# Abundance Estimates of Antarctic Minke Whales from the Historical IDCR/SOWER Survey Data Using the OK Method

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## ABSTRACT

This document presents the specifications of the OK method and the results on the estimation of the abundances of Antarctic minke whales from the historical IDCR/SOWER survey data. The method is based on a design-based approach with the revised hazard probability model, which was applied to the data obtained by the surveys from 1985/86 to 2003/04. The averaged values of $g(0)$ over all school sizes by taking heterogeneity into account were 0.47 for CPII and 0.53 for CPIII. The abundance for each management area was estimated using the "survey-once" method. The total abundances in the survey areas were 1,048,801 for CPII and 720,526 for CPIII without the common northern boundaries (CNB), and 1,086,588 for CPII and 665,074 for CPIII with introducing the CNB. Obviously, the advanced method with consideration of $g(0)$ estimation reduced the difference in comparison with the abundance estimates with $g(0) = 1$. In terms of the area-specific estimates, the differences between CPII and CPIII were quite small for Areas III, IV and VI, while those for Areas I, II, and V were large. These results clearly warrant necessity of future area-specific investigation.

## 1. INTRODUCTION

The International Decade of Cetacean Research - Southern Ocean Whale and Ecosystem Research (IDCR/SOWER) surveys have been conducted annually in the Antarctic since the 1970s. The sightings data of Southern Hemisphere minke whales (*Balaenoptera bonaerensis*) have been collected as one of main purposes of the IDCR/SOWER surveys. The sightings data consist of three circumpolar sets of cruises: 1978/79-1983/84 (1st circumpolar: CPI), 1985/86-1990/91 (2nd circumpolar: CPII), and 1991/92-2003/04 (3rd circumpolar: CPIII). The abundance estimates for Southern Hemisphere minke whales (*Balaenoptera bonaerensis*) were estimated by conventional line transect methods (Branch and Butterworth, 2001; Matsuoka et al., 2003; Branch, 2006). The abundance estimates for the 3rd circumpolar surveys obtained from the IDCR/SOWER data showed a dramatic decrease compared with the 2nd circumpolar surveys. Some members in the Scientific Committee of International Whaling Commission (IWC/SC) doubted whether it was the true decrease. Consequently, IWC/SC has listed a number of possible causes that might result in the change in estimates (IWC, 2002).

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 survey trackline, commonly called $g(0)$, is equal to 1. However, the diving behaviour of cetaceans can lead to this assumption being violated, even if the animal occurs on the trackline. Since minke whales are relatively small baleen whales, it is often difficult for observers on the sighting vessel to detect them so that $g(0)$ tends to be less than 1 (Schweder et al., 1997; Skaug et al., 2004; Okamura et al., 2005). IWC (2002) suggested that the difference of the abundance estimates of Branch and Butterworth (2001) would possibly be attributed to changes in $g(0)$ to some extent. Fortunately, the IDCR/SOWER surveys have conducted double-platform line transect sampling with independent observers, which gives the information needed to estimate $g(0)$. In this paper, we provide the revised abundance estimates of CPII and CPIII with $g(0)$ estimation by independent observer data.

There is a remarkable difference in mean school sizes between CPII and CPIII data (Branch and Butterworth, 2001; IWC, 2002). Mean school sizes could be overestimated if one uses a conventional line transect method with $g(0) = 1$ when $g(0)$ is in fact less than 1. Since $g(0)$ and mean school size are closely related to each other (Cooke, 1985; Butterworth, 2002), the trend and abundance estimates of Southern Hemisphere minke whales could be miscalculated unless there is an appropriate allowance for $g(0)$ and bias in mean school size. The survey effort of IDCR/SOWER surveys is divided into the Closing and Passing modes. In the 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. The Closing mode data therefore provide more accurate information on school size, while the Passing mode data are representative of double-platform line transect sightings collected by independent observers. Okamura et al. (2005) gave a basic model to estimate $g(0)$ and a school size distribution for IDCR/SOWER data dealing with the Closing and Passing mode data together in their analysis method. Okamura and Kitakado (2008a) modified their model and showed that it could provide relatively small bias of abundance estimates for the simulated data produced by IWC (Palka and Smith, 2004, 2005). We use the hazard probability model used in Okamura and Kitakado (2008a) for the real IDCR/SOWER datasets to estimate the abundance estimates. Since the real data are more complicated than the simulated data, we make a slight change on the model of Okamura and Kitakado (2008a) so that, for example, it includes the distance from the ice edge as a covariate.

The next section describes the data and the methodology used in this paper. Section 3 presents the results and discussion.

## 2. MATERIALS AND METHODS

### 2.1. The data

We use the IDCR/SOWER standard dataset extracted from DESS by M. L. Burt (July 27, 2005). We basically follow the procedure in Branch and Butterworth (2001, 2006) as far as possible to process data for analysis. However, when we have some differences in the procedure due to the difference of the analysis methods, we handle the data in a fashion unique to ourselves. For example, we use duplicate sightings to estimate $g(0)$ and confirmed school sizes in the Passing and Closing modes to estimate school size distribution unlike Branch and Butterworth (2001). The details of our procedure are given below.

#### Circumpolar set

We use 1985/86 - 2003/04 data, which correspond to CPII and CPIII.

#### Vessel Speed

The vessel speeds recorded in the effort records are used. Notice that they are not constant during the surveys. When the value is 888 (variable speed) or 999 (missing), we use the preset speed, 12 knot (before 1986/87) and 11.5 knot (after 1987/88).

**Survey effort**

The survey effort is calculated by the vessel speed times the traveled time in the effort records. We use all the data with different activity codes without excluding the codes "BH" and "BL" according to Branch (2006).

**Species**

We use data with the species code 04, 91, 92, 39. "Like minke" is included.

**Sea state**

We use a new category for simplicity in that 0-2 is good (0) and 3-5 is bad (1).

**Platform**

The original category is the following: 1 - topman in standard barrel, 2 - topman in IO position, 3 - upper bridge, primary observer, 4 - upper bridge, not primary observer, 5 - 1 and 4 simultaneously, 6 - 2 and 4 simultaneously.

We use a new category in that 1 & 5 $\rightarrow$ A, 2 & 6 $\rightarrow$ B, and 3 & 4 $\rightarrow$ C as in Appendix B.

**Sighting distances and angles**

Bias-corrected distances and angles are used. Angles are truncated at 90 degrees and transformed to radian. We use the perpendicular and forward distances transformed from the radial distances and angles in the analysis. The perpendicular distances transformed are truncated at 1.5 nautical miles, while the forward distances are not truncated.

**School size**

Best school size estimates are used.

**Duplicate**

Duplicate sightings in the IO-tracking searching under closing mode in 1987/88 are removed.

We adopt "definite" duplicates as the true duplicates under passing mode. When any covariate other than sighting distances and angles is different in a duplicate sighting, we conform to the following rules:

- School size: If confirmed school size is only one, we used the value. If there are multiple confirmed school sizes or no confirmed school size, we then used the value of the platform with the highest sighting position based on the notion that a topman was the most reliable.
- Confirmation status of school size: If we have at least one confirmed school size, it was defined as confirmed.
- Sea state: When the sea states were different, we adopted the sea state with the earlier record time.
- Vessel speed: When the vessel speed was different, we used the averaged value.

