Collision Risk Modelling technical report

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Collision risk modelling proposed approach for Hywind

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The proposed approach to collision risk modelling with respect to seabirds for the Hywind II floating turbine project off Eastern Scotland

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1 Introduction

This document discusses the proposed approach to collision risk modelling for the Hywind II floating turbine project. It focuses on seabirds using the area for foraging and other purposes that are assumed to move randomly through the development area during the time they are present.

The proposed approach follows the Band (2012) guidance and use the same mathematical models.

2 Species selection

We selected seabird species for collision risk analysis by considering in combination:

- abundance across the study area;
- estimates of the proportion of birds at rotor height; and,
- a generic index of the potential vulnerability of species to collision impacts (Furness et al 2013).

For all seabird species, Table 1 presents the estimated proportion of birds flying above 15m based upon all birds recorded in flight during the Hywind surveys, irrespective of whether recorded on or off effort, or within or outside snapshot counts. The maximum estimated flying height recorded for any bird seeing during Year 1 surveys was 80m. The rotor swept height for the proposed development extends from 21m to 175m above sea level (Table 3). So, the estimated proportion birds above 15m will overestimate the proportion of birds potentially flying at rotor swept height.

Furness et al. (2013) derived an index, the total risk score, of the vulnerability of marine bird populations to collision impacts at Scottish offshore wind farms. In Table 1 we present this index as the relative total risk score, expressing it as a percentage of its value for the species it identifies as the most vulnerable to collision impacts, herring gull (total risk score:1306). Table 1 also presents the estimated proportion of birds flying at blade height that Furness et al. (2013) use in calculating their index.

Collision risk can only potentially have a significant impact on the population of a species if a sufficient proportion of that population occurs within the development area. Therefore generally we have only selected species for collision risk analysis where the total number of observations during snapshot counts (which provide the basis of density and abundance estimates of flying birds) across all surveys was more than three (Table 1). For most species these numbers will represent the presence a of very small percentage of the relevant regional, national and international populations. However, to absolutely guarantee that no species for which a collision risk analysis could potentially conclude a significant impact was excluded, for breeding seabirds with UK populations of less than 40,000 birds that are qualifying interests for UK SPAs we include all species that were recorded during snapshot counts and thus have density and abundance estimates greater than zero. Thus, arctic skua, great skua and common tern were added to the list of species for further consideration. For seven species excluded at this stage (red-throated diver, sooty shearwater, common scoter, Pomarine skua, black-head gull, glaucous gull and little auk) no birds were recorded during snapshot count, and therefore the density and abundance estimates, and thus collision risk mortality estimates for these species would necessarily be zero. Three other species excluded at this stage (Manx shearwater, common gull and lesser black-backed gull) were recorded during snapshot counts, but the total of number of observation in each case was three or less, and all three of these species, although qualifying interests for UK SPAs, have UK breeding populations in excess of 40,000 pairs. All other species were considered for collision risk analysis.

With respect to the proportion of birds at rotor height and vulnerability to collision impacts we include all species for which the estimated proportion of birds flying above 15m was greater than 1% based upon the Hywind data or for which the relative total risk score was greater than 10% according to Furness et al. (2013).

On this basis the species identified for further collision risk analysis are gannet, Arctic skua, great skua, herring gull, great black-backed gull, kittiwake, common tern and Arctic tern. Of the species selected for further analysis, gannet, arctic skua, great skua, herring gull, great black-backed gull and kittiwake all satisfy both the criteria that the % of birds recorded on site flying above 15m should be greater than 1% and the criteria that the relative total risk score should be greater than 10%. No common and arctic terns were recorded above 15m on site, but this could potentially reflect the small sample size available for estimating flight heights in both cases, and both species were selected because they have relative total risk scores greater than 10%. The numbers of observations of arctic skua, great skua and common tern was two or less in all cases, but these three species have been included because they are all qualifying species for UK seabird SPAs, with UK national populations of less than 40,000.

To conclude, eight species have been selected for further collision risk analysis: gannet, Arctic skua, great skua, herring gull, great black-backed gull, kittiwake, common tern and Arctic tern. The criteria we have used for identifying these species are very inclusive and guarantee that no species for which collision risk might represent a significant impact in conservation terms will have been excluded.

3 Data

3.1 Density of flying birds

We will base our estimates of the density of flying birds used in the collision risk analyses on the data collected during boat based surveys using standard ESAS methodologies (Camphuysen *et al.* 2004). Surveys of the Hywind study area have been conducted on 20 survey dates between June 2013 and May 2014. The data for flying birds is collected during snapshot counts, and no distance data is recorded. Therefore we have to assume 100% detection.

For each species, we calculate density estimates for flying birds on each survey date using the Horvitz Thompson like estimator (Thomas *et al.* 2010, Borchers and Burnham 2004) provided by the dht function in the mrds package. The variance of the density and abundance estimates provided by mrds has two components: 1) uncertainty in the estimate of the probability of detection and 2) uncertainty in the encounter rate estimate. With respect to estimating the contribution of the variance in encounter rate to the overall variance estimate, we use the default option (varflag=2). The detection function models fitted using mrds's ddf function provide estimates of the variance associated with the probability of detection estimates which are used by the dht function to estimate the contribution from this source to the overall variance estimate. For birds in flight we fit our own customised detection function model, which assumes 100% probability of detection for all sightings, with no variance in the estimates. Using this customised detection function model allows us to use dht to estimate density for birds in flight. The estimates of uncertainty (standard errors and confidence limits with associated degrees of freedom) which accompany these density estimates assume no uncertainty in the estimate of the probability of detection but do take into account the uncertainty associated with the estimate of encounter rate. We use these estimates of uncertainty in the density of flying birds in calculating our estimates of the overall uncertainty of the collision risk mortality estimates (see section 4.6).

3.2 Flight height distribution

3.2.1 The two potential bases

There are two potential bases for estimating flight height distributions.

1) Data collected on site.
2) The generic flight height models constructed under the auspices of the SOSS project (Cook et al. 2012, Johnston et al. 2014a,2014b). The revised Crown Estate guidance on using collision risk modeling to assess bird collision risks for offshore wind farms (Band 2012) suggests that where site specific data is inadequate, the predictions of these generic models should be used to provide the flight height distributions required for both basic and extended collision risk modeling.

3.2.2 The SOSS generic flight height models

Under commission from the Crown Estate SOSS group, Cook et al. 2012 used novel methods to construct generic models that predict the flight height distribution for 25 marine bird species based upon flight height data from surveys of 32 potential offshore wind farms. This work has now been extended, with the revised models now published in the peer reviewed scientific literature (Johnston et al. 2014a, Johnston et al. 2014b). The spreadsheet holding the predictions of these models has been downloaded from the SOSS web site. We have used the updated version of this spreadsheet that was created following the publication of a corrigendum to the original peer reviewed paper in May 2014 (Johnstone et al. 2014a, 2014b).

3.2.3 Fitting alternative distributions to flight height data collected on site.

Band (2012) suggests that normally, the bird survey data available for a particular site is insufficient to provide a full flight height distribution. However, in this case we are in the fortunate position of having sufficient data, of sufficient quality to allow full flight distributions to be modelled for four of the eight species: gannet, herring gull, great black-backed gull and kittiwake. For each of these four species there are over 250 observations (Table 1). Often for environmental impact studies with respect to offshore wind farms flight heights for birds are recorded into just three categories: below, within and above rotor swept height (e.g. most of the studies underpinning the SOSS generic flight height models, Johnston et al. 2014a, 2014b, Cook et al. 2012). For this study observers have recorded flight height as accurately as possible, resulting in flight height estimates which analyses (to be documented in the final report) suggest are accurate to within 10m. We have reclassified the data into categories that reflect this level of accuracy (0-15m, 15-25m, 25-35m,35-45m 45-55m etc.). For each species, we used minimum distance estimation, as implemented by the *mde* function in the *actuar* package (Dutang, C., Goulet, V. & Pigeon, M. 2008.), to fit the following theoretical distributions to this flight height data:

- Exponential (1 parameter: rate)
- Log normal (2 parameters: meanlog and sdlog)
- Gamma (2 parameters: (shape and rate)
- Pareto (2 parameters: shape and scale)
- Generalised Pareto (3 parameters: shape1,shape2 and scale).

