

Project 2009/23

**Evaluation of WA Humpback surveys
1999, 2005, 2008: Where to from here?**

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SUMMARY

Three sets of aerial line transect surveys were conducted in 1999, 2005 and 2008 to estimate the population size of humpback whales during their northward migration along the Western Australian coast. In 2005 and 2008, the aerial surveys were augmented with short land-based surveys during the expected peak of the migration. The three sets of surveys have all been previously analysed (Bannister and Hedley, 2001; Paxton et al., in press; Hedley et al., in press), but perhaps due to inconsistencies between the three analyses, have yielded equivocal results on abundance and trend. The estimates from these three analyses seem to imply some unlikely rates of increase, assuming that the maximum plausible biological rate of increase is about 11.8% (Zerbini et al., 2010).

In this report, we attempt to smooth out these irregularities and adopt a more consistent analytical approach to re-analyse the three sets of surveys. The aerial line transect data are used to estimate relative abundance for each year, giving estimates of surface-available whales of 5130 (95% CI 3380-8750) in 1999; 6070 (95% CI 4420-11,020) in 2005; and 11,820 (95% CI 9720-16,400) in 2008. Rate of increase from 1999 to 2008 is thus 9.7% p.a. (CV=0.25).

The land-based surveys were conducted with the general aim of calibrating the relative estimates in order that absolute abundance could also be estimated. In 2005, the land-based survey was conducted in an area to the north of Shark Bay, at Quobba. Here, a large proportion of whales were observed to be milling, rather than migrating in a clear direction. Thus, we considered that these data were not useable for the purposes of the comparative analysis of migrating whales in this report. In 2008, the land-based survey was conducted at Cape Inscription, at the north of Dirk Hartog Island. There were difficulties with this survey also: the observation stations were low and many whales migrated well beyond the visual range of the survey. We attempted to use these data to calibrate the aerial survey estimates but the method was unsuccessful. We were able to utilize data from focally-followed pods during the 2008 survey to estimate surface availability, and thus a conservative estimate of absolute abundance in 2008 of 28,830 (95% CI 23,710-40,100).

The baseline analyses presented in this report rely on various analytical assumptions and data selection. Sensitivity analyses are presented to assess the effects of these decisions.

1: INTRODUCTION

Three sets of aerial line transect surveys were conducted in 1999, 2005 and 2008 to estimate the population size of humpback whales during their northward migration along the Western Australian coast. In 2005 and 2008, the aerial surveys were augmented with short land-based surveys during the expected peak of the migration. The three sets of surveys have all been previously analysed (Bannister and Hedley, 1999; Paxton et al., in press; Hedley et al., in press), but perhaps due to inconsistencies between the three analyses, have yielded equivocal results on abundance and trend. The estimates from these three analyses seem to imply at least some implausible rates of increase, assuming that the maximum biological rate of increase is about 11.8% (Zerbini et al., 2010).

Full descriptions of each survey are reported in Bannister and Burton (2000), Bannister et al. (2006) and Bannister et al. (2009). Here, we provide a broad general outline, noting similarities and differences between the surveys, together with reasons for either excluding data, or for making data selection decisions in order to attempt to streamline the data across the surveys.

1.1 Aerial surveys: data collection and summaries

The surveys were conducted as single-platform aerial line transects, with one observer searching from each side of a high-wing, twin-engine aircraft. With the exception of four flights in 2008, these were undertaken using a Partenavia P68B under charter from Tropicair Services Pty Ltd., flying out of Carnavon, WA. The data collection followed similar but not identical protocols for each survey.

The survey areas overlapped (Figure 1), but differed substantially in coverage, both in latitudinal range and in area. In 1999, 14 flights were successfully flown, from 3rd July – 16th August. In 2005, only 12 flights were successfully flown, from 24th June – 15th August. In 2008, the number of successful flights was 26, with coverage from 24th June – 19th August.

In each survey, observers recorded ‘Species’ for each pod sighted, and where possible, the swimming direction of the pod. In some cases, it was not possible to confirm the species identification: uncertain classifications for ‘possible humpbacks’ (‘HB?’) were made in 1999 and 2008, but not in 2005. Of all whales sighted in 1999 (including those on transits), 48% were recorded with a swimming direction, and 35% were recorded as travelling northwards (which throughout this report, we mean N, NE or NW). 8% of humpback whale sightings were classified as ‘HB?’

In 2005, sightings were simply recorded as ‘HB’. Compared with 1999, greater emphasis was placed on recording a swimming direction, resulting in 70% of the sightings being assigned a direction; 43% were recorded as travelling north.

In 2008, definite resightings were recorded as such, but also a new field designated ‘possible’ resightings. Directions were recorded for 62% of sightings; 39% of the total were recorded as travelling north 18% of sightings were classified as ‘HB?’

The resulting implications for the data used in this report are:

- (i) a need to ensure that a consistent portion the sightings are compared across surveys; and
- (ii) that the sightings used appropriately represent the northward-migrating part of the population.

For comparisons across surveys, all ‘HB?’ sightings were assumed to be humpback whales, as it was considered that only a very small proportion of these would be any other species. Additionally, a sensitivity analysis was conducted to examine how the results might be affected by this assumption.

Differences in recorded proportions of sightings travelling northwards? may be real, or they may be artefacts of the different emphasis placed on recording swimming direction. These are not easy to disentangle, but what can be done is to use a proportion of the sightings with an unknown direction in the analysis. These sightings were randomly allocated a direction, as in Paxton et al. (in press) and Hedley et al. (in press)., according to the relative proportions of swimming directions recorded on the same day. Thus a sighting of unknown direction would have a 75% chance of being included in the analysis if three-quarters of the sightings that day were recorded as travelling north. This approach should provide datasets which are more consistent across surveys, being less susceptible to vagaries in data recording, but perhaps more importantly, it is considered that these datasets more accurately represent the northward-migrating population. Henceforth, datasets constructed using northward-migrating and unknown-directional whales are referred to as ‘NM+’; datasets using northward-migrating whales only simply as ‘NM’. The former are used for the baseline analyses presented in this report; some sensitivity analyses were conducted based only on NM whales.

1.2 Land-based surveys: a brief summary and some issues

Land-based surveys operated in 2005 and 2008. In 2005, the survey was originally planned to operate from a remote location on the west coast of Dirk Hartog Island. Offshore from there, humpback whales had previously been sighted migrating relatively close to the shore. In the event, logistical issues could not be surmounted, and the survey had to change location and operate from Quobba, a mainland location about 50km north of Carnavon. The 2005 survey was a single-platform survey, operating for 13 days during 9th – 22nd July. The platform itself was located 1.2km inshore. Observers recorded whale sightings using the tracking software Cyclopes (E. Kniest, University of Newcastle, NSW), and on a sample of sightings, conducted ‘focal follows’, recording every visible surfacing of a pod in order to provide information on surfacing and diving intervals. Whilst the land-based operations themselves were generally successful, the whales were not so cooperative! Many pods were observed to be milling, or changing direction from north to south. Their behaviour was considered not to be typical of the northward-migrating population, and was perhaps strongly influenced by – or even part of – the ‘resting area’ identified within Shark Bay.

Thus a new location for the 2008 land-based survey was required. Cape Inscription, a site at the north of Dirk Hartog Island was the most logistically-feasible (albeit remote) option, offshore from which whales would have been expected to be migrating, and a significant proportion at least would be in visible range of the observers. In 2008, it was possible to operate a double-platform for part of the survey; for the remainder, single platform survey was conducted. It was intended to focally follow a random sample of sighted pods. The highest accessible point at Cape

Inscription was just 25.5m above sea level. This significantly reduced the researchers' visual range, and even within range, a substantial proportion of theodolite measurements to sightings was either considered (by the researchers, one of whom (RAD) is an author of this report) to be unreliable or was missing. Beyond about 8km, whales were sighted 'on the horizon'; many whales migrated past Cape Inscription at considerably greater distances from the shore.

Therefore, the utility of the land-based surveys for calibrating the aerial survey relative abundance estimates is quite small, for entirely different reasons. We do not consider it appropriate to use the 2005 land-based survey for calibration at all – the whales' behaviour off Quobba presents difficulties in tracking pods; at that time they were not migrating. Furthermore, the aerial survey data in the northern part of the 2005 survey area must also include a high proportion of the 'inside-the-Bay' animals, which are not intended to be included in estimates of the northward-migrating population. Additionally the latitudinal width (N-S distance) of the 2005 survey area was almost 200km – much more than the distance a northward-migrating whale (perhaps with an average speed of 5-6km/h) would be expected to cover in one day. Potentially, therefore, double-counting could have occurred – at least on surveys flown on consecutive days. For these reasons, we excluded the northern part of the 2005 survey area, setting the northern boundary to a line of latitude at 24°43.8' S, very similar to that in 1999.

The difficulties encountered during the 2008 survey do not entirely preclude investigating further use of its data, but do suggest that any resulting calibrated estimates (i.e. those 'corrected for $g(0)$ ') should be treated with appropriate caution. We estimate $g(0)$ and apply the correction to the 2008 data only. Comparing estimates from the aerial survey and the land-based survey, Hedley *et al.* (in press) estimated $g(0)$ s ranging from 0.32 to 0.61. The principle factor causing the difference was whether, after truncating land-based sightings to 12km offshore, sightings made – but for which it was not possible to obtain a theodolite measurement – were additionally included.

1.3 Analysis outline

The original project proposal outlined the following approach for analysing these data:

- 1) Analyse the aerial data from the East-West oriented transects from the three sets of surveys using conventional line transect estimation (or multiple covariate distance sampling). This will yield 'baseline' relative density estimates of surfacing whales, but these would be (substantially) negatively biased estimates of absolute density. Use an appropriate form of non-linear model to estimate the total number of whales throughout the migration season.
- 2) As for (1), but using additional data from other legs, fit spatio-temporal models to provide estimates of changes in the relative density of surfacing whales throughout the migration season.
- 3) Re-examine the 2005 and 2008 land-based data to determine which, if any, of ' $g(0)$ ' correction factors are most appropriate. Apply these consistently across the surveys to compare absolute abundance.

