REPORT ON A RED-THROATED DIVER AGENT-BASED MODEL TO ASSESS THE CUMULATIVE IMPACT FROM OFFSHORE WIND FARMS

Report commissioned by the Environmental Group

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Data sheet

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Content

Summary

The local effect of the presence of offshore wind farms on the distribution of Red-throated Divers have been assessed in several studies. These results indicate that Red-throated Divers are less abundant within and around an offshore wind farm post-construction compared to pre-construction.

Such displacement does not cause direct mortality, and the local effect is therefore not easily assessed in terms of the impact on the population level. Hence an agent-based model was developed in an attempt to assess the impact of these displacements on the general population.

Model development was carried out using a Pattern-Oriented Modelling procedure which involved developing the model in an iterative cycle comparing model performance against real world data patterns via an inverse modelling procedure. The result is that the extent to which the model predicts impacts of windfarms correctly is directly related to the quality of real world test data available.

Having established the model we compared the potential impact of 3 wind farm development scenarios encompassing the full range of possible wind farm developments in the region covering the entire Baltic and the eastern North Sea from the Netherlands in the south to mid Norway in the north.

The assessments were based on TWO BASIC assumptions. FIRSTLY, that windfarm development removed habitat pro-rata by area and did not have a wider reaching implication for diver resources. Based on this assumption, evaluation of the simulations led to predictions of minimal impacts of the proposed windfarm developments. Primarily this was due to the avoidance behaviour of the divers, whereby they would fly around or over windfarms, rather than perceiving windfarms as barriers to movement. THE SECOND ASSUMPTION IS THAT THE DATA USED TO DEVELOP THE MODEL WAS REPRESENTATIVE OF THE DIVER POPULATION BEHAVIOUR. HENCE, the results presented here must be INTERPRETED IN THE LIGHT OF THESE ASSUMPTIONS AND THE AVAILABLE DATA.

1 Problem description

Red-throated Divers are long-lived birds with a high annual survival rate and a relatively low annual reproduction rate. Outside of the breeding season they have a strictly marine distribution. They appear in Danish waters during autumn, winter and spring. Hardly any Red-throated Divers appear in Danish waters in summer.

Red-throated Divers are protected in relation to the Danish Game and Wildlife Act and is listed under appendix C1 in relation to the EU Birds Directive. With this level of protection the species had attention in relation to Environmental Impact Assessments concerning offshore wind farms in Denmark and other EU countries. Experiences from Denmark and the United Kingdom indicate that Divers are displaced from offshore wind farm areas and their near surroundings.

The aim of the present work was to evaluate to which extent such displacements could potentially impact the species at the population or subpopulation level. The evaluation was performed for three scenarios of offshore wind farm development; one reflection the present status for the study area and two future scenarios with medium to high development rate. By this approach we also introduce a method to address potential cumulative impacts from anthropogenic activities.

The model was constructed to evaluate the impact of marine wind farms on Red-throated Divers, migrating through or overwintering in the inner Danish waters. The approach taken was to model the movement of divers to and from breeding locations using a density and environmental conditions function to determine their energy balance. The model should be able to simulate migration matching the patterns of birds found in the inner Danish waters by aerial counts.

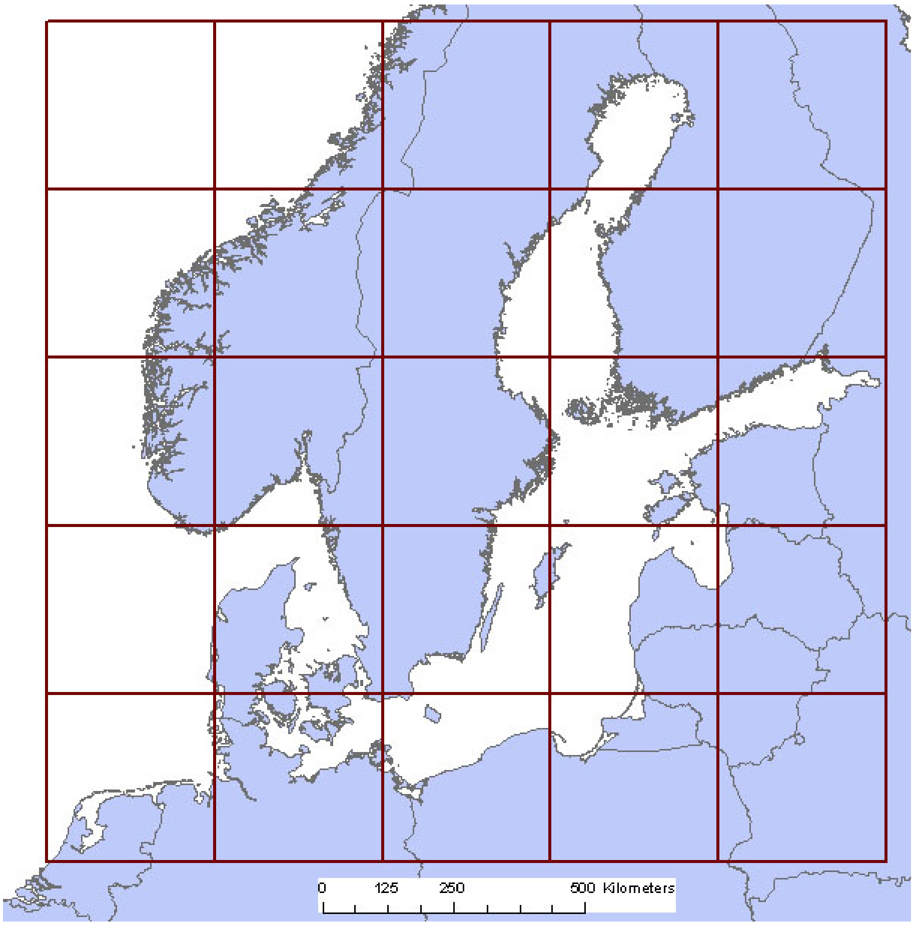
This was not a simple task since there is much information that is not known. For example, these birds are migratory and some spend the winter in this area, but not all and neither this proportion nor the total bird population is known. Additionally we know little about the details of migration for these birds, we primarily only have counts of stationary birds and observation of day migrations. Hence, there is no data currently available on migration routes, proportions of birds crossing landmasses, nor details of night migration. Another constraint is that we cannot measure direct impacts in the field, only avoidance. As a result impacts will be assessed as relative cumulative effects of disturbance to the migration route.

The study is part of The Environmental Monitoring Programme for the Danish offshore demonstration wind farms Horns Rev 1 and Nysted, administered by The Environmental Group consisting of The Danish Energy Agency, The Danish Nature Agency, Vattenfall and DONG Energy. The work was conducted under contract with Vattenfall Vindkraft A/S, and sponsored by the Danish energy consumers through a public service obligation.

2 Data Description

The model landscape covering the study area was created as a 500 x 500 m grid in a rectangular area (Figure 1), resulting in a total more than 1 million grid cells, of which less than 50% are in marine areas. The rectangular model area covers the entire Baltic Sea. To the south it covers most of the Dutch Wadden Sea. To the west the area extents ca. 200 km west of Jutland (see Figure 1).

Figure 1. The model area, divided into 25 squares. The entire study area covers more than 1 million grid squares.



The knowledge of winter distribution and temporal and spatial distribution patterns are poorly known. A description of general distribution patterns in Danish waters was made modelled from survey data for the winter of 2008, but the quality of the spatial model for divers prevented the use of that for this purpose (Petersen & Nielsen 2011). From previous surveys, surface covering density model estimates are only available within limited areas (Petersen et al. 2006a, 2010). Within four limited areas in the Danish waters surveys of divers have been carried out frequently from 1999 up until 2007. These surveys were all performed as part of EIA (Environmental Impact Assessment) and environmental monitoring programmes relating to offshore wind farm projects. The four areas are Horns Rev, Aalborg Bugt, Omø Staalgrunde and Rødsand (Figure 2). Data on spatio-temporal distribution of wintering/migrating red-throated diver from these four areas was used to calibrate the model.

Figure 2. The position of four Danish areas from which red-throated diver temporal and spatial distribution patterns was derived.

In addition migration timing was used for the calibration, extracting data from the Danish DOF-basen (www.dofbasen.dk), from the Swedish Artsportalen (http://www.artportalen.se/birds/default.asp) and from a migration observation point in northwest Estonia.

To all marine grid cells a bathymetric depth was extracted, using a bathymetric data set from the BALANCE project (http://www.balance-eu.org/). Likewise a distance to nearest coast was calculated for each grid cell. Modelled hydrographical data were obtained from the MyOcean platform (http://www.myocean.eu.org/). Sea surface temperature data were extracted to all marine grid cells for every sixth day through the year of 2008.

The positions of the offshore wind farms used in the scenarios are based on position input from the Danish Energy Agency.

2.1 General Approach

Agent-based model (ABM) - a general description

We designed and built an agent-based model (ABM) specifically for this project. An ABM is a computational model for simulating the actions and interactions of autonomous individuals in a defined virtual world, with a view to assessing their effects on the system as a whole. This is clearly analogous to integrating the response of individuals into a population response which, when considering impact assessment in ecology, is the level at which interest and protection goals are usually aimed.

Of course there are many models of ecological populations and many approaches, but there are a number of characteristics of ABMs which set them apart from other more traditional approaches. These characteristics can be broadly described as being their explicit consideration of spatio-temporal variability, and their ability to include individual behavior, with population responses being emergent features. Thus animal behavior such as patterns of movement can be simulated so that a dispersing animal moves in very different ways depending upon its type (e.g. bird, mouse, beetle, human), or condition (e.g. hungry, satiated). This provides a huge predictive potential compared to more aggregated approaches.

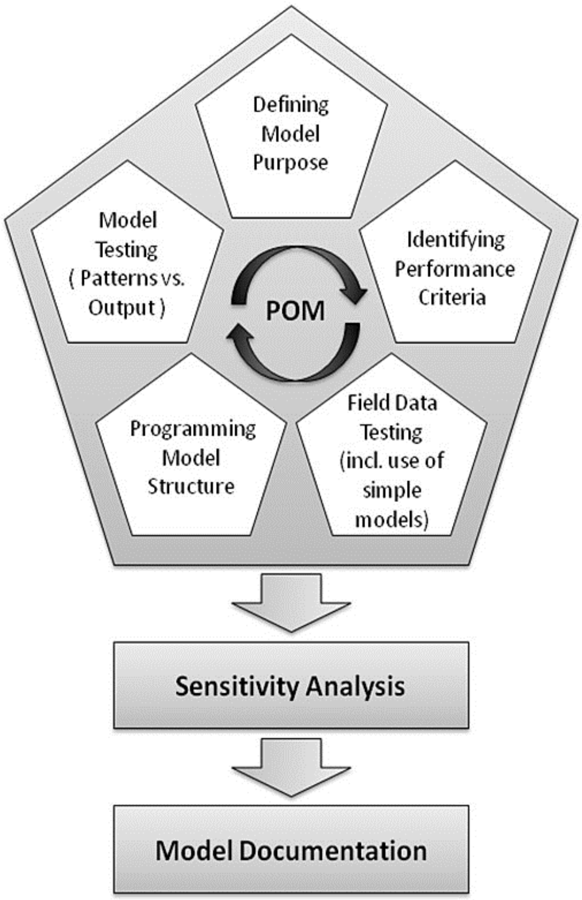
These properties have resulted in the use of ABMs in a wide and steadily increasing range of applications. In 1996 there were 31 agent-based papers published (source ISI Web of Knowledge), but by 2006 the number had risen to 494, and to date there are almost 1000 with ABMs as the main focus. Some varied examples include simulations of immune system responses to perturbations (Folcik et al. 2007); of ethnic diversity in economically and spatially structured neighbourhoods (Fossett and Senft 2004); of entry and exit routes to a baseball stadium under a range of conditions including simulation of terrorist attack (Redfish 2008); and of urban evacuation strategies (Chen and Zhan 2008). Current use of ABMs in risk and impact assessment is limited, but their usage in related areas is increasing. Recent developments include models of whale watching by tour boats, including evaluation of the risks to the whale population (Anwar et al. 2007), epidemiology (e.g. (Mikler et al. 2007, Muller et al. 2004)), the exploitation of limited renewable resource (Brede et al. 2008), and conservation (Mathevet et al. 2003, Satake et al. 2007). ABMs help understand biological systems because, unlike physical systems, there is heterogeneity in their components, and this heterogeneity affects the overall dynamics of the system (DeAngelis and Gross 1992, Louzoun et al. 2001); in short because variation in space and time matter in biological systems, and ABMs deal with this very well.