The case with different covariates by different platforms in a duplicate sighting is few and therefore the above minor adjustment will have little effect on abundance estimation.

**Truncation**

Perpendicular distances are truncated at 1.5 nautical miles according to conventional method (Branch and Butterworth, 2001). When the sightings are duplicates, we use the averaged distances for the simultaneous duplicates and the distances of later sightings for the delayed duplicates.

### 2.2. The hazard probability model and the likelihood function

The detection probability density function of the animal positioned at the perpendicular distance $x$ and the forward distance $y$ assuming a Poisson surfacing pattern with the mean surfacing rate $\lambda$ is

$$p(x,y) = \frac{\lambda}{v} Q(x,y) \exp\left\{ -\frac{\lambda}{v} \int_y^\infty Q(x,y')dy' \right\}, \tag{1}$$

where $v$ is the vessel speed, and $Q(x,y)$ is a hazard probability function based on a logistic function (Appendix A). The parameters in Eq. (1) are linked to various factors such as school size, weather condition (Beaufort Sea State), platform type, circumpolar set, and survey area, which are potentially important on abundance estimation (Appendices A and B). We use 6 point Gaussian integration for all the integrals hereafter. In addition, we replace $\sum_{s=1}^{\infty}$ by $\sum_{s=1}^{s_{max}}$ with $s_{max} = 30$ for the application to the real data.

We construct a likelihood function conditioned on detection patterns and confirmation status of school size (Appendix B). For the confirmed school size, the likelihood function is

$$P_C(x_i, y_i, u_i, s_i) = \frac{c_k p_k(x_i, y_i, u_i | s_i)\pi(s_i)}{\mathrm{esw}_k}, \tag{2}$$

and for the unconfirmed school size, the likelihood function is

$$P_U(x_i, y_i, u_i, z_i) = \frac{\displaystyle\sum_{s=1}^{\infty}(1-c_k)\rho(z_i|s)p_k(x_i, y_i, u_i|s)\pi(s)}{\mathrm{esw}_k}, \tag{3}$$

where $k$ is an index that denotes Passing/Closing mode, $c_k$ is the probability of school size confirmation dependent on some covariates such as true school size, $\rho(z_i|s)$ is the probability that the school size is recorded as $z_i$ given the true school size is $s$ and the observed school size $z_i$ is unconfirmed. $u_i$ is a type of detection pattern, $p_k$ is a detection probability density function given the mode $k$ and the detection pattern $u_i$, and $\pi(s)$ is a probability mass function of true school size, and $\mathrm{esw}_k$ is

$$\mathrm{esw}_k = \int_0^{x_{max}} \int_0^\infty \sum_{s=1}^{\infty} \sum_{u}^{\text{all patterns}} p_k(x,y,u|s)\pi(s)dxdy. \tag{4}$$

For the simplification of calculation, when $z_i \geq z_{max}$, the above probability for the unconfirmed school size is modified to

$$P_U(x_i, y_i, u_i, z_i \geq z_{max}) = \frac{\displaystyle\sum_{s=1}^{\infty}(1-c_k)\{1 - \sum_{z=1}^{z_{max}-1} \rho(z|s)\}p_k(x_i, y_i, u_i|s)\pi(s)}{\mathrm{esw}_k}. \tag{5}$$

The mean value of true school size distribution, $\pi(s)$, is linked to the interaction of circumpolar set and survey area, and the logarithm of distance from the ice edge (Appendix C). The confirmation probability is dependent on survey mode, weather condition, perpendicular distance (for Passing mode) and radial distance (for Closing mode) (Appendix C).

The total likelihood function is then given by

$$L = \prod_{i=1}^{n_C} P_C(x_i, y_i, u_i, s_i) \times \prod_{i=1}^{n_U} P_U(x_i, y_i, u_i, z_i), \tag{6}$$

where $n_C$ and $n_U$ are the numbers of the sightings with confirmed and unconfirmed school size, respectively. We estimate parameters by maximizing the logarithm of the total likelihood function.

**2.3. Abundance estimation**

We use only the Passing mode data in abundance estimation to circumvent possible biases that the Closing mode data involve (Kishino and Kasamatsu, 1987; Branch and Butterworth, 2001), while we use both of the Closing and Passing mode data for parameter estimation as above mentioned. The population size is then estimated with a Horvitz-Thompson-like estimator,

$$\hat{P} = \frac{A}{2L} \sum_{i=1}^{n_P} \frac{\phi_0(\eta_i) + \phi_1(\eta_i)}{\sum_{s=1}^{\infty} \hat{\mathrm{esw}}_{A \cup B \cup C}(s|\eta_i)\hat{\pi}(s|\eta_i)}, \tag{7}$$

where $n_P$ is the number of the sightings in the Passing mode, $L$ is total survey distance, $A$ is the size of survey area, $\eta_i$ is a vector of covariates except for school sizes, and the numerator corresponds to the mean school size derived from a parametric distribution of school size (Appendix C).

An estimator for the unconditional asymptotic variance of $\hat{P}$ is then

$$\hat{\mathrm{var}}(\hat{P}) = \left[ \left\{ \frac{d\hat{P}(\theta)}{d\theta} \right\}^T I(\theta)^{-1} \frac{d\hat{P}(\theta)}{d\theta} \right]_{\theta=\hat{\theta}} + \frac{A^2}{J-1} \sum_{j=1}^{J} \frac{l_j}{L} (\hat{D}_j - D)^2, \tag{8}$$

where $\theta$ is a vector of estimated parameters, $I(\theta)$ is the Fisher information matrix obtained from the second derivative of the log-likelihood function that is often substituted by the Hessian matrix, and $l_j$ ($j = 1, \ldots, J$; $\sum l_j = L$) is a replicated line. $\hat{D}_j$ is the density on replicate line $j$. If there is no sighting on replicate line $j$, $\hat{D}_j$ is defined as being equal to zero.

When the abundance estimates are obtained by strata, taking account of common estimated parameters across strata, the abundance estimate and its variance for the whole area are given by

$$\hat{P}_{\text{all strata}} = \sum_h A_h \hat{D}_h, \tag{9}$$

$$\hat{\mathrm{var}}(\hat{P}_{\text{all strata}}) = \left[ \left\{ \frac{d\hat{P}_{\text{all strata}}(\theta)}{d\theta} \right\}^T I(\theta)^{-1} \frac{d\hat{P}_{\text{all strata}}(\theta)}{d\theta} \right]_{\theta=\hat{\theta}} + \sum_h \frac{A_h^2}{J_h - 1} \sum_{j=1}^{J_h} \frac{l_{j,h}}{L_h} (\hat{D}_{j,h} - D_h)^2, \tag{10}$$

where the subscript $h$ is the index of stratum.

The covariance between abundance estimates with different years taking account of common parameters is calculated by

$$\hat{\mathrm{cov}}(\hat{P}_1, \hat{P}_2) = \left[ \left\{ \frac{d\hat{P}_1(\theta)}{d\theta} \right\}^T I(\theta)^{-1} \frac{d\hat{P}_2(\theta)}{d\theta} \right]_{\theta=\hat{\theta}}, \tag{11}$$

where the subscripts denote different years and areas. The correlation matrix is obtained from the estimated variances and covariances.