This approach has not been rigidly adhered to. Following exploratory analyses along the lines above, it was evident that conventional line transect estimates were giving very similar estimates per flight to those from the spatio-temporal model. The model-based approach should in theory at least provide higher precision (since it uses more of the available data) and so duplicating the analysis in this way did not seem appropriate. The following

alternative approach was therefore adopted, in the expectation of providing less ambiguity in the results.

- 1) Using sightings data separately from the three sets of surveys, estimate detection functions, considering the most appropriate forms for a 'best' analysis for a particular year, and a most consistent analysis across years.
- 2) Using the results from 1), fit spatio-temporal models to each set of survey data.
- 3) Using the results from 1) and 2), fit migration-count models to each set of survey data, and thus estimate relative abundance for 1999, 2005 and 2008.
- 4) For 2008 data *only*, use the land-based and aerial survey data to estimate a 'g(0)' correction factor to allow absolute abundance to be estimated.
- 5) Examine the sensitivity in results to various factors in the analysis, including:
 - a) using NM whales, rather than NM+ whales
 - b) choice of left-truncation distance (aerial survey)
 - c) inclusion/exclusion of possible humpback whale sightings 'HB?'
 - d) inclusion/exclusion of possible resightings
 - e) inclusion of 'structural zeros' in the migration models

The 'baseline' analysis was based on:

- NM+ whales (with mean school size being estimated from NM whales only)
- Sightings recorded as 'HB' and 'HB?'
- Inclusion of *possible* resightings (although *definite* resightings were excluded)
- Structural zeros in the migration model on 13th April and 27th October
- An assumed migration speed of 5.56km/h
- Inclusion of land-based sightings with no recorded distance
- A 98-day assumed northward-migration period from 1st June – 7th September.
- A reduced survey area for 2005, with northern boundary at 24°43.8' S.

'Most consistent' and 'best' (which could potentially be the same) perpendicular distance truncation distance for the detection function were to be determined and applied. The importance of this aspect of the analysis was in estimation of the effective strip width. Owing to the fact that the surveys were aerial line transects, a rectangular strip under the aircraft was unsurveyed. Where clinometer readings are available, the width of this strip can be calculated, but typically it extends outwards to a wider strip which may contain sightings but is ineffectively surveyed (due to observer discomfort or whatever). Sightings data may be 'left-truncated' at distances close to the transect line to accommodate this problem; however, unlike some right-truncation (exclusion of sightings a long way from the line), estimation of the detection function (and thus of the effective strip width) is generally quite sensitive to the choice of left-truncation distance.

The higher number of NM+ pods seen in 2008 compared to the previous two surveys is evident from Figure 2, which shows the number of sightings per flight, by survey. These data are unadjusted for the different size of survey areas: 2422, 1555 and 1920 nmiles² for 1999, 2005 and 2008 respectively. Better coverage was achieved in 2008. Although flights were flown for a similar temporal span in 2005, the coverage was much patchier, with no obvious migration 'peak'. In 1999, the temporal span was shorter still, and flights, during the second half of the survey at least, were widely spaced. The coverage achieved has implications for estimating the 'migration curve' – the numbers of whales expected to be in the area per day, throughout the migration period. Integrating under this estimated curve across the expected period of migration gives us

our abundance estimate. Only 14 (for 1999) and 12 (for 2005) data points are available for estimation of the curve for these years. Precision would thus be expected to be poor.

2: DETECTION FUNCTION ESTIMATION

For each survey, heading angles were corrected for aircraft drift, and perpendicular distances (x) were calculated from the recorded declination angle (θ) and corrected heading angle (ϕ) using the following formula (e.g. Pike *et al.*, 2008):

$$x = h(\tan(90 - \theta))\sin(\phi),$$

where h is flight altitude.

Exploratory analyses were conducted within the software *Distance* 6.0 Release 2 (Thomas *et al.* 2010), to examine the distribution of perpendicular distances, and how detectability varied with covariates.

2.1 Perpendicular distance distributions in 1999, 2005 and 2008

Via visual analysis of the perpendicular distance distributions (Figure 3), a left-truncation distance of 0.7km and a right-truncation distance of 4.5km were selected. Covariates which could affect detectability and were potentially available for inclusion in the scale parameter of a half-normal detection function model were: *cloud cover*; *pod size*; *observer*; *sea state*, and *sightability* (a subjective factor with three levels: excellent, good and moderate). After left and right truncation, models including each covariate individually were compared with a perpendicular distance-only model, using Bayes Information Criterion (BIC). In all cases except for that with *observer* as a covariate, there was no improvement to the detection function model. In two cases (*sightability* and *pod size*), BIC did indicate that the covariate would improve the fit, but in these cases the addition of the covariate led to counter-intuitive results (e.g. the probability of detection decreased with *pod size*). Figure 4 shows the levels of difference between the fitted detection functions by observer. For observer CB, the figure suggests that some sightings within about 1km of the transect line were missed, with a fairly uniform probability of detection between 1-3km. For observer MB, left-truncation at 0.7km appears adequate, and a more typical distribution of detection distances is obtained, with detectability decreasing with distance from the line. For one observer (CJ), there were only 13 sightings, so the model was re-fitted excluding these sightings to check that the factor *observer* was still significant. Indeed it was, but the estimated effective strip half-width from these exploratory analyses was identical, albeit with mildly improved precision. (Observer effects are also more difficult to quantify across surveys than a variable such as sea state.)

As for 1999, visual inspection of perpendicular distance distributions suggested left and right truncation distances of 0.7km and 4.5km were also appropriate for 2005 (Figure 5). Covariates available were as for 1999, except that the *observer* covariate represented side of the aircraft from which the sighting was made, rather than the individual observer. No improvements to the distance-only detection function model were made by the inclusion of covariates *pod size*, *observer*, or *sea state*. The inclusion of *cloud cover* in the detection function did improve provide a mild improvement to the fit, and a slightly reduced effective strip half-width. Detectability was

found to be higher when cloud cover was lower. This is somewhat surprising; our expectations were that cues were actually more detectable in cloudy conditions.

The results for 2008 were somewhat different. Sighting distances were closer to the trackline, perhaps reflecting some better training of observers in this survey – certainly much less left-truncation of the data was required in order accommodate the ‘dip’ in sightings close to the trackline (Figure 6). Visual inspection suggested a right-truncation distance of 4.5km was still reasonable, though it reduced the dataset by about 16%. Based on the results from 1999 and 2005 (and since this was the truncation distance for NM+ whales used by Hedley *et al.*, in press), we chose this distance for our baseline analysis. In theory, estimation should be fairly robust to the choice of right-truncation distance; left-truncation is a different story. Inclinometer readings taken on the 2008 survey indicated that sightings were obscured from view within a 2x40m and a 2x260m strip for the Partenavia and Cessna respectively. However, as in Hedley *et al.* (in press), we found evidence that sightings were being missed from the Partenavia beyond 40m, and thus we adopted their approach here, choosing to truncate the data differently from 1999 and 2005, at 0.26km. Sensitivity to this choice is considered in section 6.2. Results from the covariate analyses were similar to those on previous surveys, with no improvement to the fit by incorporating *observer* and *seastate* effects. A small improvement (according to BIC) could be obtained by incorporating *cloud* (but as for 2005, with lower detectability in higher cloud cover). The covariate *pod size* was significant, but again, the resultant model suggested lower detectability of larger schools. *Sightability* was found to improve the fit slightly, and apparently in the ‘right’ direction (counter to what is reported in Hedley *et al.*, in press).

In summary, there is some mild evidence that the use of covariates could provide some small improvement to the detection function model, but there is no strong case for including a covariate in these comparative analyses. We were particularly reluctant to use the subjective factor *sightability* especially as it appeared to be having the opposite effect on detectability in 2008 as it did in 1999. Our decision not to fit models incorporating cloud cover is based on our personal observations that the effect detected is counter to what we have observed. Little is lost by adopting (perhaps more) robust perpendicular distance-only models across the three sets of surveys, save some very small loss in precision. Although only half-normal models were considered in the multiple covariate distance sampling analyses above, for each survey, a distance-only hazard-rate form for the detection was also fitted. For all three years, Akaike’s Information Criterion (AIC) was lower for the half-normal form and thus we adopted the perpendicular distance-only half-normal model for the analyses here.

3: SPATIO-TEMPORAL MODELLING OF THE AERIAL SURVEY DATA

3.1 Estimating relative abundance per survey flight

In this section, we first provide a brief description of the spatio-temporal model used to estimate ‘snapshot’ abundance of the number of whales in the survey areas, following the approach taken by Hedley *et al.* (in press) in their analysis of the 2008 data.

For each survey, transects covered on effort were divided into segments of length approximately equal to 10 nmiles (18.5km), and the number of pods sighted in each segment was calculated. The midpoint of each segment was used as its location, and an offset variable was computed as the logarithm of the effective area of the segment, where the effective area is given by twice the

segment length multiplied by the estimated effective strip half-widths from a perpendicular distance-only half-normal detection function. Potential spatial covariates were *Latitude*; *Longitude* and *Bottom depth* – sourced from a 1' by 1' grid from the U.S. National Geophysical Data Center, NOAA Satellite and Information Service (www.ngdc.noaa.gov/mgg/bathymetry). In addition, *Day* (where Day 1 was defined to correspond to 2nd June, the assumed start of the whales' northward migration period) was a potential temporal covariate.

Model fitting and model selection were conducted in the *mgcv* package (Wood, 2008) available in R (R Development Core Team, 2010). A number of forms for the smoothing components of the spatial models were considered, but none of these showed evidence for including *Bottom depth* in the model. GCV score was used to compare models; the final selected model was a tensor product smooth (Wood, 2006) of a two-dimensional thin-plate spline of *Latitude* and *Longitude*, and a thin-plate spline of *Day*.

$$\log [E(nsight_i)] = te(Latitude_i, Longitude_i, Day_i) + \log(estimated\ effective\ area_i) + X_i$$

where $E(nsight_i)$ was assumed to follow a Tweedie distribution with scale parameter 1.1, and te is a tensor product of thin-plate spline smooths of *Latitude* and *Longitude*, and *Day*. The offset variable for the i^{th} observation, $\log(estimated\ effective\ area_i)$, was estimated using the effective strip widths estimated from the distance sampling analysis. X is a vector of first derivatives and was used to propagate variance, penalized according to the Hessian of the respective detection function fit (Williams *et al.* 2011).

