An improved method for line transect sampling in Antarctic minke whale surveys

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ABSTRACT

The series of abundance estimates for Antarctic minke whales obtained using standard line transect methods from IWC/SOWER surveys imply drastic (and probably unrealistic) changes in true abundance. One possible factor is that the detection probability on the trackline, $g(0)$, may have decreased with the introduction of inexperienced observers in the most recent surveys. Additionally, mean observed school size may have decreased in the third circumpolar survey in comparison with the second survey. This paper introduces an extended and generalised hazard probability model without the assumption that $g(0)=1$ to estimate true school size distribution in the population. The proposed method uses a survey design that combines the use of both passing mode with independent observers and closing mode in which the vessel turns off the trackline and closes with the sighting for confirmation of school size and species. The abundance estimate is based on the Horvitz-Thompson estimator in an unequal detectability sampling scheme. The method is applied to the IDCR/SOWER dataset of Antarctic minke whales for illustrative purposes.

KEYWORDS: ANTARCTIC MINKE WHALE; ABUNDANCE ESTIMATE; *g*(0); SCHOOL SIZE; SURVEY-VESSEL; SOWER; MODELLING

INTRODUCTION

The abundance of whales and dolphins in an area are frequently estimated using distance-based line transect sampling (e.g. Buckland *et al.*, 1993; IWC, 2005a; b; c). Put simply, this entails usually an observer following a pre-determined line, searching for animals on and near to that line and measuring the distances and angles to each detected animal. One of the important assumptions in conventional line transect sampling is that all animals on the line are detected without failure, i.e. the probability of seeing an animal if it occurs on the trackline, commonly called $g(0)$, is equal to 1. However, the diving behaviour of cetaceans can lead to this assumption being violated, even if they occur on (or below) the trackline. Double-platform line transect surveys are often conducted to try to resolve this problem (Cooke, 1997; Schweder *et al.*, 1997; Skaug and Schweder, 1999). Such surveys enable collection of data for estimating the probability of missing animals, i.e. duplicate sightings from independent observers.

The International Decade of Cetacean Research – Southern Ocean Whale and Ecosystem Research (IDCR/SOWER) surveys have been conducted annually in the Antarctic since the late 1970s (Branch and Butterworth, 2001). The main purpose of these surveys has been to collect sightings data to estimate the abundance of Antarctic minke whales (*Balaenoptera bonaerensis*). Sightings data from these surveys consist of three circumpolar sets of cruises: 1978/79-1983/84, 1985/86-1990/91 and 1991/92-2003/2004. The survey effort of IDCR/SOWER surveys is divided into closing and passing modes. In closing mode, when a school of whales is detected, the vessel turns off the trackline and closes with the sighting to confirm the school size and species. Survey data in 'closing mode' may cause some bias in school density, but gives more accurate information on school size (Branch and Butterworth, 2001). 'Passing' mode represents double-platform line transect sightings with independent observers. Data collected under passing mode contain valuable information about $g(0)$. However, since a vessel is not allowed to leave the trackline for confirmation of school size and species identification of detected animals, school size (and sometimes species identification) estimated from many of the schools detected in passing mode may be unreliable.

The abundance estimates of Antarctic minke whales have been estimated by conventional line transect methods with $g(0)=1$ (Branch and Butterworth, 2001). The abundance estimates for the third circumpolar survey obtained from IDCR/SOWER data showed a dramatic decrease compared with the second circumpolar survey. Branch and Butterworth (2001) reported that the abundance estimates for the third circumpolar survey are 45% (passing mode only) and 55% (closing mode only) of those for the second circumpolar survey. Although the third circumpolar survey data are not fully analysed, a substantial decrease in estimates from the third circumpolar survey on the basis of standard line transect methods (Buckland *et al.*, 1993; Branch and Butterworth, 2001) is obvious, although whether such drastic declines in true abundance are real is the subject of considerable work; the Scientific Committee of the International Whaling Commission (IWC) has listed a number of possible causes that might result in the change in estimates (IWC, 2002). Two proposed causes for the decline are changes in the detection probability on the trackline and changes in the distribution of school size. The focal point of this paper is how to estimate changes of $g(0)$ and school size distribution.

A new efficient method for estimating the abundance of diving animals from double-platform line transect survey data was recently developed by Okamura *et al.* (2003). This method concentrated on the estimation of $g(0)$ based on double-platform line transect sampling, but ignored the problem of possible downward bias of school size estimates in passing mode. As noted above, the size of detected

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schools is rarely confirmed in passing mode, and the observed mean school size in passing mode is generally less than that of closing mode. This paper considers the question of the removal of bias induced by unconfirmed school size under passing mode.

MATERIALS AND METHODS

Data requirements

This method requires: the perpendicular and forward distances of sightings; on-board determination of whether each detection is either a single sighting, a simultaneous sighting or delayed duplicate sighting (see below); school size estimates; and the confirmation status (i.e. how certain the observers are that the estimate is good) of school size for each sighting under both passing and closing mode. The simultaneous duplicate sighting represents detection of the same animal at the same time by multiple platforms and the delayed duplicate sighting represents detection of the same animal at different times by multiple platforms. For illustrative purposes, this method has been applied to the 1989/90 IDCR data, although these do not completely satisfy the above data requirements. Necessary data processing for the IDCR data is described after the explanation of the model.