## 3. RESULTS AND DISCUSSION

We used the model given in Appendices A-C for abundance estimation. The model was slightly modified according to the comments made in the SOWER abundance workshop (IWC, 2008). For example, the forward distances were not truncated and the model used a parametric model of bias in unconfirmed school size. Apart from these modifications, a prominent feature of the model is a novel handling of errors in recorded times. Okamura and Kitakado (2007a) suggested that the errors of recorded times could have a relatively big impact on abundance estimation. The model of Appendices A-C takes account of such errors of recorded times and performed well for the simulated data. This method can also cope with various problems such as large errors of sighting distances in duplicates presented in Okamura et al. (2003, 2005).

Vessel speeds, school sizes, weather conditions, platforms, circumpolar sets, Areas, and distances from the ice edge were employed as the covariates or the factors. See the Appendices for the mathematical details. Any formal model selection was not carried out because of time constraint. However, the basic formulation of the model we used is the same as the model we used in the simulation tests, which performed very well for the simulated data (Okamura and Kitakado, 2008a).

The SOWER abundance workshop listed necessary diagnostic plots (IWC, 2008). The diagnostic plots will be presented in our accompanying paper (Okamura and Kitakado, 2008b).

Table 1a shows $g(0)$s and esws categorized by the circumpolar sets and true school sizes. The $g(0)$s and esws of CPII were smaller than those of CPIII. The $g(0)$s for schools were 0.47 and 0.53 for CPII and CPIII, respectively. The $g(0)$s for single animals were less than 0.5, while the $g(0)$s for groups with more than 9 animals were close to 1. Table 1b shows $g(0)$s categorized by the platforms and true school sizes. The $g(0)$s and esws for the upper bridge were the highest. This reason is probably that the upper bridge has many observers.

Table 2 shows the predicted observed school size distribution by true school sizes and perpendicular distance classes. Almost 60% consisted of single animals in the shortest distance category, while single animals were less than 30% in the distances with more than 0.9 n.miles.

Tables 3-8 provide $g(0)$s, mean school sizes, esws for schools and whales, abundance estimates, densities, and their CVs estimated by stratum. Likewise Table 1, the $g(0)$s and esws were smaller for CPII compared with CPIII. However, since mean school sizes estimated from the model became smaller than the observed ones, the effects of $g(0)$ and esw were a bit offset by the trade-off relationship between the mean school size and $g(0)$ (Cooke, 1985; Butterworth, 2002). For example, in the survey of Area III in 1987/88, Branch (2006) gave 3.29 to 4.77 for mean school sizes, and 0.574 to 0.505 for esws, while our result in the same area and year is ca. 1.69 to 1.78 for mean school sizes and ca. 0.24 to 0.30 for esws. Notice that this is not rigorous comparison, since Branch (2006) used the confirmed sightings in Closing mode only to estimate mean school size while we used the confirmed sightings in both Passing and Closing modes, our detection model was different from that of Branch (2006), and so on.

Table 9 shows abundance estimates and densities of CPII and CPIII for Management Areas using the "survey-once" method (Branch, 2005; Branch and Butterworth, 2006) with and without the Common Northern Boundaries (CNB: IWC, 2008). We did not use the analysis option of extrapolation for unsurveyed areas as in Branch and Butterworth (2001) and Branch (2006), since the simple extrapolation might distort the true difference. For example, simple extrapolation to the unsurveyed areas using estimated densities in surveyed areas would overestimate the abundance of CPII.

With or Without the CNB, the overall trends were similar in general. The total abundances in the survey areas were 1,048,801 for CPII and 720,526 for CPIII without the common northern boundaries (CNB), and 1,086,588 for CPII and 665,074 for CPIII with introducing the CNB. The corresponding ratio of total abundances of CPII:CPIII was 1.00:0.69 without the CNB and 1.00:0.61 with the CNB. This shows that the method with consideration of $g(0)$ estimation reduces the difference in comparison with the abundance estimates with $g(0) = 1$ given by Branch and Butterworth (2001) and Branch (2006). In terms of the area-specific estimates, the differences between CPII and CPIII were quite small for Areas III, IV and VI, while those for Areas I, II, and V were large. The abundances in Area I for CPIII were considerably low. This reason is that the abundance estimates in 1999/2000 used in the "survey-once" method are extremely low compared with the abundance estimates within the corresponding areas in 1993/94. If we use the abundances of whole survey in 1993/94 excluding the 1999/2000 survey, the total abundance in Area I for CPIII exceeds 100,000 animals.

Excluding Area I, in terms of both abundance and density, Areas II and V showed a considerably bigger decline than other areas (Table 9). Since Areas II and V have the Weddell Sea and the Ross Sea respectively, a big polynia tends to be made up. It is important to develop a method to estimate the proportion of minke whales residing in the pack ice. In fact, when we remove abundance estimates of Areas II and V which tend to be influenced by the sea ice on a large scale because of the complex coastlines, the ratio for total abundances of CPII:CPIII becomes 1.00:0.87 without the CNB and 1.00:0.77 with the CNB. These results clearly warrant necessity of future area-specific investigation. In addition, the difference of total abundances must be investigated taking account of the uncertainty such as the additional variances (Kitakado and Okamura, 2005; Kitakado and Okamura, 2008).

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**Appendix A detection probability function of sighting cues**

The hazard probability model is given by a logistic form,

$$Q(x,y) = \frac{1}{1+\exp[\sigma(\tau_x x^{\gamma_x} + \tau_y y^{\gamma_y}) + \omega]} \tag{A.1}$$

where $\sigma$, $\tau_x$, $\tau_y$, $\gamma_x$, and $\gamma_y$ are scalar parameters with positive values. The parameter $\omega$ is related to several covariates with a log-link function as follows:

$\log(\sigma) \sim \log(\text{School.size}) + \text{Weather}$,

$\omega \sim \log(\text{School.size}) + \text{Weather} + \text{Platform} + \text{Circumpolar.set} + \text{Area}$.

In addition, the surfacing rate $\lambda$ in Eq. (1) is modeled to be a function of school size,

$\log(\lambda) \sim \log(\text{School.size})$,

where the coefficient of log(School.size) is constrained to be positive.

**Appendix B Specification of detection function for each sighting pattern**

There are three platforms with two independent observers and one semi-independent observer in the Passing mode while there are two platforms with no independent observer in the Closing mode. The detection pattern in the Passing mode is therefore complicated by taking account of duplicate sightings.

**B-1. Passing mode**

Passing mode has three sighting platforms, the top barrel and the IO booth with independent observers, and the upper bridge with semi-independent observers or researchers. We can have information needed to estimate $g(0)$ from the sighting patterns of independent observers (Schweder et al., 1997; Cooke, 1997; Cooke, 2001; Okamura et al., 2003, 2005). The probability density function for each sighting pattern is given below. The contribution to the likelihood function of detection with each sighting pattern is calculated by each probability density times the probability mass density of school size (Appendix C) divided by $\text{esw}_{A\cup B\cup C}$ when school sizes are confirmed. When school sizes are unconfirmed, the numerator is summed up over all school sizes. $\text{esw}_{A\cup B\cup C}$ is given by

$$\begin{aligned}\text{esw}_{A\cup B\cup C} = \sum_{s=1}^{\infty} \Bigg[ \int_0^{x_{max}} \int_0^{\infty} \frac{\lambda}{v} Q_{A\cup B\cup C}(x,y|s) \\ \times \exp\left\{-\frac{\lambda}{v}\int_y^{\infty} Q_{A\cup B\cup C}(x,y'|s)dy'\right\} dxdy \Bigg] \pi(s),\end{aligned} \tag{B.1}$$

which is equal to Eq. (4) when $k$ = Passing mode.

