track length on angular deviation. A constant heading was used throughout the track for each run and tested at all changes in heading between 1° and 30° for each track length. Figure 3.7 shows that shorter tracks have smaller angular deviations than longer tracks, even with the same variation in headings. The change in heading in longest tracks needs only to be very small to account for a large angular deviation. For many of the shortest tracks, the constant change in heading would need to be greater than that allowed by the Merlin software at each new position, to produce an angular deviation approaching the maximum (table 3.1). Equally, longer tracks would need to have very small changes in heading to be retained following the filter for angular deviation.

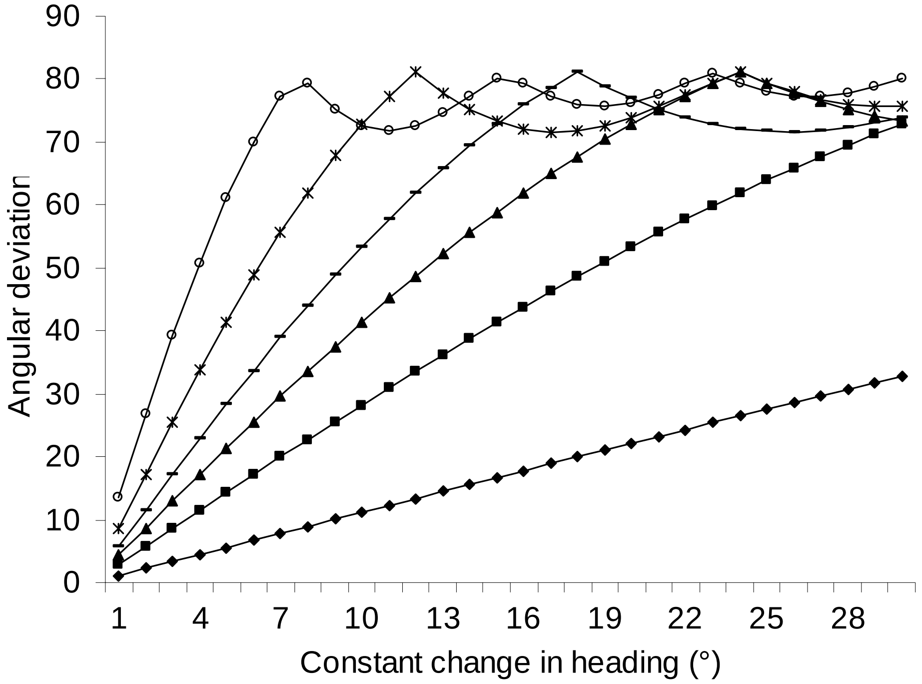

Figure 3.7. Plots of the angular deviation of tracks with constant incremental changes in heading. Tracks with 4 positions (diamonds), 10 positions (squares), 15 positions (triangles), 20 positions (horizontal bars), 30 positions (asterisks), and 50 positions (open circles) are shown.

Table 3.1. Summary statistics detailing the influence of track length on different aspects of angular deviation. The minimum constant increase in heading required for tracks to reach the maximum value of angular deviation is shown, along with the greatest value that angular deviation can take given the parameters of Merlin software (maximum change in heading of 30°. The maximum constant change in heading between positions that would allow tracks to be retained following the angular deviation filter is also shown.

Track length	Heading change when angular deviation reaches max	Greatest angular deviation possible within software parameters	Max constant heading increase with angular deviation less than 20
4	90	32.76	18
10	36	72.78	7
15	24	81.03	4
20	18	81.03	3
30	12	81.03	2
50	8	81.03	1

Simulated tracks were generated, which allowed a random change in heading between positions, constrained within 30° in each direction to mirror the criteria within the Merlin software. One thousand tracks of length 30 moves were generated. The frequency distribution of their angular deviation (figure 3.8) shows a peak at 23°, with a steady decline to the maximum value of 81.03°. The peak does not coincide with either of the peaks in the data from June 2006, or with the peak from December 2006. This indicates that the large proportion of tracks recorded in both June 2006 and December 2006, with high angular deviation values, are more variable than would be expected if they were random movements.

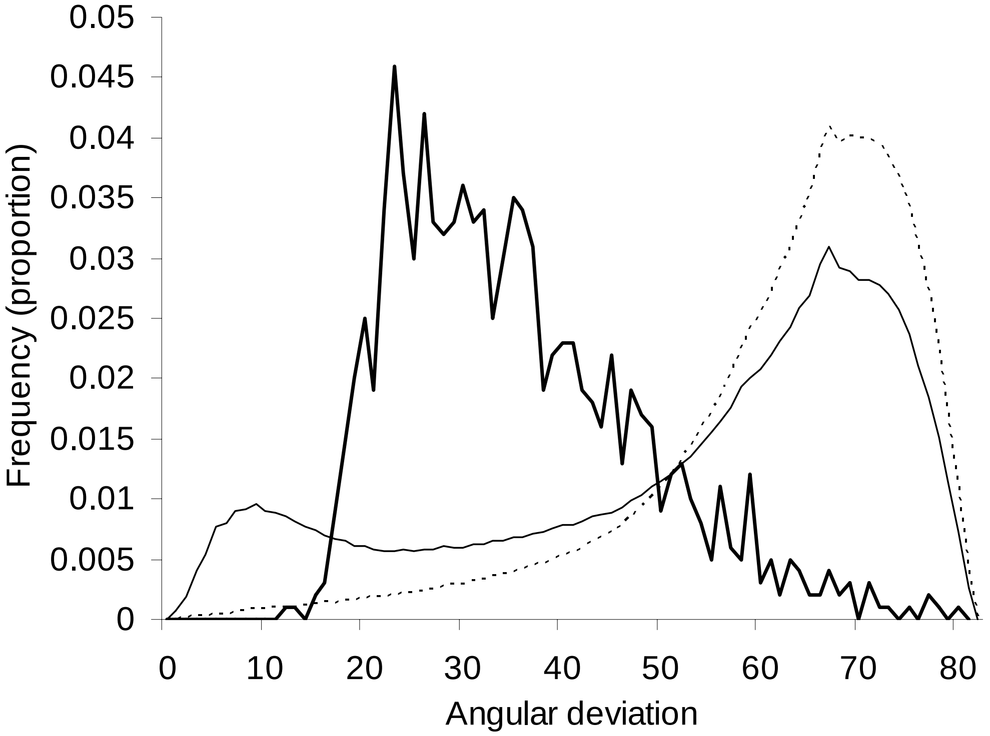

Figure 3.8. Frequency distribution plots of angular deviation. Data from tracks recorded in June 2006 are shown with a thin solid line. Those from December 2006 are shown with a thin dashed line. Data from 1000 simulated tracks, with random changes in heading within the Merlin software's parameters are shown with a heavy solid line. All data are shown as proportional to the total number of tracks within that dataset, to allow comparability between datasets.

Biological patterns

The number of radar tracks recorded in a one hour period was compared to the number of birds recorded visually by the ornithologist in the same hour (figure 3.9) (see chapter two for methods). Clutter obscured the scanned area closest to the radar and the extent of this depended on the weather conditions. Therefore, visual data from the closest 500 m were excluded from the comparison. Any observations made in moderate or poor visibility conditions were also excluded as they were likely to underestimate the numbers of birds at further distances. Data were collected concurrently on 28 hours, from six days between June 2006 and August 2007 (table 3.2). This is a small dataset because there were only 90 days on which data were collected by the radar and on many of these occasions the visual observer was not present. The two datasets correlate well and have a statistically significant positive relationship (r=0.875, t=9.223, d.f.=27, p<0.001). Clusters in the plot are related to year, with greater numbers of both visual and radar detections in 2006.

Table 3.2. Dates of concurrent radar and visual observations.

Date	**Number of hours with concurrent radar and visual observations**
25th July 2006	6
26th July 2006	9
26th April 2007	1
24th July 2007	5
25th July 2007	6
26th July 2007	1

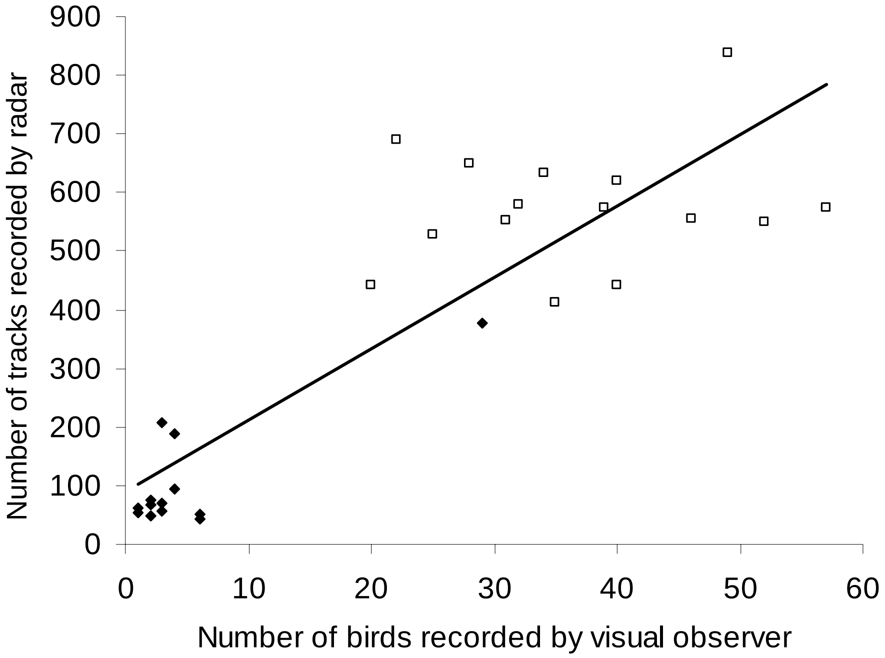

Figure 3.9. Plot of the number of birds recorded in a 10 minute visual scan, against the number of radar tracks recorded in the same hour. Data from 2006 are shown with open squares and data from 2007 are shown with filled diamonds.

A diel pattern was also evident in the average number of tracks recorded by the radar in each hour of the day (figure 3.10), with fewer tracks recorded at night than during the day. There also appeared to be an increase in activity in the morning. Tracks were categorised as being recorded during the day if they began between sunrise and sunset, and during the night if they began between sunset and the next sunrise. Since sunset and sunrise times change throughout the year, the times for the middle day of the month were applied to all observations within that month. A significant difference was found between the number of tracks recorded during the day and the number recorded at night (Wilcoxon test, W=522167, p<0.001).

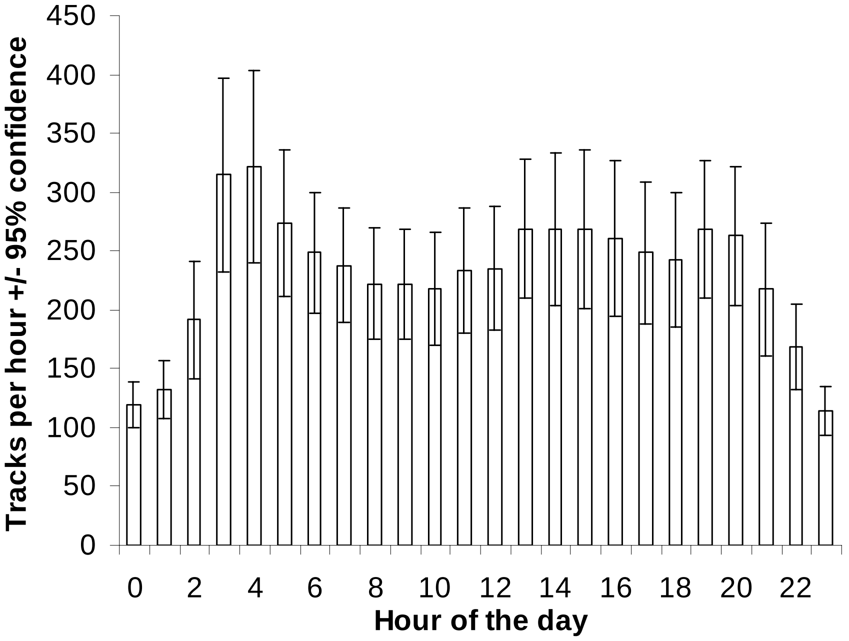

Figure 3.10. The number of radar tracks recorded per hour of observation in different hours of the day. The data were collected over more than one year so sunset and sunrise times vary. Times are standardised to GMT.

Seasonal patterns were also evident in the number of tracks, standardised for the number of hours of observation (figure 3.11). There was a large difference in activity at the site between the two years. Similar results were shown from visual line transect surveys (see chapter six). Despite this, a similar seasonal pattern was evident in both years, with peaks in activity in late spring and summer, particularly in June, and declining in the autumn and winter.

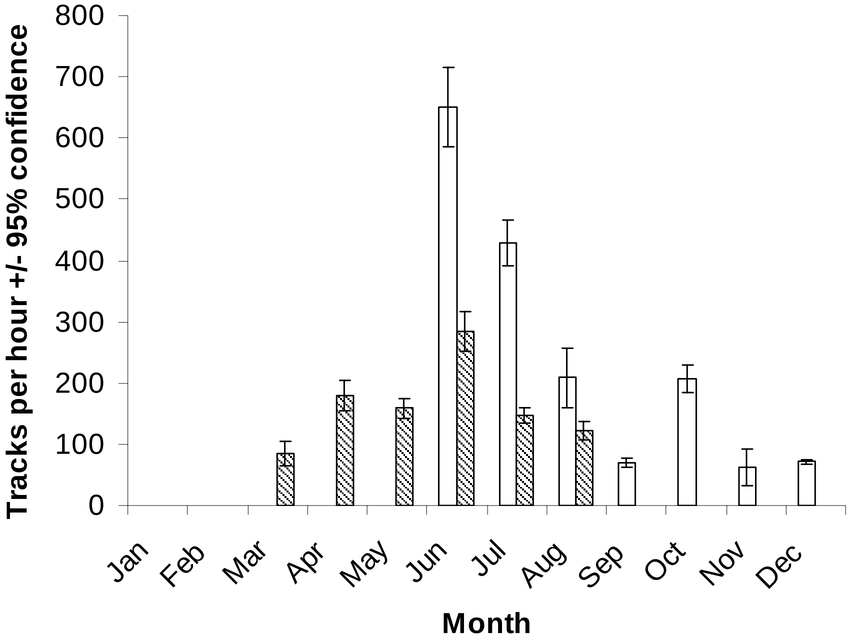

Figure 3.11. The number of radar tracks recorded per hour of observation across different months. Empty bars represent data collected in 2006 and hatched bars represent data collected in 2007.

DISCUSSION

Data filtering and system reliability

Radar malfunction caused potentially useful data to be lost, with 46.75% of days with wind speeds of less than 15 knots having no data recorded because of technical problems. These problems varied from power loss, to errors caused by the difference between British and American date systems. The remote nature of the site meant that problems were not always identified quickly, so a short power outage could result in the loss of data from a whole week. Telecoms personnel on the Beatrice Alpha platform were trained to identify problems and to restart the system. This helped reduce down time, but use of a dedicated bird radar operator on site would further improve this. The establishment of the remote link to the radar PC in November 2006 allowed some problems to be rectified remotely. However, any problem that had shut the system down, such as power outage, still required manual intervention.

Clutter is a serious problem with the data collected from the Merlin radar system. In order to obtain a robust dataset, conservative filtering criteria were used, which removed a very large proportion of tracks. However, the dataset remaining after filtering was still sufficiently large for analyses. It may be expected that a more conservative track length filter would be sufficient to filter out clutter types tracks with highly variable headings, since these tracks have to satisfy the radar software’s criteria over longer periods. This would remove the requirement for a filter based on angular deviation. If this was the case, there would be a strong negative correlation between track length and angular deviation, with longer tracks showing less variability in heading. However, only very weak correlation was found between track length and angular deviation and the correlation was positive (figure 3.6). The result was statistically significant, but this was due to the large sample size, to which correlation analysis is very sensitive. The correlation was negative when only the longest tracks were used, but was still very weak. Angular deviation was also shown to generally increase in longer in tracks (figure 3.7 and table 3.1). Overall, these results indicate that the track length and angular deviation filters are both necessary, because they assess independent characteristics of the tracks.

For some analyses, it may be desirable to increase the required minimum number of positions in a track somewhat, to give more information on the behaviour of the target. Longer tracks must also have adhered to the Merlin software's tracking parameters for longer durations and may therefore represent more reliable targets. Such tracks are also likely to have small changes in heading between positions, to have been retained following the angular deviation filter (figure 3.7 and table 3.1). However, using data from the same radar software, Meesters *et al*. (2007), found that classification trees could separate bird targets from clutter by using only tracks with more than 1.5 positions recorded. In practice, since the number of positions can only be an integer, they used all tracks with two or more positions (Krijgsveld *et al.*, 2005). The radar data collected by the Central Science Laboratory, also using Merlin software, are filtered to give only tracks that last for 10 seconds or longer (Parnell *et al.*, 2006; Walls *et al.*, 2007), which is comparable with the track length filtered used here. Using only the track length filter with the data collected in this study would have left many tracks that may not be genuine bird tracks. In particular, tracks with large angular deviations would have accounted for a very large proportion of the dataset, as is evident in figure 3.5.

Direct assessment of the suitability of filtering criteria was not possible in this study, because of the difficulties in gathering track data that are certainly either birds or waves. It is likely that some tracks with angular deviations larger than 20° are genuine bird targets, for example, foraging birds making large changes in heading to capture prey. Equally, it is possible that some of the tracks remaining in the filtered dataset are directional waves. The greatest problem is that tracks that are recorded have been through the Merlin software's algorithms and therefore do not necessarily represent tracks that an observer might identify. In this study, tracks could change heading by a maximum of 30° between positions, and could have a maximum speed of $35ms^{-1}$, meaning that the maximum distance between two positions recorded 2.3 seconds apart was 80.5 m, giving the radar a potential search area of 3393 m^2. Any object within this area, which conforms to the minimum reflectivity criteria mentioned previously could be identified as the next location of a particular target, especially if the original target is obstructed. For example, a genuine bird target could be tracked, which then reduces altitude to below the maximum wave height, resulting in the wave being tracked rather than the bird. The software makes attempts to join targets that may be from the same track, so it is possible that several, unconnected targets could be joined together in a track. Such tracks would be likely to have high angular deviations.

The frequency distribution of “random” tracks (figure 3.8) indicated that tracks with angular deviations smaller than around 20° were less variable than would be expected by chance and equally, that the large proportion of tracks with large angular deviations, from both June 2006 and December 2006 are more variable than would be expected by chance. It is possible that such tracks are created when the software “chases” the nearest wave crest with high signal intensity within its search area, which may be unrelated to the previous wave. The “random” tracks presented here are a crude representation, because the radar will allow one out of every five positions to not adhere to the tracking criteria, allowing the possibility of changes greater than 30° between some positions. This simulation also uses tracks of the same length, which would not be the case in reality. However, the method does provide a useful first step to illustrate patterns in angular deviation.

Waves may also create linear tracks, with small angular deviation values under some circumstances, which would lead to them being retained in the filtered dataset. This may be most likely to occur when there is a big, directional swell at the site, when the crest of the same wave would be likely to be tracked over a sustained period of time. Further filters could be developed to remove data from days where there is a high risk of this happening, by using wave height data.

Random walk models may be of some use in discriminating between different track types. Correlated random walk models assume that the next move in a track is likely to be in the direction of the head of the animal (Turchin, 1998). This is likely to be a good representation of many of the tracks in the dataset, as a result of the restricted change in heading between positions imposed by the software. It may be possible to use such a model to extract foraging birds from the dataset. Such tracks are probably filtered out currently, since we would expect such movements to be less linear than flights through the area (e.g. Weimerskirch *et al*., 2002; Guildford *et al*., 2008). Models such as first passage time and area restricted search have been widely used to determine seabird foraging areas from tracking data (Pinaud & Weimerskirch, 2006; Pinaud, 2008; Weimerskirch *et al*., 2009), but few have attempted to use correlated random walk models. Bailey & Thompson (2006) found that bottlenose dolphins, *Tursiops truncatus*, rarely conformed to a correlated random walk model, but their movement could be modelled using a biased correlated random walk. This infers that as well as making foraging decisions based on recent experience, the animals had preferences for particular foraging locations. This may well be the case with foraging seabirds, as well as with birds passing through the area en route to other foraging areas. Biased correlated random walk models assume that the heading is also influenced by the absolute direction of movement as well as by the direction of the previous moves, inferring that animals are aiming to reach a particular destination (Turchin, 1998).

Unfortunately, it is also likely that tracks of waves may conform to these two types of models. Tracks with highly variable headings, in which the radar tracks the crests of many different waves within its restricted search area, may conform to a correlated random walk. Equally, directional wave movements, such as might be expected with a large swell, may conform to a biased correlated random walk model. This is largely because any track that has been recorded by the Merlin software must already have met the criteria of not changing heading by more than 30° in each move. Move length variables in the random walk models may help to filter out some of these clutter tracks (Kareiva & Shigesada, 1983), but this is also constrained because the Merlin software has a maximum distance between locations.

It would be desirable to assess quantitatively what a genuine bird track would look like in the dataset. If this could be achieved, analyses such as classification trees could be used to determine more accurately which filters best select for genuine bird targets and random walk models could be tested to determine their applicability. There are several possible methods for this, but none that is perfect. One method, which has been used by other workers in this field involves “truthing” a track on the radar screen, with paired visual observations, to assign species and flock size (e.g. Krijgsveld *et al.*, 2005; Parnell *et al.*, 2006; Walls *et al.*, 2007). However, the studies that have used this technique have generally been concerned with tracking migrating flocks of birds such as geese, which are easily distinguished because of their size, number and the altitude at which they fly. Identifying an individual seabird moving between waves and matching it to a radar observation is much more complex and relies heavily upon subjective decisions made by an observer.

Non-radar methods, such as attaching high resolution GPS tags to seabirds, could be used to determine how birds move when transiting an area or foraging. The tags could be set to record positions at short time intervals, to allow comparability with the temporal scale recorded by the radar (2.3 seconds). Many newer GPS tags have positional accuracy up to ± 15 m, making them comparable with the radar (accuracy of ± 5.43 m in this study). The data criteria from the Merlin software and the filters developed here could be applied to the tracks produced by the tag data, to find how well such "real" targets would have been tracked by the radar. The disadvantage of this technique is that birds must be caught to attach the tag and to remove it, to acquire the data. This is not simple at many sites, and is likely to mean that birds are caught from a colony, so the sample will only represent the movements of birds foraging to feed chicks. Gathering data at such high resolution also means that the sample is likely to consist of data from only one day or less, so no data will be collected outside of the breeding season. At present, no data exist at this resolution outside of the breeding season to determine whether the samples are representative of year round movement behaviour of birds. It is also likely that the study birds will not perform all types of flight during the short time period in which the tag is recording.

A further method might be to film flocks of birds at offshore locations. This could be achieved through attaching a camera to an oil platform, or deploying it remotely from a remote controlled aeroplane. The film could then be analysed at a later date, allowing tracking of all members of the flock, recording their turning angles and move lengths between particular time periods. However, attaching a camera to a fixed installation such as an oil platform may mean that few birds are ever recorded and also mean that their movements are recorded in the horizontal plane. Determining distance moved away from the camera may be difficult. Filming from an aeroplane increases the chances of capturing images of birds flying, but may disturb the birds and lead to non-typical flight patterns being recorded.

Biological patterns

The strong correlation between the numbers of tracks recorded by the radar and the number of birds observed by the ornithologist gives some confidence in the reliability of the filtered data. The difference in numbers of tracks recorded and number of birds observed can in part be explained by the fact that the ornithologist made instantaneous counts, which lasted for a maximum of 10 minutes, while the radar was recording for the full hour period.

Additionally, the ornithologist made observations over a 90° arc in comparison with the 240° arc covered by the radar. It is also expected that the radar should be able to detect more birds than a visual observer, since it can make observations very quickly over a large area, without fatigue. Other workers have shown that radar is able to detect targets more regularly than either audio or audio visual surveys, and that it can detect smaller groups of birds (Bigger *et al.*, 2006).

Data are clustered by year, with fewer birds sighted and fewer tracks recorded by the radar in 2007 than 2006. All but one data point were collected in July of either 2006 or 2007, when data from the ornithologist (see figure 2.2) showed greater numbers of both auks and gulls in 2006 than 2007. The clustering demonstrates these changes in abundance, but does not invalidate the conclusion that there is a good correlation between visual and radar observations, since both techniques reflect the differences in abundance during the two periods.

During the breeding season, birds with chicks may return to the colony at night, which may explain the reduction in activity at the site. Outside of the breeding season, common guillemots *Uria aalge* have been shown to form roosts on the water at night (Camphuysen, 1998), which would cause them not to be recorded by the radar software, since this can only track moving targets. Over-night roosts occur at the site, dominated by gulls such as black-legged kittiwake *Rissa tridactyla* (personal observation). This might explain the increase in activity early in the morning, as birds leave the roost to find foraging areas.

There were clear differences in activity levels at the site between 2006 and 2007. One wind turbine and one turbine base were installed at the site in July 2006, and the second turbine installed in July 2007. However, results from boat-based surveys presented in chapter six demonstrate that it is unlikely that turbine installation caused reductions in activity levels at the site because fewer birds were recorded overall in 2007, including control areas. Survey data also show an increase in bird abundance at the site throughout the spring, in common with activity levels recorded by the radar.

Seabirds generally disperse following the breeding season, when the tie to breeding colony is removed (Stone *et al.*, 1995). Previous surveys of the Moray Firth showed considerably higher densities of all species recorded at the Beatrice site during the late spring and early summer in comparison with the non-breeding season (Stone *et al.*, 1995). The peak in activity observed by the radar in June in both years could be related to adults taking chicks to sea (Stone *et al.*, 1995).

Uses of radar data

Seasonal and diel patterns of activity are two examples of the kinds of data that can be gathered by using radar to track birds. Since visual methods do not allow data collection at night, radar fills a significant gap in our understanding of the use of the site by birds. Spatial patterns in the location of tracks may allow investigations of the likelihood of birds passing through areas where turbines might be sited, and about potential avoidance behaviour, which is a key unknown in collision risk models. Other potential uses of radar data are explored in chapters four and five of this thesis. For example, the potential for determination of the breeding colonies used by birds at the site is explored in chapter four and factors affecting collision risk, such as flight speed, and flight directions in relation to wind are investigated in the context of the Band collision model (Band *et al.*, 2007) in chapter five.