Likelihood function

A hazard probability model is used to estimate the detection function and $g(0)$, of which a detailed description is given in Appendix 1. In IDCR/SOWER passing mode, sightings from an incompletely independent platform (IIP) on an upper bridge of a vessel account for a large proportion of the total (Okamura *et al.*, 2003). Therefore, two independent platforms (A: top barrel and B: independent observer (IO) booth) and an incompletely independent platform (C: upper bridge) are considered. Sightings made by completely independent platforms (CIP) on the top barrel and the IO booth of a vessel are immediately communicated to the IIP on the upper bridge. Hence, duplicate sightings by the IIP could never be classed as delayed duplicates after detection by the CIP, although duplicates by the CIP may have been delayed after detection by the IIP. Therefore, the output from the initial sighting is categorised according to 11 types of detection (u); A, B, C, $A \times B$, $A \to B$, $B \to A$, $C \to A$, $C \to B$, $C \to A \times B$, $C \to A \to B$, and $C \to B \to A$, where for instance $A \times B$ and $A \to B$ denote simultaneous and delayed duplicates between A and B, respectively. The detection probability in passing mode is then written as $p_1(x, y, u|s)$ where x is perpendicular distance, y is the forward distance, u is the type of detection, and s is the true size of the detected school. Dependency of school size is modelled using the equation like $\log(\sigma) = a_0 + a_1 \log(s)$, where σ is a parameter of detection probability function. Closing mode has two sighting platforms, a top barrel, A and an upper bridge, C of a vessel. These two platforms are completely dependent, i.e. one platform immediately knows of any detection by another platform. The type of detection in closing mode simply becomes the combination of the top barrel and upper bridge, $A \cup C$, and the detection probability in closing mode is then written as $p_2(x, y, A \cup C|s)$. For all platforms, measurement error in distances is not considered here.

As would be expected, the proportion of unconfirmed school sizes in passing mode was much higher than that in closing mode during the 1989/90 IDCR survey (see Table 1). Mean unconfirmed school size tends to be lower than mean confirmed school size, possibly due to overlooking part of a school. This leads to an underestimate of abundance when only passing mode school size data are used, if the difference between confirmed and unconfirmed school size is not taken into account. Both passing and closing mode data can be used simultaneously to estimate the true probability distribution of school size in the population. The assumption here is that confirmed school size reflects the probability distribution of true school size, given it is detected, while unconfirmed school size is biased to some degree.

Buckland *et al.* (1993) and Borchers (1999) suggested using a probability distribution of school size to correct for the size bias of detected schools; if large schools are detected at greater distances than small schools, mean school size will be biased upwards. Antarctic minke whale surveys have a more complicated structure of school size bias due to the ‘confirmation’ process. A probability distribution of ‘unconfirmed’ school size conditioned on unobserved true school size is used here. Since confirmation status is also a stochastic event, it is treated probabilistically. The mathematical details are given in Appendix 2.

Putting the above-mentioned hazard probability model (Appendix 1) and correction method for mis-estimation of school size (Appendix 2) together, the log-likelihood function for sighting distance (x, y), type of detection (u), observed school size (z), confirmation status (c), and survey mode (t) is given by:

$$\log(L) = \sum_{t=1}^{2}\sum_{i=1}^{n_t}(c_i \log\{p_t(x_i, y_i, u_i \mid z_i) d_t(z_i)\pi(z_i)\}$$
$$+(1-c_i)\log[\sum_{s=z_i}^{\infty} p_t(x_i, y_i, u_i \mid s)\rho(z_i \mid s)\{1-d_t(s)\}\pi(s)] \quad (1)$$
$$-\log\{\sum_{s=1}^{\infty} esw_t(s)\pi(s)\})$$

where:

n_t is the sample size under each mode;
$p_1 = p_1(x_i, y_i, u_i|s)$, a detection probability in passing mode and is altered following the type of detection, p_2 is equal to

$$p_2(x, y, A \cup C \mid s) = \frac{\lambda}{v} Q_{A\cup C}(x, y) \exp\left\{-\frac{\lambda}{v}\int_y^{\infty} Q_{A\cup C}(x, y)dy\right\}$$

which is a detection probability in closing mode;

esw_1 and esw_2 are effective search half-widths in passing and closing mode, respectively (Appendix 1);

$\pi(s)$ is the probability distribution of true school size;

$\rho(z|s)$ is the probability distribution of observed school size given the animals are detected and unconfirmed;

$d(z)$ represents the probability that the animals with school size z are confirmed (Appendix 2).

Parameters are then estimated by maximising the log-likelihood, $\log(L)$. When $c_i = 1$ (all i) and $d_t(z) \equiv 1$, the log-likelihood function corresponds to those of Buckland *et al.* (1993) and Borchers (1999). When $d_t(z) = d_t$, the log-likelihood function is equal to the log-likelihood function conditioned on the confirmation status.

The density estimator of animals based on the Horvitz-Thompson estimator (Horvitz and Thompson, 1952) is then given by:

$$\hat{D} = \frac{1}{2L}\sum_{i=1}^{n_1} \frac{\{\hat{\phi}_0(1-\hat{\phi}_1)/\hat{\phi}_1\}+1}{\sum_{s=1}^{\infty} e\hat{s}w_1(s)\hat{\pi}(s)} \quad (2)$$

where L is total survey distance, and the numerator is derived from $\phi_1 = \phi_0/\{\phi_0 + E(s) - 1\}$ using the parameters of a negative binomial distribution (Appendix 2). Note that the parameters in relation to $\rho(z|s)$ and $d(s)$ are nuisance parameters and not used in density estimation. Only passing mode data were used in density estimation, since density estimation under closing mode causes additional biases, such as an upward bias through deviations from the trackline and a downward bias from neglect of secondary sightings (Branch and Butterworth, 2001).

