# Distribution and abundance of sperm whales off Albany, WA

Final Report for the Australian Marine Mammal Centre, Department of the Environment, Water, Heritage and the Arts

30 September, 2010

Rob Harcourt[1], Sharon Hedley[2] and John Bannister[3]

1. Graduate School of the Environment, Macquarie University NSW 2109.
2. Centre for Research into Ecological and Environmental Modelling, Buchanan Gardens, University of St Andrews, St Andrews, Fife KY16 9LZ, U.K.
3. The Western Australian Museum, Locked Bag 49, Welshpool DC, WA 6986.

## Abstract

This is the Final Report under the agreement between the Australian Marine Mammal Centre and Macquarie University. The project progressed largely as detailed in the original funding proposal attached to the funding agreement. Fieldwork proceeded with minor delays and the anticipated number of aerial survey flights was achieved. The submission of this final report has unfortunately been delayed by three months due to injury to the analyst (SH), but the project has been completed on budget.

Flights were scheduled to have taken place during the three months from early-September to the end of November. In the event, extremely poor weather conditions delayed the commencement of the survey first flight until 25$^{th}$ September, 2009, although it was possible to conduct some training flights (including equipment testing) prior to this date. The survey period was extended until early December, partly to compensate for the delayed start, and partly in an attempt to increase the sample size of sperm whales for the analysis, as it was evident that more sightings of sperm whales were being made towards the end of the survey period than at the beginning (when very few were encountered). A total of 48 sperm whale pods (comprising 278 individuals) were seen either on- or off-effort. Of these, 40 pods included at least one adult bull sperm whale – defined as males over 35 feet (10.67m) in length, and thus termed ‘catchable’ during previous whaling operations in the area; 84 adult bulls were seen in total.

In this report, we present indices of abundance intended to be comparable with indices based on the number of ‘catchable’ whales calculated from data from the sperm whaling operations off Albany between 1968 and 1978 (Kirkwood, 1980). Based on the indices alone, a significant decline in the number of adult bulls is found. However, closer inspection of the data which formed the bases of the earlier indices revealed some inconsistencies which are probably not possible to resolve. We thus conclude that whilst the indices are useful for comparing abundance during the decadal span of the whaling operation, without considerable effort in reviewing the earlier data in detail, too many uncertainties exist for reliable comparison with the equivalent index from the 2009 survey.

A second objective of the survey was to collect data to enable the baseline abundance of sperm whales in the region to be estimated, using line transect analyses, yielding estimates of 29 (95% CI: 12-73) for all sperm whales and 14 (95% CI: 7-32) for adult males. These estimates are not corrected for either availability or perception bias, and thus represent estimates of the number of surface-available whales, assuming that a pod at the surface on the trackline was detected with certainty. Visual surveys, especially aerial surveys, are not well suited for estimation of sperm whale abundance; acoustic surveys, especially when combined with a visual component (e.g. Barlow and Taylor, 2005), are undoubtedly more appropriate (Leaper *et al.*, 2003). Nonetheless, the estimates in this report provide the first relative abundance estimates of sperm whales in the region, and may provide useful reference if such further work is undertaken.

## 1. Introduction

The area off Albany, with a narrow and very steep-to continental shelf, is the only sperm whale habitat in Australian waters where historical data are available (see Bannister, 1968). It is one of the few known sperm whale habitats off Australia as a whole; others include the edge of the continental shelf southeast of Kangaroo Island, SA, off Tasmania and south of Sydney on the east coast. While sightings and strandings of sperm whales are relatively frequent around the coast, no quantitative evidence of Australian sperm whale abundance from any source is currently available.

Sperm whaling operations took place off Albany, Western Australia from 1956-78, causing a substantial decline in the 'Albany stock' (Bannister *et al*., 1996, based on Kirkwood and Bannister, 1980, and Kirkwood *et al*., 1980). Data on which those assessments were based were largely from commercial 'spotter' aircraft employed to locate whales and assist the catcher boats during the chase. These aircraft flew throughout the commercial whaling season (from March/April to November).

Daily records of the number of whales seen from the aircraft are available from 1962 onwards. Between 1962 and 1966, a single-engined float plane was employed; this aimed to cover a restricted area off Albany once per successfully completed flight. From 1967, it was replaced by a more efficient twin-engined aircraft. Its greater speed allowed for a larger area (Figure 1) to be covered more than once, although sightings were logged only once. The resultant change in strategy meant that simple indices of abundance such as the number of whales (or more typically, males) seen per flying unit were not comparable, leading Kirkwood and Bannister (1980) to suggest that data from the single-engined plane (1962-66) together with the first year of data from the twin-engined aircraft (1967) should be discounted for the purposes of assessing the trend in abundance of the stock.

Following the cessation of the Albany whaling operations, a proposed design for a dedicated survey programme for sperm whales off Albany was developed (Kirkwood, 1980) to provide for the long-term monitoring of populations of sperm whales in that area. In particular, it focused on investigating the feasibility, optimum timing, duration and costs of a programme that would yield comparison with data recorded during commercial aerial spotting operations from 1962-1978. This programme was never undertaken. The utility of conducting a survey as outlined in Kirkwood's (1980) report was reported by Hedley (2006), and hence this project was undertaken in 2009. The primary objective was to obtain abundance indices of the Albany sperm whale population that are comparable with previous indices obtained used data from the sperm whaling operations conducted off Albany, Western Australia.

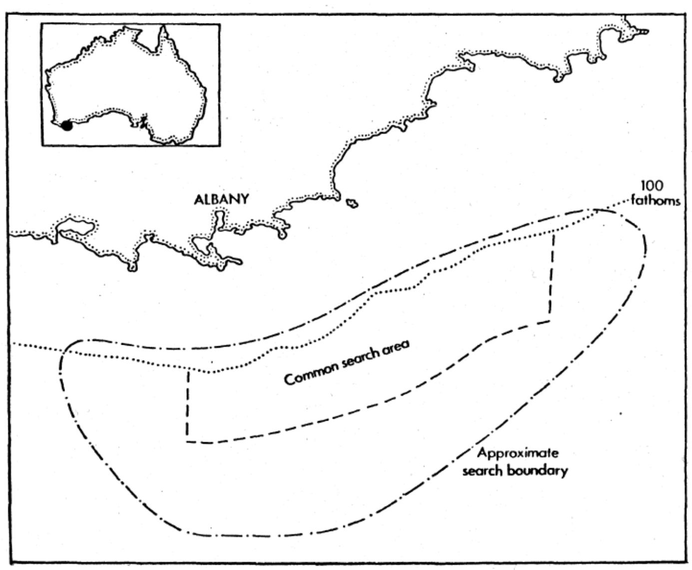



**Figure 1** Search areas off Albany for commercial spotter aircraft. Area labelled 'Common search area' searched from 1962-1978; area indicated by 'Approximate search boundary' searched using twin-engined aircraft from 1967-78. Reproduced from Kirkwood and Bannister (1980).

## 2. Survey design and field methods

### *3.1 Survey area and tracklines*

In the three decades since the cessation of whaling off Albany, advances in survey methods and technology have been immense. Data are digitally recorded, locations may be determined using GPS navigation and much of the line transect methods (and software) have been developed. There is relatively little reference material on precisely how the spotter aircraft operated; we were reliant on personal experience (JLB) and the information contained in Kirkwood (1980) and references therein to try to replicate the data collection so that it was compatible with that of the whaling operations. The first consideration was the survey area. In order to ensure maximum flexibility in analyses and to maximize the chances of seeing whales, Kirkwood (1980) recommended that the larger area denoted in Figure 1 by 'Approximate search boundary' be searched using a standard grid of parallel transects. The co-ordinates of this search area were not available, so an approximate boundary was determined manually by referral to nautical charts.

Trackline design was undertaken in *Distance* v5.0 Release 2 (Thomas *et al*., 2010), with parallel transects oriented perpendicular to the major axis of the survey region. Different transect spacings were considered; the final proposed design resulted in 12 transects approximately 10.5 nautical miles (nmiles) apart (Figure 2), covering 386 nmiles on transect, and 630 nmiles in total, including transits to and from the airport and connecting legs between transects.