We have two distances by independent observers in the delayed duplicates. We use the averaged distances for the simultaneous duplicates and the distances of the latter sightings for the delayed duplicates, since the latter sightings tend to have the distances closer to the vessel which are generally likely to be more accurate. The distances of the first sightings are calculated by adding the vessel speeds times the differences of the recorded times between the two sightings to the distances of the latter sightings.

In the IDCR/SOWER surveys before 1988/89, the sighting time was recorded in a "minute" unit, and "second" was omitted. We therefore add to the model to apply to the data before 1988/89 the additional sturcture taking account of uncertainty by rounding the sighting time to the nearest minute.

1. $A$

$$p(x,y,A) = \frac{\lambda}{v}\left\{Q_{A\cup B}(x,y) - Q_B(x,y)\right\}\exp\left\{-\frac{\lambda}{v}\int_0^y Q_B(x,y')dy'\right\}$$
$$\times \exp\left[-\frac{\lambda}{v}\left\{\int_y^\infty Q_{A\cup B}(x,y')dy' + \int_{y+vT}^\infty Q_{A\cup B\cup C\setminus A\cup B}(x,y')dy'\right\}\right], \tag{B.2}$$

where $T = 90/3600$h (before 1988/89) and $T = 60/3600$h (after 1989/90).

2. $B$

Same as $A$ except for exchanging the symbols $A$ and $B$.

3. $C$

$$p(x,y,C) = \frac{\lambda}{v}\left\{Q_{A\cup B\cup C}(x,y) - Q_{A\cup B}(x,y)\right\}$$
$$\times \exp\left[-\frac{\lambda}{v}\left\{\int_0^y Q_{A\cup B}(x,y')dy' + \int_y^\infty Q_{A\cup B\cup C}(x,y')dy'\right\}\right]. \tag{B.3}$$

4. $A \times B$

$$p(x,y,AB) = \frac{\lambda}{v}\Bigg(Q_A(x,y)Q_B(x,y)\exp\left\{-\frac{\lambda}{v}\int_y^\infty Q_{A\cup B}(x,y')dy'\right\}$$
$$+Q_A(x,y)\exp\left\{-\frac{\lambda}{v}\int_y^\infty Q_A(x,y')dy'\right\}$$
$$\times\left[\exp\left\{-\frac{\lambda}{v}\int_{y+vT}^\infty Q_{A\cup B\setminus A}(x,y')dy'\right\} - \exp\left\{-\frac{\lambda}{v}\int_y^\infty Q_{A\cup B\setminus A}(x,y')dy'\right\}\right]$$
$$+Q_B(x,y)\exp\left\{-\frac{\lambda}{v}\int_y^\infty Q_B(x,y')dy'\right\}$$
$$\times\left[\exp\left\{-\frac{\lambda}{v}\int_{y+vT}^\infty Q_{A\cup B\setminus B}(x,y')dy'\right\} - \exp\left\{-\frac{\lambda}{v}\int_y^\infty Q_{A\cup B\setminus B}(x,y')dy'\right\}\right]\Bigg) \tag{B.4}$$

where $T = 90/3600$h (before 1988/89) and $T = 60/3600$h (after 1989/90).

5. $A \to B$

For the dataset before 1988/89,

$$p(x,y,A\to B) = \frac{\lambda}{v}$$
$$\times\left[\exp\left\{-\frac{\lambda}{v}\int_{y+v(\tau_{AB}+T)}^\infty Q_{A\cup B\setminus B}(x,y')dy'\right\} - \exp\left\{-\frac{\lambda}{v}\int_{y+v(\tau_{AB}-T)}^\infty Q_{A\cup B\setminus B}(x,y')dy'\right\}\right]$$
$$\times Q_B(x,y)\exp\left\{-\frac{\lambda}{v}\int_y^\infty Q_B(x,y')dy'\right\} \tag{B.5}$$

where $T = 30/3600$h and $\tau_{AB} \geq 120/3600$h.

For the dataset after 1989/90,

$$
\begin{aligned}
p(x,y,A\to B) &= \left(\frac{\lambda}{v}\right)^2 Q_B(x,y)\{Q_{A\cup B}(x,y+v\tau_{AB})-Q_B(x,y+v\tau_{AB})\}\\
&\times\exp\left[-\frac{\lambda}{v}\left\{\int_{y+v\tau_{AB}}^{\infty} Q_{A\cup B\setminus B}(x,y')dy' + \int_y^{\infty} Q_B(x,y')dy'\right\}\right]
\end{aligned}
\tag{B.6}
$$

where $\tau_{AB} > 60/3600$h.

6. $B \to A$

Same as $A \to B$ for exchanging the symbols $A$ and $B$.

7. $C \to A$

For the dataset before 1988/89,

$$
\begin{aligned}
p(x,y,C\to A) = \frac{\lambda}{v}&\left[\exp\left\{-\frac{\lambda}{v}\int_{y+v(\tau_{CA}+T)}^{\infty} Q_{A\cup B\cup C\setminus A\cup B}(x,y')dy'\right\} - \right.\\
&\left.\exp\left\{-\frac{\lambda}{v}\int_{y+v(\tau_{CA}-T)}^{\infty} Q_{A\cup B\cup C\setminus A\cup B}(x,y')dy'\right\}\right]\\
&\times\{Q_{A\cup B}(x,y)-Q_B(x,y)\}\\
&\exp\left[-\frac{\lambda}{v}\left\{\int_y^{\infty} Q_{A\cup B}(x,y')dy' + \int_0^{y} Q_B(x,y')dy'\right\}\right]
\end{aligned}
\tag{B.7}
$$

where $T = 30/3600$h and $\tau_{AB} \geq 120/3600$h.

For the dataset after 1989/90,

$$
\begin{aligned}
p(x,y,C\to A) &= \left(\frac{\lambda}{v}\right)^2 \{Q_{A\cup B}(x,y)-Q_B(x,y)\}\\
&\times\{Q_{A\cup B\cup C}(x,y+v\tau_{CA})-Q_{A\cup B}(x,y+v\tau_{CA})\}\\
&\times\exp\left\{-\frac{\lambda}{v}\int_{y+v\tau_{CA}}^{\infty} Q_{A\cup B\cup C\setminus A\cup B}(x,y')dy'\right\}\\
&\times\exp\left[-\frac{\lambda}{v}\left\{\int_y^{\infty} Q_{A\cup B}(x,y')dy' + \int_0^{y} Q_B(x,y')dy'\right\}\right]
\end{aligned}
\tag{B.8}
$$

where $\tau_{CA} > 60/3600$h.

8. $C \to B$

Same as $C \to A$ for exchanging the symbols $A$ and $B$.