The abundance estimator is given by $\hat{P} = a{\cdot}\hat{D}$, given the area size a. An estimator for the unconditional asymptotic variance of $\hat{P}$, as in Okamura *et al.* (2003), is then:

$$\hat{\text{var}}(\hat{P}) = \left[\left\{\frac{dP(\underline{\theta})}{d\underline{\theta}}\right\}^T I(\underline{\theta})^{-1}\frac{dP(\underline{\theta})}{d\underline{\theta}}\right]_{\underline{\theta}=\hat{\underline{\theta}}} + \frac{a^2}{J-1}\sum_{j=1}^{J}\frac{l_j}{L}(\hat{D}_j - \hat{D})^2 \quad (3)$$

where $\underline{\theta}$ is a vector of parameters in (1), $I(\underline{\theta})$ is the Fisher information matrix obtained from the log-likelihood function that is often substituted by the Hessian matrix, and l_j ($j = 1, \ldots, J$; $\Sigma\, l_j = L$) is a replicate line. If there is no sighting in replicate line l_j, $\hat{D}_j$ is defined as being equal to 0. Although abundance estimates by stratum are required, duplicate data are sparse in each stratum so that $g(0)$ estimation tends to be biased. Therefore, estimates of the detection function, effective search half-width and school size distribution are obtained by pooling detection distance data and school size data across strata. Assuming that effective search half-width and mean school size are common to all strata, the abundance estimate and its variance for the whole area are given by:

$$\hat{P}_{all} = \sum_h a_h \hat{D}_h \quad (4)$$

$$\hat{\text{var}}(\hat{P}_{all}) = \left[\left\{\frac{dP_{all}(\underline{\theta})}{d\underline{\theta}}\right\}^T I(\underline{\theta})^{-1}\frac{dP_{all}(\underline{\theta})}{d\underline{\theta}}\right]_{\underline{\theta}=\hat{\underline{\theta}}} + \sum_h \frac{a_h^2}{J_h-1}\sum_{j=1}^{J_h}\frac{l_{j,h}}{L_h}(\hat{D}_{j,h} - \hat{D}_h)^2 \quad (5)$$

where the subscript h is index of stratum.

Application of the proposed model to IDCR/SOWER data

The 1989/90 IDCR/SOWER data were used to investigate the reliability of the method developed above (see Table 1). The 1989/90 data generally correspond to those collected from IWC Management Area I (between 60°W and 120°W; see Donovan, 1991). Area I has a relatively stable ice-edge so it seemed appropriate to concentrate the problem on the estimation of $g(0)$ and school size, without the additional confounding factor of a changing ice-edge.

The detection by observers other than independent observers was re-coded as detection by incompletely independent observers so that sightings were not distinguished between an upper bridge and other incompletely independent platforms such as the bridge. The method requires a sufficient number of duplicates, so sighting data pooled across strata were used to estimate effective search half-width and school size distribution. Duplicates recorded as ‘possible’ as well as ‘definite’ were used as duplicates for acquiring sufficient sample size for $g(0)$ estimation. Inclusion of ‘possible’ duplicates should have little effect on outcomes in this example because the number of possible duplicates is only 3 out of 89. Although the model requires a clear distinction between simultaneous and delayed duplicates, the independent observer data under passing mode of IDCR/SOWER surveys have no such distinction at present. Therefore, for the purposes of this study it was provisionally assumed that duplicate data with a difference between sighting times less than 20 seconds were simultaneous duplicates. If the time between sightings was more than 20 seconds, it was assumed that they were delayed duplicates with a difference of sighting (radial) distances and sighting angles as the auxiliary information. For duplicates and triplicates, school size was not always confirmed by all platforms. It was assumed that a school confirmed by at least one platform was confirmed, and the observed school size was used. When different platforms had different unconfirmed school size estimates for duplicates and triplicates, the school size estimate from the initial observer was used. Observations without confirmation status were considered unconfirmed.

For simplicity, only school size was considered as a covariate in this paper. Other possible covariates might be the difference in platform and weather conditions. The logarithm of school size s was linked with the parameters as follows:

$\log(\sigma) = a_{10} + a_{11}\log(s)$;
$\log(\tau) = a_{20} + a_{21}\log(s)$;
$\text{logit}(\mu) = a_{30} + a_{31}\log(s)$;
$\log(\lambda) = a_{40} + a_{41}\log(s)$;
$\text{logit}(b) = a_{50} + a_{51}\log(s)$;
$\text{logit}(d_1) = a_{60} + a_{61}\log(s)$; and
$\text{logit}(d_2) = a_{70} + a_{71}\log(s)$.

The number of estimated parameters was 18 including the parameters $\underline{\phi}$, γ_1 and γ_2. Formal model selection was not conducted. The sightings data that were detected behind the vessel and the delayed duplicates recorded by incompletely independent observers were discarded prior to any analyses.

Increasing forward distances were found in some duplicates, possibly due to measurement error. To avoid this problem, a method that focused on an initial forward distance by integrating over remaining forward distances in detection probability was adopted. Perpendicular and forward distance data were not truncated.

RESULTS

A summary of data used is shown in Table 1. Mean school size in closing mode is larger than mean school size in passing mode (P-value <0.001 by t-test). This indicates that school size in passing mode is probably underestimated due to missing part of the group. Both mean perpendicular and forward distances in passing mode are larger than those in closing mode. The difference in perpendicular distances is statistically significant (P-value = 0.002 by t-test), but the differences in forward distance are not (P-value = 0.114 by t-test). This probably reflects the greater number of observers in passing mode.

The estimated parameters are summarised in Table 2 and the results from the proposed model are shown in Table 3. Most often, a blow was the sighting cue for Antarctic minke whales. Estimated mean blowing rate, $\hat{\lambda}$, in 1989/90 was 33.9 blows per whale per hour, taking into account that vessel speed was constantly set at 11.5 knots. This value is less than the 48 blows per whale per hour from the experiment reported by Ward (1988). Since that experiment was conducted under excellent weather conditions, the lower estimate here may be due to variable weather conditions. Estimated $\hat{\mu}$, which is the level parameter of surfacing detection probability, was small. This reflects the fact that minke whales are likely to be missed because of their small blows and body size, even though they surface frequently.

The estimated $g(0)$ was 0.61 when it was averaged over school sizes (Table 2). The mean effective search half-width in 1989/90 was 0.36 (CV=0.15), which was less than the estimates from passing mode data (0.419-0.916) given by Branch and Butterworth (2001). As a result, the total population size (89,181, CV=0.187) estimated by this method was larger than the estimate (61,169, CV=0.192) of Branch and Butterworth (2001). The CV was slightly lower than that of Branch and Butterworth (2001) but because Branch and Butterworth (2001) provided stratified estimates, direct comparison is impossible. In addition, because their standard method only used information on perpendicular distance and confirmed school size under closing mode, their estimate may be less precise than that here. The values of $g(0)$ and effective search half-width for each school size are shown in Fig. 1.