Once fitted to the along-transect data, the model allows prediction of pod density at all locations within the survey area, for any day. Whale density was estimated by multiplying the daily pod density surfaces by a spatial school size surface (estimated from a generalized additive model (gam) with gamma error distribution). In this way, a series of whale density surfaces for all days within the assumed migration period was estimated (separately for each survey). Snapshot abundance was obtained by integration under the corresponding density surface for each day. To convert these estimates into daily (24 hour) estimates, the rate of passage through the survey area was estimated assuming an average speed of travel of 5.56km/h (estimated from the focally followed pods from 2008; Hedley *et al.*, in press) for the baseline analysis. A wide range of swimming speeds have been reported for migrating humpback whales (Noad and Cato, 2007).

Latitudinal widths (d_{lat}) for the three survey areas were 166.2, 107.8, and 86.7 km, hence the snapshot estimates were multiplied by a correction factor equal to $(5.56 \times 24)/d_{lat}$ to convert them to daily estimates. (Estimated variance in speed of travel was not incorporated in the variance of the final abundance estimates.)

3.2 Structural zeros and the migration model

Figure 2 illustrates the pod counts per flight, albeit prior to any distance truncation, but even from this figure, it is evident that any attempt to fit a migration curve to the 1999 and 2005 data (at least) requires a bit of 'statistical jiggery-pokery'. In their analysis of the 1999 data, Bannister and Hedley (2001) added structural zeros – zero counts at the assumed start and end times of the migration period – and restricted the possible shape of the migration curve to that of a Gaussian model. (The software used, GWNORM (Buckland, 1992), also allowed for Hermite polynomial adjustment terms to be added if required.) Paxton *et al.* (in press) took a more circumspect approach for the 2005 data. Though they fitted flexible gams (modelling presence/absence, then density based on presence), they placed some restriction on the smoothing degrees of freedom, and did not add structural zeros. This resulted in a fit showing broad fidelity to the data, but

inferences across the whole assumed migration period could only be made with certain caveats. Even though the 2008 survey comprised 26 successful flights from 24th June – 19th August, Hedley *et al.* (in press) still added structural zeros (on 2nd June and 7th September) to their spatio-temporal gam, thus tying down the migration curve at those times.

By experimentation, it became clear that for this comparative analysis structural zeros would be necessary to obtain ‘believable’ migration curves, that is, curves for which the counts are close to zero at the start and end periods of the presumed migration. Setting counts to zero on 2nd June and 7th September across years was however unsuccessful; it tied down the ends, but did not allow much of a steady change in numbers prior to the start, and after the end, of the flights. Therefore we inserted structural zeros 50 days earlier and 50 days later (13th April and 27th October). This is as if a survey had been conducted on those dates and no sightings were made. The spatio-temporal model in section 3.1 above is then fitted with these additional zero counts in the data. The resulting migration curves are shown in Figure 7.

Integration under these curves for the assumed migration period of 2nd June – 7th September results in estimates of relative abundance for each of the surveys (Table 1).

Year	\hat{N}	95% CI
1999	5130	(3880 - 8750)
2005	6070	(4420 - 11,020)
2008	11,820	(9720 - 16,440)

Table 1 Estimated relative abundance of northward-migrating humpback whales from the three sets of surveys. Numbers based on NM+ whales, i.e., those recorded as travelling north plus a fraction of unknown-direction whales, randomly allocated a northward direction.

The numbers in Table 1 suggest no significant difference in relative abundance from 1999 to 2005 (as borne out by the raw data in Figure 2), but a significant increase from 1999 to 2008, at an estimated rate of increase of 9.7% p.a. (CV=0.25). From these figures, the 2005 estimate appears to be an underestimate, although precision is low. If the rate of increase is assumed correct, the point estimate for 2005 should be around 8950 whales, almost 3000 more than the estimate in Table 1. Paxton *et al.* (in press) give an absolute estimate of 19,400 whales (95%CI: 10,800 – 59,700), with a relative estimate of 6014 after applying their $g(0)$ correction of 0.31. The similarity in point estimates is a little surprising given that the Paxton *et al.* (in press) figure includes whales sighted in the northern part of the 2005 area, animals presumed in our analysis not to be migrating.

Potentially, the 1999 estimate could be slightly high. Swimming at 5.56km/h, a humpback whale could travel about 130km; the latitudinal width of the survey area exceeded this distance by 36km. Thus, there is a possibility that some double counting of whales may have occurred in 1999, at least on those days near the beginning of the survey when flights were conducted on consecutive days. We expect this to have had only a small effect on the estimate, but haven’t checked (e.g. by reducing the size of the survey area as we did for 2005).

4: CALIBRATING THE RELATIVE ESTIMATES IN 2008 USING THE LAND-BASED SURVEY

As described in section 1.2, although the land-based survey in 2005 was operationally successful, the utility of these data for calibration of the aerial surveys of the northward-migrating population is extremely doubtful. We did not use them in our analyses.

The 2008 land-based survey was beset with practical difficulties, notably the low platform height and the distance offshore of the whales. The analysis we conducted for this report therefore was intended to provide an update the Hedley *et al.* (in press) estimates, based on the comparative results described above. We had planned to estimate a calibration factor using the land-based survey data, and had reasoned that to do so it was appropriate to use all land sightings with a recorded distance offshore *plus* those with no recorded distance, noting that a (probably small) proportion of those with no distance recorded may have been beyond the 12km truncation distance. A calibration may be based on a regression of estimates from the land-based survey (assumed to be absolute) on equivalent ones from the same area of the sea from the spatio-temporal model on the same days as the land-survey. The slope of the regression provides the calibration factor, $\hat{g}(0)$. However, as can be seen from Figure 8, there is little evidence of any correlation. A simple regression, heavily dependent on the single point with high estimated count (58) gives an estimate of 0.28, but this increases to 0.35 on removal of the high-leverage point. Absolute abundance based on these estimates would vary from 41,580 down to 33,860, and although it could be argued that $g(0)$ estimates in this range may well be feasible for the aerial surveys, our analyses conducted for this report suggest that the data are inadequate for the purposes of calibration.

Two questions arise: (1) what is a reasonable estimate of $g(0)$ (and thus absolute abundance)?; and (2) is the land-based survey method worth pursuing in future, perhaps with more time dedicated to its operation?

In the next section we consider the use of the focally-followed pods to estimate a correction for surface availability, as a first step in attempting to address the first of these questions using existing data sources. Regarding the second question, if the results from combined aerial surveys and land-surveys cannot be reconciled, then perhaps the answer is no. Whilst the land-based survey method has been very successful in surveying the humpback whales migrating along the east coast, these whales pass much closer to the shore, well within the visible range of the observers. If a land-based survey was to be used to survey the west coast animals, then we know that many whales would be migrating far beyond the observers' range. Without some correlation between the sets of estimates from the two types of survey, it is hard to imagine how one might quantify the proportion missed offshore from the land using an aerial survey.

5: USING FOCAL FOLLOWS TO ESTIMATE POD AVAILABILITY

In the 2005 survey, a large proportion of pods were not migrating within the study site. Using focal follow data of non-migrating groups to estimate pod availability of migrating groups is not realistic. Therefore we only consider here the use of the 2008 land-based focal follow data, for which a mean estimate of surfacing time s and diving time d had previously been calculated as 405s and 246s respectively (as reported in Hedley *et al.*, in press).

There are two main issues associated with using the focal follow dataset to generate a measure of pod availability at the surface for sighting: (a) biased sampling, and (b) the difficulty of

separating respiration dives and deep dives (and the relevance to this of whales being detectable from the aircraft even if they are below the surface).

In 2008, owing to problems with the land-based station height, it was only possible to select pods which migrated close to the shore as focal follow subjects. Those migrating further than about 7km from the shoreline were too difficult to accurately capture all behaviours. However, only a small proportion of the population migrates within 7 km from the shore-line at this site. If close-in pods were not available, pods that were visually easy to follow had to be chosen (in other words, pods which spent a lot of time on the surface). This selectivity introduced both a distance bias (a preference for pods closer to shore) and a sightability bias (when choosing pods further offshore, the pods had to be easy to follow) and probably resulted in an inflated surfacing time and therefore in pod availability.

‘Surfacing dives’ of humpback whales are short and shallow dives that occur during respiration bouts and ‘deep dives’ are dives in which the pod disappear for a longer period of time. The length of the ‘deep dive’ is defined as the time from which the last pod member disappears to the time when the first pod member re-appears, and the ‘surface interval’ is defined as the time spent on the surface between deep dives which thus incorporates all ‘surfacing dives’. Discriminating between ‘deep’ and ‘surfacing’ dives can be problematic (Hooker and Baird, 2001).

In a previous study on the east coast humpback whale population, focal follow data was used to differentiate between shallow respiration dives and deep dives. For every pod, the time between each successive sighting (sighting lag time) was measured. A K-means clustering technique was used to separate the dataset into two normal distributions; ‘short lag time’ (mean = 21s; SD = 13; n = 376) and ‘long lag time’ (mean=229s; SD = 177; n = 223). The minimum ‘deep dive’ cut off time was designated to be 60 seconds to allow for error (there were only eight sighting lag times between 53 and 59 seconds and a maximum cut off time of 550 seconds for deep dives was used. Previous observations in this area (over five field seasons) have shown that deep dive times of migrating pods usually average between 4-5 minutes, with a maximum of 10 minutes. Therefore, any lag time under 60 seconds was designated to be a shallow respiration dive.

We attempted similar methodology for the focally-followed pods from 2008, but encountered difficulties. The sighting lag times did not fall into two normally distributed categories, but ranged from 1 second to 20 minutes (Figure 9) and was highly variable within and between measured pods. The previous estimate of pod availability at the surface used this prior categorization developed from an east coast dataset as well as looking for dive patterns within each focally followed pod to try and separate the surface interval and deep dives. The total time spent in a surface interval was used as the measure of pod availability. However, this assumes that if a pod is in a surface interval then it is available for sighting, and if it is in a deep dive then it is not. Qualitatively at least, this provides evidence that the use of mean surfacing interval and mean deep diving interval to represent a measure of availability for detection gave misleading results and did indeed overestimate pod availability, leading to an inflated $g(0)$ of 0.72 (Hedley *et al.* in press).