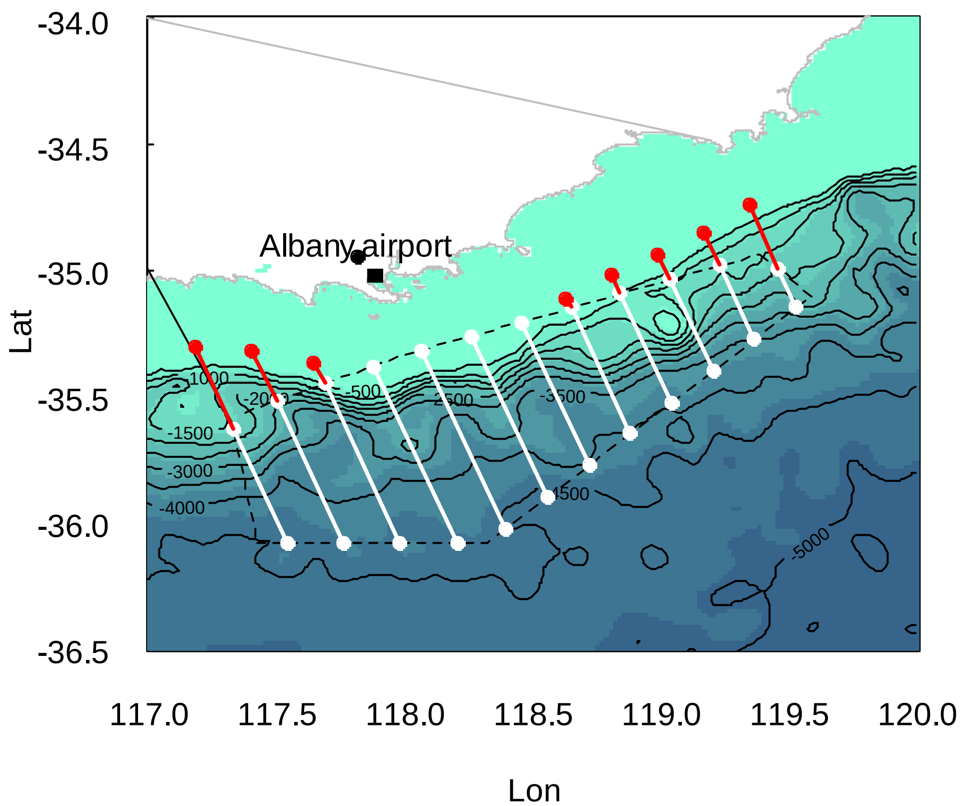



**Figure 2** Waypoints, trackline design and survey region for the 2009 survey, with bathymetry detailed (in metres). Prior to 20th October, planned survey tracklines were as shown in white. From this date onwards, easternmost and westernmost transects were extended northwards (red waypoints and lines).

During the course of the survey, and in consultation with the aircraft charter company, NorWest, the six easternmost and three westernmost transects were extended northwards. It was considered unlikely that the whaling operations would have surveyed, at least regularly, in the locations of the extended transects (the 'Approximate search boundary' in Kirkwood (1980) encompassed the operations of the spotter aircraft). However, by mid-October, and after completion of 24 flights (of which 13 comprised full or considerable partial survey effort), only 15 bull sperm whales had been sighted (in 6 pods) on transect effort, with an additional 2 pods (12 bulls) being seen off effort. Therefore, this modification was made in order to cover more of the shelf region (Figure 2), in an attempt to increase the sample size.

### *2.2 Survey flight methodology*

Aerial survey data were collected using a single-platform configuration consisting of two observers (one on each side of the aircraft). The aircraft, a twin-engined Cessna 337, flew at 1500ft (457m) at a speed of 120 knots (222 km/h). Sightings of animals were recorded and time-stamped on Microtrack digital voice recorders (M-Audio Microtrack 24/96) using Dick Clark aviation headsets and Aviall (Avix A4000) portable intercom systems. For each sighting of a sperm whale pod, the declination angle of its abeam location was measured using a hand-held Suunto clinometer (Suunto PM-5/360 PC); species, group size and behaviour were also recorded. Times of sightings were taken as the times when the declination angle was recorded. Microtrack voice recorders were synchronized with the time from a GPS to match sightings with location. Sightings recorded on the Microtrack were transcribed into Excel spreadsheets after the flight Digital SLR's were used to photograph sperm whales and other cetaceans along with estimated lengths to verify observer sightings and provide independent estimates of whale species, length and status. Independent of observer sightings, a SONY HDR –XR520V full HD video camera mounted in the cargo pod of the aircraft recorded images of all cetaceans and other animals near the surface on the trackline underneath the plane.

## 3. Data summary

A total of 61 flights was flown. Four flights were classified as Training or video camera-testing flights. 18 flights were aborted with either no or very little survey effort (due to poor weather). 12 flights were incomplete surveys. 15 flights were completed full surveys; 12 flights were 'half-surveys' (two flights completed on the same day with all transects surveyed once). 40 sperm whale pods (160 individuals) were seen on-effort; an additional 8 pods (118 whales) were sighted off-effort. Further details are given in Appendix 1.

## 4. Comparable abundance indices with historical data

### *5.1 Indices of relative abundance*

In this section, we report on the calculation and comparison of relative indices of abundance of bull sperm whales from flights during the whaling operations and similar ones from the survey. Data from the whaling operations were digitally encoded and the mean number of bulls seen on the first morning flight was used as a relative index. In his report, Kirkwood (1980) notes that this index is the most appropriate index that could be used from these data for a number of reasons including:

i. The afternoon flights did not record the whales thought to have been recorded during the morning flight.
ii. The number of hours flown skews the index: longer flights tended to occur when few, if any, whales were seen, and shorter flights resulted from flights which

encountered whales (since the spotter aircraft then spent time helping the whalers locate the whales).

Additionally, he concluded that the numbers seen from September-November showed a similar annual trend to numbers seen throughout the season (April-November). We thus compared the September-November index with ones calculated from the 2009 survey. For the whaling data, we compared ‘Total numbers of bulls’ with ‘Total numbers of bulls in the area’ (which corresponds to the ‘Approximate search boundary’ of Figure 1). The apparent decreasing trend in both measures from 1968-78 can be seen in Figure 3. To calculate the index for 2009, data from the 15 completed full surveys and 12 half-surveys were used – i.e. a total of 27 flights or 21 surveys. Using all sightings, including sightings made off-effort or beyond the designated search area, the mean number of bulls seen per flight was 3.33; this reduced to 2.43 when only the on-effort sightings were included. For all indices, we used flights with visibility/sightability recorded as ‘Fair’ or better, and sea states 0-2.

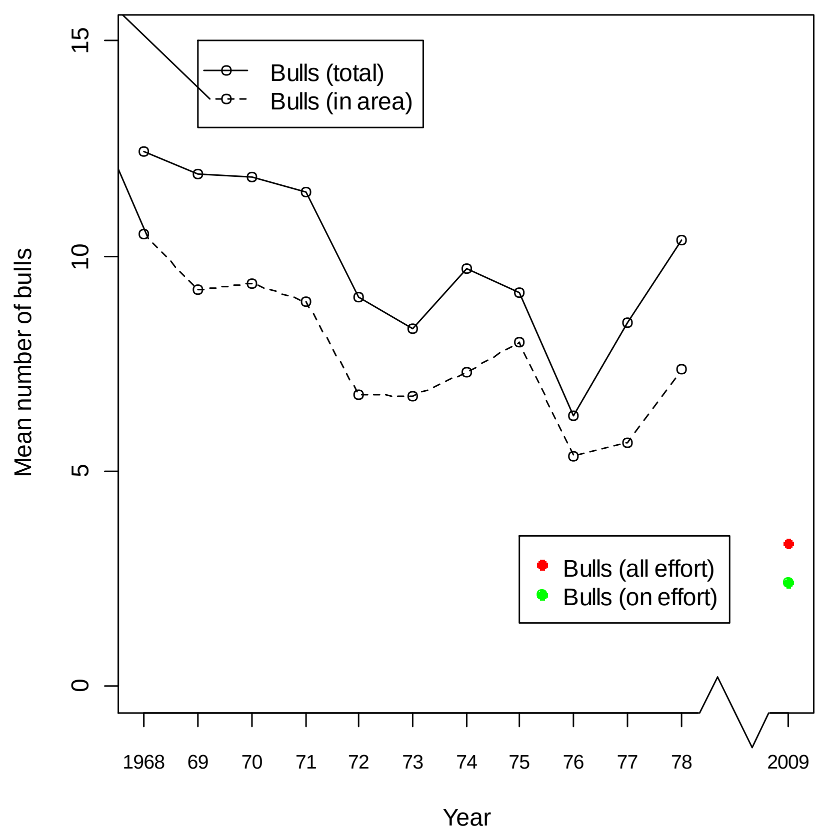



**Figure 3** Comparison of the mean number of bulls seen on the first morning flights from the September-November whaling data, and the mean number seen on the 2009 survey. Total numbers (solid line) are comparable with those plotted in Figure 2 of Kirkwood (1980). Numbers seen “in area” (as denoted on sightings record) are depicted by the dashed line. The red circle is the mean number of bulls seen during flights undertaken on the 2009 survey; the green circle is the mean number seen ‘on effort’ during this survey.