Fig. 2 shows the fitted values predicted from the method with observed school size, distance and duplicate-categorical data. The predicted values appear to fit well with the observed data despite no truncation or smearing of the data (e.g. Buckland and Anganuzzi, 1988). Although the fit of school size distributions from passing mode/confirmed and closing mode/unconfirmed does not look good, this may reflect the low sample size. The sample size of sighting data in closing mode is 155, while the sample size in passing mode is 449. This difference may cause the discrepancy between observed and predicted distance distributions in closing mode because common parameters in detection function were assumed for passing and closing modes. Because the 1989/90 data had some 'bunching' at zero perpendicular distance, the plot of perpendicular distance did not show a 'shoulder' near the line. The method is not dependent directly on probability density at zero distance unlike the standard method (Buckland *et al.*, 1993) so that the result might be robust against the presence of a shoulder; but this requires further investigation in the future. The fit may be improved by taking into account suitable truncation, smearing, other forms of the detection function and additional covariates.

Fig. 3 shows the expected number and proportion of confirmed individuals in schools recorded as unconfirmed, and the expected proportion of confirmed schools in passing and closing modes. These variables were plotted against school size because they were all modelled as functions of school size. The proportion of confirmed individuals in schools recorded as unconfirmed was about 0.4-0.7 for school sizes greater than 1. Substantial components of school sizes of about 5 are likely to be missed when they are recorded as 'unconfirmed'. The expected proportion of confirmed schools in passing and closing modes showed the

Table 2

Summary of estimated parameters in the detection function. The symbols used in this table are following the notation used in the text except where they were averaged using estimated school size distribution. $E(s)$ is estimated mean school size in the population.

	γ_1	γ_2	σ	τ	μ	λ/v	$\mu\lambda/v$	$g(0)$	*esw*	$E(s)$
Estimate	1.20	2.15	0.43	1.53	0.10	2.95	0.29	0.61	0.36	1.91
CV	0.12	0.09	0.15	0.06	0.31	0.41	0.17	0.11	0.15	0.08

Table 3

The abundance estimates of minke whales in the IDCR/SOWER 1989/1990 Area I surveys, along with estimated coefficients of variation (CV), where A is area size (n.miles^2), L is survey distance (n.miles), n_s is number of schools sighted, D_w is density of whales, and P is estimated population size. N, E, W and S in the name of stratum denote North, East, West and South of the corresponding area. B denotes 'Bay'.

Stratum	A	L	n_s	N_s/L	D_w	P	CV
EN	153,029	750.2	45	0.060	0.157	23,970	0.300
ESB	62,594	793.1	66	0.083	0.217	13,601	0.560
WN	168,761	606.7	32	0.053	0.138	23,245	0.328
WS	45,128	830.9	200	0.241	0.629	28,365	0.249
Total	429,512	2,981	343	0.115	0.208	89,181	0.187

Table 1

Summary of 1989/90 IDCR/SOWER data.

	n	n_p	s_p	s_c	$P_{uc}(P)$	$P_{uc}(C)$	pd_p	fd_p	pd_c	fd_c	%dup
Estimate	498	343	1.85	2.84	0.95	0.14	0.50	1.18	0.37	1.06	25.4
CV	-	-	0.05	0.10	-	-	0.05	0.04	0.08	0.06	-

The symbols used in this table denote the following:
n = number of all schools sighted under passing mode and closing mode (no truncation/no smearing).
n_p = number of all schools sighted under passing mode only (no truncation/no smearing).
s_p = mean school size in passing mode.
s_c = mean school size in closing mode.
$P_{uc}(P)$ = proportion of unconfirmed school size in passing mode.
$P_{uc}(C)$ = proportion of unconfirmed school size in closing mode.
pd_p = mean perpendicular distance under passing mode.
fd_p = mean forward distance under passing mode.
pd_c = mean perpendicular distance under closing mode.
fd_c = mean forward distance under closing mode.
%dup = the percentage of duplicates, #dup./$n_{A \cup B \cup C}$ x 100.

opposite trend; the decreasing trend in passing mode perhaps seems counter-intuitive. However, it may reflect the fact that the judgment of confirmation in passing mode is dependent on the perpendicular distance to the school, rather than its size, because the survey vessel does not leave the trackline line. The fact that confirmation of closing mode is increasing with school size is convincing. The estimated proportion shows most sightings are confirmed in closing mode and most are unconfirmed in passing mode.

DISCUSSION

The method proposed in this paper enables us to estimate $g(0)$ and true school size distribution in the population. Furthermore, various covariates can be dealt with in the estimation process with flexibility. The diagnostic plots indicate the method is quite promising for the abundance estimation of Antarctic minke whales. The effective search half-width in the model is fundamentally based on the hazard probability model proposed in Okamura *et al.* (2003). Additionally, parameters of the true school size distribution can be estimated within the consistent estimation process proposed in this paper. The proposed model is easy to interpret and can be considered a likelihood-based model with random effects (Pawitan, 2001). It enables the use of various techniques based on a likelihood principle in a similar way to Schweder *et al.* (1997) and Skaug and Schweder (1999). The sensitivity of the proposed method will be investigated through extensive simulation study in the near future by the Scientific Committee of the IWC.

When mean unconfirmed school size is larger than mean confirmed school size, the true school size distribution cannot be estimated, due to the assumption constrained on the model. This assumption is quite reasonable, because observers usually tend to miss whales in schools detected at a distance from the vessel. Larger unconfirmed school sizes may occur under certain circumstances. For instance, Mori *et al.* (2002) reported that during the SSII experiments on the 1985/86 IDCR cruise 'as observers began to realise that they were tending to appreciably underestimate school size at abeam time, their abeam estimates started to increase in an attempt to compensate, and the experiment was consequently suspended'. If records of school sizes estimated by observers before closure under closing mode exist, they can be incorporated into the likelihood function for closing mode, improving the precision of the estimates. If unusually large unconfirmed school sizes occur, the model will not provide correct estimates. To avoid such a problem in the future, it is important to instruct observers carefully about the definition of unconfirmed school size.