We measured distance using the Cramér-von Mises method. We have also evaluated the fit of the SOSS generic flight height model to the same data using the same distance criteria.

For each show, figures 1 and 2 show respectively the probability density functions and cumulative distribution functions based upon each of these models fitted to the empirical data. In this context the probability density function describes the relative likelihood a bird will fly at a given height. The probability a bird will fly between two heights is found by integrating the probability density function over that range. The empirical probability density function is calculated as the proportion of birds within each flight height category, divided by the range of heights covered (e.g if 80% of birds fly between 0 and 15 metres, the probability density would be 0.8/15 = 0.053). The cumulative distribution function describes the probability that a bird will fly at or below a given height. It is the integral of the probability density function from 0 to the given height. The empirical cumulative distribution function is the observed proportion of birds below a particular height, evaluated at the upper boundary of each height category.

For each species, Table 2 presents the parameter estimates and distance measurements between the fitted and empirical cumulative distribution function for each of the theoretical distributions fitted to the data. It also gives the distance between the predictions of the SOSS generic flight height model and the empirical cumulative distribution function for each species. Within each species, distributions are sorted in order of increasing distance between the fitted and empirical cumulative distribution functions, so that the best fitting model appears first, and the worst fitting model last.

For all four species, the gamma distribution provides the best fit to the data (Table 2) closely followed by the generalised pareto distribution. As would be expected given it is based upon a different data set, the SOSS model provides the poorest fit to the data for all four species. Visual inspection of both the probability density functions (Figure 1) and the cumulative distribution functions (Figure 2) suggests that the gamma model closely fits the observed data for all species. The collision risk modeling is based upon the cumulative distribution function (Figure 2). The cumulative distribution function for the SOSS model provides a close fit to the observed data for gannet, but shows considerable departures from the observed departure for the other three species (Figure 2b, 2c, 2d). For herring gull in particular the SOSS model suggests a qualitatively different relationship between flight height and density to that in observed data (Figure 1b): it suggests densities are greatest just above sea level whereas the empirical data suggests densities are greatest at 15-25m above sea level. In contrast, the gamma model, and also the generalised pareto and log normal models capture this observed peak in densities at intermediate flight heights (Figure 1b).

These results suggest that the gamma distribution fitted to the site specific data for these four species will provide a sound basis for collision risk modelling. Although the predictions of the SOSS generic model aren't completely at odds with the site specific data, there are differences.

For the other four species (arctic and great skua, common and arctic tern) we suggest that sample sizes are inadequate to support the modelling of flight height distribution on site specific data, even at the most basic level of estimating the proportion of birds at rotor swept height. Thus all collision risk modelling for these four species will be based upon the generic model.

For common tern and arctic tern, with sample sizes of 3 and 54 respectively, no birds were recorded at rotor swept height and so on the basis of site specific data the estimated proportion of birds at rotor swept height, and thus collision risk mortality would be zero. For the other two species, arctic skua and great skua, although birds were recorded at rotor swept height with sample sizes of just 6 and 11 respectively, any estimate of the proportion of birds at rotor swept height is likely to be unreliable. Thus, for all four of these species, either the sample size is inadequate to provide a reliable estimate of the proportion of birds at rotor swept height from site-specific data, or this estimate is zero. Therefore for all four of these species we will rely solely on the generic flight height models to furnish our flight height distributions.

3.3 Wind farm design and operation

With respect to the parameters defining the design and operation of the wind farm we are evaluating a single development scenario, defined by the parameter estimates given in tables 3.

The number of turbines, the number of turbine blades, the radius of the turbines and the hub height above sea level for the development are all precisely known, and fixed (Table 3a).

More limited information is publicly available with respect to the shape of the turbine blade. We have a single average pitch estimate for the whole blade, and an estimate of the maximum chord width (Table 3a). To estimate the chord width along the blade we will assume the shape of the blade, in terms of chord width relative to maximum chord width, is the same as that of the standard turbine in the spreadsheet accompanying the Band 2012 guidance (Table 3b).

As well as an estimate of the average rotation rate of the blades throughout the year, we also have an estimate of the average rotation rate expected in each month (Table 3c). We will use the latter to calculate our estimates of collision risk.

Wind availability, the estimated proportion of time wind speeds will fall between the cut-in and cut out speeds and so functional turbines will be operating, is estimated as 99.4% throughout the year. Up time, the estimated proportion of time turbines will be functioning, excluding down time due to technical failure and maintenance is estimated as 99.5% throughout the year. Multiplying these together yields an estimates of the average proportion of time turbines are expected to operate throughout the year of 98.9% (Table 3a).

As these are floating turbines, there is no need to consider the effects of tides or global warming on sea levels (Band 2012): Hub height is defined relative to sea level, and remains constant.

3.4 Ornithological parameters

Table 4 summarises the species specific information that we propose to use for the collision risk modelling. This information has been gleaned from standard sources.

For the wingspan and length estimates we use the mid point of the range of wingspan and length estimates given in the Field Characters section of the Concise Birds of the Western Palearctic (Snow and Perrins 1998).

With the exception of gannet and common tern, all the flight speed estimates are taken from Alerstam et al. 2007. For gannet, the flight speed estimate is taken from Pennycuick (1987,1997). For common tern it is based upon the estimates given in Wakeling and Hodgson (1992), weighting the separate estimates given for different wind directions by sample size. All estimates are for birds in powered, flapping flight apart from the estimate for gannet, which is for birds alternating between flapping, and gliding flight (flap-gliding). For all species, we have assumed that birds are in flapping flight rather than gliding flight when estimating the probability of collision. This yields higher, more conservative, probabilities of collision, and reflects both the most commonly used type of flight for the species concerned, and the type of flying for which we have flight speed estimates.

All of the Hywind survey data was collected during day light hours, but seabirds are also regularly active after dark. In the absence of other evidence, Band (2012) suggests that the extent of bird flight activity at night relative to that during the day time should be estimated on the basis of Garthe and Huppop’s (2004) index of nocturnal activity. The same index has been used by Furness et al. (2013) in the calculation of their index of risk to collision. This index subjectively ranks species from 1 (hardly any flight activity at night) to 5 (much flight activity at night). It is based upon the published literature, field experience, personal observations and expert opinion. Band recommends that the 1-5 rankings of this index should translated to levels of activity which are respectively 0%, 25%, 50%, 75% and 100% of daytime activity.

Table 4 gives the nocturnal index, and corresponding translation into nocturnal activity relative to day time activity for each of the species concerned. As recommended by Band (2012) we will use these estimates of nocturnal activity by default when estimating collision risk mortality. However, we note that many (but not all, Garthe and Huppop 1996) of the assessments of nocturnal activity which underpin the Garthe and Huppop index are based on observations at breeding colonies. As Band (2012) acknowledges, levels of nocturnal activity at sea are likely to differ from those observed at the breeding colonies, and vary seasonally. Thus, we think our estimates of collision risk mortality after dark are unlikely to be accurate.

During the winter months in particular, when nights are long relative to days, nocturnal collision risk mortality could potentially have a large influence on the overall estimates of collision risk. Therefore, as well as reporting the overall estimates of collision mortality for each season, we also report the proportion of this mortality estimated to occur after dark.

3.5 Daylength

Following Band (2012) we use Forsythe et al.'s (1995) model to estimate day length given the time of year and latitude. Changing the value of a single parameter in this model provides a choice between various standard definitions of day length based on the position of the sun with respect to the horizon at the start and end of each day (Forsythe et al. 1995). Under some of these definitions a period of twilight is included within day light hours whilst under others it is excluded. The Band (2012) guidance does not discuss the appropriate definition of day length. However the fixed parameter value used in the spreadsheet accompanying the guidance enacts the definition used by the US government, that sunrise/sunset is when the top of the sun is apparently even with the horizon (Definition 3 in Forsythe et al.'s Table 1). This definition does not include twilight within day light hours. For the purposes of defining the period birds adhere to patterns of diurnal rather than nocturnal activity it would seem appropriate to include any twilight period within daylight hours. Therefore when calculating day length we set the appropriate parameter value so that civil twilight is included within day light hours (Definition 4 in Forsythe et al.'s Table 1), where civil twilight as defined as the period during which light is considered to be bright enough to perform ordinary outdoor activities without artificial light (Forsythe et al. 1995). This will yield higher estimates of collision risk mortality than would result using the spreadsheet accompanying Band's guidance.