It is equally important that we are aware of the limitations of radar systems as well as knowing what we can learn from them. Clearly, there are still lessons to be learned regarding the removal of sea clutter from the dataset, although the filters developed here take the first steps towards this. Further studies should focus on validating and refining these methods, perhaps using some of the techniques discussed above.

The radar and software system described here is not capable of determining the species of bird being tracked. It may be possible to use flight speed to determine taxa, although there are likely to be overlaps between some groups (Bruderer & Boldt, 2001). Classification of data from tracking radars has been able to distinguish five groups; small and large song birds, small and large waterbirds, and swifts, using wing beat frequency (Bruderer, 1997; Liechti, 1993), but such studies are not possible with low power marine surveillance radar. Larkin (1991) was able to use radar cross section, which is the size of the target on the radar screen, in conjunction with flight speed to separate birds and insects, but this requires high quality wind data to allow airspeed to be calculated, and again, used tracking radar.

This radar system also cannot determine the number of birds being tracked, because a target could be a single bird, or a flock. Target size, measured as radar cross section, is unlikely to be a reliable indicator of the number of birds, because a target of a particular size may be one goose, or a flock of passerines, for example and will change depending on the orientation of a target to the radar (Eastwood, 1967). Paired visual observations have been used in most other studies to rectify this (Desholm & Kahlert, 2005; Hüppop *et al.*, 2002 (as cited in BSH, 2007); Krijgsveld *et al.*, 2005; Schmaljohann *et al.*, 2008), but this is not possible during hours of darkness and necessitates the presence of a visual observer, which is unlikely to be possible during all the periods that a radar could be running. Visual observations of individual seabirds are also difficult to make in high seas states.

The height of targets can be measured using radar with the antenna modified to spin in the vertical plane (Cooper *et al.*, 1991; Harmata *et al.*, 1998b; Harmata *et al.*, 2003; Krijgsveld *et al.*, 2005; Parnell *et al.*, 2006; Walls *et al.*, 2007). This was not attempted in the present study. Legal constraints prevent the vertically scanning and horizontally scanning radars from being linked to give a real time three dimensional picture of the area, and linking the two datasets later is very complex. Therefore, the height profile produced by the vertical radar cannot give information on proximity to the wind turbine sites. Tracking radars can be used to obtain such data (Hedenström *et al.*, 2002), but are not widely available.

Finally, where radar is used in post construction monitoring, it can never be determined with certainty that a particular target actually collided with a wind turbine. This is because the radar and tracking software might easily lose the track of a bird passing behind the turbine. The algorithm used to determine a genuine bird target also uses the change in direction of a track; any change in direction greater than 30°, such as may be associated with avoidance behaviour, will result in the track no longer meeting the qualifying criteria for being recorded by the software.

CONCLUSIONS

The off the shelf boat tracking software originally provided with the radar (MaxSea Professional) was not fit for purpose, since it was not possible to export tracks in a usable format and anti-clutter settings removed all potential bird targets. Consequently, specialised software had to be purchased, at additional cost. It is recommended that future studies recognise this and budget accordingly. The Merlin radar system has produced data that are useful for assessing bird movements over large time periods, at fine temporal scale. Biological patterns in the data are consistent with our knowledge of the ecology of the site and the good correlation between visual and radar data gives us confidence that the patterns are true.

Clutter filters within the DeTect software continue to be improved, but the databases produced must still be considered to be the starting point for further processing and analysis. Consequently, these data must be heavily filtered to ensure that they are robust. The current filters used constrain potential investigations of non-linear movements through the area, but further work may provide methods to extract such movements from the clutter data. The lack of species identity also constrains some analyses and since the data used in analyses will consist of a range of species, the behaviour of one species may mask the behaviour of others. Despite these problems, the radar system has given us an insight into the use of the site by birds that would not have been possible from traditional visual methods alone.

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Chapter four

Using radar to assess site use by birds

INTRODUCTION

An important question in EIA for offshore wind farms is whether the site is used by birds from protected breeding colonies. If this is the case, planning for the wind farm must take this into consideration and mitigation methods must be considered, including moving the development to a different site. It is therefore important to gather data that can answer this question reliably, but methods for this can be difficult. Birds that are satellite, GPS or radio tagged at colonies may never go near the proposed wind farm site, and as developments move further offshore this becomes even more likely. The difficulties of catching birds to tag outside the breeding season also mean that there is likely to be a seasonal bias in the data collected.

Radar provides a potential solution for this, since flight movements and directions can be monitored relatively easily. Auks, such as guillemots, have been shown to fly directly between feeding and nesting sites during the breeding season (Wanless *et al.*, 1990). Radar studies have shown that the direction of flight of Alcids returning to the colony is correlated with the at sea foraging distribution (Lilliendahl *et al.*, 2003), indicating that flights between foraging sites and the colony are direct. Tagging studies have shown that Brünnich's guillemots *Uria lomvia* make several stops on flights out from the colony, indicating that they are searching for foraging locations, but make fewer stops on the more direct return journey (Benvenuti *et al.*, 1998). This indicates that radar monitoring of flight directions at sea may be able to distinguish where birds passing through the area are breeding.

Many radar studies aim to produce estimates of the number of birds passing through a site (Hüppop *et al.*, 2002 (as reproduced in BSH, 2007); Parnell *et al.*, 2006; Schmaljohann *et al.*, 2008; Walls *et al.*, 2007). This is complicated by the fact that a single target on the more commonly used marine surveillance radar may be made up of one or several birds. Methods have been proposed to calibrate radar and to estimate the detection probability of different species of bird, allowing the calculation of more accurate density estimates (Schmaljohann *et al.*, 2008). However, the techniques are difficult to replicate because Schmaljohann *et al.* (2008) used X-band tracking radar with a peak power output of 150 kW, specifically designed for avian research, which is not widely available. In order to quantify the number of birds moving through an area, the radar antenna was also modified. This may cause health and safety problems, requiring an accredited electrician to carry out the work, depending on the platform on which the radar is deployed.

Harmata *et al*. (1999) were the first to suggest that distance sampling methods could be used to improve estimates of the number of birds flying through an area. They used line transect methods and demonstrated that the results compared well with estimates collected through visual surveys (Harmata *et al.*, 1999). Distance analysis was then used to inflate the number of targets at greater distances from the radar. Since this study, distance methods have advanced to include point transect methods (Buckland *et al.*, 2001), which are more appropriate when considering radar data collected from a fixed point. These methods were employed by Hüppop *et al*. (2002) (as reproduced in BSH (2007)), who showed that the probability of detecting birds declined with distance, when using a vertically scanning X-band radar. The study then went on to inflate the number of targets detected at greater distance from the radar.

Even when using methods such as distance analysis and calibration, it can be extremely difficult to quantify the number of birds using a site. Distance analysis requires information on cluster size to give accurate density estimates and also assumes that the true distribution of targets within the study area is homogeneous, which may not be true and may be a key feature of the use of the site by birds. The most appropriate use of distance analysis is to produce detection functions to inform the choice of range.

Marine surveillance radar can be used effectively to monitor relative use of a site, through the number of tracks recorded per unit time, as well as being able to monitor the patterns of flights through the area. Comparison of detection of marbled murrelets *Brachyramphus marmoratus* by audio visual and radar techniques showed that considerably more birds were detected by radar at dusk (Burger, 1997). Radar could also detect smaller concentrations of birds, with audio visual techniques rarely detecting any birds when fewer than 10 groups were detected by the radar (Bigger *et al.*, 2006). Results presented in chapter three of this thesis also show that visual and radar detections are correlated, but with many more detections by radar. Clearly, radar has the capability of being a useful tool for detecting movement through a site, but without an assessment of the detection capability at all ranges, it is difficult to determine whether such observations are representative of movements throughout the range of the radar.

The strength of a radar signal is attenuated at increasing distances from the antenna. The power at a particular distance is given by the power at source, divided by the area of the sphere at that distance, $4\pi r^2$ (Eastwood, 1967), since radar waves extend from the antenna in three dimensions. Equally, for a target to be detected by the radar, the signal must be returned, which also results in loss of power. This means that whatever range is selected, detection will always be greatest close to the radar and will decline to the outer edges of the range. Typical marine surveillance radars can be set at operational ranges from 0.5 NM up to 100 NM.

Automatic detection and tracking systems often use a pixel grid to divide the study area. The size of each pixel increases with increased radar range, thus reducing the resolution of spatial data. Selecting the operational range is therefore a trade-off between gathering data over a wide area, the ability to detect targets and the resolution of data collected. Any study design must therefore be informed by knowledge of the optimal detection range of the radar used. However, only two studies have been found that included details of the detection range. First, Harmata *et al*. (1999) showed that detection declined to approximately 50% at 3000 m from the radar, when using a maximum range of 5.6 km. Second, Hüppop *et al*. (2002) (as reproduced in BSH (2007)) showed that detection with a vertically scanning X-band radar declined with distance, with the peak detection distance occurring at less than 50% of the maximum range.

Aims

This study aims to determine whether radar can be used to assess the use of the site by breeding seabirds considering flight directions taken. The working hypothesis is that tracks recorded during the breeding season may head towards, or from the breeding colonies to the northwest of the site, indicating that birds passing through the site are breeding at protected sites. The detection range of the radar will also be investigated, using two methods; considering frequency distributions of the number of tracks at increasing distance from the radar, and using distance analysis to calculate an effective detection radius. The results from the two techniques will be compared.

METHODS

Data were collected using S-band marine surveillance radar, situated on the Beatrice Alpha platform in the Moray Firth, Scotland. The radar was equipped with automatic detection and tracking software to enable it to track birds (see chapter three). The area covered by the radar had a 1.5 NM (2778 m) radius; this was split by the software into a grid of 1024 by 1024 pixels. Each pixel has length $\frac{Range}{512}$, which is equal to 5.43 m, and the accuracy of the system is ±1 pixel, as stated by the manufacturer. The radar only scans an arc of 240°, because the remaining 120° arc is obscured by the oil platform. The x and y coordinates of the location of targets were recorded every 2.3 seconds. To maintain a track, the target had to be successfully detected in three out of four consecutive scans. The range of the radar covers the locations of two wind turbines installed in July 2006 and July 2007, at 1524 m and 2226 m from the radar respectively.

Data were filtered to remove sea clutter (see chapter three) and to ensure that only high quality tracks were used, based on the following criteria:

1. Data were excluded from any days with a mean wind speed greater than 15 knots
2. Tracks with an angular deviation (equivalent of standard deviation for circular data) greater than 20° were rejected
3. Only tracks lasting for 30 seconds or longer, or with 9 or more locations recorded in the track were included in the final dataset

Data from June 2006 and June 2007 were used to investigate the direction of flights made during the breeding season. Data from June in each year were used to allow comparability in bird behaviour. One thousand tracks were randomly sampled from each of the months to allow a balanced design and reasonable sample size for comparison. These tracks account for 3.86% and 14.43% of the post-filtered tracks recorded in June 2006 and June 2007 respectively. Random samples of track IDs were selected in the statistical package R and the detail of these tracks was then extracted from the original databases.

Analysis

The x and y coordinates of locations in the tracks (recorded as pixels) were converted to values in metres, by multiplying by 5.43 m to aid analysis.

Site use

Use of the site by birds was assessed by considering the headings of flights through the area from the 1000 randomly sampled tracks from June 2006 and June 2007. The tracks were sampled from a heavily filtered dataset and contained only relatively straight tracks. These were most likely to represent birds flying through the area, rather than using the area for foraging. Frequency distributions of flight directions in each of the months were plotted in 10° groups and the mean flight direction was calculated using a circular mean. The difference between the distributions in the two years was tested using a Watson's two sample test, which is non-parametric and accounts for the circular nature of the data. These analyses were carried out in the CircStats package in R (Lund & Agostinelli, 2007). Correlation analyses were undertaken to determine whether the track length and angular deviation filters influenced the direction of flight.

The main seabird species using the site, such as common guillemot *Uria aalge*, razorbill *Alca torde* and black-legged kittiwake *Rissa tridactyla*, are likely to be feeding chicks at colonies in June (Stone *et al.*, 1995), requiring regular trips between the colony and foraging sites. However, there may be birds at the site that are non-breeders, or are breeders that have already failed. The closest colonies to the study site are approximately 22 km to the northwest (figure 4.1). They are designated as Special Protection Areas (SPA) because of the breeding seabird assemblage that they host, which includes internationally important numbers of common guillemot, razorbill, shag *Phalacrocorax aristotelis*, black-legged kittiwake and herring gull *Larus argentatus* (JNCC, 2001).

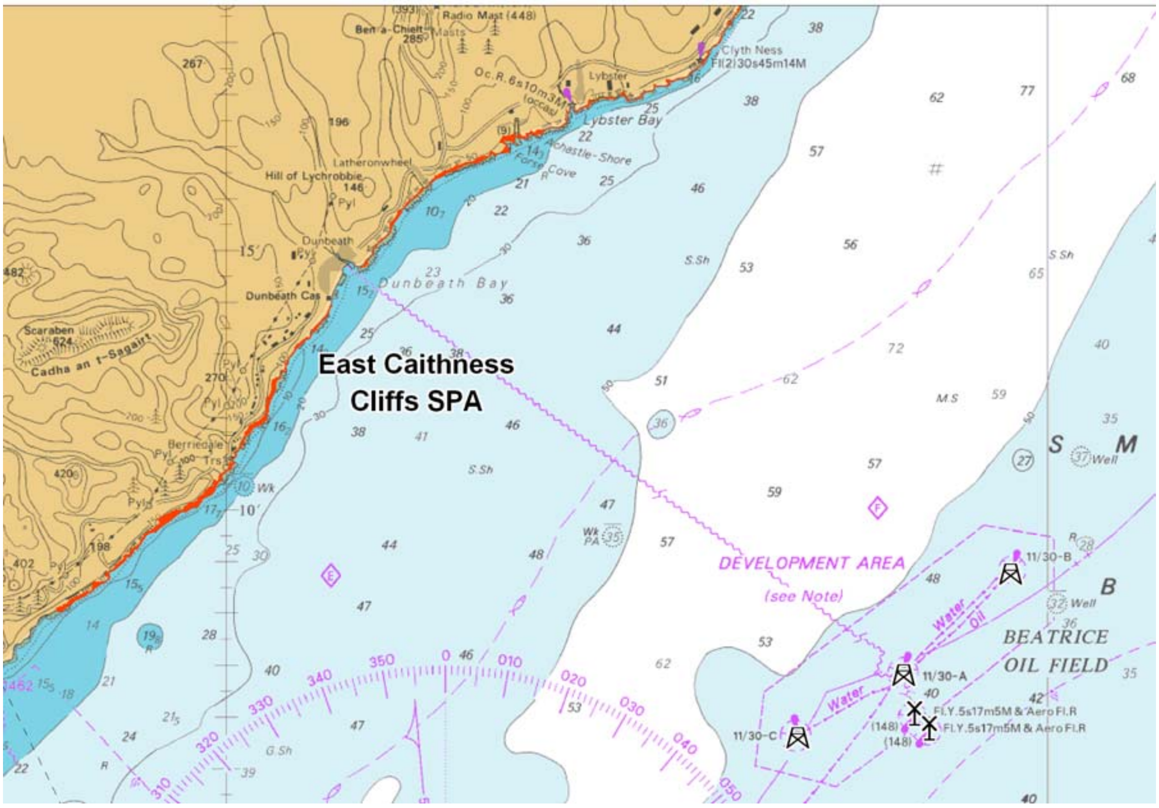


Figure 4.1. Chart showing the location of the East Caithness cliffs SPA (marked red, along the coast) in relation to the study site at the Beatrice oil field. The radar used in this study is based on the Beatrice Alpha oil platform, which is the middle of the three platforms (⊠). © Crown Copyright and/or database rights. Reproduced by permission of the Controller of Her Majesty's Stationary Office and the UK Hydrographic Office (www.ukho.gov.uk) Licence number 13599.

Detection analysis

To investigate detection of birds by the radar, the distance between the radar and the first position in every track from the 1000 track sample from June 2006 and June 2007 was calculated. This position was used because it is the earliest point in the dataset at which the radar software recognises the target as a bird, or flock of birds. The frequency of points occurring in each 100 m distance band from the radar was calculated and these frequencies were divided by the area of the band, to give the number of detections per square metre (figure 4.2). This was necessary because the area scanned by the radar increased with the square of distance (area=πr^2), thereby increasing the number of targets likely to be detected, even with no increase in the probability of detection. The maximum distance band was 3400 m from the radar, because all targets were counted within this range. This distance is greater than the range selected on the radar. This is possible because the radar can receive signal returns from greater distances than the range limit. The software processes the raw radar data in a square pixel grid, which has sides that are twice the length of the range of the radar, which is the radius of the more common circular display. Therefore, the targets at greater distance than the radar range are located in the corners of the software's pixel grid. The band of peak detection was determined by identifying the area which contained 75% of the total density of tracks. This was carried out for the data collected in both June 2006 and June 2007.

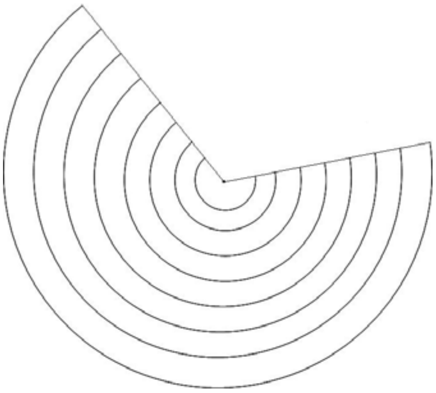


Figure 4.2. Diagram illustrating the 100 m distance bands, from the radar (central). The blank area to the north is not scanned due to the radar being sited on the corner of the oil platform. Actual bands extended to 3400 m, because all targets were detected within this area.

Distance analysis (Buckland *et al.*, 2001) was used to estimate the effective detection radius in both years to compare with the analysis of peak detection. Point transect methods, in Distance software version 5 (Thomas *et al.*, 2006) were used, and the data were imported as the radial distance in metres to the target from the radar. Tracks in the sample dataset may have been made by a single bird or a flock, and the radar cannot discriminate between these. Each target was imported as an individual object without clustering because no information on cluster size was available from the radar data. This would constrain any effort to calculate a density estimate, but is a reasonable approach here as only detection is being estimated.

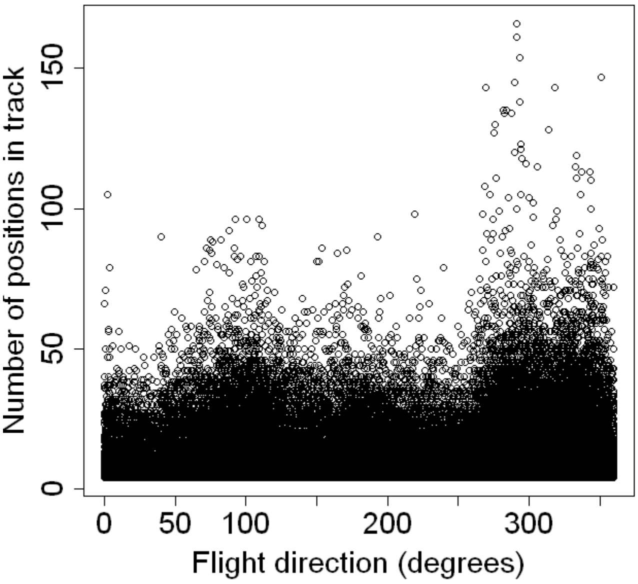
Distance analysis assumes that all objects at the observation point are detected. However, the radar is unable to detect targets close to itself. To account for this, left truncation at 300 m was used to remove the band close to the radar with few bird target detections (figure 4.3). This meant that targets detected within 300 m of the radar were excluded from the analysis. In both June 2006 and 2007, this accounted for only 14 tracks. The probability that a target at the observation point was detected (g(0)) was then assumed to be 1. This is likely to hold as a result of the left truncation used, because the radar is unlikely to disturb birds at distances greater than 300 m. Data were stratified by year to allow estimation of the effective detection radius for each year independently. In both years, the model used a half normal key with cosine adjustment.

RESULTS

Site use

A significant, but very weak correlation (r=0.059, t=21.02, d.f.=126199, p<0.001) was found between flight direction and track length and also between flight direction and angular deviation (r=-0.053, t=-18.8242, d.f.=126199, p<0.001) (figure 4.3). The significance is likely to be attributable to the large sample size, and the strength of the correlation suggests that there is no influence of the data filters on the direction of flights.

a.



b.

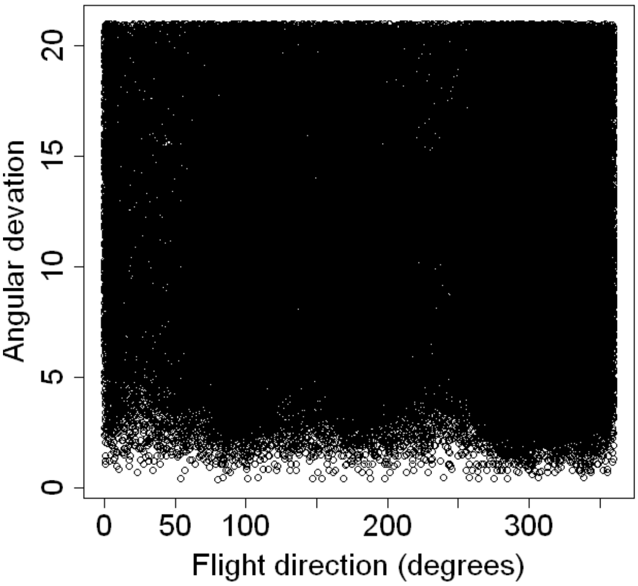
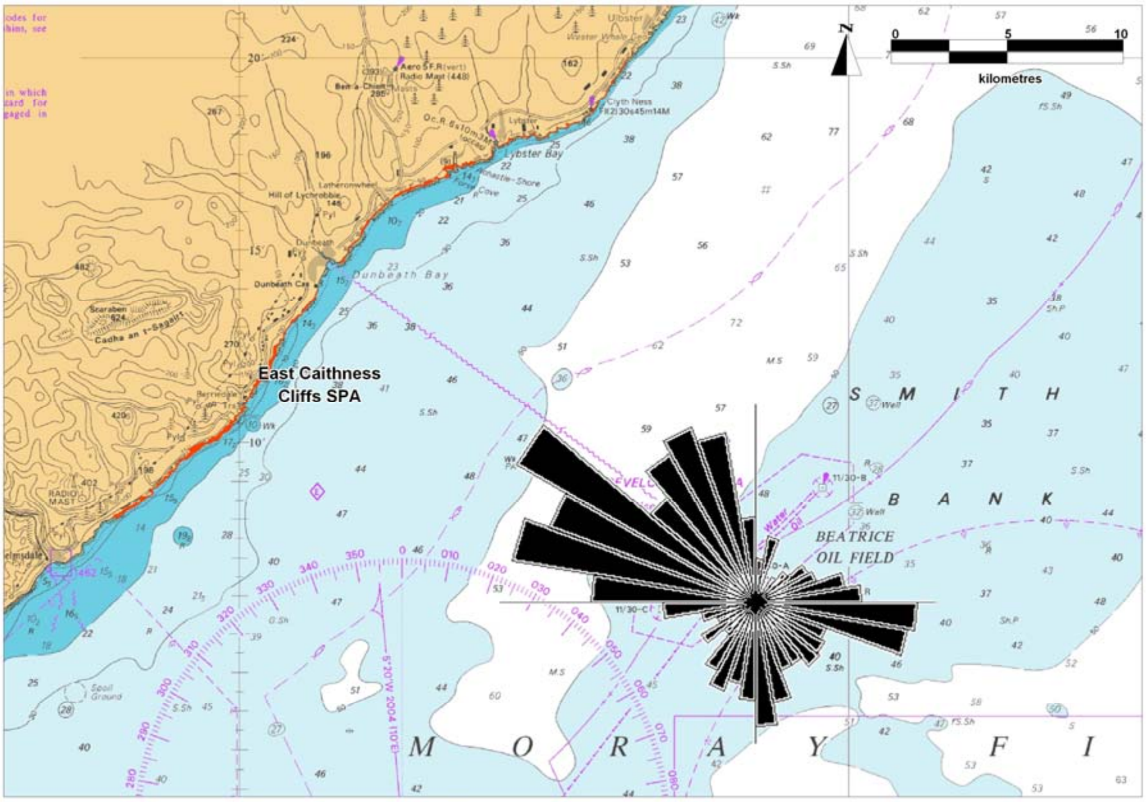


Figure 4.3. Plots of track length (a) and angular deviation (b) against flight direction.

Flights through the study area were in the same predominant direction in both years (figure 4.4). The mean flight direction in June 2006 was 298° and the modal class was 300° to 310°. In June 2007 the mean flight direction was 303° and the modal class was 290° to 300°. Direct flights made in the mean directions from the study site are likely to arrive at the southern part of the East Caithness cliffs SPA (figure 4.4), but any flight with a heading of 280° to 350° will arrive at the protected site. However, the distribution of directions was found to be significantly different between the two years (Watson's test, test statistic=0.8449, d.f.=998, *p* <0.001). This is likely to be the result of the greater number of tracks moving through the site in directions heading away from the East Caithness cliffs in 2006.

a.



b.