*5.2 Distribution of the number of bulls seen*

The relative abundance indices do not provide any measure of error – though clearly, on the premise that the data were indeed collected in a similar manner on the survey as for the spotter aircraft, the survey values indicate a drop in the average number of bulls in the area. In order to investigate this perhaps surprising outcome more closely, we re-examined the distribution of the number of bulls seen on each morning flight. In the Kirkwood (1980) report, data reporting the frequency distribution of the number of bulls seen per flight are presented in Table 2. These data were reported as the observed numbers seen 'for visibility at least fair' and 'sea state not exceeding 2'. Having digitized the data as part of this analysis, and assuming that the visibility codes given in Table 3 (Kirkwood, 1980) are correct, we found that the frequency distribution in Kirkwood (1980) was likely to include sightings made in 'Poor' conditions (visibility code 3) and sea state up to Beaufort 3. Assuming sperm whales are less detectable from the air in such conditions, this would have had the effect of reducing the average number of whales seen, or in terms of the frequency distribution, increasing the number of flights with few or no whales sighted.

A revised frequency distribution for the data from 1968-78 is shown as the barplots in Figure 4, for sea states up to 2, and visibility at least fair. As Kirkwood had indicated, the distribution showed a high frequency of zero sightings (143), and a long tail, suggesting that when sperm whale bulls were seen it was usually in relatively small groups but not always (but see section 5.3). Four distributions for these data were considered: the Pólya-Aeppli distribution (with Poisson number of groups and Geometric group sizes); zero-inflated Poisson and Geometric distributions, and a compound Poisson distribution (with Gamma group sizes). The probability density functions of these four distributions are given in Appendix 2.

Goodness-of-fit of these distributions were compared visually and using $\chi^2$ goodness-of-fit tests. Test statistics are shown in Table 1. As can be seen in Figure 4, the results in Table 1 suggest that either the Pólya-Aeppli distribution or the zero-inflated Geometric distribution fit the data reasonably; the former is marginally better according to its goodness-of-fit. We therefore focus our comparisons using this distribution.

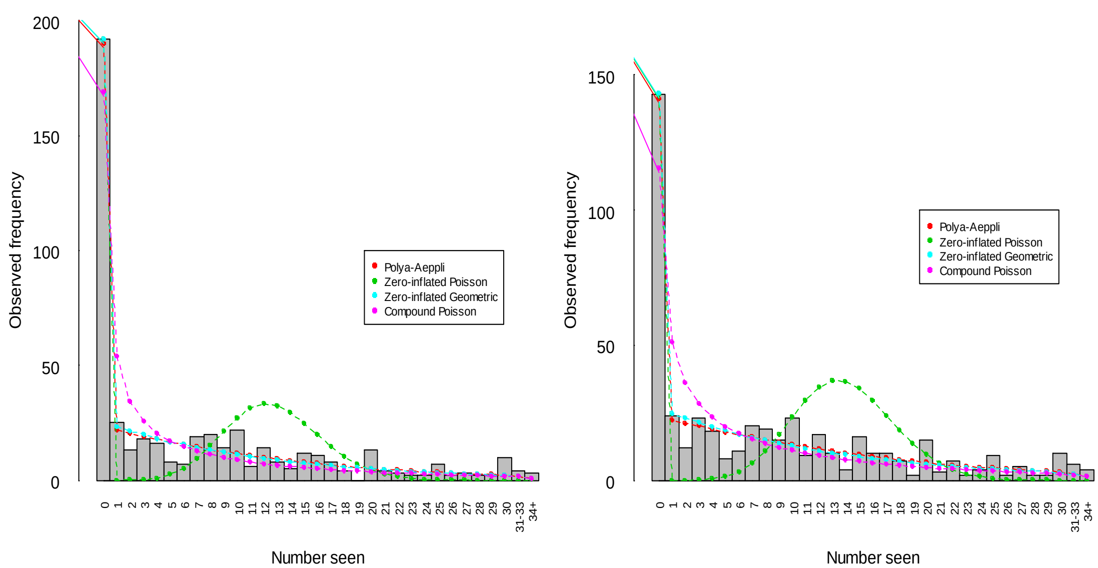



**Figure 4** Distribution of number of bull sperm whales seen on the first morning flight in September-November from 1968-78. Conditions restricted to at least 'Fair' visibility and sea state up to Beaufort 2. Fitted distributions shown as described. Left panel = bulls seen in area. Right panel = total number of bulls.

| | Pólya-Aeppli | Zero-inflated Poisson | Zero-inflated Geometric | Compound Poisson |
|---|---|---|---|---|
| Seen in area | 101.5 | 143,240.2 | 109.3 | 194.8 |
| Total seen | 94.4 | 158,854.5 | 107.3 | 179.0 |

**Table 1** $\chi^2$ goodness-of-fit statistics from fitting Pólya-Aeppli, zero-inflated Poisson, zero-inflated Geometric and compound Poisson distributions.

The Pólya-Aeppli distribution was also fitted to the relatively sparse 2009 data. These data were derived from the 21 completed surveys. The data and fitted distributions are shown in Figure 5 (using the same frequency bins as for the whaling data).

The pdf of the Pólya-Aeppli distribution is given by

$$\Pr(N = x) = \begin{cases} e^{-\theta} & x = 0 \\ e^{-\theta} p^x \sum_{j=1}^{x} \binom{x-1}{j-1} \frac{[\theta(1-p)/p]^j}{j!} & x = 1, 2, \ldots \end{cases}$$

for $\theta > 0$ and $0 < p < 1$. The mean of the response is $\theta/(1-p)$ and variance $\theta(1+p)/(1-p)^2$. The log-likelihood function is given by

$$l(\theta, p) = \sum_{i=1}^{n} I(x_i = 0)(-\theta) + I(x_i > 0)\left\{-\theta + x\log(p) + \log\left[\sum_{j=1}^{x_i} \binom{x_i - 1}{j-1} \frac{(\theta(1-p)/p)^j}{j!}\right]\right\}.$$

The negative log-likelihood was minimized using the function ‘optim’ in R (R Development Core Team, 2009), and estimates of the mean number of bulls seen were calculated using the above formula. Percentile confidence intervals were calculated by simulation from the posterior distribution of the parameters (see, for example, Wood (2006; p.246-7)), and were compared with analytical confidence intervals calculated using the expression for the variance above. For the whaling data (with 488 morning flights), either method of interval calculation should suffice; for the survey data (with only 21 samples), the percentile method is preferable. The resulting mean values and their confidence intervals are shown in Table 2.

| | Mean | S.E. | Percentile Int | Confidence Int |
|---|---|---|---|---|
| 1968-78: In area | 7.70 | 0.49 | (6.80, 8.71) | (6.74, 8.67) |
| 1968-78: Total | 9.82 | 0.55 | (8.74, 10.93) | (8.75, 10.90) |
| 2009: Total | 2.59 | 0.98 | (1.22, 5.35) | (0.90, 4.28) |
| 2009: On-effort | 1.89 | 0.80 | (0.76, 4.34) | (0.50, 3.28) |

**Table 2** Estimates of the mean number of adult bull sperm whales as calculated from the estimated distribution of the numbers per flight (a Pólya-Aeppli distribution).