4 Approach

4.1 Implementation

To calculate our estimates of collision risk mortality we have implemented the mathematical models described in Band 2012 in R. Extensive checks show that given the same parameter values, our R code yields the same estimates of collision risk mortality as the spreadsheet accompanying Band's guidance. Implementing the collision risk modelling in R rather than using the spreadsheet accompanying Band's guidance provide a number of advantages:

- It allows us to integrate our software for estimating collision risk mortality with our software for calculating density estimates using the R package mrds. This provides density estimates with associated estimates of uncertainty to be used in our collision risk analysis. We use these estimates of uncertainty for the density estimates in calculating our overall estimates of uncertainty for the collision risk mortality.
- It allows us to use simple distribution models fitted to the site specific flight height data as well as the SOSS generic flight height models as the basis for collision risk modelling.
- It allows us to use simulation modelling to estimate the overall uncertainty of the collision risk estimate, and to assess the individual contribution of different sources of uncertainty to this overall estimate of uncertainty.

4.2 Basic versus Extended model

Band (2012) suggests collision risk should be assessed under two different models:

1. A basic model which assumes birds within rotor swept height are evenly distributed with respect to flight height.
2. An extended model which takes into the actual distribution of flight heights with account the actual flight height distribution of birds.

All the available evidence, whether from generic data (Johnston et al. 2014a) or from site specific data (see above) suggests that seabirds have flight height distributions that are heavily skewed towards low flight heights. Therefore, the assumption of the basic model that birds are evenly distributed over rotor swept height is clearly unrealistic. So, for all species we will concentrate primarily on results from the extended model and only briefly report the results of the basic model in appendices.

4.3 Site specific versus generic flight height data

Where possible, we prefer to estimate collision risk mortality based upon the simple distribution models fitted to the site specific flight height data as described above rather than use the generic SOSS flight height distribution models. The reasons for this are:

- Models based upon site specific data completely avoid the potential problems raised by Band (2012) that could arise if ecological differences between this site and those providing the data upon which the generic model is based lead to differences in behaviour and flight heights so that the generic model is a poor predictor of flight heights at this particular site.
- Although the generic flight height distribution models provided by Cook et al. predict flight height distribution at a fine resolution (e.g. 1m categories) they are based upon data most of which was collected a much coarser resolution (e.g. flight heights typically classified into just three categories, below, within or above rotor swept height). With flight height estimates accurate to within 10m, the resolution of the flight height data upon which a site specific flight distribution model is based is much higher and closer to the resolution at which predictions are required. Thus, in terms of data quality alone, the predictions of a site specific model should be more reliable.
- The simple distributions we used invariably provide a very close and convincing fit to the data. The SOSS model generally provided a much poorer fit.
- The simplicity (1-3 parameters) and well understood basis of the simple standard theoretical distributions we fitted makes them preferable as a modelling framework to the flexible but arbitrary cubic splines fitted by Cook et al.
- As discussed below in section 4.6, we think that if we use site specific data we can provide a robust assessment of the effects of sampling uncertainty in the flight height data on the overall uncertainty of the collision risk mortality estimate. We do not think such an assessment is possible if we derive our flight height distribution from the SOSS generic model.

4.4 How we calculate the estimates for each species: combining the two types of collision risk model with the two potential sources of flight height data

Combining the two types of collision risk model with the two potential sources of flight height data yields four potential options for estimating collision risk mortality:

1. The basic model using site specific flight height data.
2. The basic model using generic flight height data.
3. The extended model using generic flight height data.
4. The extended model using site specific flight height data.

Band 2012 recommends that a collision risk assessment for a specific site should not be based solely on the use of generic data. Where generic data is used, he recommends that the collision risk mortality based upon the first three of these options shoud generally be stated. He suggests that normally there will not be sufficient data to construct a full flight height distribution but where this is possible, the results of option 4 should also be reported.

For the four seabird species selected for collision risk analysis where there is adequate site specific data (i.e. more than 250 sightings, Table 1) to support the modelling of flight distribution (gannet, herring gull, great black-backed gull and kittiwake) we present assessments of collision risk mortality based upon all four of these approaches.

For the four other species (Arctic skua, great skua, common tern and arctic tern where there is insufficient data to support the modelling of flight height distributions on the basis of site specific data we will present the results of both the basic and extended model based upon the generic flight height data.

In summary, for those species with adequate sample sizes the main report will focus on collision risk modelling using the extended model with flight height distributions based on site specific data. For the four rarer species the main report will again focus on the extended model, but this time based upon the generic flight height data/models. In addition appendices will report:

- Results for common species based on applying the extended model to the generic flight height data.
- Results for all species based on applying the basic model to the generic flight height model.
- Results for common species based on applying the basic model to the site specific data.

Therefore, for the four species where sufficient data is available to fit a site specific flight height distribution, we concentrate primarily on the results from the extended model applied to this site specific data. In appendices we also briefly report the results of the basic model applied to the same data, and both the extended and the basic model applied to the generic data.

For the four species where there is insufficient data to fit a site-specific flight height distribution, we concentrate primarily on the results of the extended model based on the generic model. In appendices we also briefly report the results of the basic model applied to the same data.

4.5 Reporting

For each species, we will present separate mortality estimates for the agreed set of seasons for that species, and also an overall annual mortality estimate. For every collision risk mortality estimate we will report

- The density of flying birds, expressed as birds/km^2 , and including birds at all flight heights.
- The details of the flight height distribution used. For flight height distributions based upon site specific data this will specify the type of distribution used, and its parameters. Where the generic flight distribution for the species is used, this will be explicitly stated.
- The estimate proportion of flying birds at rotor swept height.
- The estimated proportion of flying birds passing through the rotors.
- The estimated proportion of the birds at rotor swept height passing through the rotors.
- The estimated number of transits through the rotors.
- The average probability of collision for each bird passing through the rotors.
- The estimated number of birds colliding with the turbines assuming no avoidance.
- Mortality estimates assuming avoidance rates of 95%, 98%, 99% and 99.5%. This is consistent with the recommendations in Band (2012) and Cook et al. (2012) with respect to the avoidance rates to use in the absence of specific information for the species in question.

Reporting in the levels of details more than satisfies Band's (2012) recommendations with respect to the level of information which should be reported for each collision risk estimate.

4.6 Assessing Uncertainty

For the four species with adequate sample sizes for fitting a site specific flight height distribution we will also use simulation modelling to assess the effects of sampling uncertainty in both the density estimates and the flight height distribution on the overall uncertainty of the collision risk mortality estimate. In particular it will estimate the 95% confidence limits for each collision mortality estimate given the sampling uncertainty (as reported by the distance R package mrds) in each of the density estimates and also the sampling uncertainty in the parameters of the flight height distribution. By running additional simulations in which sampling uncertainty is "switched off" one by one in the flight height estimates but not the density estimates, and then vice versa, it will assess the contribution of each of these sources of uncertainty to the overall uncertainty of the collision risk mortality estimate.

Thus, using simulation modelling we will investigate the separate and combined effects of sampling uncertainty in the flight height data and density data on the overall estimates of uncertainty for the collision risk mortality estimates. Following Band (2012) we will express this uncertainty with respect to its effects on the 95%

confidence limits for the overall estimate of collision risk mortality. We will also investigate the particular potential bias that could be introduced into collision risk estimates if observers tended to underestimate flight heights, and thus the proportion of birds flying through rotor swept height. In particular, it is our intention to investigate the effects on collision risk mortality estimates if flight heights are consistently underestimated by 5m or by 10m. This will be achieved post the fitting of simple distribution models to the site specific data by assuming the estimate provided by the model for the proportion of birds below a given height x actually represents the proportion of birds below the height x+y, where y is the bias. Band (2012) suggests that we should also attempt to assess the effects of uncertainty in other parameters on the overall estimate of collision risk mortality. Therefore, as well as allowing us to assess the effects of sampling uncertainty in flight heights and densities on the overall collision risk mortality estimate, the simulation engine we have constructed would potentially allow us to assess the effects of uncertainty in other parameters on the overall estimate of uncertainty, and also their individual contribution. In particular, given an estimate of the upper 95% confidence limit as well as the central estimate for a given parameter the simulation engine would also potentially allow us to assess the effects of uncertainty in the following parameters on the overall collision risk estimate:

- rotor speed,
- body length,
- wing span,
- flight speed,
- the proportion of time turbines are active,
- the proportion of the night birds are active.