The model cycle

Agent-based models (ABMs) are gaining popularity in most scientific fields due to their ability to describe complex systems from first principles. Yet, they are also criticised for being 'black boxes' and impossible to fully understand. This is mainly due to the difficulty of testing, documenting and communicating the wealth of mechanisms built into such models. However, testing these complex adaptive models has been aided by recent advances in pattern-oriented modelling (POM (Grimm et al. 2005)), which is becoming a widely used framework (Grimm and Railsback 2005, Grimm et al. 1996, Wiegand et al. 2004, Wiegand et al. 2003). POM evaluates model behaviour and reduces parameter uncertainty by comparing model responses to real world data at multiple hierarchical levels. The greater the number of real world patterns the model can predict simultaneously the greater the confidence in the model.

In developing the red-throated diver ABM we have used a POM approach linked to the modelling cycle developed by Topping et al. (2010), (Fig. 3). This is an iterative process preceding a sensitivity analysis. At the point of writing this report we have developed the model to the point where sensitivity analysis can be carried out.

Figure 3. The model cycle showing an iterative testing and development cycle followed by sensitivity analysis and documentation.



There have also been recent advances in the documentation of ABMs. The Overview, Design and Detail protocol (ODD) (Grimm et al. 2006) attempts to divide the model description into overview and detailed sections. The latter section should provide enough information for reconstruction of the model by a third party. However, for large simulation models the ODD approach is impractical for documentation to the level that would allow replication of the model due simply to the volume of information required. On the other hand, simulation models are based on programming code, which provides the complete description of the model, but in a form only accessible to the experienced programmer. Hence, ideally ODD and code should be combined to form a comprehensive but approachable documentation. This approach was used by Topping et al. (2010) in developing the ODdox documentation protocol. ODdox extracts comments from the program code using doxygen (van Heesch 1997) to create a standard format documentation of an ABM, incorporating most of the features of ODD with a full software engineering documentation of the source code and has been implemented here for the red-throated diver model. ODdox is an html format, although its main page can be extracted and has been presented below under Current Model Description.

2.2 Specific model approach

Current model description

The model documentation source is the ODdox (html code accompanying this report), however to provide an idea of the model structure and processes the main page has been extracted as Appendix I. Note however, that the html code includes hyperlinks to the code where there is more information and the possibility of verifying the code itself. The text in Appendix I is therefore not to be considered the complete documentation.

Model development

Initially it was hypothesized that water temperature and prey (fish) availability might be the drivers for movement of the birds, in winter away from poor weather, in summer pressing against inclement gradient in order to reach the breeding season as soon as possible, whilst maintain fish supply. Unfortunately there is insufficient data on fish availability and dynamics to be able to predict this with any degree of certainty, hence this driver could not be used. The potential of a temperature driver was, however, tested during model development. As a result it was demonstrated that the birds could not be using this cue to move since both the timing and pattern of water temperature change did not match those of the divers. Hence, although early version (Version I), of the model used temperature and depth as primary drivers they could not re-create the temporal pattern of movement.

The major processes in action in Version I were therefore:

1. The date of starting migration from both winter and summer quarters
2. Location suitability assessment using water temperature and water depth as quality determinants.
3. A density-dependent factor decreasing location suitability with increasing bird density
4. A direction of preferred movement (summer or winter migration).

The next major model version (Version II), used depth and temperature but added a migratory urge driven movement. Hence the major difference between these two versions was:

1. The rate of movement was altered depending upon the distance to goal relative to the time left before the goal should be reached. Hence, birds with a long way to goal but a short time would move faster.

Version II provided a good temporal fit, but did not capture the spatial details of observed bird distributions. Major deviations were found in the number of birds that were present in the Danish waters in winter, and also in the pattern of movement of birds to and from the breeding ground. This pattern was more diffused than migratory bird observations would suggest.

The current version (Version III), of the model incorporated breeding ground location as a parameter enabling differentiation in direction, distance and timing of migration. This allowed differentiation in timing of migration movements and also in location of overwintering grounds. Version III differed from Version II in the following:

1. Each bird was given a specific breeding region. This region was assigned pro-rate based on input files describing the locations and proportion of population assumed to breed there.
2. The location of breeding area determined the timing of breeding migration. The further from the overwintering grounds the breeding location was the later migration would start towards them.
3. Given the rules specified for Version II above, this combination resulted in a system of migration typified by long-flights late in the season for long-distance migrating birds, and early short distance movement for birds with less distant breeding locations.

This form of the model was accepted as structurally capable and re-creating the diver real world observed diver patterns and was selected for further testing. Excellent fits to observational data we obtained (primarily to stationary bird counts), and this version was taken further to calibration and subsequent sensitivity analysis. This is a time consuming process due to the high dimensionality of the parameter space that needs to be tested. A more thorough description of the movement rules is given in the ADdox (Appendix 1, sections 3.2.2 and 3.2.3)

The Baltic population of Red-throated Diver was set to be 10,000 birds at the initiation of each simulation in this model, which must be regarded an arbitrary population size. The estimated population size for Red-throated Diver in Western Palaearctic is 150,000-450,000 (Delany & Scott 2006). The size of the Baltic part of that population is unknown, but is expected to be considerably higher than 10,000 individuals.

POM results

Pattern Oriented Modelling (POM) testing was carried out by comparing the deviation from observed bird counts in space and time to those created by the model. Initial testing utilized a single model run of 11 years, of which the first year was discarded before analysis. The average density of birds present in the counting areas was calculated over the remaining 10 simulation years. Note that these are not years in real time, but pseudo replicates of the same year. After initial screening, when fitting the model parameters 10 replicates of each parameter combination were used to avoid stochastic bias (although between run variability was very low).

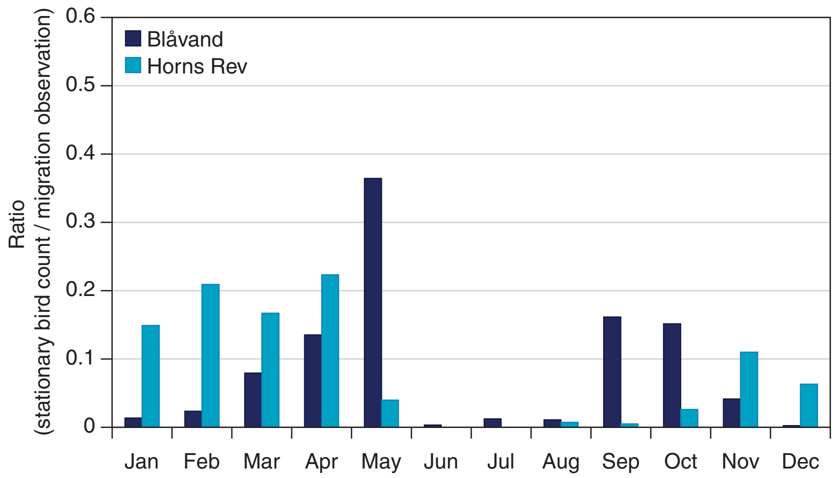


Figure 4. Comparison between migration observation and stationary bird counts for the same location. Note that there is considerable difference in the temporal distribution of birds between these two counting methods.

As noted above, two types of data were available for testing, density estimates from selected areas and migration observations from selected migration points. Since birds moving past a point may or may not rest near that point it is not expected that the two types of data will show similar pattern. Indeed a comparison of Horns Rev (Fig 4) demonstrates that there are considerable differences in the timing of peak numbers. As a result migration observation was only used as a secondary data set in the POM testing carried out for the model.

Input data for breeding areas was not varied during this process, however, these locations and proportions are critical to correct model functioning. The current values therefore represent the current state of our knowledge and since there is no way to sensibly select other realistic inputs these values were fixed for the duration of this testing.

Following the modelling cycle, all versions of the model were subjected to calibration in an attempt to find an acceptable fit to the observed diver spatio-temporal distributions. Figure 5 shows the best fit obtained using Version II of the model to observations of stationary wintering birds. Although this version captured much of the basic pattern, there were clearly large discrepancies between model and observation.

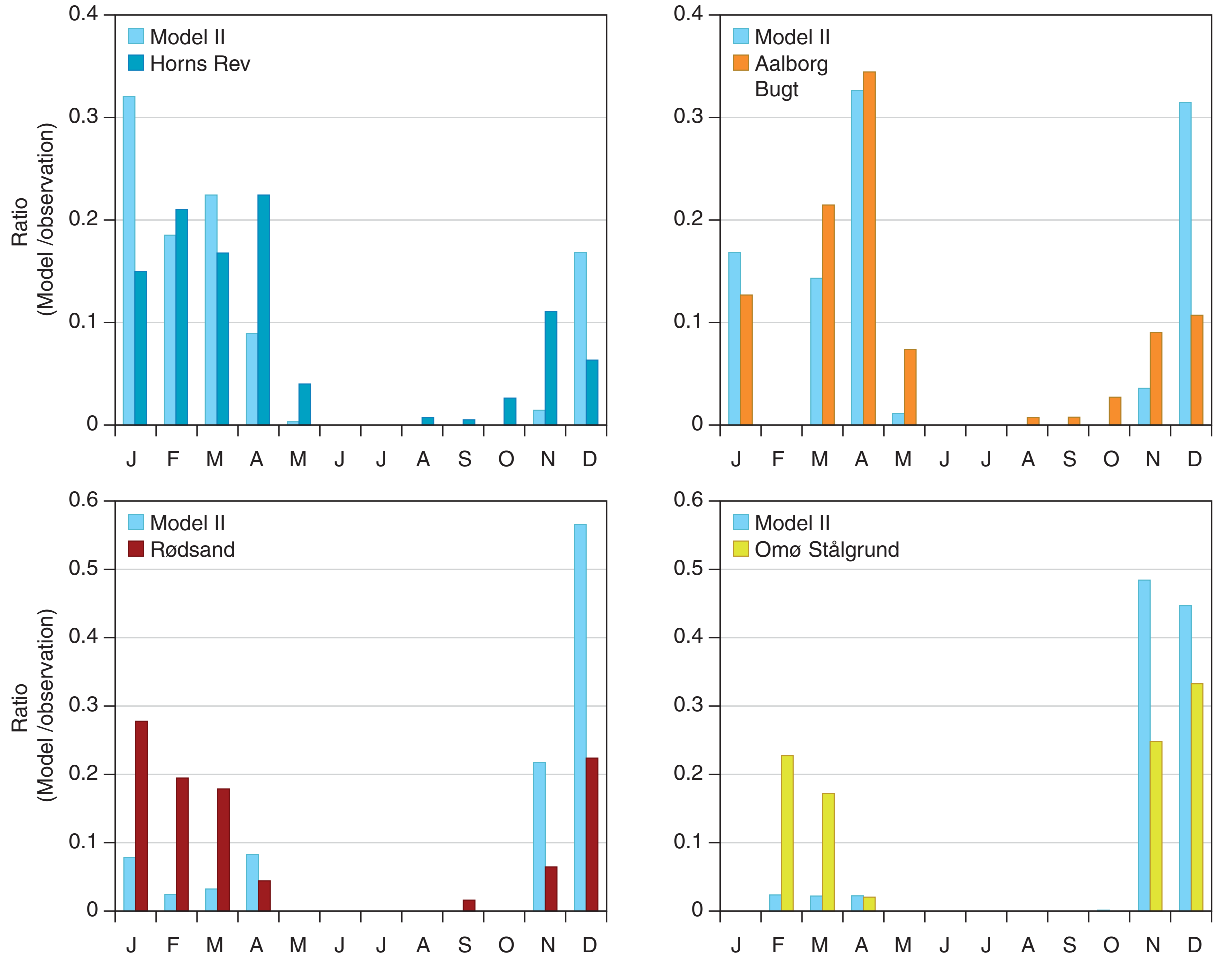


Figure 5. Model Version II best fit to observational data. y-axis is proportion of birds observed. A – Horns Rev; B – Aalborg Bugt; C – Rødsand; D – Omø Stålgrund. Note that Horns Rev and Aalborg Bugt have a better fit than the south easterly count areas.

Version III testing indicated a much better fit to the observed data than Version II and was subjected to an initial ad hoc hill climbing fitting process. This is demonstrated in Figure 6, where the reduction in squared differences is plotted against different parameter combinations. Stationary counts were considered to be of greater significance than migration observations (see above), hence migration observations were only used as a secondary guide to fitting. The results of the fitting were a very close fit to the stationary bird counts, and an acceptable fit to migration observations (Fig. 7). Since the variation in real world observations is likely to be large (Petersen et al. 2006b), further refinements to the fit were considered unnecessary.