Therefore, it may be more appropriate to use lag time between successive sightings as the measure, regardless of whether the dive was a short respiration dive or longer deep dive. For example, a pod in which sighting lag times are less than 10 seconds apart is probably available for sighting from the aerial platform throughout that sighting period. A pod which dives (and therefore may have a sighting lag time of greater than 10 seconds) may be available for sighting for a small part of that dive (where they are visible underwater, or the footprint is still visible) and unavailable for sighting when it reaches a particular depth.

The following analysis calculates the average proportion of time a pod is available for sighting based on a conservative criterion of 10 seconds ($n = 22$ focally followed pods). The assumption is that pods are available for sighting if the time between successive sightings is 10 seconds or less. If the sighting lag time is more than 10 seconds, pods are available for sighting for only 10 seconds (to account for visibility below the surface, hanging blows and/or footprints). A less conservative measure of 20 seconds was also used for comparison.

Lag time (seconds)	Mean time (in seconds) available	Mean total time (in seconds)	Mean proportion of time available
20s	11.8 (7.1)	28.7 (62.2)	0.41 (0.19)
10 s	7.6 (3.2)	28.7 (62.2)	0.28 (0.13)

Table 2 Mean proportion of time available for sighting based on the 10 and 20 second criteria for the 22 focally followed pods from the 2008 land-based survey. Standard deviations in parentheses.

With an average deep-diving time of about 4.5 minutes, and a time window of 66 s (as per Hedley *et al.*, in press) and using the availability approach of Barlow *et al.* (1988), then $\hat{g}(0)$ is 0.41 using the conservative lag time of 10s, or 0.47 using the less conservative measure. Given the relative uncertainties associated with estimating $g(0)$ in the present analysis, it seems most appropriate to adopt, for now at least, the estimate with the more conservative assumption of a 10s lag time (0.41), from which absolute abundance for 2008 is 28,830 (95% CI 23,710 – 40,100)¹.

6: SENSITIVITY TO ASSUMPTIONS AND DATA SELECTION

In undertaking this analysis, it has become clear that the estimates produced can vary widely according to assumptions made and to different, but apparently reasonable, data selection decisions. Having presented what we consider to be our base-case analysis above, we now examine the effects of these different assumptions and uses of the data.

6.1 Using NM whales vs. NM+ whales

During the surveys, observers recorded the ‘swimming direction’ of humpback whales. A pod recorded with a northward swimming direction was classified as ‘northward migrating’ or ‘NM’ for short. For a high proportion of the sightings, and as expected from an aerial survey, it was not possible for the observers to determine a swimming direction². As outlined in section 1.3, the baseline analysis therefore used data from sightings of NM whales together with some of the unknown-direction whales (i.e. NM+ whales). Using the same left and right truncation distances

¹ There is no component of variance due to $g(0)$ estimation in this interval.

² In some cases it was possible to determine that a pod was milling, in which case this would be the recorded ‘swimming direction’.

of 0.7km and 4.5km for 1999 and 2005, and 0.26km and 4.5km for 2008, the NM data were analysed as described in sections 2 and 3. The results (Table 2) show that for 2005 and 2008, the use of NM+ whales increases abundance by a fairly large, but different, amount (14% and 28% respectively). For all three years, the estimated effective strip-widths (esws) are lower for the NM analysis than for the NM+ analysis; as expected direction is more readily determined from pods closer to the trackline. In 1999, where no difference was seen in the estimates, the narrower esw for NM whales appears to have compensated for the lower encounter rate.

The estimated rate of increase from 1999 to 2008 is reduced from 9.7% to 7.9% p.a. (CV= 0.27).

Year	n_{NM+}	n_{NM}	esw_{NM+}	esw_{NM}	\hat{N}_{NM+}	95% CI	\hat{N}_{NM}	95% CI	% diff
1999	301	162	2.36	2.00	5130	(3880 - 8750)	5140	(3890 - 8780)	+0.2
2005	161	135	2.51	2.40	6070	(4420 - 11,020)	5190	(3490 - 10,550)	-14.5
2008	706	495	2.67	2.32	11,820	(9720 - 16,440)	10,150	(8100 - 15,540)	-28.1

Table 3 For NM and NM+ whales, and for each survey year, numbers (n) of pods after left and right truncation, estimated effective strip half-widths (esw) in km, and estimated relative whale abundance (\hat{N}), with 95% confidence intervals in parentheses. Subscripts denotes dataset: NM or NM+ pods. The percentage difference in relative abundance (% diff) is expressed relative to \hat{N}_{NM+} .

6.2 Different Left-Truncation values

In this report, although exploratory analyses were conducted separately by year, the preference was to standardize where it seemed reasonable to do so. In 1999 and 2005, the perpendicular distance distributions indicated that a rather large rectangular strip under the aircraft was obscured (of width 2×0.7 km) whereas in 2008, the data supported inclinometer measurements much more closely, and a narrower strip (2×0.26 km) was excluded by left-truncation of the data. This suggests that in 2008, observers were searching more frequently closer to the trackline, a practice recommended in general for aerial surveys (Buckland *et al.* 2001, pp.280-287).

For this sensitivity analysis, we compared the baseline results with (a) no left-truncation, and (b) left-truncation at 1.0 km (as implemented, in their analysis of the 2005 data, by Paxton *et al.*, in press). As expected, zero left-truncation had a large effect for the 1999 and 2005 estimates – a large component of this owing to the inflated estimated esws (Table 4a). The effect for 2008, with only 0.26km truncation in the baseline analysis, was much smaller. In all cases, point estimates of abundance were lower. Left-truncation at 1km had a moderate effect on the estimated esws but with the lower encounter rate as a result of the extra-truncation, abundance was again lower. The largest effect, as expected, was for 2008, where the data supported a much smaller truncation distance.

Year	$n_{0.7}$	n_0	$esw_{0.7}$	esw_0	$\hat{N}_{0.7}$	95% CI	\hat{N}_0	95% CI	% diff
1999	301	326	2.36	3.08	5130	(3880 - 8750)	4266	(3220 - 7170)	-16.8
2005	161	172	2.51	3.07	6070	(4420 - 11,020)	4840	(3400 - 8260)	-20.3
2008	706	741	2.67	2.86	11,820	(9720 - 16,440)	11,520	(9470 - 16,130)	-2.5

Table 4(a) For each survey year, numbers (n) of NM+ pods after right truncation at 4.5km, estimated effective strip half-widths (esw) in km, and estimated relative whale abundance (\hat{N}), with 95% confidence intervals in parentheses. Subscripts denote dataset: 0.7 = left-truncated at 0.7km; 0 = no left-truncation. The percentage difference in relative abundance (% diff) is expressed relative to $\hat{N}_{0.7}$.

Year	$n_{0.7}$	n_1	$esw_{0.7}$	esw_1	$\hat{N}_{0.7}$	95% CI	\hat{N}_1	95% CI	% diff
1999	301	255	2.36	2.24	5130	(3880 - 8750)	4270	(3220 - 7170)	-16.7
2005	161	144	2.51	2.53	6070	(4420 - 11,020)	5350	(3680 - 9710)	-11.9
2008	706	541	2.67	2.51	11,820	(9720 - 16,440)	9300	(7460 - 13860)	-21.3

Table 4(b) For each survey year, numbers (n) of NM+ pods after right truncation at 4.5km, estimated effective strip half-widths (esw) in km, and estimated relative whale abundance (\hat{N}), with 95% confidence intervals in parentheses. Subscripts denote dataset: 0.7 = left-truncated at 0.7km; 1 = left-truncation at 1.0km. The percentage difference in relative abundance (% diff) is expressed relative to $\hat{N}_{0.7}$.

6.3 Exclusion of possible humpback whales, ‘HB?’

In the 2005 survey, all humpback whales were recorded as ‘HB’, but in 1999 and 2008 some sightings were recorded as possible humpbacks, ‘HB?’ It is our understanding that almost all ‘HB?’ sightings would actually be humpback whales, and thus for the baseline analysis, they were included in both years. Exclusion of the 8% of sightings that were recorded as ‘HB?’ in 1999 reduced estimated abundance by about 4% (Table 5). As might have been expected, esw is also lowered. For 2008, excluding the possible humpbacks (comprising 11% of the sightings) reduced the abundance estimate by about 5%.

Year	$n_{0.7}$	$n_{no?}$	$esw_{0.7}$	$esw_{no?}$	$\hat{N}_{0.7}$	95% CI	$\hat{N}_{no?}$	95% CI	% diff
1999	301	277	2.36	2.21	5130	(3880 - 8750)	4930	(3700 - 8620)	-3.9
2008	706	625	2.67	2.46	11,820	(9720 - 16,440)	11,200	(9110 - 16390)	-5.2

Table 5 For 1999 and 2008, numbers (n) of NM+ pods after right truncation at 4.5km, estimated effective strip half-widths (esw) in km, and estimated relative whale abundance (\hat{N}), with 95% confidence intervals in parentheses. Subscripts denote dataset: 0.7 = both ‘HB’ & ‘HB?’ sightings, as for the baseline analysis; ‘no?’ = ‘HB?’ excluded. The percentage difference in relative abundance (% diff) is expressed relative to \hat{N} .

6.4 Exclusion of possible resightings

Eleven ‘possible resightings’ occurred in the 2008 data; definite resightings were excluded from all analyses. Relative abundance is very slightly reduced, to 11,670 (95% CI 9600-16,360). This estimate is as equally valid as that from the baseline analysis – whether possible resightings should be included is open to question, but the effect here is small enough that it is not of concern.

6.5 No structural zeros in the migration model

The spatio-temporal models of section 3 were fitted freely, with no additional structural zeros to force low counts at the start and end of the migration period (Table 6). As well as the resultant increase in estimated abundance, Figure 10 shows the unlikely predicted migration counts, demonstrating the need for structural zeros given the flight schedules. In 2008, a more ‘typical’ curve is predicted but even with 26 successful flights, the fitted model does not predict very low counts at the start and end of the migration period because these flights did not span the entire period.