However, in all of these cases there is little or no empirical evidence upon which to base an estimate of upper 95% confidence limits. Although Band (2012) suggests that in the absence of empirical data we will should rely on expert judgement we think this will result in uncertainty estimates in which we can have little confidence, with a weak scientific basis. Therefore we will restrict our formal assessment of uncertainty to those elements where there is sufficient empirical data to provide a meaningful assessment: sampling uncertainty in the flight height and density estimates. We will also provide an assessment of the bias that could arise in collision risk mortality if observers underestimate flight heights by 5m or 10m as this seems realistic. With respect to the other parameters, for which there is no strong empirical basis on which to assess uncertainty, we do not propose conducting formal analyses to evaluate their individual contributions to the level of uncertainty in the collision risk mortality estimate. However, when reporting our estimates of collision risk mortality as well as presenting estimates for the standard avoidance rates (95%, 98%, 99% and 99.5%) we will also present estimates for a wider range of avoidance rates (e.g. 0%, 50% and 90%) so that during the assessment process the consequences of our estimates of collision risk mortality being out by up several orders of magnitude can easily be evaluated. This would allow us to conclude, for example, that even if our estimates are out by a factor of 10 there would still be no significant impact in conservation terms or, alternatively, even if we are only slightly underestimating collision risk this could potentially have serious consequences in conservation terms. Given the lack of robust empirical data with respect to the variation in many parameters of the collision risk model, this seems to us a more robust way of assessing the effects of potential uncertainty for these parameters than relying on expert judgement.

As detailed below, there is only a single development scenario under consideration. However, following the same argument as above if multiple development scenarios were under consideration our intention would be to present separate collision risk mortality estimates for each scenario rather than attempt to estimate a combined uncertainty across scenarios as suggested in the Band guidance. Our reasoning is that to present an overall estimate would require estimating the relative likelihood of each of the different scenarios, which would be highly speculative and subject to error.

Using simulation modelling to estimate uncertainty provides us with sufficient flexibility to deal with the full range of potential ways in which uncertainty might manifest itself, and in particular to deal with the scenarios which commonly arise where the model for combining uncertainties suggested by Band (2012) does not apply. Band's model for combining uncertainties only applies to the uncertainty of products and assumes either the same number of degrees of freedom for all elements, or large sample size in all cases. It does not apply to the uncertainty of sums/means (e.g. the uncertainty of the mean density of birds across a number of surveys, each with an uncertainty estimate) or to the situation where parameters appear in multiple places in the model (e.g. an increase in the flight speed estimate would increase the estimated number of transits through the turbines, but reduce the estimate probability of collision for each bird passing through the turbines).

To estimate the effect of uncertainty in density estimates on the collision risk mortality estimate we run multiple simulations in each of which we recalculate the collision risk mortality estimate replacing the central estimate of density for each survey by an estimate random sampled from the distribution of estimates implied by its 95% confidence limits. The empirical 95% confidence limits for the collision risk mortality estimates from these multiple simulations allows us to estimate the effects of uncertainty in density estimates on the overall uncertainty in the collision risk mortality estimate. This approach assumes that all uncertainty in the density estimates results from the uncertainty within the individual estimates. The dates/times at which surveys occur are assumed to provide a representative sample of the actual variation in density for the period over which collision risk mortality is being estimated (e.g. the breeding season for a particular species). Given there is likely to be genuine variation in density between survey/dates it is not clear how uncertainty resulting from the survey/dates not being representative could be assessed.

To assess the sampling uncertainty in the site-specific flight height data, and the effects of this uncertainty on the overall uncertainty of the collision risk mortality estimate we use multiple runs of a simulation model. In each run of the simulation model, the flight height data is resampled and the simple distribution model refitted, and the collision risk mortality estimate recalculated. This provides robust estimates of the sampling uncertainty in the flight height data, and its effects on the overall uncertainty of the collision risk mortality estimate.

As well as providing a central estimate, the generic flight height models provide upper and lower confidence limits for the proportion of birds expected within each 1m flight height category. Band (2012) suggests that by replacing the central estimate of the proportion in each height band by its upper confidence limit when estimating collision risk an upper confidence limit for collision mortality taking into account uncertainty in the flight height distribution can be estimated. Similarly, it is suggested that using the lower confidence limit for the proportion in each height band in place of the central estimate can provide a lower confidence limit for collision mortality. However, there is a fundamental flaw in this approach as the proportions of birds at different flight heights are not independent of one another: a higher proportion of birds at one height must mean a lower proportion at another height. The proportion of birds at each flight height cannot be at its upper confidence limit, or lower confidence limit, at all heights without violating the requirement that the proportions of birds across all heights must sum to one. Thus, the approach proposed by Band (2012) for estimating the uncertainty in collision risk estimates introduced by sampling uncertainty in the flight height data when the generic flight height model is used does not appear to be valid, with no obvious alternative. Therefore we suggest that another advantage of using the site specific data is it allows us to make robust assessments of the effects of sampling uncertainty in flight height estimates on the overall uncertainty of the collision risk mortality estimate, which will not be possible if we use the generic flight height models.

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Table 1: Data for birds in flight used to select species for collision risk analysis

		Hywind data			Furness et al. 2013		Selection criteria satisfied			
Species	UK breeding population (pairs)	No of obs for density estimation	No of obs for flight height estimation	% of birds above 15m	% of flights at blade height	Relative Total risk score	Abundance criteria satisfied	>1% of birds above 15m	Relative Total Risk Score >10%	Selected
Red-throated diver	1,300	0	2	50.0%	5	16%	N	Y	Y	N
Fulmar	501,600	431	1788	0.1%	1	4%	Y	N	N	N
Sooty shearwater		0	1	0.0%	0	0%	N	N	N	N
Manx shearwater	299,700	3	20	0.0%	0	0%	N	N	N	N
Storm petrel	25,700	15	53	0.0%	2	7%	Y	N	N	N
Gannet	218,500	213	873	19.5%	16	56%	Y	Y	Y	Y
Common scoter		0	2	0.0%	3	7%	N	N	N	N
Pomarine skua		0	2	100.0%			N	Y		N
Arctic skua	2,100	1	6	16.7%	10	25%	Y	Y	Y	Y
Great skua	9,600	1	11	18.2%	10	25%	Y	Y	Y	Y
Black-headed gull	138,000	0	1	0.0%	18	22%	N	N	Y	N
Common gull	48,700	3	9	33.3%	23	46%	N	Y	Y	N
Lesser black-backed gull	112,000	2	4	0.0%	30	74%	N	N	Y	N
Herring gull	139,200	130	448	63.6%	35	100%	Y	Y	Y	Y
Glaucous gull		0	1	0.0%			N	N		N
Great black-backed gull	16,800	91	269	57.6%	35	94%	Y	Y	Y	Y
Kittiwake	378,800	306	1262	30.9%	16	40%	Y	Y	Y	Y
Common tern	11,800	2	3	0.0%	7	18%	Y	N	Y	Y
Arctic tern	53,400	8	54	0.0%	5	15%	Y	N	Y	Y
Guillemot	948,921	241	1361	0.0%	1	3%	Y	N	N	N
Razorbill	125,357	32	170	0.6%	1	2%	Y	N	N	N
Little Auk		0	4	0.0%	1	1%	N	N	N	N
Puffin	580,700	54	337	0.3%	1	2%	Y	N	N	N
White-winged gull sp.		0	1	100.0%						
petrel sp.		0	1	0.0%						
skua sp.		0	1	0.0%						
large gull sp. (HG, LB or GB)		0	11	90.9%						
auk sp.		2	11	0.0%						
Guillemot/razorbill		6	63	0.0%						

