SATELLITE-TRACKING OF BEWICK'S SWAN MIGRATION IN RELATION TO OFFSHORE AND ONSHORE WIND FARM SITES: FINAL REPORT

L.R. Griffin, E.C. Rees & B. Hughes

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Tel 01453 891900 Fax 01453 890827 Email conservation@wwt.org.uk

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Cover photograph: Bewick's Swan in flight, by Colin Butters.

Table of Contents

1. EXECUTIVE SUMMARY

1.1 From winter 2013/14 onwards, the Wildfowl & Wetlands Trust tracked Bewick's Swan movements in relation to offshore and onshore wind farms along their migration route, with a particular focus on the birds' flight-paths between Britain and mainland Europe, to inform the UK Government's offshore energy Strategic Environmental Assessment including for offshore wind farm development in the North Sea region.

1.2 The main aims of the project were to describe Bewick's Swan migration routes from and to Special Protection Areas (SPAs) in the UK, in relation to areas proposed for offshore wind farm development in the North Sea, and to determine the total number of wind farm sites (both offshore and onshore) encountered by individual birds during their migration through northwest Europe. Additionally, the total number of turbines that occurred along the swans' flight-lines was estimated from the tracking data, to provide information for future collision risk and cumulative impact assessments for the species.

1.3 A total of 22 Bewick's Swans were marked with solar-powered collar-mounted UHF-GSM-GPS data loggers: 8 in winter 2013/14 and 14 in 2014/15. Seven of the 2013/14 loggers did not provide the detailed data required for the study, but those deployed in 2014/15 were fully functional. Location data recorded up to 6 March 2016 were included in the analyses presented in this report. At least hourly location data were recorded for 14 birds that crossed the North Sea on at least one occasion, and a total of 18 "independent" spring migration tracks from the UK (noting that two sets of birds seemed be associating as pairs/siblings) were recorded by early March 2016. Autumn migration for 2 swans tracked on returning to the UK was also recorded in detail, with GPS fixes at ≤70 minute intervals.

1.4 The Bewick's Swan tracks were inferred as being straight lines between consecutive GPS data points within a GIS. Only track segments where GPS fixes were ≤ 70 minutes apart were included in the analyses of wind farm areas likely to be encountered by the birds. Tracks that came within an 80m radius of a wind turbine were taken as indicative that the turbine was on the bird's flight-line, with 80m being the current maximum radius of the rotors for wind turbines in Europe.

1.5 The study found that there was a high level of Bewick's Swan movement across the East Anglia ONE wind farm footprint; 83% of swan tracks (n=18 tracks) and all (100%) of tagged swans crossed the site during migration from and/or to the UK in spring and autumn 2014–2016. Inspection of the mapped tracks indicates that the swans move across the whole of the footprint area. None of the tagged Bewick's Swans were found to cross UK offshore wind farms further north (*i.e.* none crossed the Hornsea or Dogger Bank sites), but one individual flew across more southerly UK wind farm sites – Greater Gabbard, Galloper B and the London Array – in autumn 2015.

1.6 A total of 52 offshore wind farm footprints (including 11 operational sites) were crossed by the swans, of which 33 (63%) were in German waters, 12 (23%) Dutch, 4 (8%) British and 2 (4%) Belgian, with one Swedish site also included.

1.7 Several birds migrated direct from the UK to Denmark or to Schleswig-Holstein in Germany, resulting in them crossing offshore wind farms in the German Bight rather than taking an overland route from the Netherlands to Germany and Denmark. This area was not included as being on the Bewick's Swans' migration route in a previous report for the Strategic Ornithological Support Services (SOSS) group, which provided guidance for assessing the numbers of migrating birds likely to pass through proposed offshore wind farm developments (Wright *et al*. 2012). Maps of the main migration zones from Europe for Bewick's Swans wintering in Britain and Ireland therefore should be updated in line with the evidence provided in the current study.

1.8 The majority of tagged Bewick's Swans departed from the UK coast during early morning (62.5%, n = 16 departures on migration) and therefore arrived at the start of the East Anglia ONE footprint under conditions of good visibility. The remaining six tagged swans (37.5%), which started their migration after sunset, typically migrated under moonlight.

1.9 Flight height data were recorded for only 5 Bewick's Swans whose tags were programmed to record altitudinal data and whose data were downloaded in the field. Nevertheless, the data indicated that the birds fly at low altitudes, with 89.2% of 323 flight height records over land and 93.0% of 201 flight height records over sea being at <150m, and with both median and modal flight heights being in the 0 to -50m band. Most flights therefore are at or below the sweep of the wind farm rotors.

1.10 In addition to the offshore wind farms, 15 Bewick's Swans with detailed tracking data encountered 322 onshore wind turbines (*i.e.* their tracks were <80m from turbines). On considering the hourly track segments that appeared from the flight height, speed or distance data to include a period of flight (thus "flight segments"), it was estimated that there was an overall encounter rate of 0.066 turbines per flight segment – *i.e.*, one turbine encountered for every ~15 flights made by the swans. Overall rate varied considerably between countries, from <0.001 (i.e. less than 1 in 1,000) encounters per flight segment for birds in the UK, compared with 0.14 in Denmark, 0.17 in the Netherlands and 0.23 in Germany, indicative of variation between these countries in onshore wind farm density. Encounter rates also varied across years for particular individuals, depending on their choice of staging or wintering site.

1.11 Given the high proportion of Bewick's Swan tracks that cross not only the East Anglia ONE wind farm site but also offshore wind farms in German, Dutch and Belgian waters, our findings show that particular care should be undertaken to assess cumulative impacts of several wind farms along the swans' migratory route, to ensure that there is no likely significant effect of these developments on the NW European Bewick's Swan population, which is in decline and listed as Endangered in the European Red List of bird species (BirdLife International 2015).

1.12 Moreover, collision risk at onshore wind farms should also be taken into account during cumulative impact assessments undertaken for birds that migrate over both land and water.

1.13 Cumulative impact assessments for onshore wind farm development in the vicinity of nationally and internationally important sites for the species should also address the potential consequences of Bewick's Swans being displaced from several feeding/roosting sites along the migration route and in the wintering range.

1.14 The importance of considering both offshore and onshore wind farms in cumulative impact assessments extends to other migratory waterbirds, and is not limited to Bewick's Swans.

1.15 International communication and publicly accessible data on proposed and constructed wind farm sites (including their precise location and the number and size of turbines) in range states is crucial if strategic and project-specific assessments are to determine cumulative effects more precisely.

1.16 The study has served to demonstrate that birds wintering at sites some distance from proposed wind farm developments may nevertheless encounter such developments during their annual migration. As such, EIAs for offshore wind farms should consider potential impacts on all SPAs designated for Bewick's Swans, not just coastal sites.

1.17 The current study illustrates that information on bird migration zones was not well founded for Bewick's Swans, despite this being a well-studied species. We therefore recommend that further tracking and also radar studies be undertaken to improve knowledge of migration routes for other migratory species where internationally important numbers (>1% of the total population) occur in the UK, and/or where SPAs have been designated for these species.

1.18 For Bewick's Swans, although 100% of tagged swans passed through the East Anglia ONE footprint, this was based on a small sample size of spring tracks, and further tracking may provide a more robust assessment of the proportion of birds crossing different parts of the footprint.

1.19 Detailed field and radar studies of swan movement in the vicinity of onshore sites in Europe would perhaps serve to determine how the birds behave in relation to different turbine spacing, and thus indicate whether the creation of east-west corridors a few hundreds of meters wide might be useful in reducing the risk of collision for migrating swans and other birds.

1.20 This report examines the frequency with which migrating Bewick's Swans encounter turbines, and are thus at risk of collision, but the effects of wind turbines in displacing birds from key feeding and roosting areas at wintering and staging sites should also be assessed in determining their cumulative impacts on migratory species. Although some individuals may become habituated to turbines and tolerate them, whether there is a percentage of the population that relocates from sites where wind farms have been constructed has yet to be ascertained. Additionally, despite the small sample size of tagged birds, existing tracking data can be examined to determine the extent to which feeding swans move within or stay outside the perimeters of constructed wind farms, most usefully at wintering and staging areas where there are higher wind farm densities on mainland Europe. This, together with national count data, may help to determine whether there is large-scale (landscape level) and/or local displacement of swans from the vicinity of wind farm sites.

1.21 Potential collision with other infrastructure – particularly powerlines – should also be included in collision risk assessments. Collisions with powerlines is the most commonly reported cause of death in swan species and there is preliminary information that elevated bird collisions with powerlines occur in the vicinity of wind farm sites, perhaps because avoidance of the more obvious turbines results in a higher rate of flux across the less obvious wires.

1.22 Access to turbine data for the remaining countries of the flyway, and also attribute data for the turbines that would allow us to determine the sweep of the rotors from more precise measures of the rotor radii, would provide a more robust measure of encounter frequency for Bewick's Swans. Modelling the probability distribution for swan tracks, rather than assuming a straight line between GPS locations, would also be beneficial for making a more comprehensive assessment of collision risk. In a more complex model, it would perhaps be possible to link turbine positioning to local wind conditions (as turbine hubs are rotated to face the prevailing wind), so that the actual rotor swept area perpendicular to a swan track at the time it travelled past the turbine can be calculated, albeit this level of detail may perhaps be merited only for swan tracks derived from GPS data collected at more frequent intervals.

1.23 A single standardised database of all offshore and onshore wind farms should be developed, not only for the UK but more widely (*e.g.* at the European level), to facilitate cumulative impact assessments.

2. INTRODUCTION

DECC (the United Kingdom Department of Energy and Climate Change) is undertaking an Offshore Energy Strategic Environmental Assessment (SEA) programme, to ensure that environmental issues are considered appropriately for offshore energy developments, including wind farm sites. As part of the SEA programme, studies are undertaken to ensure a sound information base on which to base the assessments. The movement of several swan and goose populations along coastal Britain and through Scotland has been described through satellite-tracking studies undertaken by WWT under contract to COWRIE Ltd. and to DECC, and these have highlighted key areas where the construction of offshore wind farms may pose a risk to these birds, particularly for Whooper Swans migrating to Iceland and for Barnacle Geese that cross the North Sea to Norway *en route* to breeding grounds on Svalbard (Griffin *et al.* 2010, 2011). Much less is known, however, about flight-lines taken by birds migrating between southeast England and the Low Countries of Continental Europe. Further tracking of bird migration was therefore recommended to clarify potential effects of wind farm development for birds moving across this part of the North Sea. Additionally, tracking migratory birds that winter at inland sites helps to identify those designated as Special Protection Areas (SPAs) under EU legislation that may be affected by offshore wind development, which should therefore be taken into account in Scoping Reports and Environmental Impact Assessments on considering the likely significant effects (LSE) of a wind farm on SPAs. Without such studies, the link between inland SPAs and offshore wind farm development would be less well understood.

2.1 The Northwest European Bewick’s Swan Population

The Northwest European Bewick’s Swan Population breeds on the European tundra of arctic Russia and migrates via staging areas in the Baltic countries to winter in northwest Europe, with major concentrations in the Netherlands and southeast England. Numbers increased during the 1980s and early 1990s to a peak of 29,000 birds in January 1995, but more recently the population has declined markedly to only 18,055 individuals by January 2010 (38% below the peak count), and national trend indices indicate that numbers have stabilised or declined further since then (Rees & Beekman 2010, Hornman *et al*. 2015, Eaton *et al*. 2015). A Bewick’s Swan Species Action Plan developed to address the issue (Nagy *et al.* 2012) therefore was adopted by the African-Eurasian Migratory Waterbird Agreement (AEWA) of the Convention on Migratory Species (the “Bonn Convention”) in May 2012. Although collisions with man-made structures was not thought to be a main cause of the initial population decline, reducing collision risk was nevertheless deemed important for halting and reversing the decline. High priority actions within the Plan therefore required that all range states, including the UK, should "*Avoid key sites and flight lines during the construction of new powerlines and wind farms*", so that collision mortality with infrastructure is minimised.

Bewick's Swans generally have a southerly distribution within the UK. The three sites of international importance for the species (Ouse Washes, Nene Washes and Severn Estuary) and three of national importance (Breydon Water/Berney Marshes, Dungeness to Pett Level and Ranworth/Cockshoot Broads in Broadland) are all in the southern part of the country (Holt *et al.* 2012). All are designated as Special Protection Areas (SPA) under the European Union's Birds Directive (Directive 79/409/EEC), with the Bewick's Swan listed as a qualifying species in each case. Of these, the Ouse Washes in southeast England is of particular importance as it generally holds 20–25% (>33% in winters 1986/87 and 2004/05) of the total flyway population in mid-winter. Gaining detailed information on the Bewick's Swan's migration route, with high frequency (hourly and sub-hourly) location data, in relation to proposed UK Round 3 (R3) wind farms off the East Anglian coast therefore was considered important for informing the potential impact of these wind farms on the species because it seemed likely that most swans would arrive in Britain over East Anglia from their other main wintering haunts in the Netherlands. Bewick's Swan flights in relation to Dutch offshore wind farms east of the R3 footprints, and to wind farms along the Baltic coast, were also of interest for assessing potential in-combination effects for several wind farms along the swans' migration route.

2.2 Preliminary tracking of Bewick's Swans caught in winter 2013/14

In March 2013, Hartley Anderson Ltd. therefore contracted the Wildfowl & Wetlands Trust on behalf of its client, the Department of Energy and Climate Change (DECC), to track Bewick's Swan movements between southeast England and the Netherlands and along the swans' migratory flyway (contract no. OESEA-12-35; Griffin *et al*. 2014). The birds were marked with solar collar-mounted UHF-GSM-GPS data loggers (supplied by Ecotone, Poland) scheduled to provide hourly and sub-hourly location data (depending on battery charge), downloaded via the mobile phone network, and the data were to be analysed in relation to offshore and onshore wind farm sites principally within the UK but also in mainland Europe.

Eight Bewick's Swans were duly fitted with the loggers in winter 2013/14 but, because there were technological issues with the novel collar-mounted GPS tracking devices, detailed hourly tracks across the North Sea were obtained for only one of the eight tagged birds in spring 2014. Five more loggers provided less frequent (6-hourly) GPS fixes, and thus gave very coarse-resolution tracks between SE England and the Continent. These coarse temporal resolution GPS tracks nevertheless indicated that four of the six swans tracked to Europe crossed the northern half of the East Anglia (R3) wind farm footprint, and that four birds also crossed consented offshore sites in Dutch/German waters (Griffin *et al.* 2014).

The study therefore was extended for one year (under contract no. OESEA-14-49), to allow replacement GPS devices sent by Ecotone in March 2014 (just after the swans had migrated from the UK) to be fitted to swans in winter 2014/15. Here we provide an overview of the earlier (2014) study (described in Griffin *et al*. 2014) and present the results of the more detailed Bewick's Swan tracking programme carried out during 2015.

3. OBJECTIVES

The main objectives and work elements, as stated in the two Bewick's Swan tracking contracts, were to:

1. Fit 20 collar-mounted radio-GPS-GSM loggers to Bewick's Swans wintering in Britain.
2. Download data on Bewick's Swans movements while the swans are in Britain and during migration.
3. Travel to continental Europe for radio-GPS logger download of additional data.
4. Incorporate wind farm locations and weather data along the Bewick's Swans' spring migration route into a GIS.
5. Analyse and report on the effectiveness of the radio-GPS-GSM logger technology, and on Bewick's Swan movements in relation to wind farm sites.

4. METHODS

4.1 OBJECTIVE 1: Fit 20 collar-mounted radio-GPS-GSM loggers to Bewick's Swans wintering in Britain

4.1.1 Winter 2013/14

Winter 2013/14 was exceptionally mild and wet, resulting in unusually low numbers of Bewick's Swans wintering in the UK. Nevertheless, a total of eight collar-mounted loggers were fitted to Bewick's Swans during three cannon-netting catches in fields near the Ouse Washes, southeast England, in January and February 2014. The tags deployed were Ecotone UHF-GSM-GPS loggers with a double solar panel and integrated click-shut plastic collar. The collars measured 50mm in height and 2mm in thickness, with an internal diameter of 51-53mm. The devices were 14mm thick and overhung the bottom edge of the collars by 6mm. Total mass of the collar+logger was 51-53g (**Figure 1**).

Figure 1. Fitting the solar Ecotone UHF-GSM-GPS collar-mounted device to a Bewick's Swan and the gap between the swan's neck and the device once fitted.

It became apparent soon after the first seven birds had been tagged that there was a software issue with the original tags, and the supplier – Ecotone, Poland – sent an engineer to the UK to upgrade 13 loggers not yet deployed. Only one Bewick's Swan (BEWI11) was caught after the upgrade, but its logger provided excellent hourly or half-hourly data until moving out of the range of the mobile phone/GSM network in the Russian arctic in spring 2014. Although the other 7 loggers did not function as intended, 6 provided less frequent (6-hourly) data during spring migration and tracks for 5 of these birds gave some indication of their migration route on crossing the North Sea. The eighth tag ceased functioning shortly after being fitted, although the swan was subsequently identified feeding in fields near the Nene Washes.

In addition to upgrading the 13 remaining loggers, Ecotone therefore supplied five new loggers to replace the defective loggers fitted to swans in January 2014, and these were carried forward for deployment in winter 2014/15.

Of the eight Bewick's Swans fitted with loggers in winter 2013/14, four returned with functioning loggers a year later in winter 2014/15 (BEW04, BEW08, BEW09 and BEWI11; **Table 1**), and the loggers for two of these (BEWI09 and BEWI11) functioned for at least 2 years, through winter 2015/16 up to the time of the production of this report on 04/04/2016. The tags for BEWI04 and BEWI08, provided data up to summer 2015, with final GPS fix transmissions from the tags on 11/05/2015 (in Russia) and 23/08/15 (in Russia), respectively. Tracking data from tag BEWI11 is included in most analyses presented in this report because this fully-functioning tag provided hourly or sub-hourly GPS fixes during the migratory periods from 2014 to 2016 inclusive. Although tag BEWI09 continues to provide location data during the swan's migration in spring 2016, it has never been a fully functional since deployment in 2014 and continues to provide only coarse temporal resolution GPS data collected at 6-hourly intervals.

Table 1. Bewick's Swans fitted with GPS devices in winter 2013/14 that were still functional in 2015 or 2016.

Catch site	**Tag ID**	**Name**	**Catch date**	**Age[1]**	**Sex[2]**	**Metal ring**	**Plastic leg ring[3]**	**Weight (kg)**
West Fen, Cambridgeshire	BEWI04	Lech	07/02/14	A	M	W00451	BPA	8.0
Southery Fen, Norfolk	BEWI08	Andres	18/01/14	A	M	W00446	APU	6.8
	BEWI09	Hope		Y	F	W00447	APV	5.4
West Fen, Cambridgeshire	BEWI11	Eileen	13/02/14	Y?	F	ZZ7740	XAC	6.8

[1] Y = yearling/2nd winter bird; A = adult; [2] M = male; F = female; [3] Plastic leg rings are yellow on yearlings and white on adults.

4.1.2 Winter 2014/15

Fourteen of the upgraded or replacement collar-mounted solar UHF-GSM-GPS data loggers provided by Ecotone in March 2014 were fitted to adult or yearling swans in winter 2014/15: ten near WWT Welney on the Ouse Washes, Norfolk/Cambridgeshire, and four at WWT Slimbridge, Gloucestershire. The two catches on the Ouse Washes were again undertaken by experienced teams using cannon-nets on sugar beet fields; at Slimbridge the swans were caught in a "swan pipe" decoy baited with grain (**Figure 2**).

Figure 2. Bewick's Swans in the swan-pipe at Slimbridge, Gloucestershire.

A total of 24 Bewick's Swans were caught during the three catches and, where possible, adult females were selected for fitting with GPS devices to try to gain information on possible breeding attempts in the High Arctic during summer 2015 and to avoid tagging two members of the same pair or family. Swans not fitted with GPS devices were colour marked with coded leg rings. A summary of the swan catch sites and dates, collar device codes, leg ring codes and biometrics is given in **Table 2**.