**B-2. Closing mode**

We have two platforms, top barrel and upper bridge, for Closing mode. Once any observer on either platform detect the animal, the sighting is communicated to other observers by the researcher immediately. Hence, there are no duplicates in the Closing mode. The detection function is given by

$$
p(x,y,A\cup C) = \frac{\lambda}{v}Q_{A\cup C}(x,y)\exp\left\{-\frac{\lambda}{v}\int_y^{\infty} Q_{A\cup C}(x,y')dy'\right\}. \tag{B.9}
$$

The contribution to the likelihood function of detection with each sighting pattern is calculated by the above probability density times the probability mass density of school size (Appendix C) divided by $\mathrm{esw}_{A\cup C}$ when school sizes are confirmed. When school sizes are unconfirmed, the numerator is summed up over all school sizes. $\mathrm{esw}_{A\cup C}$ is given by

$$\mathrm{esw}_{A\cup C} = \sum_{s=1}^{\infty}\left[\int_0^{x_{xmax}}\int_0^{\infty}\frac{\lambda}{v}Q_{A\cup C}(x,y|s)\right.$$
$$\left.\times\ \exp\left\{-\frac{\lambda}{v}\int_y^{\infty}Q_{A\cup C}(x,y'|s)dy'\right\}dxdy\right]\pi(s), \tag{B.10}$$

which is equal to Eq. (4) when $k$ = Closing mode.

**Appendix C Scool size distribution**

The probability mass function of true school size is given by a truncated negative binomial distribution,

$$\pi(s) = \frac{\Gamma(\phi_0+s-1)}{\Gamma(\phi_0)\Gamma(s)}\left(1-\frac{\phi_0}{\phi_0+\phi_1}\right)^{s-1}\left(\frac{\phi_0}{\phi_0+\phi_1}\right)^{\phi_0}, \tag{C.1}$$

where $\phi_0 > 0$, $\phi_1 > 0$, and the parameter $\phi_1$ is linked to the following covariates,

$\log(\phi_1) \sim$ Circumpolar.set $\times$ Area + $\log(d_{\text{ice}} + 1.0)$,

where $d_{\text{ice}}$ is the distance from the ice edge, which is used to represent the latitudinal gradient of school size. Note that $\mathrm{E}(s) = \phi_1 + 1$.

The probability mass function of unconfirmed school size given true school size is also given by a truncated Poisson distribution,

$$\rho(z|s) = \frac{\mu^{z-1}\exp(-\mu)}{\Gamma(z)}, \tag{C.2}$$

where $\mu = \beta(s-1) > 0$ and the parameter $\beta$ is linked to the following covariates,

$\log(\beta) \sim$ Survey.mode.

Note that $\mathrm{E}(z) = \mu + 1$.

The probability of confirmation status $c_k$, which is given separately for each survey mode, is linked to the following covariates,

$\mathrm{logit}(c_k) \sim \log(s) + \sqrt{x^2+y^2}$ + Weather (for Closing mode),

$\mathrm{logit}(c_k) \sim \log(s) + x$ + Weather (for Passing mode).

Table 1. The summary of g(0)s and esws for schools and whales using the Passing mode data. The upper panel shows the values categorized by the circumpolar sets and true school size classes, while the lower panel shows the values categorized by the weather conditions and true school size classes. The subscripts "s" and "w" denote schools and whales. The subscripts "A", "B", and "C" denote Topman, IO person, and Upper bridge, respectively.

a) categorized by CP and true school size

| CP | School size | all | 1 | 2 | 3-4 | 5-9 | 10+ |
|---|---|---|---|---|---|---|---|
| CPII | $g(0)_s$ | 0.473 | 0.392 | 0.579 | 0.713 | 0.840 | 0.929 |
| | $g(0)_w$ | 0.597 | 0.392 | 0.579 | 0.717 | 0.846 | 0.933 |
| | $esw_s$ | 0.273 | 0.166 | 0.351 | 0.566 | 0.882 | 1.216 |
| | $esw_w$ | 0.475 | 0.166 | 0.351 | 0.576 | 0.903 | 1.234 |
| CPIII | $g(0)_s$ | 0.532 | 0.458 | 0.645 | 0.767 | 0.875 | 0.946 |
| | $g(0)_w$ | 0.640 | 0.458 | 0.645 | 0.772 | 0.881 | 0.948 |
| | $esw_s$ | 0.316 | 0.205 | 0.420 | 0.655 | 0.975 | 1.278 |
| | $esw_w$ | 0.516 | 0.205 | 0.420 | 0.665 | 0.995 | 1.292 |

b) categorized by weather condition and true school size: only g(0)s for schools by platform

| Weather | School size | all | 1 | 2 | 3-4 | 5-9 | 10+ |
|---|---|---|---|---|---|---|---|
| good | $g_A(0)_s$ | 0.296 | 0.223 | 0.373 | 0.509 | 0.675 | 0.829 |
| | $g_B(0)_s$ | 0.208 | 0.147 | 0.261 | 0.379 | 0.545 | 0.733 |
| | $g_C(0)_s$ | 0.334 | 0.262 | 0.414 | 0.542 | 0.694 | 0.836 |
| bad | $g_A(0)_s$ | 0.249 | 0.184 | 0.316 | 0.444 | 0.612 | 0.784 |
| | $g_B(0)_s$ | 0.172 | 0.120 | 0.216 | 0.322 | 0.479 | 0.674 |
| | $g_C(0)_s$ | 0.286 | 0.221 | 0.359 | 0.482 | 0.635 | 0.792 |

Table 2. Predicted observed school size distribution by true school sizes (1-10) and perpendicular distance using the Passing mode data.

| | perpendicular distance | | | | |
|---|---|---|---|---|---|
| | 0.0-0.3 | 0.3-0.6 | 0.6-0.9 | 0.9-1.2 | 1.2-1.5 |
| school size | | | | | |
| 1 | 0.569 | 0.470 | 0.378 | 0.299 | 0.235 |
| 2 | 0.160 | 0.170 | 0.170 | 0.160 | 0.147 |
| 3 | 0.091 | 0.110 | 0.124 | 0.130 | 0.131 |
| 4 | 0.057 | 0.075 | 0.091 | 0.103 | 0.110 |
| 5 | 0.038 | 0.051 | 0.066 | 0.079 | 0.089 |
| 6 | 0.025 | 0.036 | 0.047 | 0.059 | 0.070 |
| 7 | 0.017 | 0.025 | 0.034 | 0.044 | 0.054 |
| 8 | 0.012 | 0.018 | 0.025 | 0.033 | 0.041 |
| 9 | 0.008 | 0.012 | 0.018 | 0.024 | 0.031 |
| 10 | 0.006 | 0.009 | 0.013 | 0.018 | 0.023 |

Table 3. Abundance estimates of minke whales obtained from the Passing mode data in Area 1 using the strata boundaries in the standard dataset. See the thext for the detailed explanation of parameters. The symbols used in this table denote the following:

Area: stratum area (n.miles2)
L: Line length (primary search effort, n.miles)
nL: number of transects
ns: number of schools sighted (primary effort)
E(s): estimated mean school size
g0: g(0) for the combined platforms
$esw_s$: effective strip-half width for schools by the combined platforms
$esw_w$: effective strip-half width for whales bythe combined platforms
P: abundance estimate
D: density of whales
CV: coefficient of variation of abundance estimate

| **Area 1** | Stratum | Area | L | nL | ns | E(s) | g0 | $esw_s$ | $esw_w$ | P | D | CV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CP II | | | | | | | | | | | | |
| 1989/90 | EN | 153,029 | 750.2 | 7 | 60 | 1.555 | 0.421 | 0.224 | 0.373 | 43,008 | 0.281 | 0.236 |
| | ESBA | 62,594 | 821.1 | 14 | 74 | 1.624 | 0.423 | 0.229 | 0.394 | 20,309 | 0.324 | 0.428 |
| | WN | 168,761 | 577.9 | 6 | 35 | 1.572 | 0.410 | 0.213 | 0.361 | 38,059 | 0.226 | 0.557 |
| | WS | 45,128 | 830.9 | 15 | 214 | 1.622 | 0.433 | 0.240 | 0.409 | 39,937 | 0.885 | 0.194 |
| | Total | 429,512 | 2980.1 | 42 | 383 | | | | | 141,314 | 0.329 | 0.185 |
| CP III | | | | | | | | | | | | |
| 1993/94 | EN | 293,196 | 749.6 | 10 | 17 | 1.560 | 0.450 | 0.235 | 0.388 | 22,040 | 0.075 | 0.752 |
| | ES | 72,249 | 544.8 | 9 | 84 | 1.599 | 0.470 | 0.262 | 0.432 | 34,563 | 0.478 | 0.366 |
| | WN | 251,735 | 459.6 | 8 | 9 | 1.542 | 0.480 | 0.270 | 0.429 | 14,267 | 0.057 | 0.236 |
| | WS | 50,596 | 566.6 | 12 | 80 | 1.611 | 0.461 | 0.249 | 0.419 | 23,194 | 0.458 | 0.154 |
| | Total | 667,776 | 2320.6 | 39 | 190 | | | | | 94,064 | 0.141 | 0.260 |
| 1999/00 | EN | 57,309 | 241.1 | 5 | 9 | 1.556 | 0.449 | 0.234 | 0.386 | 7,105 | 0.124 | 0.349 |
| | ES | 23,632 | 179.8 | 7 | 9 | 1.616 | 0.468 | 0.265 | 0.439 | 3,662 | 0.155 | 0.195 |
| | WN | 110,906 | 349.9 | 6 | 2 | 1.549 | 0.445 | 0.232 | 0.381 | 2,120 | 0.019 | 0.619 |
| | WS | 20,506 | 243.0 | 7 | 7 | 1.604 | 0.477 | 0.265 | 0.438 | 1,820 | 0.089 | 0.377 |
| | Total | 212,353 | 1013.8 | 25 | 27 | | | | | 14,707 | 0.069 | 0.274 |
| 2000/01 | EN | 127,789 | 378.3 | 12 | 2 | 1.550 | 0.466 | 0.244 | 0.398 | 2,144 | 0.017 | 0.510 |
| | ES | 29,080 | 303.8 | 10 | 19 | 1.593 | 0.442 | 0.233 | 0.392 | 6,220 | 0.214 | 0.309 |
| | Total | 156,869 | 682.2 | 22 | 21 | | | | | 8,364 | 0.053 | 0.283 |

Table 4. Abundance estimates of minke whales obtained from the Passing mode data in Area 2 using the strata boundaries in the standard dataset. The symbols are the same as in the caption of Table 1.

| **Area 2** | Stratum | Area | L | nL | ns | E(s) | g0 | $esw_s$ | $esw_w$ | P | D | CV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CP II | | | | | | | | | | | | |
| 1986/87 | EBAY | 15,242 | 125.8 | 4 | 40 | 2.060 | 0.564 | 0.386 | 0.685 | 12,923 | 0.848 | 0.358 |
| | EM | 69,908 | 431.2 | 5 | 75 | 1.953 | 0.508 | 0.306 | 0.565 | 38,931 | 0.557 | 0.196 |
| | EN | 124,057 | 427.7 | 3 | 45 | 1.922 | 0.504 | 0.300 | 0.552 | 41,897 | 0.338 | 0.375 |
| | ES1 | 23,142 | 277.4 | 5 | 20 | 2.026 | 0.511 | 0.310 | 0.584 | 5,449 | 0.235 | 0.622 |
| | ES2 | 44,975 | 710.0 | 16 | 114 | 2.015 | 0.541 | 0.352 | 0.635 | 20,861 | 0.464 | 0.259 |
| | WBAY | 11,505 | 31.8 | 1 | 11 | 1.994 | 0.508 | 0.306 | 0.573 | 12,965 | 1.127 | 0.038 |
| | WN | 95,361 | 201.0 | 2 | 2 | 1.943 | 0.558 | 0.374 | 0.649 | 2,466 | 0.026 | 1.111 |
| | WS1 | 10,270 | 91.7 | 2 | 14 | 1.978 | 0.507 | 0.304 | 0.568 | 5,096 | 0.496 | 0.429 |
| | WS2 | 21,143 | 259.6 | 5 | 7 | 1.997 | 0.512 | 0.309 | 0.578 | 1,842 | 0.087 | 0.205 |
| | WS3 | 79,605 | 839.0 | 14 | 82 | 1.986 | 0.535 | 0.344 | 0.619 | 22,743 | 0.286 | 0.243 |
| | Total | 495,208 | 3395.1 | 57 | 410 | | | | | 165,175 | 0.334 | 0.122 |
| CP III | | | | | | | | | | | | |
| 1996/97 | EN | 241,928 | 660.7 | 17 | 25 | 1.455 | 0.551 | 0.310 | 0.453 | 21,667 | 0.090 | 0.319 |
| | ES | 67,072 | 665.6 | 18 | 37 | 1.515 | 0.581 | 0.356 | 0.525 | 8,031 | 0.120 | 0.372 |
| | WN | 113,687 | 194.0 | 5 | 8 | 1.446 | 0.545 | 0.301 | 0.440 | 11,322 | 0.100 | 0.716 |
| | WS | 23,028 | 230.0 | 8 | 40 | 1.516 | 0.577 | 0.347 | 0.514 | 8,867 | 0.385 | 0.210 |
| | Total | 445,715 | 1750.3 | 48 | 110 | | | | | 49,888 | 0.112 | 0.255 |
| 1997/98 | ES1 | 47,036 | 385.2 | 8 | 48 | 1.514 | 0.557 | 0.319 | 0.480 | 14,018 | 0.298 | 0.468 |
| | ES2 | 10,451 | 142.8 | 5 | 24 | 1.532 | 0.555 | 0.319 | 0.486 | 4,246 | 0.406 | 0.727 |
| | WN | 52,135 | 253.3 | 4 | 5 | 1.473 | 0.567 | 0.330 | 0.482 | 2,335 | 0.045 | 0.304 |
| | WS | 32,620 | 303.2 | 10 | 1 | 1.500 | 0.527 | 0.289 | 0.440 | 280 | 0.009 | 0.918 |
| | EN1 | 84,726 | 345.1 | 7 | 9 | 1.472 | 0.565 | 0.334 | 0.486 | 4,921 | 0.058 | 0.255 |
| | EN2 | 80,013 | 258.6 | 4 | 7 | 1.457 | 0.558 | 0.328 | 0.475 | 4,864 | 0.061 | 0.396 |
| | Total | 306,981 | 1688.3 | 38 | 94 | | | | | 30,664 | 0.100 | 0.332 |
| 1999/00 | ENA | 7,361 | 34.2 | 2 | 0 | - | - | - | | 0 | 0 | - |
| | ESA | 6,494 | 54.6 | 2 | 0 | - | - | - | | 0 | 0 | - |
| | Total | 13,855 | 88.8 | 4 | 0 | | | | | 0 | 0 | - |