All seabird UK breeding population estimates taken from JNCC (2013) apart from red-throated diver which was taken from Baillie et al. (2014). Numbers of pairs for Guillemots and razorbills calculated by multiplying estimates of the numbers of individuals on breeding ledges by 0.67 (Mitchell et al. 2004)

Table 2: Fit of different theoretical distributions and the SOSS generic model to the flight height data for individual species

Species	Distribution	Parameter	Value	Parameter	Value	Parameter	Value	Distance
Gannet	gamma	shape	0.95	rate	0.10	NA	NA	0.00005
	genpareto	shape1	105.36	shape2	0.96	scale	999.48	0.00006
	pareto	shape	98.09	scale	900.21	NA	NA	0.00006
	exp	rate	0.11	NA	NA	NA	NA	0.00006
	lnorm	meanlog	2.05	sdlog	0.77	NA	NA	0.00016
	SOSS	NA	NA	NA	NA	NA	NA	0.00029
Herring gull	gamma	shape	3.80	rate	0.19	NA	NA	0.00037
	genpareto	shape1	99.50	shape2	3.99	scale	500.10	0.00041
	lnorm	meanlog	2.90	sdlog	0.50	NA	NA	0.00110
	exp	rate	0.05	NA	NA	NA	NA	0.04984
	pareto	shape	51.32	scale	999.94	NA	NA	0.05167
	SOSS	NA	NA	NA	NA	NA	NA	0.05667
Great black backed gull	gamma	shape	2.40	rate	0.12	NA	NA	0.00267
	genpareto	shape1	52.07	shape2	2.54	scale	401.11	0.00293
	lnorm	meanlog	2.84	sdlog	0.61	NA	NA	0.00521
	exp	rate	0.05	NA	NA	NA	NA	0.02461
	pareto	shape	51.97	scale	999.91	NA	NA	0.02593
	SOSS	NA	NA	NA	NA	NA	NA	0.02890
Kittiwake	gamma	shape	1.94	rate	0.15	NA	NA	0.00023
	genpareto	shape1	80.42	shape2	2.00	scale	499.94	0.00025
	lnorm	meanlog	2.41	sdlog	0.61	NA	NA	0.00046
	exp	rate	0.09	NA	NA	NA	NA	0.00283
	pareto	shape	69.31	scale	800.06	NA	NA	0.00309
	SOSS	NA	NA	NA	NA	NA	NA	0.00524

Table 3: Estimates for parameters defining the design and operation of turbines

Table 3a: Most parameters

Number of turbines	5
Number of blades on each turbine	3
Turbine radius	77 m
Hub height above sea level	98 m
Maximum chord width	5.5m
Blade pitch	10^0
Proportion of time turbine are operating	98.9%

Table 3b: Variation in chord width along the blade length based upon the standard blade profile from the spreadsheet accompanying the Band (2012) guidance

Standard blade profile from "Single transit collision risk" spreadsheet in Band (2012) workbook			
Distance along blade / turbine radius	chord width / maxium chord width	distance along blade (m)	Chord width (m)
0.00	0.73	0.00	4.02
0.05	0.73	3.85	4.02
0.10	0.79	7.70	4.35
0.15	0.88	11.55	4.84
0.20	0.96	15.40	5.28
0.25	1.00	19.25	5.50
0.30	0.98	23.10	5.39
0.35	0.92	26.95	5.06
0.40	0.85	30.80	4.68
0.45	0.80	34.65	4.40
0.50	0.75	38.50	4.13
0.55	0.70	42.35	3.85
0.60	0.64	46.20	3.52
0.65	0.58	50.05	3.19
0.70	0.52	53.90	2.86
0.75	0.47	57.75	2.59
0.80	0.41	61.60	2.26
0.85	0.37	65.45	2.04
0.90	0.30	69.30	1.65
0.95	0.24	73.15	1.32
1.00	0.00	77.00	0.00

Table 3c: Average turbine rotation rate for each month (rpm)

Month	Average rotation rate (rpm)
January	9.1
February	8.7
March	8.6
April	8.1
May	7.8
June	7.6
July	7.7
August	7.8
September	8.4
October	8.7
November	8.9
December	8.9
Overall	8.3

Table 4: Species specific parameters for collision risk modelling

	Length (cm)			Wingspan (cm)							
Species	Min	Max	Mid point	Min	Max	Mid point	Flight speed (m/s)	Flight speed source	Flapping or gliding	Nocturnal activity score	Night time activity as % of day time activity
Gannet	87	100	93.5	165	180	172.5	14.9	Pennycuick 1997	Flapping	2	25%
Arctic skua	41	46	43.5	110	125	117.5	13.8	Alerstam et al. 2007	Flapping	1	0%
Great skua	53	58	55.5	132	140	136	14.9	Pennycuick 1997	Flapping	1	0%
Herring gull	55	67	61	138	150	144	12.8	Alerstam et al. 2007	Flapping	3	50%
Great black-backed gull	64	78	71	150	165	157.5	13.7	Alerstam et al. 2007	Flapping	3	50%
Kittiwake	38	40	39	95	120	107.5	13.1	Alerstam et al. 2007	Flapping	3	50%
Common tern	31	35	33	77	98	87.5	9.2	Wakeling and Hodgson 1992	Flapping	1	0%
Arctic tern	33	35	34	75	85	80	10.9	Alerstam et al. 2007	Flapping	1	0%

Figure 1: Probability density functions (pdfs) for different theoretical distributions and the SOSS generic flight height model fitted to the observed flight height data. (black histogram: observed; red line: fitted values)