Table 2. Bewick's Swan catch sites in 2014/15, with biometrics data, GPS device numbers and adopted swan names. The swans were named by WWT staff, by farmers at the catch sites and by schools in different parts of Europe (Germany, Poland, Estonia, Russia) near staging sites used by the swans during their 2015 spring migration. [1] A = adult, Y = yearling. [2] M = male, F = female.

Catch site	Catch date	Tag ID	Name	Age[1]	Sex[2]	Metal ring	Plastic leg ring	Weight (kg)
Four Scores Farm, Feltwell Anchor, Norfolk	17/12/14	BEWI01	Leo Beringstedt	Y	M	ZY2673	XAH	7.2
Slimbridge, Glos.	19/01/15	BEWI03	Maisie	A	F	W38905	UNN	6.4
		BEWI12	Butters	A	F	W38904	UNF	6.1
		BEWI13	Beabrooks	Y	M	W38903	XDA	5.9
		BEWI16	Emilia	A	F	W38901	UPB	6.2
Shell Farm, Prickwillow, near Littleport, Cambs.	21/01/15	BEWI17	Martina Two	A	F	W38908	ULI	5.7
		BEWI18	Wim Tijsen	A	F	W38909	UNB	6.65
		BEWI19	Daisy Two	A	F	W38911	UNS	6.25
		BEWI20	Zolotitsa	A	M	W38912	UNU	6.5
		BEWI21	Pola	A	F	W38913	UNT	6.2
		BEWI22	Charlotte	A	F	W38914	UNX	6.0
		BEWI23		A	F	W38915	UNV	6.5
		BEWI25	Julia Two	A	F	W38917	UPC	5.8
		BEWI26	Leho	A	F	W38916	UNZ	6.1

4.2 OBJECTIVE 2: Download data on Bewick's Swans movements while the swans are in Britain and during migration

The loggers fitted to the Bewick's Swans are capable of transmitting the GPS fixes (location data) live to the Ecotone website at a rate of 4 GPS fixes per GSM transmission in areas with good mobile phone network coverage. They can be re-programmed remotely (via the Ecotone web interface control panel) to record GPS location data at frequencies ranging from every 30 min to once every 24 h, as required depending on battery charge.

Despite the loggers deployed in 2014 not functioning as intended, location data for these tags were recorded c. 3–4 times a day and downloaded on a near-daily basis via the GSM. Along with the GPS fixes, data were also collected on whether or not the tag was moving (thus providing a crude measure, assuming that the tag was still on the bird, of whether the swan was alive and active), and on temperature and battery charge.

All 14 GPS devices fitted in winter 2014/15 functioned well from the time of catching, collecting GPS data for all of the feeding and roosting sites used up until the 2015 spring migration. Battery levels were managed interactively via the Ecotone web-panel and remote GSM contact with the devices so that they remained at 3.8–4.1 volts. This enabled us to set different GPS schedules for different tags for the swans' spring migration over the North Sea, and to obtain as much live GPS detail as possible (via the GSM link) on the individuals' flight-path in relation to proposed offshore wind farm areas, without compromising battery charge levels to the extent of losing the GSM link and risking tags having insufficient power to collect GPS data during the North Sea crossing. Where battery charge was an issue for some birds during low light levels of February, the devices were given reduced GPS schedules for the GSM component of the tags and the detailed GPS data were collected subsequently via the UHF data logger component of the tag (see Section 4.3 below). GPS data from the UHF logger are stored in a separate memory area of the tag, which can be downloaded in the field via a handheld Yagi antenna and base station from up to 1 km line-of-sight, assuming that it can be found in the field and that the tag remains functional. We therefore aimed to balance, on managing the settings via the web-panel, the likelihood of being able to obtain data stored via the UHF link against trying to obtain all data live over the GSM link when battery power is low.

Hourly GPS data were thus collected four times a day via the GSM, but with a temporal resolution of 30 min for some of the tags during different phases of the migration, and UHF-GPS data being collected at 15 or 30 minute intervals whenever possible. Overall, a total of 129,985 Bewick's Swan locations (GPS fixes) were recorded via the 22 loggers fitted in winters 2013/14 and 2014/15 up to the time of data analysis for this report (*i.e.* 6 March 2016), as described in Section 5.1.2 below.

4.3 OBJECTIVE 3: Travel to continental Europe for radio-GPS logger download of additional data

The UHF component of the tags permitted extra GPS data to be collected and downloaded in the field via a Yagi antenna, typically over 300–500m line-of-sight, although sometimes up to 1km or more if the landscape allows. GPS fixes can be obtained for download, via the UHF Yagi link, at rates of between one per minute (or even continuously) to one every four hours. Due to the low light levels expected in February, at the time of the Bewick's Swans' spring migration across the North Sea, the tags were mainly programmed to collect four GPS fixes per day for GSM transmission once per day. Additional GPS fixes were also recorded at 15 minute intervals however, for download via the UHF link once the swans had arrived in mainland Europe.

4.3.1 Flight height data recorded by the tags

Although the overall aim of the Bewick's Swan tracking study was to collect detailed *x,y* (latitude, longitude) positions of the swans at as fine a spatial and temporal resolution as possible in the North Sea region, improved functionality of the GPS devices in 2014/15 indicated that a proportion of the tags would retain enough battery power to collect *z* (flight height) information. Collecting 3-D GPS information uses more battery power than 2-D fixes, because the GPS unit has to be on for a longer time period in order to acquire enough satellites in view for good triangulation. For this reason, and because Ecotone tags have not previously been programmed to collect height data, a precautionary approach was adopted and only five of the tags (BEWI17, 18, 19, 21 and 22) were initially programmed (via their UHF component prior to deployment) to collect these height data in case the adjustment affected the overall operation of the tags. These tags were thus scheduled to record altitudinal data during the swans' migration across the North Sea in spring 2015.

Height data on this version of the tracking device cannot be provided by the GSM component of the tags and indeed it was realised during the course of the 2014/15 winter that the tags could not be programmed (via the Ecotone web-panel) to collect the height data remotely. Ecotone had thought that remote download of the height data might be possible with this version of the tag but, after many attempts, found that they could not yet do so. Thus, as with the additional GPS data, it was necessary to download the height data stored on the five logger devices via a UHF link with a Yagi and base station in the field during spring 2015, and on the swans' return to the wintering grounds in winter 2015/16. A sixth tag, for BEWI12, was programmed in the field to collect height data (once the additional GPS data had been safely downloaded during fieldwork in Denmark in spring 2015), to increase the number of birds for which flight height data were available from autumn 2015 onwards.

The tags were additionally programmed via the Ecotone Tracker software interface to transmit a "pinger" radio signal every 8 seconds, and to try to download their data every 1, 5 or 10 min if they got a "handshake" with the Ecotone base station and Yagi. The pinger has a much greater detection range than the data download distance and is often detectable over 1–2 km. The pinger only contains information about the tag identity and the time remaining until the next possibility for data download, but it is very useful for facilitating a full download of the data recorded on the logger. The tags can be programmed to come on or go off at certain times, via either the GSM or UHF link. They were set to be on 24 hours per day, and the pinger was activated to allow data download every five minutes, during attempts to download the additional location, speed and height data from the loggers.

Fieldwork in the UK and on the Continent to download the height data and the extra GPS fixes (*i.e.* those recorded at 15 minute intervals) via the UHF component of the tags was undertaken over three main periods:

March 2015 – Sweden, Denmark and Germany were visited to download data from tags BEWI01, 12 (this tag was then programmed to collect height data), 13, 16, 19 and 22. In Poland, Lech Iliszko of

Ecotone kindly agreed to help and downloaded some data from tags BEWI17 and 20, birds that were acting as though paired;

December 2015 – The Netherlands, Denmark and Germany were visited to download data from tags BEWI17, 21, 22 and 26. Tag BEWI20 was also targeted in Denmark but did not have enough battery power to allow for a download;

February 2016 – Data were downloaded at the Ouse Washes and at Slimbridge, UK, from tags BEWI11 and 26 and tags BEWI03 and 12, respectively.

Additional location data were thus recorded for 11 birds (BEWI01, 11, 12, 13, 16, 17, 19, 20, 21, 22 and 26) with flight height data obtained for swans BEWI12, 17, 19, 21 and 22.

4.3.2 Treatment of the flight height data recorded by the tags

The Ecotone tracking devices collect height data as height above the Geoid model of the Earth's surface (with the EGM96 geoid approximating to mean sea level). The UNAVCO Geoid Height Calculator at:

http://www.unavco.org/software/geodetic-utilities/geoid-height-calculator/geoid-height-calculator.html

calculates a geoid undulation at the WGS84 latitude and longitude of a point specified, to give an orthometric height above or below the geoid model at that point, with WGS84 being the most recent version of the world geodetic system. Latitudes, longitudes and height values obtained from the tags were therefore processed using the online calculator to determine flight height for locations where the birds were travelling at ≥ 5 knots (*i.e.* at ≥ 2.6 m/s) and assumed to be flying. It should be noted, however, that Lech Iliszko of Ecotone gave the specifications of the tags as follows:

"*In 'ECO' mode 80% of GPS positions are within 20 m range* (*i.e.* the setting of the Bewick's Swan tags, because they had only enough battery power for this)*, in 'MED' mode 90% of GPS positions are within 20 m range and in 'HIGH' mode 95% are within 20 m range. Usually, in good reception conditions, the GPS accuracy is much better and 95% positions are within 10 m range. The error of altitude readings, according to the GPS system specification is twice as large as the ground accuracy. Altitude is calculated as "ellipsoidal altitude" and it adds additional error which depends on local ellipsoid specification*". Hence the UNAVCO 'Geoid Height Calculator' correction applied above.

Given that the Bewick's tags were all on 'ECO' mode during the study, the height data should be treated as giving an *indication* as to the height "zone" within which the swans typically travel when over the land or over the sea, rather than as a precise measure of the altitude of flight.

4.4 OBJECTIVE 4: Incorporate wind farm locations and weather data along the Bewick's Swans' spring migration route into a GIS

All data handling operations and spatial analyses were carried out in the freeware package QGIS 2.8.6-Wien available at http://qgis.org/en/site (QGIS 2014. Quantum GIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org).

4.4.1 Incorporating Bewick's Swan tracks into the GIS

4.4.1.1 Treatment of the swan GPS fixes within the GIS

The Bewick's Swan location data were imported into a GIS and, within the GIS, line segments were created between each successive GPS location collected for a bird. These segments were given the attributes of the "to" locations used to create them, with the "from" location also being added as an attribute. The time difference and distance between each pair of consecutive locations was calculated and used to filter the swan track segments. Track segments where the time difference between the pair of GPS locations was ≤70 minutes were retained for further analysis of the swans' movements in relation to distances from wind farm footprints (offshore) or wind turbine locations (onshore). This time difference was chosen because it maximised the data available for analysis whilst reducing the likelihood of errors being introduced on assuming that the swans fly in a straight line between the pairs of GPS fixes. Line segments created between fixes recorded at 15 minute intervals clearly provide a better indication of true route taken by the swan than for one created between a pair of fixes six hours apart. Although most of the GPS data collected were recorded at 60 minute intervals or less, some slight aberrations in the timing of GPS fix acquisitions meant that a time window of 70 minutes or less could capture useful extra data describing swan movements whilst reducing the potential for spurious tracks. These data were saved in the projected ISN2004 Lambert Azimuthal Equal Area (LAEA) Europe EPSG:5638 coordinate system.

Where the track segments depicted the route taken by a swan from its UK wintering site, across the North Sea, to the point at which it makes landfall on the Continent, the segments were used to create pseudo-point positions within the database which were allocated latitude and longitude values, and the distance to the previous and subsequent GPS locations were then calculated. The distance from these pseudo-fixes to the actual GPS fixes were used to determine the times at which these significant "events" occurred, *i.e.* when the bird started its migration, started crossing the North Sea and completed the crossing of the North Sea. Pseudo-fixes were likewise calculated where detailed data were available on the swans' return migration across the North Sea in autumn, albeit fewer detailed tracks were available because of low battery charge in the tags at this time, and/or birds not returning to the UK to winter. The times were calculated either from a knowledge of the distance between GPS fixes and the time difference between them (*e.g.* for the half-hourly or hourly GSM-GPS fixes, the distance to a pseudo-fix was used to determine the proportion of the travel time to use) or, for the UHF-GPS fixes (which had a resolution down to 15 minutes in some cases), speed data were collected by the tags and so this could be used to calculate the time taken for a distance to be covered. In this way, additions or subtractions of time differences, ranging from 3–30 minutes, could be used to assign accurate times to these pseudo-fixes. The calculations assumed that the birds flew at a constant speed between GPS locations, and along a straight line (*i.e.* least cost) route, which seem reasonable assumptions for fixes up to one hour apart.

Standardised maps of the countries of the world were downloaded from www.thematicmapping.org (TM_WORLD_BORDERS-0.1 shapefile, compiled by Bjorn Sandvik from a dataset derived by Schuyler Erle from public domain sources), and a spatially congruous coverage of global ocean areas from www.marineregions.org/downloads.php. A fine-resolution 250m gridded dataset of height values for the land area of northwest Europe was obtained from http://srtm.csi.cgiar.org (see Jarvis *et al*. 2008). This height data grid has been re-sampled by CIAT to a 250m grid with data holes filled by interpolation – for a region up to 60 degrees latitude north and south of the equator – from the NASA Shuttle Radar Topographic Mission (SRTM) which provides 90m resolution data. Hence these data did not completely cover some of the GPS fixes in the northern Russia tundra areas. All datasets were available in WGS84 format and were clipped within the GIS to the NW European area of interest covered by the international flyway of the swans. They were then saved in re-projected ISN2004 Lambert Azimuthal Equal Area (LAEA) Europe EPSG:5638 format, so that distance calculations and operations within the GIS could be conducted in metres.

Within the GIS, the swan GPS data points were intersected with the ocean area, country borders and land height datasets, with the attributes at these locations transferred to the GPS data points of swan locations. At the coastal fringes, where there was some limited overlap between the ocean area and land borders datasets, the ocean areas dataset was given priority. For 165 of the GPS data points the locations fell within "sliver polygons" between the two datasets, so these points were classified manually as sea area or country, on referring to BING aerial imagery.

4.4.2 Incorporating weather data into the GIS

4.4.2.1 UK Met Office weather station data

In order to analyse the conditions under which the birds chose to start their migrations from UK wintering sites (Slimbridge or the Ouse Washes) and continue them across the North Sea, automated data download was put in place for a suite of nine Met Office weather stations running in an east-to-west band through southern England. The station at Filton was ~28km from the Slimbridge wintering site, and that at Marham ~20km from the departure points of the Ouse Washes birds. The main UK coast departure or arrival points for the tracked swans were within 20–60 km of either the Weybourne or Wattisham stations. The weather stations provided hourly readings for wind direction (as 45 degree compass divisions), wind speed (miles h^{-1}), visibility (km), temperature (˚C), pressure (hPA) and the change in pressure (hPa/s^{-1}), as well as a general weather observation regarding cloudiness, rain and mist/fog.

4.4.2.2 Treatment of the weather data in the GIS

The distance to the nearest weather station was calculated for the entire set of swan GPS fixes in the UK and up to 50km from the coast. The identification numbers of the closest weather stations were then added as attributes to the swan GPS fixes in the GIS. A variable was then created whereby all of the GPS times (in hh:mm:ss format) for the swan fixes within the UK and its coastal waters were rounded up or down to the nearest hour. The hourly weather variables from the nearest weather station were then added within the GIS as attributes to the swan GPS data points for this derived date and time variable.

4.4.3 Incorporating wind farm data into the GIS

4.4.3.1 Offshore wind farm data

The main aim of the current project was to understand the possible cumulative offshore wind farm collision risk to which migrating Bewick's Swans might be exposed within the North Sea area and more widely, during the swans' migration to and from internationally important wintering sites for the species in the UK. Offshore wind farm footprint and attribute data for the North Sea and Kattegat areas therefore were downloaded as a shapefile (file last updated 21/07/2015) from the OSPAR (Oslo-Paris convention for the Protection of the Marine Environment of the North-East Atlantic) website www.ospar.org in March 2016.

The offshore wind farm location data were in WGS84 format and were saved in the projected ISN2004 Lambert Azimuthal Equal Area (LAEA) Europe EPSG:5638 coordinate system within the GIS. The polygon areas were then intersected with the selected finer temporal resolution (≤70 minute) track segments, so that the attributes of each wind farm footprint crossed by each swan track could be added to the relevant line segments. If a segment crossed more than one wind farm footprint, then the attributes of each wind farm would be added to the segment's attribute table.

4.4.3.2 Onshore wind farm data

An additional aim of the current study was to assess the possible extra cumulative risk to Bewick's Swans posed by onshore wind farms across NW Europe. A different approach to the acquisition of wind turbine or wind farm footprint data had to be taken depending on the country involved. Initially some useful contacts were established through email although some, after lengthy interchanges and effort by those in the relevant countries, resulted in dead ends. This was especially the case for Germany where Data Protection issues eventually meant that no organisation was able to provide detailed location data for onshore sites. This process was time-consuming, so wind farm or turbine data were not sought for countries thought likely to have relatively minor wind turbine infrastructure, and/or those where tagged individuals did not occur or were present for a limited period. These countries included Belarus, Belgium, Finland, France, Lithuania, Poland, Russia and Sweden. The countries for which onshore turbine data were obtained and/or digitised included Denmark, Estonia, Germany, Latvia, the Netherlands and the United Kingdom.

For Denmark, the individual positions of existing operational turbines were downloaded from http://www.ens.dk/en/info/facts-figures/energy-statistics-indicators-energy-efficiency/overview-energy-sector/register updated to August 2015 (link to website kindly provide by Ib Krag Petersen). Some inspection of the data in relation to current BING imagery within the GIS suggested the data were consistently accurate even though a disclaimer is carried on the website. The attribute data associated with the point locations included turbine height, rotor diameter, turbine make and wattage rating.

For Estonia, the individual positions of the existing operational turbines were kindly provided by Leho Luigujõe, having been digitised by the Institute of Ecology and Earth Sciences at the University of Tartu. These data were inspected in relation to BING imagery and again appeared to be accurate. The attribute data associated with the point locations included turbine height, rotor diameter, turbine make and wattage rating.

For Germany, a website was discovered at www.thewindpower.net, where turbine data for the whole of Europe are collated. Michaël Pierrot at the 'Wind Power' site kindly extracted and provided the German data for free including attributes for turbine height, manufacturer, wattage rating, number of turbines, commissioning date and status. The point data represented the location of wind farm areas rather than individual turbines. No guarantee as to the accuracy of the data was given. Preliminary inspection of these data in relation to the current BING imagery soon revealed that the points often had no discernible turbines in association with them and that they were often at the centre of a town or village and so perhaps represented the place name of a wind farm that was nearby. Occasionally a point would hit the centre of a larger wind farm, but often a wind farm could not be found within a 2km or more radius of the point and so the data were deemed too inconsistent to be of use in the current study. Therefore a secondary method was developed whereby the finer temporal resolution track segments of ≤70 minutes extrapolated between pairs of GPS fixes for each swan were "buffered" within the GIS to 2.5km either side of the line. These buffered track segments were then used to examine the underlying BING imagery at a 1:10,000 scale, with the imagery examined by eye for the characteristic shadow cast by a turbine and/or its white outline (the BING aerial imagery is typically taken at an angle to the turbines rather than directly overhead) whilst panning along the track segment. Where the darker line of the shadow met the whiter line of the turbine structure, a point was digitised and given an identification number in the GIS. In this way all turbines for these specifically selected track segments could be digitised up to ~2–2.5km either side of the extrapolated route of the tracked swans. Where turbines at the edge of a wind farm were within the 2.5km buffer area, all turbines within that wind farm were digitised.

For Latvia, wind farms areas were kindly provided as a polygon shapefile by Roland Lebuss with polygon attributes including the number of turbines, turbine height, rotor diameter and wattage rating. He suggested the file was likely to be incomplete because of the great difficulty in getting the information about sites from local and national authorities. Where turbines could be seen on the BING imagery at these wind farm locations, these were digitised within the GIS under the current project.

For the Netherlands, data on individual turbine locations were kindly provided by Steven Velthuijsen of http://www.windstats.nl/ (with thanks to Abel Gyimesi for making enquiries on our behalf). The attribute data associated with the point locations included turbine height, rotor diameter, turbine make and wattage rating. Some inspection of the data in relation to current BING imagery within the GIS suggested the data were consistently accurate.