Table 5. Abundance estimates of minke whales obtained from the Passing mode data in Area 3 using the strata boundaries in the standard dataset. The symbols are the same as in the caption of Table 1.

| **Area 3** | | Area | L | nL | ns | E(s) | g0 | $esw_s$ | $esw_w$ | P | D | CV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CP II | | | | | | | | | | | | |
| 1987/88 | EN | 168,881 | 514.5 | 7 | 8 | 1.692 | 0.444 | 0.239 | 0.425 | 9,283 | 0.055 | 0.450 |
| | ES | 87,677 | 666.3 | 8 | 48 | 1.778 | 0.494 | 0.302 | 0.528 | 18,733 | 0.214 | 0.476 |
| | WN | 148,821 | 358.0 | 7 | 35 | 1.697 | 0.466 | 0.267 | 0.462 | 46,887 | 0.315 | 0.485 |
| | WS | 74,351 | 486.9 | 9 | 121 | 1.752 | 0.463 | 0.264 | 0.471 | 61,922 | 0.833 | 0.210 |
| | Total | 479,730 | 2025.8 | 31 | 212 | | | | | 136,825 | 0.285 | 0.202 |
| CP III | | | | | | | | | | | | |
| 1992/93 | EN | 150,547 | 562.2 | 5 | 10 | 1.555 | 0.505 | 0.286 | 0.452 | 7,382 | 0.049 | 0.508 |
| | ES | 23,207 | 478.3 | 12 | 18 | 1.613 | 0.531 | 0.327 | 0.518 | 2,152 | 0.093 | 0.362 |
| | WN | 210,035 | 784.3 | 8 | 42 | 1.566 | 0.500 | 0.278 | 0.445 | 32,025 | 0.152 | 0.349 |
| | WS | 61,527 | 893.7 | 15 | 157 | 1.606 | 0.516 | 0.302 | 0.485 | 29,136 | 0.474 | 0.205 |
| | Total | 445,316 | 2718.4 | 40 | 227 | | | | | 70,694 | 0.159 | 0.188 |
| 1994/95 | WN | 148,803 | 457.9 | 7 | 21 | 1.557 | 0.488 | 0.265 | 0.426 | 20,179 | 0.136 | 0.346 |
| | WS | 51,938 | 505.3 | 11 | 52 | 1.603 | 0.502 | 0.284 | 0.461 | 15,276 | 0.294 | 0.446 |
| | PRYD | 21,096 | 203.5 | 4 | 48 | 1.618 | 0.488 | 0.266 | 0.443 | 15,123 | 0.717 | 0.310 |
| | ESW | 33,854 | 234.2 | 4 | 32 | 1.601 | 0.501 | 0.280 | 0.456 | 13,391 | 0.396 | 0.509 |
| | ENW | 69,342 | 318.0 | 4 | 17 | 1.565 | 0.496 | 0.273 | 0.438 | 10,712 | 0.154 | 0.508 |
| | Total | 325,033 | 1718.8 | 30 | 170 | | | | | 74,681 | 0.230 | 0.199 |

Table 6. Abundance estimates of minke whales obtained from the Passing mode data in Area 4 using the strata boundaries in the standard dataset. The symbols are the same as in the caption of Table 1.

| **Area 4** | | Area | L | nL | ns | E(s) | g0 | $esw_s$ | $esw_w$ | P | D | CV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CP II | | | | | | | | | | | | |
| 1988/89 | BN | 17,486 | 412.9 | 12 | 28 | 1.672 | 0.389 | 0.202 | 0.368 | 4,908 | 0.281 | 0.229 |
| | BS | 6,520 | 144.5 | 3 | 50 | 1.704 | 0.392 | 0.206 | 0.380 | 9,351 | 1.434 | 0.790 |
| | EN | 181,166 | 606.0 | 6 | 17 | 1.633 | 0.389 | 0.201 | 0.358 | 20,733 | 0.114 | 0.263 |
| | ES | 52,441 | 255.8 | 7 | 49 | 1.725 | 0.415 | 0.233 | 0.422 | 37,825 | 0.721 | 0.242 |
| | WN | 156,617 | 716.6 | 7 | 5 | 1.650 | 0.385 | 0.198 | 0.358 | 4,551 | 0.029 | 0.396 |
| | WS | 58,693 | 245.7 | 5 | 23 | 1.662 | 0.393 | 0.207 | 0.372 | 22,249 | 0.379 | 0.360 |
| | Total | 472,923 | 2381.6 | 40 | 172 | | | | | 99,617 | 0.211 | 0.160 |
| CP III | | | | | | | | | | | | |
| 1994/95 | ESE | 26,192 | 225.3 | 4 | 17 | 1.525 | 0.430 | 0.219 | 0.359 | 6,887 | 0.263 | 0.605 |
| | ENE | 77,339 | 312.7 | 4 | 5 | 1.502 | 0.420 | 0.212 | 0.343 | 4,385 | 0.057 | 0.410 |
| | Total | 103,531 | 538.0 | 8 | 22 | | | | | 11,272 | 0.109 | 0.522 |
| 1998/99 | EN | 169,387 | 578.7 | 14 | 21 | 1.499 | 0.440 | 0.233 | 0.370 | 20,134 | 0.119 | 0.229 |
| | ES | 70,193 | 685.9 | 25 | 34 | 1.538 | 0.441 | 0.238 | 0.386 | 11,399 | 0.162 | 0.175 |
| | WN | 105,396 | 377.9 | 10 | 29 | 1.515 | 0.420 | 0.213 | 0.348 | 28,786 | 0.273 | 1.034 |
| | WS | 42,605 | 472.4 | 15 | 32 | 1.548 | 0.446 | 0.239 | 0.390 | 9,498 | 0.223 | 0.336 |
| | Total | 387,581 | 2114.8 | 64 | 116 | | | | | 69,817 | 0.180 | 0.433 |

Table 7. Abundance estimates of minke whales obtained from the Passing mode data in Area 5 using the strata boundaries in the standard dataset. The symbols are the same as in the caption of Table 1.