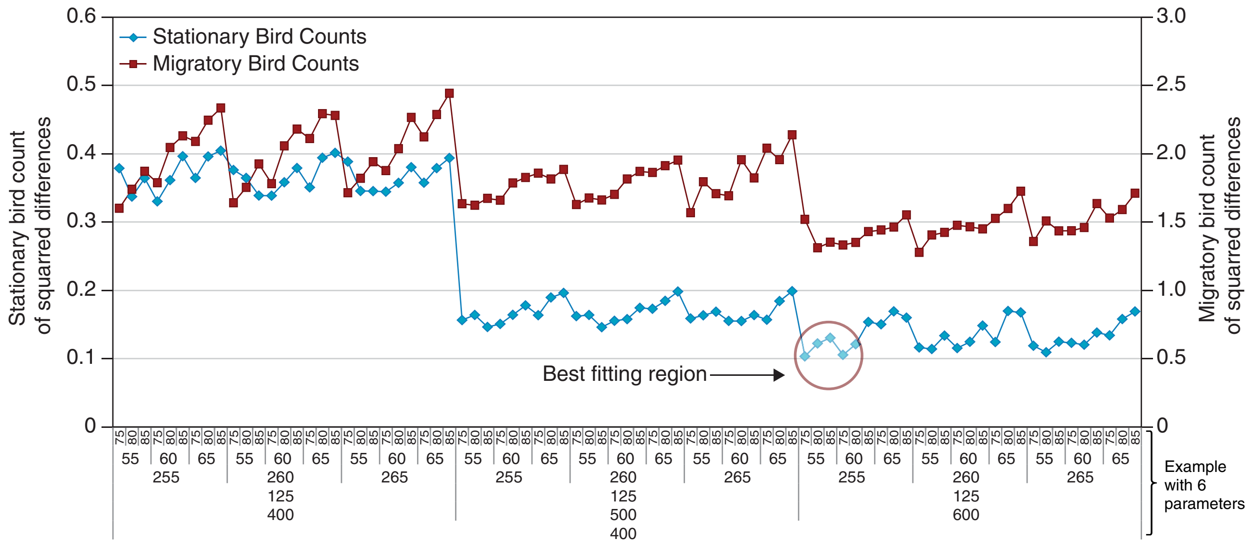


Figure 6. Example Result of POM testing showing the result of varying parameters on squared difference statistics.

During this fitting process two interesting observations resulted. The first is that the only way a good fit could be obtained was to have a delay in long-distance migration starting day of more than 60 days. Secondly, the fit was not improved by delaying the return date from breeding grounds to the migration jumping-off point. This may indicate more synchronised return, but migration to the breeding ground being subject to behavioural or environmental constraints.

An example of the visual appearance of a model run is given in Figure 8, where a spring situation is shown.

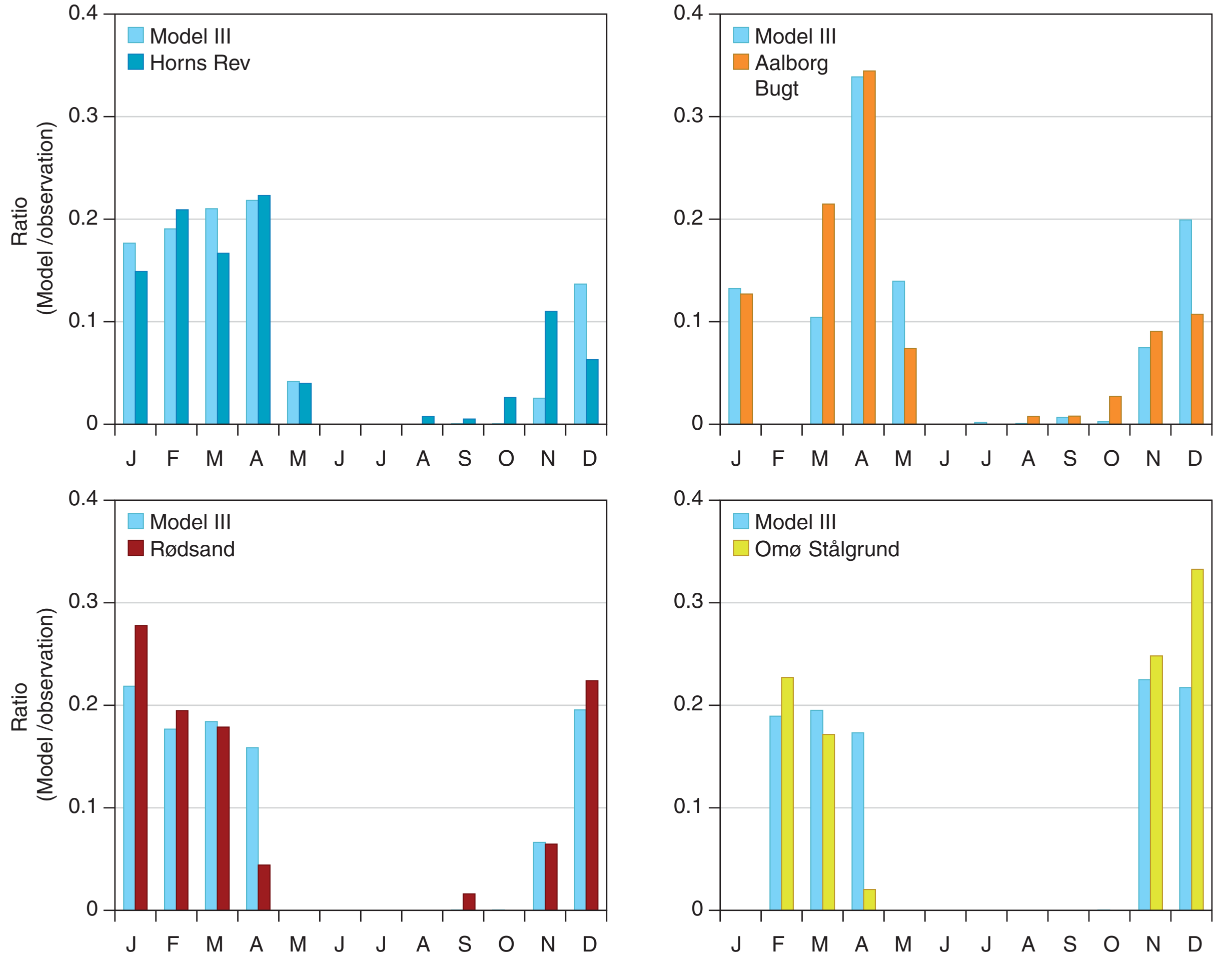


Figure 7. Version III best fit between model and observational data of stationary birds. A – Horns Rev; B – Aalborg Bugt; C – Rødsand; D – Omø Stålgrund. There are still some inconsistencies but these were not considered critical due to the innate variability of real world counts.

Table 1. Final fitted parameter values used for sensitivity analysis and subsequent scenario simulations.

Parameter No.	Parameter Name	Fitted Value
1	WINTER_TARGETX	848
2	RETURN_FROM_WINTER	34
3	MAXDAYVARIATION	72
4	RETURN_FROM_BREEDING	242
5	DEPART_BREEDING	130
6	CLOSE_ENOUGH	403
7	DIST_SHORE	1078
8	MIN_DEPTH	6
9	MAX_DEPTH	39
10	DENS_HIGHTHRESH	34
11	DENS_LOWTHRESH	3
12	TEMP_THRESH	3
13	EN_MAXFLIGHT	1000
14	EN_FLYING	2
15	EN_FOODINTAKECONST	300
16	EN_RESERVE_MAX	1575

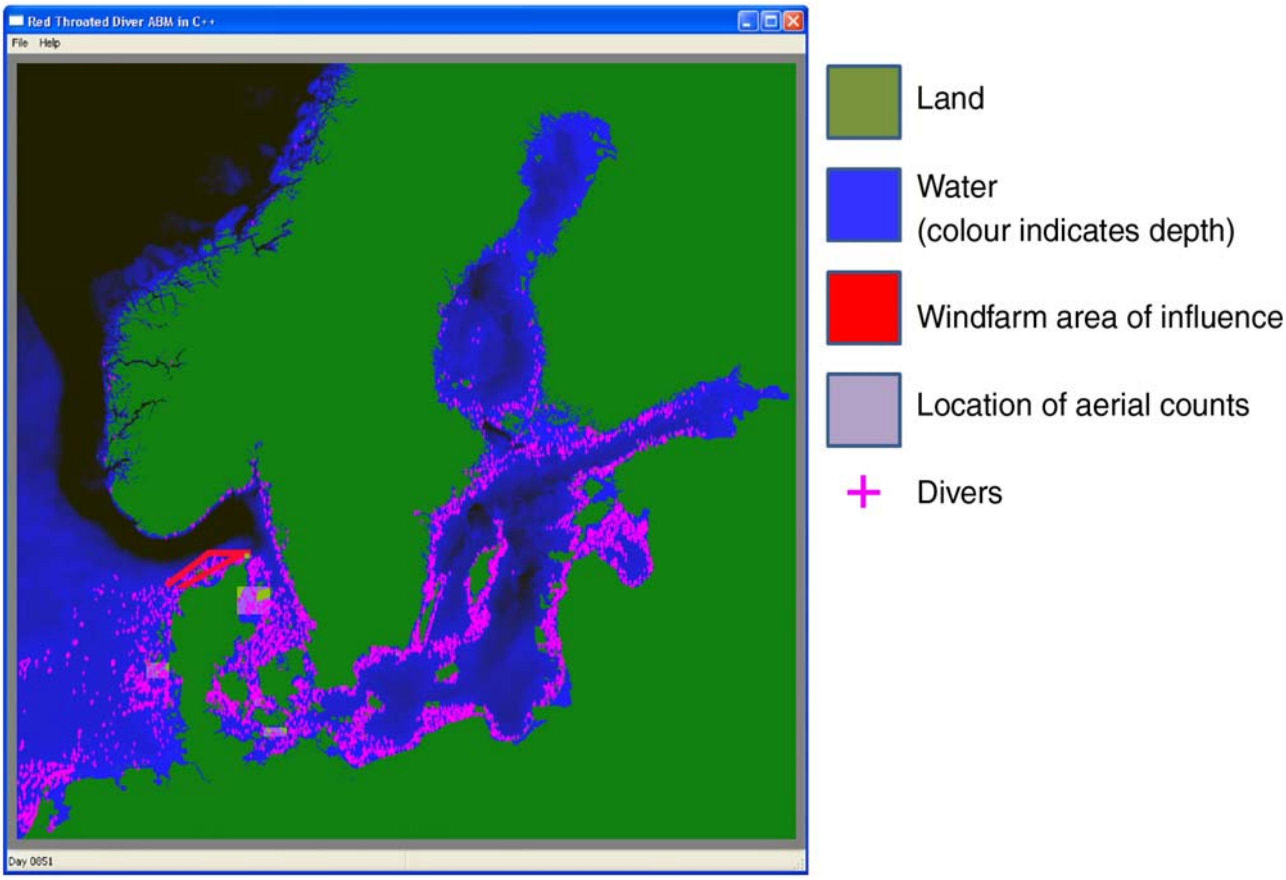


Figure 8. An example of the visual appearance of the model run for a spring migration situation. The position of wind farms and the location of the aerial surveys are difficult to see under the diver dots.

3 Sensitivity Analysis

Once the model had been calibrated to obtain an acceptable fit, the model parameters were subjected to a sensitivity analysis. This was achieved by varying each parameter in turn by ±5%, 10%, 20%, 40% and 80%. For some parameters where the low integer values did not allow for this variation the range was either and/or restricted to integer steps e.g. lower density dependence threshold (DENS_LOW_THRESH).

The results of the sensitivity analysis are presented below for each parameter in turn, and the function of each parameter is explained. Each graph shows two response variables, population size and a measure of fit. Population size was the number of extant birds of an initial population size of 10,000 individuals after 10 simulation years, whilst the measure of fit was the sum of squared differences between the proportions of birds seen at each survey location and date in the model compared to the real world observation. Note that the upper limit for poor fit to the real world data were fixed as 1.0. Hence values greater than 1.0 were truncated to 1.0 which indicates a near complete mismatch between real world and model.

3.1 Parameter 1 WinterTargetX

This parameter controls bird migration direction in winter. Its function is to provide an x-coordinate target which forms part of the information from which an individual birds winter location can be determined. Each bird has a breedingjumpx, breedingjumpy, breedinggoalx, breedinggoaly, assigned as being one of the breeding locations and associated point of departure from the sea. The bird's winter target location was calculated by:

$$winterLocationX = breedingjumpx\,(\tfrac{t}{d}) + WinterTargetX$$

$$winterLocationY = breedingjumpx\,(\tfrac{t}{d}) + maxY$$

where:

d = distance between WinterTargetX,maxy & breedingjumpx,breedingjumpy coordinate pairs

$$t = (e^{-f^{0,25}}) - (e^{-g^{0,25}})$$

f = distance between *WinterTargetX,maxY* and the *breedinggoalx,breedinggoaly* coordinate pairs

g = distance between *WinterTargetX,max*Y and the furthest *breedinggoalx,breedinggoaly* coordinate pairs

maxy = most southerly y-coordinate (in this case 3200). NB NW corner of the map is 0,0.