For the UK, data were kindly provided on wind farm locations by Seb Rae as an export file from http://www.renewableuk.com/en/renewable-energy/wind-energy/uk-wind-energy-database/index.cfm though again no guarantee of data accuracy was given. Attribute information included number of turbines, wattage rating and stage of development. On inspection of the data in relation to BING imagery for sites classed as operational or under construction, it was again apparent that wind farms were not being depicted consistently and that there were often points where no wind turbine or wind farm could be discerned. It was noted how there were occasions in the raw data where the x,y coordinates were given as Lat/Long values or as UK OS grid references with no distinction between the two and sometimes it was not clear which system was being used. This will have resulted in large errors in the plotting of some sites and it would have taken too much time to try to check each site against any mention of its true location on the internet. This dataset therefore was abandoned and turbine locations along the swans' migration routes were digitised within the GIS, as described above for the wind farms in Germany.

In preparing the German and UK datasets, only turbines within ~2.5km of the track segments flown by swans had been digitised. To be consistent with these data, for Denmark, Estonia, Latvia and the Netherlands, only turbines (classed as operational or under construction in those datasets) within a 2.5km buffer either side of the selected swan track segments were selected and "clipped" from the total spatial layer within the GIS. Although some of the data sets gave an indication of the name as to which wind farm a turbine belonged, this was inconsistent between countries (and non-existent for Germany and the UK). In order to be able to identify a turbine to a wind farm area, each turbine point in the GIS therefore was buffered to a 1km radius. If this circular buffered point was now joined to its neighbours (*i.e.* ≤2km away), all of the turbine points within this whole shape were then selected and named according to the nearest town or village, which was usually within 20km. As with the German and UK data, any turbines falling outside the 2.5km buffer but still within the range of the buffered turbine points were also retained. Although this method of aggregating turbines into wind farm polygons provided a somewhat arbitrary naming of the wind farm sites, it was thought to be a worthwhile procedure for identifying any turbines and sites overflown repeatedly by the same or different swans over time.

Rotor width data were not available for the digitised turbines in Germany and the UK, so a tracked swan was said to have crossed or "encountered" that turbine if the detailed (≤70 minute) track segment was within 80m of that turbine location. The 80m radius was selected because the maximum rotor radius was up to ~80m in some other countries, and because the aim was to keep the definition quite tight and not exaggerate unduly the number of turbines that the swans might be encountering on a daily to yearly basis. For example, there might be many tens of turbines within 1km of a track flown by a swan, but only one or two that were quite close to the actual track flown by the swan. Distances from the turbines to each detailed track segment therefore were calculated within the GIS, and the attributes of those turbines ≤80m from the swans' tracks (*i.e.* the identification numbers and wind farm names) were added as attributes to the relevant track segments.

5. RESULTS

5.1 Objective 5: Analyse and report on the effectiveness of the radio-GPS-GSM logger technology, and on Bewick's Swan movements in relation to wind farm sites

5.1.1 Fate of the GPS tags

During early spring 2015, BEWI19 and BEWI23 started their migration synchronously from the Ouse Washes on 17/02/15 and travelled 80km east within one hour. Both then stopped migrating and settled on fields near Hornsea Mere, where they roosted and fed for five days before BEWI23 was predated by a fox on 23/02/2015. The GPS device was recovered in August 2015 at the site of a fox den, and the scattered remains of other swans were also found in the same field. GPS fixes obtained from the tag suggested that the swan was predated at night on a field roost pool, rather than being scavenged as a carcass. BEWI19 continued her migration on 26/02/15, and subsequently returned to the Ouse Washes in winter 2015/16.

The tag on swan BEWI01 stopped moving during migration through Russia on 16/05/15 and the swan is presumed to have died. BEWI16 was in Gotland, Sweden, when her tag stopped moving on 08/06/15; swan remains and the tag were later recovered from the area.

Eleven of the 14 Bewick's Swans fitted with GPS/GSM loggers in winter 2014/15 are known to have migrated to the Russian arctic and all returned to within the range of the mobile phone network (summer location data downloaded) in autumn 2015. The loggers for three of these swans (BEWI13, 18 and 25) stopped working rather suddenly however, when they were migrating strongly through Russia (*i.e.* on schedule, with long distances covered to known staging areas) during October 2015, with BEWI13's tag ceasing to function on 01/10/15, BEWI18 on 09/10/15 in Russia and BEWI25 on 17/10/15.

Eight of the 2014/15 batch of tags therefore were still functioning during winter 2015/16, along with two tags fitted to swans in winter 2013/14: BEWI09 (partial location data) and BEWI11 (full location data). Immediately prior to the start of the spring migration period in 2016, the tag for swan BEWI17 (who had been wintering in the Dutch/German border area) became stationary on 06/02/16 and then went offline with low power. Zooming onto its location using BING imagery clearly showed that the tag was directly beneath a major powerline and pylons that the swan had crossed during the morning. Inspection of the area in Germany a few days later revealed swan remains (feathers), but unfortunately the main carcass and the tag had been taken away, probably by a fox.

By spring 2016, six swans with functional tags had returned to winter in the UK (four others remained on the Continent including BEWI09, BEWI17, BEWI21 and BEWI22), with two in the Slimbridge area (BEWI03 and BEWI12) and four on the Ouse Washes (BEWI11, BEWI19, BEWI20 and BEWI26). All six birds made their eastward migration across the North Sea back to the Continent between 18/02/16 and 21/03/16, a similar period to that recorded in 2015. Note that although the later migrations of swans BEWI11 and BEWI26 in 2016 (crossing the North Sea on 17/03/16 and 21/03/16, respectively) are used to describe the migration window, they are not included in the bulk of the analyses because their movements occurred after the final database had been prepared and analysis was underway.

5.1.2 Number of GPS fixes collected by tags that were functional in 2015 and 2016

Up to 07/03/16, a total of 129,985 GPS fixes had been obtained from the 18 GPS collar-mounted devices recording data in winter 2014/15 onwards, including the 2014 data for the four swans originally fitted with tags in winter 2013/14 that returned in 2014/15 (**Table 3**). For the set of 15 fully functional tags (*i.e.* those fitted in winter 2014/15 plus BEWI11), the mean number of fixes (±S.D.) was 8,294 (±5,808) with a minimum of 428 (for BEWI23, which was predated by a fox before reaching North Sea coast in spring 2015) and a maximum of 19,669 (BEWI03). For tags on the eight swans that completed at least one full return migration, the mean number of fixes (±S.D.) was 11,740 (±5,729) with a minimum of 4,201 (BEWI20) and a maximum of 19,669 (BEWI03). The difference in the number of fixes collected by each tag can be attributed to variation in the battery performance of each tag. For instance, BEWI20 could not be set to record as high a rate of GPS fixes as often as the other tags. Moreover, it proved more straightforward to download the UHF data from some of the tags than from others, with swan BEWI20 repeatedly managing to evade UHF download opportunities (once in the UK and three times in Europe), whereas BEWI03 resided on the pond in front of the Swan Observatory at WWT Slimbridge and so all of her location data could be downloaded quite easily.

GPS fixes were recorded not only during the spring and autumn migratory flights, but also whilst the birds were at their spring and autumn staging sites, and on the breeding and moulting grounds in the Russian high arctic (**Figure 3**). Yet although much valuable information was gained on the swans' distribution and movements during the summer months, even with the updated tags it was apparent that there remains an issue with the memory capacity for tags that had stored UHF-GPS data, because locations for the April–May period had been lost for many of them by the time data were downloaded in December.

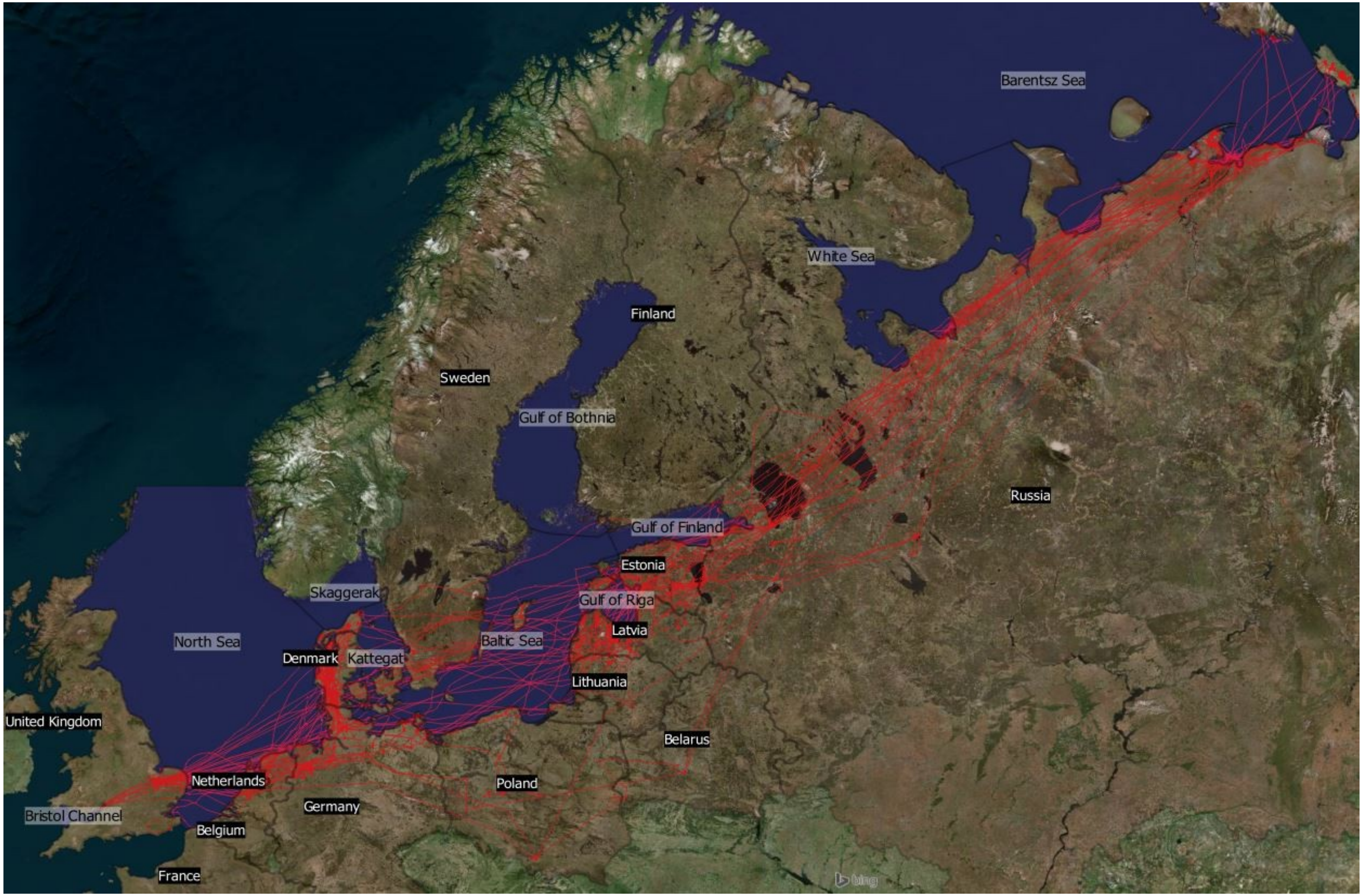

Figure 3. Bewick's Swans' migration route (eastward and westward migrations = red lines, extrapolated between GPS fixes) for the 18 swans tracked between January 2014 and early March 2016, showing the sea areas and countries referred to in this report.

Table 3. Summary of the total number of GPS fixes (N_GPS) collected by 18 tagged Bewick's Swans each year, from January 2014 to March 2016, and the number of tracking days over which they were functional (N_days) between the earliest (Min. date) and latest dates (Max. date) each year. Shading denotes tags deployed in winter 2013/14 that remained functional into winter 2014/15, though BEWI04 and 08 did not function in the current (winter 2015/16) reporting period.

Tag code	**2014**				**2015**				**2016**				**Total**
	Min. date	**Max. date**	**N_GPS**	**N_days**	**Min. date**	**Max. date**	**N_GPS**	**N_days**	**Min. date**	**Max. date**	**N_GPS**	**N_days**	
BEWI01[1]	17/12	31/12	109	15	01/01	27/05	4497	147					**4606**
BEWI03					19/01	31/12	18530	347	01/01	07/03	1139	67	**19669**
BEWI04	07/02	31/12	1130	231	01/01	11/05	574	109					**1704**
BEWI08	20/01	26/12	1115	261	14/02	23/08	355	74					**1470**
BEWI09	18/01	31/12	942	241	01/01	31/12	1142	287	01/01	06/03	311	63	**2395**
BEWI11	13/02	31/12	6360	304	01/01	31/12	4533	360	01/01	07/03	1185	67	**12078**
BEWI12					13/01	31/12	17414	351	01/01	06/03	911	66	**18325**
BEWI13[2]					13/01	01/10	5866	204					**5866**
BEWI16[3]					13/01	10/06	5429	148					**5429**
BEWI17[4]					21/01	31/12	8093	307	01/01	09/02	247	40	**8340**
BEWI18[5]					21/01	09/10	3161	121					**3161**
BEWI19					21/01	31/12	4670	296	01/01	06/03	613	66	**5283**
BEWI20					21/01	31/12	3846	258	10/01	06/03	355	57	**4201**
BEWI21					21/01	31/12	7777	315	01/01	07/03	553	67	**8330**
BEWI22					21/01	31/12	10096	270	01/01	06/03	684	66	**10780**
BEWI23[6]					21/01	23/02	428	34					**428**
BEWI25[7]					21/01	17/10	2668	192					**2668**
BEWI26					21/01	31/12	12672	314	01/01	07/03	2580	67	**15252**
Total			**9656**	**1052**			**111751**	**4134**			**8578**	**626**	**129985**

[1] BEWI01 was tagged on 17/12/2014 and migrated as far as Lake Sheksninskoye, west of St. Petersburg, Russia, where it probably died on 16/05/15 as the tag position remained static after that time, the battery charge declined and the activity meter fell to zero;
[2] BEWI13 stopped transmitting during autumn migration on 01/10/15, the last GPS fix being just west of St. Petersburg;
[3] BEWI16 migrated to the island of Gotland, Sweden, where it spent the second half of May before dying on 08/06/15. The GPS device was recovered and the remains of a swan were found at the location;
[4] BEWI17 collided with powerlines in Germany and died on 06/02/16;
[5] BEWI18 stopped transmitting during autumn migration on 09/10/15, the last GPS fix being close to Archangelsk, Russia;
[6] BEWI23 started its migration from the Ouse Washes on 17/02/15 and travelled 80km east within one hour. It then stopped migrating and settled at a roost pool on fields near Hornsea Mere and fed in that area for five days before being predated by a fox. The GPS device was recovered in August 2015 at the site of a fox den, and the scattered remains of other swans were also found in the same field. GPS fixes obtained from the tag suggested the swan was predated at night on a field roost pool, rather than being scavenged as a carcass.
[7] BEWI25 stopped transmitting during autumn migration on 17/10/15, the last GPS fix being just south of St. Petersburg.

5.2 Bewick's Swan spring migratory dates, times and conditions

5.2.1 On leaving the wintering sites

Fourteen tagged Bewick's Swans tracked on eastward migration in spring 2015 departed from their UK wintering sites on dates ranging from 09/02/15 ("pair" BEWI17/20) to 19/03/15 (BEWI18) (**Table 4, Figure 4**). Four of these birds were acting as two "pairs", however, so it seems that there were 12 swan "units" migrating independently from the UK in spring 2015. The birds set off on migration during periods of relatively high (998–1,034 hPA) and typically rising (for 10 of the 12 migrating units) atmospheric pressure, mostly under clear conditions with little cloud on days of good (≥ 5km) visibility, although haze reduced the visibility for two of the migrating birds. The "pair" of BEWI17/20 left the Ouse Washes under apparently foggy conditions of very poor visibility, though fog can be localised and might only have been at ground level. No migrations commenced in rainy conditions. Nine of the 12 independent departures on eastward migration were backed by a south-westerly or westerly wind, with two occurring during southerlies and one in northerly winds. All of the 2015 eastward migrations were initiated under conditions of light to moderate breeze, however, of 2–17 mph (2–4 on the Beaufort scale).

Timing of migration was clustered at the start and end of the day, from 06:43-09:49h and from 18:15-00:24h, in both summer and autumn (**Figure 4**). It was considered that all migrations from the wintering sites as far as the North Sea coast were conducted under reasonable-to-good light conditions, based on an assessment of the prevailing cloud conditions and availability of sunlight or, if the sun was more than 6 degrees below the horizon (*i.e.* after civil twilight, where civil twilight is *"from sunset until the sun reaches 6 degrees below the horizon in the evening, and from when the sun reaches 6 degrees below the horizon to sunrise in the morning*"), then the availability of moonlight was taken into account. A moon above the horizon with > 40% of its disk illuminated was considered to be a reasonable source of light. Under these definitions only one migrating unit (BEWI19/23) was considered to have migrated under conditions of poor visibility and this may be the reason why BEWI19/23 settled on fields at Thurne, near Hornsea Mere, and did not migrate as far as the North Sea coast.

Data on the onset of the 2016 spring migration were available for three of the tagged swans that wintered in the UK in 2015/16 (swans BEWI03, BEWI12 and BEWI19), which left their wintering sites heading east in the period from 18/02/16 to 02/03/16. All three migrated under relatively high (1,004–1,017 hPA) and rising atmospheric pressure, mostly under fairly clear conditions with little cloud (except that BEWI12 migrated in the rain), on days of good (≥ 10km) visibility. Wind conditions at the onset of migration were more variable than in 2015, with the three swans migrating in northerlies, westerlies and south-easterly winds respectively, but again wind speeds were low at <10mph so were only light-to-gentle breezes (2–3 on the Beaufort scale). Only BEWI12 can be considered to have migrated, at least as far as the North Sea coast, under conditions of very poor visibility, having set off from Slimbridge in the rain at 21:22h with the sun at -32 degrees below the horizon (and increasingly so as the migration continued overnight) and the moon at -46 degrees below the horizon.

Detailed data were only available for one bird (BEWI11) in 2014, for assessing the timing and conditions under which the bird migrated. This bird migrated under the same general conditions as described for the 2015 cohort above (**Table 4**).