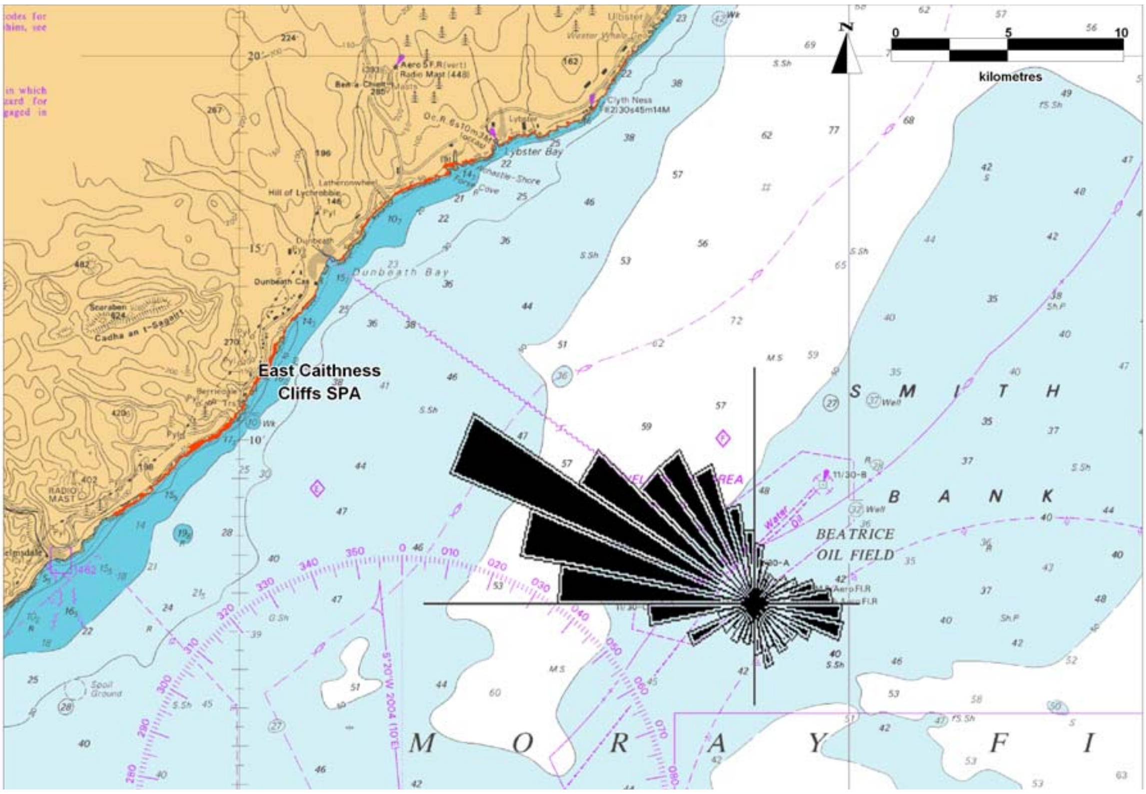
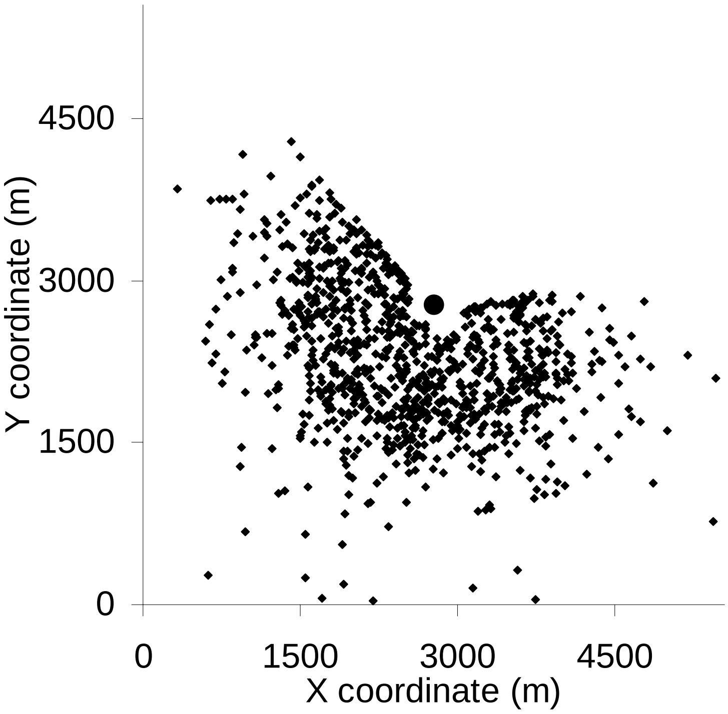


Figure 4.4. Circular frequency distributions of the directions of flights made in (a) June 2006 and (b) June 2007, plotted on charts showing the East Caithness Cliffs SPA in red. Divisions are 10º. © Crown Copyright and/or database rights. Reproduced by permission of the Controller of Her Majesty's Stationary Office and the UK Hydrographic Office (www.ukho.gov.uk) Licence number 13599.

Detection analysis

The spatial distribution of the first position in each track is similar in the samples from both June 2006 and June 2007 (figure 4.5), with at least 50% of tracks beginning within 1100 m of the radar in both years. The number of tracks beginning at greater distances falls off sharply, with less than 10% of tracks beginning 1800 m or more from the radar in both years. Targets are spread evenly across the radar's 240° field of view.

a.



b.

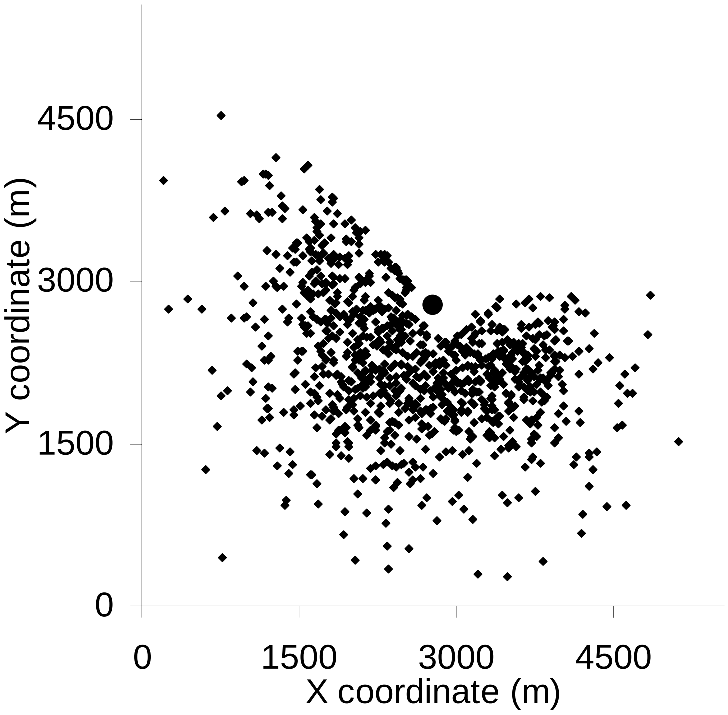


Figure 4.5. The location of the first position in each of 1000 tracks randomly sampled from June 2006 (a) and June 2007 (b). The large central circle represents the location of the radar and the area to the north of it is obscured by the Beatrice Alpha platform and so is blank.

The density of tracks per square metre was highest in both June 2006 and June 2007 at a distance of 300-400 m (figure 4.6). In June 2006, the area between 400 m and 1200 m contained 73.26% of the total density of tracks and in June 2007, the same area contained 73.44% of the total density of tracks. This area can therefore be identified as the area of peak detection in both years.

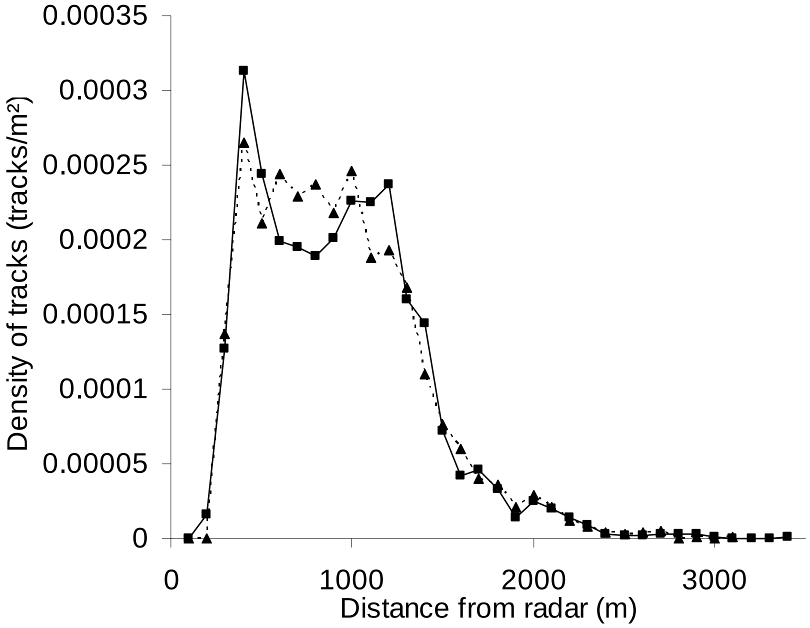


Figure 4.6. The distribution of the density of tracks (tracks per m^2) at increasing distance from the radar in June 2006 (solid line with square points) and June 2007 (dotted line with triangular points).

Distance analysis showed that the effective detection radius was similar between the two years (figure 4.7). The values were also similar to the maximum distance of peak detection found by considering the density of tracks at increasing distance from the radar (figure 4.6), with effective detection radii of 1193 m in June 2006 and 1303 m in June 2007.

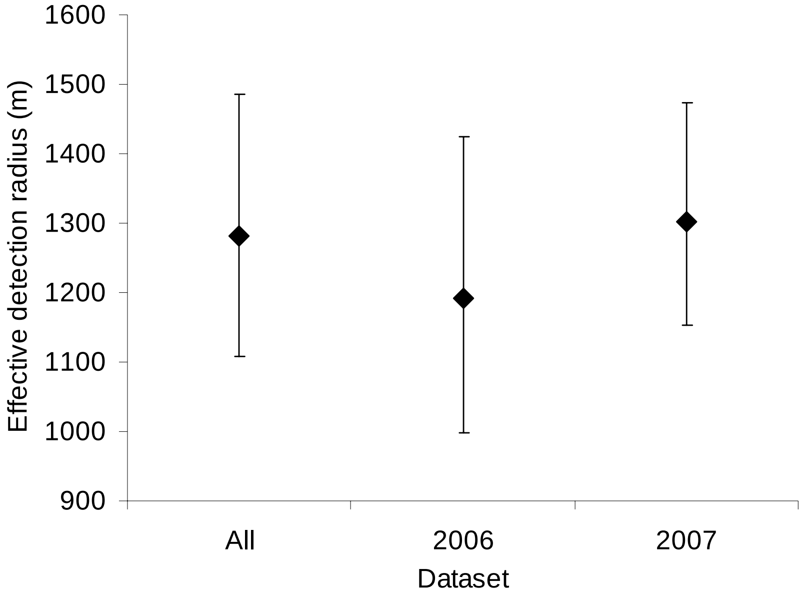


Figure 4.7. Plot of the effective detection radius calculated using Distance analysis for all data and for data collected in 2006 and 2007 individually. Error bars are 95% confidence.

DISCUSSION

Site use

The filters used to remove clutter from the radar data were shown not to influence the direction of flights (figure 4.3). These filters leave only relatively straight tracks, which are likely to represent flights straight through the study area, rather than foraging flights which are likely to have much more variable directions. This does not mean that birds do not forage in the study area, but that this behaviour is unlikely to be detected with this technique. The direction of flights through the study area was similar in both June 2006 and June 2007 (figure 4.4). In both years, the mean and modal flight directions were towards the East Caithness cliffs SPA, indicating that these flights were likely to be made by birds returning to feed chicks or to roost near breeding sites. Fewer flights were recorded heading out to the site from the colony direction. This may be because birds will initially head in the direction of the nearest known foraging location and then move on to areas further away. Benvenuti *et al*. (1998) used loggers that recorded direction on Brünnich's guillemots to demonstrate that on the way to find foraging areas, birds made several stops, presumably searching for food. Flying into the colony, birds tended to make fewer stops. Wanless *et al*. (1990) demonstrated that common guillemots tended to fly directly to foraging areas. The contrast with Benvenuti *et al*.'s (1998) study may occur if Brünnich's guillemots were failing to find food in the first foraging location they travelled to.

The significant difference found between the two distributions of flight direction is likely to be due to greater spread in the data from June 2006. This may indicate that more birds were choosing the site as a foraging location in 2006, since more flights were made heading towards the site in June 2006 than in June 2007. This may result from a difference in the availability of food in the vicinity of the study area. Data presented in chapter six show that birds were considerably more abundant at the site in 2006 than in 2007 and that this is likely to have been influenced by environmental conditions that may have increased the availability of food.

The results of the investigation into flight directions indicate that radar can be a useful tool for determining where birds using the site might be breeding. This helps to answer questions about the potential impact of a wind farm development on breeding populations. Using radar from a fixed platform at a potential wind farm site could give an overview of the likely breeding colonies used by birds at the site. Moreover, it may also be possible to determine the foraging areas of birds from a particular colony by locating a radar on a breeding cliff to measure the direction of flights in and out of the colony. The direction from which a bird returns to the colony is likely to be the best indication of where it successfully found food since there is no need to continue foraging once adequate prey have been obtained. However, Benvenuti *et al*. (1998) experimentally relocated Brünnich's guillemots and found that birds did not take a straight line route back to the colony if land masses were present. Instead, they took routes around the coast line; such behaviour must be considered carefully in the analysis of this type of data.

The filtered dataset used in this study has limitations, because only tracks passing through the area are included. It is therefore not possible to determine whether birds are foraging in the area, or foraging at sites further from the colony and transiting through. Further studies, such as tracking birds from specific colonies of interest with GPS (Guildford *et al.*, 2008) or radio tags (Perrow *et al.*, 2006) will give more detailed information on the proportion of birds at particular colonies using the site. Such data will also show the residence time in the study area, which may influence the risk of collision (Band *et al.*, 2007).

Detection analysis

Examination of the density of tracks at increasing distance from the radar (figure 4.6) and the results from the distance analysis showed similar patterns. Together, they suggest that the maximum distance that this radar effectively detects birds is at around 1200 m to 1300 m. This was also consistent between years; June 2006 and June 2007 showed very similar patterns (figure 4.6 and figure 4.7). These results were gathered with the radar set to a maximum range of 1.5 NM (2778 m), meaning that peak detection is at around 45% of the maximum range. In this study, one wind turbine was 1200 m from the radar and so was within this range, but the second was not, which meant that avoidance or impact studies could not be carried out. Similar studies aiming to investigate fine scale before and after effects of turbine installation on birds or avoidance behaviour should aim to ensure that the area of interest is within 45% of the maximum range. A compromise might be to increase the range from the 1.5 NM used in this study, but increasing this too much reduces fine scale resolution. For studies requiring high resolution data to be collected, a range no greater than 3 NM is suggested. This is considerably smaller than the maximum range capability of most marine surveillance radar, which can extend to 100 NM.

Similar results in detection capability were shown by Hüppop *et al*. (2002) (as reproduced in BSH (2007)). They used vertically scanning X-band radar with a maximum range of 2500 m, which is similar to the range selected in this study. The similarity in range means that there is not sufficient justification to extrapolate the results presented here to studies considering larger scale movements such as migration of wildfowl. Such studies often use a larger maximum range, usually around 11 km (e.g. Krijgsveld *et al.*, 2005; Parnell *et al.*, 2006; Walls *et al.*, 2007), because fine scale resolution is not necessary to study migrating wildfowl flocks. Optimal detection range should be calculated for each situation individually when planning studies to ensure that enough targets are detected in the areas of interest to give the statistical power required for impact studies. Reports and papers from radar studies often give the radar range selected, but very few have documented any consideration of detection range (Harmata *et al.*, 1999; Hüppop *et al.*, 2002 as reproduced in BSH (2007)). This should be an important part of any spatial study of movements through a wind farm area.

For distance analysis it was necessary to truncate the datasets by removing the closest 300 m to the radar. This was because very few observations were made within this area and is therefore considered unavailable for data collection (Buckland *et al.*, 2001). This is a common problem in radar studies, because clutter is worse close to the radar (Cooper *et al.*, 1991; Krijgsveld *et al.*, 2005). This is because areas close to the radar are sampled proportionally more by radar waves radiating out from the antenna than areas further away.

The distribution of tracks shown in figure 4.5 would be expected if all of the birds were randomly distributed throughout the scanned area, because detection is highest closer to the radar and falls with increasing distance. This situation might occur if birds are foraging in the area and then begin to make directed flights that the radar would track more easily, or if birds take off from the water within the scanned area. However, for birds flying directly through the scanned area, we might expect that there would be a band of detections further from the radar, at the distance at which the bird first becomes available for detection. It is likely that flights presented here are a combination of direct transits, transitions between foraging and transit, and transitions between resting and transit. This makes it difficult to determine whether the distribution presented here is the true expected distribution.

It may be appropriate in some situations to assess detection experimentally to produce empirical detection curves which could be used to test predicted detection based on the software's algorithms. This could be achieved by moving a known target through the area scanned by the radar and comparing the tracks produced. The target could be made airborne through attachment to a helium filled weather balloon, or a kite and moved by towing with a boat (or vehicle on land). The known target's position could be recorded with a high resolution GPS tag to give tracks that could be overlaid with the radar data. The clocks on the GPS and radar computer should be synchronised. The characteristics of the "flight" must meet the criteria used by the radar software for detecting avian targets, and therefore the target must move at an appropriate speed, have appropriate radar cross section and must not make large changes in direction. These criteria are different for each radar and situation, so specific values should be determined for each study. The horizontal distance between the balloon or kite and the target, and between the target and the boat (or vehicle) must be at least one pixel of the radar software, in this case 5.43 m. If the target, boat and kite or balloon, are separated by less than this, the software may detect them as a single target, increasing the likelihood of detection. Schmaljohann *et al*. (2008) suggest a method for testing detection using electronically produced "targets", which may be worth further investigation.

A protocol using a kite to lift a dead herring gull, with a GPS tag attached was trialled during this study. This was unsuccessful because the boat's top speed of 10 knots (approximately 5 ms^{-1}) was not sufficient to emulate the speed of bird. The protocol should work well if a boat which can travel at speeds of approximately 20 knots is used. Loss of communication between the boat on site and the remote radar operator on land due to poor mobile telephone signal at sea also contributed to the problem.

CONCLUSIONS

The data presented here clearly show that radar can be used as a technique to gather initial data on the breeding location of birds using a wind farm site and also potentially for determining foraging areas of birds tracked from colonies. Deploying a radar on land would be logistically more simple than deployment offshore. Alternative techniques such as satellite, GPS or radio tracking may be necessary to gather more detailed data on bird uses of the site and the amount of time spent there. At short ranges, of around 1.5 NM, it seems that the limit of peak detection of S-band marine surveillance radar is at approximately 50% of the maximum range. However, few other studies have considered this, so it is unclear whether this is true over greater maximum ranges. Detection ranges should be included in all radar studies considering the use of space by birds.

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Chapter five

The effect of flight speed on the risk of collision between birds and wind turbines

INTRODUCTION

The most direct impact of wind turbine developments on avian populations is likely to result from collision with a turbine blade. Studies of tern colonies in Belgium have found that collision with turbines may cause 3% to 4.4% additional mortality per year for common terns *Sterna hirundo*, 1.8% to 6.7 % for little terns *Sterna albifrons* and 0.6% to 0.7% for sandwich terns *Sterna sandvicensis* (Everaert & Stienen, 2007). This increase in mortality would have a significant effect on small populations. As a result of this, a collision risk assessment is required for sensitive species found to be present in significant numbers, as part of the EIA for new developments. In the UK, the standard method for calculating collision risk is a model developed by Scottish Natural Heritage (SNH) and known as the Band model (Band *et al.*, 2007), although some developments have used variations of this (Talisman Energy (UK) Limited, 2005). The original model has two stages; the first calculates the number of birds likely to fly through a risk area per year and the second calculates the probability of collision for birds in that risk area. The risk area is effectively a square window around the turbine blades, the length and width of which is the same as the blade length. The depth of the window changes along the blade length since the blades are tapered to the tips. The results of the two stages are combined to allow an estimation of the number of birds that might collide with the turbines per year.

Collision probability when flying through the risk area is calculated for distances along the blade at 5% increments and for different orientations away from the vertical and is given in the form $p(r, \varphi)$ where r is the radius from the hub and φ is the angle of the radial line from the hub. This probability is integrated over the swept area of the turbine to give values for bird transits through any part of the rotor. Dimensions of the rotors and the bird length are used to calculate the probability of collision of a bird flying through the rotors. The method of flight (either flapping or gliding) is included in the model in order to account for the larger volume of air that a flapping bird occupies. A spreadsheet containing these calculations is available (SNH, 2000) to allow standardised calculation of the collision risk for use in EIA. The probability of collision at a radius r from the hub is given by:

$$p(r) = (b\Omega/2\pi v)\left[K \,|\pm c\sin\gamma + \alpha\, c\cos\gamma\,| + \begin{array}{ll} L & \text{for } \alpha<\beta \\ w\alpha F & \text{for } \alpha>\beta \end{array}\right]$$

where

b = Number of blades
Ω = Angular velocity of rotor (radians/sec)
c = Chord width of blade
γ = Pitch angle of blade
R = Outer rotor radius
L = Length of bird
w = Wingspan of bird
β = Aspect ratio of bird (L/w)
v = Velocity of bird through rotor
r = Radius of point of passage of bird
α = $v/r\,\Omega$
F = 1 for a bird with flapping wings
= $(2/\pi)$ for a gliding bird
K = 0 for one-dimensional model (rotor with zero chord width
= 1 for three-dimensional model (rotor with real chord width)

This is calculated at increasing distance from the hub, taking into account the change in chord width at that distance (based upon a generic turbine design). Two cases are calculated and combined, the first being upwind flight and the second downwind flight. This refers to the angle of approach to the turbine, rather than any biological effect of upwind or downwind flight. The method of flight (either flapping or gliding) is included in the model in order to account for the larger volume of air that a flapping bird occupies. This only has more effect on the model results for flights made closer to the turbine hub, since at these distances the volume of air occupied by turbine blades is greater. However, the distance at which this occurs varies with turbine and bird velocity, since the equation above shows that the function $w\alpha F$ is only used when $\alpha > \beta$.

Clearly, the more flights a bird makes through the risk area, the greater the chance of colliding. The number of flights can be strongly influenced by bird behaviour, for example, a study of common terns found that male birds accounted for 78% of collision fatalities during the incubation and early chick rearing periods, due to their provisioning role at this time (Stienen *et al.*, 2008).

McAdam (2005) produced a variation of the Band model and found that accounting for bird flight height altered the predicted collision risk considerably, with the Band model tending to underestimate collision risk close to the turbine hub, but overestimating it at other heights. This finding is supported in a study by Kikuchi (2008), which also found that flight at the hub height had the highest risk of collision. A review of the Band model found that bird length and wing span had little influence on the predicted collision risk (Chamberlain *et al.*, 2005). It also showed that turbine characteristics such as the blade length, rotation period and pitch angle had variable and non-linear effects. These characteristics are available from the turbine manufacturers, allowing easy quantification of the effects. However, the value of pitch angle varies along the length of the blade, and also changes with wind conditions, making this more difficult to incorporate into the model.

Bird flight speed is included in the calculations of the Band model and is usually given as the species' mean airspeed (the speed at which the bird is moving relative to the air around it) as this is the most commonly published speed (e.g. Pennycuick, 1997). However, for the model to function correctly, it requires the ground speed of birds, because this is the speed at which the bird will pass through the rotors. Ground speed takes into consideration the effect of wind speed and direction on airspeed and gives the resultant speed over the ground. There will necessarily be more variation in ground speed than airspeed because of the large range of possible values that wind speed and direction can take. Using the airspeed of a bird assumes that there is no influence of the wind on flight speed, which will only be true on windless days. The effect of wind can create a large difference between airspeed and ground speed, with migrating birds able to increase their speed by 30% by selecting favourable wind speeds and directions (Liechti & Bruderer, 1998), which will reduce energetic costs.

Birds flying during the breeding season may not be able to select the most favourable winds since they must return to a nest (Spruzen & Woehler, 2002) and may consequently reduce their ground speed by flying into headwinds. However, overall energetic demands are greater during this period due to the need to attend the colony to incubate or feed chicks (Stone *et al.*, 1995). Many studies of seabirds have shown that they are capable of using wind directions to improve efficiency when feeding chicks. For example, Cape gannets *Morus capensis* were shown to return to the colony in the direction of the prevailing wind, reducing their energetic requirements when carrying prey loads (Adams & Navarro, 2005) and wandering albatross *Diomedea exulans* have been shown to cover greater distance and to fly faster during the fledging period through the use of favourable winds (Salamolard & Weimerskirch, 1993).

McAdam's (2005) model showed that birds which flew directly into the prevailing wind had twice the collision risk of birds flying in the safest direction. Chamberlain *et al.*'s (2005) review of the Band model also found that flight at low speeds could increase collision risk, with this increasing exponentially for flight speeds slower than 5 ms^{-1}. These authors suggested that it was unlikely that birds would be flying this slowly, but did not consider the effect of wind on flight speeds. Similarly, Kikuchi (2008) found no effect of reduced flight speed on collision risk, but did not consider flight speeds of less than 8 ms^{-1}.

Ground speed is a mathematical vector made up of components of airspeed and direction and wind speed and direction. It is intuitive that there will be variation in wind variables resulting in variation in ground speed, but airspeed has also been found to vary with wind conditions. For example, Spear & Ainley (1997a) found that all seabirds increased their airspeed in headwind conditions. Furthermore, flapping birds decreased their airspeed in tailwinds, while gliding birds did not change their airspeed in response to tailwinds. Migrating birds have also been predicted to increase their airspeed when flying into headwinds to maintain their progress in relation to the ground and reduce it when flying with a tailwind (Liechti, 1995; Pennycuick, 1978) and empirical tests of this have generally found it to be true (Hedenström *et al.*, 2002; Miller *et al.*, 2005). This is supported by energetic studies in small passerines which found that birds are metabolically more capable of increasing flight speed than they are of flying with increased mass (Engel *et al.*, 2006).

Other theoretical work has hypothesised that birds will increase their airspeed when they are feeding young, as long as the time saved can be spent foraging and providing a greater quantity of food to the young (Norberg, 1981). However, this seems to be related to a species' ability to increase its flight speed. For example, Alcids, such as Brünnich's guillemot *Uria lomvia* were shown to be less able to increase foraging speed than northern fulmars *Fulmarus glacialis*, during the breeding season (Elliott & Gaston, 2005). A review of this topic (Houston, 2006) found little empirical evidence to support the hypothesis and suggested that one problem is the assumption that time saved in transit can be used in gathering extra food which may not hold in all cases, particularly when prey are patchily distributed.