Varying the WinterTargetX parameter from its chosen value (848) produced large impacts on fit, with a value of 200 resulting in a model out of bounds condition (designated as 1.0 on the deviation from fit axis). Population density was however, less sensitive to this parameter.

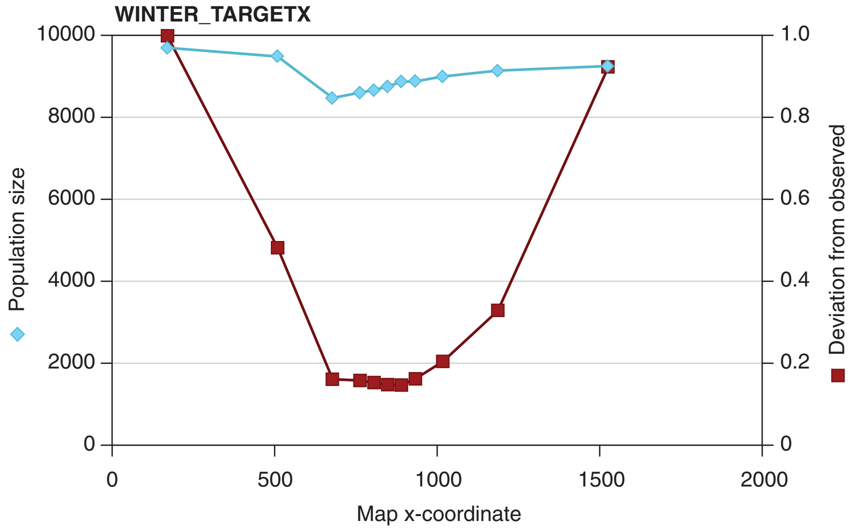


Figure 9. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter WINTER_TAGETX. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.

3.2 Parameter 2 RETURN_FROM_WINTER

This parameter fixes the day the divers return from their wintering grounds. Each diver will have its own date for return based on this date with modification for distance to be travelled by MaxDayVariation (parameter 3). The fit parameter showed a clear optimum, but was not particularly sensitive. Chosen value = 34.

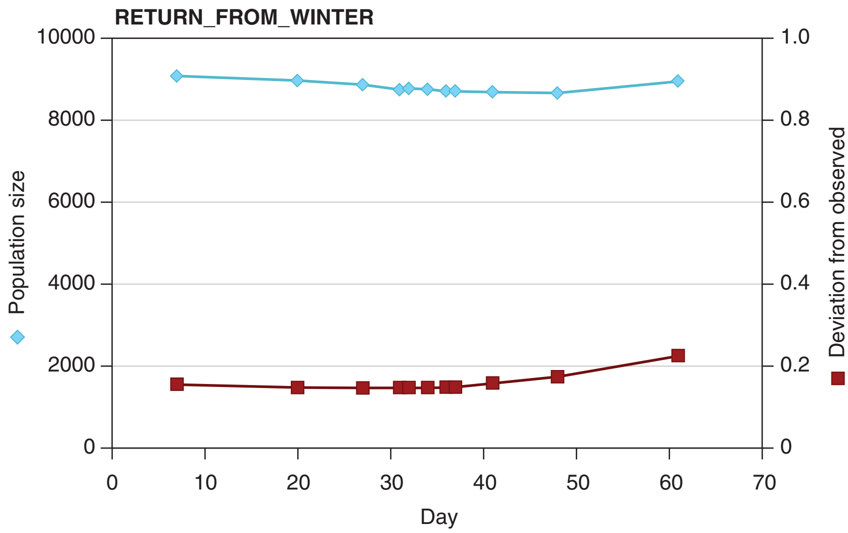


Figure 10. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter RETURN_FROM_WINTER. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.

3.3 Parameter 3 MAX_DAY_VARIATION

This parameter controls the variation about the date of return from overwintering grounds as a function of the distance between winter and breeding grounds. MaxDayVariation is the maximum difference permitted and the delay for each breeding location is determined proportionally to the distance between the two locations. Hence, the breeding location furthest from its winter location will have MaxDayVariation added to the WinterReturnDay (parameter 2). This parameter affected both the fit and population size. There was a clear optimum for fit, but the response of population density was weakly 'V'-shaped. The increase in population size after value 80 was a function of a number of birds not making the full migration, and hence increasing survival. This effect was also seen in other parameters when values went out of sensible bounds. The value of 72 days fits well with the maximum expected variation in return dates between short and long distance migrants (see discussion). Chosen value = 72.

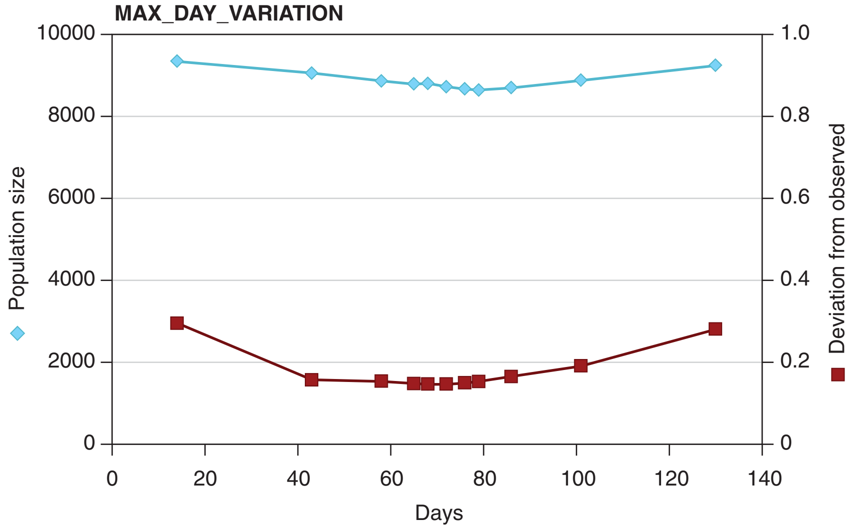


Figure 11. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter MAX_DAY_VARIATION. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.

3.4 Parameter 4 RETURN_FROM_BREEDING

This parameter determines the date of initiating return from breeding for all birds. On this date, all birds will return to a location with suitable depth and distance to coast within 100km of their particular breedingjump, breedingjumpy coordinate. The deviation from observed measure for this parameter showed flat central response to the parameter values tested, but a steep decline in fit with extreme parameters. Selection of this parameter was therefore done by choosing one of the optimum values that made sense in terms of the real world observational data, but also where a reasonable level of population loss occurred. This ensured that the model was in a sensitive range and could respond to changes due to scenario inputs. Chosen value = 242.

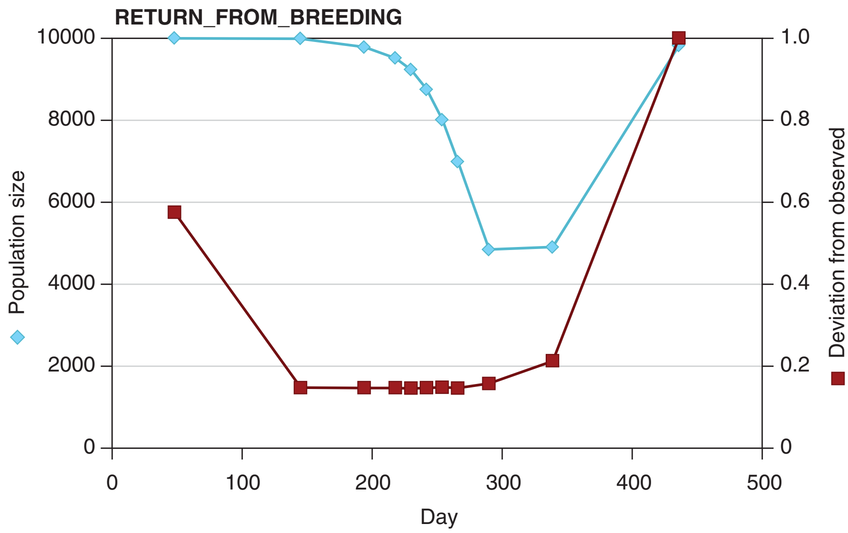
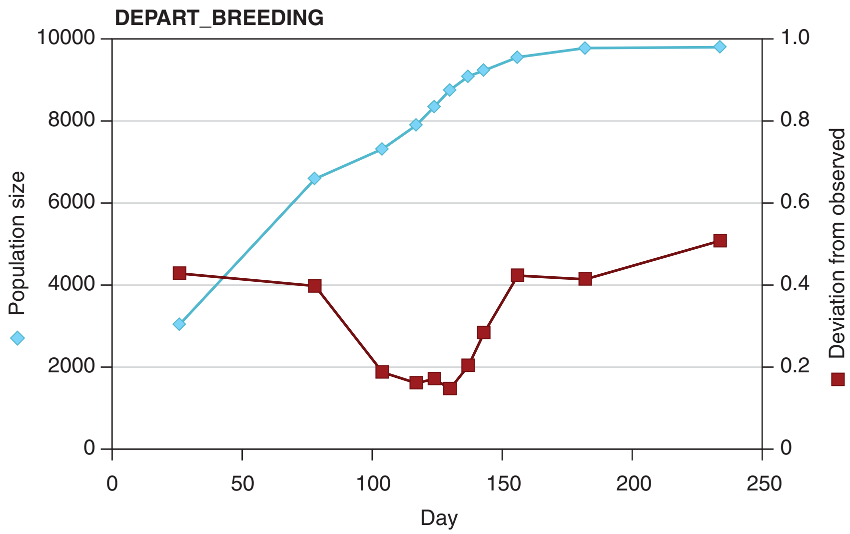


Figure 12. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter RETURN_FROM_BREEDING. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.

3.5 Parameter 5 DEPART_BREEDING

This parameter represents the date at which the birds should arrive at the jump off point from the sea to fly to their breeding grounds (i.e. the point at which they temporarily leave the simulation). This parameter showed a clear optimum and affected the fit and population levels significantly. The final parameter value fits well with expectations of when the first birds would arrive at breeding jump off points. Chosen value = 130, or 9th May.

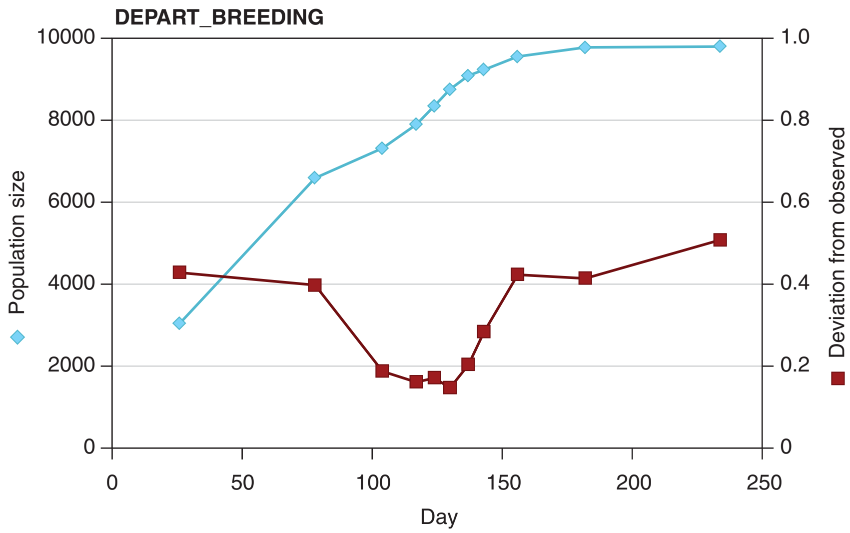
Figure 13. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter DEPART_BREEDING. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.



3.6 Parameter 6 CLOSE_ENOUGH

This parameter is the distance to a target (e.g. breeding jump off coordinate) within which the diver is assumed to have reached the target and no longer moves following migration rules. This parameter's primarily function is to generate a dispersed pattern of diver positions in over-wintering areas, although it also functions to prevent build up of divers at jumping off locations. Measure of fit was particularly sensitive to this parameter as might be expected, but population size was also affected with the more precise requirements resulting in loss of birds. Chosen value = 408.