Figure 1a: Gannet

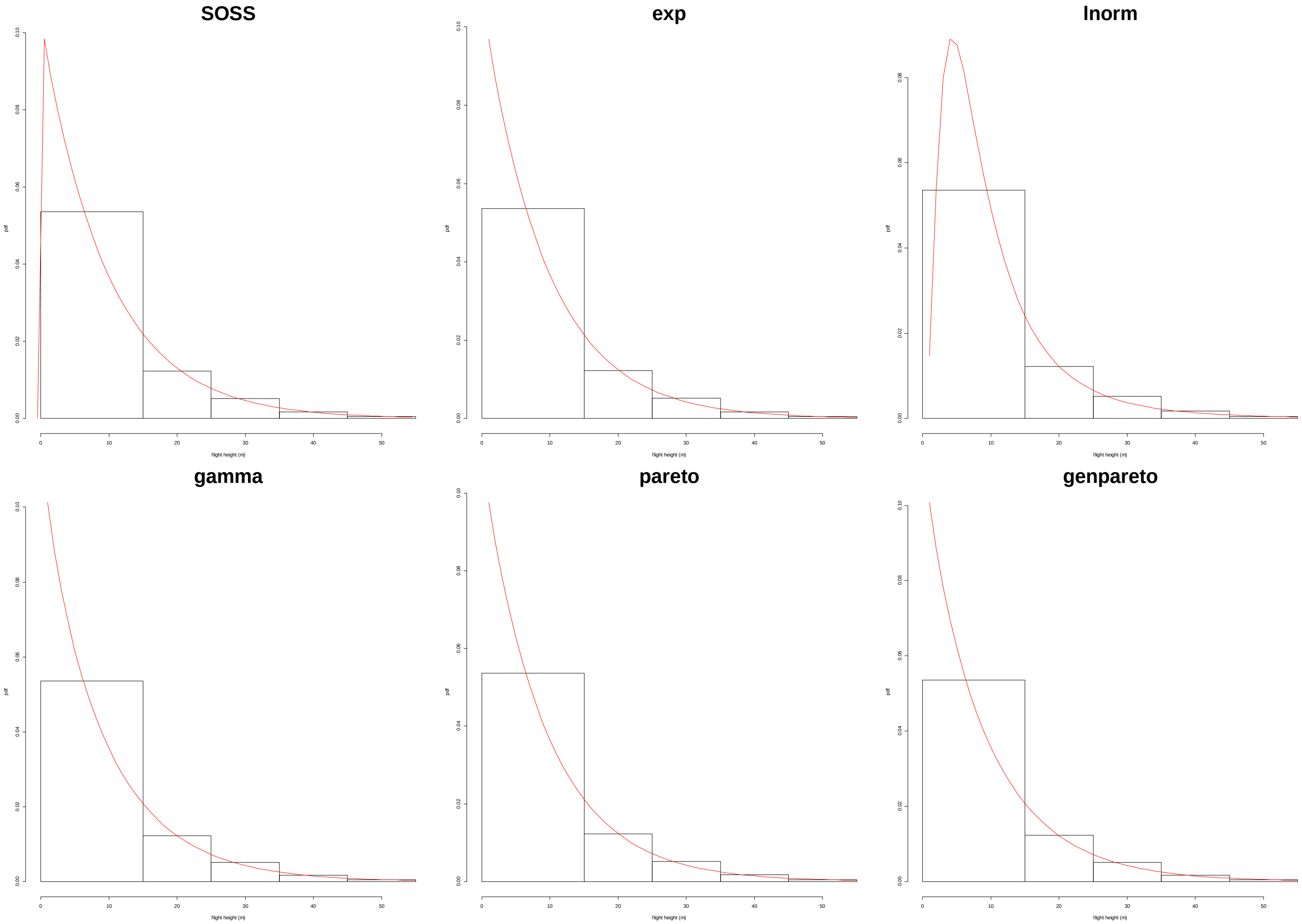

Figure 1b: Herring gull

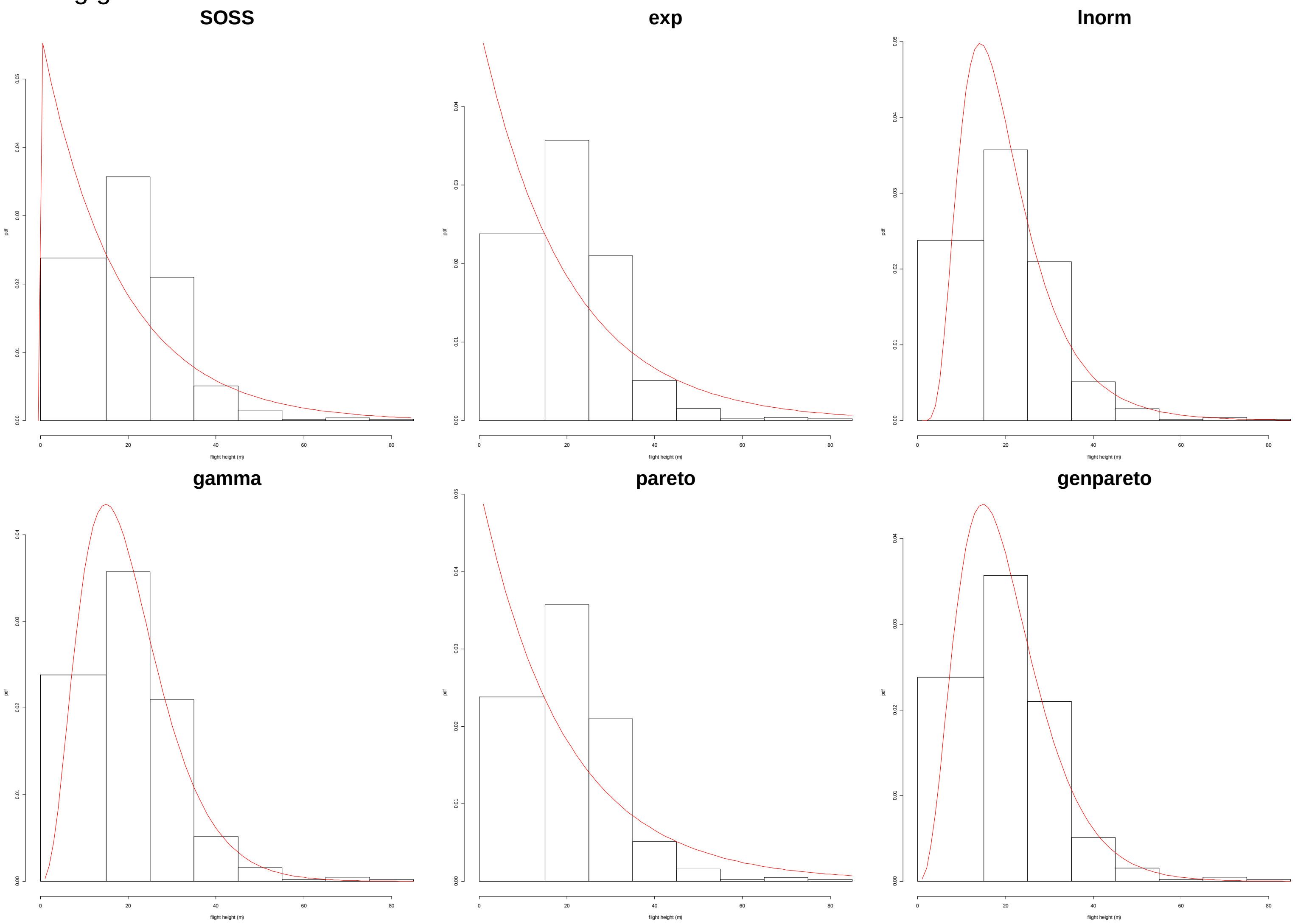

Figure 1c Great black-backed gull

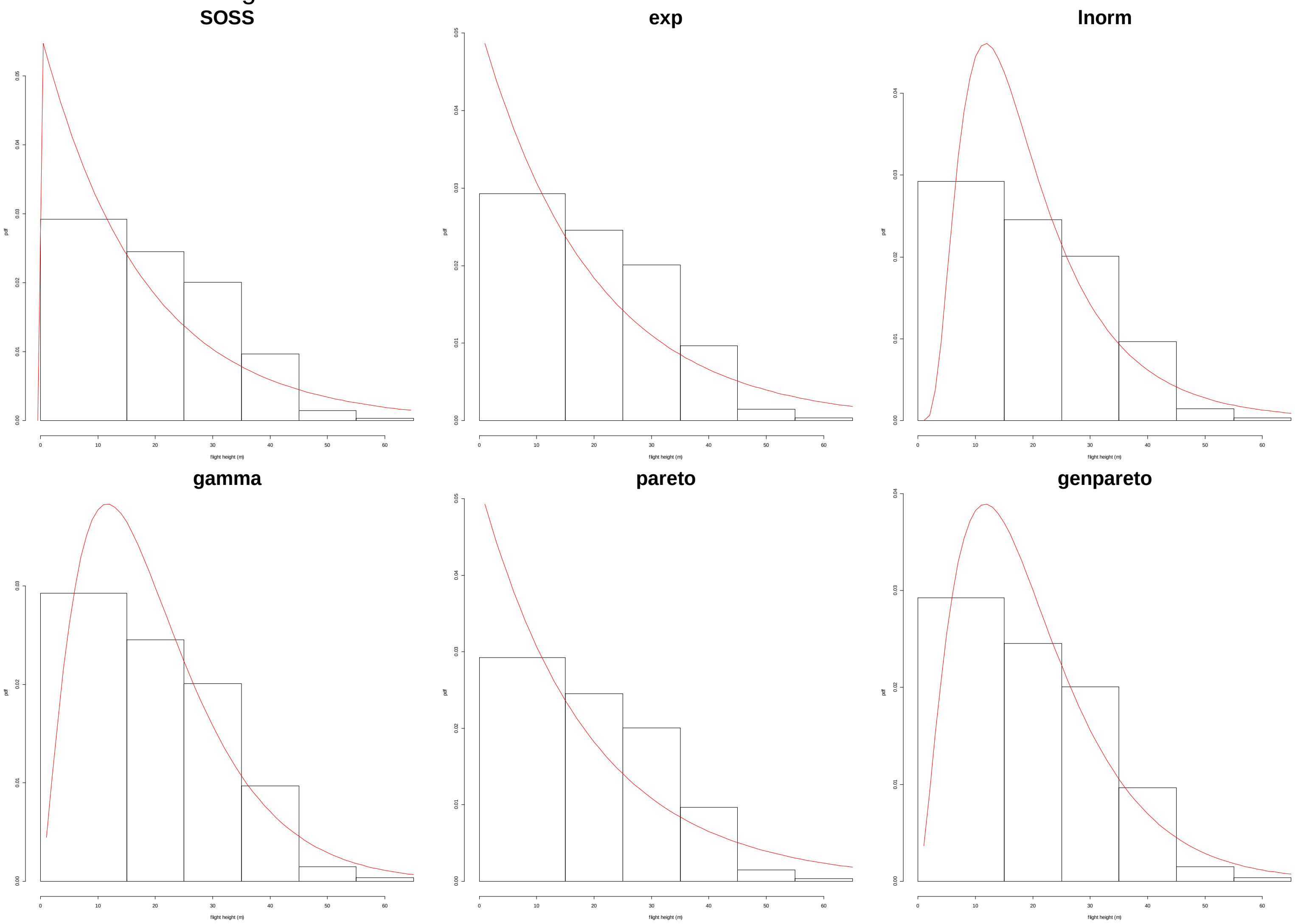

Figure 1d: Kittiwake

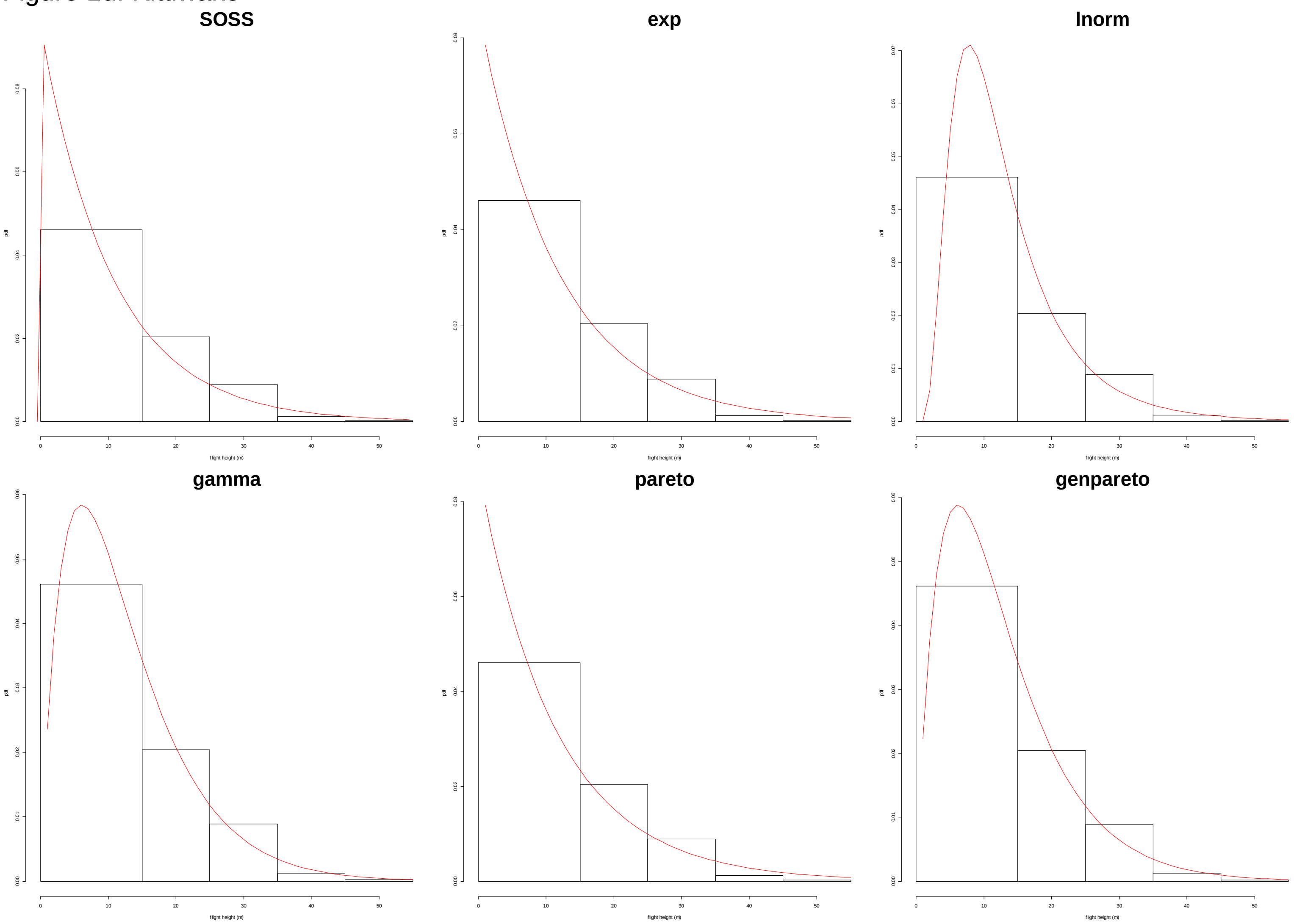

Figure 2: Cumulative distribution functions (cdfs) for different theoretical distributions and the SOSS generic flight height model fitted to the observed flight height data for gannets. (black lines: fitted values; red circles: observed).