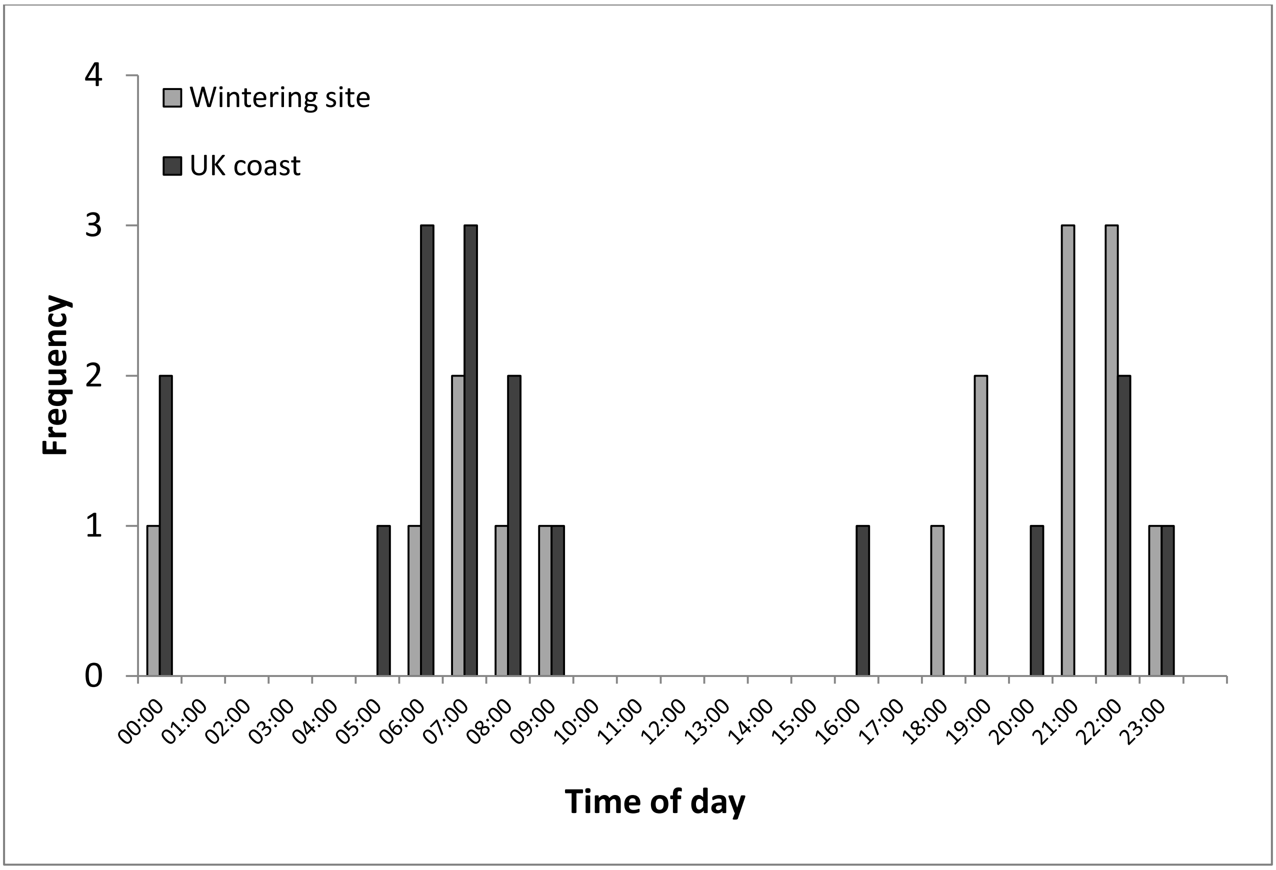

Figure 4. Number of tagged Bewick's Swans that embarked on migration from UK wintering sites (Slimbridge or the Ouse Washes) in each hour of the day, and the time at which the birds crossed the UK coastline heading east across the North Sea, in 2014–2016. The single case of a swan (BEWI26) crossing the UK coast at 16:30h in autumn 2015 may represent a navigational reorientation movement, rather than a true migration, because the bird was in the UK for only ~34 hours (albeit at the Dungeness SPA, a site of national importance for Bewick's Swans) before returning to the Netherlands.

Table 4. Key weather and light conditions during eastward migration for 15 swans on leaving UK wintering sites and crossing the North Sea in 2014-2016. Tracking data were only considered where GPS fixes were ≤ 1h apart. Stages completed under inclement conditions or poor visibility (*i.e.* sun and moon both below the horizon with poor weather conditions) are shaded grey.

Variables: * 'Site' codes; 'SLM' = Slimbridge area, Gloucester and 'OW' = Ouse Washes area, Norfolk/Cambridgeshire; ** 'Sun or moon altitude' is in degrees above or below the horizon and 'Moon disk' refers to

		Start of migration*			Light level start of migration **			Weather conditions start of migration***						Depart UK coast		Light level depart UK coast			Weather conditions depart UK coast						Arrival Europe****			Light level arrival Europe			North Sea crossing		
Year	Tag (BEWI)	Date (dd/mm)	Time (hh:mm GMT)	Site	Sun altitude (˚)	Moon altitude (˚)	Moon disk (%)	Wind direction	Wind speed (mph)	Visibility (km)	Pressure (hPA)	Change (PA/s)	Observation	Date (dd/mm)	Time (hh:mm GMT)	Sun altitude (˚)	Moon altitude (˚)	Moon disk (%)	Wind direction	Wind speed (mph)	Visibility (km)	Pressure (hPA)	Change (PA/s)	Observation	Date (dd/mm)	Time (hh:mm GMT)	Country (code)	Sun altitude (˚)	Moon altitude (˚)	Moon disk (%)	Route (km)	Time (hr)	Mean speed (kph)
2015	01	27/02	00:24	OW	-46	20	63	W	5	15	1015	↑	clear	27/02	06:08[1]	-6	-19	66	SW	10	17	1016	↑	clear	27/02	08:22	NL	14	-18	67	181	2.2	80.4
2015	03	02/03	18:15	SLM	-5	29	92	SW	13	35	1014	↑	clear	02/03	20:47	-29	47	93	SW	15	50	1011	↑	clear	02/03	22:57	NL	-42	47	93	245	2.2	112.8
2016	03	24/02	23:00	SLM	-44	27	96	N	1	35	1018	↑	pc	02/03	07:36	8	17	47	SW	15	30	995	↓	mc	02/03	10:52	NL	28	-5	45	331	3.3	101.5
2014	11	22/02	07:00	OW	-1	17	55	SW	6	20	1004	↑	pc	22/02	08:00	8	12	54	SW	6	20	1005	↑	pc	22/02	11:00	NL	26	-12	53	306	3.0	102.2
2015	12	02/03	22:26	SLM	-39	51	93	SW	14	40	1015	↑	pc	03/03	00:59	-43	37	93	SW	17	50	1012	↑	clear	03/03	02:35	NL	-34	22	94	196	1.6	122.4
2016	12	02/03	21:22	SLM	-32	-46	41	W	9	45	1004	↑	rain	03/03	07:29	7	19	37	NW	15	20	1003	↑	rain	03/03	10:16	NL	28	7	36	180	2.8	64.5
2015	13	24/02	21:58	SLM	-38	26	42	SW	9	17	1014	↑	mc	25/02	06:07[2]	-7	-22	45	SW	6	9	1013	↓	rain	25/02	08:41	NL	16	-9	46	225	2.7	83.9
2015	16	03/03	19:29	SLM	-16	31	97	SW	17	40	1019	↑	pc	03/03	23:09	-43	47	97	SW	21	50	1017	↑	mc	04/03	06:25[3]	DK	1	-9	98	527	5.8	91.6
2015	17[a]	09/02	08:06	OW	4	9	77	SW	2	0.4	1034	↓	fog	09/02	09:44	16	-6	76	SW	4	2.5	1034	↑	mist	09/02	15:15	NL	11	-46	74	177	5.5	32.1
2015	18	19/03	09:49	OW	30	30	2	N	11	5	1034	↑	hazy	21/03	05:48[4]	-2	-6	1	N	22	13	1022	↑	rain	21/03	09:15	NL	29	26	1	183	3.7	49.6
2015	19[b]	17/02	19:32	OW	-22	-34	2	S	5	15	1040	↑	pc	26/02	06:54	0	-20	56	SW	18	6	1009	↓	hazy	26/02	15:33	DK	9	40	60	584	8.6	67.5
2016	19	18/02	21:33	OW	-38	54	85	SE	5	10	1017	↑	clear	18/02	22:42	-46	50	85	SW	11	50	1016	↑	pc	19/02	01:32	NL	-45	26	86	197	2.8	69.7
2015	20[a]	09/02	08:06	OW	4	9	77	SW	2	0.4	1034	↓	fog	09/02	09:44	16	-6	76	SW	4	2.5	1034	↑	mist	09/02	15:15	NL	11	-46	74	177	5.5	32.1
2015	21	17/02	07:22	OW	1	10	4	W	9	20	1031	↑	clear	17/02	08:35	11	18	4	NW	8	25	1034	↑	clear	17/02	10:37	NL	24	23	4	155	2.0	75.9
2015	22	21/02	06:43	OW	-4	-12	8	W	7	9	998	↑	hazy	21/02	07:53	7	-1	8	W	10	8	997	↑	hazy	21/02	10:22	NL	24	22	9	195	2.5	78.9
2015	23[b]	17/02	19:32	OW	-22	-34	2	S	5	15	1040	↑	pc	n.a.											n.a.								
2015	25	01/03	22:54	OW	-42	48	87	W	13	20	998	↑	pc	02/03	00:07	-45	40	88	SW	19	35	996	↑	clear	02/03	01:44	NL	-39	24	88	201	1.6	124.4
2015	26	07/03	22:12	OW	-37	18	96	S	12	17	1020	↓	clear	07/03	22:56	-40	23	96	SW	20	29	1019	↓	clear	08/03	00:33	NL	-41	31	96	208	1.6	129.0
2015	26	n.a.												31/10[5]	16:31	-1	-20	78	E	3	1.8	1024	↑	mist	31/10	17:50	FR	-13	-15	77	65	1.3	49.2

the percentage of the moon's surface that was lit; *** 'Change' is the relative change in air pressure over time where '↑' = an increasing trend and '↓' a decrease; 'Observations' include 'pc' = partly cloudy and 'mc' mostly cloudy; **** 'Country' code is given as 'NL' = Netherlands, 'DK' = Denmark and 'FR' = France.

Tag associations: [a] = BEWI17 and BEWI20 were either part of a pair/sibling or other form of close association and are thus not independent observations; [b] = BEWI19 and BEWI23 were either part of a pair/sibling or other form of close association and are thus not independent observations; BEWI23 was predated at a stopover site between the Ouse Washes and the coast.

Data: [1] = prior to this time BEWI01 loafed for ~4.5 hours on the North Sea ~2km from the UK coast (not included in the average speed calculation); [2] = prior to this time BEWI13 loafed for ~5 hours on the North Sea ~3km from the UK coast (not included in the average speed calculation); [3] = prior to this time BEWI16 loafed for ~1.5 hours on the North Sea ~40km from the DK coast (not included in the average speed calculation); [4] = prior to this time BEWI18 loafed for ~4 hours on the North Sea ~9km from the UK coast (not included in the average speed calculation); [5] = BEWI26 made the crossing from the Netherlands to the UK twice during winter 2015/16, with the first visit on 30/10/15 only lasting 34 hours before the bird returned to France and then the Netherlands; this should possibly be recognised as a re-orientation movement rather than as a true migratory movement between staging sites where birds typically stay for many weeks.

5.2.2 On crossing the North Sea in spring

The 12 independently migrating swan units tracked on eastward migration in spring 2015 crossed the North Sea on dates ranging from 09/02/15 (“pair” BEWI17/20) to 21/03/15 (BEWI18). In 2016, the dates were 18/02/16 (BEWI19) to 03/03/16 (BEWI12) for the three birds for which data were available for this report (with BEWI11 and BEWI26 migrating a little later, on 17/03/16 and 21/03/16 respectively, after analysis and report production had commenced). In 2014 detailed data were only available for one bird, BEWI11, with which to assess the timing and conditions under which the bird migrated. This bird migrated under the same general conditions as described for the 2015 cohort above (**Table 4**).

In 2015 the birds left the UK coastline at two main times of day: during the evening between 20:47–00:59h (5 individuals) and in early morning between 05:48–09:44h (8 individuals). In 2016 the three birds migrated at 07:29h, 07:36h and at 22:42h, *i.e.* at times similar to those recorded for the 2015 cohort (**Figure 4**). Those leaving the UK coast during early morning would arrive at the East Anglia ONE footprint in daylight conditions. The remaining swans, which started their migration after sunset, typically migrated under moonlight. Only BEWI13 and BEWI18 appeared to undertake at least the first part of their flight across the North Sea in conditions of poor visibility, with both birds departing from the UK when the sun and moon were below the horizon (albeit during civil twilight), probably in rainy conditions. Conditions would however have improved rapidly as the sun rose and if the rain was localised to the Met Office station area.

Weather conditions during 2015 whilst the birds continued their migrations across the North Sea were mostly good, with relatively high (996–1,034 hPA) and rising (for 9 of the 12 migrating units) atmospheric pressure under generally clear conditions with good (≥6km) visibility, although two birds migrated in the rain and two in misty conditions with visibility of 2.5km. The three birds tracked in spring 2016 similarly departed from the UK during relatively high (995–1,016 hPA) and rising (2 of 3) atmospheric pressure periods, but under cloudy or rainy conditions. Most swans started their spring migration across the North Sea on following (“tail”) winds from the southwest in 2015 (ten of the migrating units), with two birds crossing when winds had a more northerly component, though all were light to moderate winds (4–22mph). In 2016 winds were again moderate (11–15mph), from the southwest in two cases, and from the northwest for one bird.

The routes taken across the North Sea for birds with detailed tracking data from 2014–2016 ranged from 155–584 km, the longer distances being for birds that migrated direct to Denmark (12%) rather than for those heading to the Netherlands (88%; **Table 4**). Journey times across the North Sea ranged from 1.6–8.6h (not including any periods spent loafing on the North Sea; four birds paused there from ~1.5–5h). Thus average ground speeds for the crossing ranged from 32–122kph (mean ± S.D. = 86.7 ± 27.5kph, n= 16), mainly depending on whether or not there was a following wind. The short crossing distances and times to the Netherlands meant that sample sizes were only ever going to be small for flight height data assessments over the North Sea. The data for BEWI26 is not included in the above assessment, because its eastward journey from the UK to France and then the Netherlands in October 2015 is not considered a typical migratory movement, but the details of its departure from the UK at this time are presented in **Table 4** for completeness.

The nearer edge of the Round 3 East Anglia ONE offshore wind farm footprint, considering the different UK exit points used by the swans along the North Sea coast, is generally reached between 15–35km offshore and extends to 65–105km before the furthest edge of the footprint area is reached. Most swans migrating east in spring therefore will arrive at western edge of the wind farm area ~10–25 minutes after leaving the UK, and then take ~35–50 minutes to pass across it.

Table 5. Key weather and light availability conditions during westward migration to the UK for two Bewick's swans that departed the Netherlands (NL) in winter during 2015 and 2016. Swan tracking data were considered only where the GPS fixes were ≤ 1hour apart. Data for the departure and arrival point on the North Sea coast were calculated from knowledge of the distance covered between GPS fixes for GSM-GPS data or from the speed reading taken by the tags for UHF-GPS data.

		Departure NL coast		**Light level at NL coast***			**Arrival UK coast**		**Light level at UK coast**			**Weather conditions UK coast****						**North Sea crossing**		
Year	**Tag (BEWI)**	**Date (dd/mm)**	**Time (hh:mm GMT)**	**Sun altitude (˚)**	**Moon altitude (˚)**	**Moon disk (%)**	**Date)dd/mm)**	**Time (hh:mm GMT)**	**Sun altitude (˚)**	**Moon altitude (˚)**	**Moon disk (%)**	**Wind direction**	**Wind speed (mph)**	**Visibility (km)**	**Pressure (hPA)**	**Change (PA/s)**	**Observation**	**Route (km)**	**Time (hr)**	**Mean speed (kph)**
2015	03	30/10	06:33	-1	27	89	30/10	12:22	23	-15	88	S	18	45	1018	↑	rain	261	5.8	45.0
2015	26	29/10	19:21	-28	10	92	30/10	06:33	-3	29	89	S	15	26	1017	↓	mc	337	11.2[1]	30.1
2016	26[2]	01/01	10:54	13	1	57	01/01	13:58	10	-23	56	SE	10	35	1020	↓	pc	210	3.1	68.6

Variables:
*'Sun or moon altitude' is in degrees above or below the horizon and 'Moon disk' refers to the percentage of the moon's surface that was lit.
**'Change' is the relative change in air pressure over time where '↑' = an increasing trend and '↓' a decrease; 'Observations' include 'pc' = partly cloudy and 'mc' mostly cloudy.
Data:
[1] = BEWI26 made at least three stops on the North Sea during the crossing (as denoted by five stationary UHF-derived GPS fixes) possibly lasting 2-3 hours in total (included in the average speed calculation).
[2] = BEWI26 made the crossing from the Netherlands to the UK twice during winter 2015/16, with the first visit on 30/10/15 only lasting ~34 hours before the bird returned to France and then the Netherlands; this should possibly be recognised as a re-orientation movement rather than as a true migratory movement between staging sites where birds typically stay for many weeks (*i.e.* 01/01/16).

5.2.3 On crossing the North Sea in autumn

Far fewer data are available for determining accurately the conditions under which the swans migrated during autumn. Detailed data were recorded for only two birds (BEWI03 and BEWI26; **Tables 5 & 6**), firstly because not all of the tagged birds returned to winter in the UK and secondly because several individuals did not reach the UK until the mid-winter (Nov–Jan) period. This meant that light levels for charging the tags were poor because of short day lengths coupled with poor weather, so autumn tracks to the UK were not recorded for swans BEWI11, 12, 19 & 20.

What could be considered the true westward migrations of BEWI03 and BEWI26 on 30/10/15 and 01/01/16 respectively follow a similar pattern to the spring migrations in that they were conducted under conditions of good light availability and were completed in a short time of 3.1–5.8 hours at flight speeds of 45–69 kph during periods of relatively high atmospheric pressure in light to moderate tail or cross winds. BEWI03 arrived at the UK coast in inclement weather but both birds experienced good visibility of 35–45 km. An earlier crossing of the North Sea by BEWI26 at 16:30h on 29/10/15, under conditions of poor visibility when the sun and moon was below the horizon, may have resulted from a westward navigational error because the bird only stayed in the UK for ~34 hours before heading back (into a gentle easterly wind) to the Netherlands (**Table 4** and **Figure 4**). This flight resulted in the bird taking over 11 hours to cross the North Sea from the Continent to the UK, probably in mostly cloudy conditions with only moonlight available, albeit there was a ~90% full moon above the horizon throughout the journey (**Table 5**).

Table 6. GPS fix rates and dates of eastward and westward (*) movements across the North Sea in 2014–2016, collected by GPS devices on Bewick's Swans for which complete high resolution tracks (and limited height data) were available (GPS fixes ≤ 1 hour apart) and thus possible extrapolation error between GPS locations was minimised.

Tag	Height data	2014	2015	2016	GPS rate (minutes)
BEWI01			27/02		15
BEWI03			02/03		15
			30/10*		30
				02/03	30
BEWI11		22/02			60
BEWI12			03/03		15
				03/03	60
BEWI13			25/02		15
BEWI16			03/03		30
BEWI17			09/02		60
BEWI18			21/03		30
BEWI19	Yes		26/02		30
				18/02	60
BEWI20			09/02		60
BEWI21			17/02		60
BEWI22	Yes		21/02		60
BEWI23			n.a.		
BEWI25			02/03		30
BEWI26			07/03		30
			29/10*		30
			31/10		30
				01/01*	30

5.3 Bewick's Swan flight height during migration over land and sea

Five of the GPS loggers (BEWI17, 18, 19, 21 and 22) were set to record height data before being fitted to Bewick's Swans in winter 2015/16. A sixth tag (BEWI12) was subsequently programmed to collect height data when the bird was encountered in Denmark in March 2015, having already migrated from the UK. Height data were downloaded from all of these tags except BEWI18, which did not leave the UK until 19/03/15 in spring 2015, so was not yet in Europe during fieldwork undertaken to collect North Sea crossing data. A renewed attempt was to have been made in autumn 2015 to download the height data stored on the logger, but the swan did not migrate further west than Russia before the tag stopped sending GPS data via the GSM network on 09/10/15.

Table 7. Summary of flight height data recorded during over sea crossings and also during over land flight for the subset of five Bewick's Swans (BEWI12, 17, 19, 21 & 22) fitted with GPS tags programmed to collect altitude data and whose data were downloaded during the eastward and westward migrations in 2015. Note: data were downloadable via the UHF link only, not over GSM.

Ocean area	Number of GPS fixes	Median height (m)	Mean height (m)	St. Dev. height (m)	Minimum height (m)	Maximum height (m)
Baltic Sea	57	-25.6	65.3	609.4	-168.4	4565.8
Barents Sea	48	3.4	22.9	59.7	-139.3	201.1
Gulf of Finland	7	193.9	223.0	220.8	-16.0	572.9
Gulf of Riga	26	-19.7	-81.8	125.4	-403.4	152.7
Kattegat	26	-38.0	-102.4	150.9	-471.8	195.5
North Sea	***27***	***-40.3***	***-56.2***	***91.8***	***-402.5***	***36.8***
White Sea	10	-11.7	157.4	514.3	-13.0	1620.6
Total	**201**	**-19.7**	**8.2**	**361.9**	**-471.8**	**4565.8**
Over land	323	-19.9	48.3	351.4	-947.6	2902.3

The flight height data downloaded from the five tags indicate that the birds typically fly at heights of under 150m, both when making sea crossings (93.0% of 201 flights) and when flying over land (89.2% of 323 flights) (**Table 7, Figure 5**). Median and modal flight heights were in the 0 to -50m band in each case. The altitude data recorded by the GPS tags were corrected for the underlying model of the shape of the Earth (the GPS carries a simplified Geoid model on board) and also the actual land surface heights. This corrected orthometric flight height range puts the birds within or below the rotor swept area of most wind turbines that they might encounter.