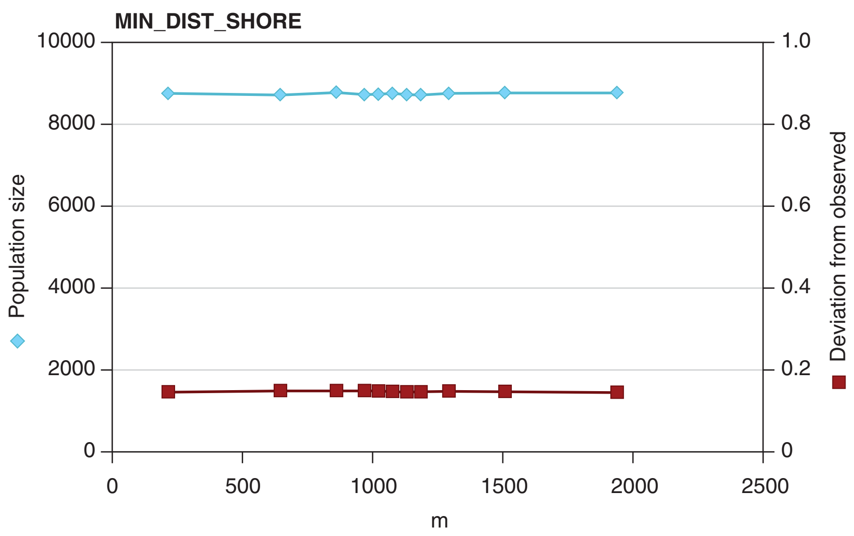
Figure 14. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter CLOSE_ENOUGH. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.



3.7 Parameter 7 MIN_DIST_SHORE

This parameter restricts the minimum distance a bird can be placed from the nearest shore. Although necessary to prevent birds actually being on land, and well documented in terms of observations that birds do not come close to shore, the model is not sensitive to this parameter with this configuration and chosen parameter values. This is due to the redundancy between this parameter and MIN_DEPTH. Should MIN_DEPTH be set to low values, then MIN_DIST_SHORE will become important; alternatively if areas with deep water were close to shore this parameter will also become useful. Since neither of these situations pertain, this parameter could be removed from the model. Chosen value = 1078.

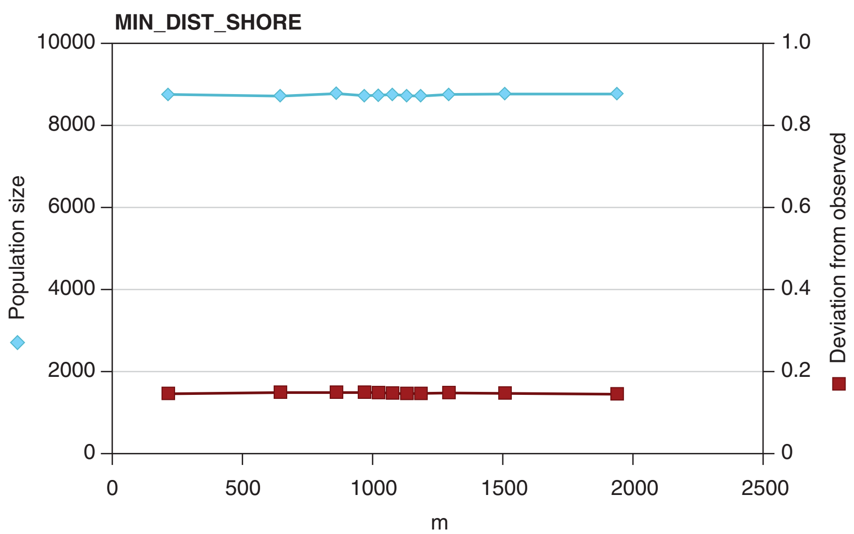
Figure 15. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter MIN_DIST_SHORE. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.



3.8 Parameter 8 MIN_DEPTH

This parameter fixes the minimum depth (m) which can be considered as suitable diver habitat. This value interacts with MinDistShore in that high values of MinDepth will invalidate locations near shore. High parameter values result in poor fits and lowered populations, but at lower values, fitting with observation of real birds, the measure of fit is relatively insensitive. Chosen value = 6.

Figure 16. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter MIN_DEPTH. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.



3.9 Parameter 9 MAX_DEPTH

Similarly to MinDepth, this parameter delimits diver habitat to being below the parameter value (m). The optimum fit was obtained at 36m, but the major pattern of response looks close to a threshold response. Clearly a maximum value of less or equal to the minimum value causes extinction due to exclusion from all areas. Again like MIN_DEPTH, within a sensible range the model was relatively insensitive to this parameter. Chosen value = 36m.

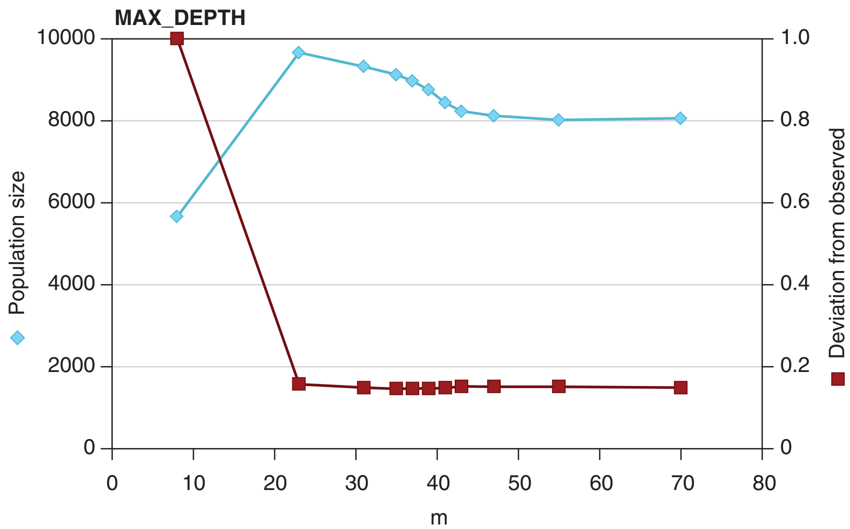


Figure 17. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter MAX_DEPTH. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.

3.10 Parameter 10 DENS_HIGH_THRESH

This parameter fixes the number of birds present in a cell at which the density results in a quality assessment of that cell of zero (i.e. totally unsuitable). This parameter together with the next parameter (LOW_DENS_THRESH) define the linear slope of the response to density. A weak optimum measure of fit was found at 34, but there was a strong threshold response starting below 30. Population size was relatively insensitive to this parameter. Chosen value = 34.

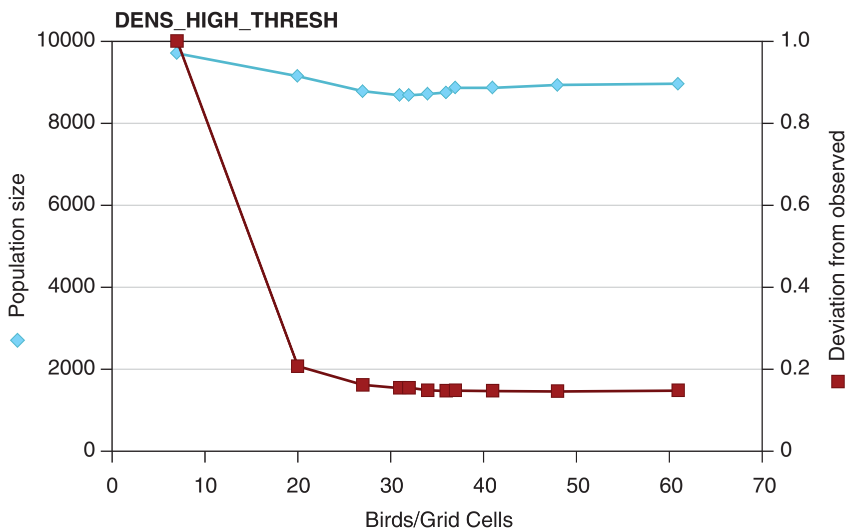


Figure 18. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter DENS_HIGH_THRESH. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.

3.11 Parameter 11 DENS_LOW_THRESH

This parameter fixes the number of birds present in a cell below at which the density does not reduce the cell quality. This parameter together with the previous parameter (LOW_HIGH_THRESH), define the linear slope of the response to density. The result is that at this density the quality of a cell is unaffected, but quality decreases linearly to zero (at DENS_HIGH_THRESH) with increasing density. Population size was insensitive to this parameter, whilst measure of fit showed slightly stronger response, but only at zero. Chosen value = 3.

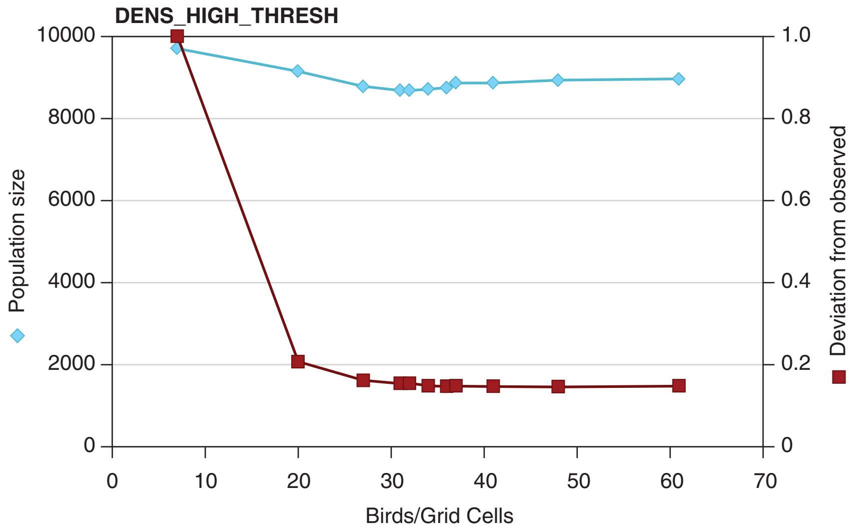


Figure 19. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter DENS_LOW_THRESH. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.

3.12 Parameter 12 TEMP_THRESH

Defines the temperature at which cell quality is 100%. Below this value cell quality is linearly reduced to zero at 0°C. Measure of fit was sensitive to changes in this parameter above the chosen value of 3.0. Population number was relatively insensitive.

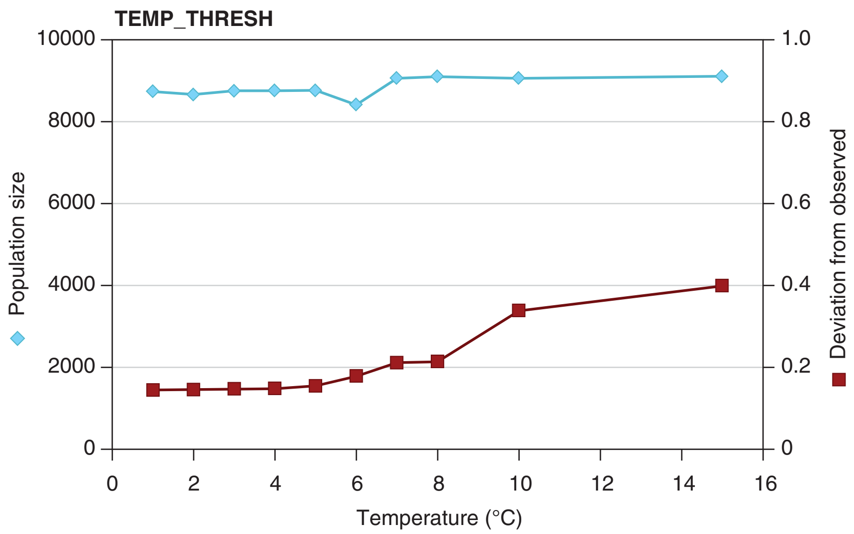


Figure 20. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter TEMP_THRESH. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.

3.13 Parameter 13 EN_MAXFLIGHT

Defined as the maximum number of cells a bird may traverse in a single flight. This parameter sets the extreme distance possible for a single flight and thus also defines the maximum possible search radius for suitable grid cells to move to. This parameter together with EN_FLYING and EN_FOODINTAKECONST and EN_RESERVE_MAX determine the energetics of flight and therefore migration potential. Since energy loss leads to death in the model these parameters also affect population size. Both population size and measure of fit were sensitive to this parameter. Chosen value = 1000.