School size bias has been taken into account by regressing school size (or the logarithm of school size) on the detection function (Buckland *et al.*, 1993). Sometimes this produces unreasonable mean school sizes less than 1 (Branch and Butterworth, 2001). The present model consistently gives reasonable mean school size estimates, and statistically deals with the distribution of true school sizes in the population.

Selection between two models with the assumption of $g(0)=1$ and $g(0)<1$ can be carried out by likelihood ratio test and AIC (Akaike, 1973). Therefore, the model greatly extends the province to which the line transect method can be applied. We recommend line transect surveys that use passing mode with independent observers and closing mode alternately, for estimating unbiased abundance of diving animals such as Antarctic minke whales, or any other marine mammal with complicated school size structure and a

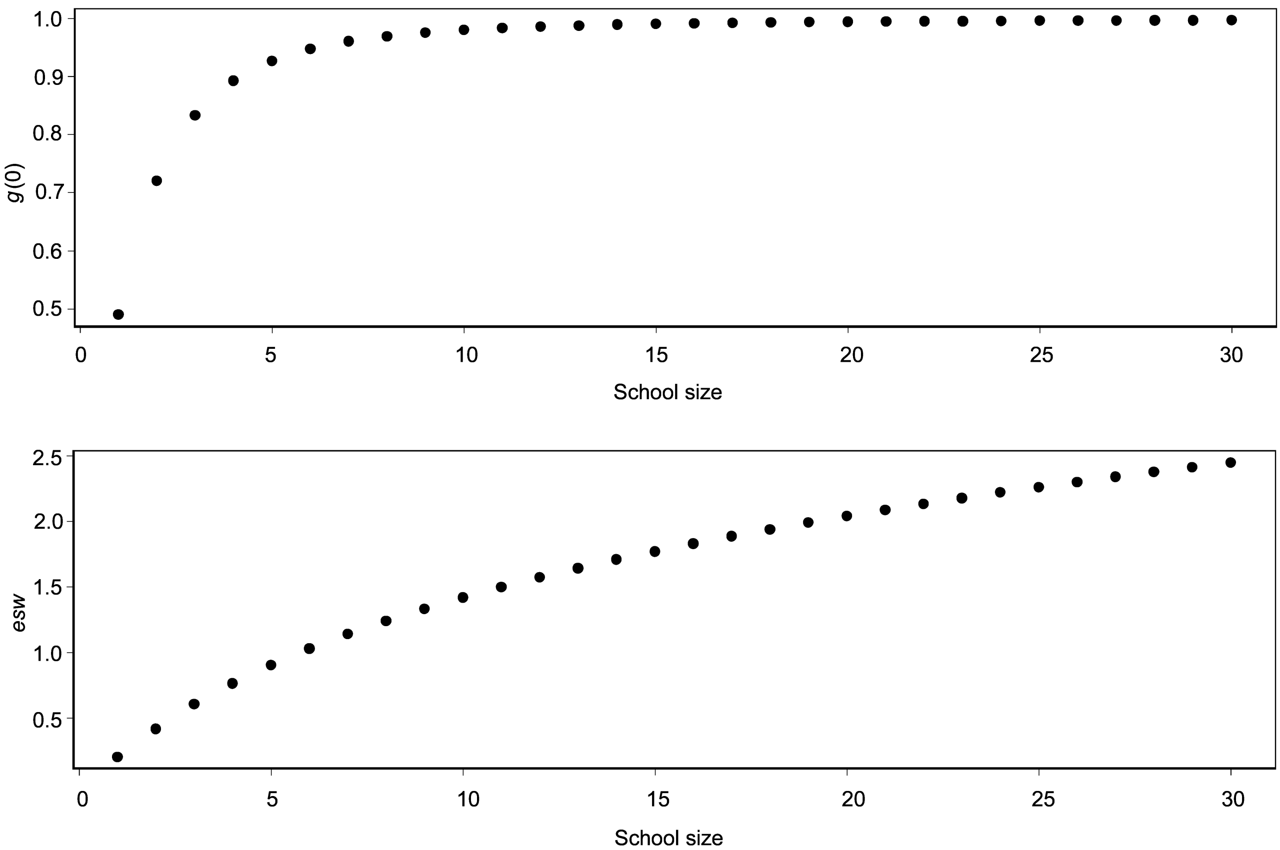

Fig. 1. Plots of the estimated $g(0)$ and effective search half-width (esw) against school size.