Year	$\hat{N}_{0.7}$	95% CI	\hat{N}_{noz}	95% CI	% diff
1999	5130	(3880 - 8750)	7750	(5680 - 22,470)	
2005	6070	(4420 - 11,020)	9370	(7130 - 13,370)	
2008	11,820	(9720 - 16,440)	13,071	(10,640 - 28,450)	

Table 6 Comparison of the baseline relative abundance estimates of NM+ whales with those obtained from models without the addition of structural zeros. Subscripts denote method: 0.7 = baseline; *noz* = no structural zeros added. The percentage difference in relative abundance (% diff) is expressed relative to $\hat{N}_{0.7}$.

6: CONCLUSIONS

- The revised relative estimate of northward-migrating humpback whale abundance in 2008 is 11,820 (95% CI 9720 - 16,440).
- The 2005 land-survey data are inappropriate for use to calibrate the aerial survey estimates as many of the whales off Quobba were not swimming northwards and are believed to be part of a ‘resting’ population within Shark Bay.
- The 2008 land-survey data do not appear to be suitable for calibration either. The limitations of the low station height coupled with the generally far-offshore location of the migrating whales lead us to conclude that any calibration is unreliable and overly-dependent on a very small number of data points.
- The 2008 focal follow data provide a useful indicator of surface-available whales, but the sample of whales followed is subject to bias; the sample favouring whales close to the shore and those which are easier to follow (and thus surface more frequently).
- A conservative correction for availability bias using the 2008 focal follow data is 0.41, and hence absolute abundance is estimated to be 28,830 (95% CI 23,710 – 40,100).

7: PERTH WORKSHOP AND DISCUSSION

A Workshop to discuss the results of this analysis, other analyses off the Western Australian coast and potentially make recommendations for future surveys of the WA humpback population is set to take place in Perth, WA from 26-27 August 2011.

This report has not only noted difficulties in operating land-based platforms from the West Coast, but has also concluded that the land-based survey data were inadequate for calibrating the aerial survey. The length of time that the land-based platform was able to operate provided only a small sample size, but even so, the method implemented in Paxton *et al.* (in press) and Hedley *et al.* (in press) appears not to be robust. Having taken a conservative approach to estimating surface availability in this report, we note that methods currently under development allow incorporation of behavioural information, such as that which would be obtained from DTags; initial results suggest that these methods will provide more accurate absolute abundance estimates. One such method (Borchers and Samarra, 2007) uses hidden Markov models, although there is a considerable overhead in the discretizing the process as required for its implementation. By using continuous Markov models, these difficulties no longer arise. This is an area of current research but software to implement at least two-state (available/unavailable) models is likely to become available in the near future.

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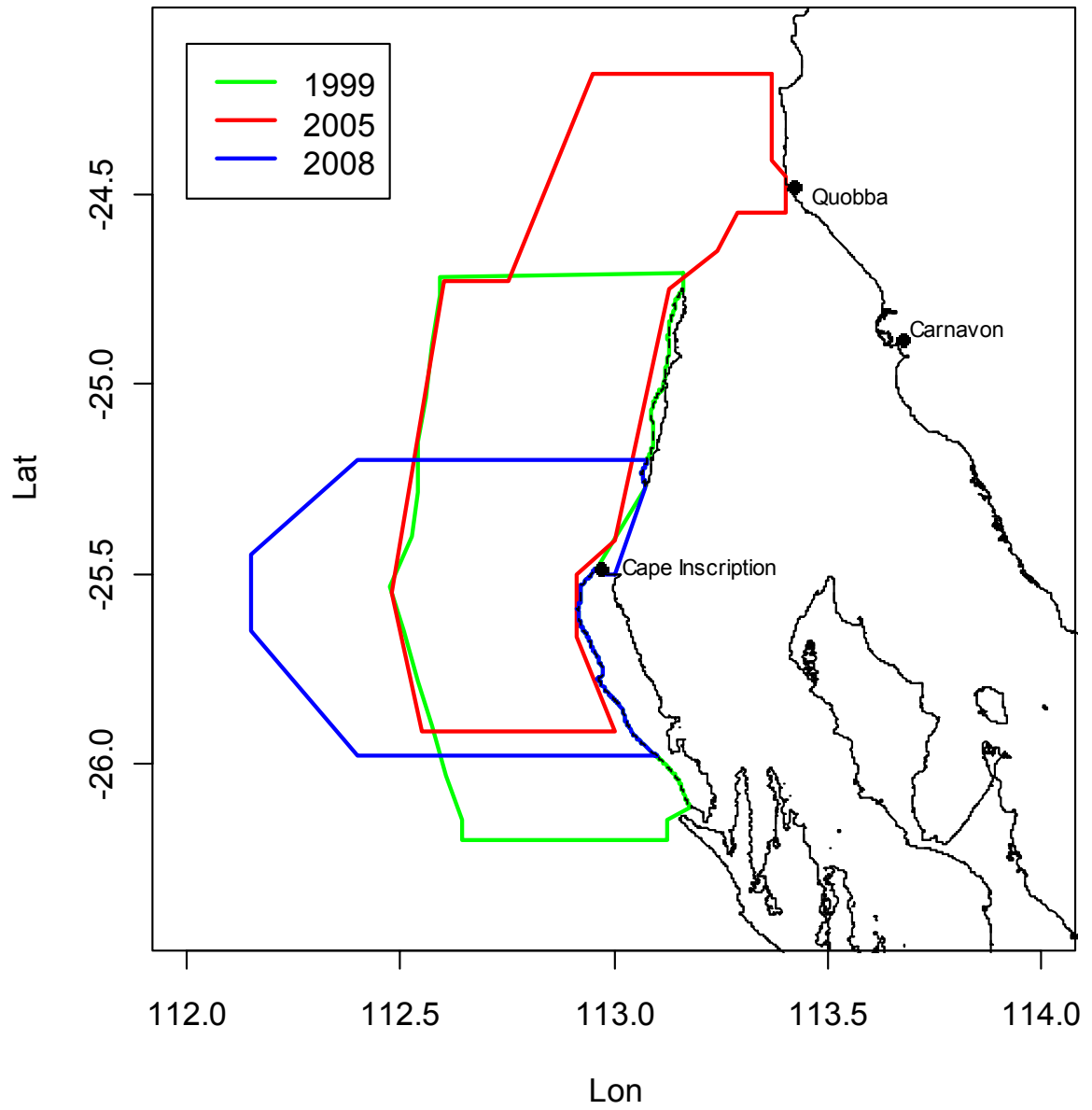


Figure 1 Survey areas for the three sets of aerial surveys conducted off Western Australia. Green=1999; red=2005; blue=2008.

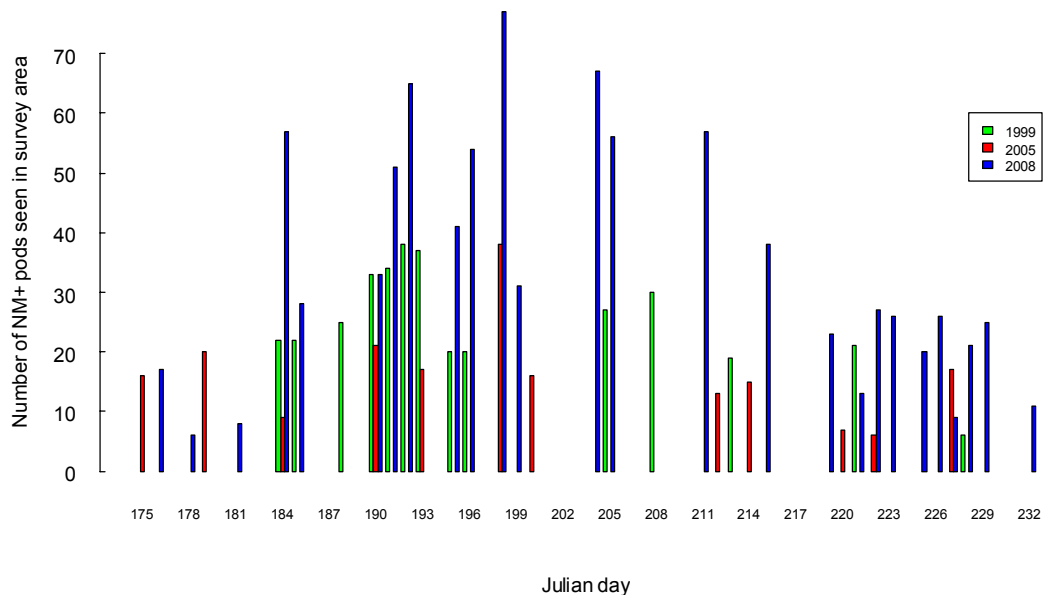


Figure 2 Numbers of northward-migrating (NM+) pods seen in the survey areas, by flight, in 1999, 2005 and 2008. Julian day 175 is 24th June in 1999 and 2005 (23rd June in 2008, a leap year); day 232 is 20th August in 1999 and 2005 (19th August in 2008).