Figure 2a: Gannet

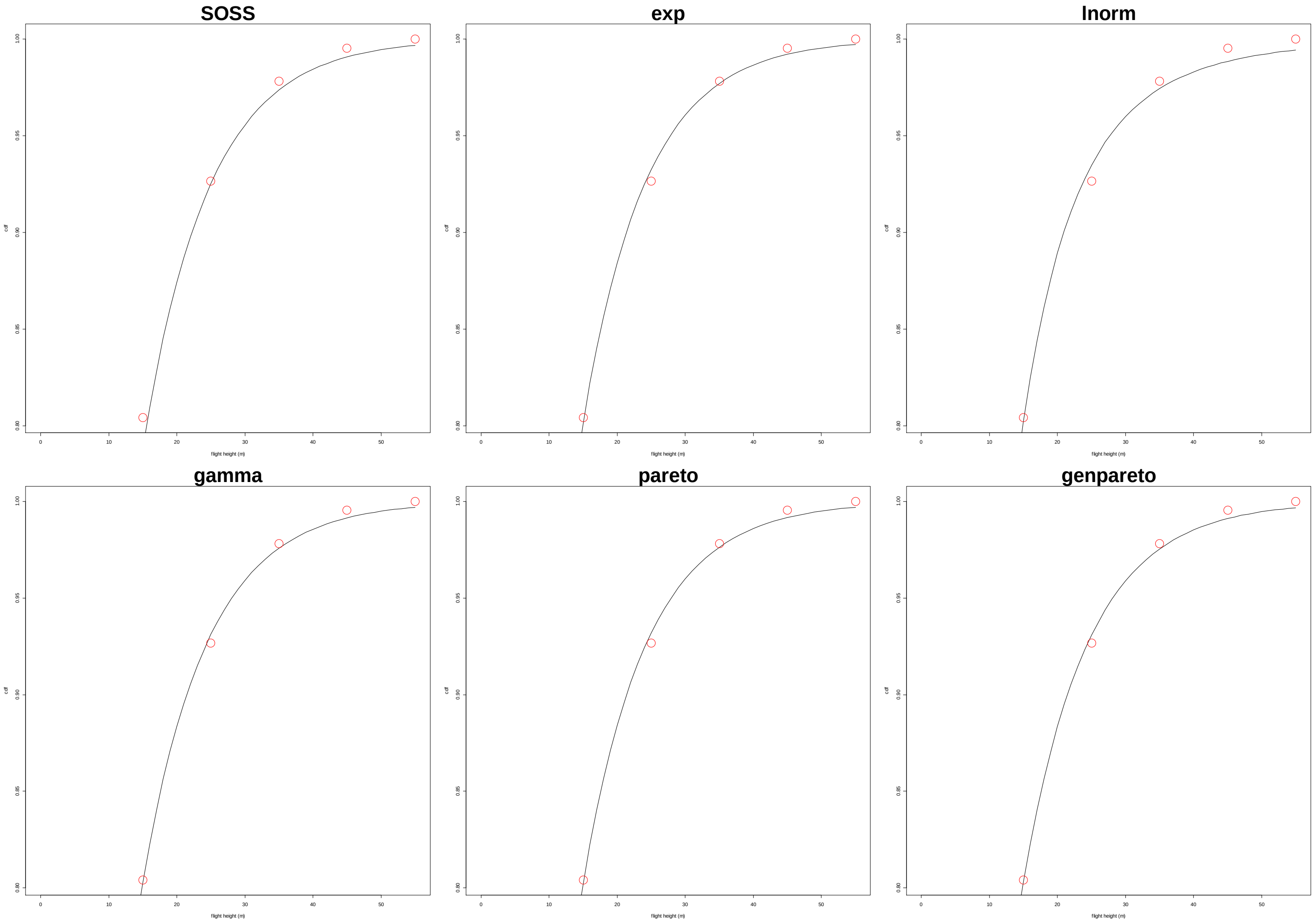

Figure 2b: Herring gull

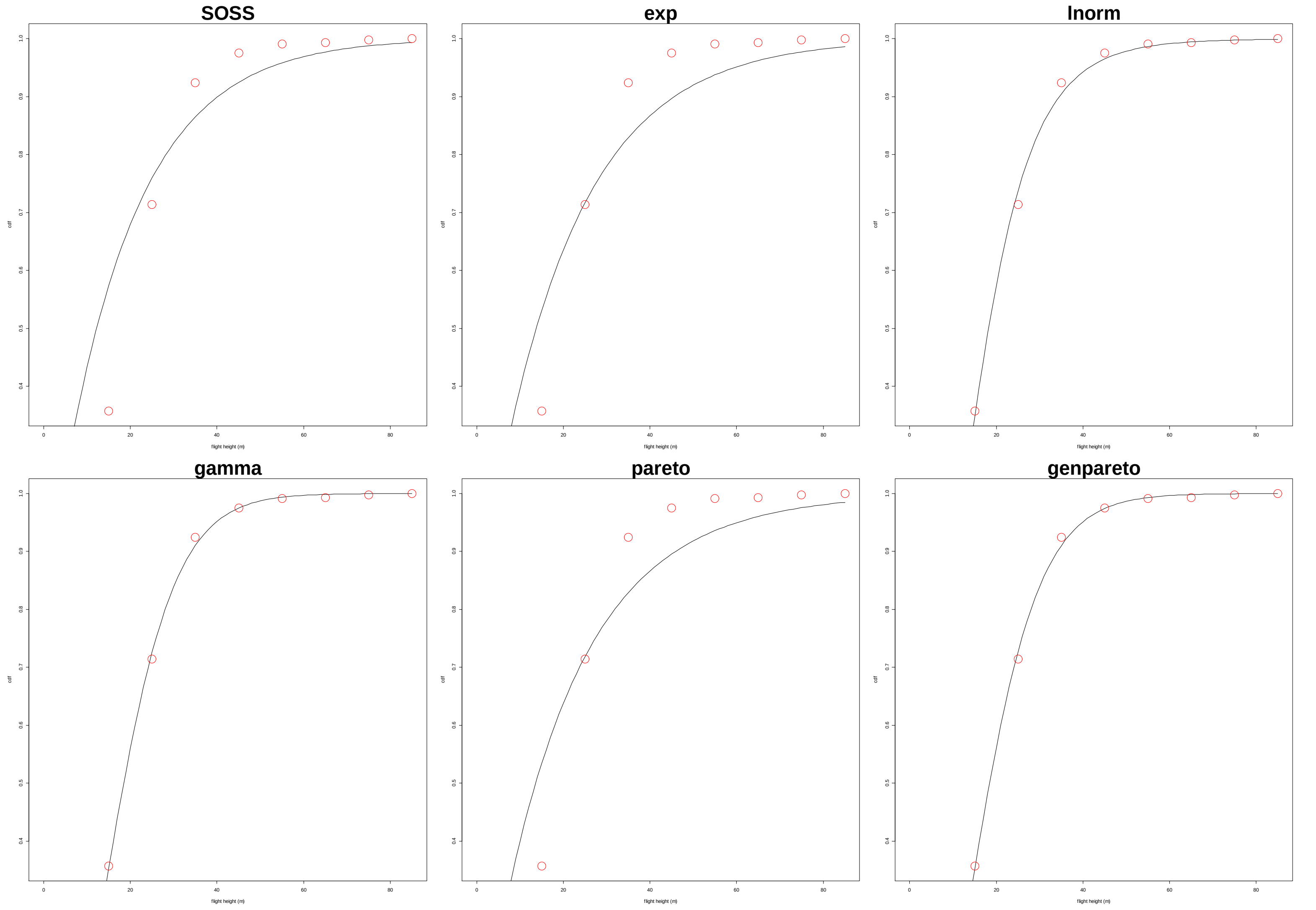

Figure 2c Great black-backed gull

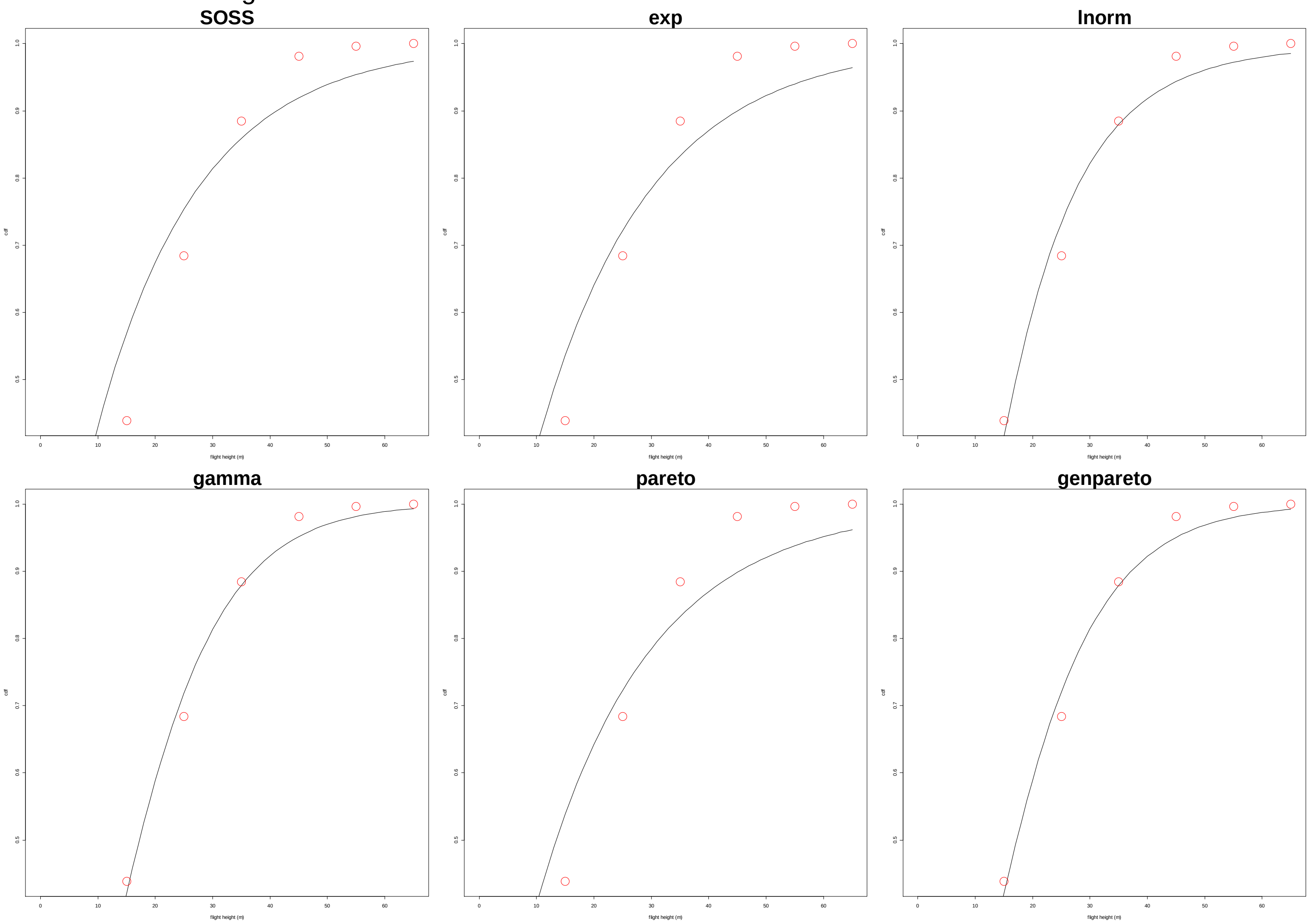

Figure 2d: Kittiwake