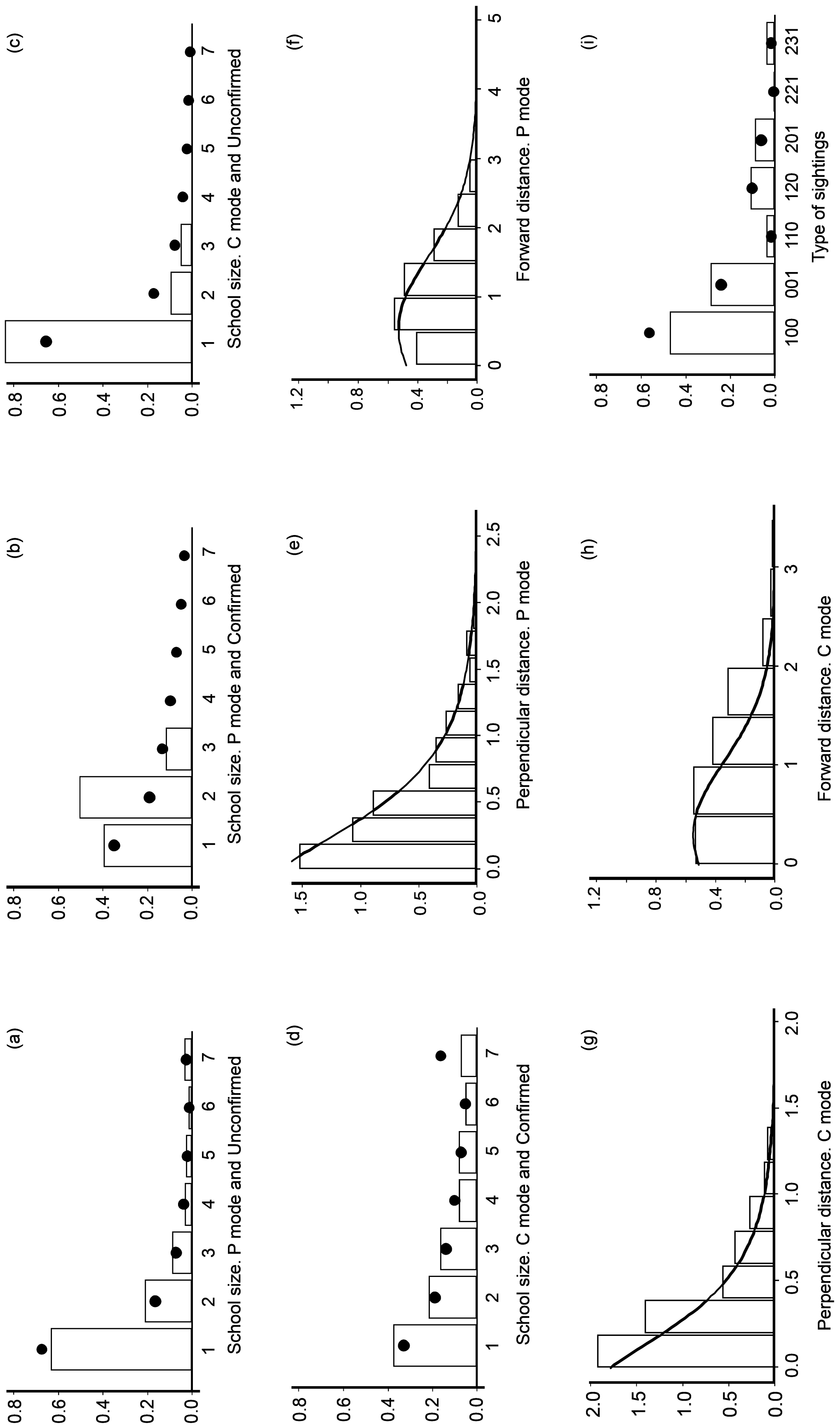

Fig. 2. The diagnostic plots for 1989/90 IDCR/SOWER data. Panels (a) to (d) show observed frequency of school size together with the model predicted frequency (●) under each survey mode and state of confirmation for observed school size. School sizes >6 were classed as size 7. Panels (e) to (h) show observed frequency of perpendicular and forward distance under each mode, with the model predicted frequency curves. Panel (g) shows frequency for the type of sightings, where 100 denotes a single detection by a CIP, 001 a single detection by a IIP, 110 a simultaneous duplicate, 120 $A \to B$ or $B \to A$, 201 $C \to A$ or $C \to B$, 221 $C \to A \times B$, and 231 $C \to A \to B$ or $C \to B \to A$. Frequency is scaled as a probability density, thus Σ the bar heights $\times$ bar widths =1.