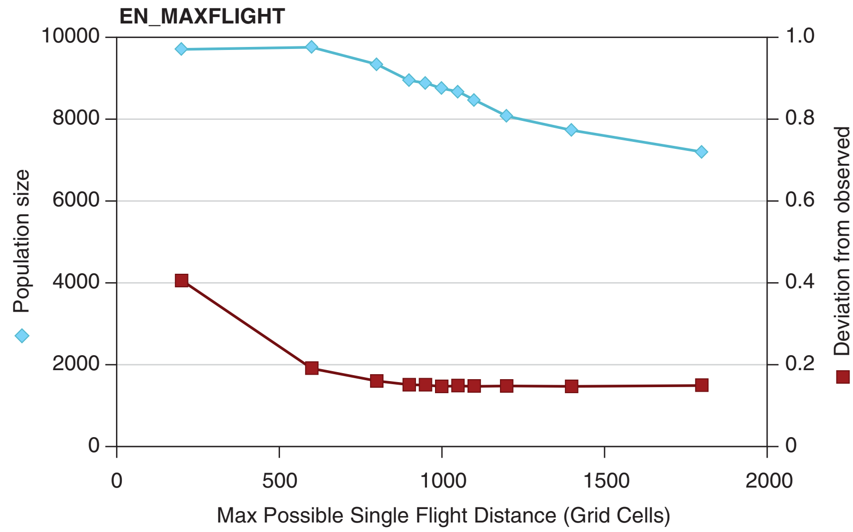


Figure 21. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter EN_MAXFLIGHT. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.

3.14 Parameter 14 EN_FLYING

This parameter defines the number of energy units used to traverse a grid cell when flying. These energy units are arbitrary; hence the value has no real world meaning. Population size was highly sensitive to this parameter, and there was a clear optimum value for measure of fit at 2.0.

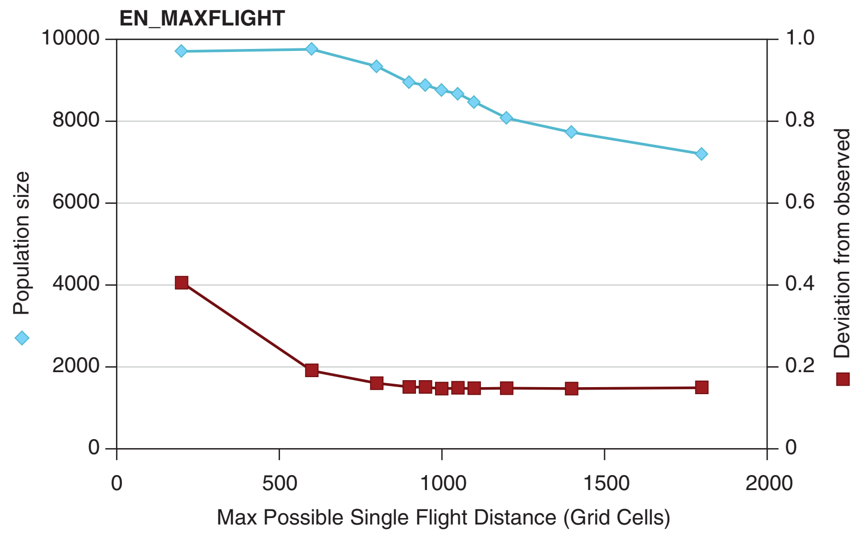
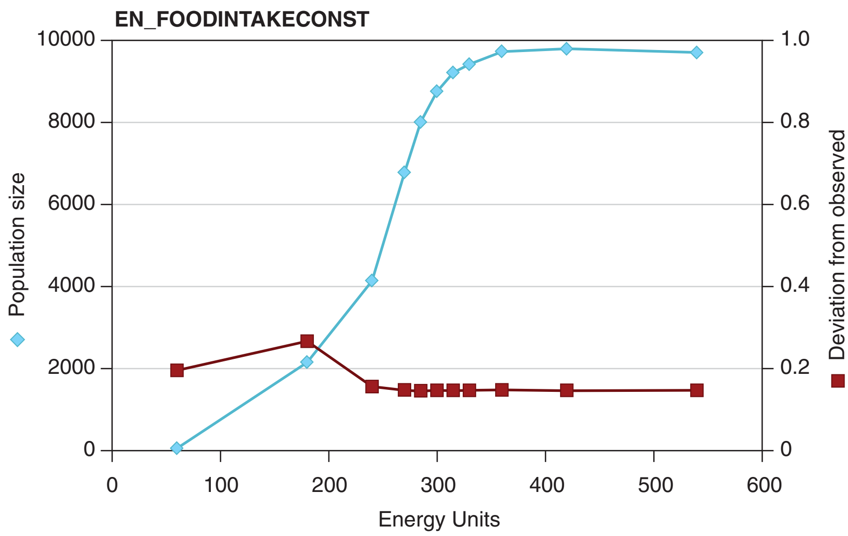


Figure 22. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter EN_FLYING. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.

3.15 Parameter 15 EN_FOODINTAKECONST

This is the rate of intake in energy units per day in perfect habitat (i.e. max quality grid square). This value is reduced by any reduction in cell quality due to density or water depth. Hence if no other birds are present in perfect depth conditions the bird will receive EN_FOODINTAKECONST energy units per day. As expected this parameter behaves very much the same was as EN_FLYING, with very high population sensitivity. Chosen value 300.

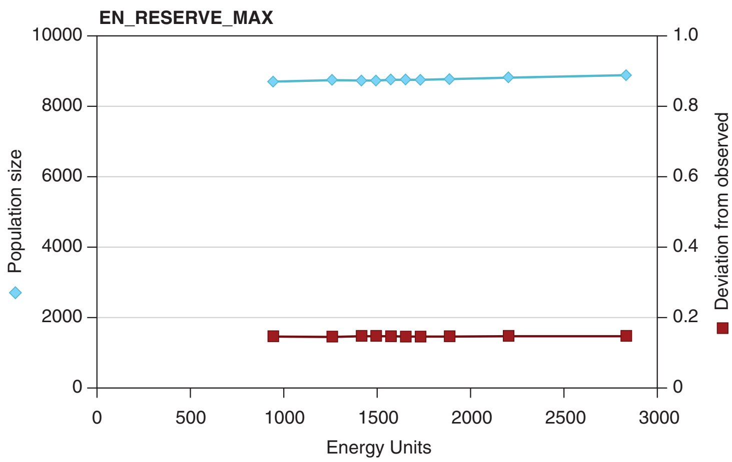
Figure 23. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter FOOD_INTAKECONST. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.



3.16 Parameter 16 EN_RESERVE_MAX

This parameter prevents birds accumulating too much energy. It provides a ceiling above which further energy resources are not utilized. The model was not particularly sensitive to this parameter although there was a weak optimum fit. This indicates that population loss occurred in extreme conditions and that for the vast majority of birds this parameter played no significant role. Chosen value = 1575.

Figure 24. Changes in model endpoints (population size at the end of a ten-year simulation and the measure of fit to observed data) with changes in the parameter EN_RESERVE_MAX. Parameter values are varied geometrically within possible ranges around a centre point chosen as the best fit.



4 Sensitivity Summary

Of the 16 parameters tested the model was relatively sensitive to ten, either in measure of fit, population size or both. CLOSE_ENOUGH and TEMP_THRESH were the only two parameters that only had major impacts on measure of fit. RETURN_FROM_BREEDING, WINTER_TARGET_X, DEPART_BREEDING, and EN_MAX_FLIGHT had impacts on both output signals, and EN_FOODINTAKECONST, EN_FLYING, MIN_DEPTH, RETURN_FROM_WINTER only impacted population size. The model was therefore most sensitive to dates of breeding departure and return, and to the parameter that directs the direction of winter migration. EN_MAX_FLIGHT indirectly determines the number of steps needed to complete a migration and therefore has a large impact on both survival and measure of fit.

4.1 Scenarios

The sensitivity analyses was performed for three scenarios of offshore wind farm development in the Danish parts of the North Sea and in the Baltic. The scenarios are based on input from the Danish Energy Agency. The Scenario 1 is a description of the 2010 development stage of offshore wind farms in Danish waters and an not complete description of existing offshore wind farms in the remaining parts of the Baltic (Figure 25). Two Swedish offshore wind farms in Kalmarsund are not represented. In the Scenario 2 all wind farms from Scenario 1 are present, along with those covered by the development plan for offshore wind farms as published by the Danish Energy Agency (Figure 26). With Scenario 3 we have included plans reaching further into the future, both for Danish and Baltic waters (Figure 27). The Scenario 3 contains all wind farms from Scenarios 1 and 2 and in addition to that it has a collection of sites with no or very initial legal process. The Scenario 3 can thus be regarded as a speculative one. These data were collated by the Danish Energy Agency.

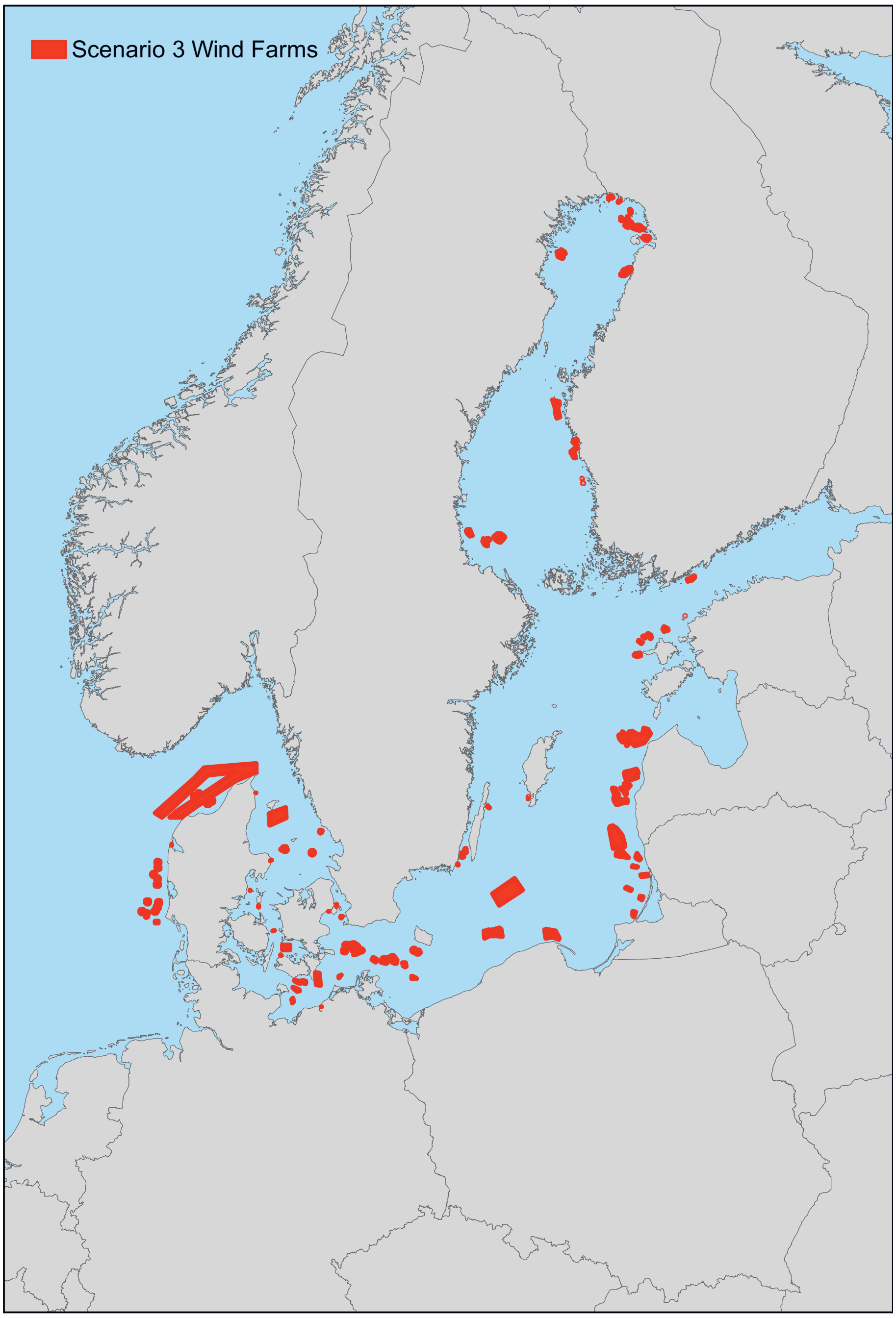
Description

The model was used to evaluate the three scenarios as a whole, for populations designated as near (breeding grounds in Norway & Sweden), intermediate (breeding grounds in Finland) and far (breeding grounds in Russia). Each scenario was run 120 times at which point confidence limits between scenario results did not overlap.

Figure 25. The size and distribution of existing offshore wind farms in late 2010. These wind farms represent the wind farm distribution of Scenario 1 in this report.

Figure 26. The size and distribution of existing offshore wind farms in late 2010 as well as potential future offshore wind farms in Danish waters. These wind farms represent the wind farm distribution of Scenario 2 in this report.

Figure 27. The size and distribution of existing offshore wind farms in late 2010 as well as speculative future offshore wind farms within the study area as provided by the Danish Energy Agency. These wind farms represent the wind farm distribution of Scenario 3 in this report.



The endpoint used for these scenarios was the total number of birds extant after 10 simulation years (denoted as population size). Given the results of the sensitivity analysis this endpoint was clearly sensitive to changes in the model and was therefore considered a reliable measure of impact on the population.