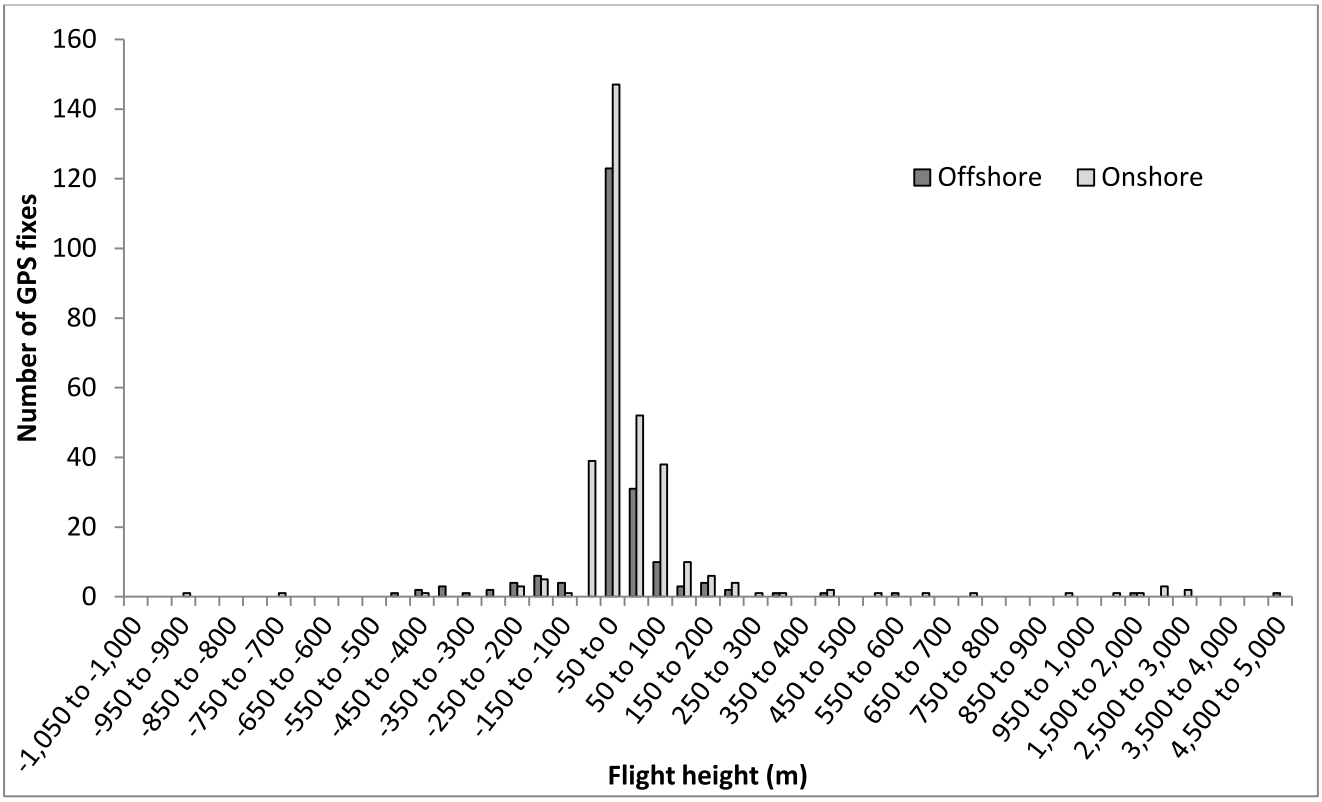

Figure 5. The number of GPS fixes recorded for Bewick's Swans that were likely to be flying (speed ≥5 knots) across land and sea areas during the 2015 and 2016 spring and autumn migrations. Negative values are recorded because of the error in the GPS reading, which is especially pronounced for the height dimension of any GPS fix. The distribution of the flight height data both onshore and offshore suggests that the swans flew at 150m or less above the land or sea surface during most flights.

5.4 Bewick's Swan movements in relation to the North Sea R3 East Anglia ONE wind farm footprint

A total of 14 Bewick's Swans (13 independent units; BEWI17/20 being classed as one unit) were tracked across the North Sea, providing 18 detailed one-way flight lines for swans moving between southeast England and the Continent during migration (spring or autumn), between spring 2014 and spring 2016. Tracks were considered only where the tags provided GPS locations ≤ 1 hour apart. Overall, 83% of the 18 tracks crossed the R3 East Anglia ONE site, and 100% of tagged birds crossed the site at some stage during the study, the break-down being: 100% of tracks in 2014 (n = 1 bird unit), 85% in 2015 (n = 12 bird units) and 75% in 2016 (n = 4 bird units). All of the 18 tracks (100%) and thus all of the 13 different bird units (100%) crossed at least one of the proposed or operational offshore sites in the North Sea region (**Table 8**). The possible re-orientation movement of BEWI26 between 29–31/10/15 (with two North Sea crossings in this period) is not included in these calculations, but the swan crossed four wind farm areas (East Anglia ONE, Greater Gabbard, Galloper B and the London Array; **Figure 6**) during this period.

The number of offshore wind farm footprints, including the R3 East Anglia ONE site, crossed during any migration (east or west) of a bird in any of the years from 2014–2016 ranged from one (*e.g.* "pair" BEWI17/20 and BEWI21) to 17 (*e.g.* BEWI18 on 21/03/15). The mean (± S.D.) number of offshore sites crossed during a migration was 4.4 (± 3.8) wind farm areas (n = 18 migratory tracks).

Details of the sites crossed are given in **Table 9**. In addition to the R3 East Anglia ONE site, 51 offshore wind farm footprints were crossed by at least one swan track, including 11 operational wind farms. Of the 52 sites including East Anglia ONE, 33 (63%) are in German waters, 12 (23%) Dutch, 4 (8%) British and 2 (4%) Belgian, with one Swedish site in the Kattegat ocean area also included. In addition to all swans migrating across East Anglia ONE, five offshore sites were crossed by two tracks of two different birds in spring 2015 and one site (Ijmuiden) was crossed by four tracks of four different birds, also in 2015.

Figures 6–8 illustrate the locations of the offshore wind farm sites named in **Table 9** in relation to the swans' migration route, with different shading indicating and their developmental status. **Figures 9–12** then show the flight-lines taken by the individual swans and how, through progressively zoomed in maps, how their individual migrations relate to the different offshore sites summarised in **Tables 8 &9**.

Table 8. Number of migratory tracks (both eastward and westward) recorded for GPS-tagged Bewick's Swans that crossed the footprints of proposed and constructed off shore wind farm areas in the North Sea. Tracks were extrapolated between GPS locations ≤ 1 hour apart. Dates for the start of migration across the North Sea are given with specific reference to the Round 3 East Anglia ONE site, and in relation to all other offshore North Sea wind farms crossed during those migrations. Where the Round 3 site was not crossed, the date of crossing the other sites is given. The total number of tracks crossing the E. Anglia site alone and in combination with the other North Sea sites is given, along with the total number of full tracks recorded for the North Sea, regardless of whether or not the birds crossed a wind farm area in each year, and the number of birds for which those detailed tracks were available.

Tag	E. Anglia 2014	Other sites 2014 [a]	E. Anglia 2015	Other sites 2015	E. Anglia 2016	Other sites 2016
BEWI01			27/02/2015	1		
BEWI03			02/03/2015	1	02/03/2016	E. Anglia only
			Not crossed	4 (28/10/15)		
BEWI11	22/02/14	3				
BEWI12			03/03/2015	2	Not crossed	4 (3/3/16)
BEWI13			25/02/2015	7		
BEWI16			03/03/2015	8		
BEWI17 [b]			09/02/2015	E. Anglia only		
BEWI18			21/03/2015	16		
BEWI19			Not crossed	5 (26/2/15)	18/02/2016	3
BEWI20 [b]			09/02/2015	E. Anglia only		
BEWI21			17/02/2015	E. Anglia only		
BEWI22			21/02/2015	2		
BEWI25			02/03/2015	2		
BEWI26			07/03/2015	4	01/01/2016	2
Total tracks (and no. of birds) crossing North Sea wind farms	1 (1)	1 (1)	11 (11)	13 (12)	3 (3)	4 (4)
All tracks (and no. of birds) crossing North Sea	1 (1)	1 (1)	13 (12)	13 (12)	4 (4)	4 (4)
% tracks (and % birds) crossing North Sea wind farm areas	100 (100)	100 (100)	85 (92)	100(100)	75 (75)	100 (100)

[a] Tracks derived from less frequent GPS data, recorded for a further 5 Bewick's Swans whose tags were not functioning properly, crossed 1–10 wind farms per bird (including the East Anglia footprint) during spring 2014 (details in Griffin *et al*. 2014).

[b] BEWI17/20 acted as a pair during migration, so are treated as one independent unit in the Total % calculations. Data for BEW20 therefore given in grey font in the Table, to indicate a non-independent record.

Table 9. Excluding the R3 East Anglia ONE site, the 51 offshore wind farm areas in the North Sea encountered by GPS-tagged Bewick's Swans during east or westward migrations in 2014–2016. 'Track' = migration date through the wind farm area.

Offshore wind farm name	Country	Status	Tag-id 2014	Track 2014	Tag-id 2015	Track 2015	Tag-id 2016	Track 2016
Aiolos	Germany	Application			BEWI18	22/03		
Albatros	Germany	Consented			BEWI18	22/03		
Amrumbank West	Germany	Operational			BEWI03	28/10		
BARD Offshore 1	Germany	Operational			BEWI16	04/03		
Bight Power I	Germany	Application			BEWI18	22/03		
Borkum Riffgrund West II	Germany	Application			BEWI18	22/03		
Breeveertien II	Netherlands	Consented			BEWI22	21/02	BEWI19	19/02
Buitengaats	Netherlands	Consented			BEWI18	22/03		
Butendiek	Germany	Operational			BEWI13	25/02		
C-power	Belgium	Operational					BEWI12	03/03
Demonstrationsprojekt Albatros 1	Germany	Consented			BEWI18	22/03		
Den Helder I	Netherlands	Consented	BEWI11	22/02	BEWI26	08/03		
Deutsche Bucht	Germany	Consented			BEWI16	04/03		
Diamant	Germany	Application			BEWI19	26/02		
EnBW He Dreiht	Germany	Consented			BEWI18	22/03		
EnBW Hohe See	Germany	Consented			BEWI16 BEWI18	04/03 22/03		
EnWB He dreiht (Complementary app.)	Germany	Consented			BEWI16	04/03		
Euklas	Germany	Application			BEWI19	26/02		
Galloper B	UK	Consented			BEWI26	30/10*	BEWI12	03/03
GlobalTech I	Germany	Operational			BEWI16 BEWI18	04/03 22/03		
GlobalTech II	Germany	Application			BEWI18	22/03		
Gode Wind 02	Germany	Consented			BEWI13	25/02		
Greater Gabbard - The Galloper	UK	Operational			BEWI26	30/10*	BEWI12	03/03
He dreiht II	Germany	Application			BEWI18	22/03		
Ijmuiden	Netherlands	-	BEWI11	22/02	BEWI03 BEWI13 BEWI25 BEWI26	02/03 25/02 02/03 08/03	BEWI26	01/01
Innogy Nordsee 2	Germany	Consented			BEWI13	25/02		
Innogy Nordsee 3	Germany	Consented			BEWI13	25/02		
Jules Verne	Germany	Application			BEWI19	26/02		
Kaskasi II	Germany	Application			BEWI03	28/10		
Kattegat offshore	Sweden	Application			BEWI22	11/03		
London Array	UK	Operational			BEWI26	30/10*		
Meerwind Sued/Ost	Germany	Operational			BEWI03	28/10		
NEPTUN I	Germany	Application			BEWI19	26/02		
NEPTUN II	Germany	Application			BEWI19	26/02		
Nordergruende	Germany	Consented			BEWI26	08/03		
Nordsee One	Germany	Consented			BEWI13	25/02		
Nordsee Ost	Germany	Operational			BEWI03	28/10		
Norther	Belgium	Consented					BEWI12	03/03
Offshore Windpark Egmond aan Zee	Netherlands	Operational			BEWI22	21/02	BEWI19	19/02
Osters Bank 1	Netherlands	Application			BEWI18	22/03		
Osters Bank 4	Netherlands	Application			BEWI16	04/03		
Prinses Amaliapark	Netherlands	operational					BEWI19	19/02
Q4 West	Netherlands	Consented			BEWI12	03/03		
Q4-WP	Netherlands	Consented			BEWI12	03/03		
Riffgat	Germany	Operational			BEWI13	25/02		
Sandbank	Germany	Consented			BEWI18	22/03		
Sandbank extension	Germany	Application			BEWI18	22/03		
Sea Wind I	Germany	Application			BEWI16 BEWI18	04/03 22/03		
Tromp Binnen	Netherlands	Consented	BEWI11	22/02	BEWI25 BEWI26	02/03 08/03	BEWI26	01/01
Veja Mate	Germany	Consented			BEWI16	04/03		
West Rijn	Netherlands	Consented			BEWI01 BEWI18	27/02 21/03		

*Possibly a re-orientation movement by BEWI26, rather than a migratory movement.

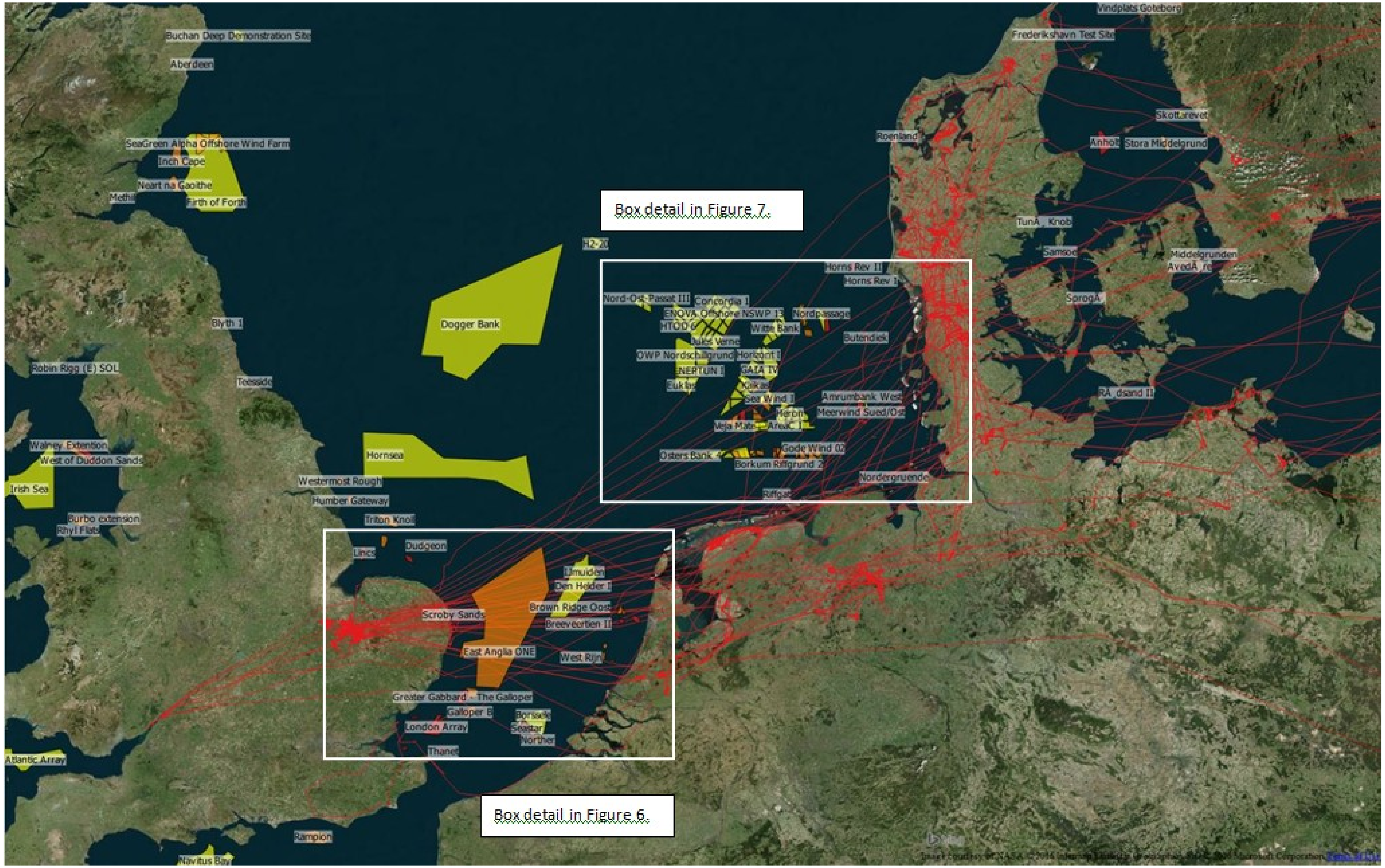

Figure 6. An overview of the main wind farm sites crossed by the tracks (red lines) of 18 GPS-tagged Bewick's Swans. This figure shows that the R3 sites to the north – Hornsea and Dogger Bank – are relatively unlikely to be encountered by Bewick's Swans from the Slimbridge and Ouse Washes areas on their eastward or westward migrations. Yellow = wind farm at the application stage, orange = consented, red = operational.

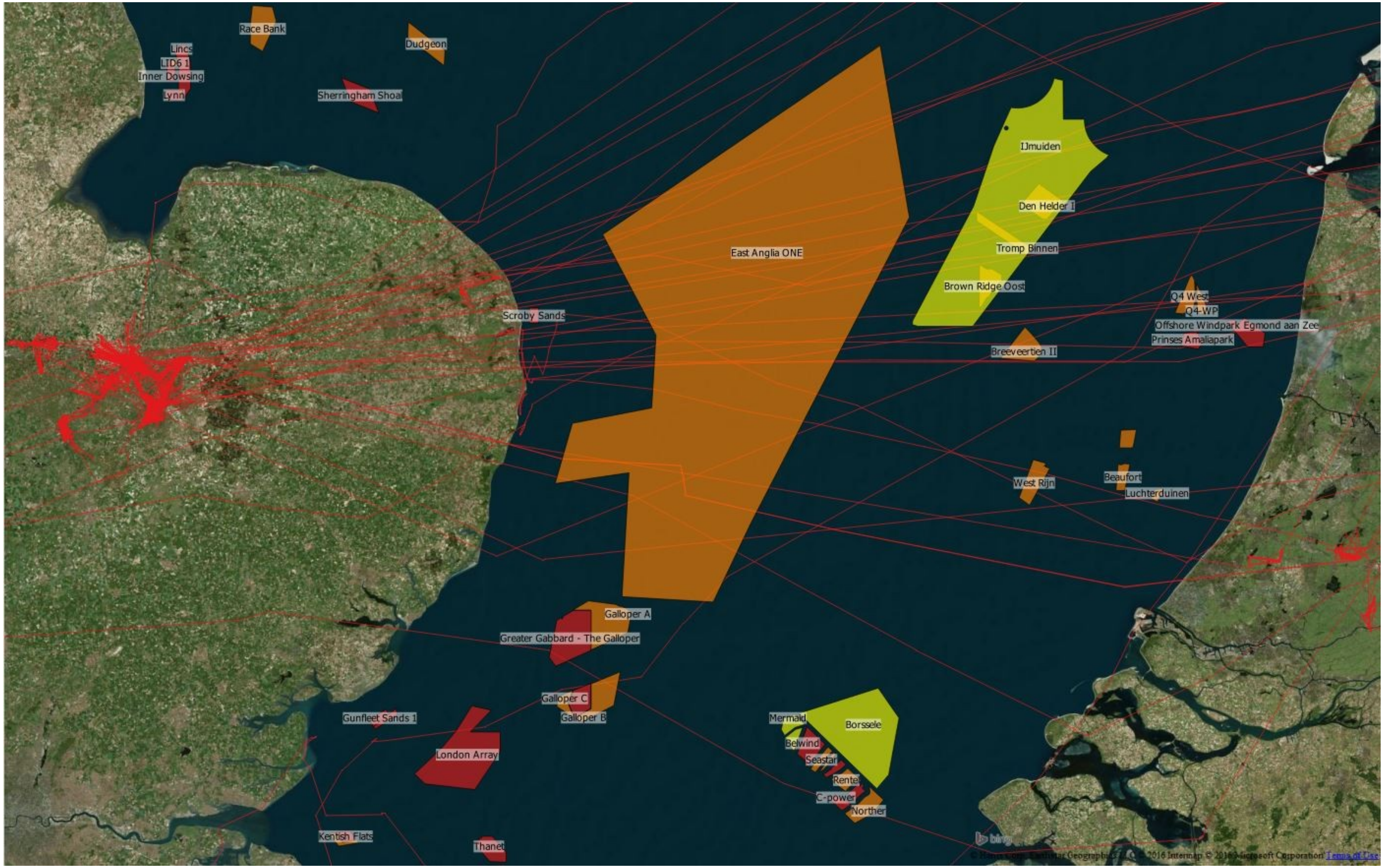

Figure 7. Bewick's Swan tracks in the southern North Sea, together with the names and development stages of offshore wind farm sites referred to in this report. Yellow = wind farm at the application stage, orange = consented, red = operational.