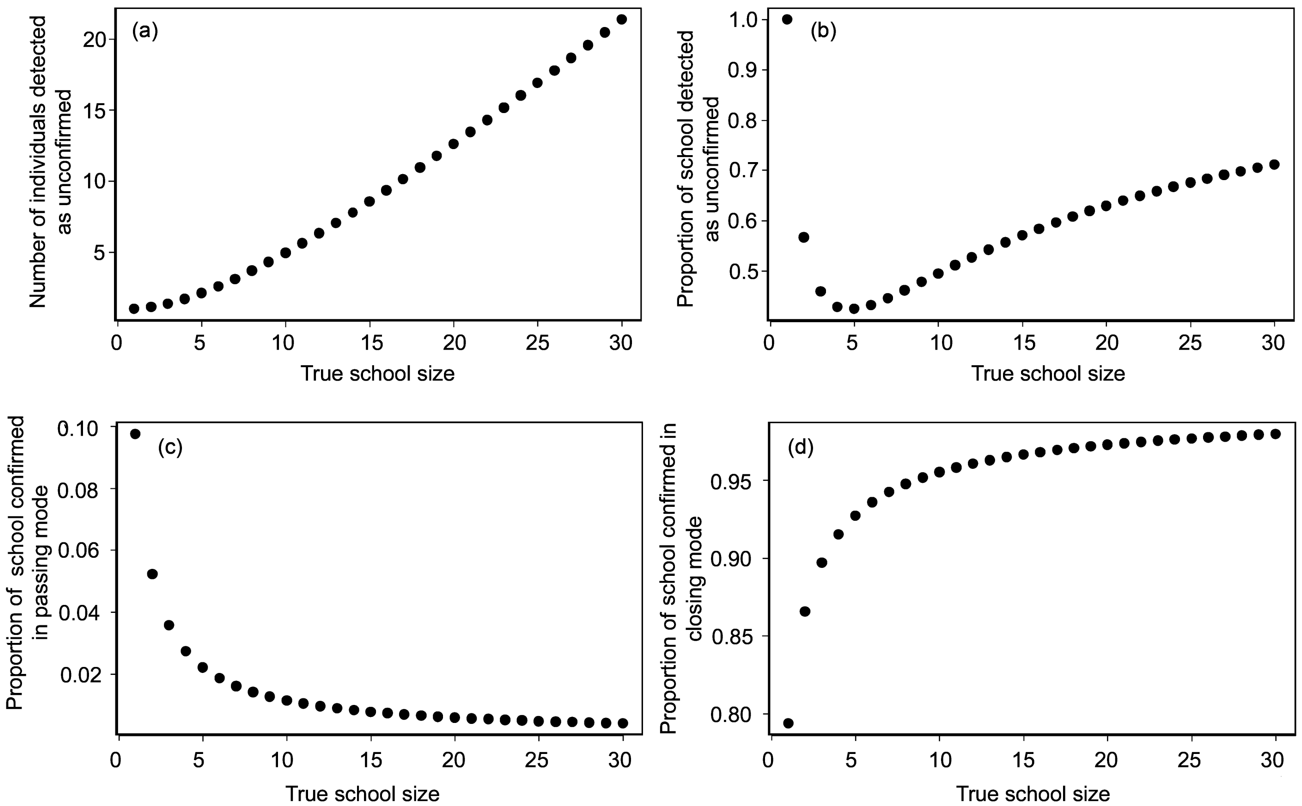

Fig. 3. Plots of the expected number of individuals (a) and proportions (b) confirmed in each school recorded as unconfirmed, and the expected proportion of each school confirmed in passing (c) and closing mode (d). All were plotted against true school size.

detection probability on the trackline of less than 1. It is essential to record sighting time and distance to whales as accurately as possible to correctly discriminate simultaneous and delayed duplicates after sighting surveys. The method proposed in this paper provides a basis for more refined methods for analysing such line transect sighting data. Since $g(0)$ and mean school size are closely related to each other (Cooke, 1985; Butterworth, 2002), the trend and abundance estimates in the population assessment can be miscalculated unless there is an appropriate allowance for bias in mean school size under passing mode. It is extremely important to obtain unbiased trends and abundance estimates for the proper conservation and management of marine resources.

ACKNOWLEDGMENTS

We thank K. Hiramatsu, D.S. Butterworth, K. Matsuoka, S.L. Hedley and M.V. Bravington for helpful discussions, and E. Ward and T. Branch for useful comments on an earlier manuscript. We also thank the officers and crew who participated in the IDCR/SOWER surveys. We are grateful for permission from the IWC office to use their data in this paper. Comments from two anonymous referees are greatly acknowledged.

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Date Received: April 2004
Date Accepted: September 2004

Appendix 1

HAZARD PROBABILITY MODEL

The hazard probability function $Q(x, y)$ is the conditional probability that a school of diving animals is detected by an observer on a sighting platform, given that it surfaced at a relative position (x, y) from a vessel and was not previously sighted by the observer, where x is the perpendicular distance, and y the forward distance in Cartesian co-ordinates. Because $Q(x, y)$ is a probability, $0 \leq Q(x, y) \leq 1$. The surfacing-diving pattern of a school of animals is modelled by a Poisson process. Then, the detection function is given by:

$$g(x) = 1 - \exp\{-(\lambda / v)\int_0^\infty Q(x, y)dy\} \qquad \text{(A1)}$$

where λ is surfacing intensity, and v is constant vessel speed (Butterworth, 1982; Cooke, 1997; Skaug and Schweder, 1999). The assumption of a Poisson process is probably robust for abundance estimation of animals with surfacing pattern such as minke whales (Cooke, 1997; Skaug and Schweder, 1999). In consideration of dependency of school size s on λ, we use the relationship, $\lambda = \lambda_1 e^{af(s)}$ where λ_1, is the surfacing intensity for a single animal and $f(s)$ is a function of school size s which has a value of 0 at $s = 1$.

The hazard probability function for a platform k ($k = A$ or B; observers are distinguished using the notation of A, B, … in this paper) is assumed to be:

$$Q_k(x, y) = \mu_k \exp\{-(x/\sigma_k)^{\gamma_1} - (y/\tau_k)^{\gamma_2}\} \qquad \text{(A2)}$$

where $0 < \mu_k < 1$, $\sigma_k > 0$, $\tau_k > 0$, γ_1, $\gamma_2 > 0$, μ_k is the level parameter of the hazard probability function, σ_k and τ_k are the scale parameters, and γ_1 and γ_2 are the shape parameters (Skaug and Schweder, 1999). The corresponding detection function from this hazard function is explicitly expressed as:

$$g_k(x) = 1 - \exp[-\lambda v^{-1} c_2^k \exp\{-(x/\sigma_k)^{\gamma_1}\}] \qquad \text{(A3)}$$

where $c_2^k = \tau_k \mu_k \gamma_2^{-1} \Gamma(\gamma_2^{-1})$, where Γ is the gamma function.

The probability density for the independent sighting data $\{(x_i, y_i, u_i), i = 1, \ldots, n\}$ is then given by:

$$\frac{p(x_i, y_i, u_i)}{esw_{A \cup B \cup C}} \qquad \text{(A4)}$$

where $p(x_i,y_i,u_i)$ is the detection probability given the initial sighting distance (x_i,y_i) and the pattern of detection u_i,

$esw_{A\cup B\cup C} = \int_0^\infty g_{A\cup B\cup C}(x)dx$,

$g_{A\cup B\cup C}(x) = 1 - \exp\{-(\lambda/v)\int_0^\infty Q_{A\cup B\cup C}(x, y)dy\}$,

$Q_{A\cup B\cup C} = 1-(1-Q_A)(1-Q_B)(1-Q_C)$, $Q_{AB} = Q_A Q_B$,

$Q_{ABC} = Q_A Q_B Q_C$ and etc (Okamura *et al.*, 2003).