Bird death, the model outcome affecting the endpoint was as a result of a bird having a negative energy balance. The energy balance is affected by the energy intake of the birds and their expenditure (Appendix 1, section 3.2.3.b). Expenditure is in terms of movement, whilst intake is affected by the quality of the grid unit in which the bird finds itself, and the number of other birds there. The quality of the grid unit is determined by depth of water, distance to shore and temperature. It is therefore dynamic, changing with season as temperature changes. Movement is described in detail in sections 3.2.2a & 3.2.3a of the ODdox. As a result of these movements new energetic intakes are calculated. The precise pattern of depth profiles will therefore have a large impact on the patterns of death.

Wind farms will affect the population size endpoint by removing habitat from the model. There is an assumption that the birds will simply avoid wind farms by a distance of 500m (incorporated in the red areas, Figures 25-27, Percival 2010). Model birds may fly over or round these obstructions, in effect treating them precisely as dry land. Collisions with wind turbines are not incorporated in this model.

5 Results

The primary result of the scenarios was that there was a detectable, but very small impact of the wind farm scenarios on the number of extant birds. Even scenario 3, where 60,000 grid cells were transformed into wind farms resulted in < 2% change in the population levels (Table 2).

Table 2. The mean population estimates for 180 model iterations for scenario 1 (S1), scenario 2 (S2) and scenario 3 (S3) respectively, modelled for the entire model population. Standard deviation and 95% confidence intervals are given. "Difference" indicates the modelled change in population size, where negative values indicates a population decline.

	S1	S2	S3
Mean	8790.0	8782.7	8639.9
SD	159.0	134.6	132.2
N	180	180	180
95% ci	23.2	19.7	19.3
Difference	NA	-0.1%	-1.7%

Indications were that populations classified as intermediate has larger impacts, but still in the region of 2%. (Table 3).

Table 3. The mean population estimates for 180 model iterations for scenario 0 (S0), scenario 1 (S1) and scenario 2 (S2) respectively, modelled for three migration strategies, far migrating populations (Far), short migration populations (Near) and intermediate migration populations (Intermediate). Standard deviation and 95% confidence intervals are given. "Difference" indicates the modelled change in population size, where negative values indicates a population decline.

	Far			Near			Intermediate		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
Mean	9074.2	9062.5	9018.7	9124.2	9116.4	9007.7	8781.3	8761.1	8625.9
SD	54.0	55.1	57.6	43.1	40.8	46.6	100.2	126.5	121.6
N	180	180	180	180	180	180	180	180	180
95% ci	7.9	8.0	8.4	6.3	6.0	6.8	14.6	18.5	17.8
Diff (%)		-0.1%	-0.6%		-0.1%	-1.3%		-0.2%	-1.8%

6 Discussion

6.1 Insights obtained & future development

Via model development and then subsequent parameter fitting we can conclude that a number of the assumptions we had made at the outset of the project were not valid. Key insights obtained in this process are:

1. That water temperature is a very poor explanatory variable for determining diver migratory movement. This is interesting because water temperature would be a good correlate with poor weather and forage conditions, it therefore appears that the birds are not optimizing their foraging via migration, but have other constraints. These are probably related to breeding site conditions.
2. There is a poor coincidence between migration observations and stationary bird counts. This is perhaps not surprising but does mean that different methods will be needed to effectively use both types of data.
3. It is crucial to our understanding of the system to incorporate the different migration destinations in the model. Unfortunately this information is sparse and a number of assumptions have been made in this process. Improving data here will help to improve model performance. This linked with '1' above lead us to suggest that a possible migration pattern is that birds with short distance to breeding may move earlier but more slowly towards their wintering grounds. This could be due to the fact that they have little to lose if forced to move south by inclement weather. Birds with a greater distance to the breeding grounds risk more by early migration because they may use resources to reach inclement conditions. Hence, our hypothesis (based on resulting model fit) is that they leave for their breeding grounds earlier, to 'leap-frog' the shorter migration birds. Model fitting suggested no evidence that the timing of return was equally displaced, however.
4. It was initially assumed that location of wind farms in critical areas e.g. narrow tracts of sea between two larger land masses would have more significant impact than placement in large open water areas. However, this appeared not to be the case, since the results of the modelling suggested that the divers can fly long distances and therefore these locations only act as barriers to local movements, rather than to migration.

The results indicated that the effect of additional offshore wind farms as indicated in Scenario 2 would have trivial impact on the overall Baltic flyway population size, with a decrease of only 0.1%. Scenario 3 showed a decrease of 1.7% for comparison. When separating the results on birds that migrate far, medium and short, it appears that the far migrating part of the population was impacted less than the two other sub-populations. This is very likely an effect of the far migrating birds utilising the Baltic for foraging and stopping during migration is expected to be far less than for the near and intermediate migrating parts of the population.

The difference between Scenario 1 and Scenario 2 is that areas with plans for future offshore wind farms in Danish marine areas have been added. So for this scenario no offshore wind farms were added in the remaining parts of the Baltic. This may be the cause of the relatively small impact on the Scenario 2 data, both in relation to the entire population and when separated into the three migration-distance groups.

Scenario 3 had far more wind farms in both Danish and Baltic marine areas. The indicated impact on the presence of more wind farms was higher. When comparing the results for the three groups of far, intermediate and short migrants it shows that the intermediate migrators are impacted more than the two other groups. This is likely to be caused by the fact that the far migrants utilise the Baltic relatively little. The short migrants mainly utilise the western parts of the Baltic. The intermediate migrants utilise parts of the Baltic with wind farms over a relatively long time frame, and thus this population seems to be effected by the offshore wind farm scenarios tested more than the two other groups.

Our knowledge about the biology of Red-throated Divers in this flyway population is limited, which led to a number of shortcomings in the creation of this model. First of all the estimated size of the population is very uncertain, and there are no knowledge about sub-populations. In the process of developing the model we learned about the data from a satellite transmitted Red-throated Diver from northeast Greenland. It migrated from the breeding ground to southeast England in three steps, and likewise in huge steps back to the breeding grounds in the same place to proceeding spring/summer (A. Mosbech pers. comm). This led to the theory that the birds migrating through the Baltic perform a leap-frog migration. Far distance migrators leave the wintering grounds late and migrate fast to the breeding grounds, while short migrating individuals more gradually move eastwards in the Baltic from late winter/early spring. When entering this migration strategy separation into the model it greatly improved the fit.

Another shortcoming is that the density estimates used to calibrate the model are tiny as compared to the general study area, and the areas are gathered in Danish waters, and thus far from evenly distributed across the study area. This means that our fitted model, although using the best available data, may be biased by small variations in the precise density estimates used.

A third important limitation was that the model builds on habitat utilisation in a simple form, with no possibility to differentiate temporal changes in habitat importance to the divers. A particular area could for example potentially be of far higher importance as a staging area in spring than in autumn. Such temporal changes could not be implemented in the present model state.

The results of this modelled approach therefore must be considered and used with great caution. The model builds on a number of assumptions that are difficult to evaluate. The present results should be considered indications of a potential impact level on the diver population from offshore wind farms. The value of the model developed here has a potential to provide more specific answers, provided a focus on future developments as indicated below.

Future development

The following are improvements and extensions to the model that appear to be desirable at this stage in the development

1. Incorporation of migration observation simulation into the model to allow comparison with the migration observation data available and provide more thorough model testing capability.
2. Improved data on breeding grounds and proportions of birds using them will help improve general model behaviour.
3. Simulation of other constraints to movement, especially shipping.
4. Modelling the birds in the breeding grounds would allow real cumulative effects to be evaluated.
5. Extension of the geographical area modelled to include the southerly wintering grounds of this species.
6. Release of the model and data as open science project. This would benefit the diver and wind farm developer/regulator community alike. Open access to the model will allow others to work with it and test it and will provide a framework for disparate data on diver ecology and behaviour.

6.2 Other anthropogenic factors

Red-throated Divers are susceptible to human disturbances while in the marine environment. From ship-based bird surveys it is known that birds often flush at distances of about 1 km from an approaching ship. Therefore, the level of human activity at sea is expected to have an influence on the distribution of Red-throated Divers (Schwemmer et al. 2011). The level of ship activity along the major shipping routes is well documented. Such activity is at the same time very predictable in its routes. A habituation towards such ship traffic is therefore more likely than a habituation towards more irregular sailing activity such as fishing vessels, hunting activity or pleasure boat activity. These latter activities are far more difficult to quantify, and we have no knowledge about the level of impact on Diver distributions as a result of these.

Red-throated Divers are susceptible to being caught in gill nets. Such bycatch events causes the bird to drown, and is thus a cause of direct mortality. The level of by-catch is poorly known, but summarised to be "hundreds" of individuals in the North Sea and the Baltic annually (Zydelis et al. 2009).

Another source of direct mortality would be from collisions between flying Red-throated Divers and wind turbines. Such mortality was not included in the modelled approach presented in this report. The level of such collisions is unknown.

The marine area is increasingly being used for renewable energy production. Offshore wind farms play the major role in this respect, but there is increased interest in wave energy, which can potentially influence the distribution of Red-throated Divers. Wave energy plants are unlikely to cause direct mortality, though.

In light of the uncertainties about the accuracy of the results from this study, combined with the poor knowledge of the level of impact from other anthropogenic impacts, as described above, we are unable to compare the importance of a displacement of Red-throated Divers away from offshore wind farms with that of other factors.

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8 Appendix I: Red-Throated Diver Agent-Based Model ODdox Documentation

1.0

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Introduction

The ODdox documentation (Topping et al, 2010) is a fusion of the ODD protocol (Grimm et al. 2006) for describing IBMs and Doxygen (http://www.doxygen.org) a standard software tool designed to increase the accessibility of program code. In ODdox documentation provides a set of html documents generated by Doxygen whcih form cross-linked documentation of all classes, methods and variables used in a progam code. This allows the user to browse through classes and see the inter-relationships in the code. At the lowest level the code is presented together with a brief description of what it does, and including the comments placed inside the code itself. The ODdox thus provides a powerful way of documentating IBMs and allowing others to choose to see precisely what has been done or to get an overview quickly without the details.

Short overview

This model simulates the movement of red-throated divers (Gavia stellata) between its breeding grounds and wintering grounds. The model was constructed to provide insight into the potential impact of marine wind farms on migration patterns and habitat usage by this species, and hence to indicate possible impacts on diver physiological condition. Data used to test the model comes from aerial surveys of birds in the inner Danish waters, and was supplemented with observational counts of migrating birds. Placement of wind farms on the map used by the model will result in avoidence by the birds, the net effect of this being indicated by an overall impact on body condition when reaching breeding.

Overview

1. Purpose

The model was constructed to evaluate the impact of marine wind farms on red throated divers, migrating through or overwintering in the inner Danish waters.
The model was constructed using behavioural rules to direct migrating birds between their wintering and breeding grounds. These rules were developed from first principles and the fit to aerial counts of divers in the inner Danish waters was used as the measure of model suitability. A secondary set of data detailing observations of migrating divers was used to further refine the model fit.
Once fitted the model was calibrated to provide an indication of the expected body condition of the divers when reaching the breeding grounds. This is the primary model output and can be used to assess relative impacts of different scenarios. It is important to note that in its current form and scope it is not possible to predict actual body condition from the model, only to provide an estimate of relative impacts.

2. State variables and scales

The mode is primarily separated into two components handled by two program classes. These are the Seascape and RedThroatedDiver classes. The seascape defines the environment into which the divers operate. Taking these in turn:

Seascape:
The scale of the seascape covers a geographic region from the southern Dutch coast at the south west, eastwards to cover all parts of the Bay of Finland and northwards to cover all parts of the Bay of Botnia. The spatial resolution of the model is 500x500m squares, and each square contains the following information:

Distance to shore
Sea depth
Water surface temperature - this information varies on a flexible temporal scale, for example every five days.

The seascape data is stored in an object of class SeascapeData. This object holds the data in arrays pointed to by SeascapeData::m_DistanceToShore, SeascapeData::m_Depth, SeascapeData::m_Temperature. Interface functions are provided to access this data e.g. SeascapeData::GetDistanceToShore.

Each red throated diver is represented by an object of the class RedThroatedDiver with the following attributes:

TMarineAnimal::m_x - current x-coordinate
TMarineAnimal::m_y - current y-coordinate
TMarineAnimal::m_state - current behavioural state
TMarineAnimal::m_daydone - signals (non/)completion of time-step behaviour.
TMarineAnimal::m_BodyCondition - Holds the current energetic reserve status.