Taken at face value, these results – together with the simple relative indices of section 5.1 – indicate a significant decline in the mean number of bull sperm whales occurring off Albany since the cessation of whaling in the area. This counter-intuitive result is re-considered in section 5.3.

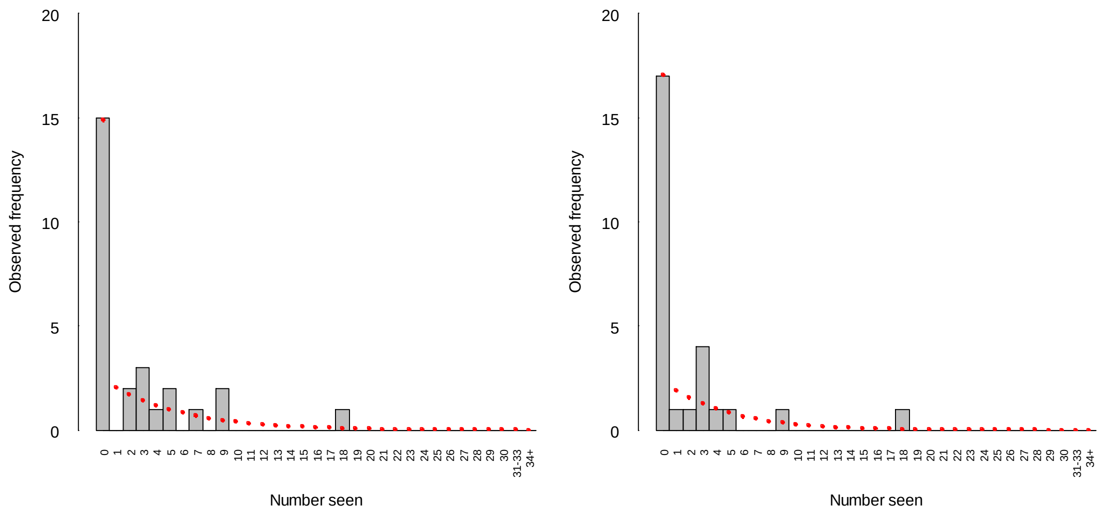



**Figure 5** Distribution of number of bull sperm whales seen on each completed survey during the 2009 survey. Conditions restricted to at least 'Fair' visibility and sea state up to Beaufort 2. Red circles show fitted Pólya-Aeppli distribution. Left panel is for all sightings and effort for full and half-surveys. Right panel is the on-effort data only.

*5.3 A real decline?*

This study has served to highlight some of the severe problems faced when trying to equate fisheries indices such as the relative indices here, or similar indices based on catch-per-unit-effort (CPUE), to more recent data. The 2009 survey was designed with the primary objective of comparing such indices. Few sources are now available to describe the activity of the aircraft during the whaling operations, and we relied heavily on the advice in Kirkwood's (1980) report to connect the past with the present with respect to designing this survey.

Nonetheless, there are several factors which potentially affect the comparative indices. Whilst Kirkwood and Bannister (1980) concluded that changes in catching efficiency were not likely to have significantly affected the indices from 1968-78, such changes are known to be problematic for CPUE indices in general, often rendering inference unreliable. It seems likely, despite our attempts to minimize the differences between the operations of the spotter aircraft and those of our survey aircraft, that the 'catching efficiency' would have been potentially very different.

It may also be possible that closer inspection of the whaling data would in fact reduce the average number of bulls seen. We have not examined this closely, but simply queried several possible outlying observations of sperm whale bulls in the 1968-78 data. In this sense, the total number of sperm whale (adult) bulls was defined as an 'outlier' if it was >40. (Only the total number of individuals was recorded on the data sheets – not the number of pods.) For these outliers, JLB referred to the original Log Sheets (an example of which is provided in Appendix 3).

Even with this simple check, some surprising discrepancies were found. On 08/10/68, 4 groups totalling 42 bulls were seen, but the Log Sheet recorded 16 of these individuals as 'young'. On 01/11/69, a single pod of 60 bulls was recorded. This tallied with the Log Sheet, but in our experience, seems large. On 8/11/69, 91 adult bulls were recorded, but the Log Sheet records 85 of these as 'young'. Other similar data entries occurred; the true extent of such anomalous records is, however, unknown.

It is beyond the scope of this project to revisit the original Log Sheets extensively, but sufficient doubts exist in the transcribed data to suggest that these data may not be as reliable for comparisons with current and future surveys as both Kirkwood (1980) in his original design, and we, in fulfilling that, had envisaged. This is not to say that the transcribed data are unreliable per se – they presumably are consistent for the period to which they apply – but that any comparisons between these data and those from the 2009 (and any subsequent surveys) would need to be treated with caution.

In our view, therefore, the comparisons of relative abundance in sperm whale indices are unreliable, and future attempts to assess abundance sperm whales off Albany should focus on estimating absolute abundance, using line transect estimation, including acoustics (Leaper *et al.,* 2003). The second objective of our study included a visual line transect estimation component; we report on the results of this component in the next section.

## 5. Line transect estimates of relative abundance

*6.1 Flights and data included in the analyses*

For this part of the analysis, data from the 27 full- or half- surveys were used, together with data from the following partially-completed survey flights (all of which had a minimum of 3.5 hours flight time): 6; 16; 18; 23; 24; 41; 50; 56 and 61 (see Appendix 1). One sperm whale sighting (a solitary bull) was recorded on an excluded flight (Flight 29).

A total of 48 pods of sperm whales (including cows, calves and juveniles in addition to adult bulls) were sighted on flights used in the analysis; 40 of these were 'on effort' and could potentially be used in the line transect analyses. Of these 40 sightings, 7 were excluded from the analysis since it had not been possible to obtain measurements of their angle of declination, and hence no perpendicular distances could be calculated. Three of the 7 sightings excluded were made by the pilot during Flight 25, when there was only one dedicated observer (P. Ensor).

It was reported that the area under the aircraft at greater than a 65º angle from the horizon (measured with an inclinometer) was not available for searching, the vertically mounted video had technical difficulties and was excluded as unreliable. At a flight altitude of 1500ft, this represents an area some 320m either side of the trackline. However, exploratory data analysis suggested that whilst some pods close to the trackline may have been missed (Figure 6), some sightings were made within the apparently 'blind' region. With so few sightings, it was decided to retain all sperm whale sightings in the analysis, but constrain the shape of the detection function to ensure that it had a 'shoulder' at small perpendicular distances.

*6.2 Line transect analysis*

Conventional line transect analysis involves fitting a detection function, $g(\cdot)$, to some perpendicular distance data ($x$), integrating this function over the search width, and on the assumption that all objects are seen at zero distance, estimating the average detection probability within the survey strip (see, for example, Buckland *et al.*, 2001). The number of detections required for reliable estimation of a detection function is about 60, although it is often possible to fit reasonable models with fewer sightings, provided that the distribution of perpendicular distances is 'well-behaved' (notably, the distribution should exhibit a 'shoulder' at small perpendicular distances).

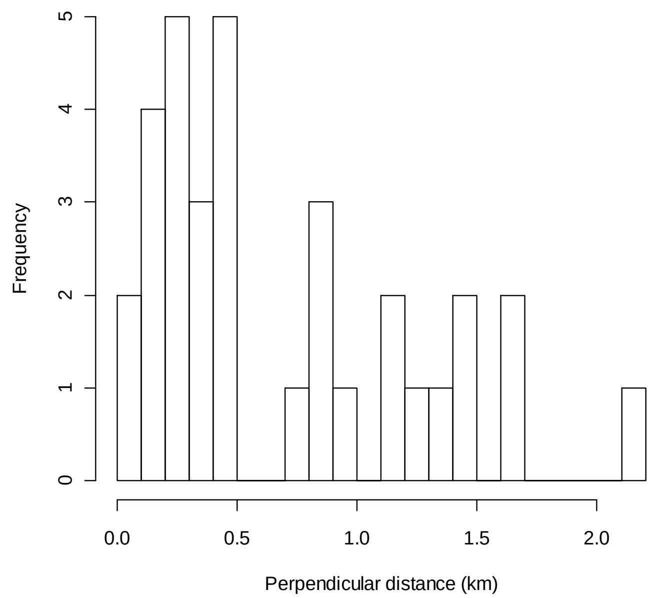



**Figure 6** Frequency distribution of perpendicular distances of sperm whale pods (bulls, cows, calves and juveniles) sighted on the 2009 survey.