Three main techniques have been used to measure flight speeds; satellite tags, ornithodolite and radar. Satellite tags are becoming increasingly accurate (up to 5 m accuracy), although some of the earlier studies (e.g. Salamolard & Weimerskirch, 1993) have accuracy of between 250 m and 1000 m. They allow species specific information to be collected on flight speeds, although wind data, required to calculate airspeed, may not be available in many of the areas seabirds move through, or at the scales at which they travel. Consequently, many of these studies (e.g. Catry *et al.*, 2004) can only consider ground speed which limits energetic studies. The ornithodolite (Pennycuick, 1982) originally consisted of a range finder and angular encoder linked to a microcomputer. Similar results could be obtained by using a surveyor's theodolite linked to a portable computer. The method allows flight speed data to be collected on any species from stable platforms or vantage points. The disadvantage is that observations can only be made during periods with good visibility, limiting data collection to day time periods without fog or heavy precipitation. Only movements within a small area close to the viewing platform can be measured, but this means that in contrast to satellite telemetry, detailed studies of airspeed can be carried out because accurate and synchronised wind speed measurements can be taken with the track data.

Radar has been widely used as a tool for collecting data on birds during migration as well as foraging (Alerstam, 2001; Alerstam *et al.*, 1993; Cooper *et al.*, 1991; Hedenström *et al.*, 2002). It allows large numbers of birds to be tracked simultaneously within a defined area, collecting data on ground speeds and flight directions. When coupled with high resolution wind measurements, this can allow for investigations of the airspeed of birds. More recently, radar has been used in wind farm studies to understand the flux of birds moving through the areas and the flight paths that are taken (Cooper, 1995; Desholm & Kahlert, 2005; Gauthreaux & Belser, 2003). Automating target detection and tracking allows data to be collected without an observer present, including periods of darkness or low visibility, in contrast with the ornithodolite.

Aims

This study aimed to look at how flight speeds affect the probability of a bird colliding with a wind turbine. Radar was used to collect empirical data on the flight speeds of birds in an offshore environment close to a wind turbine development, to allow realistic parameters to be used in collision risk models. The data allowed an assessment of the times and conditions under which birds are more likely to perform flights that have a higher risk of collision. Key questions were: whether collision probability varies with speed; how different airspeed and ground speed are for individual birds; the extent to which birds fly with or against the wind and temporal variation in this and; whether there are any species differences in the proportion of head- or tailwind flights.

METHODS

An S-band marine surveillance radar (FAR-2137S, Furuno) sited on an offshore oil platform in the Moray Firth, Scotland was used to record movements of birds near a wind turbine development. The radar was equipped with tracking software (Merlin, DeTect Inc. Florida) that allowed automatic detection of potential bird targets and recorded tracks to a database. The position of targets was recorded every 2.3 seconds and was accurate to approximately 5.5 m. The radar was allowed to run continuously and data presented here were collected between June 2006 and October 2007. From July 2006, one 5 MW wind turbine was installed at the site, and a second installed in July 2007.

The radar data contain x and y coordinates for each position in the recorded track, which were converted to values in metres, along with the time at which they were recorded. These were used to calculate the average ground speed of each track. The direction of flight was also recorded for each position and a circular mean (Zar, 1998) was taken of these values, to give an average heading for the track. Wind speed and direction data were logged automatically on the oil platform, at a height of approximately 86 m above sea level. No correction was made for the altitude of wind measurement because bird flight heights were not known. Wind speed was recorded with an accuracy of ± 1 knot. The average wind speed and direction in the 10 minutes previous to the track beginning was used to allow for time synchronisation errors and to remove the effect of wind gusts. Wind direction, which was recorded as the direction that the wind was coming from, was converted to the direction it was moving towards by adding 180° to values less than 180° and subtracting 180° from values greater than 180°, to be consistent with the directions of bird movement. Wind speed was converted from knots to metres per second (ms^{-1}) for the same reason.

These data were used to calculate the airspeed of the tracks. Wind speed and ground speed make up two sides of a triangle and the third side is airspeed. All angles were converted to radians for the calculations. The smallest difference between flight direction and wind direction was found (including differences that crossed the boundary between 0 and 2π), as this is the only known interior angle of the triangle. The cosine rule; $c^2 = a^2 + b^2 - (2ab\cos C)$, was then used to calculate the length of the third side of a triangle, since very few of the triangles created had right angles. The two other sides had lengths equal to the ground speed and wind speed of the track (figure 5.1).

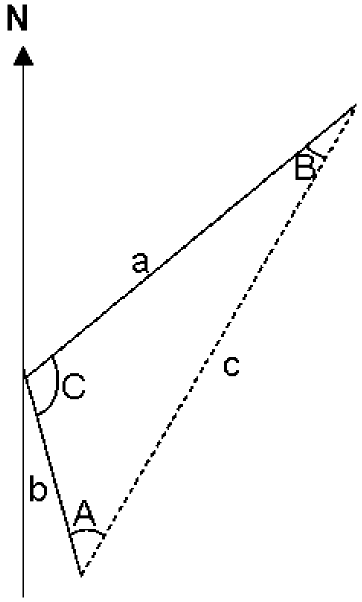

Figure 5.1. Diagram showing examples of the position of speeds and directions. C is the angle between the bird's resultant direction (after the wind has altered its course) and wind direction and c is the airspeed (ms^{-1}). A is the angle between wind direction and the bird's actual heading (before the wind alters its course) and a is the ground speed (ms^{-1}). B is the angle between the bird's resultant heading and its actual heading and b is the wind speed (ms^{-1}).

Airspeed values in this analysis are likely to be underestimates because the radar is only capable of measuring distance in the horizontal plane. If the bird is moving in the vertical plane at the same time as flying horizontally, its recorded flight speed will be lower than its actual airspeed. This will not affect measurements of ground speed since this is related to the bird's progress in relation to the ground and will also not affect calculated collision risk so long as the value used is ground speed.

Data quality was substantially affected by the occurrence of sea clutter (false targets caused by the movement of water) and so all data in these analyses were filtered (see chapter three):

1. to reject data collected on days with a mean wind speed greater than 15 knots.
2. to reject tracks with an angular deviation greater than 20°.
3. to include only tracks lasting for 30 seconds or longer.

The length of time that the target must have been tracked was extended to 30 seconds in this chapter, from the four scans used in chapter 3 because analyses of average flight speed are likely to be more accurate with longer tracks.

Further to these filters, a constraint was placed on the range of airspeed. Published airspeeds of birds commonly found in the study site, measured by ornithodolite (Pennycuick, 1982) (table 5.1) showed that it was unlikely that birds were flying at airspeeds slower than 10 ms^{-1} or faster than 20 ms^{-1}. No measure of variability in these values was available and so data were filtered to allow only airspeeds of between 5 ms^{-1} and 30 ms^{-1}, to remove targets moving unrealistically quickly or slowly, which may include aircraft, boats and insects (Larkin, 1991). It is possible that some slow tracks were genuine bird targets, because the radar only measures movement in the horizontal plane.

Table 5.1. Mean airspeeds, wing spans and lengths for species commonly found in the study area. Sources: Pennycuick (1997) and Mullarney *et al*. (1999)

Species	**Mean airspeed (ms^{-1})**	**Wing span (m)**	**Length (m)**
Common guillemot – *Uria aalge*	19.1	0.61-0.73	0.38-0.46
Razorbill – *Alca torde*	16.0	0.60-0.69	0.38-0.43
Atlantic puffin – *Fratercula arctica*	17.6	0.50-0.60	0.28-0.34
Black-legged kittiwake – *Rissa tridactyla*	13.1	0.93-1.05	0.37-0.42
Herring gull – *Larus argentatus*	9.9	1.23-1.48	0.54-0.60
Great black-backed gull – *Larus marinus*	13.0	1.44-1.66	0.61-0.74
Gannet – *Morus bassanus*	14.9	1.70-1.92	0.85-0.97
Great skua – *Catharacta skua*	14.9	1.25-1.40	0.50-0.58
Northern fulmar – *Fulmarus glacialis*	13.0	1.01-1.17	0.43-0.52

Data from November 2006 were also removed from further analysis, because only 34 tracks were available from this month, all of which had extreme values of airspeed. The remaining dataset contained 113,081 relatively straight tracks for analysis. These are likely to represent birds passing through the area, rather than foraging within it. These tracks were distributed throughout the year, although 23% of them were recorded in June 2006 and 17% in July 2006 (figure 5.2). Tracks were coded for the season (breeding or non-breeding) in which they were recorded, to allow analyses of the effect of different behaviour during these periods. The breeding season was defined as the months of May, June and July, since these are the times when adult birds are most likely to be attending nests to incubate and feed chicks (Stone *et al.*, 1995).

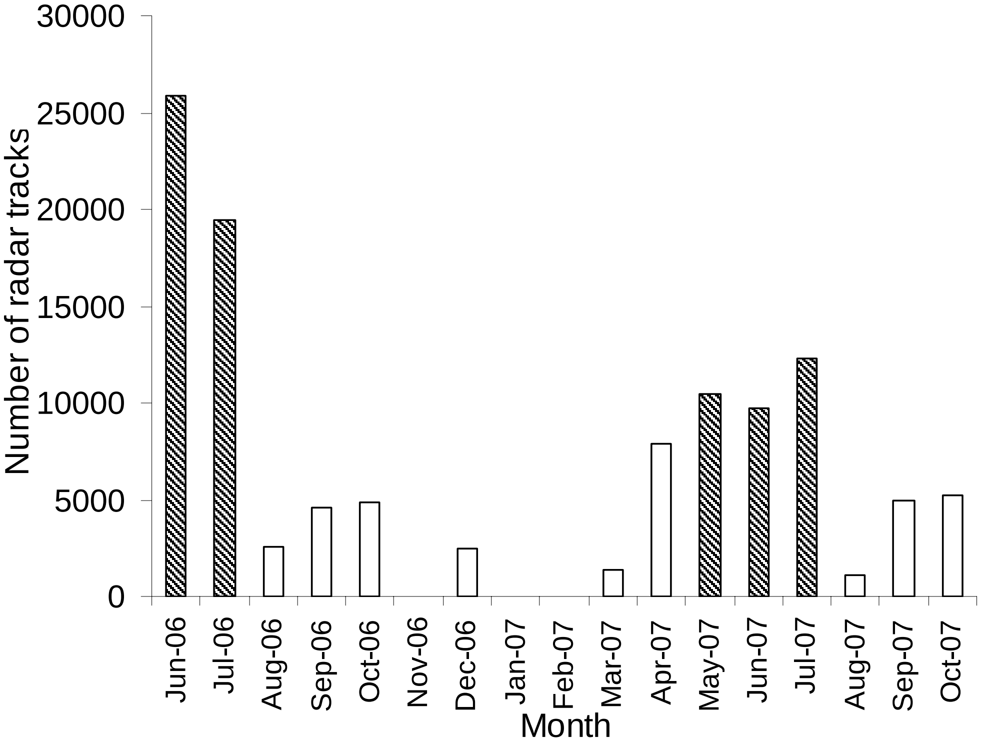

Figure 5.2. The monthly totals of tracks recorded by the radar and remaining in the dataset after filtering out potential clutter. Hatched bars represent months that were considered to be in the breeding season and empty bars represent months outside this period.

Analysis

Collision probability in relation to flight speed

Collision probabilities at different flight speeds and under head and tail wind conditions were calculated from the second part of the Band model. Therefore, the results presented represent collision probabilities, assuming that all flights are made directly through the turbine risk area. The turbine parameters of the REpower 5 MW turbines installed at the Beatrice demonstrator site were used (table 5.2). The Band model will only allow one value for pitch, but the manufacturers give the value as a range between 0° and 91°. Therefore, the value for pitch is the largest value used in McAdam's (2005) model based on the same turbines, which accounts for changes in pitch. Values used for bird flight speed, length and wing span are taken as the mean of the maximum values for all species listed in table 5.1. No distinction was made between species because the radar data collected in this study cannot discriminate between species. Birds are assumed to be flapping rather than gliding because auks, which are the most common group of birds at the site (see figure 2.2), flap continually and gulls will vary their flight strategy between flapping and gliding, with energetic demands (Shamoun-Baranes & van Loon, 2006).

Table 5.2. Parameters used in the calculation of collision probability (http://www.repower.de/fileadmin/download/produkte/5m_uk.pdf). Pitch is an assumed value from McAdam (2005), since it ranges from 0° to 91° along the length of the blade.

Parameter	Value
1D or 3D	3D
Number of blades	3
Maximum chord	4.73 m
Pitch	10°
Rotor diameter	126 m
Rotation Period	6.32 seconds
Wing span	1.19 m
Bird length	0.56 m

Difference between airspeed and ground speed

Comparisons were made between airspeed and ground speed of each target using paired Wilcoxon signed rank tests, which are non-parametric, because the variances in the data were not homogenous. Further analysis of the slowing effect caused by flying into headwinds was carried out by considering the distribution of the difference between ground speed and airspeed. Circular correlation tests were carried out to determine the extent to which wind direction affected flight direction, using the CircStats package in R (Lund & Agostinelli, 2007).

Temporal variability in flight direction relative to the wind

The proportion of tracks flying into headwinds was investigated with respect to three levels of time: year (2006 or 2007), season (breeding or non-breeding), and time of day (dawn, day, dusk or night) using a generalised linear model, with a quasibinomial distribution and a logit link function, because the data were found to be overdispersed after initial investigations using a binomial distribution. Pairwise interaction terms were also included in the model, but the three way interaction was excluded because this would create a fully saturated model. Model simplification was carried out using nested models, starting from the full model with all three pairwise interaction terms

$$y \sim Year : Season + Year : TimeofDay + Season : TimeofDay$$

and removing individual interaction terms to find whether this significantly affected the model. The significance of the removal was tested with ANOVA F tests and terms were removed if there was no significant difference to the amount of variation explained by the model. Plots of the residuals were inspected to validate the final model.

Head or tail wind flights were classified using the value of ground speed minus airspeed. If this value was positive, the track was moving with a tailwind, since ground speed was greater than airspeed and conversely, if the value was negative, the track was moving with a headwind since airspeed must have been greater than ground speed. Season was used in place of month because the same months did not always have data in both years (see figure 5.2). The factor levels for time of day were defined by using the times of sunrise and sunset. Dawn was defined as the period one hour before and one hour after sunrise and dusk as the period one hour before and one hour after sunset. Day was defined as the period between dawn and dusk and night as the period between dusk and dawn.

Proportion of head and tail wind flights in different species

Airspeed data from June 2006 showed a bimodal distribution. The two peaks in airspeed lay approximately at the speeds that would be expected from gull species and from auks, particularly guillemots (see table 5.1). These data were used to investigate potential species differences in the proportion of head or tail wind flights. Tracks with airspeeds in the modal classes of these two peaks were considered, to find whether there was a difference in the proportion of head or tail wind flights.

Analyses were carried out in R version 2.7.1.

RESULTS

Collision probability in relation to flight speed

Collision risk for birds flying through the turbine risk area was calculated from the Band model for ground speed values ranging from 1 ms^{-1} to 40 ms^{-1}, maintaining the separation of head and tail wind cases (figure 5.3).

Flying into a headwind had a higher collision risk than flying with a tailwind at all flight speeds. Flight at low ground speed presented an increased risk of collision, for example, flights at 10 ms^{-1} in headwind conditions have a 9.5% probability of collision, but this increased to 14.2% if the ground speed decreased to 5 ms^{-1} and to 52.8% if the ground speed was reduced to 1 ms^{-1}.

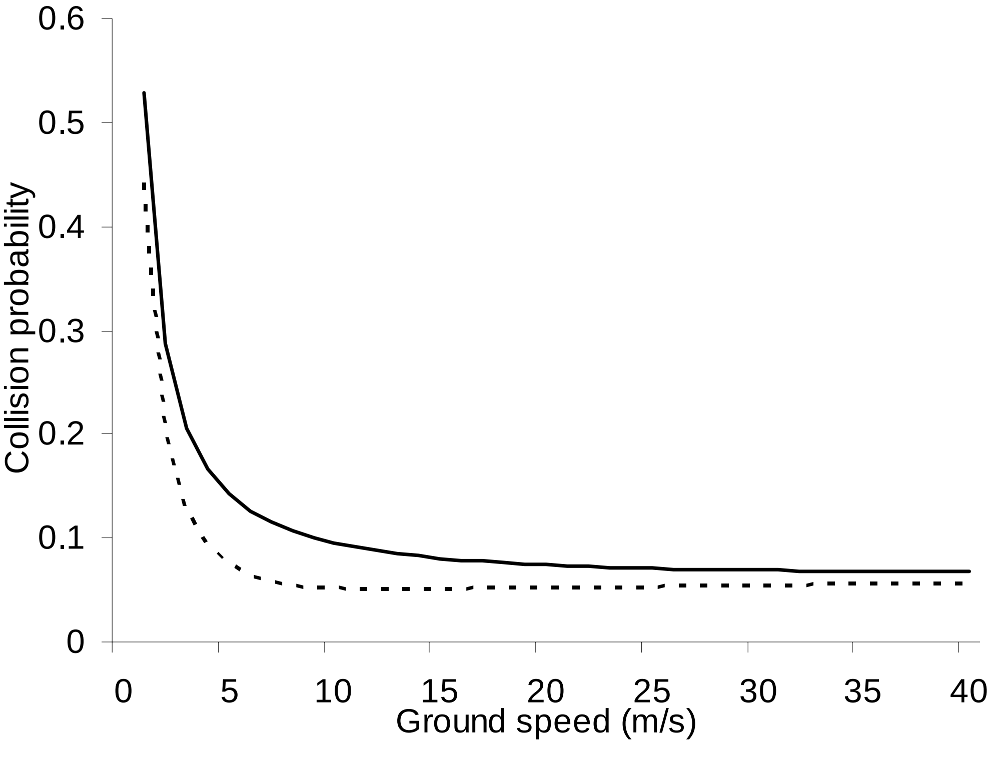

Figure 5.3. Collision risk for birds flying through wind turbine rotors at different speeds as calculated by the Band model. The solid line represents flight into a headwind and the dashed line represents flight with a tailwind.

Difference between airspeed and ground speed

Airspeed ranged between 5.00 ms^{-1} and 29.98 ms^{-1} due to the constraints placed on the data. The mean value was 14.34 ms^{-1} although a slight shoulder is detectable at values greater than this, up to around 20 ms^{-1} and the standard deviation was 4.03 ms^{-1} (figure 5.4). Ground speed ranged more widely, from 1.02 ms^{-1} to 36.51 ms^{-1}. The mean was 13.63 ms^{-1}, with a standard deviation of 4.72 ms^{-1}, also indicating a wider spread in ground speed than in airspeed. A paired Wilcoxon signed rank test showed that there was a significant difference between the values of airspeed and ground speed for individual tracks ($V=3792797296$, $p<0.001$), with a median difference of 0.500 ms^{-1}.

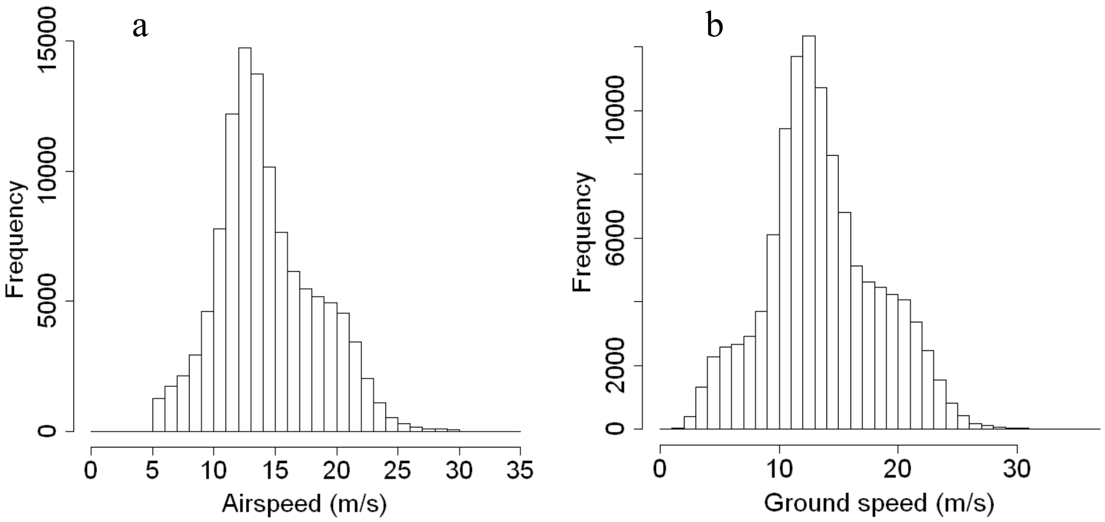

Figure 5.4. Frequency distributions of (a) airspeed (V_a) and (b) ground speed (V_g) of radar tracks.

Ground speed was lower than airspeed in 55.88% of all tracks, indicating that a small majority of birds were flying into headwinds. Of those headwind tracks, 16.78% (18,976 tracks) had ground speeds of less than 10 ms^{-1}, the value at which there is a 10% or greater risk of collision. The slowest tailwind flight had a ground speed of 5.08 ms^{-1}, which would have a 7.42% probability of collision. To quantify this effect, ground speed minus airspeed was calculated for every track (figure 5.5). The mean of this distribution shows that on average, ground speed was 0.707 ms^{-1} slower than airspeed. The standard deviation is 3.190 ms^{-1} showing considerable spread in the data. The distribution is left skewed, indicating that some tracks are affected by wind speed and direction to a much greater degree than others. The left tail of the distribution, at values of ground speed minus airspeed lower than -5 ms^{-1} contains 8.6% of the data, or 9798 tracks.

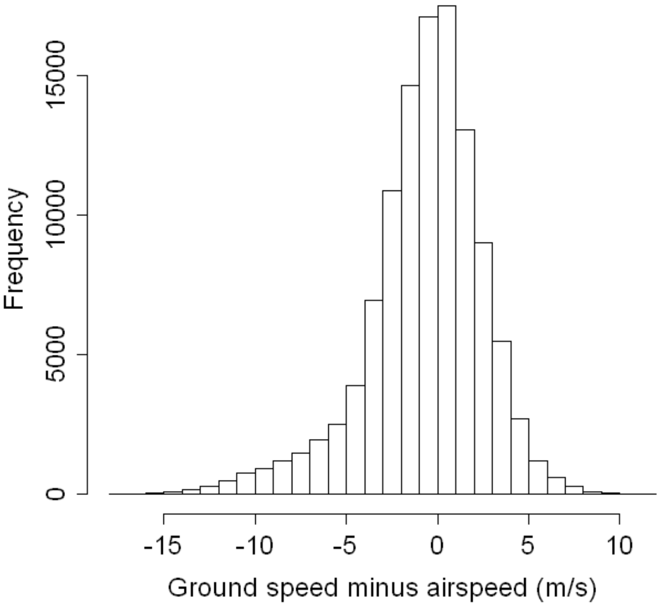

Figure 5.5. The frequency distribution of ground speed minus airspeed of individual radar tracks.

Variability in flight direction relative to the wind

Most flights in the dataset were in a north-westerly direction (figure 5.6a), with a mean flight direction of 323°. The mean wind direction recorded at the same time as the flights in this dataset was 291° (figure 5.6b), but the mean wind direction throughout the period of June 2006 to October 2007 was 41° (figure 5.6c). The difference between the two distributions of wind direction is significant (Wilcoxon test, W=60882356709, $p<0.001$).

The correlation between flight direction and wind direction within a track was very weak, but statistically significant (r=0.0185, test statistic=6.204, d.f.=113079, $p<0.001$, circular correlation). The correlation is slightly stronger for tracks recorded during the breeding season (r=0.0224, test statistic=6.311, d.f.= 77867, $p<0.001$, circular correlation), and tracks recorded during non-breeding seasons show no statistically significant correlation between flight direction and wind direction (r=-0.0038, test statistic=-0.725, d.f.= 35212, $p=0.469$, circular correlation).

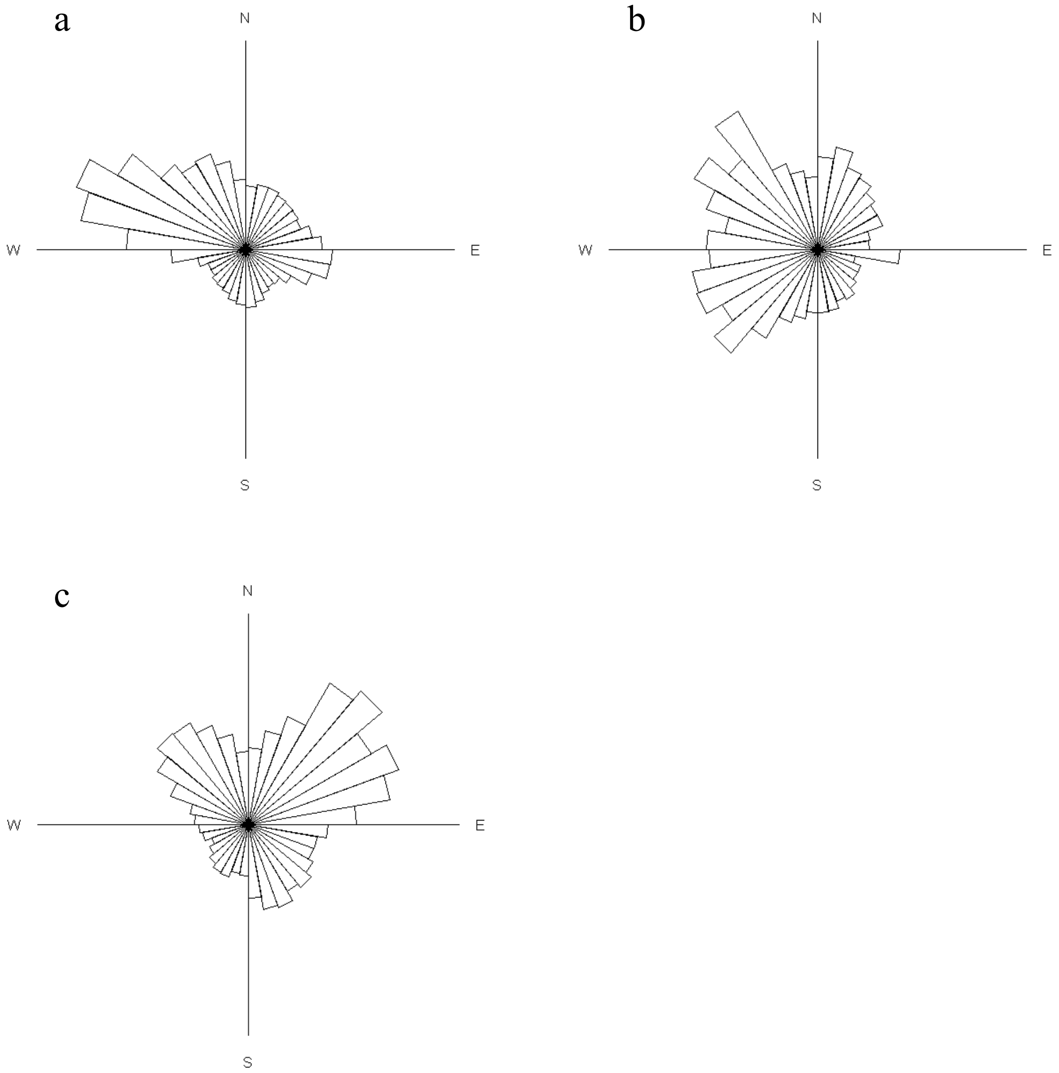

Figure 5.6. Circular frequency distributions of (a) flight directions, (b) wind directions for radar tracks, and (c) overall wind directions for the period between June 2006 and October 2007. Wind directions are the direction the wind was moving towards, rather than the standard of direction that it moved from.