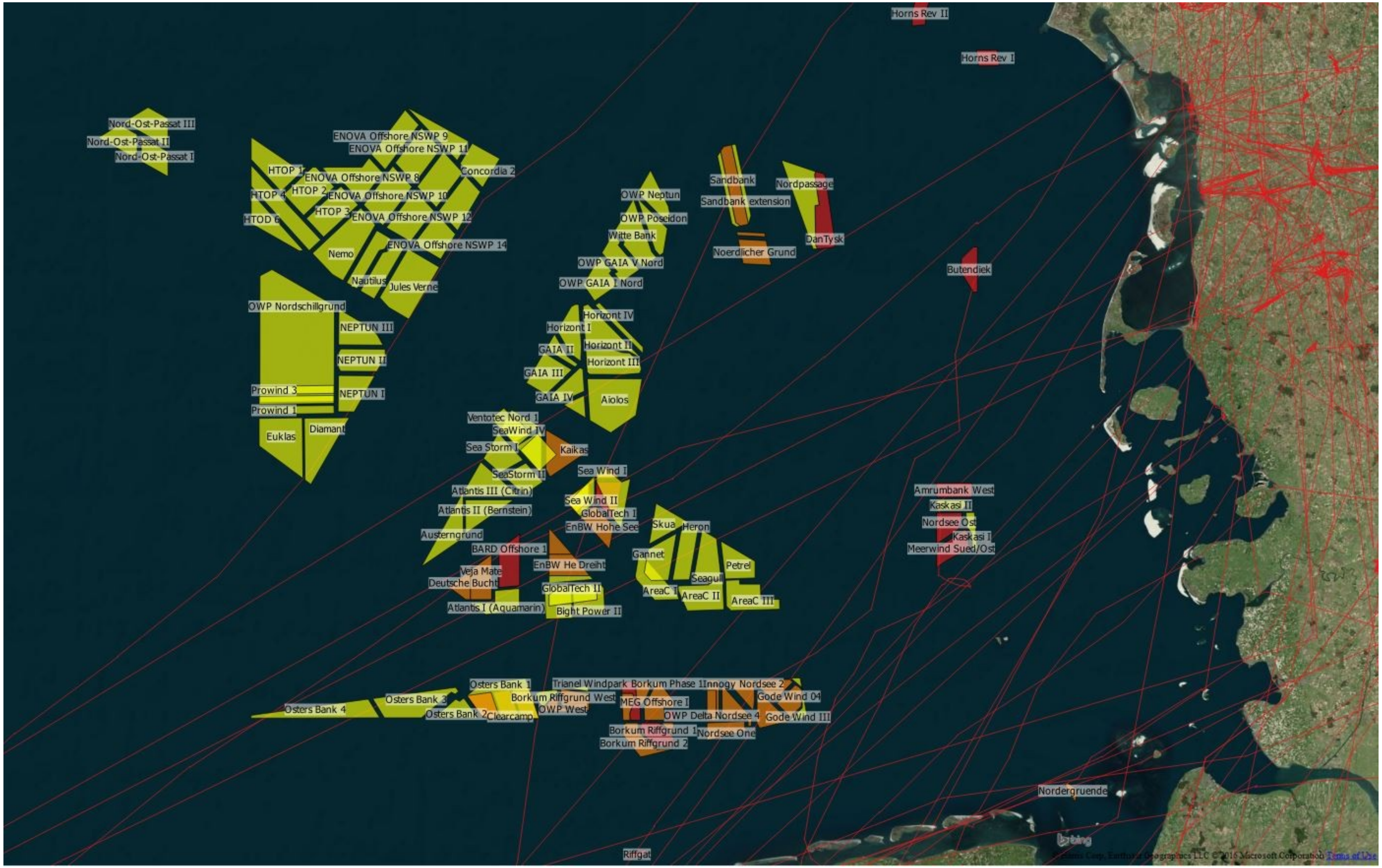

Figure 8. Bewick's Swan tracks in the eastern North Sea, together with the names and development stages of offshore wind farm sites referred to in this report. Yellow = wind farm at the application stage, orange = consented, red = operational.

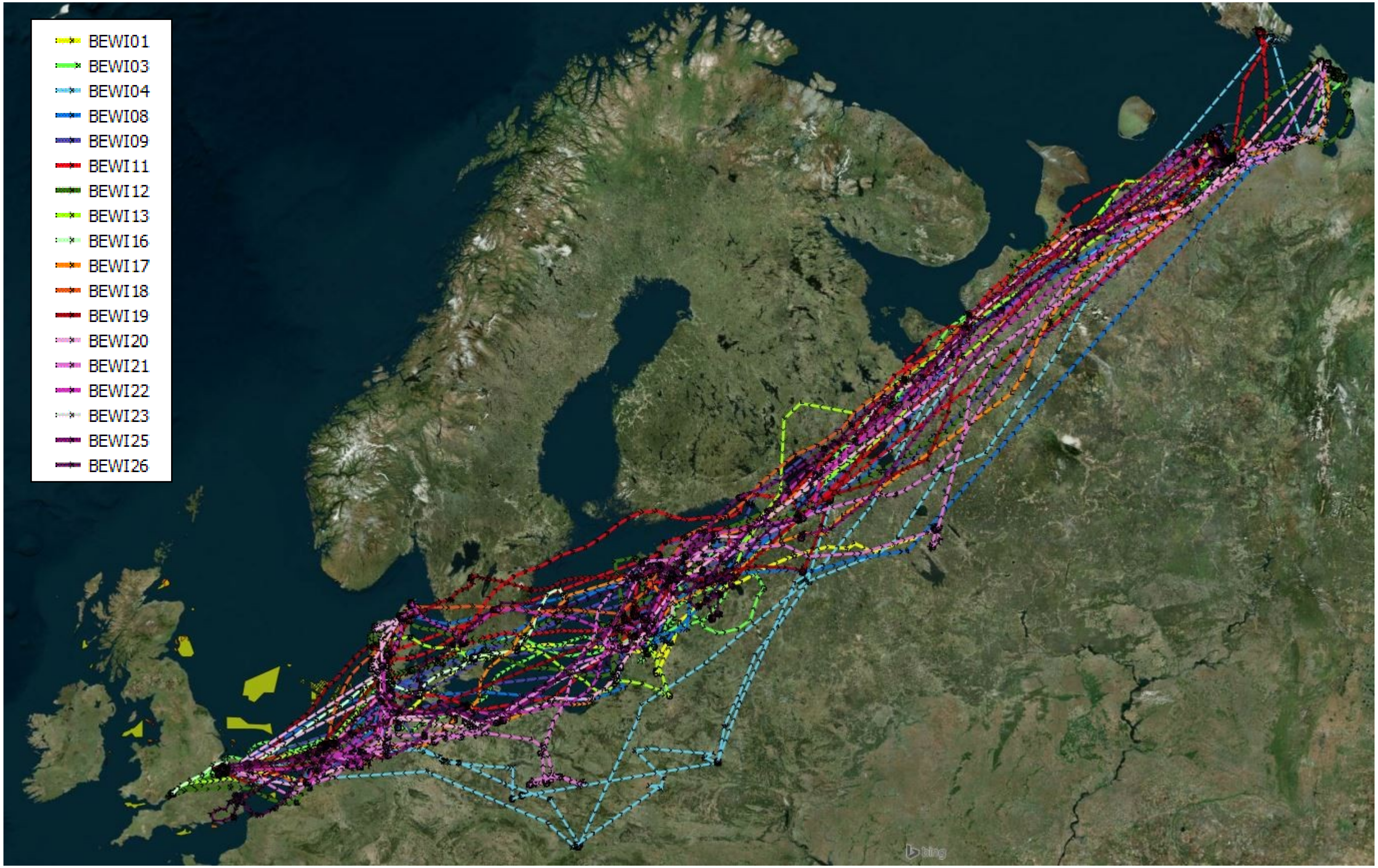

Figure 9. An overview of the tracks taken by 18 GPS-tagged Bewick's Swans referred to in this report, migrating between 2014 and 2016, having been caught at two major wintering sites in the UK (Slimbridge & the Ouse Washes). Arrows on tracks in this and subsequent figures denote the direction of bird travel.

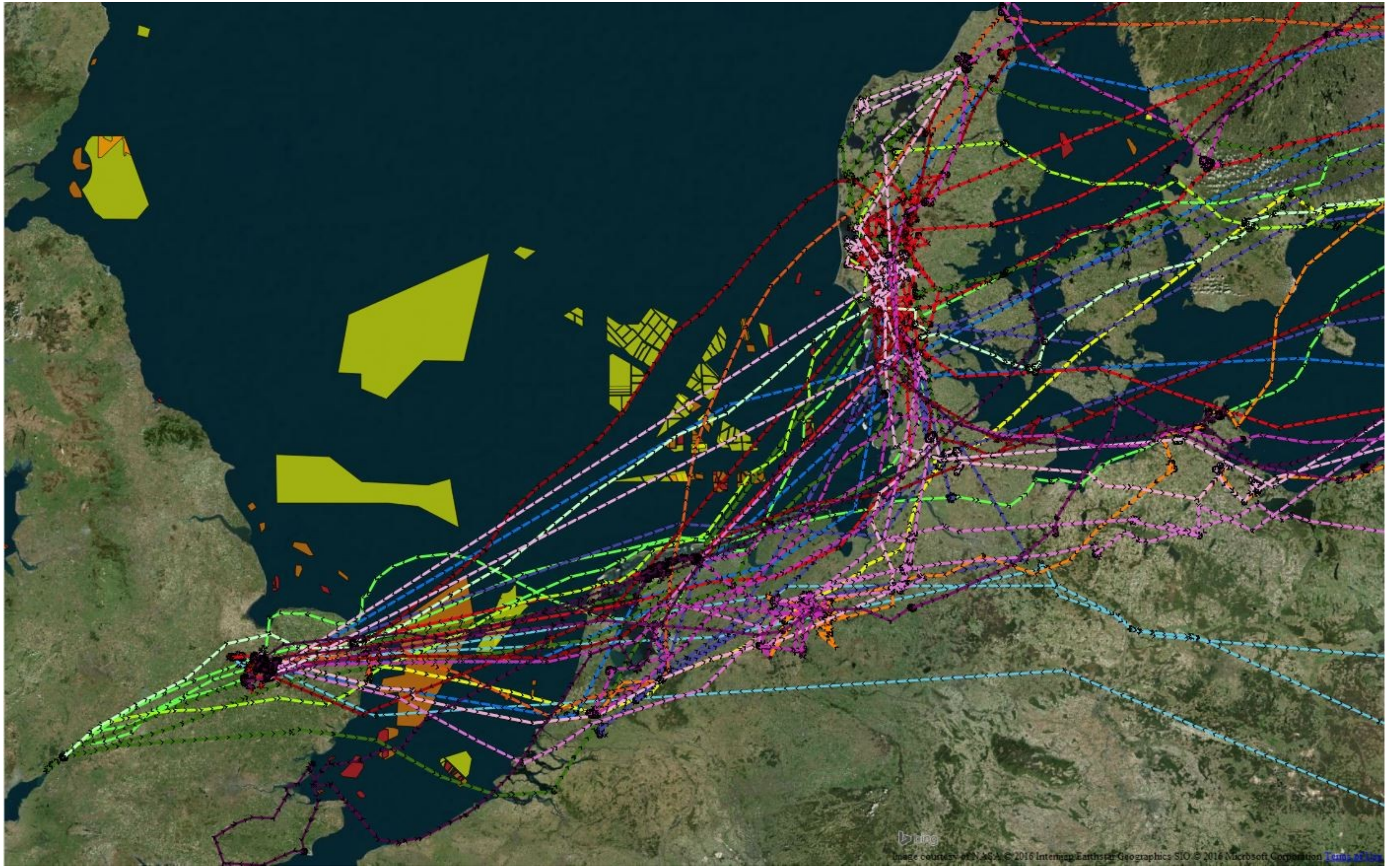

Figure 10. NW European part of the flyway of the 18 GPS-tagged Bewick's Swans (legend as per **Figure 9**). Track overlap with proposed areas of offshore wind farm development in the southern North Sea is given in greater detail in **Figures 11 & 12**.

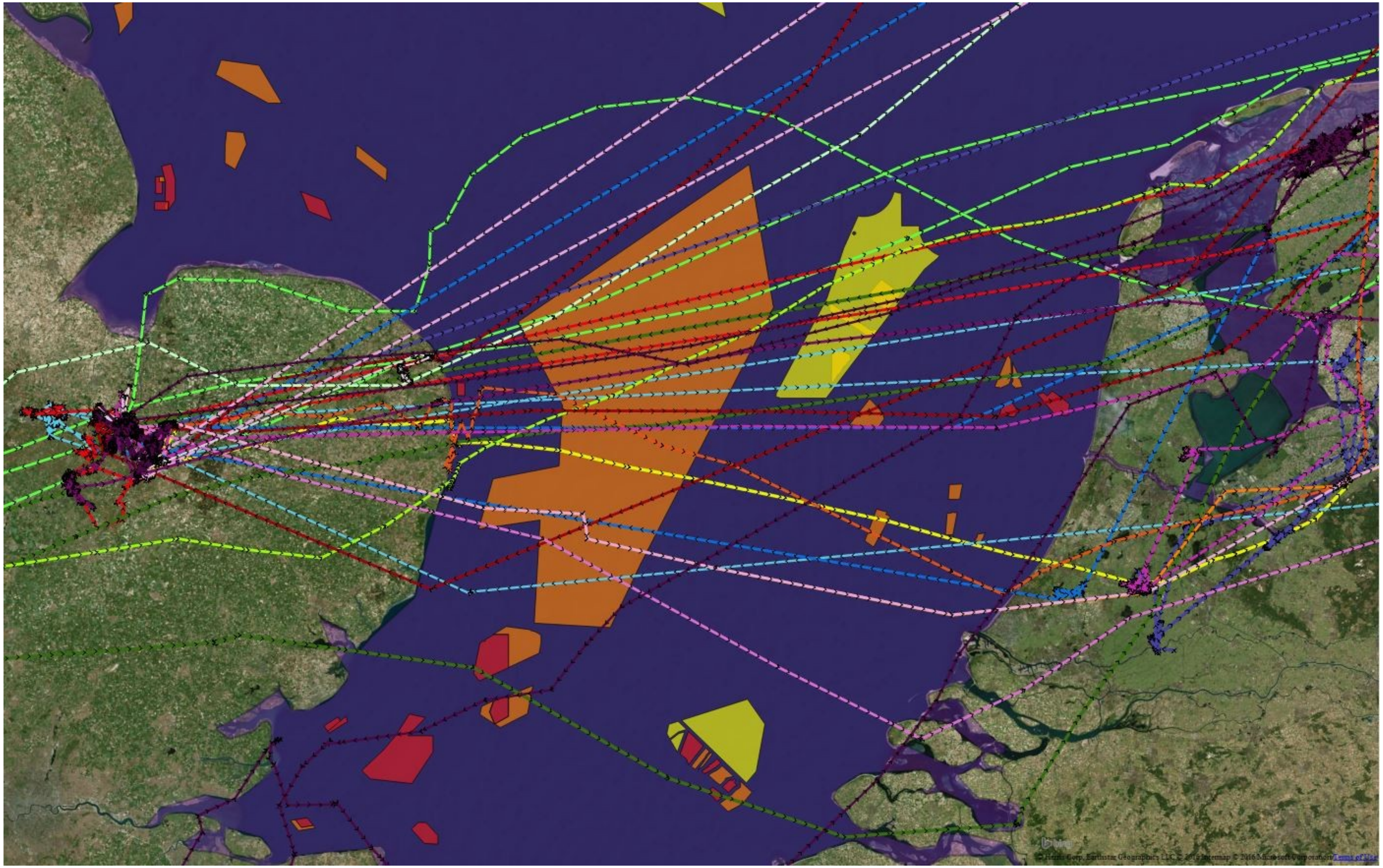

Figure 11. The 18 tracks (arrows indicate east and west migratory legs) of the GPS-tracked Bewick's Swans in relation to the main consented offshore UK wind farm area of the 'East Anglia ONE' Round 3 site. Legend as per **Figure 9**, with green colours representing four swans tagged at Slimbridge and yellow to darker reds and purples the 11 birds tagged on fields near the Ouse Washes. The tracks variously shaded blue refer to three birds with part-functional tags from winter 2013/14: BEWI04, 08 and 09.

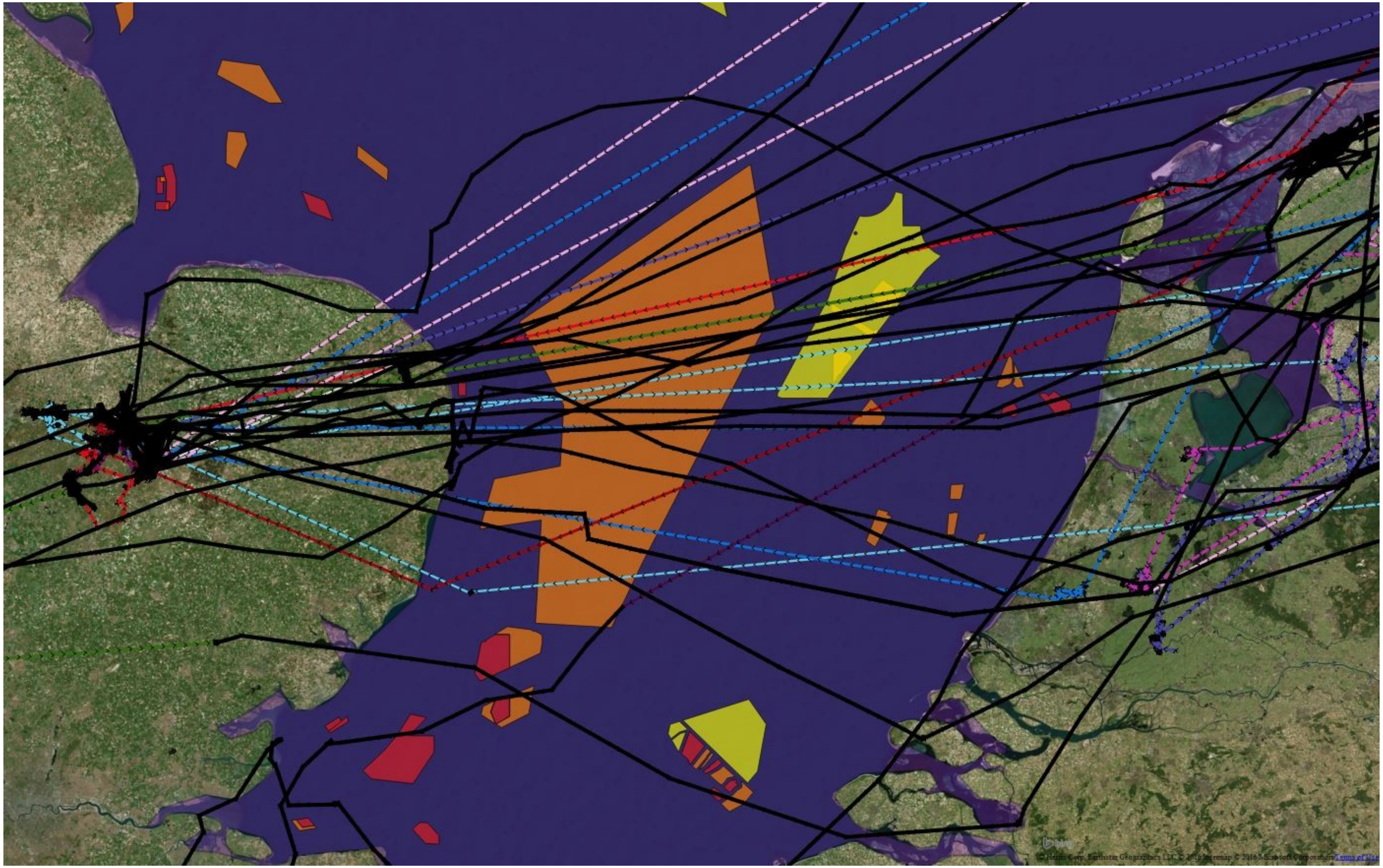

Figure 12. For area near the R3 East Anglia ONE Round site (as in **Figure 11**), black lines indicate the migratory track segments (east and west) for the 14 GPS-tagged Bewick's Swans that had fully functional tags with GPS fixes ≤ 70 minutes apart (*i.e.* those used in most analyses presented in this report). Tracks with a coarser temporal resolution remain coloured here, and conclusions drawn from these data are less robust.