The 2009 sperm whale data were analysed using conventional line transect estimation in the software *Distance 6.0* release 2 (Thomas *et al.,* 2010). The objectives of these analyses were to obtain an estimate of (a) the average relative abundance of sperm whales in the area; and (b) the average relative abundance of adult bull sperm whales in the area.

The survey area (outlined by the dashed lines in Figure 2) spanned 13,125km$^2$. Search effort outside of this area (on the extended transects) was included in density estimation. Realized survey effort together with sightings made (on- or off-effort) is shown separately by flight in Figure A4 (Appendix 4).

In *Distance*, two forms of the detection function were considered: the half-normal (with cosine adjustment terms) and the hazard-rate (also with cosine adjustments). Model selection was by Akaike's Information Criterion (AIC). Each survey (where two flights undertaken on the same day constituted a single survey) was considered as a replicate, and the mean density was estimated as the effort-weighted average of the density estimates for each survey.

Although with such low numbers of sightings the analysis options were restricted, incorporation of covariates in the scale parameter of the detection function was considered (Marques and Buckland, 2003). For this aspect of the analysis, only the half-normal detection function was considered. Covariates included cloud cover, sea state, wind speed and sightability code (a subjective measure of the viewing conditions with possible values: Nil, Poor, Fair or Good). However AIC values suggested no improvement to the fit of the detection function compared to the perpendicular distance-only form, for which a simple half-normal (with no adjustments) was selected in preference to the hazard-rate form.

Detection function fits, superimposed on histograms of the frequency of sightings at given perpendicular distances are shown in Figures 7 and 8, for all sperm whales and for adult bulls respectively. Each figure shows two plots – the left panel is for all flights used in the analysis, and the right panel is the data and fit when the analysis is restricted to full surveys only. Kolmogorov-Smirnoff tests indicated no significant lack-of-fit.

Estimated abundance, $\hat{N}$, is given by:

$$\hat{N} = \frac{A \cdot \hat{E}(s) \cdot n}{2L\hat{\mu}},$$

where $A$ is the survey area; $\hat{E}(s)$ is the estimated mean pod size; $n$ is the number of detections within a perpendicular truncation distance ($w$) of the transect line; $L$ is the length of trackline surveyed on effort; and $\hat{\mu}$ is the estimated effective strip half-width ($\int_0^w \hat{g}(x)dx$). Estimated mean pod size was estimated by regressing the log(observed pod size) against $\hat{g}(x)$, thus accommodating greater detectability of larger pods. Results are tabulated in Table 3, separately for all sperm whale pods and bulls, and by the data (i.e. flights) used in the analyses.

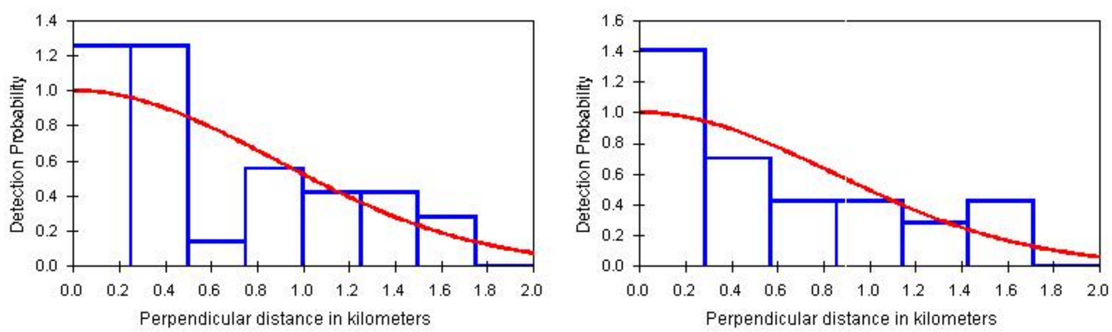



**Figure 7** Histograms of perpendicular sighting distances to sperm whale pods on the 2009 survey, with fitted detection functions. Left panel includes data from full and partially-completed surveys (number of sightings=31). Right panel includes data from full surveys only (n=26).

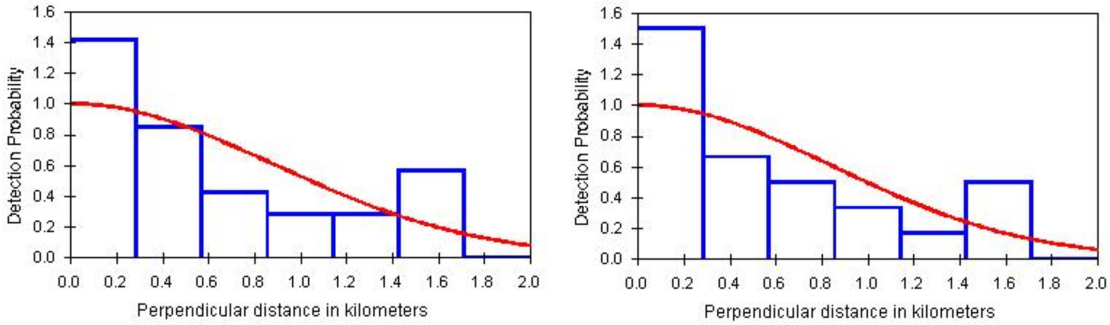



**Figure 8** Histograms of perpendicular sighting distances to adult bull sperm whale pods (or pods of mixed composition but comprising at least one adult bull) on the 2009 survey, with fitted detection functions. Left panel includes data from full and partially-completed surveys (number of sightings=27). Right panel includes data from full surveys only (n=22).

| | Flights | Area (km$^2$) | *n* | *L* (km) | $\hat{E}(s)$ | $\hat{\mu}$ (km) | $\hat{N}$ |
|---|---|---|---|---|---|---|---|
| Adult bull sperm | Full+part | 13,125 | 27 | 18,310 | 1.66 (1.26-2.20) | 1.09 (0.80-1.48) | 14 (7-32) |
| | Full only | 13,125 | 22 | 14,495 | 1.82 (1.33-2.49) | 1.05 (0.75-1.46) | 17 (7-44) |
| All sperm | Full+part | 13,125 | 31 | 18,310 | 2.93 (1.82-4.71) | 1.08 (0.80-1.45) | 29 (12-73) |
| | Full only | 13,125 | 26 | 14,495 | 3.44 (1.97-6.00) | 1.04 (0.76-1.43) | 39 (13-115) |

**Table 3** Abundance estimates ($\hat{N}$) of sperm whales. *n* is the number of sightings within a perpendicular distance of 2km; *L* is the length of transect surveyed; $\hat{E}(s)$ is the estimated mean pod size; $\hat{\mu}$ is the estimated effective strip half-width. 95% confidence intervals are given in parentheses.

The estimates in Table 3 are derived from two sets of data: flights which constituted a full survey of the area (‘Full only’) and these flights plus some partially-completed flights for which a reasonable amount of survey effort had been achieved (‘Full+part’). Provided the effort on the partially-completed flights was not correlated with whale density (and we have no evidence to suggest it was – completion of transects was weather-dependent), then the estimates which include these flights (and are more precise), are preferred. Effort-weighting the estimates by survey yielded mean estimates during the period. Resulting ‘best’ estimates from the 2009 survey are 29 (95% CI: 12-73) for all sperm whales, and 14 (95% CI: 7-32) for adult bulls.

As a sensitivity test to examine the effect of not left-truncating the distance data to account for a blind area underneath the aircraft, further analyses were undertaken with left-truncation of the data at 150m (a smaller blind region than that measured, but with some empirical support – see Figure 6). The abundance estimate increased to 32, but with lower precision (95% CI: 13-87).