The proportion of headwind flights varies temporally at different scales (figure 5.7). Model simplification, using nested models found that the simplest model removed time of day as a variable, but retained the variables Year and Season and the interaction between them: $y \sim Year : Season$.

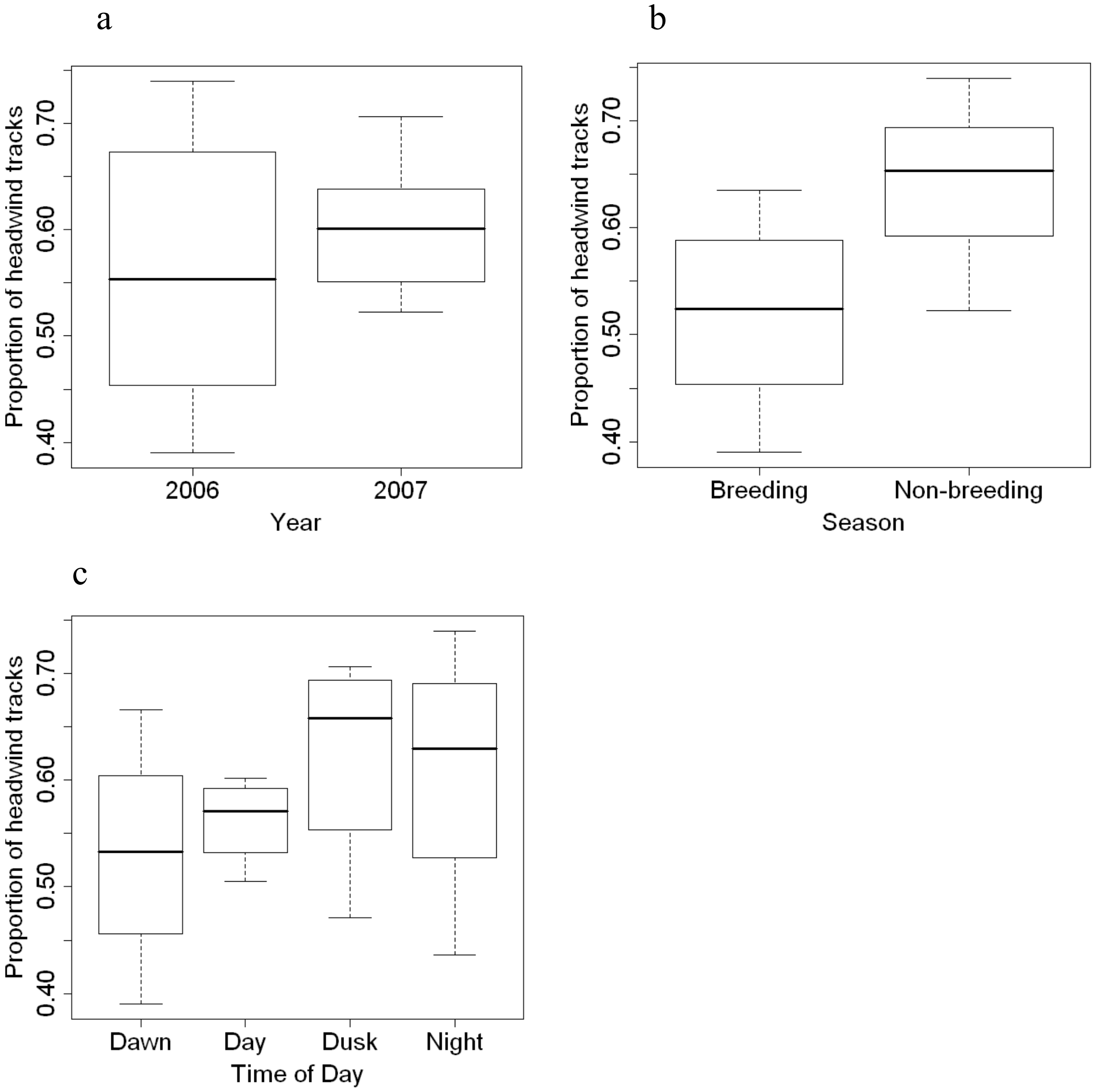

Figure 5.7. Three scales of temporal variability in the proportion of headwind tracks: (a) Interannual variation between 2006 and 2007, (b) seasonal variation between breeding and non-breeding seasons and (c) variation throughout the day. The thick horizontal lines represent the median value, the boxes represent the first and third quartiles and the vertical lines extend to 1.5 times the interquartile range.

These results (table 5.3) showed that both Year and Season had a significant effect on the proportion of headwind flights recorded, and that the interaction between these variables was also significant. Flights in 2007 were significantly more likely to be into headwinds than those made in 2006. Flights made during the non-breeding season were significantly more likely to be into headwinds than during the breeding season. A significant interaction was found between season and year, with the proportion of headwind flights decreasing in the non-breeding season in 2007 compared with the breeding season in 2006.

Table 5.3. Results of a binomial generalised linear model on the proportion of headwinds observed, with year, season, time of day and the interactions between these factor levels. Interactions are noted with a colon e.g. Year:Season denotes the interaction between the variables Year and Season.

Variable	**Coefficient**	**Standard error**	**t**	**P**
Intercept	-0.045	0.073	-0.617	0.5486
Year (2007)	0.336	0.114	2.959	0.0119
Season (non-breeding)	0.800	0.156	5.123	<0.001
Year (2007):Season (non-breeding)	-0.662	0.210	-3.147	0.0084

Proportion of head and tail wind flights in different species

Airspeed and ground speed in June 2006 showed bimodal distributions (figure 5.8). The modal classes of the two peaks are 13-14 ms^{-1} and 20-21 ms^{-1}, which correspond closely with the published airspeeds for kittiwakes (13.1 ms^{-1}) and guillemots (19.1 ms^{-1}) (see table 5.1), which are the most commonly occurring gulls and Alcids at the study site.

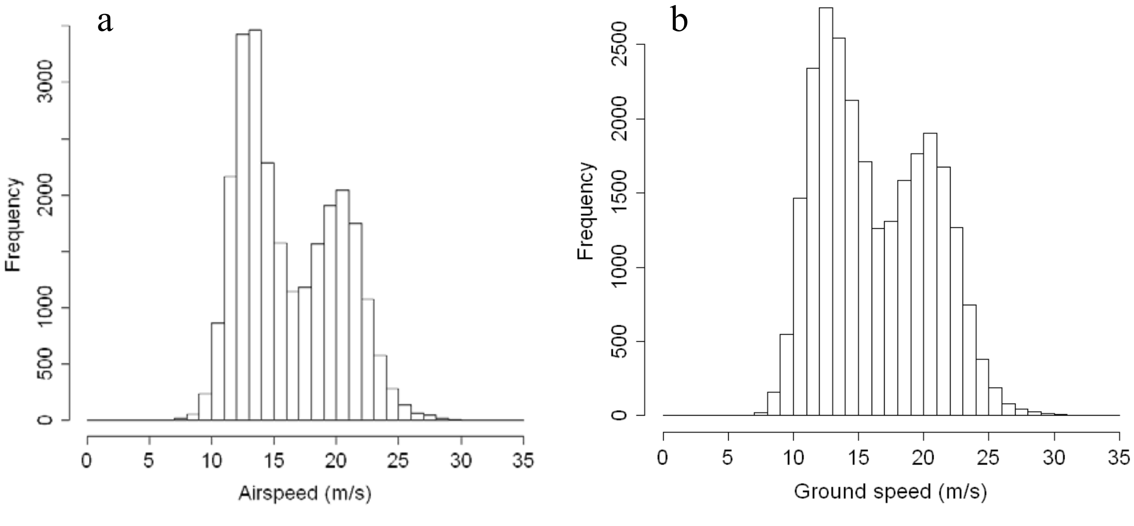

Figure 5.8. Frequency distribution of (a) airspeed and (b) ground speed of radar tracks recorded in June 2006.

Tracks with modal airspeed values in the two peaks of airspeed in June 2006 were taken as samples of the two species groups to investigate whether there were any differences in the species' responses to wind direction. The sample of tracks assumed to represent gulls all have airspeed values between 12 and 14 ms^{-1}, while those assumed to represent auks have airspeed values between 19 and 21 ms^{-1}. A total of 10,857 tracks fall into these two categories, with 3962 classified as auks and 6895 classified as gulls.

The majority of birds in both species groups flew with tailwinds, with 52.93% of auk tracks and 51.08% of gull tracks moving with the wind. The mean ground speed for tracks classified as gulls was 13.09 ms^{-1}, with a standard deviation of 1.94 and for tracks classified as auks was 20.25 ms^{-1}, with a standard deviation of 2.30. The distributions overlap somewhat (figure 5.9), indicating that wind speed and direction have an impact on both species' groundspeeds.

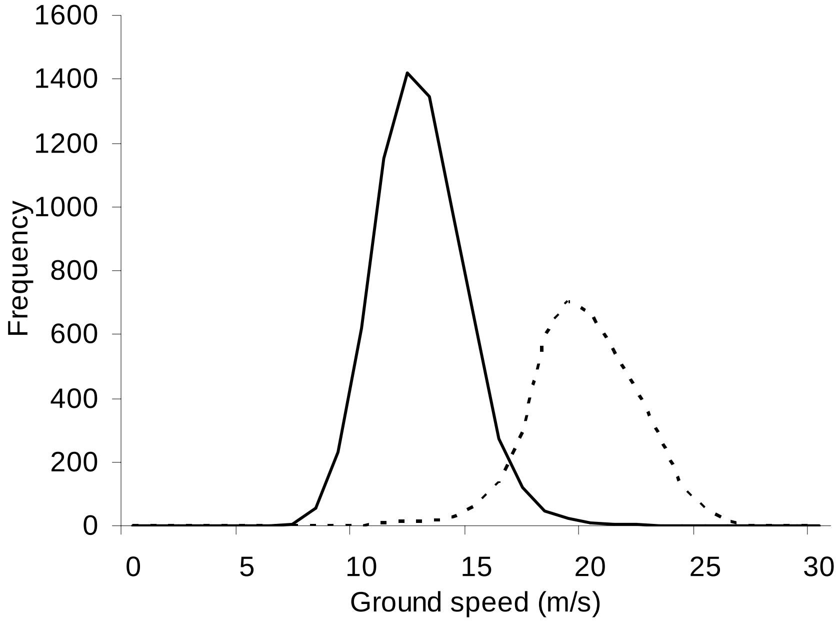

Figure 5.9. Frequency distributions of ground speed for individual tracks classified as gulls (solid line) and auks (dashed line) on the basis of airspeeds recorded in June 2006.

DISCUSSION

Collision probability in relation to flight speed

Estimates of collision probability for birds flying through the turbines at the Beatrice site have a clear negative relationship with flight speed and increase very quickly at flight speeds less than 5 ms^{-1} (figure 5.3). This is in common with the findings of Chamberlain *et al.*'s (2005) review of the same collision model. Using a similar model, but only allowing flights as slow as 8 ms^{-1}, Kikuchi (2008) found no significant relationship between collision probability and flight speed. If the same minimum speed was applied to collision risk calculated here, a maximum collision probability of 10.68% would be obtained and a similar conclusion would be drawn, demonstrating the need to include measurements of ground speed rather than airspeed.

Additionally, the collision probabilities calculated here, from the Band model, were higher in all cases in headwind conditions. This is a result of approaching the rotors from the rear, rather than any biological effect of flight under these conditions. The two circumstances of slow flight speed and headwind flight are highly likely to co-occur since flying into a headwind will reduce the ground speed of a bird.

Difference between airspeed and ground speed

On average, ground speed was 0.707 ms^{-1} slower than airspeed. Airspeed is more commonly used in collision risk assessments, so using the ground speed value will give a small increased risk of collision. However, the distribution of ground speed minus airspeed demonstrates that there are many tracks where the difference is considerably larger than this, giving birds a much increased risk of collision. The peak value of airspeed lies around the range of speeds expected from gulls at the site, but the shoulder is closer to values expected from auks. This could be interpreted to mean that there are many more gulls at the site than auks, but it is likely that the lower flight height of auks (Garthe & Hüppop, 2004) may cause their tracks to be caught in the clutter data and filtered out.

Chamberlain *et al.* (2006) used Bewick's swans *Cygnus columbianus* as a case study to demonstrate the effect of reducing flight speed. The 10% reduction in speed from 20 ms^{-1} to 18 ms^{-1} resulted in a 9.07% increase in collision risk; the second highest increase after variations in avoidance rates. Clearly, the ground speeds recorded in this study are considerably lower than this and in some cases the difference between airspeed and ground speed is large enough to increase the collision risk substantially. All the data presented here were collected on days with average wind speeds of less than 15 knots. Average wind speeds at the site throughout the study period were 17.88 knots, with a maximum of 79.20 knots, indicating that the effect of wind on flight speeds could be considerably greater than is reported here.

Variability in flight direction relative to the wind

Several studies of seabird flight during the breeding season have shown that birds are capable of using wind speed and direction to their advantage to gain speed or to reduce energy expenditure (Adams & Navarro, 2005; Salamolard & Weimerskirch, 1993). Weimerskirch *et al*. (2000) showed that wandering albatrosses flew fastest in tailwind conditions and had heart rates similar to birds resting on land. Birds in this study reduced the number of headwind flights made in the breeding season (table 5.3) and had a weak but significant correlation between flight direction and wind direction (figure 5.6), which may indicate that they are altering their flight patterns in relation to the wind to reduce energetic costs during this period. The lack of species discrimination in the data limits such conclusions because the wing morphology of different species will influence the potential responses. For example, Procellariids tend to fly across winds, whereas auks and gulls tend to fly into and across headwinds (Spear & Ainley, 1997b).

Correlation analysis is sensitive to sample size, being more likely to return a significant result from a larger dataset. Despite a large number of observations (35,213), the correlation between wind and flight direction outside of the breeding season was found not to be significant, giving strength to the argument that birds alter their behaviour in relation to the wind during the breeding season. The significant difference between the wind direction during flights recorded by the radar and the overall wind direction throughout the study period may indicate that birds are deliberately choosing to fly in favourable winds. However, the data filtering process may confound this because only data collected on relatively calm days are included and it is possible that winds from a particular direction will be stronger than others. Consequently, data from days with different wind directions may be filtered out as suggested by the differences between figures 5.6b and 5.6c.

The results demonstrate that there is variation throughout the year in the proportion of flights made into headwinds, but also that there is interannual variation. The reasons for this are unclear, but may be related to variability in wind direction or to variation in the location of prey. There are also fewer data from 2007 than 2006. Time of day was removed from the model because it did not explain a significant amount of the variation in the proportion of headwind flights. Conversely, Salamolard & Weimerskirch (1993) found that wandering albatrosses flew significantly faster during the day than at night in all periods of the breeding season, indicating that for some species, the time of day can influence aspects of flight behaviour.

Proportion of head and tail wind flights in different species

The bimodal distributions of airspeed and ground speed in June 2006 probably reflect the calm weather conditions in that month, allowing a large amount of high quality data to be collected. The data filters used to remove clutter were also developed on this dataset and so may be more effective at selecting avian patterns for these data. There is little difference in the proportion of headwind flights made by the two species groups considered. Charadriiformes (including Alcids and Larids) in general are known to primarily fly into and across headwinds (Spear & Ainley, 1997b), so differences may not be expected. The slower airspeed of gulls and the consequent reduction in groundspeed increases their risk of collision compared with auks. In combination with this, gulls also fly at higher altitudes (Garthe & Hüppop, 2004), closer to turbine blade height, which increases the number of flights they are likely to make through the risk area.

Flights in this study were categorised as being performed in head or tail winds depending on the value of airspeed minus groundspeed because this shows the predominant influence of the wind on flight. However, this does not account for side wind conditions, where birds cut across the wind. The majority of flights in this dataset were not performed under pure head or tail wind conditions and some species, for example Procellariids such as the northern fulmar, specialise in flight across the wind (Spear & Ainley, 1997b). Optimal flight speeds for birds increase as the angle of the wind to the flight track increases, making it more efficient to increase airspeed in sidewind conditions, since compensation must be made in the bird's flight angle (Liechti *et al.*, 1994). Further analyses could investigate the effect of changing the magnitude of the head or tail wind.

In this study, radar has allowed large samples of flights through the wind turbine area to be collected throughout the day and in 14 months (figure 5.2). Since positions are logged every 2.3 seconds, average flight speeds can be calculated accurately and positions are recorded with an error of approximately 5.5 m. Other techniques such as satellite telemetry would have explained more about an individual bird's movements, but would not necessarily have been focussed on the study site and would not have given data at such frequent intervals or with such positional accuracy. Also, it may not have been possible to assess the difference between airspeed and ground speed since data on wind speed and direction are not available for all areas that the birds might visit. The ornithodolite (Pennycuick, 1982) would have given site specific data, but analyses of the importance of time of day could not have been carried out since no data could be collected at night. This technique also requires an observer to be present, whereas the radar in this study detected and tracked targets automatically, allowing a larger dataset to be collected. The disadvantage of operating the radar system in this way is that no information can be gathered on species identity, creating a heterogeneous dataset, with large amounts of variability that cannot be explained with only environmental data.

CONCLUSIONS

Ground speed has a clear influence on collision probability, with slower flight increasing the risk of collision. Headwind flights also have a higher risk of collision at all speeds. Since the two are likely to co-occur, with headwind flight generally being slower than tailwind flights, any behaviour which increases the chance of flying into headwinds is likely to increase collision risk. Analyses showed that overall, ground speed, which incorporates the effect of wind speed and direction, was significantly lower than airspeed and although the magnitude of this may not cause a large increase in collision risk under these conditions, the effect under stronger winds may be much more important. During the breeding season, when birds are likely to be transiting between nesting and foraging sites more regularly, they are more likely to fly in a similar direction to the wind and also reduce the proportion of flights they make into headwinds, thereby reducing their collision risk. Interannual variation was observed in the proportion of headwind flights, although the causes of this are unclear.

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Chapter six

Boat-based surveys to investigate the effect of wind turbine installation and environmental factors on seabird abundance

INTRODUCTION

EIA for offshore wind turbine developments typically include a visual survey of birds, many of which have been conducted from boats. There are robust guidelines available from COWRIE on how these should be carried out (Camphuysen *et al.*, 2004), which update the European Seabirds at Sea (ESAS) protocols (Tasker *et al.*, 1984; Webb & Durinck, 1992).

Line transect and strip transect surveys are routinely used to assess animal populations in the wild. In line transects, the observer moves along a predetermined line and records the perpendicular distance to all study objects, whereas in strip transects, the observer is expected to record all study objects to a predetermined perpendicular distance (Sutherland, 1996). Strip transects are therefore analogous to moving quadrat samples (Camphuysen *et al.*, 2004). They assume that detection of the study object is the same at all distances within the strip, which is unlikely to be true. Line transect methods do not make this assumption, instead, it is assumed that detection will decrease with increasing distance from the transect line. As a result, a detection function is usually fit to the data during analysis to account for objects that were not detected.

The detection function can be determined using several methods, but the most common method uses distance sampling (Buckland *et al.*, 2001) and the associated software (Thomas *et al.*, 2006). Using this method, a detection function is estimated by fitting a curve to the histogram of perpendicular frequencies and assuming that at some distance, μ, an equal number of study objects are not detected as are detected at further distances (Buckland *et al.*, 2001). This value is known as the effective strip width and is used to produce a probability density function for detection, which inflates raw counts to account for reduced detection at greater distances from the survey line. Analysis of distance sampling data to produce density estimates is generally carried out in the program Distance (Thomas *et al.*, 2006).

Line transect studies can be carried out on foot (e.g. Fleming & Guiliano, 1998), or from a vehicle (e.g. Boano & Toffoli, 2002) and surveys at sea (Komdeur *et al.*, 1992) are carried out from either a boat (e.g. Hyrenbach *et al.*, 2001; Russell *et al.*, 1999) or an aeroplane (e.g. Fewster *et al.*, 2008; Southwell *et al.*, 2008). The observation methods used vary little between different modes of transport. In many studies, particularly of animals that are only visible for short periods, such as cetaceans, the distance and bearing to the object are recorded (Dawson *et al.*, 2008) and perpendicular distance is calculated later. The study object is often a species or group of species, but line transects have also been used in studies of animal signs, such as faeces (e.g. Bailey & Putman, 1981; Marques *et al.*, 2001), nest counts (Plumptre, 2000) or calls (Hastie *et al.*, 2005). The cluster size, or number of objects present is also recorded, as well as the species where it is possible to determine this. Where species identity is not evident, identity is recorded to the highest taxonomic level possible.

The COWRIE guidelines suggest that line transect and distance sampling techniques should be used to estimate the density of birds sitting on the water. However, for flying birds there is the potential for recounting the same individuals of some species (e.g. fulmars, which are known to follow boats) and for missing birds of other species that are easily disturbed by the presence of a boat (for example seaduck). Therefore COWRIE guidelines suggest that snapshots at regular time intervals should be used for birds that are flying. All birds flying in a 180° arc forward of the boat's progress are counted, with the aim of recording easily disturbed species before they move out of the area.

The recommendation is that the vessel used for surveys is no smaller than 20 m and that it should have a viewing platform at least 5 m above the sea surface. Observations should not be made in conditions exceeding sea state 5, because increases in sea state reduce detection probability. In contrast with radar studies, it is also not possible to carry out observations during periods of darkness, or low visibility due to fog. However, the cost of chartering a boat larger than 20 m can be high and in some cases, suitable vessels are not available. Using a smaller boat may be the only option under these circumstances. This will reduce the range of sea states under which surveys can be undertaken.

Although distance sampling has become a standard technique for seabird (e.g. Camphuysen *et al.*, 2004) and cetacean (e.g. Dawson *et al.*, 2008) surveys at sea, other researchers have made good use of Poisson family generalised linear models (GLM) (Pebesma *et al.*, 2005) and generalised additive models (GAM). The Poisson family is useful when using count data because it assumes that all values are positive integers and that variance increases with mean. Clarke *et al*. (2003) used Poisson GAMs, in the analysis of seabird at-sea data, to produce population estimates which were comparable to colony counts. GLMs and GAMs also have the advantage of allowing analysis of the effect of environmental variables on the distribution and counts of animals. It is possible, in the Distance program, to include covariates in the model (Marques & Buckland, 2003), but these are used to modify the density estimate, rather than to test their effect on density.

Studies to detect environmental impacts generally take the form of Before-After-Control-Impact (BACI) studies (Underwood, 1992, 1994). In the case of wind farms, such studies would survey several control sites at the same intensity as the impact site, both before and after installation of turbines. The densities or counts of birds should be analysed with respect to two factor level variables: before or after, and control or impact. There may be statistically significant differences between the data collected before and after, or the data at the control and impact sites, but a significant impact can only be identified by a significant interaction between the two variables (Underwood, 1994).

However, Ellis & Schneider (1997) found that studies using an impact gradient (IG), taking samples at regular intervals from the impact site could have more power to detect changes than standard BACI designs. In BACI sampling design, several samples are taken at the impact and control site. However, the extent of impact is likely to vary within the area of the impact site. IG sampling designs account for this by taking samples on a line of increasing distance from the impact and using the measured distance as a continuous explanatory variable in a regression analysis. A significant impact must still be identified through a significant interaction between the distance and the factor level variable of before or after impact. de Lucas *et al*. (2005) used an IG study design to show that there was no significant impact of wind turbine installation on small mammal populations. This approach was also used to show that common eiders *Somateria mollissima* made 50% fewer flights within wind farms, than in areas 200-400 m and 400-600 m outside the wind farm and were up to 60% less likely to land within the wind farm (Larsen & Guillemette, 2007).

The aim of most ship-based surveys carried out for EIA is to determine what species are present and in what numbers. This can inform further studies into specific impacts on individual species. However in many cases, post construction studies have been required by statutory authorities, to determine whether there has been an impact on the numbers and distribution of birds at the site. Unfortunately, few data have been published from such studies. Of the studies that have been published, few have shown a significant impact. For example, de Lucas *et al*. (2004) found no effect on the abundance of soaring birds after wind turbine construction and Devereux *et al*. (2008) found that of four functional groups of wintering farmland birds, only pheasant *Phasianus colchicus* showed changes in distribution. It is likely that in many cases, other external factors are key determinants of the numbers and distribution of birds. Detailed knowledge of these factors is required to allow assessment of more subtle anthropogenic effects. As a result, it is often the case that impact studies do not have enough power to distinguish the impacts of wind turbines from natural variation.

A key external factor in determining abundance and distribution of seabirds at a particular site is likely to be the availability of food, and some studies have shown that seabird densities can be used as proxies for productivity (Cairns, 1987). Fauchald *et al*. (2002) showed that guillemot (*Uria* spp.) densities were better explained by oceanographic parameters (sea surface temperature, sea surface salinity and spatial variance in temperature and salinity) than by year, indicating that the birds were more likely to respond to environmental characteristics than to be site faithful between years.