For instance, when all three platforms see a school of animals, say, first C, then A and then B, let y_1, y_2, y_3 ($y_1 > y_2 > y_3$) be forward distances of each initial sighting, the probability function is given by:

$$p(x, y_1, y_2, y_3, C \to A \to B) = \left(\frac{\lambda}{v}\right)^3 Q_B(x, y_3)\{Q_A(x, y_2) - Q_{AB}(x, y_2)\}\{Q_C(x, y_1) - Q_{CA}(x, y_1) - Q_{CB}(x, y_1) + Q_{ABC}(x, y_1)\}$$
$$\times \exp\left(-\frac{\lambda}{v}\left[\begin{array}{l}\int_{y_3}^\infty Q_B(x, y')dy' + \int_{y_2}^\infty \{Q_{A\cup B}(x, y') - Q_B(x, y')\}dy' \\ + \int_{y_1}^\infty \{Q_{A\cup B\cup C}(x, y') - Q_{A\cup B}(x, y')\}dy'\end{array}\right]\right). \qquad \text{(A5)}$$

Appendix 2

CORRECTION FOR UNDERESTIMATION OF SCHOOL SIZE

Let the probability distribution of true school sizes in the region be $\pi(s)$, $s = 1, 2, 3, \ldots$. This distribution applies to all the schools in the population whether they are detected or not. For instance, as in Borchers (1999), it can be assumed that the school sizes have the probability distribution:

$$\Pr(s) = \pi(s) = \frac{\Gamma(\phi_0 + s - 1)}{\Gamma(\phi_0)\Gamma(s)}(1-\phi_1)^{s-1}\phi_1^{\phi_0}, \ \phi_0 > 0, \text{ and } 0 < \phi_1 < 1 \quad \text{(B1)}$$

where ϕ_0 is allowed to be continuous for flexibility following Borchers (1999). It should be noted that (B1) is a negative binomial distribution for $s - 1$ if ϕ_0 is an integer.

Let I be the indicator variable of the detection, i.e.

$$I = \begin{cases} 1, & \text{if detected} \\ 0, & \text{if missed} \end{cases} \quad \text{(B2)}$$

The detection probability of animals with school size s is then:

$$\Pr(I = 1 \mid s) = esw(s)/W \quad \text{(B3)}$$

Here $esw(s)$ is effective search half-width for a sighting with school size s and W is the maximum perpendicular distance from the transect line. The probability distribution of detected schools is then:

$$\Pr(s \mid I = 1) = \pi^*(s) = \frac{esw(s)\pi(s)}{\sum_{s=1}^{\infty} esw(s)\pi(s)} \quad \text{(B4)}$$

where W is cancelled out (Buckland *et al.*, 1993).

Taking into account negatively biased estimation for unconfirmed school sizes, it is further assumed that the observed unconfirmed school sizes (z) is less than true school size s and $E(z - 1 \mid I = 1, s) = b(s - 1)$, $0 < b < 1$. The parameter b is usually dependent on school size, environmental factors, and distance to sighting objects. Effects of covariates for the parameter b are incorporated through logistic link function, that is, $\mathrm{logit}(b) = a_0 + \Sigma a_i X_i$, where values of a are parameters and values of X are covariates. It is assumed that only school size s affects b, denoted $b(s)$, however it would be easy to incorporate environmental or other factors. A parametric probability distribution for unconfirmed school size z ($z = 1, 2, \ldots, s$) is then assumed to be:

$$\Pr(z \mid s) = \rho(z \mid s) = \frac{\Gamma(s)}{\Gamma(z)\Gamma(s-z+1)} b(s)^{z-1}\{1-b(s)\}^{s-z} \quad \text{(B5)}$$

This is the binomial density for $z - 1$ given true school size s. The probability distribution of observed school size, given it is detected and unconfirmed is then:

$$\Pr(z \mid I = 1) = \rho^*(z) = \frac{\sum_{s=z}^{\infty} \rho(z \mid s) esw(s)\pi(s)}{\sum_{s=1}^{\infty} esw(s)\pi(s)} \quad \text{(B6)}$$

where $\sum_{z=1}^{s}\sum_{s=z}^{\infty} \rho(z \mid s) esw(s)\pi(s) = \sum_{s=1}^{\infty} esw(s)\pi(s)$.

Equation (B6) implies that the mean of the unconfirmed school size minus 1 is equal to the mean of the confirmed school size minus 1 times the parameter b, i.e. $E_{\rho^*}(z - 1) = E_{\pi^*}\{b(s)(s - 1)\}$, where it is noted that the probability distributions are defined for $z - 1$ and $s - 1$. This is derived as follows:

$$E_{\rho^*}(z-1) = \sum_{z=1}^{\infty}(z-1)\rho^*(z) = \frac{\sum_{z=1}^{\infty}(z-1)\sum_{s=z}^{\infty}\rho(z \mid s) esw(s)\pi(s)}{\sum_{s=1}^{\infty} esw(s)\pi(s)}$$

$$= \frac{\sum_{s=1}^{\infty} esw(s)\pi(s)\sum_{z=1}^{s}(z-1)\rho(z \mid s)}{\sum_{s=1}^{\infty} esw(s)\pi(s)} = \frac{\sum_{s=1}^{\infty} esw(s)\pi(s)E(z-1 \mid I=1, s)}{\sum_{s=1}^{\infty} esw(s)\pi(s)}$$

$$= \frac{\sum_{s=1}^{\infty} b(s)(s-1) esw(s)\pi(s)}{\sum_{s=1}^{\infty} esw(s)\pi(s)} = E_{\pi^*}\{b(s)(s-1)\}$$

Therefore, $E_{\rho^*}(z)$ always has to be equal to or less than $E_{\pi^*}(s)$ because

$$E_{\rho^*}(z) - E_{\pi^*}(s) = E_{\pi^*}\{b(s)(s-1)\} + 1 - E_{\pi^*}(s)$$
$$= E_{\pi^*}[\{b(s)-1\}(s-1)] \le 0 \ (0 < b(s) < 1, \ s \ge 1).$$

Finally a model of school confirmation is needed because confirmation status can change due to school size and environmental factors. The output of confirmation status is a sequence of 'Bernoulli trials' where each trial gives one of two possible outcomes, labelled 0 (unconfirmed) and 1 (confirmed). By letting the additional random variable c represent the outcome of each trial and the parameter d represent the probability that the animal is confirmed, the probability of confirmation status in each trial is $d^c(1-d)^{1-c}$. Effects of covariates for the parameter d are incorporated through logistic link function. However, it is assumed that only school size s and survey mode t affects d and denotes $d_t(s)$, where $t = 1$ denotes passing mode and $t = 2$ closing mode.