## 6. Summary

The survey had been planned with the main objective of estimating the likely recovery of sperm whales off Albany post-whaling. Indices of abundance of sperm whale adult bulls from whaling operations (using 'spotter' aircraft) were available from 1968-78, and the survey was designed largely following the contemporaneous advice provided in Kirkwood (1980). The survey region was chosen to cover the area searched during those operations, and as recommended by Kirkwood (1980), for comparative purposes, the data collection and analyses was focused on adult sperm whale bulls, since these animals (over 35 feet in length) were targeted by the whalers. In this study, species size and identity were confirmed using photographs of the animals taken with a fixed length lens and using pixel counts to provide high confidence in size estimates. These were further calibrated against a fixed scale on observer's windows that provided a size estimate for each respective declination

The 2009 indices of sperm whale bull abundance were significantly lower than those from the 1968-78. Some exploration of the original Log Sheets recorded during the whaling operations raised some doubts about whether the data used for calculation of the abundance indices were consistent – in particular with respect to some inclusion of 'young' bulls included as adults and also some surprisingly high pod sizes of adult bulls. In truth, without considerable effort in reviewing those data in detail, it is not possible to determine how reliable they are. While they remain valid as indices of relative abundance for the decades to which they pertain, comparisons between them and those from the 2009 survey remain problematic.

During the 2009 survey, a total of 61 flights were undertaken, of which 34 provided data for estimation of sperm whale abundance using line transect techniques. Average abundance in the area off Albany during the survey period was estimated at 29 (95% CI: 12-73) for all sperm whales, and at 14 (95% CI: 7-32) for adult bull sperm whales. Neither of these estimates incorporate either a correction for whales missed on the trackline (perception bias) or a correction for whales submerged (availability bias). The latter, in particular, would be large for a long diving species such as sperm whales, but we do not embark on this speculative exercise here. If estimates of absolute abundance are required, it is strongly recommended that combined visual and acoustic surveys (e.g. Barlow and Taylor, 2005) are undertaken.

## 7. Acknowledgements

This research was made possible through funding from the Department of Environment, Water, Heritage and the Arts, Australian Marine Mammal Centre, Australian Antarctic Division. We thank Prof Helene Marsh at James Cook University for loan of the Microtrack. The flights were co-ordinated initially by Joshua Smith, and then by Paul Ensor. We extend our thanks to the other observers, especially Maryrose Gulesserian, but also Ian Westhorpe and Rod Moir. JLB thanks the Western Australian Museum Trustees and Chief Executive Officer for continued provision of /facilities and administrative assistance.

## References

Bannister, J.L. 1968. An aerial survey for sperm whales off the coast of Western Australia. *Australian Journal of Marine Freshwater Research*, 19: 31-51.

Bannister, J.L., Kemper, C.M. and Warneke, R.M. (1996). The action plan for Australian cetaceans. Wildlife Australia, Endangered Species Program, Project Number 380. Australian Nature Conservation Agency, Canberra, ACT, Australia (unpublished). 242 pp.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L. and Thomas, L. 2001. *Introduction to distance sampling: estimating abundance of biological populations*. Oxford University Press, London. 432pp.

Hedley, S.L. 2006 Review of Report on an Aerial Survey for Sperm Whales off Albany, Western Australia. University of St Andrews report to Macquarie University (unpublished). 7pp.

Kirkwood, G.P. 1980. Report on pilot study for design of aerial survey for sperm whales off Albany, Western Australia. CSIRO Division of Fisheries Report to the Australian National Parks and Wildlife Service (unpublished). 22pp.

Kirkwood, G.P. and Bannister, J.L. 1980. Revised abundance indices for sperm whales off Albany, Western Australia. *Rep. int. Whal. Commn (Special issue 2)*: 89-91.

Leaper, R., Gillespie, D., Gordon, J. and Matthews, J. 2003. Abundance assessment of sperm whales. Paper SC/55/O13 presented to the Scientific Committee of the International Whaling Commission, Berlin, 2003 (unpublished). 5pp.

Marques, F.F.C. and Buckland, S.T. 2003. Incorporating covariates into standard line transect analyses. *Biometrics*, 59: 924-935.

R Development Core Team 2009. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Thomas, L., S.T. Buckland, E.A. Rexstad, J. L. Laake, S. Strindberg, S. L. Hedley, J. R.B. Bishop, T. A. Marques, and K. P. Burnham. 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. *Journal of Applied Ecology,* 47: 5-14.

Wood, S.N. 2006. *Generalized Additive Models: An Introduction with R.* Boca Raton: Chapman and Hall-CRC. 391pp.