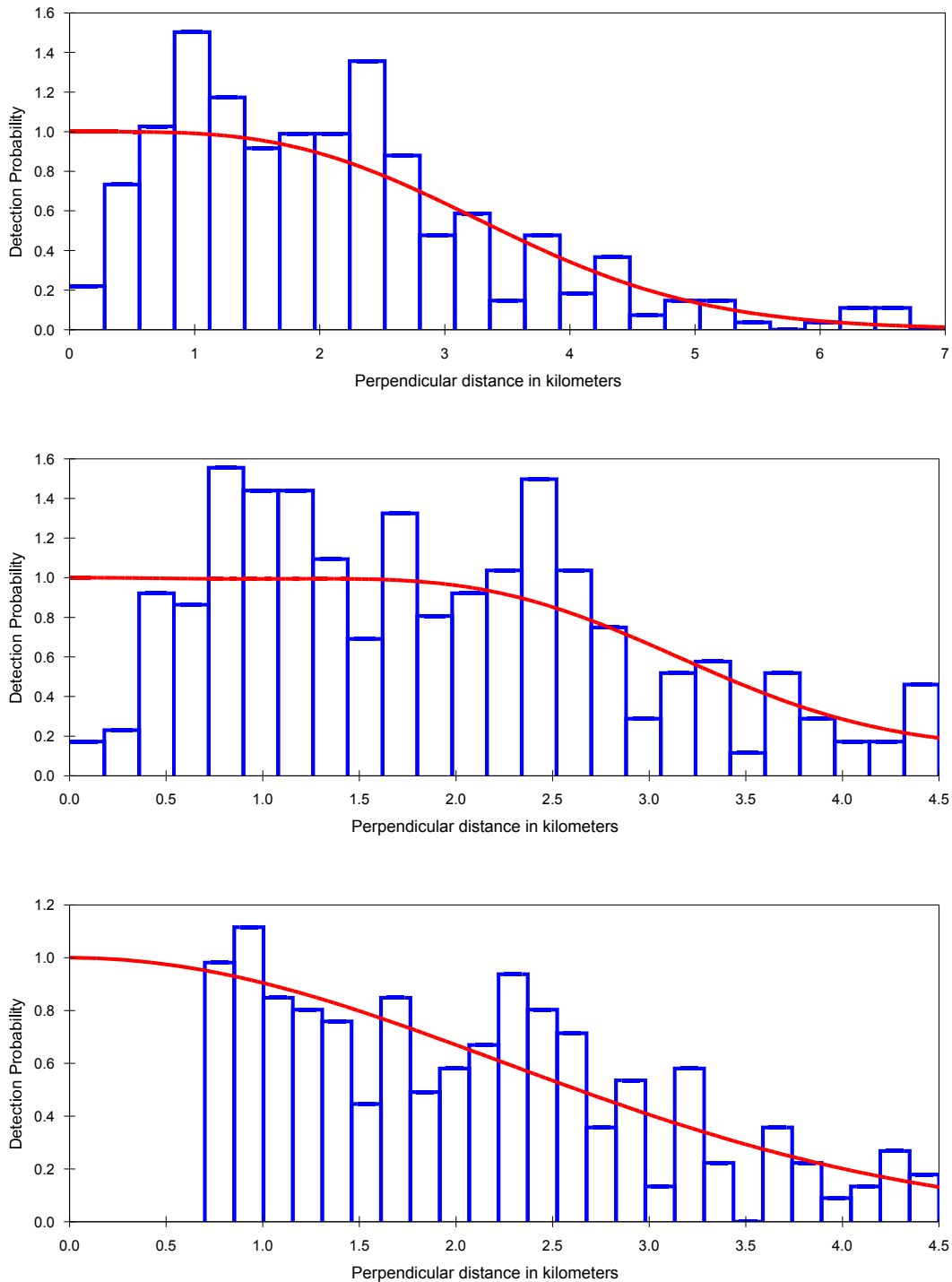


Figure 3 Perpendicular distance distributions (bars) and fitted half-normal detection functions (red curves) for the 1999 survey data, pooled across all flights. The top panel is for all sightings within 7km (12 or 3% of sightings excluded beyond this distance); the middle panel shows sightings after truncation of the tail of the distribution at 4.5km (a further 18 sightings excluded) and the bottom panel shows the distribution following left-truncation at 0.7km (a further 35 sightings excluded).

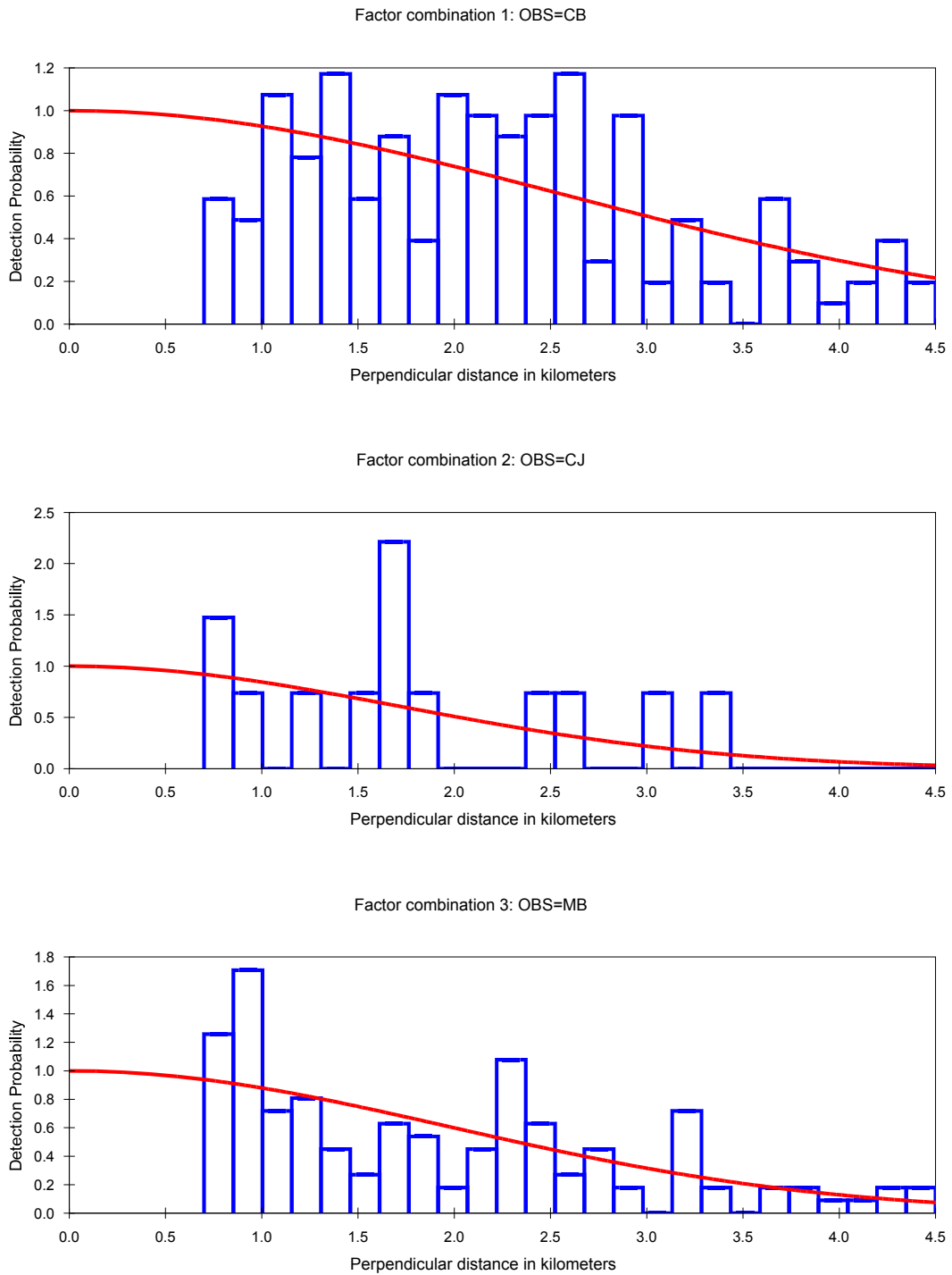


Figure 4 Perpendicular distance distributions (bars) and fitted half-normal detection functions (red curves) for the truncated 1999 survey data, pooled across all flights, with Observer fitted as a factor in the scale parameter of the model.

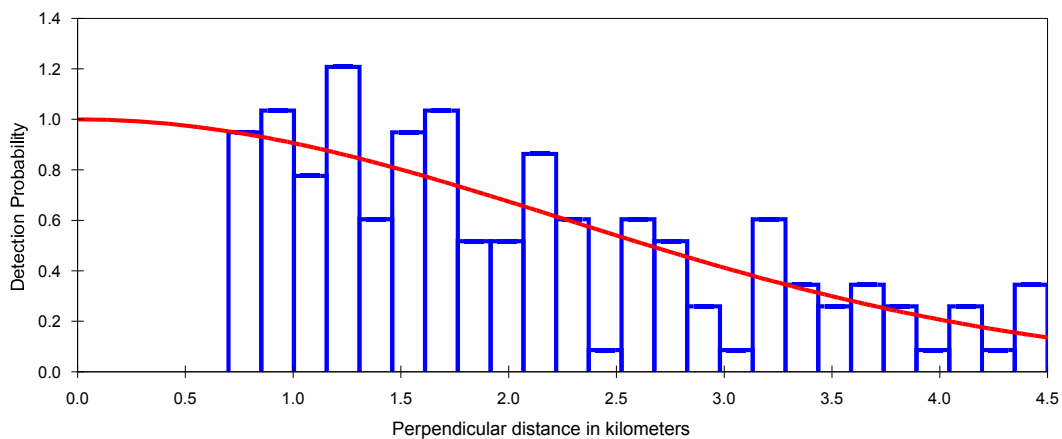
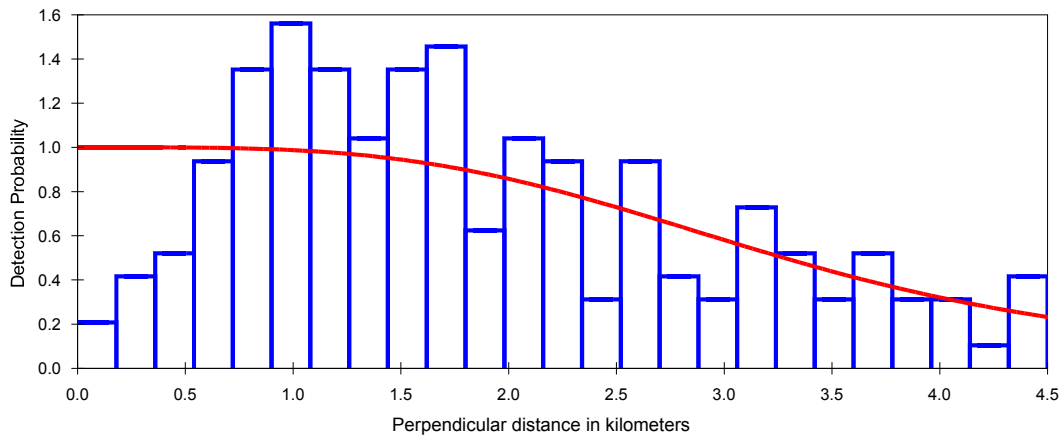
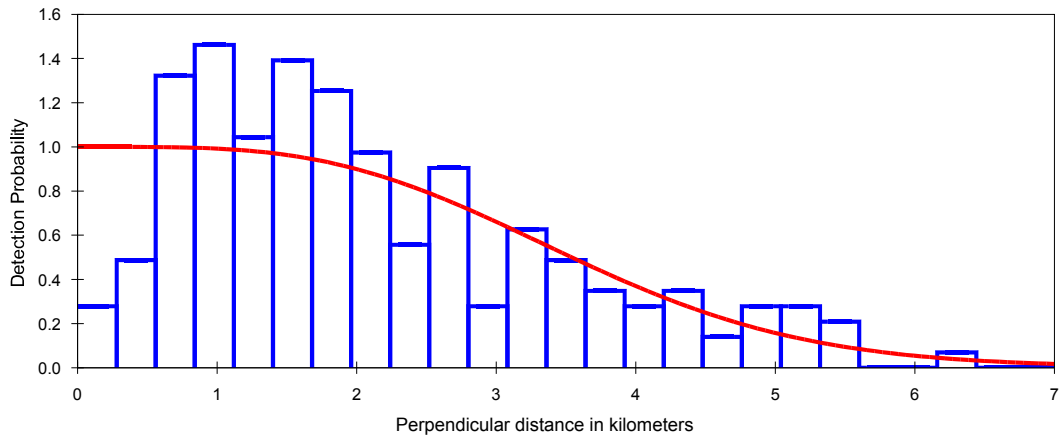