Sea surface temperature is the most regularly used oceanographic parameter in seabird studies (e.g. Becker & Beissinger, 2003; Erwin & Congdon, 2007), since it is relatively easy to measure and can, in some cases be acquired through remote sensing (e.g. Palacios *et al.*, 2006). This is most likely to be influenced by the amount of received solar radiation (increase in temperature with increased radiation) and wind speed (decrease in temperature as a result of mixing with cooler waters). Processes controlling productivity deeper in the water column are influenced to some extent by solar radiation and wind speed, but also by tide. Thermoclines and haloclines are areas in the water column where the cooler, saline and more nutrient rich deep waters abut against the warmer, fresher and nutrient poor surface waters.

In these areas there can be high levels of primary productivity and piscivorous seabirds in the eastern tropical Pacific were found to be more abundant in areas with thermoclines (Spear *et al.*, 2001). In the south eastern Bering Sea, Brünnich's guillemots *Uria lomvia*, equipped with temperature and depth loggers have also been shown to feed in areas just below the thermocline (Takahashi *et al.*, 2008), while planktivorous least auklets *Aethia pusilla* in the northern Bering Sea, were shown to preferentially forage in stratified water, either at fronts, or thermoclines (Russell *et al.*, 1999). In the eastern tropical Pacific, seabirds feeding on fishes and squid were found to be associated with deep and strong thermoclines, while planktivorous species associated with shallower thermoclines in more stratified water (Vilchis *et al.*, 2006). Several of the fish and squid eating species in the study were dependent on larger fish and marine mammals to push prey to the surface, demonstrating that the relationship between oceanography and prey availability for top predators can be complex. Common guillemots *U. aalge* in the shelf waters of the North Sea were shown to forage in stratified waters with more than one thermocline present (Daunt *et al.*, 2003). However, Grémillet *et al*. (2008) also showed that although waters in the Benguella upwelling are highly productive, the absence of pelagic fishes may have influenced a decline in Cape gannet *Morus capensis* colonies in Namibia. This indicates that oceanography alone cannot be relied upon to define key foraging areas.

Aims

The first aim of this study was to determine whether it is possible to effectively carry out seabird surveys from a small boat. Since the weather conditions required for operating offshore in a small vessel are more restrictive than in larger vessels, this was carried out through an analysis of weather data and a comparison with the number of surveys carried out. The second aim was to investigate whether there was an impact of turbine installation on counts of birds using the areas close to the turbine and jacket. Finally, the study aimed to determine the extent to which environmental variables affect bird densities within the study area.

METHODS

Study site

The Beatrice wind turbine demonstrator project is located next to the Beatrice Alpha oil platform in the Moray Firth, Scotland. The oil platforms and turbine locations are approximately 22 km offshore, on the Smith Bank, which is a sandy bank, at approximately 40 m depth (figure 6.1 and see figure 2.1). Wright & Begg (1997) found that the Moray Firth had high densities of common guillemots during the breeding season and that these aggregations could be explained by sandeel *Ammodytes marinus* presence. Sandeels are known to be important prey for a range of seabirds in the North sea, including black-legged kittiwakes *Rissa tridactyla* (Lewis *et al.*, 2001) and common guillemots (Finney *et al.*, 1999). The North Sea has seen a significant decline in sandeel stocks, as measured from landings data (ICES, 2007), which has been implicated in declines of breeding colonies of several seabird species (Frederiksen *et al.*, 2008).

Field work

Surveys were carried out on six occasions between April and June 2006 and on five occasions between April and July 2007. All surveys carried out in 2006 were prior to any installation activity at the site and the surveys in 2007 were carried out with one fully installed turbine and one jacket (wind turbine substructure) installed. Two of the five surveys in 2007 were incomplete due to fog at the site. All surveys were carried out in the spring as this is the time when there are the highest densities of birds in the Moray Firth (Stone *et al.*, 1995), and is also the breeding season for all of the species recorded in the area.

To ensure high standards of health and safety while working from a small boat offshore, a weather forecast produced by the UK Meteorological Office, specifically for the Beatrice oil field was used to inform decisions about whether a survey could be carried out on a given day. Surveys were only planned for days when the forecast for the period that the boat would be on the water predicted wind speeds of less than 10 knots, swell heights of less than 1 metre, significant wave heights of less than 1.5 metres, good visibility and low lightning risk. A minimum of two days was allowed between surveys to avoid problems with the independence of data points. Radio contact with the Beatrice Alpha platform was maintained throughout the time spent in the oil field. This was critical after the wind turbines were installed because the survey route passed through the 500 m exclusion zone around the structures.

A 10 m catamaran which operates as a dive charter boat from Lossiemouth on the southern coast of the Moray Firth was used for most of the surveys. The boat was Marine and Coastguard Agency coded for commercial use and provided a stable platform with adequate deck space for equipment and procedures to be carried out safely. Cruising speed was approximately 10 knots, giving a travel time to the site of around 3 hours. On occasions when this boat was not available, either a 5.8 m RIB (Rigid Inflatable Boat) or a 9.5 m RIB was used from Cromarty. These boats were capable of cruising at 20 knots, giving a travel time of approximately 2 hours.

A 10 km line transect was surveyed on all visits to the site (figure 6.1). The transect line passed directly between the two turbine locations and extended 5 km either side, in a north easterly direction. In 2007 the line ran through the midpoint between the two turbines, but in 2006, the line was positioned 200 m to the south of this. The transect line was moved north in 2007 to avoid collision with the jacket of the second turbine. The nearest distance from the transect line to the installed wind turbine was approximately 375 m. The transect line was designed so that each end of the line was far enough from the turbine site to be used as control sites.

Guidance for survey design was taken from both the COWRIE report on boat-based surveys (Camphuysen *et al.*, 2004) and the European seabirds at sea protocols (Webb & Durinck, 1992), with modifications made for the study area and species. The boat travelled at a constant speed of approximately 6 knots and so covered the transect line in around 55 minutes. Two observers surveyed continually, with one looking out over the port side of the boat and the other over the starboard side in positions opposite each other. Observer eye level was approximately 2 m above sea level. Identical waterproof 8 x 42 magnification binoculars were used by each observer to identify bird species. On six of the surveys, the same two experienced ornithologists were used, but on the remaining five, one observer was experienced, while the second observer was varied and was less experienced.

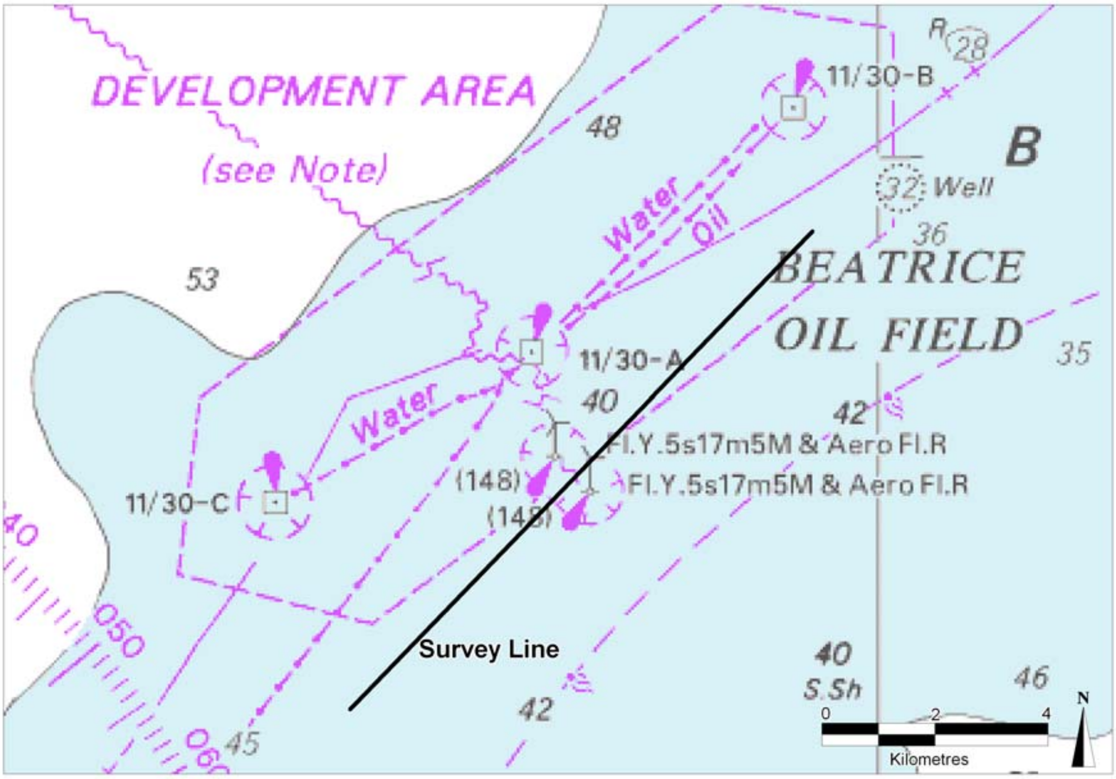

Figure 6.1. The 10 km survey line, passing between the two wind turbine locations and to the south of the three oil platforms in the Beatrice field (Alpha, Bravo and Charlie). © Crown Copyright and/or database rights. Reproduced by permission of the Controller of Her Majesty's Stationary Office and the UK Hydrographic Office (www.ukho.gov.uk) Licence number 13599.

A GPS logged the position of the boat at intervals of at least every 30 seconds, and each observer was given a watch with the time synchronised to the GPS. Observers recorded all birds that crossed an imaginary line perpendicular to the boat's movement. The time at which this occurred was noted to allow for post calculation of position from the GPS. The number and species of bird was recorded, along with the distance from the boat. Distance to the bird was recorded in 50 m bands from the boat, to a maximum of 200 m because observations made beyond this distance are less likely to be reliable, given the observer height. This enables abundance estimates for birds at the site to be calculated using distance sampling (Buckland *et al.*, 2001).

The behaviour of birds was also recorded during the survey, from a list of nine possible behaviours (table 6.1). These behaviours were subsequently categorised as either flying or associated with the water. Any bird that touched the sea surface was noted as being associated with the water. Such birds were considered to be using the area, rather than just passing through, which may be the case with flying birds.

Table 6.1. List of behaviours and definitions used during visual line transect surveys of seabirds.

Behaviour	**Definition**
Aggression	Chasing, pecking or flapping wings at another animal.
Avoidance	Moving to escape predators, including humans, boats and kleptoparasites (e.g. skuas). Includes swimming, diving, and flying.
Diving	Diving into or under the water, for a purpose other than foraging. This category used for all diving behaviour, unless foraging behaviour explicitly observed
Feeding	Seen consuming food, holding fish, or feeding young
Flying	Directional flying not associated with foraging. This category used for all flying behaviour, unless foraging behaviour explicitly observed
Foraging (while flying or diving)	Flying with the purpose of foraging. Including aerial pursuit, skimming, dipping, surface pecking and active searching. OR Diving with the purpose of foraging. Includes deep plunging, pursuit plunging, pursuit diving, bottom feeding and active searching.
Preening	Cleaning feathers with bill, or flapping in the water to clean feathers
Sleeping	Sitting on water with eyes closed or bill tucked under wing
Sitting	Sitting on the water, displaying no other distinguishable behaviour. Includes passive swimming.

A third observer recorded environmental data every 15 minutes during the survey. Wind speed and direction, swell height, cloud cover and precipitation were all estimated. Concurrently, an anemometer on the Beatrice Alpha platform recorded wind speed and direction every minute. The anemometer ran continuously, throughout the entire study period and data were retrieved at regular intervals from the platform.

Once the abundance survey was completed, the boat was turned around and travelled south west on a parallel line, 200 m to the south. Seven sample stations were identified on this line (figure 6.2), at intervals of 2 km, and with an additional station at the midpoint between the two turbine locations (leaving an interval of 1 km on either side). Temperature profiles were recorded at each of the stations, using either a temperature, depth and salinity logger (DST CTD, Star-Oddi, Reykjavik) or a temperature and depth logger (DST Milli, Star-Oddi, Reykjavik). Both types of logger were able to detect changes in temperature of 0.03°C and were set to record once a second. The logger was lowered into the water using a hand operated winch at a rate of approximately 10 m per minute, although this was not controlled. Once it had reached the bottom, it was pulled backed to the surface at the same rate. The boat's engines remained running at the stations, but were not engaged. No anchor was deployed, so the boat was free to drift. Loggers were downloaded on return to the laboratory. Data from 11th May 2006 were not available due to a logger malfunction. The occurrence of fog at the site reduced the number of samples taken to three stations (stations 1, 4 and 7) on 27th April 2007 and meant that no stations were sampled on 3rd July 2007.

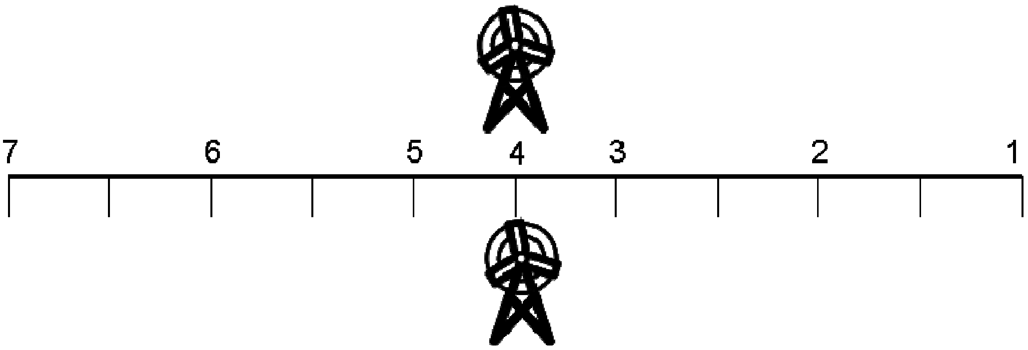

Figure 6.2. Diagram of the location of sampling stations (not to scale). The thin vertical lines are 1 km markers, along the 10 km transect line (thick horizontal line). The numbers represent the station locations, with station 4 directly between the two wind turbine locations.

Data processing and analysis

Assessment of survey methods

Wind speed and direction data from the anemometer on the Beatrice Alpha platform were used to determine the total possible number of surveys that could have been undertaken at the site in the springs (April, May and June) of 2006 and 2007. The data were filtered according to the following criteria:

1. the mean average wind speed for the day must have been 12 miles per hour or less (equivalent Beaufort sea state 3)
2. the mean average wind speed for the previous two days must have been 20 miles per hour or less, to avoid working in high swell

3. no survey must have been carried out in the previous two days, to allow independence of data points

Surveys were also not planned to be carried out in fog, or reduced visibility, but data on the occurrence of fog throughout the spring were not available.

Impact gradient test on bird counts

The distance from each bird observation to the midpoint of the survey line was calculated. The midpoint of the line was the closest point on the transect to the turbine locations, and passed between the two turbines (figure 6.1) at a distance of approximately 375 m from each in 2007. The line was approximately 200 m south in 2006, prior to turbine installation. The observations were then grouped into 50 bands of 100 m length. This band length was chosen because positions for birds were calculated by interpolation of GPS positions which were taken at least every 30 seconds. Travelling at 6 knots, the distance between points would be 92.6 m, which would be the maximum error in a positional estimate. Positions given by the GPS were accurate to approximately 7 m. Grouping data in these bands assumes that there is no difference in habitat between the two sides of the transect line that would influence counts of birds. It is likely that this assumption is valid because the water depth and sediment type is constant (BGS, 2003). GPS data were not available for the survey on 24th April 2007, so these data were not included in this analysis.

Poisson family generalised linear models were used to investigate the counts of birds in each distance band (Distance) and between the two years (Year), as well as the interaction between the two variables. A significant interaction term would indicate an effect of turbine installation on the distribution of birds in the study site (Underwood, 1994). Two models were used, one for auks and one for gulls, since these two groups represent the largest numbers of birds at the site and also show different feeding methods, with auks being pursuit divers (Camphuysen & Webb, 1999), easily capable of diving to the bottom at this site (Piatt & Nettleship, 1985), and gulls being mostly surface foragers (Camphuysen & Webb, 1999).

The data contained a large proportion of zeros, which led to overdispersion in both models. This was ameliorated to some extent by using a quasipoisson distribution. The models were validated by considering plots of the residuals.

Environmental influences on bird densities

Overall density estimates for each survey were calculated using Distance software (Thomas *et al.*, 2006). Densities of birds on the water and flying birds were calculated separately, because the two groups have different detection probabilities. Distance sampling uses these data to produce a detection probability function, which inflates the density estimate. In all analyses, the value of g(0) was assumed to be 1 since no independent data were available to calculate this empirically. The assumption is likely to hold because the species surveyed were typically auks and gulls, which are not known to respond at long distance to boat movements, unlike, for example divers and diving ducks (Webb & Durinck, 1992). A sampling fraction of 1 was used in the analysis, because data were collected by two observers. Data were analysed as clusters, in bands of 50 m out to a limit of 200 m from the boat. Observations were assumed to be made at the middle distance value of the assigned band. Any observations made beyond 200 m were removed from analyses.

Temperature data were used to investigate the effect of oceanographic parameters on bird densities. The temperature profiles from each sample station were processed independently and an average value was taken for the survey day. No calibration of either temperature or depth measurement was attempted, so all values used are relative. Data from the logger’s descent were used in analyses, because the logger was generally lowered more slowly down through the water. This led to more data points being collected on the descent than the ascent.

Temperature was plotted against depth (figure 6.3a) to obtain a value for sea surface temperature. This was taken as the last value before the logger began to descend through the water. A ten observation moving average of temperature change was plotted against depth, to identify areas with a large amount of temperature change over a short distance (figure 6.3b), which may indicate the presence of a thermocline.

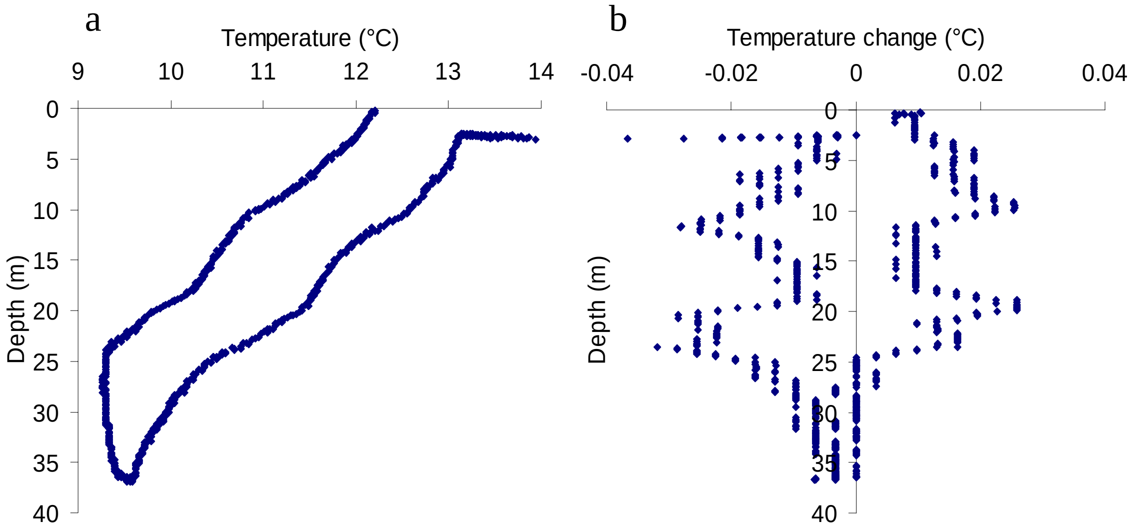

Figure 6.3. Examples of the plots used to measure oceanographic parameters from the temperature profiles. Temperature against depth plots (a) were used to measure sea surface temperature and temperature change against depth plots (b) were used to measure the depth and gradient of thermoclines. In plot a, the furthest right part of the line is the descent and the furthest left the ascent. In plot b, negative changes in temperature were found on the descent, and positive changes on the ascent.

Thermoclines were identified in the plots of temperature change as horizontal peaks, which generally took the shape of a "less than" symbol (<), indicating a relatively large temperature change over a short vertical distance. The strength of the thermocline was calculated as the change in temperature between the top and bottom of the thermocline divided by the change in depth, to give a gradient of temperature change. In many cases, more than one thermocline was present in the temperature profile. All thermoclines were measured, but only information on the shallowest and deepest was used in further analysis. The rationale for this was that surface feeding birds such as kittiwakes are likely to respond to the shallowest thermocline, whereas diving birds such as guillemots will be able to take advantage of deeper thermoclines, in areas where more nutrients may be available. The mean value from all profiles taken on each survey day was used in further analyses.

The average values of density of birds on the water and flying birds were investigated in relation to the mean average oceanographic variables for the survey day. The density of birds was log transformed in both cases to account for the very large values on 26th June 2006 and to make the distribution normal. Two separate linear models were used to test the effect of the oceanographic variables on birds on the water and flying birds.

Each dataset consisted of 10 samples, which limited the number of environmental variables that could be tested. Variables related to the exact depth of thermoclines were not used because the error in depth measurement was unknown. The remaining variables were: gradient of the deepest thermocline, gradient of the shallowest thermocline and sea surface temperature. However, initial data exploration found all three of these variables to be collinear. Linear models were produced with both birds on the water and flying birds, with each of the three variables separately, and the variable which gave the model with the lowest AIC value was selected.

RESULTS

Assessment of survey methods

Given the criteria for suitable weather conditions, a maximum of 10 surveys could have been completed in the spring of both years using a small survey vessel, with more surveys possible in June of both years and in May of 2007 (figure 6.4). The aim of carrying out six surveys in the spring of each year was therefore achievable, although this did not account for days with fog at the site, which occurred on several otherwise suitable days in 2007. Had the criteria been changed to allow surveys in up to sea state 5 conditions (24 miles per hour winds), a total of 18 could have been completed in 2006 and 22 in 2007.

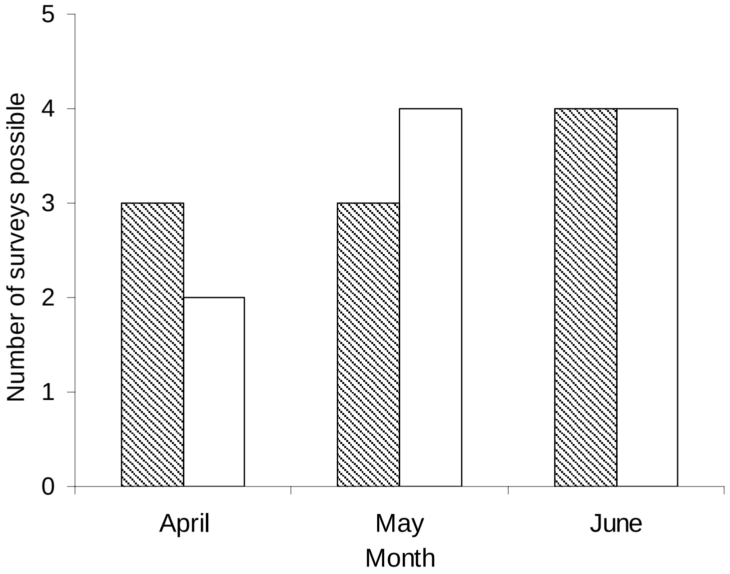

Figure 6.4. The maximum number of surveys possible in April, May and June of 2006 (hatched bars) and 2007 (empty bars), given wind speed and survey independence constraints.

Overall counts of both auks and gulls were higher in 2006 than in 2007 (table 6.2) and counts of auks were generally higher than counts of gulls. Fog caused the loss of some data on surveys in 2007.

Table 6.2. Summary of total counts of auks and gulls counted during line transect surveys at the Beatrice site. The start time of the survey, the average Beaufort sea state and any missing data are also noted. The survey on 3rd July 2007 only covered 50% of the transect due to fog.

Date	**Time of survey (GMT)**	**Auks**	**Gulls**	**Sea state**	**Missing data**
19th April 2006	10:08	21	4	3	
11th May 2006	10:15	81	26	3	No temp
5th June 2006	09:29	62	73	3	
8th June 2006	09:42	137	57	1	
16th June 2006	09:27	729	174	1	
26th June 2006	09:48	1027	868	1	
24th April 2007	11:50	95	3	2	No GPS
27th April 2007	10:02	32	15	2	3 temp measurements
16th May 2007	12:38	39	39	4	
7th June 2007	10:28	148	11	0	
3rd July 2007	10:41	50	10	1	No temp

Impact gradient test on bird counts

Auks

Of 2421 auks recorded throughout all surveys, 1027 were identified to species level, of which 79.55% were common guillemots and 18.60% were razorbills *Alca torde*. Considerable variability was evident in the counts of auks from 2006 (figure 6.5), indicating a patchy distribution of these species throughout the transect. High numbers are probably related to the two surveys conducted in late June 2006 (table 6.2).

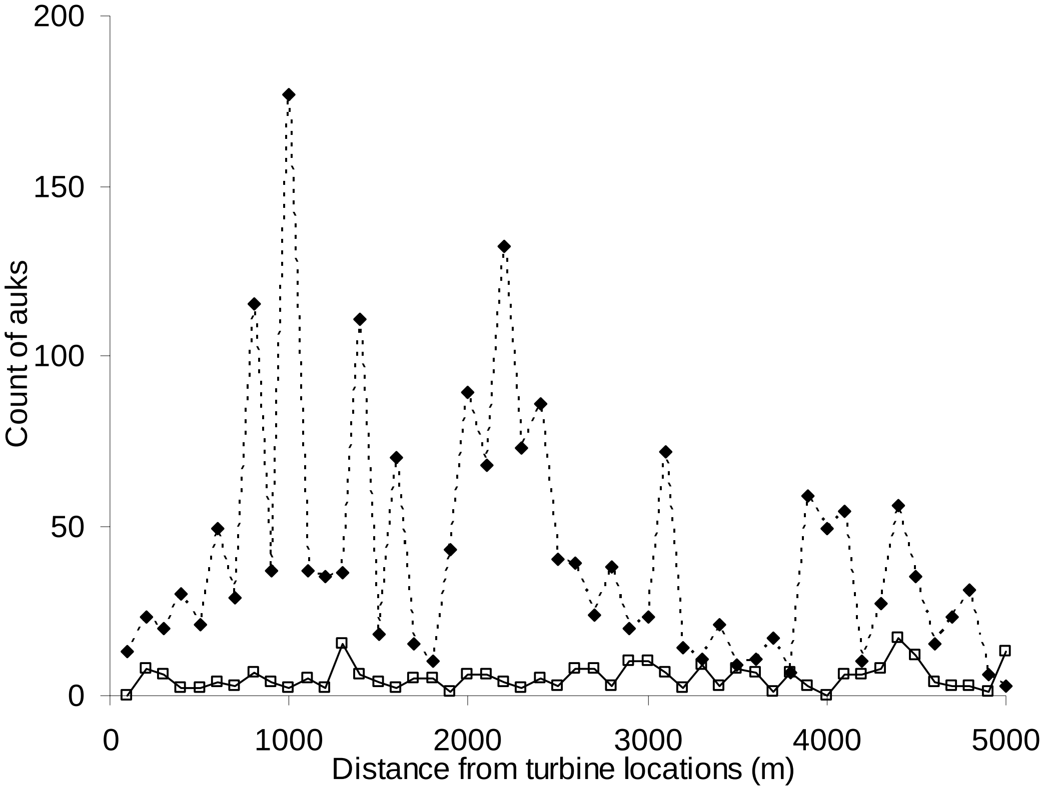

Figure 6.5. Total counts of auks, from all survey days (excluding 24th April 2007) at increasing distance from the turbine locations in 2006 (dotted line and filled diamonds) and 2007 (solid line and empty squares). "Turbine location" is the closest point on the transect to the turbine sites.