## Appendix 1: Details of each flight

| | | | | | | On-effort | | Off-effort | |
|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Flt** | **Hours** | **Type** | **Transects** | **Obs** | **#pods** | **#whales** | **#pods** | **#whales** |
| 08/09/2009 | 1 | 4.1 | Training | 12-5 | JS+MG | | | | |
| 09/09/2009 | 2 | 0.3 | Aborted | - | JS+MG | | | | |
| 13/09/2009 | 3 | 1.1 | Aborted | 12 | JS+MG | | | | |
| 15/09/2009 | 4 | 0.3 | Aborted | - | JS+MG | | | | |
| 15/09/2009 | 5 | 0.4 | Aborted | - | JS+MG | | | | |
| 19/09/2009 | 6 | 4 | Aborted | 12-6 | JS+MG | 0 | 0 | 0 | 0 |
| 22/09/2009 | 7 | 0.2 | Camera trial | - | JS+MG | | | | |
| 22/09/2009 | 8 | 0.2 | Camera trial | - | JS+MG | | | | |
| 25/09/2009 | 9 | 5.5 | Full | 12-1 | JS+MG | 1 | 5 | 0 | 0 |
| 26/09/2009 | 10 | 3.3 | Full (part 1) | 12-7 | JS+MG | 0 | 0 | 2 | 15 |
| 26/09/2009 | 11 | 2.7 | Full (part 2) | 6-1 | JS+MG | 0 | 0 | 1 | 7 |
| 27/09/2009 | 12 | 5.57 | Full | 12-1 | JS+MG | 0 | 0 | 1 | 70 |
| 30/09/2009 | 13 | 5.6 | Full | 12-1 | JS+MG | 0 | 0 | 0 | 0 |
| 03/10/2009 | 14 | 0.4 | Training | - | PE+MG | | | | |
| 04/10/2009 | 15 | 5.7 | Full | 12-1 | PE+MG | 0 | 0 | 0 | 0 |
| 05/10/2009 | 16 | 4.4 | Aborted | 12-5 | PE+MG | 0 | 0 | 0 | 0 |
| 09/10/2009 | 17 | 0.4 | Aborted | - | PE+IW | | | | |
| 10/10/2009 | 18 | 4.8 | Aborted | 12-4; part of 3 | PE+IW | 1 | 6 | 0 | 0 |
| 14/10/2009 | 19 | 1.8 | Aborted | parts of 12, 11, 10 | PE+IW | 0 | 0 | 0 | 0 |
| 15/10/2009 | 20 | 5.5 | Full | 12-1 | PE+IW | 0 | 0 | 0 | 0 |
| 16/10/2009 | 21 | 5.9 | Full | 12-1 | PE+IW | 3 | 3 | 1 | 1 |
| 17/10/2009 | 22 | 1.4 | Aborted | 12; part of 11 | PE+IW | 0 | 0 | 0 | 0 |
| 17/10/2009 | 23 | 3.8 | Aborted | 12-7; part of 6 | PE+IW | 1 | 1 | 0 | 0 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 18/10/2009 | 24 | 3.9 | Aborted | 1-7; part of 8 | PE+IW | 2 | 2 | 0 | 0 |
| 20/10/2009 | 25 | 6.1 | Full | 12-1 | PE | 4 | 4 | 0 | 0 |
| 21/10/2009 | 26 | 6.3 | Full | 12-1 | PE+RM | 1 | 1 | 1 | 1 |
| 22/10/2009 | 27 | 2.7 | Aborted | 12-9 | PE+MG | 0 | 0 | 0 | 0 |
| 26/10/2009 | 28 | 1.5 | Aborted | 12-11 | PE+MG | 0 | 0 | 0 | 0 |
| 26/10/2009 | 29 | 1.4 | Aborted | 10-9 | PE+MG | 1 | 1 | 0 | 0 |
| 27/10/2009 | 30 | 2.6 | Aborted | parts of12 & 10; 9-7 | PE+MG | 0 | 0 | 0 | 0 |
| 30/10/2009 | 31 | 4.1 | Full (part 1) | 1-8 | PE+MG | 0 | 0 | 0 | 0 |
| 30/10/2009 | 32 | 2.6 | Full (part 2) | 9-12 | PE+MG | 0 | 0 | 0 | 0 |
| 31/10/2009 | 33 | 2.2 | Aborted | 12-9 | PE+MG | 0 | 0 | 0 | 0 |
| 02/11/2009 | 34 | 6.1 | Full | 12-1 | PE+MG | 0 | 0 | 0 | 0 |
| 03/11/2009 | 35 | 2.6 | Full (part 1) | 12-9 | PE+MG | 0 | 0 | 0 | 0 |
| 03/11/2009 | 36 | 4.2 | Full (part 2) | 8-1 | PE+MG | 0 | 0 | 0 | 0 |
| 04/11/2009 | 37 | 0.7 | Aborted | - | PE+MG | | | | |
| 05/11/2009 | 38 | 0.7 | Aborted | - | PE+MG | | | | |
| 07/11/2009 | 39 | 4 | Full (part 1) | 1-4; 12-11 | PE+MG | 1 | 3 | 0 | 0 |
| 07/11/2009 | 40 | 3.5 | Full (part 2) | 10-5 | PE+MG | 2 | 3 | 0 | 0 |
| 08/11/2009 | 41 | 3.7 | Aborted | 8 (part); 6-1 | PE+MG | 0 | 0 | 1 | 18 |
| 09/11/2009 | 42 | 3.9 | Full (part 1) | 12-7 | PE+MG | 0 | 0 | 0 | 0 |
| 09/11/2009 | 43 | 3.1 | Full (part 2) | 6-1 | PE+MG | 0 | 0 | 0 | 0 |
| 10/11/2009 | 44 | 1.5 | Aborted | - | PE+MG | | | | |
| 11/11/2009 | 45 | 0.5 | Aborted | - | PE+MG | | | | |
| 15/11/2009 | 46 | 4 | Full (part 1) | 6-1 | PE+MG | 0 | 0 | 0 | 0 |
| 15/11/2009 | 47 | 4 | Full (part 2) | 12-7 | PE+MG | 0 | 0 | 0 | 0 |
| 16/11/2009 | 48 | 0.8 | Aborted | - | PE+MG | | | | |
| 16/11/2009 | 49 | 0.9 | Aborted | - | PE+MG | | | | |
| 17/11/2009 | 50 | 5.4 | Aborted | 12-10; parts of 9 &6; 5-1 | PE+MG | 1 | 1 | 0 | 0 |
| 20/11/2009 | 51 | 1.7 | Aborted | Transects12-11 | PE+MG | 0 | 0 | 0 | 0 |
| 21/11/2009 | 52 | 1.7 | Aborted | - | PE+MG | | | | |
| 22/11/2009 | 53 | 6.4 | Full | 12-1 | PE+MG | 4 | 9 | 0 | 0 |
| 23/11/2009 | 54 | 6.4 | Full | 12-1 | PE+MG | 2 | 45 | 1 | 6 |
| 24/11/2009 | 55 | 6.8 | Full | 12-1 | PE+MG | 13 | 48 | 0 | 0 |
| 27/11/2009 | 56 | 4 | Aborted | 12-9; parts of 8-5 | PE+MG | 0 | 0 | 0 | 0 |
| 28/11/2009 | 57 | 6.4 | Full | 12-1 | PE+MG | 1 | 19 | 0 | 0 |
| 29/11/2009 | 58 | 1.3 | Aborted | Part of 12 | PE+MG | 0 | 0 | 0 | 0 |
| 03/12/2009 | 59 | 6.1 | Full | 12-1 | PE+MG | 1 | 8 | 0 | 0 |
| 04/12/2009 | 60 | 6.2 | Full | 12-1 | PE+MG | 0 | 0 | 0 | 0 |
| 05/12/2009 | 61 | 4.5 | Aborted | 12-5 | PE+MG | 1 | 1 | 0 | 0 |

**Table A1**: Flight summary for the 2009 survey. Greyed-out flights were not included in the analyses. Only Full surveys (in one or two parts) were used in calculating comparative indices between 1968-78 and 2009.

## Appendix 2: Probability distributions for frequency distributions

Four distributions were considered for fitting the frequency distribution of number of bull sperm whales seen from the whaling data. Their pdfs are given below

*Pólya-Aeppli*

For $\theta > 0$ and $0 < p < 1$,

$$\Pr(N = x) = \begin{cases} e^{-\theta} & x = 0 \\ e^{-\theta} p^x \sum_{j=1}^{x} \binom{x-1}{j-1} \frac{[\theta(1-p)/p]^j}{j!} & x = 1, 2, \ldots \end{cases}$$

*Zero-inflated Poisson*
For $\theta > 0$ and $0 < p < 1$,

$$\Pr(N = x) = \begin{cases} (1-p) + pe^{-\theta} & x = 0 \\ \dfrac{pe^{-\theta}\theta^{x}}{x!} & x = 1, 2, \ldots \end{cases}$$

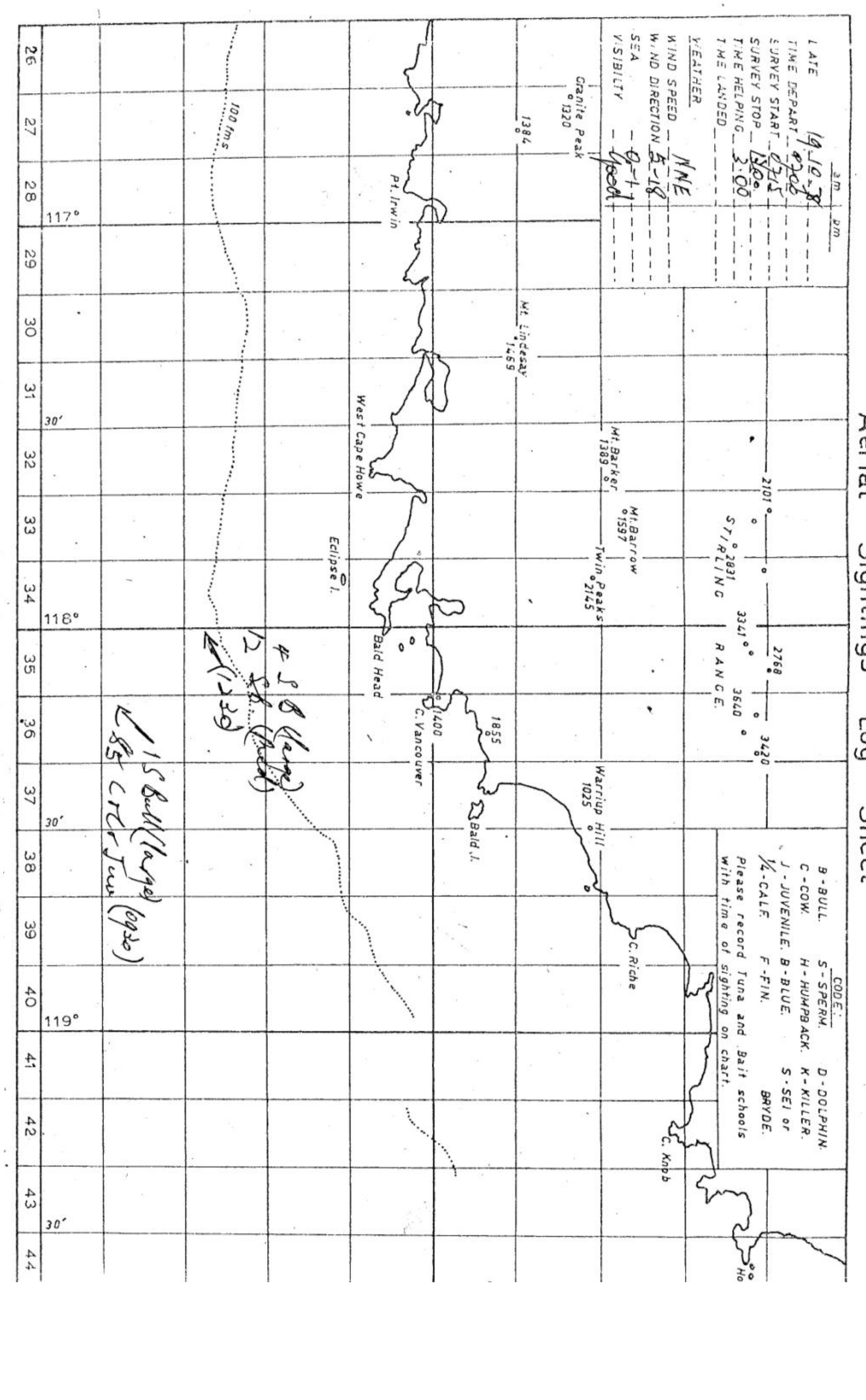
*Zero-inflated Geometric*
For $0 < \theta < 1$ and $0 < p < 1$,

$$\Pr(N = x) = \begin{cases} p + (1-p)\theta & x = 0 \\ \theta(1-p)(1-\theta)^{x} & x = 1, 2, \ldots \end{cases}$$