Figure 5 Perpendicular distance distributions (bars) and fitted half-normal detection functions (red curves) for the 2005 survey data, pooled across all flights. The top panel is for all sightings within 7km (8 or 4% of sightings excluded beyond this distance); the middle panel shows sightings after truncation of the tail of the distribution at 4.5km (a further 14 sightings excluded) and the bottom panel shows the distribution following left-truncation at 0.7km (a further 20 sightings excluded).

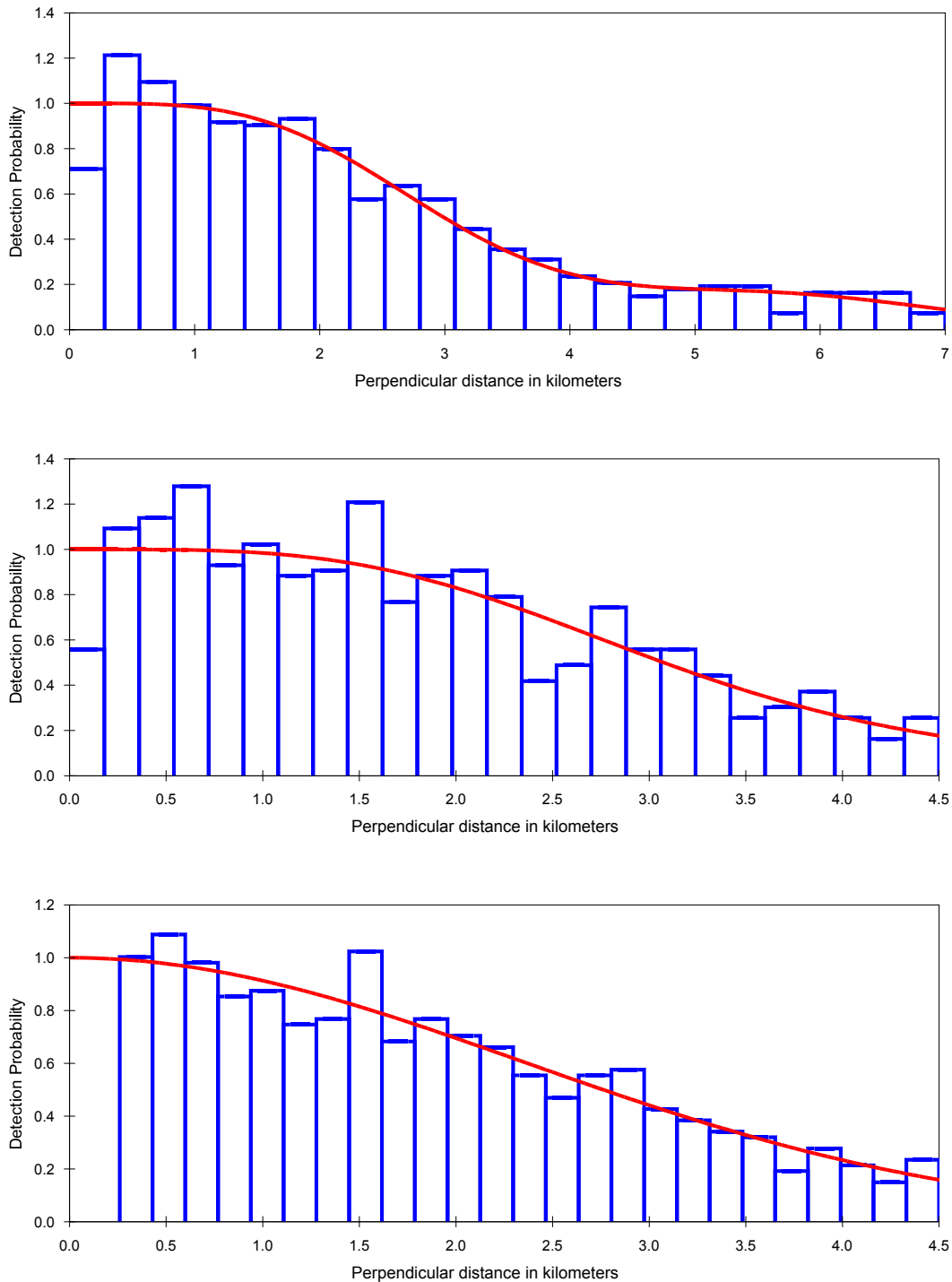


Figure 6 Perpendicular distance distributions (bars) and fitted half-normal detection functions (red curves) for the 2008 survey data, pooled across all flights. The top panel is for all sightings within 7km (57 or 8% of sightings excluded beyond this distance); the middle panel shows sightings after truncation of the tail of the distribution at 4.5km (a further 89 sightings excluded) and the bottom panel shows the distribution following left-truncation at 0.26km (a further 43 sightings excluded).

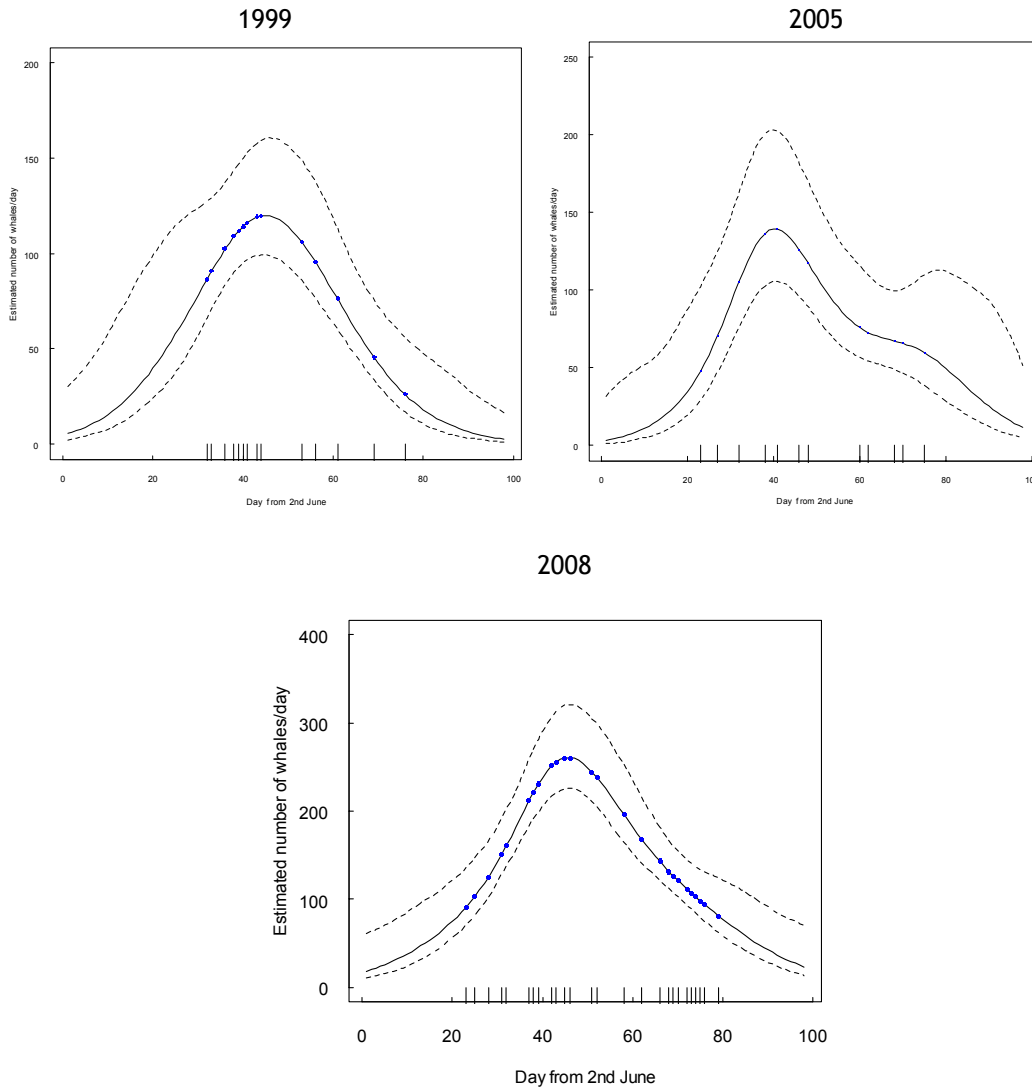


Figure 7 Migration curves for 1999, 2005 and 2008 showing the estimated number of whales passing through the survey area each day. Note that the plots are shown with different scales. The ‘rug plot’ along the horizontal axis shows days on which successful flights were conducted – resulting in the blue point estimates shown on the curves. Dashed lines are upper and lower 95% confidence intervals. The models were fitted with the addition of zero counts on 13th April and on 27th October.