RedThroatedDiver::m_breedinggoalday - Individual goal for reaching migration jump point as a Julian day.
RedThroatedDiver::m_winterreturnday - Individual day for returning to the migration jump point (Julian day).
RedThroatedDiver::m_winterarriveday - Individual goal for reaching overwintering location (Julian day).
RedThroatedDiver::m_breedinggoalx - Breeding x-coordinate on land.
RedThroatedDiver::m_breedinggoaly - Breeding y-coordinate on land.
RedThroatedDiver::m_breedingjumpx - Breeding migration jump-off point x coordinate. This is the x-coordinate of the location from which the bird leaves the sea.
RedThroatedDiver::m_breedingjumpy - Breeding migration jump-off point y coordinate. This is the y-coordinate of the location from which the bird leaves the sea.
RedThroatedDiver::m_winteringx - Winter target x-coordinate. This is the x-coordinate of the location that the bird needs to arrive close to before RedThroatedDiver::m_winterarriveday.
RedThroatedDiver::m_winteringy - Winter target y-coordinate. This is the y-coordinate of the location that the bird needs to arrive close to before RedThroatedDiver::m_winterarriveday.

3. Process Overview and Scheduling

3.1 Scheduling

The main time-step of the model is one day, and is controlled from MyFrame::StartASim This results in the following being done on a daily basis:

1. If running in GUI mode then updating the map positions through PopulationManager::UpdateMap
2. If in GUI mode re-drawing the map MyMap::ShowBitmap2
3. Updating the seascape environmental information and dates through Seascape::TurnTheWorld. This controls the Julian day updating and indexes each day's water temperature data.
4. Calling all divers to carry out their daily behaviour and carry out any model output procedures through PopulationManager::DoTimeStep. This is the main daily loop for the divers and is comprised of the following parts:

DoBefore

Any pre-behavioural step functions are carried out here. These are to clear data from the old output probes, run the probes and then output new data.

DoStep

This is the main behavioural control. It is iteratively called until all divers report that behaviour is finished for the day (via m_daydone == true).

DoAfter

Currently unused

DoEndStep

This removes any diver objects that have died during the last timestep.

DoAlmostLast

Saves the body condition of the RTDivers

DoLast

Loops through all the divers and removes any dead diver objects then calculates the density of each diver in a 2x2km grid square.

See PopulationManager::DoBefore, PopulationManager::DoStep, PopulationManager::DoAfter, PopulationManager::DoEndStep, PopulationManager::DoAlmostLast, PopulationManager::DoLast, PopulationManager::ClearProbes PopulationManager::RunProbes, & PopulationManager::OutputProbes for more details

3.2 Processes

The main dynamic processes are the change in water temperature with time (effectively an input variable) and the movement of the divers. Diver movement is controlled by RedThroatedDiver::DoStepBehaviour which (apart from initialisation and death) calls one of three behaviours:

3.2.1. RedThroatedDiver::stInExternalBreedingArea - whilst the birds are in the breeding area there is no explicit simulation of their activities. Just for visual purposes they are placed at the top-right hand corner of the map. At each timestep each bird tests whether it is the Julian day for its return (held in globals::DIVER_RETURN_FROM_BREEDING). When this day is reached the divers are placed within 300 grid units (150 km) from their jumping off point.

3.2.2. RedThroatedDiver::stDispersingBreeding - this comprises of three basic steps:

3.2.2.a. Movement - rate and type of movement to breeding is determined by the date, current location, migration goal, energetic status, & destination environmental conditions.
RedThroatedDiver::DispersingToBreeding is responsible for carrying out the movement part of this behaviour. Movement is determined by calculating the nearest vector (N,NE,E,SE,S,SW,W,NW) and distance to the migration jump-off point. The maximum distance physiologically possible to fly is determined, and if the jump-off point is close enough to be within globals::CLOSE_ENOUGH distance the bird moves in a weakly directed movement towards the jump-off point. If not withing globals::CLOSE_ENOUGH the bird must move towards the jump-off point in a more directed manner dependent upon the time left to reach its goal. Each bird has an individual date to start this movement and to reach its goal. The rate of movement de-

pends on the distance divided by the number of days to reach the goal (migPull). Distance to be travelled (d) = (migPull/2) + Rd(migPull), where Rd is a random number between 0.0 & 1.0. If 'd' is greater than the energetic flight limit, then 'd' is reduced to this limit. In addition to 'd', the directedness of the movement is determined by RedThroatedDiver::CalcAddConstBreeding. The precise movement made is determined by RedThroatedDiver::Beeline if directedness is maximum, otherwise by RedThroatedDiver::OctagonSearchVariable. Beeline calculates the direct movement path towards goal, and allows birds to move in this direction as long as there is not zero forage at the next destination location (primarily this means that the water depth profile must be suitable for them to land). OctagonSearchVariable, however, provides a much more flexible movement dependent upon the directedness required. The search for the next location is based on an octagon with radius 'd'. The face facing the optimum direction is searched first, then the faces either side. Searching is performed by testing the quality of forage using RedThroatedDiver::TestForagePosition2, and if the result is greater than a threshold there is a probability of acceptance. During the search the best forage location is remembered in case no locations pass the threshold & probability combination. The directedness of the search determines whether 1,3,5,7, or 8 faces of the octagon are searched. If no search locations are selected, the movement is abandoned at this distance, and a new distance is found using the same equation. This process is repeated iteratively until a possible location is found.

3.2.2.b. Updating energetics - done by RedThroatedDiver::UpdatePhysiology, this takes the energetic cost of flight and the forage obtainable based on the environmental information at current location to determine the net effect on the overall energetic balance of the bird. Death of the bird results if the energetic balance is zero.

3.2.2.c. Check for breeding jump off points and return the relevant behavioural state, done by RedThroatedDiver::TestBreedingPosition, which determines whether the bird is within 25km of its jump-off point, if so a transition to is made to exhibit the breeding in external area behaviour at the next time step (see above).

3.2.3. RedThroatedDiver::stDispersingWinter - very similar to RedThroatedDiver::stDispersingBreeding, comprising the same three steps but with the targets being the individual birds wintering goal.

3.2.3.a. Movement - rate and type of movement to wintering goal is determined by the date, current location, migration goal, energetic status, & destination environmental conditions.
RedThroatedDiver::DispersingToWinter is responsible for carrying out the movement part of this behaviour. Movement is determined by calculating the nearest vector (N,NE,E,SE,S,SW,W,NW) and distance to the wintering goal. The maximum distance physiologically possible to fly is determined, and if the jump-off point is close enough to be within globals::CLOSE_ENOUGH distance the bird moves in a weakly directed movement towards this point. If not withing globals::CLOSE_ENOUGH the bird must move towards the wintering goal in a more directed manner dependent upon the time left to reach its goal. Each bird has an individual date to start this movement and to reach its goal. The rate of movement depends on the distance divided by the number of days to reach the goal (migPull). Distance to be travelled (d) = (migPull/2) + Rd(migPull), where Rd is a random

number between 0.0 & 1.0. If 'd' is greater than the energetic flight limit, then 'd' is reduced to this limit. In addition to 'd', the directedness of the movement is determined by RedThroatedDiver::CalcAddConstWintering, which results in a more focussed movement earlier than in moving to breeding. Unlike breeding there is no rapid movement to the goal when time is short, hence OctagonSearchVariable is the only location search method used in moving to wintering grounds (see stDispersingBreeding above for details).

3.2.3.b. Updating energetics - done by RedThroatedDiver::UpdatePhysiology, this takes the energetic cost of flight and the forage obtainable based on the environmental information at current location to determine the net effect on the overall energetic balance of the bird. Death of the bird results if the energetic balance is zero.

3.2.3.c. Check for breeding jump off points and return the relevant behavioural state, done by RedThroatedDiver::TestBreedingPosition, which determines whether the bird is within 25km of its jump-off point, if so a transition to is made to exhibit the breeding in external area behaviour at the next time step (see above).

Design

4. Design Concepts

4.a Emergence
Emergent properties are the patter of movement to breeding and wintering grounds and the energetic status of the birds.

4.b. Adaptation
Divers in the model do not the possess the ability to adapt.

4.c Fitness
Fitness is embodied in the emergent property energetic status.

4.d Prediction
Prediction is not used.

4.e Sensing
The birds can sense the depth of water (zero for land) and water temperature. They can determine the forage potential of any location.

4.f Interaction
Interaction between the birds is a result of a density-dependent coefficient on foraging calculated for each location tested by PopulationManager::GetDensityFunc. The density dependent function is a linear relationship between two threshold densities, the upper with a value of zero, the lower with a value of one. The lower represents a threshold at and below which there is no density dependent reduction in forage. The upper determines the gradient of response to increasing density.

4.g Stochasticity
Stochasticity is built into the movement selection in both selection from an even distribution of distances to test within variable ranges depending on migration urge (time to goal), distance to goal, and current bird energetic status. There is also potential for stochasticity in acceptance of a forage loca-

tion, although currently this value is set at 1% rejection chance. See RedThroatedDiver::OctagonSearchVariable for details.

4.h Collectives

Collectives are not used in this model.

4.i Observation

Model output is separated into two parts. There is a visual interface showing the daily locations of birds as the model runs. Primary output is, however, based on a set of location specific probes (rectangles) which are assessed for the presence of birds each day by PopulationManager::DoBefore. The date and location of any birds which died during the simulation is recorded in a text output file, and the energetic status of the birds when reaching breeding is also recorded for each individual bird each year by PopulationManager::SaveMeanBodyCondition.

5. Initialisation

The model starts with divers being placed within 400 grid units of the orgin of the map (0,3200). Each diver starts the simulation with a full energetic reserve and is placed in a location which provides more than zero forage. Data us not collected from the simulation until one full simulation year has been run and the divers are present in their wintering grounds.
Water temperature data is looped, and starts on January 1st.
The proportion of birds migrating to each of a variable number of breeding location needs to be specified together with the x/y location of the breeding site and the jump-off point on the map (last sea location on route to breeding).
On running the model each bird will calculate two individual attributes based on the its migration goal. These are the date it leaves its wintering grounds and the wintering ground goal. This is done by RedThroatedDiver::RedThroatedDiver, the diver constructor. Dependent upon input parameters specifying the maximum deviation in timing for the furthest migration point, the birds will choose wintering goals and timings such that shorter migration results in earlier movement, and shorter distance to wintering grounds. This is a linear function of distance (although model inputs can alter this to power curves).

6. Inputs

Model inputs are the water depth, water temperature and distance to shore. Parameter values can be controlled by the RTD_Config.cfg file e.g.:

```
# ***************************************************
# Configuration file for the Red Throated Diver ABM
# ***************************************************
# The number of years to run #
TIMESTEPS_TO_RUN (int) = 2190
# How many divers to start the simulation with #
DIVER_START_NO (int) = 1000
# Diver minimum distance to shore #
DIVER_MIN_DIST_SHORE (int) = 1000
# Diver minimum water depth #
DIVER_MIN_DEPTH (int) = 5
# Diver maximum water depth #
```

DIVER_MAX_DEPTH (int) = 35
Diver minimum water temperature for foraging
DIVER_TEMP_THRESH (int) = 5
Diver increase in forage per degree water temperature
DIVER_TEMP_SLOPE (float) = 0.5
Lower value for forage threshold acceptance
DIVER_FORAGETHRESHOLD (float) = 0.35
Diver probability for acceptance of forage above DIVER_FORAGETHRESHOLD#
DIVER_FORAGEACCEPTPROB (float) = 0.01
Density dependence lower threshold # DENS_LOWTHRESH (int) = 100
Density dependence upper threshold # DENS_HIGHTHRESH (int) = 400
Default diver depart for breeding date # DIVER_DEPART_BREEDING (int) = 140
Default diver return from breeding date # DIVER_RETURN_FROM_BREEDING (int) = 260
Default diver return from winter date # DIVER_RETURN_FROM_WINTER (int) = 60
Default diver get to winter goal date # DIVER_GET_TO_WINTER (int) = 330
Daily food intake with maximum forage # EN_FOODINTAKECONST (float) = 500.0
Maximum flight distance allowed per day # EN_MAXFLIGHT (float) = 2000.0
Cost of flying per 500m # EN_FLYING (float) = 0.5
Maximum energy reserve # EN_RESERVE_MAX (float) = 8000.0
Maximum possible variation in depart breeding date # MAXDAYVARIATION (int) = 80
Default winter target x-coord # SS_WINTER_TARGETX (int) = 400
Default winter target y-coord # SS_WINTER_TARGETY (int) = 3200
Distance within which breeding or wintering goals are considered reached # CLOSE_ENOUGH (int) = 50
Data output specification file # PROBES_FILE (string) = "RTD_ProbesList.txt"
**
END FILE # **

7. Interconnections

There are no external interconnections or submodels.

8. References

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REPORT ON A RED-THROATED DIVER
AGENT-BASED MODEL TO ASSESS
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WIND FARMS