5.5 Bewick's Swan movements in relation to onshore wind turbines and wind farms

Bewick's Swans' flight-lines were also analysed in relation to the location of onshore wind farms and individual turbines in countries along the swans' migration route (**Table 10**).

Table 10. Number of wind farms and turbines analysed in relation to their proximity (within ~2.5km) to detailed Bewick's Swan tracks of detailed (≤ 70 minutes between GPS fixes).

Country	No. wind farms considered	No. turbines considered	Notes
Germany	133 Wind farms were separated by ruling that ">2km between turbines = different wind farms"	2185	In the absence of accurate wind farm/turbine location data for Germany, turbine locations were digitised from current (March 2016) BING imagery background for all areas within ~2.5km of detailed (≤ 70 minutes between GPS fixes) track segments recorded for each swan. Turbines digitised included a proportion that extended beyond 2.5km of a swan's track if they formed part of the same wind farm site as others within 2.5km of the track.
Denmark	334	1873	
Netherlands	140	1336	
UK	13	105	
Estonia	14	51	
Latvia	7	46	

Despite these total numbers of onshore turbines occurring within ~2.5km of detailed (≤ 70 minutes between GPS fixes) swan track segments in each country, the swan tracks passed close (≤ 80m) to far fewer turbines during the course of daily foraging and roosting routines or annual migratory flights. This 80m band provides a fairly strict criterion for assessing which turbines swans might encounter or interact with during a flight. Conversely, however, many turbines are smaller than this in radius, and if turbines are facing the wind and the wind is perpendicular to the track of the swan at the time of travel, then the rotor swept area would be negligible in relation to the area of the swan's track that it covers.

All six countries for which onshore turbine data were available were included when considering the possible cumulative impact of Bewick's Swans encountering several wind farms whilst migrating and wintering in northwest Europe (**Table 11**). Swans for which > 100 detailed track segments were available within these six countries crossed to within 80m of 0 wind turbines (BEWI26 in 2016), ranging up to 72 wind turbines (38 wind farms, BEWI11 in 2014), in any one tracking year. There was substantial variation in the number of turbines and wind farms encountered by different swans within years, and also for the same bird between years. This variation in the number of wind farms encountered depended not only on the amount of data available for an individual in a tracking year but also on where it staged or wintered during the course of that year, with some countries having higher densities of turbines in areas used by the swans to feed and roost. In order to try to standardise this variation, the turbine encounter rate was expressed as a proportion of the number of detailed track segments recorded for a bird per country per tracking year (**Table 11**; **Appendix 1** also gives details of how many tracking days and the number of GPS fixes within those periods were collected by each bird per country per tracking year). Detailed track segments (*i.e.* with GPS fixes ≤70 minutes apart) were considered to represent flight periods if the GPS locations were >500m apart.

This filter was necessary to remove track segments where birds were either roosting or feeding/loafing within 80m of a turbine, and thus amassing records of proximity to the turbines at up to hourly intervals that did not represent a possible flight past a turbine. In these cases only the flight into and/or out of the feeding/roosting area was considered in calculating encounter rates.

On considering the total number of onshore turbines located in the vicinity (<80m) of tracks recorded for 15 swans during 26 tracking years, for 4,854 track segments that likely included periods of flight, it was estimated that 322 turbines were encountered by the birds. This provides an overall encounter rate of 0.066 turbines per extrapolated flight segment – *i.e.*, one turbine encountered for every ~15 flights made by Bewick's Swans. The overall rate varies considerably between countries, however, with swans having an overall encounter rate of <0.001 whilst in the UK, compared with 0.14, 0.17 and 0.23 in Denmark, the Netherlands and Germany, respectively. Thus tagged swans in Germany are estimated as encountering one turbine on their flight-line for every 4–5 flights. Encounter rates may also vary greatly for particular individuals in different years, depending on where a swan chooses to stage or winter. For instance, BEWI11, who spent 40 days staging in Denmark in spring 2014 (from 22/02/14–03/04/14) and also wintered in Denmark in 2014/15 recorded an encounter rate of 0.23 (for 311 valid track segments) for 2014, whereas in 2015/16 it wintered in the UK and recorded an encounter rate of 0 (for 116 valid track segments) for 2016. This probably can be attributed to the UK having a lower density of onshore turbines in the lowland areas used by the swans, and also to BEWI16 feeding to the northeast of the operational Velling Maersk/Taendpibe wind farm whilst roosting on Ringkøbing Fjord, West Jutland, during spring 2014 (tracks illustrated in **Figure 13**). The mean (±S.D.) encounter rate with turbines per swan (treating each tracking year independently) is 0.06 ±0.07. These encounter rates do not differentiate between two different turbines or wind farms crossed by a bird versus the same turbine or wind farm crossed twice by a bird.

If the number of different wind farms encountered by a swan is considered then in most countries it can be seen that very few sites are encountered by more than one bird, with only Germany registering more than two sites (eight sites) that were crossed by more than one bird (**Table 12**).

Preliminary inspection of the Bewick's Swans' migratory tracks within the UK suggest that the birds (particularly those wintering further west) follow valleys or lower lying areas during migration, rather than taking the shortest routes to the UK exit/entry points or Continental destinations (**Figure 14**). Such information should help to guide further planning of the location of onshore wind farms in the UK, and perhaps more widely.

Table 11. The total number of onshore wind farm areas where extrapolated tracks recorded for GPS-tagged Bewick's Swans passed within the maximum rotor swept area of a turbine (*i.e.* ≤80m from the turbine's central mapped position) in the United Kingdom (UK), the Netherlands (NL), Denmark (DK), Germany (D), Latvia (LV) and Estonia (EST) from 2014–2016. The number of turbines and wind farms encountered by a bird is summed for each track segment extrapolated between GPS fixes ≤70 minutes apart. Therefore individual turbines or wind farms were counted more than once if a bird passed the turbine at different times of the day. In order to estimate the rate of encounter of swans with turbines, the total number of track segments when the bird was likely to be flying (*i.e.* where GPS fixes were ≤70 minutes apart and there was a distance of >500m between the fixes) was calculated for each country in each study year.

Tag-ID	Year	UK turbines	UK wind farms	NL turbines	NL wind farms	DK turbines	DK wind farms	D turbines	D wind farms	LV turbines	LV wind farms	EST turbines	EST wind farms	Total turbines	Total windfarms	UK tracks	NL tracks	DK tracks	D tracks	LV tracks	EST tracks	Total tracks	UK turbine rate	NL turbine rate	DK turbine rate	D turbine rate	LV turbine rate	EST turbine rate	Total turbine rate
BEWI01	2014													**0**	**0**	0	0	0	0	0	0	**0**							
	2015					2	1	3	3					**5**	**4**	133	15	1	56	28	1	**234**	0	0	2.00	0.05	0	0	**0.02**
BEWI03	2015			6	4	3	2	15	4	3	1	3	1	**30**	**12**	27	12	4	24	155	101	**323**	0	0.50	0.75	0.63	0.02	0.03	**0.09**
	2016							19	8					**19**	**8**	36	0	25	3	0	0	**64**	0		0	6.33			**0.30**
BEWI11	2014	1	1	2	2	61	30	8	5					**72**	**38**	26	1	266	5	5	8	**311**	0.04	2.00	0.23	1.60	0	0	**0.23**
	2015					7	1							**7**	**1**	0	0	130	0	0	0	**130**			0.05				**0.05**
	2016													**0**	**0**	116	0	0	0	0	0	**116**	0						**0**
BEWI12	2015			3	3	37	31							**40**	**34**	15	4	215	18	122	69	**443**	0	0.75	0.17	0	0	0	**0.09**
	2016					1	1	1	1					**2**	**2**	3	9	8	5	0	0	**25**	0	0	0.13	0.20			**0.08**
BEWI13	2015					4	3							**4**	**3**	14	0	99	0	6	38	**157**	0		0.04		0	0	**0.03**
BEWI16	2015					3	3							**3**	**3**	9	0	64	0	0	0	**73**	0		0.05				**0.04**
BEWI17	2015			7	1			31	19					**38**	**20**	40	3	0	174	87	19	**323**	0	2.33		0.18	0	0	**0.12**
	2016													**0**	**0**	0	0	0	0	0	0	**0**							
BEWI18	2015			6	4	3	2							**9**	**6**	133	8	31	0	134	12	**318**	0	0.75	0.10		0	0	**0.03**
BEWI19	2015					3	2			1	1			**4**	**3**	159	0	26	0	106	23	**314**	0		0.12		0.01	0	**0.01**
	2016					2	1							**2**	**1**	13	3	27	4	0	0	**47**	0	0	0.07	0			**0.04**
BEWI20	2015							6	4					**6**	**4**	38	2	1	84	94	5	**224**	0	0	0	0.07	0	0	**0.03**
	2016													**0**	**0**	0	0	13	0	0	0	**13**			0				**0**
BEWI21	2015							4	3					**4**	**3**	32	8	0	12	0	3	**55**	0	0		0.33		0	**0.07**
	2016													**0**	**0**	0	0	0	8	0	0	**8**				0			**0**
BEWI22	2015					12	8	16	12					**28**	**20**	100	45	93	24	132	32	**426**	0	0	0.13	0.67	0	0	**0.07**
	2016													**0**	**0**	0	0	6	0	0	0	**6**			0				**0**
BEWI23	2015													**0**	**0**	59	0	0	0	0	0	**59**	0						**0**
BEWI25	2015			1	1			2	1					**3**	**2**	99	4	0	12	1	60	**176**	0	0.25		0.17	0	0	**0.02**
BEWI26	2015			38	26			8	3					**46**	**29**	144	261	1	57	48	284	**795**	0	0.15	0	0.14	0	0	**0.06**
	2016													**0**	**0**	212	2	0	0	0	0	**214**	0	0					**0**
Total		1	1	63	41	138	85	113	63	4	2	3	1	**322**	**193**	1408	377	1010	486	918	655	**4854**	0.001	0.17	0.14	0.23	0.004	0.005	**0.07**

(a)

(b)

Figure 13. Movements of Bewick's Swan BEWI11 between fields used for feeding to the northeast of the operational Velling Maersk/Taendpibe wind farm and roosting areas on Ringkøbing Fjord, Denmark. (a) = overview of the movements, and (b) = zoomed view of the feeding area, illustrating some of the turbines.

Figure 14. Detailed swan track segments (red lines = swan tracks of ≤70 minutes extrapolated between subsequent GPS fixes) in relation to the topography of the UK (m).

Table 12. The number of different onshore wind farm areas crossed by the 14 GPS-tagged Bewick's Swans for which detailed tracking data were available (*i.e.* track segment duration ≤70 minutes between GPS fixes) from 2014 to 2016. Different tracking years were classed as independent data for the same bird if repeat migrations were made.

	United Kingdom	Netherlands[1]	Denmark[2]	Germany[3]	Latvia	Estonia	Total
BEWI01	0	0	1	3	0	0	**4**
BEWI03	0	4	2	11	1	1	**19**
BEWI11	1	2	17	5	0	0	**25**
BEWI12	0	3	11	1	0	0	**15**
BEWI13	0	0	3	0	0	0	**3**
BEWI16	0	0	2	0	0	0	**2**
BEWI17	0	1	0	13	0	0	**14**
BEWI18	0	3	2	0	0	0	**5**
BEWI19	0	0	3	0	1	0	**4**
BEWI20	0	0	0	4	0	0	**4**
BEWI21	0	0	0	3	0	0	**3**
BEWI22	0	0	5	12	0	0	**17**
BEWI25	0	1	0	1	0	0	**2**
BEWI26	0	14	0	3	0	0	**17**

[1] = one site was crossed by two different birds: BEWI17 & BEWI18.
[2] = two sites were crossed by two different birds: BEWI13 & BEWI18 and BEWI19 & BEWI22.
[3] = seven sites were crossed by two different birds: BEWI01 & BEWI22, BEWI17 & BEWI20 (pair or close associates; two times), BEWI03 & BEWI22 (three times), BEWI03 & BEWI11; and one site was crossed by three different birds: BEWI17, BEWI20 and BEWI22.

6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

6.1 A total of 22 GPS-GSM loggers were fitted to Bewick's Swans during the course of the study (8 in winter 2013/14; 14 in 2014/15) of which 18 were providing location data in winter 2014/15. These yielded at least hourly location data for 15 individuals leaving UK wintering sites and 14 crossing the North Sea on at least one occasion from winter 2014/15 onwards, with a total of 18 "independent" spring migration tracks from the UK (noting that two sets of birds seemed be associating as pairs/siblings: BEW 17/20 and BEWI19/23) and 2 autumn migrations to the UK recorded in detail (*i.e.* with GPS fixes at ≤70 minute intervals) in 2014–2016. Autumn migration data recorded for 4 more birds wintering in the UK were not included because low light levels reduced battery power and thus location frequency in the tags. Migration routes were also recorded for swans originally tagged in the UK that wintered in Continental Europe in subsequent years. Seven of the 8 tags deployed in winter 2013/14 did not function properly (so provided only coarse resolution data on the swans' movements, reported in Griffin *et al*. 2014) of which 4 returned with at least partially-functioning loggers in winter 2014/15. The coarse resolution data are not analysed in detail here, but it's perhaps worth noting that these tracks fell within the range of the more detailed swan tracks recorded by the fully-functioning tags fitted in winter 2014/15.

6.2 The Bewick's Swan tracks recorded within the GIS were taken as being straight lines between consecutive GPS data points, and as such it's not possible to state for certain that a track really crossed a wind farm footprint unless one of the GPS locations fell within a wind farm area. Nevertheless, by confining track segments included in the analyses to those where there were ≤ 70 minutes between GPS fixes, we aimed to be rigorous and realistic in our assessment of offshore and onshore areas likely to be encountered by the birds. Using only an 80m radius around onshore turbine positions was similarly conservative as some earlier studies (*e.g.* Griffin *et al*. 2011, WWT Consulting 2015) have considered sites of 1–5km or even 20km from a wind farm as indicative of it being on the migration route of a bird.

6.3 Overall, the study found that there was a high level of Bewick's Swan movement across the East Anglia ONE wind farm footprint, with 83% of swan tracks (n=18 tracks) and all (100%) of tagged swans crossing the site on migrating from and to the UK in spring and autumn during 2014–2016. Moreover, inspection of the mapped tracks indicates that the swans move across the whole of the footprint area.

6.4 None of the tagged Bewick's Swans were found to cross UK wind farms further north (*i.e.* none crossed the Hornsea or Dogger Bank sites), but there was some less frequent movement over UK wind farms further south: Greater Gabbard, Galloper B and the London Array.

6.5 A total of 52 offshore wind farm footprints (including 11 operational sites) were crossed by the swans, of which 33 (63%) were in German waters, 12 (23%) Dutch, 4 (8%) British and 2 (4%) Belgian, with one Swedish site in the Kattegat also included. Several birds migrated direct from the UK to Denmark or to Schleswig-Holstein in Germany, resulting in them crossing the wind farms in the German Bight rather than taking an overland route from the Netherlands to Germany and Denmark. This area, which contains a substantial number of wind farms (see **Figure 8**), was not included as being on the Bewick's Swans' migration route in a report providing guidance for assessing the numbers of migrating birds likely to pass through proposed offshore wind farm developments (for inclusion in collision risk model used to calculate mortality estimates, and to apportion this mortality to specific SPA populations; Wright *et al*. 2012). Maps of the main migration zones for Bewick's Swans wintering in Britain and Ireland therefore should be updated in line with the evidence provided in the current study.

6.6 The majority of the tagged Bewick's Swans departed from the UK coast during early morning (62.5% of 16 birds departing on spring migration headed over the coast between 05:00–08:00h; **Figure 4**) from c. mid-Feb to first week of March under High Pressure conditions. The birds therefore arrived at the start of the East Anglia ONE footprint under conditions of good visibility. The remaining swans, which started their spring migration after sunset, typically migrated in moonlit conditions.

6.7 Flight height data were recorded for only 5 Bewick's Swans whose tags were programmed to record altitudinal data and whose data were downloaded via Yagi in the field. Nevertheless, the data indicated that the birds fly at low altitudes over both land and sea, with most at <150m and with median and modal flight heights both in the 0 to -50m band. These low flight heights are similar to those recorded for Whooper Swans tracked using PTT satellite transmitters (Griffin *et al*. 2010, 2011). It also means that most flights are at or below the sweep of the wind farm rotors.

6.8 In addition to the offshore wind farms, 15 Bewick's Swans with detailed tracking data encountered 322 wind turbines (*i.e.* their tracks were <80m from turbines) for 4,854 track segments that likely included periods of flight, in 26 tracked-years recorded for these individuals between 2014 and 2016. This provided an overall encounter rate of 0.066 turbines per extrapolated flight segment – *i.e.* one turbine encountered for every ~15 flights made by the swans. The overall rate varies considerably between countries, with swans having an overall encounter rate of <0.001 whilst in the UK, compared with 0.14 in Denmark, 0.17 in the Netherlands and 0.23 in Germany. Seven onshore sites in Germany were crossed by at least 2 different birds in the period 2014–2016 and three sites by 3 different birds. Encounter rates also varied across years for particular individuals, depending on their choice of staging or wintering site.

Recommendations

6.9 Given the high proportion of Bewick's Swan tracks that cross not only the East Anglia ONE wind farm site but also offshore wind farms in German, Dutch and Belgian waters, our findings show that particular care should be undertaken to assess cumulative impacts of several wind farms along the swans' migratory route, to ensure that there is no likely significant effect of these developments on the NW European Bewick's Swan population, which is in decline and listed as Endangered in the European Red List of bird species (BirdLife International 2015).

6.10 Moreover, collision risk at onshore wind farms should also be taken into account during cumulative impact assessments undertaken for birds that migrate over both land and water.

6.11 The importance of considering both offshore and onshore wind farms in cumulative impact assessments extends to other migratory waterbirds, and is not limited to Bewick's Swans.

6.12 International communication and publicly accessible data on proposed and constructed wind farm sites (including their precise location and the number and size of turbines) in range states is crucial if strategic and project-specific assessments are to determine cumulative effects more precisely.

6.13 The study has served to demonstrate that birds wintering at sites some distance from proposed wind farm development may encounter the development during their annual migration. As such, EIAs for offshore wind farms should consider potential impacts on all SPAs designated for Bewick's Swans, not just the coastal sites.