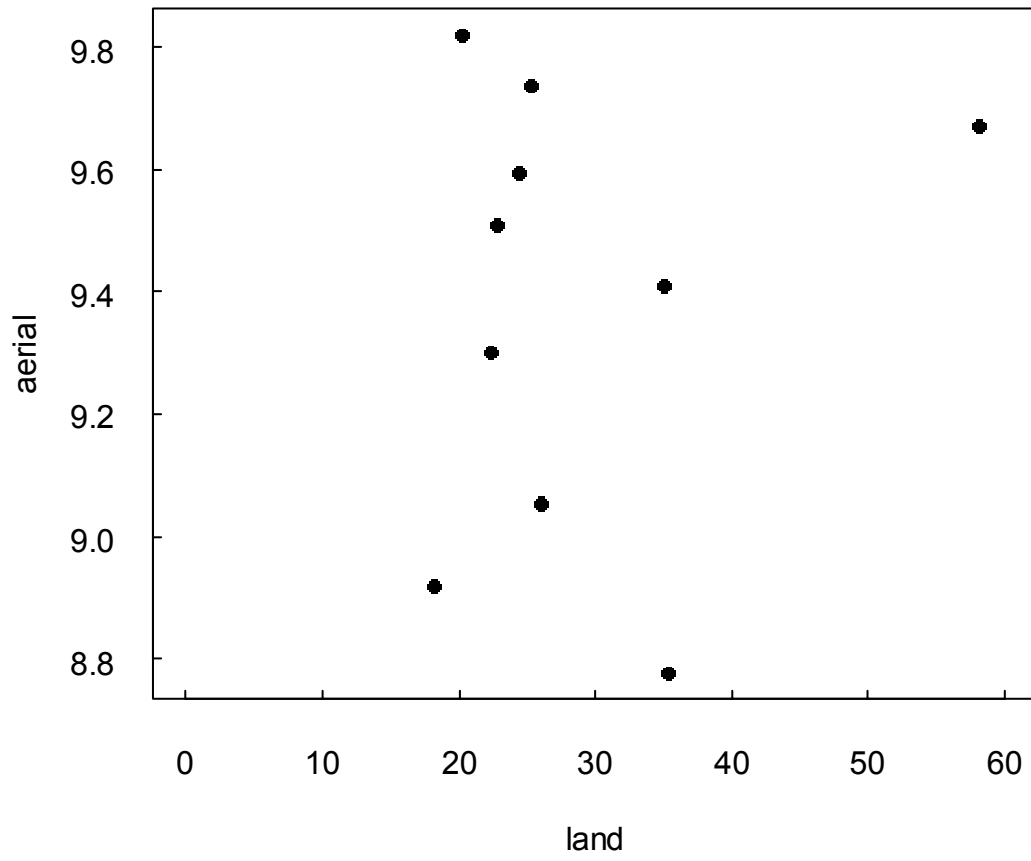


Figure 8 Estimated daily numbers of humpback whales passing within 12km of the shore based on aerial densities around Cape Inscription plotted against the similarly-adjusted land-based counts from the 2008 survey.

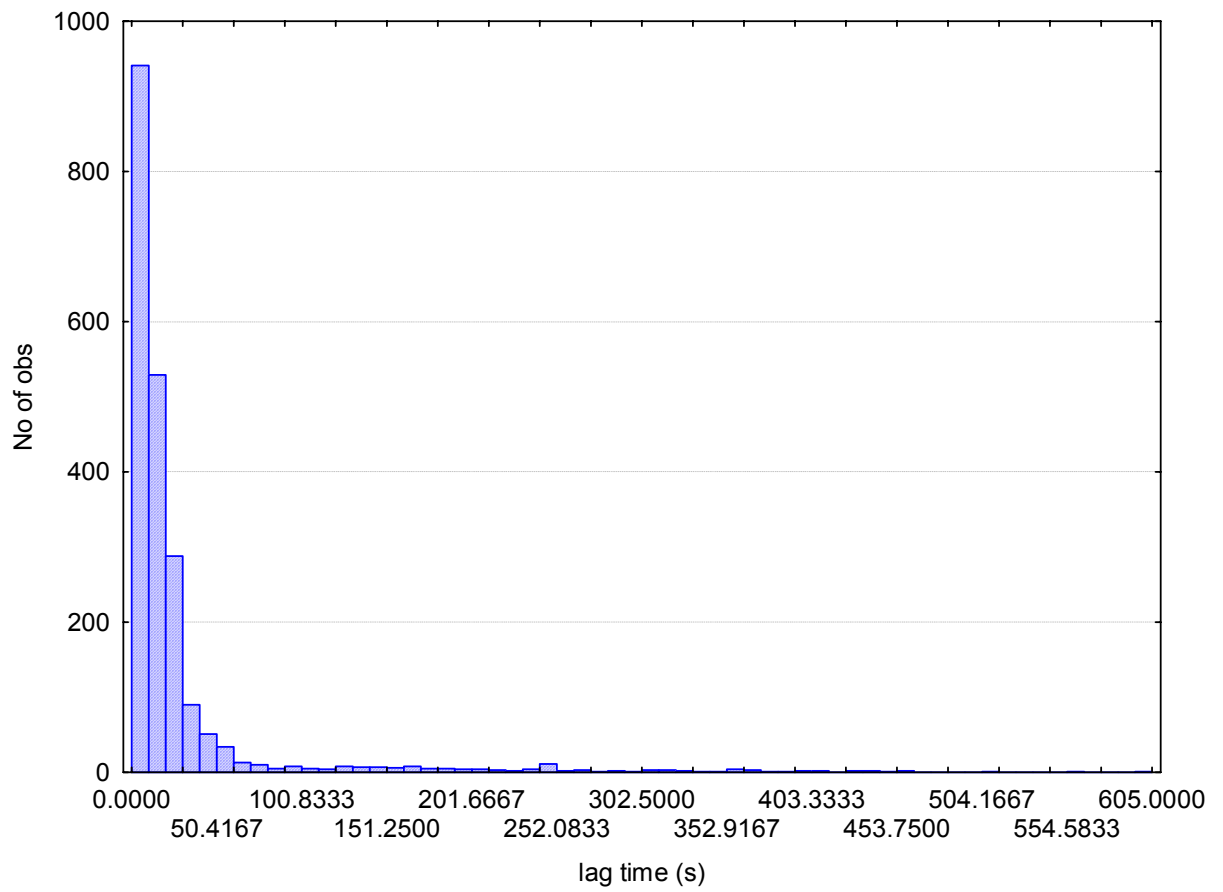


Figure 9 Distribution of sighting lag times (in seconds) of focally-followed pods from the 2008 land-based survey.

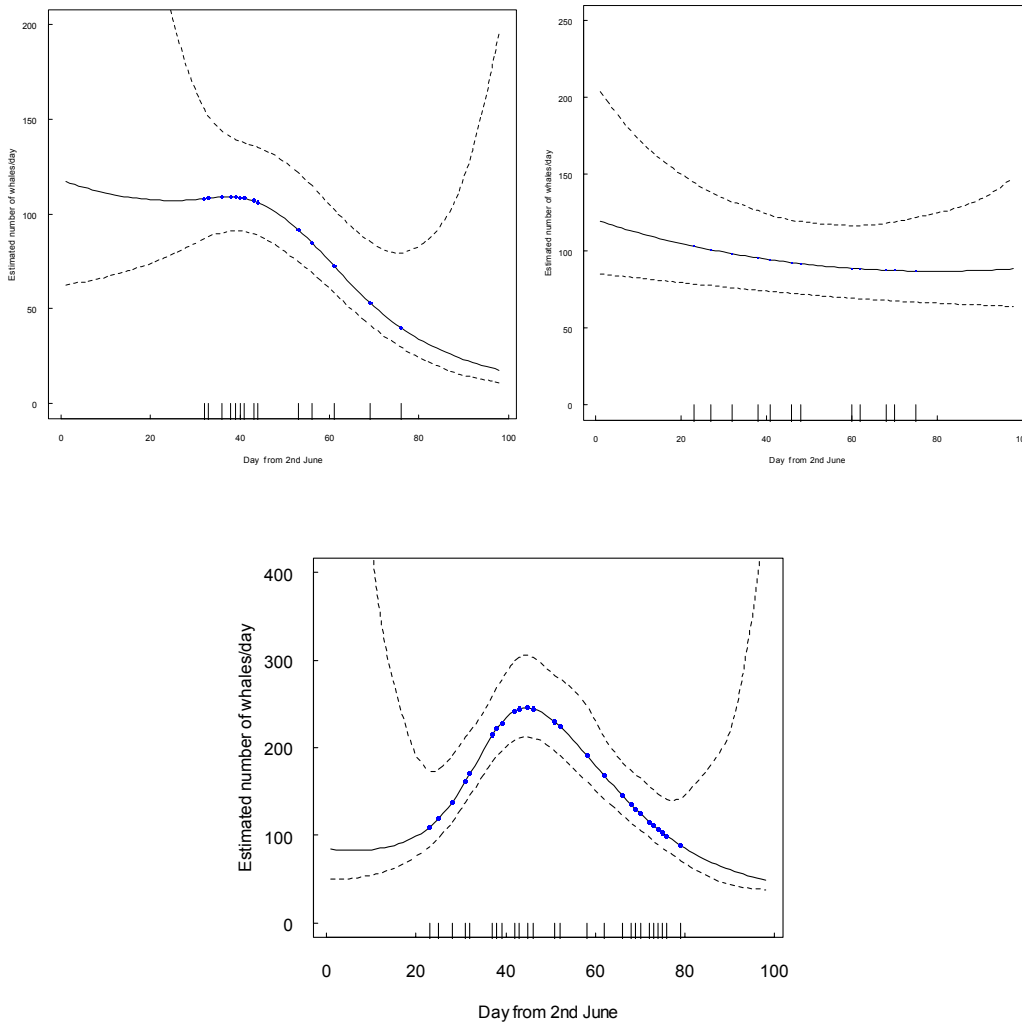


Figure 10 Migration curves for 1999, 2005 and 2008 showing the estimated number of whales passing through the survey area each day, **when the spatio-temporal model is fitted with no structural zeros**. Note that the plots are shown with different scales. The ‘rug plot’ along the horizontal axis shows days on which successful flights were conducted – resulting in the blue point estimates shown on the curves. Dashed lines are upper and lower 95% confidence intervals.