The generalised linear model for the counts of auks (table 6.3) showed that there were significantly fewer birds recorded at greater distances from the midpoint of the survey line in 2006. There were also significantly fewer auks recorded in 2007 than in 2006. No significant interaction was found between the two variables, indicating that there was no effect of turbine installation on counts of auks detected at this scale.

Table 6.3. The results of a generalised linear model of the counts of auks in bands of increasing distance from the turbine locations and between years. Data collected in 2006 were prior to turbine installation, while data collected in 2007 were post-construction.

Variable	**Coefficient**	**Standard error**	**t**	**P**
Intercept	2.3135	0.2063	11.209	<0.001
Distance	-0.0002	0.0001	-2.091	0.0371
Year (2007)	-2.319	0.7046	-3.291	0.0011
Distance:Year (2007)	0.0003	0.0002	1.205	0.2288

However, plots of the residuals showed a considerable amount of structuring, indicating that there was some unexplained variation in the data (figure 6.6). The groupings evident in the plot of predicted values against residuals are related to the large difference between years. This is demonstrated in the plot of year against residuals, in which the data from 2006 centre at a value lower than zero, with many outlying large values. These large values are likely to have been created in the two surveys in late June 2006, with high densities of birds recorded. Repeating the analysis with a negative binomial distribution did not improve the residuals.

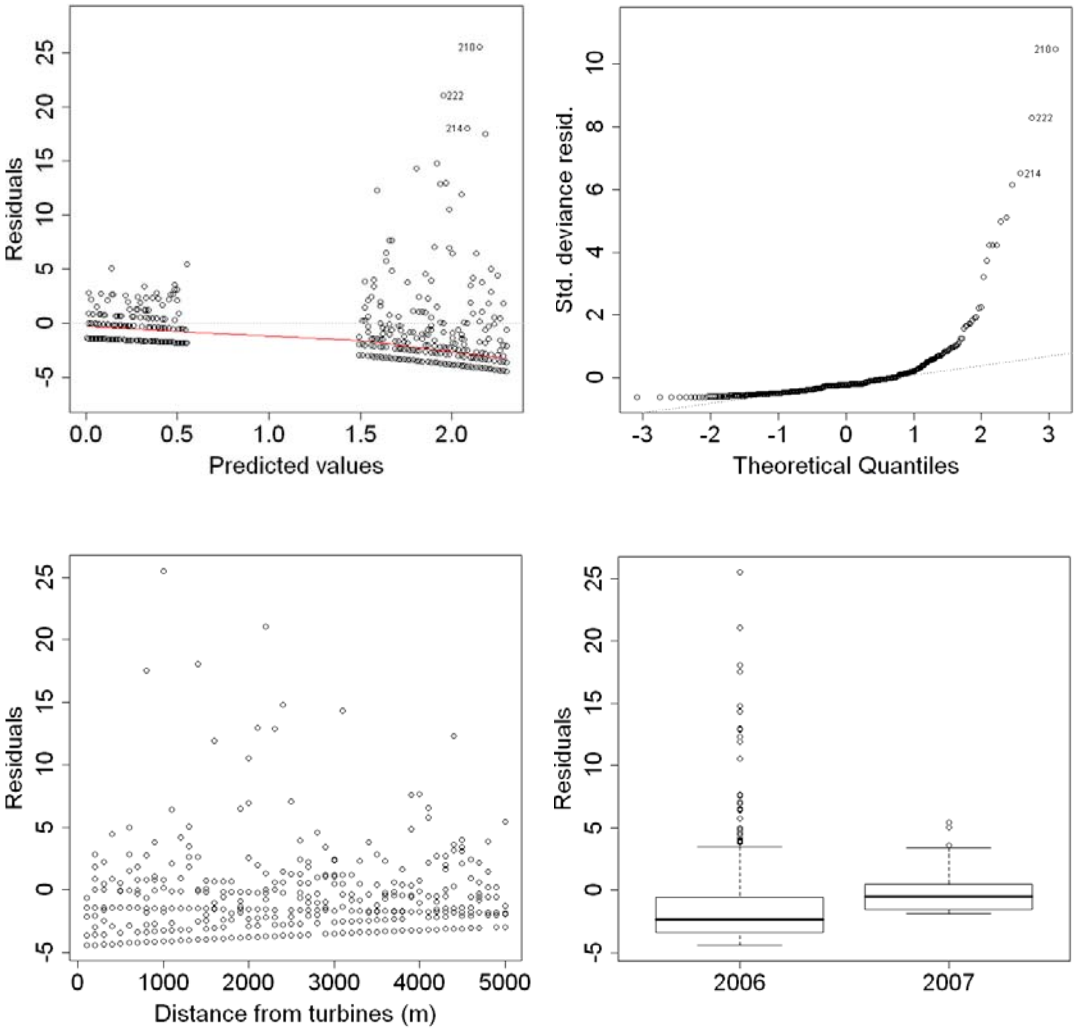

Figure 6.6. Plots of the residuals from the generalised linear model of auk counts at the Beatrice site. Clear structuring is evident in the plots of predicted values against residuals as well as in the plots of residuals against the explanatory variables. The plot of theoretical quantiles (QQ plot) shows that the residuals are also not normally distributed.

Gulls

Of the 1280 gulls recorded throughout all surveys, 1216 were identified to species level, and 95.32% of these were black-legged kittiwake. There was considerable variation in the counts of gulls at different distances from the midpoint of the survey line (figure 6.7), which suggests that, like the auks, gulls were patchily distributed at the site. It is also likely that the high counts of gulls in 2006 were recorded on the surveys in late June (see table 6.2). Numbers in 2007 were lower than 2006, although the generalised linear model (table 6.4) did not find that this difference was significant.

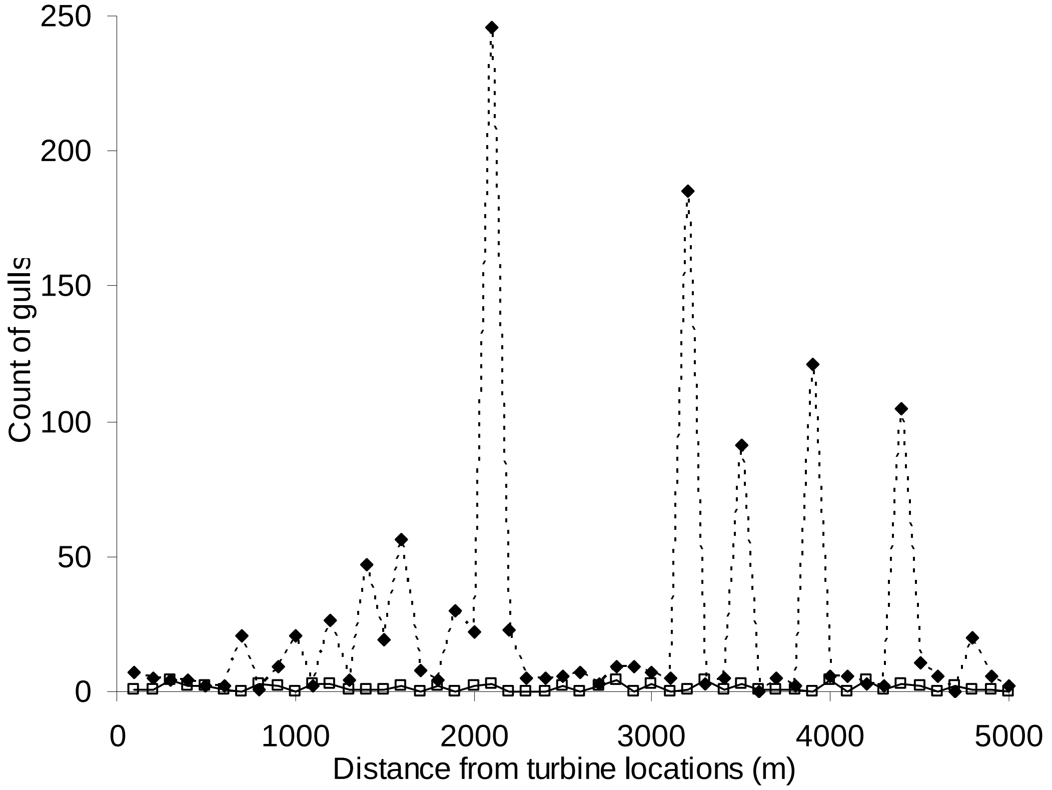

Figure 6.7. Total counts of gulls from all survey days (excluding 24th April 2007) at increasing distance from the turbine locations in 2006 (dotted line and filled diamonds) and 2007 (solid line and empty squares). "Turbine location" is the midpoint of the survey line and is the closest point to the turbine sites.

The generalised linear model also found that there was no significant effect of distance from the midpoint of the survey line on gull counts in 2006, which is likely to have been influenced by the patchy distribution observed. There was also no significant interaction between year and distance from the survey midpoint, indicating no effect of turbine installation on gull counts. However, again, the plots of residuals showed considerable structuring (figure 6.8), in the same manner, and this, as with the analysis of auk counts, is also due to the large variability between years and to the individual days in 2006 with very large counts.

Table 6.4. The results of a generalised linear model of the counts of gulls in bands of increasing distance from the turbine locations and between years. Data collected in 2006 were prior to turbine installation, while data collected in 2007 were post-construction.

Variable	**Coefficient**	**Standard error**	**t**	**P**
Intercept	1.128	0.47117	2.395	0.0170
Distance	0.0001	0.0002	0.636	0.5248
Year (2007)	-2.036	1.800	-1.131	0.2585
Distance:Year (2007)	-0.0001	0.0006	-0.202	0.8400

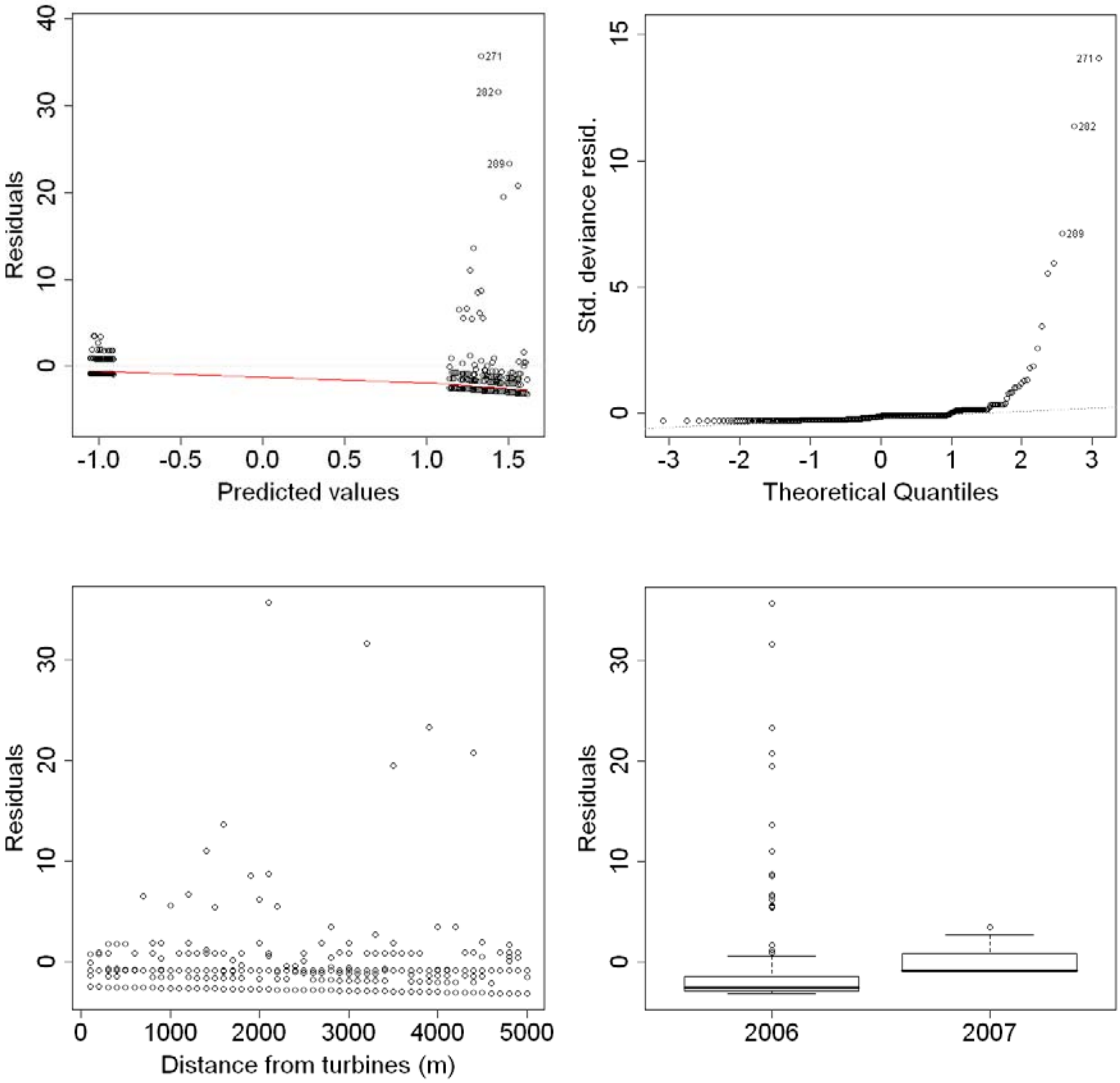

Figure 6.8. Plots of the residuals from the generalised linear model of gull counts at the Beatrice site. Clear structuring is evident in the plots of predicted values against residuals as well as in the plots of residuals against the explanatory variables. The plot of theoretical quantiles (QQ plot) shows that the residuals are also not normally distributed.

Environmental influences on bird densities

Distance analysis produced combined estimates of the density of all species, for both birds on the water and flying birds, for each of the survey days (figure 6.9). On the majority of occasions, low densities of birds (around 10 to 20 birds km^{-2}) were observed at the site. However, on two occasions in June 2006, considerably higher densities were observed, to a maximum of 438 birds km^{-2} for birds on the water on 26th June 2006. No similar increase in densities was seen in June 2007.

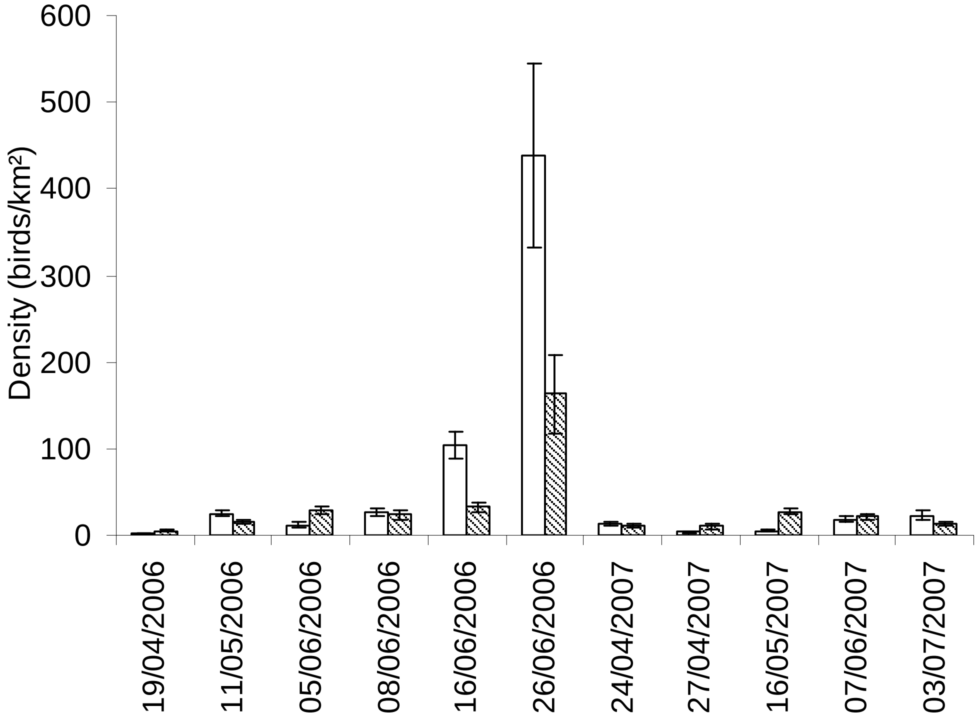

Figure 6.9. Density estimates of birds on the water (empty bars) and flying birds (hatched bars), along a 10 km transect at the Beatrice site. Survey dates are given on the x axis. Error bars are standard deviation.

Linear models were produced of the density of birds on the water and the density of flying birds along the transect line, with oceanographic parameters. The parameter that gave the model with the lowest AIC value in both cases was the gradient of the deepest thermocline. This showed a significant positive relationship with log bird density in both cases (tables 6.5 and 6.6). There is clear grouping by year in both datasets (figure 6.10), which is consistent with the inter-annual variability in the counts of auks and gulls presented in figures 5.5 and 5.7. However, adding year as a factor level variable improved the model of birds on the water, but deteriorated the model of flying birds, based on AIC scores.

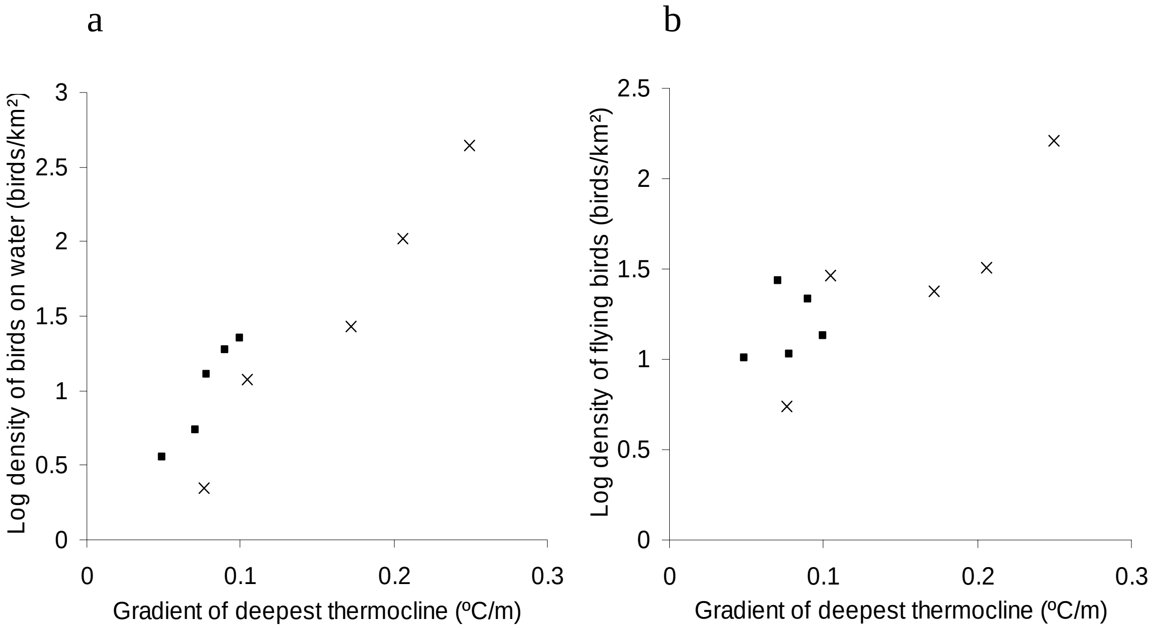

Figure 6.10. Plots of the relationship between the gradient of the deepest thermocline and: (a) the log of density of birds on the water, and (b) the log density of flying birds. Data collected in 2006 are represented by crosses and in 2007 by squares.

Table 6.5. The results of a linear model of the density of birds on the water at the Beatrice site, with the gradient of the deepest thermocline and year as explanatory variables.

Variable	**Coefficient**	**Standard error**	**t**	**P**
Intercept	-1.1444	0.4568	-2.505	0.0407
Gradient of deepest thermocline	28.4869	2.6150	10.894	<0.001
Year (2007)	1.2518	0.3292	3.802	0.0067

Table 6.6. The results of a linear model of the density of flying birds at the Beatrice site, with the gradient of the deepest thermocline as the explanatory variable.

Variable	**Coefficient**	**Standard error**	**t**	**P**
Intercept	1.730	0.394	4.392	0.0023
Gradient of deepest thermocline	11.025	2.915	3.782	0.0054

DISCUSSION

Assessment of survey methods

The planned six surveys over the months of April, May and June could feasibly have been completed in both 2006 and 2007. However, this does not take account of other weather variables such as fog, which occurred regularly in 2007, or of the availability of the boat and crew. It also does not account for curtailment of surveys when the weather was not as favourable as was forecast, or for surveys not carried out in suitable conditions because the forecast was for less favourable weather. A combination of these factors meant that only five surveys were completed in 2007. Using a larger boat would have increased the range of weather conditions in which surveys were possible. Surveys should not be conducted in conditions worse than sea state 5 because detection of birds is substantially reduced beyond this (Camphuysen *et al.*, 2004). However, the data on wind speed throughout the study period suggest that almost twice as many surveys could have been completed. For this study, the increased cost of chartering a larger boat would have been unfeasible. For larger scale projects, the costs of paying crew members on days where surveys were not possible will need to be considered as this will offset the cost of boat charter.

The survey methodology differed slightly from the standard COWRIE and ESAS guidelines; flying birds were recorded in the same manner as birds on the water, instead of taking snapshots. This had the advantage of allowing a specific location to be recorded for flying birds, rather than a broad area, as well as simplifying data collection for less experienced observers. It may have resulted in some birds being flushed from the transect line before they were recorded, but the effect of this was minimised by the suite of species at the site, most of which were not easily disturbed. Equally, some birds may have been counted more than once, but this is only a serious problem for birds that follow boats and although fulmars are known for this, there was rarely more than one fulmar near the boat, making it easy to keep track of the individuals.

The methodology worked well on most survey days. The only exception was on the 26th June 2006, when there were high densities of birds at the site. It was difficult to delineate flocks and to make notes on every flock, since this involved looking away from the survey strip. Therefore it is likely that cluster sizes were increased, as smaller flocks were grouped together and also that a proportion of birds were not counted. Methods were suggested in Camphuysen *et al*. (2004) for making snapshot scans of flying birds when high densities are present. These were not employed because they would have made the survey less comparable with others. Using Dictaphones instead of making hand written notes may have improved the rate of observations made.

Impact gradient test on bird counts

The impact gradient test showed no significant effect of turbine installation on the counts of either auks or gulls. Numbers were lower in 2007 than 2006, but this did not interact with distance from the midpoint of the survey line; there were fewer birds at all distances along the survey in 2007. Since the far ends of the transect line were designed to be used as control sites, it is unlikely that this was related to the installation of a turbine and jacket. One of the few studies to show an impact of offshore turbine installation was on eiders (Larsen & Guillemette, 2007) which are more easily disturbed than the most abundant species found in this study (Camphuysen *et al.*, 2004).

However, the models for counts of both auks and gulls could not be validated, due to large amounts of structuring in the residuals, indicating that there is unexplained variation in the data. This is likely to be due in part, to the patchy nature of the observations, with many distance bands recording no birds and a few, particularly in the two surveys in late June 2006, having high numbers of observations, in discrete areas. These large counts seem to be linked to environmental variation at the site (figure 6.10). Such data have been rank transformed by other authors (Fauchald *et al.*, 2002), but this removes the ability to quantify changes, which was felt to be important here. Transformations were attempted and the models were also run with a negative binomial distribution, but none of these attempts improved the validity of the models. The results of these models must be treated with caution. Although it is likely that accounting for the few large values would make the models less statistically significant (increase p value), which would lead us to the same conclusion, that installation of the wind turbines did not have a measurable effect on the number of birds at the site, it is possible that improved models may instead indicate that the installation of the wind turbine did have a significant impact on counts of auks and gulls at the site.

It is possible that the experimental design was unable to detect changes. The survey line passed the turbine at a minimum distance of 375 m, so any avoidance response occurring at closer distance than this will not have been recorded. The vessels used in this study were not able to travel closer to the turbines than 300 m because of safety restrictions. In Larsen & Guillemette's (2007) study, eiders avoided wind turbines at distances of 200 m, so this study may not be sensitive enough to detect changes, especially if the birds have habituated to the turbine through regular use of the area. However, the tail end of a response at the closest distances should still be evident if this was the case.

Environmental influences on bird densities

In contrast to the analysis of the impact of turbine installation, the oceanographic variable considered, gradient of the deepest thermocline, showed a highly significant relationship with the density of birds found at the site. This compares well with studies from the eastern tropical Pacific, where piscivorous birds were shown to preferentially forage in areas with strong thermoclines (Spear *et al.*, 2001) and also with other studies in the North Sea where common guillemots were found to forage in areas with thermoclines (Daunt *et al.*, 2003). Sandeels on Dogger Bank in the North Sea were shown to be more abundant in areas with stratified water and also to be more likely to be present in 2006 than in the preceding two years (van der Kooij *et al.*, 2008). This may provide a link between the oceanography and high densities of birds observed on the surveys in late June 2006.