6.14 As illustrated by the current study, information on bird migration zones is not well founded for some species. We therefore recommend that further tracking and also radar studies be undertaken to improve knowledge of migration routes for other migratory species where internationally important numbers (>1% of the total population) occur in the UK, and/or where SPAs have been designated for these species.

6.15 For Bewick's Swans, although 100% of tagged swans passing through the East Anglia ONE footprint, this was based on small sample size of spring tracks, and further tracking may provide a more robust assessment of the proportion of birds crossing different parts of the footprint.

6.16 Detailed field and radar studies of swan movement in the vicinity of onshore sites in Europe would perhaps serve to determine how the birds behave in relation to different turbine spacing, and thus indicate whether the creation of east-west corridors a few hundreds of meters wide might be useful to migrating swans and other birds.

6.17 This report examined the frequency with which migrating Bewick's Swans encounter turbines, and are thus at risk of collision, but the effects of wind turbines in displacing birds from key feeding and roosting areas at wintering and staging sites should also be assessed in determining their cumulative impacts on migratory species. Although some individuals may become habituated to turbines and tolerate them, whether there is a percentage of the population that relocates from sites where wind farms have been constructed has yet to be ascertained. Additionally, despite the small sample size of tagged birds, existing tracking data could be examined to determine the extent to which feeding swans move within or stay outside the perimeters of constructed wind farms, most usefully at wintering and staging areas where there are higher wind farm densities on mainland Europe. This, together with national count data and data on potential explanatory variables (*e.g.* variation in food supply; competition from other species for food resources), may help to determine whether there is large-scale (landscape level) and/or local displacement of swans from the vicinity of wind farm sites.

6.18 Potential collision with other infrastructure – particularly powerlines – should also be included in collision risk assessments. Collisions with powerlines is the most commonly reported cause of death in swan species (*e.g.* Brown *et al*. 1992) and there is preliminary information that elevated bird collisions with powerlines occur in the vicinity of wind farm sites (Klop & Brenninkmeijer 2014, Brenninkmeijer & Klop 2015), perhaps because avoidance of the more obvious turbines results in a higher rate of flux across the less obvious wires.

6.19 Access to turbine data for the remaining countries of the flyway, and also attribute data for the turbines that would allow us to determine the sweep of the rotors from more precise measures of the rotor radii, would provide a more robust measure of encounter frequency for Bewick's Swans. Modelling the probability distribution for swan tracks, rather than assuming a straight line between GPS locations, would also be beneficial for making a more comprehensive assessment collision risk. In a more complex model, it would perhaps be possible to link turbine positioning to local wind conditions (as turbine hubs are rotated to face the prevailing wind), so that the actual rotor swept area perpendicular to a swan track at the time it travelled past the turbine can be calculated. Albeit this level of detail may perhaps be merited only for swan tracks derived from GPS data collected at more frequent intervals.

6.20 A single standardised database of all offshore and onshore wind farms should be developed to facilitate cumulative impact assessments.

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9. APPENDICES

Appendix 1. Summary of the total number of GPS fixes (N_GPS) collected during tracking days (N_days) by 18 collar tagged Bewick's Swans over the course of the study in each of the country and ocean areas along the eastward or westward migration routes from 2014 to 2016 with the earliest (Min. date) and latest dates (Max. date) each year for which data were collected.

Tag code	Country or ocean	2014				2015				2016				Total fixes
		Min. date	Max. date	N_GPS	N_days	Min. date	Max. date	N_GPS	N_days	Min. date	Max. date	N_GPS	N_days	
BEWI01	Estonia					23/04	23/04	1	1					
	Germany					27/02	22/03	949	24					
	Latvia					23/03	23/04	341	15					
	Lithuania					23/03	23/04	437	20					
	Netherlands					27/02	27/02	26	1					
	Russia					23/04	27/05	280	35					
	Sweden					23/03	23/03	3	1					
	United Kingdom	17/12	31/12	109	15	01/01	27/02	2371	58					
	Baltic Sea					22/03	23/03	10	2					
	Kattegat					22/03	22/03	1	1					
	North Sea					27/02	27/02	78	1					
BEWI01 Total		**17/12**	**31/12**	**109**	**15**	**01/01**	**27/05**	**4497**	**159**					**4606**
BEWI03	Denmark					28/10	28/10	7	1	02/03	07/03	206	6	
	Estonia					20/03	27/10	1154	21					
	Germany					03/03	10/03	389	8	02/03	02/03	3	1	
	Latvia					11/03	28/10	1821	30					
	Lithuania					12/03	19/03	769	8					
	Netherlands					02/03	30/10	18	3					
	Russia					23/04	27/10	9363	185					
	Sweden					28/10	28/10	8	1					
	United Kingdom					25/01	23/11	54	11	23/01	02/03	312	12	
	Baltic Sea					03/03	28/10	572	10					
	Barents Sea					10/05	28/09	297	19					
	Bristol Channel					19/01	31/12	3745	105	01/01	24/02	601	55	
	Gulf of Finland					23/04	23/04	1	1					
	Gulf of Riga					19/03	11/04	195	5					
	Kattegat					28/10	28/10	11	1					
	North Sea					02/03	30/10	107	5	02/03	02/03	17	1	
	White Sea					09/05	28/09	19	2					
BEWI03 Total						**19/01**	**31/12**	**18530**	**416**	**01/01**	**07/03**	**1139**	**75**	**19669**
BEWI04	Belarus	21/03	26/04	237	28	22/03	02/05	134	29					
	Germany	21/02	13/12	15	7	22/02	04/03	60	10					
	Lithuania	22/10	22/10	1	1									
	Netherlands					22/02	22/02	1	1					
	Poland	28/02	29/11	218	42	05/03	23/03	75	19					
	Russia	27/04	23/10	404	127	02/05	11/05	9	3					
	United Kingdom	07/02	31/12	86	19	01/01	22/02	290	50					
	Barents Sea	06/06	01/10	152	73									
	North Sea	27/12	27/12	4	1	22/02	22/02	2	1					
	White Sea	09/05	11/05	13	3	10/05	11/05	3	2					
BEWI04 Total		**07/02**	**31/12**	**1130**	**301**	**01/01**	**11/05**	**574**	**115**					**1704**
BEWI08	Denmark	23/02	29/10	84	22									
	Estonia	15/03	22/10	50	15									
	Germany					18/02	11/03	71	12					
	Latvia	19/03	26/04	115	23	13/03	24/03	24	8					
	Lithuania	26/03	16/04	92	17	12/03	13/03	11	2					
	Netherlands	08/11	17/11	37	10	17/02	18/02	3	2					
	Poland					11/03	11/03	1	1					
	Russia	05/05	21/10	583	157	12/03	23/08	221	50					
	Sweden	23/10	24/10	5	2									
	United Kingdom	20/01	26/12	94	18	14/02	17/02	21	4					

	Baltic Sea	22/10	22/10	1	1	11/03	11/03	1	1					
	Barents Sea	19/09	19/09	1	1									
	Gulf of Riga	14/03	19/03	19	6									
	Kattegat	24/10	24/10	1	1									
	North Sea	23/02	02/11	14	5	17/02	17/02	2	1					
	White Sea	04/05	03/10	19	6									
BEWI08 Total		**20/01**	**26/12**	**1115**	**284**	**14/02**	**23/08**	**355**	**81**					**1470**
BEWI09	Denmark	13/02	25/12	151	42	11/03	11/03	1	1	07/02	11/02	15	5	
	Estonia	12/03	09/11	36	13	20/03	01/04	49	13					
	Germany	10/02	22/11	11	4	16/02	11/03	66	15	28/01	06/03	148	33	
	Latvia	11/03	12/03	14	2	12/03	28/10	89	23					
	Lithuania					11/03	11/03	1	1					
	Netherlands	28/12	31/12	19	4	01/01	29/12	273	56	01/01	26/01	109	26	
	Russia	03/04	01/11	395	120	01/04	05/10	399	122					
	Sweden	10/03	10/03	1	1	28/10	28/10	1	1					
	United Kingdom	18/01	09/02	73	16									
	Baltic Sea	10/03	10/03	1	1	28/10	28/10	1	1					
	Barents Sea	31/05	28/09	87	38	11/06	28/09	157	58					
	Gulf of Finland	04/04	18/04	55	11									
	Gulf of Riga	10/03	11/11	94	27	20/03	09/10	11	5					
	Kattegat	09/03	10/03	3	2	28/10	28/10	1	1					
	North Sea	10/02	28/12	2	2	29/10	31/12	85	35	01/01	28/01	39	22	
	White Sea					06/05	07/05	8	2					
BEWI09 Total		**18/01**	**31/12**	**942**	**283**	**01/01**	**31/12**	**1142**	**334**	**01/01**	**06/03**	**311**	**86**	**2395**
BEWI11	Denmark	22/02	31/12	3671	94	01/01	31/12	2938	157	01/01	03/01	9	3	
	Estonia	05/04	01/11	27	3	01/10	28/10	105	17					
	Finland					22/04	22/04	2	1					
	Germany	22/02	22/02	7	1					03/01	03/01	1	1	
	Latvia	04/04	04/04	14	1	11/11	11/11	1	1					
	Russia	06/04	01/11	1725	170	22/04	28/10	1267	170					
	Sweden	03/04	04/04	12	2	21/04	21/04	9	1					
	United Kingdom	13/02	22/02	208	10					05/01	07/03	1169	63	
	Baltic Sea	04/04	04/04	17	1	22/04	13/11	9	3					
	Barents Sea	30/05	02/10	240	41	23/05	25/09	41	17					
	Gulf of Bothnia					22/04	22/04	2	1					
	Gulf of Finland	06/04	01/11	130	23	22/04	24/04	49	3					
	Gulf of Riga	04/04	03/11	94	6	28/10	11/11	36	14					
	Kattegat	03/04	03/04	25	1	21/04	14/11	6	2					
	North Sea	22/02	12/11	74	10	07/12	31/12	22	6	04/01	04/01	6	1	
	White Sea	04/05	29/05	116	25	20/05	22/05	46	3					
BEWI11 Total		**13/02**	**31/12**	**6360**	**388**	**01/01**	**31/12**	**4533**	**396**	**01/01**	**07/03**	**1185**	**68**	**12078**
BEWI12	Denmark					05/03	31/12	2906	81	01/01	06/03	109	6	
	Estonia					23/03	23/10	1112	28					
	Germany					03/03	05/03	260	3	04/03	04/03	14	1	
	Latvia					22/03	24/10	1897	34					
	Lithuania					22/03	22/03	2	1					
	Netherlands					03/03	03/03	5	1	04/01	04/03	34	6	
	Russia					29/04	06/10	6948	150					
	Sweden					20/03	26/10	181	4					
	United Kingdom					15/01	03/03	45	11	07/01	03/03	93	34	
	Baltic Sea					21/03	26/10	226	7					
	Barents Sea					21/05	03/10	487	22					
	Bristol Channel					13/01	02/03	2653	47	21/01	02/03	631	42	
	Gulf of Finland					26/04	06/10	38	4					
	Gulf of Riga					23/03	23/10	91	13					
	Kattegat					19/03	27/10	107	4					
	North Sea					03/03	17/12	16	2	04/01	04/03	30	3	
	White Sea					08/05	20/05	440	13					
BEWI12 Total						**13/01**	**31/12**	**17414**	**425**	**01/01**	**06/03**	**911**	**92**	**18325**
BEWI13	Denmark					25/02	19/03	2452	23					
	Estonia					24/03	08/05	717	46					
	Finland					30/09	30/09	2	1					

	Latvia					24/03	24/03	30	1					
	Lithuania					22/03	24/03	64	3					
	Russia					22/03	01/10	377	90					
	Sweden					20/03	20/03	5	1					
	United Kingdom					21/02	25/02	19	3					
	Baltic Sea					20/03	22/03	93	3					
	Barents Sea					21/05	21/05	1	1					
	Bristol Channel					13/01	24/02	1903	42					
	Gulf of Finland					01/10	01/10	1	1					
	Gulf of Riga					24/03	24/03	3	1					
	Kattegat					19/03	20/03	34	2					
	North Sea					25/02	26/02	165	2					
BEWI13 Total						**13/01**	**01/10**	**5866**	**220**					**5866**
BEWI16	Denmark					04/03	23/03	783	20					
	Sweden					23/03	10/06	1796	80					
	United Kingdom					20/02	03/03	21	3					
	Baltic Sea					13/05	16/05	68	4					
	Bristol Channel					13/01	03/03	2624	49					
	Kattegat					09/03	23/03	96	11					
	North Sea					03/03	04/03	41	2					
BEWI16 Total						**13/01**	**10/06**	**5429**	**169**					**5429**
BEWI17	Estonia					10/04	17/10	368	14					
	Germany					10/02	31/12	1735	81	01/01	09/02	243	40	
	Latvia					22/03	06/10	430	21					
	Lithuania					14/03	22/03	364	9					
	Netherlands					09/02	10/02	3	2	17/01	03/02	4	2	
	Poland					10/03	13/03	75	4					
	Russia					13/03	06/10	3999	142					
	Sweden					20/10	21/10	9	2					
	United Kingdom					21/01	09/02	351	20					
	Baltic Sea					25/02	13/11	614	30					
	Barents Sea					05/09	02/10	73	14					
	Gulf of Finland					11/04	12/04	2	2					
	Gulf of Riga					06/10	17/10	40	6					
	North Sea					09/02	13/02	24	3					
	White Sea					05/05	09/05	6	5					
BEWI17 Total						**21/01**	**31/12**	**8093**	**355**	**01/01**	**09/02**	**247**	**42**	**8340**
BEWI18	Denmark					22/03	07/04	407	17					
	Estonia					07/05	08/05	22	2					
	Latvia					08/04	06/05	682	29					
	Netherlands					21/03	22/03	8	2					
	Russia					08/05	09/10	145	14					
	Sweden					07/04	08/04	12	2					
	United Kingdom					21/01	21/03	1776	60					
	Baltic Sea					08/04	08/04	4	1					
	Gulf of Finland					08/05	08/05	8	1					
	Gulf of Riga					06/05	07/05	8	2					
	Kattegat					22/03	07/04	9	4					
	North Sea					20/03	22/03	74	3					
	White Sea					09/05	04/10	6	4					
BEWI18 Total						**21/01**	**09/10**	**3161**	**141**					**3161**
BEWI19	Denmark					26/02	21/11	865	52	23/02	06/03	225	13	
	Estonia					14/03	07/10	85	13					
	Germany					13/10	23/10	14	5	19/02	23/02	48	5	
	Latvia					16/03	11/10	776	27					
	Netherlands									19/02	19/02	6	1	
	Russia					07/04	27/09	599	118					
	Sweden					13/03	13/03	86	1					
	United Kingdom					21/01	31/12	2060	76	01/01	18/02	296	49	
	Baltic Sea					13/03	13/10	25	4	19/02	19/02	4	1	

	Barents Sea					29/08	15/09	5	5					
	Gulf of Riga					14/03	06/10	56	5					
	Kattegat					12/03	13/03	10	2					
	North Sea					26/02	22/11	56	14	18/02	04/03	34	4	
	White Sea					01/05	17/09	33	10					
BEWI19 Total						**21/01**	**31/12**	**4670**	**332**	**01/01**	**06/03**	**613**	**73**	**5283**
BEWI20	Denmark					24/11	31/12	82	33	03/02	06/03	241	33	
	Estonia					10/04	24/10	30	9					
	Germany					10/02	24/11	1870	31					
	Latvia					22/03	22/11	524	49					
	Lithuania					14/03	22/03	184	9					
	Netherlands					09/02	10/02	4	2					
	Poland					11/03	13/03	26	3					
	Russia					13/03	05/10	459	104					
	United Kingdom					21/01	09/02	533	20	10/01	02/02	89	24	
	Baltic Sea					25/02	23/11	65	8					
	Barents Sea					05/09	25/09	2	2					
	Gulf of Finland					11/04	11/04	1	1					
	Gulf of Riga					10/04	21/10	11	6					
	North Sea					09/02	08/12	47	4	05/02	01/03	25	8	
	White Sea					05/05	08/05	8	4					
BEWI20 Total						**21/01**	**31/12**	**3846**	**285**	**10/01**	**06/03**	**355**	**65**	**4201**
BEWI21	Denmark					03/12	13/12	24	11					
	Estonia					18/03	10/11	28	9					
	Germany					17/02	31/12	226	42	01/01	07/03	553	67	
	Lithuania					12/11	13/11	3	2					
	Netherlands					17/02	18/12	31	6					
	Poland					24/02	17/03	565	22					
	Russia					08/04	05/11	5833	170					
	United Kingdom					21/01	17/02	392	28					
	Baltic Sea					23/02	13/11	29	7					
	Barents Sea					01/06	02/10	210	18					
	Gulf of Riga					18/03	11/11	434	24					
	North Sea					17/02	17/02	2	1					
BEWI21 Total						**21/01**	**31/12**	**7777**	**340**	**01/01**	**07/03**	**553**	**67**	**8330**
BEWI22	Denmark					22/02	11/03	1638	18	04/03	06/03	116	3	
	Estonia					24/04	26/10	679	23					
	Germany					22/02	31/12	431	59	01/01	03/03	29	5	
	Latvia					24/03	27/10	778	34					
	Lithuania					26/10	27/10	38	2					
	Netherlands					21/02	06/12	708	17	04/01	03/03	516	60	
	Poland					28/10	28/10	4	1					
	Russia					25/04	06/10	816	45					
	Sweden					11/03	24/03	754	14					
	United Kingdom					21/01	21/02	1235	32					
	Baltic Sea					24/03	29/10	56	4					
	Barents Sea					13/07	26/09	2592	72					
	Gulf of Finland					25/04	06/10	30	3					
	Gulf of Riga					24/04	26/10	274	18					
	Kattegat					26/02	11/03	11	3					
	North Sea					21/02	29/10	52	3	04/01	04/03	23	6	
BEWI22 Total						**21/01**	**31/12**	**10096**	**348**	**01/01**	**06/03**	**684**	**74**	**10780**
BEWI23	United Kingdom					21/01	23/02	428	34					
BEWI23 Total						**21/01**	**23/02**	**428**	**34**					**428**
BEWI25	Denmark					07/03	09/03	18	3					
	Estonia					23/03	01/05	685	40					
	Germany					02/03	07/03	110	6					
	Latvia					23/03	23/03	1	1					
	Netherlands					02/03	02/03	4	1					
	Poland					09/03	23/03	361	15					
	Russia					02/05	17/10	405	91					
	United Kingdom					21/01	02/03	1023	41					

	Baltic Sea					07/03	23/03	14	3					
	Barents Sea					03/05	03/05	1	1					
	Gulf of Finland					01/05	02/05	36	2					
	Gulf of Riga					23/03	23/03	1	1					
	North Sea					02/03	02/03	3	1					
	White Sea					03/05	03/05	6	1					
BEWI25 Total						**21/01**	**17/10**	**2668**	**207**					**2668**
BEWI26	Belgium					31/10	31/10	5	1					
	Denmark					08/03	08/03	4	1					
	Estonia					09/03	05/10	1068	46					
	France					31/10	31/10	3	1					
	Germany					08/03	29/10	940	23					
	Latvia					24/03	07/10	256	14					
	Lithuania					07/10	07/10	2	1					
	Netherlands					08/03	31/12	2444	64	01/01	01/01	6	1	
	Russia					03/04	05/10	4605	111					
	Sweden					08/03	09/03	34	2					
	United Kingdom					21/01	31/10	1247	48	01/01	07/03	2548	67	
	Baltic Sea					08/03	26/10	64	7					
	Barents Sea					13/06	28/09	1288	33					
	Gulf of Finland					30/04	30/04	1	1					
	Gulf of Riga					09/03	06/10	98	9					
	Kattegat					08/03	08/03	19	1					
	North Sea					07/03	31/12	582	38	01/01	01/01	26	1	
	White Sea					29/09	30/09	12	2					
BEWI26 Total						**21/01**	**31/12**	**12672**	**403**	**01/01**	**07/03**	**2580**	**69**	**15252**
Overall Total		**18/01**	**31/12**	**9656**	**1271**	**01/01**	**31/12**	**111751**	**4760**	**01/01**	**07/03**	**8578**	**711**	**129985**