*Compound Poisson (with Gamma compounding density)*
For $0 < \theta < \infty$ and $0 < p < \infty$,

$$\Pr(N = x) = \binom{x + \theta - 1}{x} \frac{p^{x}}{(p+1)^{\theta + x}} \qquad x = 0, 1, \ldots$$

# Appendix 3: Example of Spotter Aircraft Log Sheet



# Appendix 4: Realized survey effort and sperm whale sightings for line transect analysis

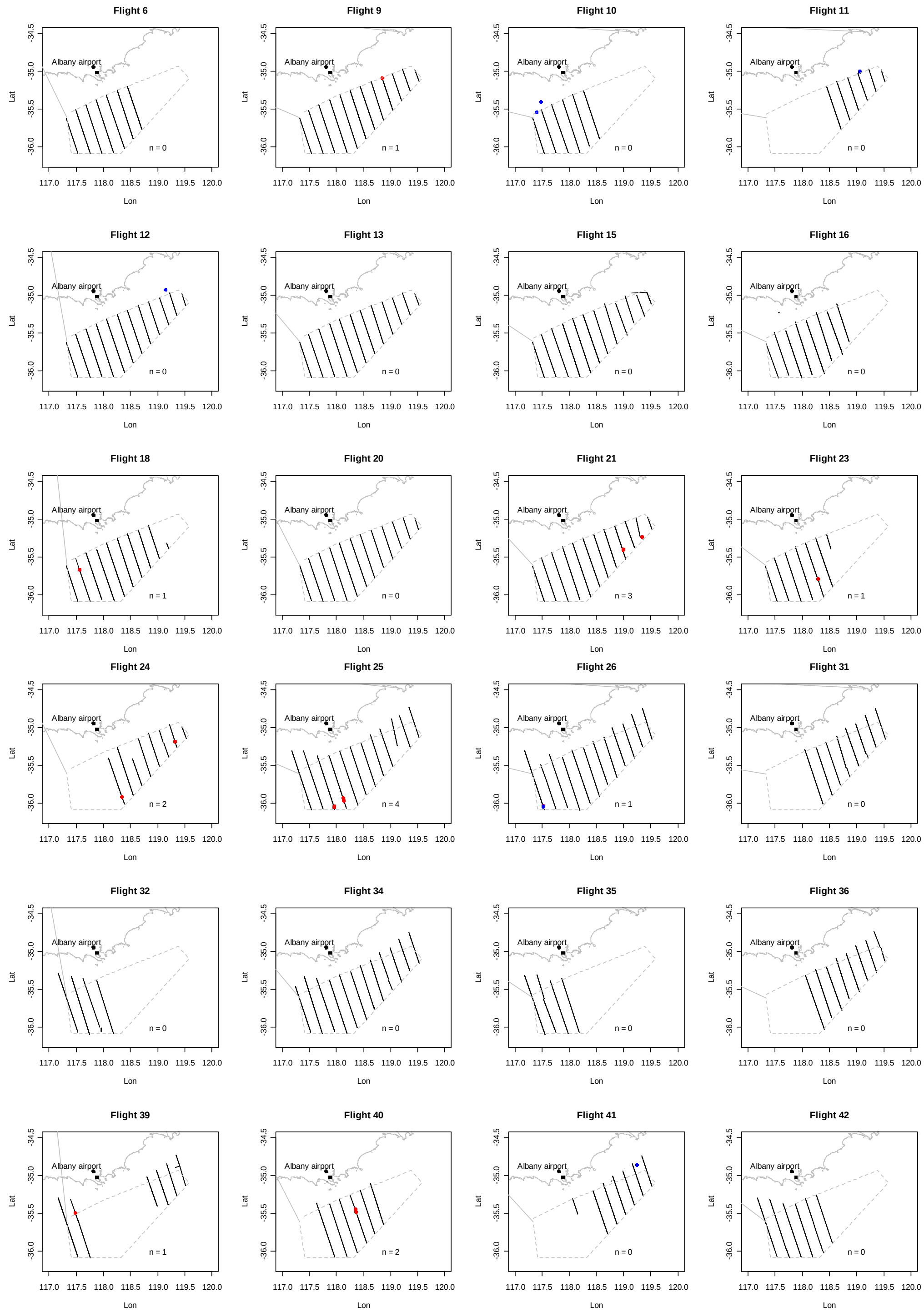



**Figure A4** (continued on next page)

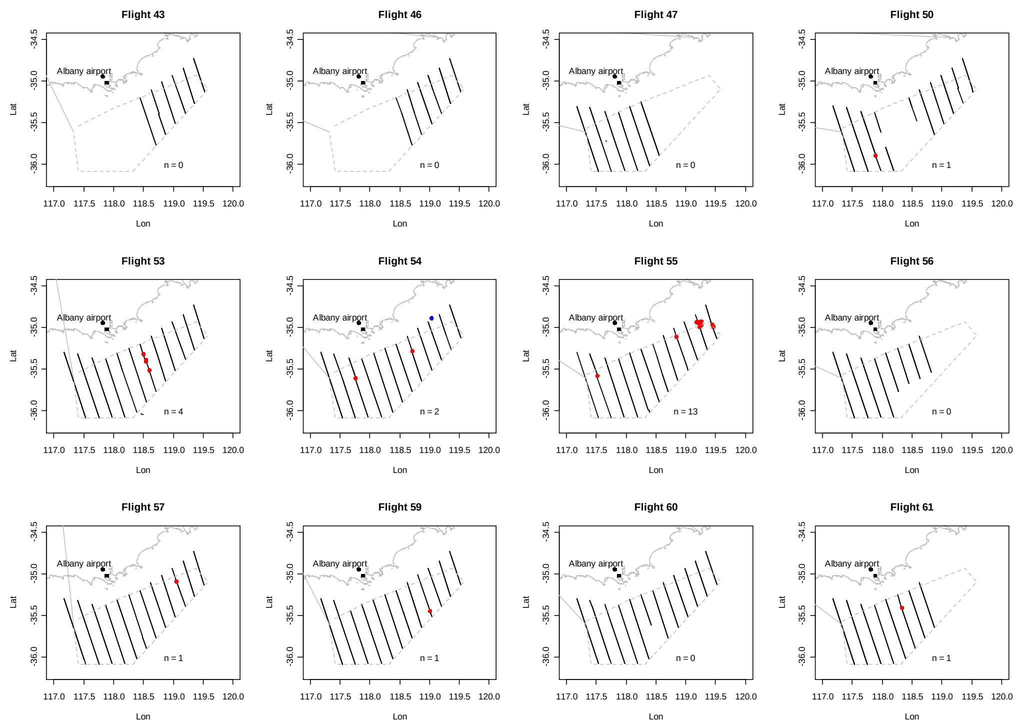



**Figure A4** (continued from previous page) Realized survey effort and sperm whale sightings made on flights included in the line transect analyses. Number (n) of on-effort sightings shown on each plot. Red circles = on-effort sightings; blue circles = off-effort sightings.