Flying birds showed a less significant result with the gradient of the deepest thermocline than did birds on the water. This is probably because auks, which are known to dive to the thermocline (Takahashi *et al.*, 2008), tend to sit on the water, whereas gulls tend to fly. Birds included in the flying category may also have been transiting through the area rather than using it for foraging. The relationship with year in the density of birds on the water demonstrates the different oceanographic regimes at the site between the two years. The collinearity between the oceanographic variables, as well as with year indicates that some external factor, unmeasured in this study may be responsible for the broad scale differences between years. Large scale environmental parameters have been shown to influence the breeding phenology of seabirds and particularly guillemots and kittiwakes in the North Sea (Frederiksen *et al.*, 2004), which will in turn influence the timing of the peak in numbers at foraging sites. Such environmental influences may have caused the peak to be later than these surveys in 2007. When locating wind farms, developers should also consider the sediment type to determine whether the area is likely to host sandeels and conduct surveys to determine this.

There were clearly high densities of birds at the site in late June 2006. The counts of auks and gulls (figures 6.5 and 6.7) show that both were present in considerable numbers during this period. The majority of gulls recorded to species level were kittiwakes, while the majority of auks recorded to species level were guillemots. Camphuysen &Webb (1999) showed that large feeding aggregations of seabirds were usually begun by auks, which probably pushed sandeels closer to the surface. Black-legged kittiwakes then began feeding on the fish within their depth range, which alerted other species to the presence of prey. Guillemot and kittiwake were the essential species for the formation of such flocks and it is possible that guillemot presence is necessary for surface feeding kittiwakes to be able to catch sandeels. Such a mechanism may well have been acting at the Beatrice site on the days of the late June surveys.

CONCLUSIONS

We detected no effect of the installation of the two wind turbines on counts of seabirds around the study site. This may have been due to the scale of sampling, but it seems more likely that within and between year differences observed in the counts and densities are the result of temporal variation in environmental conditions at the site in late June 2006. This will be important for future offshore wind developments to note because the environmental variables which seem to have created good foraging conditions in 2006 could occur at other sites. Such natural variability can complicate assessments of environmental impact and must be taken into account through the collection of several years of baseline data.

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Chapter seven

General discussion

INTRODUCTION

Increases in the number of offshore wind farms have been proposed to allow the increases in capacity of offshore wind required to meet the UK government's target of 15% renewable energy by 2020 and the European Union's target of 20% renewable energy by 2020 (EU Renewable Energy Directive, 2009; DECC, 2009). EIA for these developments must be robust, thorough, practical and be open and transparent about uncertainties, to ensure that offshore wind has as little impact on seabirds as possible. The central aim of this thesis was to assess the feasibility of using surveillance radar to track movements of birds in offshore locations, with limited observer input. Two key objectives were to assess whether the system could collect good quality data when left to run automatically, and to identify how the resulting data could contribute to our understanding of the environmental impacts of offshore wind farms. The thesis also aimed to investigate any impacts of installation of the Beatrice demonstrator turbines on seabird abundance and distribution and to compare this with the effects of environmental variation.

Practicalities of using radar offshore

Deploying a bird tracking radar system in an offshore environment is difficult. This study took advantage of the presence of a permanently manned offshore platform on which to situate the radar (chapter three). This platform was stationary and provided a permanent electrical supply as well as the technical capacity to monitor the radar remotely. However, problems were still encountered with software malfunctions which caused it to shut down and interruptions in the power supply, which required the whole system, including the radar itself to be restarted. These resulted in data losses, but once the problem was identified, it was possible for the platform telecoms crew to make changes. Crew may not be present, or available to perform these functions on other platforms.

Using a platform that is less permanent, and lacking the extensive infrastructure that is available on an oil platform will raise additional problems. The COWRIE remote techniques report suggests using the meteorological masts installed to assess the wind resource at a site as platforms for installing radar (Desholm *et al.*, 2005) as has been carried out at the Horns Rev development in Denmark and in the Netherlands (Christensen *et al.*, 2004; Krijgsveld *et al.*, 2005). If meteorological masts are built as substantial structures with accommodation, this may be possible, but newer masts are often built to be unmanned installations.

Power supplies are likely to be limited and it may be necessary to provide additional power to the platform for the radar and associated equipment. The radar unit used in this study required a power input of around 800 W, while a PC with high graphics specification is likely to require around 500 W. If a vertically scanning X-band radar was also used, this is likely to require 500 W to 700 W depending upon model and would require a second PC to process the data. It will therefore be necessary to have around 2.5 kW of power available at all times. For renewable power sources such as wind turbines and solar panels, there will be significant periods when power output is much lower than the peak output, so the installed capacity should be in the region of 25 kW. Small scale wind turbines are unlikely to be able to provide this amount of power, since the larger of these turbines currently produce a peak output of between 10 kW and 20 kW, and the meteorological mast may not be large enough to accommodate such a turbine. These turbines are also not designed for use at sea, so may suffer as a result of exposure to salt water. Solar panels produce considerably less power than turbines, with some of the largest rated at 80 W. It therefore seems likely that the radar would have to be powered by petrol fuelled generator, which would have to be refuelled regularly, requiring access to the mast.

Data would also need to be transported from the platform manually, unless methods for transmitting up to 10 GB of databases per day by satellite could be developed. Alternative platforms may include jack up barges or large ships if they can be made stable enough to allow the automatic detection and tracking software to function correctly. However, using such platforms for long term monitoring is unlikely to be financially feasible, so studies should be designed that can be carried out over specific time periods.

Working on an offshore oil platform also requires a high level of understanding and training in health and safety procedures. During this study, there were some cases where modifications to the hardware, or the installation of other pieces of equipment were not possible because of rules on electrical safety, required to reduce spark potential. Such rules are clearly essential for ensuring safety on an oil platform, but those constraints must be recognised when planning radar studies in this environment.

Any platform must also be close enough to the proposed development to allow an appropriate radar range to be used. In this study, a range of 1.5 NM (2.78 km) was selected to give high resolution coverage of the area. Other wind farm related radar studies of migration, using S-band surveillance radar, have used greater ranges, typically around 11 km (Krijgsveld *et al.*, 2005; Parnell *et al.*, 2006; Walls *et al.*, 2007), as a compromise between range coverage and target detection. However, results presented in chapter four indicate that detection decreases at distances greater than 50% of the total range. To ensure that appropriate quality data are collected, all areas of interest should be well within the maximum range of the radar. Future studies should also ensure that the maximum range and the peak detection distance are presented in the protocols.

The areas with exclusivity agreements for the Scottish territorial waters round of offshore wind can all theoretically be covered by a single radar operating at 11 km range, since this covers an area of 380 km^2, while the largest agreed wind farm site is 150 km^2 (The Crown Estate, 2009a). However, to ensure that all turbines are within 50% of the radar's range, an area of only 95 km^2 can be observed and this assumes that the radar is situated at the centre of the wind farm, with the turbines radiating out from that central point. For Round 3 of offshore wind, the indicative areas provided by The Crown Estate (The Crown Estate, 2009b) are considerably larger than the Scottish round sites, although it is unlikely that any single development would cover the entire area. It may therefore be necessary to have more than one radar system in use at a particular site.

If a suitable platform is available, the results presented in this thesis demonstrate that an automatic radar system can be left to run without the need for having an observer (chapter three). If the platform is unmanned, system function should be checked every two to four weeks to reduce data loss through software errors or breaks in the power supply. The radar and associated PCs should be equipped with an uninterruptible power supply (UPS) to ensure that power loses do not damage the hardware.

This study highlights that the databases retrieved from these automatic detection and tracking systems can only be regarded as a starting point for analysis. Sea clutter seriously affected the quality of the data collected and meant that a high proportion of the tracks in the databases were spurious. Highly conservative clutter filters were developed to remove these tracks (chapter three), based on track length, angular deviation and wind speed. It is likely that they also removed genuine bird tracks, particularly those of foraging birds, which are likely to show greater variation in heading (e.g. Fauchald & Tveraa, 2003; Pinaud, 2008; Suryan *et al.*, 2006; Turchin, 1998). Other studies have created training datasets of tracks that have been visually verified as either birds or clutter, to create filters for the whole dataset using classification trees (Meesters *et al.*, 2007). Track length was found to be the most important characteristic in grouping the data as birds or clutter, which gives a less conservative filtering process than that used in this study. Radar data collected by CSL are also filtered only on track length (Parnell *et al.*, 2006; Walls *et al.*, 2007). Nevertheless, the temporal patterns in the datasets presented in chapter three showed significant correlations with visual observations as well as being consistent with previous knowledge of the biology of the site and with the results of visual surveys (chapter six). The studies that only use track length have been carried out at either onshore sites, or sites in sheltered waters, which reduces the extent of clutter in the dataset. The studies also had observers present to verify radar tracks as being birds or clutter, whereas the radar in the present study ran autonomously. For sites in less sheltered offshore waters, and without an observer present, this study suggests that filters may need to be more conservative to ensure the quality of the data. Site specific filters may be necessary for other studies and may not need to be so conservative in areas or during time periods with lower levels of sea clutter.

Recommended techniques to answer EIA questions

Results from this thesis have demonstrated that marine surveillance radar is a useful technique to answer some of the generic and site-specific questions related to offshore wind farm EIA. However, in many cases, other techniques can provide additional and sometimes more suitable data. The key generic and site-specific questions are discussed below.

Generic questions

Flight speeds

Results presented in chapter five of this thesis show that ground speed can have a significant effect on collision probability of birds, as calculated by the Band model (Band *et al.*, 2007) and that wind speed and direction can affect the resultant ground speed of birds. Ground speeds are readily collected with horizontally scanning surveillance radar.

Combining these data with locally collected wind speed and direction data (chapter five), allows calculation of airspeed which may allow some discrimination between species groups (chapter five) and has been used previously to remove insect contamination from datasets by removing tracks with airspeeds of less than 5 ms^{-1} (Larkin, 1991). In order to gather data on the flight speeds of particular species, a human observer must be present because species identity cannot be determined from the radar data. However, the results presented in chapter five of this thesis demonstrate that it may be possible to group some seabird species based on airspeed.

Many of the published airspeeds of seabirds were collected using an ornithodolite, which finds the angle and range to a bird and saves this information on a portable computer along with the time of the observation (Pennycuick, 1982a). When used on land, this can be used to give three dimensional information about bird flight height, as well as speed. However, at sea, elevation angle could not be measured, due to the movement of the boat, so no flight height data could be collected (Pennycuick, 1982b, 1982a). The ornithodolite is not commercially available, but similar measurements could be taken with a surveyor's theodolite connected to a computer.

Alternatively, ground speeds could be measured by using GPS tags on birds (Guildford *et al.*, 2008; Weimerskirch *et al.*, 2002) or over longer periods, at lower resolution, by satellite tracking (Miller *et al.*, 2005; Weimerskirch *et al.*, 2000). Most studies that have used tags to track movements of seabirds have caught the birds at colonies, indicating that instrumenting them with such devices during the breeding season should not present too large a problem. However, all of the previously studied colonies have relatively easy access, which is not the case at every site around the UK. It may be possible to catch birds with a fleyg net from cliff tops, or from the water close to the colony. Outside of the breeding season, GPS tags are unlikely to be a useful technique because catching birds is more difficult at sea and the bird must be re-caught in order to retrieve the tag and data. Satellite tags can transmit data via the Argos system, so do not need to be removed from the bird. Careful consideration should be given to tag mass in relation to bird mass, which should never exceed 5% (Gaunt & Oring, 1997), and in many cases should be substantially less than this (e.g. Phillips *et al.*, 2003; Wanless *et al.*, 1988). A person who is trained and licensed by the British Trust for Ornithology to apply rings to the study species independently (BTO C-permit) and to attach devices to birds must be present when devices are attached.

Flight heights

Flight height has a clear influence on the probability of collision with turbine blades, since birds flying higher or lower than the sweep of the blades cannot collide. The Band collision model also considers changes in the probability of collision at different heights, due to changes in the velocity of the blades at different distances from the hub (Band *et al.*, 2007). However, McAdam (2005) showed that this method significantly under estimated collision close to the hub and over estimated it for birds flying near the tips of the blades. Flight height has been measured successfully using vertically scanning surveillance radar (e.g. Cooper *et al.*, 1991; Harmata *et al.*, 1999; Krijgsveld *et al.*, 2005). However, clutter was evident to some extent in the lower altitudes in all of these studies. For example, Cooper *et al*, (1991) found that clutter affected the nearest 25 m to the radar, while Krijgsveld *et al*. (2005) found that clutter was evident in the nearest 400 m. Krijgsveld *et al*. (2005) were able to filter much of the clutter out and presented data in altitude bands of 0 m to 50 m, 50 m to 150 m, 150 m to 250 m and higher than 250 m. These bands would not be suitable to determine whether birds were flying at altitudes which put them at risk of collision if used at the Beatrice site because the turbine blades span the range of 20 m to 120 m above sea level. In order to assign heights to species, an observer must be present, as the radar is unable to discriminate this. A large number of measurements, made under different conditions should be taken for each species, to provide a range of flight heights and to allow investigation of how weather conditions influence this (Shamoun-Baranes *et al.*, 2006). The use of vertically scanning radar was not attempted in the present study.

The ornithodolite technique described above could be used to determine flight heights, in situations where a stable platform was available (Pennycuick, 1982a). Flight heights at sea will be difficult to collect unless a structure such as an oil platform could be made available. Flight heights from land are of limited value because they are likely to be influenced by the necessity for the bird to reach a nest site. Photogrammetry could also be used to gather data on flight height. This requires two cameras taking photographs in synchrony, with a fixed separation and the horizon present in all photographs. The difference in the distance to the bird from the edge of the photograph between the two pictures allows measurement of the distance from the photographer to the bird. This is calibrated by taking photographs of an object at known distances. The height of the bird above the horizon in the photograph can then be used to calculate the flight height of the bird, through trigonometry. The photographs can be taken from a boat, as long as the height above sea level of the cameras is known. Increasing the separation of the cameras increases the range over which measurements can be taken, but with a separation of 1 m, the working range is around 150 m.

Flight mode

Whether birds are flapping or gliding has an influence on their collision probability when passing through turbine blades since flapping wings take up a larger volume of airspace than gliding wings. For this reason, the flight mode is included as a parameter in the Band collision model (Band *et al.*, 2007). It would not be possible to collect this kind of data with surveillance radar. The most appropriate technique would be visual observations of flight, or use of a military tracking radar (Shamoun-Baranes & van Loon, 2006) if available. Visual observations could be combined with surveillance radar and wind speed data (chapter five) to allow an assessment of the conditions under which different flight modes are employed. Such data could be used to modify parameters in the Band model for different situations.

Species disturbance

Identifying the species most likely to be disturbed by wind turbines will allow EIA to focus on the most vulnerable species. Species vulnerabilities can be assessed using methods similar to those of Garthe & Hüppop (2004), which consider various factors from species' flight manoeuvrability to population status, and assign qualitative values to allow comparison between species. Several methods could be used to gather the data required for this, including radar and visual techniques, but it is likely to require the use of a suite of techniques.

Visual behavioural studies will also be useful in determining disturbance, if they can be carried out before and after wind farm construction. A suitable platform will be required that does not influence bird behaviour. After arriving at the site, whether this be by boat, or by walking to an observation area of a fixed platform, observations should not be carried out for the first 10 minutes, or until birds are no longer paying particular attention to the observer. Behavioural definitions should use similar criteria to the European Seabirds at

Sea surveys (Webb & Durinck, 1992) to allow for high levels of discrimination between behaviours and to allow data collection to be standardised between studies. Protocols such as instantaneous scan sampling (Altmann, 1974) are likely to be the most appropriate because sampling periods can be standardised, making surveys repeatable. Differences in the amount of time performing non-vigilant activities, such as preening and in particular, foraging, may indicate an effect of disturbance.

Avoidance behaviour

The extent to which birds avoid wind farms and individual wind turbines is critical in establishing likely mortality from collision, since only birds making flights in the swept area of the turbine blades can collide. Surveillance radar can be used to assess movements through the area and the data may be useful for BACI or impact gradient studies (Ellis & Schneider, 1997; Underwood, 1994). Desholm & Kahlert (2005) carried out a study of avoidance, using surveillance radar operating from an offshore meteorological mast at the Nysted wind farm in Denmark. They showed that the number of common eider *Somateria mollissima* flocks entering the wind farm after construction was lower by a factor of 4.5 than flew through the area before construction. They also demonstrated that only 0.6% of flocks passing through the wind farm during the day and 0.9% passing through at night were close enough to be at risk of collision.

Radar studies could consider similar variables, such as differences in the distance at which birds approach areas before and after turbine installation and also in conditions with or without turbine blades turning. Radar data can be gathered with more precision than would be possible with visual surveys or tracking studies; in this study positions were accurate to ± 5.43 m. However, it is not possible to use radar to reliably determine whether a target actually collided with a wind turbine because a track passing closely behind or in front of the turbine may appear to be on a collision course, and the tracking algorithm may not recognise it as the same target when it reappears. Species identity will also be required for these assessments and therefore concurrent visual observations must be undertaken.

Likelihood of flocking

Studies considering flocking in relation to wind farm developments have so far focussed on flocks passing through the site on migration. However, flocking should also refer to roosting birds gathered on the water, since all of these birds must enter and leave the site at similar times. Over night roosts of up to 200 herring gulls and kittiwakes were observed on the water around the Beatrice Alpha platform (personal observation). Therefore, it will be important to recognise not only the migratory periods during which the risk of flocks passing through sites will be highest, but also the conditions that might make the wind farm, or an adjacent site an attractive roost. Determining the factors that make an attractive roost site will require visual surveys of roosts to be carried out as well habitat surveys, which should include factors such as light levels and colours at the installations, which may attract birds (Poot *et al.*, 2008).

Broad scale radar data, using weather radar systems, have been used to study patterns of migration across the USA (Russell *et al.*, 1998) and more recently, to identify migration stopover sites throughout the Great Lakes basin (Bonter *et al.*, 2009). Similar studies in the UK could be used to determine the timing of peak migration throughout the country. Such studies should ideally be carried out by a single research group or consortium and the findings made available to all developers because they will require the cooperation of the Meteorological Office to supply data and aid with interpretation.

Site specific questions

Counts and identity of species using the site

EIA require an inventory of species using a site and counts of those species, to determine whether a particular development is likely to impact vulnerable species. The species composition throughout the year must be assessed since the site may host breeding, foraging or migratory birds, or all three. Some researchers have been able to identify bird species groups by using data from a tracking radar (Bruderer & Boldt, 2001; Komenda-Zehnder *et al.*, 2002; Liechti, 1993), but the most appropriate method for determining species identity is through visual observations. Equally, the most thoroughly tested and robust methods for assessing numbers of birds are visual. Radar has been used by some workers to count birds (Burger, 1997; Desholm & Kahlert, 2005), but has always been accompanied by visual observations. Abundance estimates from radar data are complicated by the fact that a target may be a single bird or a flock and also by decreased detection at increased distance (chapter four), in the same way as visual methods. Counts are likely to be more reliable when using more sophisticated radar systems, for example where methods have been developed to estimate abundance using calibrated fixed beam tracking radar (Schmaljohann *et al.*, 2008). However, the modifications suggested in these methods are unlikely to be compatible with offshore platform health and safety regulations, and few workers will have access to radar units as powerful as the 150 kW X-band radar used in Schmaljohann *et al.*'s (2008) study.

Use of the site

Birds may use a site for foraging, loafing, roosting, or may pass through on migration, or on the way to foraging sites. Analysis of movement patterns can help to determine whether the birds are using the area for foraging or are in transit (e.g. Fauchald & Tveraa, 2003; Guildford *et al.*, 2008; Pinaud, 2008; Turchin, 1998). The data required for such analyses could be collected using surveillance radar as long as these systems were set at short range, to give high target resolution. The filters that I used in chapter 3 of this study would remove any foraging movements of this kind, but it may be possible to use tracks higher angular deviation values. Tracks with angular deviations between 20° and 40° did not fall within the peak area of tracks that were likely to be clutter and so could be used to investigate less linear movement. However, this could only be carried out on very calm days because of the risk of including clutter in the analysis.

Visual behavioural observations will also be of use during daylight hours. Such methods will allow much more detail to be recorded about the use of the site, for example, whether birds were seen with food, or with chicks. Methods similar to those discussed for assessing disturbance could be used.

Flight paths through the site

The direction of flights in relation to wind speed and wind direction can affect the probability of collision for birds passing through turbine rotors (chapter five). It is therefore possible that migrants, or birds transiting to foraging sites, may be at greater risk of collision under particular wind conditions. Visual surveys could be carried out during the day, but will not be able to provide data at night, or during conditions of poor visibility. Surveillance radar studies could be used to investigate the rate of movement through the site and also the flight paths taken. Such studies have been carried out at several wind farm sites in the UK to investigate migration movements (e.g. Lincs and Sheringham shoal) (Parnell *et al.*, 2006; Walls *et al.*, 2007), using S-band radar and the same automatic detection and tracking software as described in this thesis (chapter 3). In these studies, the radar range used was 11 km, which is a compromise between spatial coverage and the resolution required to detect flocks of birds such as geese.

Movements through the site to foraging areas may be made by smaller flocks, or individual birds and the species are likely to be smaller than geese. Therefore a shorter range may be required in order to detect smaller targets. The 1.5 NM range used in this study (chapter three) will allow detection of individuals, but does not give good spatial coverage. On this particular radar, increasing the range to 3 NM also increases the minimum pulse length that can be used, from 0.07 µs to 0.15µs, which will reduce resolution. This compromise may have to be made, and it may also be necessary to use more than one radar unit to allow data collection over the entire wind farm site. Alternatively, particular areas could be prioritised for high resolution data collection. This type of deployment of radar should be informed by data on the most important areas for transiting birds, which could be collected by operating the radar at a broader scale for an initial period, or through visual abundance and distribution surveys.

Breeding colony location

Birds using a potential development site during the breeding season may be nesting at protected colonies. Many site designations protect birds even when they are not at the colony, since additional mortality away from the colony may impact on the site condition (EC Birds Directive, 1979). It is therefore important to determine the breeding locations of birds at the site. Radar can be used to give an overview of this, by monitoring the direction of flights to and from the site (chapter four), since some species of seabird, such as guillemots, have been shown to make direct flights between colony and feeding sites (Wanless *et al.*, 1990). Radar studies can also be carried out from breeding colonies of interest (Lilliendahl *et al.*, 2003), to determine whether the flight directions taken out towards feeding areas overlap with the study area.

Alternative techniques, such as radio tracking (Perrow *et al.*, 2006) or GPS tracking (Guildford *et al.*, 2008) would also provide data on the extent of use of the site by individual birds. Radio tracking is an intensive process, because signal strength is not great enough to allow tracking from land, and therefore requiring a boat with crew to track the bird. In the UK to date, this has only been attempted by Perrow *et al.* (2006) on little terns *Sterna albifrons* from a colony within 2 km of the Scroby Sands wind farm.

Impact assessment

The results presented in chapter six highlight that impacts of offshore wind turbines on bird distribution and abundance at sea will be difficult to determine, because of large amounts of environmental variation, unconnected with the development. However, the data for the impact assessment in this study were collected with only one turbine and a base jacket installed, and the potential impacts from larger developments remains uncertain. Impact studies for future large-scale developments will need to be carefully designed in order to detect small changes, not attributable to environmental variation. Using only one year of baseline and one year of impact data increases the chances of data being collected in years with anomalously high or low abundances of birds at the site. Guidance from Scottish Natural Heritage for onshore developments states that one year of baseline data should be the minimum (SNH, 2005), but that post construction monitoring should take place over the 15 year period following installation (SNH, 2009). This will only be feasible if the monitoring is low intensity and of relatively low cost.

Changes in abundance of birds at the site may not be the most sensitive indicator of impact, and it may be more important to consider bird behaviour. For example, considering the proportion of birds foraging at the site, or carrying out passive behaviours, such as roosting or preening may show greater changes. Such data could be analysed in a similar way to the abundance and distribution data, using BACI or impact gradient methods, where the interaction between the before and after factor and the control or impact factor must be significant to indicate an impact (Ellis & Schneider, 1997; Underwood, 1994). Selecting control sites where no impact is expected requires a prior understanding of the likely scale of the impact. Sites that are too close, may also be impacted by the installation of turbines, which could lead to no impact being detected, even if there was a significant impact. However, sites that are too far away from the impact are likely to differ in other characteristics and may consequently indicate a significant impact, which is actually attributable to some other effect. The same issues apply to impact gradient designs, where the gradient must consider areas at great enough distance from the wind turbines to allow robust impact assessments.

Finding a significant impact in either behaviour or abundance of birds following the installation of a wind farm must also be put into the context of population effects and of other factors affecting seabird populations. Reductions in seabird breeding success have been recorded in the UK since 2004 (Mavor *et al.*, 2008; Wanless *et al.*, 2005) and have been attributed to reduced food availability (Wanless *et al.*, 2005), which may be a result of climate change (Frederiksen *et al.*, 2007; Frederiksen *et al.*, 2004), over-fishing (Frederiksen *et al.*, 2008) or a combination of these factors. The potential additional impacts of disturbance, increased transit times to foraging sites and collision risks as a result of the presence of wind farms may exacerbate these existing impacts. However, the exclusion of boats from areas around wind turbines may also effectively create no-take zones for fishing, which may be exploited by seabirds.

Lessons learned during this project have been disseminated through contributions to a COWRIE report entitled “Revised best practice guidance for the use of remote techniques for ornithological monitoring at offshore windfarms” (Walls *et al.*, 2009). Learning from previous wind farm developments is made difficult because there is currently no central repository for environmental statements or reports on post-construction impacts. This has been widely discussed by developers and consultants, and COWRIE have developed guidance on the quality of data that should be archived (Seeley *et al.*, 2008), but to date, a repository for such data is yet to be created.

CONCLUSIONS

This thesis aimed to test the use of marine surveillance radar as a technique to monitor bird movements at offshore wind farm sites. This was largely successful, with radar operating without an operator for extended periods. However, only birds travelling through the area could be reliably detected. The use of a permanent oil platform made many aspects of the installation and maintenance easier, but also made some aspects more complicated. Other studies may not have such a platform available, which will limit the applicability of some of the findings presented here. Radar can be a useful technique for answering questions about movement through the site, but it must be viewed as one technique within a suite available.

The thesis also aimed to determine whether there were any changes in seabird abundance and distribution following turbine installation. The results of this study demonstrate that impacts can be difficult to assess against background environmental variation. Such variation also contributes to the cumulative impacts on seabirds and should be taken into consideration in the EIA for all wind farm developments.

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