| **Area 5** | | Area | L | nL | ns | E(s) | g0 | $esw_s$ | $esw_w$ | P | D | CV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CP II | | | | | | | | | | | | |
| 1985/86 | EM | 165,912 | 1041.2 | 10 | 182 | 1.694 | 0.500 | 0.294 | 0.495 | 84685 | 0.510 | 0.310 |
| | EN | 279,611 | 844.0 | 8 | 68 | 1.657 | 0.477 | 0.264 | 0.448 | 70972 | 0.254 | 0.329 |
| | ES | 107,717 | 739.2 | 8 | 191 | 1.692 | 0.507 | 0.291 | 0.493 | 81743.8 | 0.759 | 0.275 |
| | WM | 166,349 | 492.0 | 4 | 53 | 1.660 | 0.485 | 0.275 | 0.463 | 54645.7 | 0.329 | 0.529 |
| | WN | 139,065 | 357.6 | 3 | 59 | 1.642 | 0.487 | 0.275 | 0.459 | 69149 | 0.497 | 0.467 |
| | WS | 104,814 | 647.6 | 13 | 103 | 1.705 | 0.492 | 0.285 | 0.486 | 50475.4 | 0.482 | 0.146 |
| | Total | 963,468 | 4121.6 | 46 | 656 | | | | | 411,671 | 0.427 | 0.146 |
| CP III | | | | | | | | | | | | |
| 1991/92 | EN | 165,429 | 505.8 | 8 | 118 | 1.813 | 0.557 | 0.338 | 0.579 | 103,971 | 0.628 | 0.188 |
| | ES | 82,039 | 687.5 | 10 | 106 | 1.851 | 0.578 | 0.371 | 0.626 | 31,935 | 0.389 | 0.375 |
| | WN | 137,734 | 337.1 | 5 | 9 | 1.811 | 0.562 | 0.345 | 0.587 | 9,714 | 0.071 | 0.755 |
| | WS | 58,643 | 470.8 | 5 | 174 | 1.833 | 0.558 | 0.341 | 0.586 | 58,602 | 0.999 | 0.513 |
| | Total | 443,845 | 2001.3 | 28 | 407 | | | | | 204,223 | 0.460 | 0.188 |
| 2001/02 | EN | 83,082 | 295.0 | 4 | 4 | 1.753 | 0.540 | 0.316 | 0.538 | 3,120 | 0.038 | 0.391 |
| | ES | 26,099 | 231.9 | 8 | 39 | 1.828 | 0.592 | 0.387 | 0.640 | 10,491 | 0.402 | 0.283 |
| | WN | 46,333 | 184.1 | 3 | 4 | 1.749 | 0.557 | 0.338 | 0.564 | 2,627 | 0.057 | 0.770 |
| | WS | 34,886 | 301.6 | 11 | 25 | 1.840 | 0.576 | 0.357 | 0.609 | 7,497 | 0.215 | 0.495 |
| | Total | 190,400 | 1012.7 | 26 | 72 | | | | | 23,736 | 0.125 | 0.228 |
| 2002/03 | EN | 135,038 | 541.3 | 16 | 16 | 1.731 | 0.583 | 0.366 | 0.594 | 9,544 | 0.071 | 0.164 |
| | ES | 126,870 | 536.0 | 12 | 39 | 1.807 | 0.588 | 0.385 | 0.633 | 21,881 | 0.172 | 0.413 |
| | W1N | 75,395 | 244.6 | 7 | 25 | 1.747 | 0.582 | 0.358 | 0.589 | 19,026 | 0.252 | 0.191 |
| | W1S | 101,237 | 228.5 | 7 | 27 | 1.828 | 0.595 | 0.394 | 0.648 | 28,016 | 0.277 | 0.244 |
| | W2N | 22,128 | 284.4 | 9 | 13 | 1.774 | 0.562 | 0.340 | 0.573 | 2,650 | 0.120 | 0.436 |
| | W2S | 21,327 | 257.1 | 14 | 20 | 1.821 | 0.575 | 0.350 | 0.596 | 4,358 | 0.204 | 0.182 |
| | Total | 481,995 | 2091.9 | 65 | 140 | | | | | 85,476 | 0.177 | 0.143 |
| 2003/04 | MID | 131,782 | 909.9 | 21 | 235 | 1.792 | 0.575 | 0.361 | 0.601 | 85,796 | 0.651 | 0.189 |
| | N1 | 123,227 | 167.7 | 7 | 4 | 1.730 | 0.603 | 0.381 | 0.613 | 6,741 | 0.055 | 0.425 |
| | N2 | 95,445 | 288.7 | 9 | 25 | 1.783 | 0.605 | 0.404 | 0.650 | 18,361 | 0.192 | 0.467 |
| | N3 | 14,598 | 112.6 | 4 | 42 | 1.812 | 0.565 | 0.353 | 0.596 | 14,124 | 0.967 | 0.162 |
| | ROSS | 56,444 | 575.8 | 19 | 139 | 1.819 | 0.572 | 0.365 | 0.612 | 34,343 | 0.608 | 0.119 |
| | Total | 421,496 | 2054.6 | 60 | 445 | | | | | 159,364 | 0.378 | 0.124 |

Table 8. Abundance estimates of minke whales obtained from the Passing mode data in Area 6 using the strata boundaries in the standard dataset. The symbols are the same as in the caption of Table 1.

| **Area 6** | | Area | L | nL | ns | E(s) | g0 | $esw_s$ | $esw_w$ | P | D | CV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CP II | | | | | | | | | | | | |
| 1990/91 | EN | 191,954 | 473.6 | 4 | 24 | 1.455 | 0.415 | 0.204 | 0.322 | 34,726 | 0.181 | 0.604 |
| | ES | 108,268 | 476.3 | 4 | 27 | 1.497 | 0.408 | 0.205 | 0.333 | 22,484 | 0.208 | 0.318 |
| | WN | 211,788 | 551.4 | 4 | 19 | 1.461 | 0.405 | 0.200 | 0.317 | 26,741 | 0.126 | 0.371 |
| | WS | 45,414 | 645.9 | 9 | 42 | 1.525 | 0.426 | 0.222 | 0.363 | 10,248 | 0.226 | 0.222 |
| | Total | 557,424 | 2147.2 | 21 | 112 | | | | | 94,199 | 0.169 | 0.263 |
| CP III | | | | | | | | | | | | |
| 1995/96 | EN | 242,073 | 533.5 | 11 | 32 | 1.353 | 0.465 | 0.239 | 0.339 | 41,695 | 0.172 | 0.242 |
| | ES | 72,349 | 561.8 | 10 | 46 | 1.384 | 0.469 | 0.244 | 0.354 | 17,010 | 0.235 | 0.289 |
| | WN | 97,945 | 280.3 | 5 | 13 | 1.355 | 0.448 | 0.219 | 0.316 | 14,030 | 0.143 | 0.327 |
| | WS | 34,051 | 314.1 | 9 | 5 | 1.383 | 0.462 | 0.236 | 0.344 | 1,603 | 0.047 | 0.288 |
| | Total | 446,418 | 1689.7 | 35 | 96 | | | | | 74,338 | 0.167 | 0.178 |
| 2000/01 | WN | 252,078 | 459.2 | 13 | 18 | 1.350 | 0.465 | 0.238 | 0.337 | 28,411 | 0.113 | 0.314 |
| | WS | 43,916 | 417.6 | 17 | 48 | 1.391 | 0.487 | 0.268 | 0.384 | 13,369 | 0.304 | 0.216 |
| | Total | 295,994 | 876.8 | 30 | 66 | | | | | 39,071 | 0.132 | 0.243 |

Table 9. Summary of abundance estimates for Management Areas with and without the common northern boundary (CNB) using the 'survey-once' method.

| Without CNB | Area | I | II | III | IV | V | VI | Total |
|---|---|---|---|---|---|---|---|---|
| CP II | Area size | 429,512 | 495,208 | 479,730 | 472,923 | 963,468 | 557,424 | 3,398,265 |
| | Abundance | **141,314** | **165,175** | **136,825** | **99,617** | **411,671** | **94,199** | 1,048,801 |
| | Density | 0.329 | 0.334 | 0.285 | 0.211 | 0.427 | 0.169 | 0.309 |
| | CV | 0.184 | 0.122 | 0.203 | 0.171 | 0.146 | 0.260 | 0.078 |
| CP III | Area size | 816,025 | 684,452 | 770,349 | 491,112 | 828,014 | 742,412 | 4,332,364 |
| | Abundance | **67,408** | **74,033** | **145,376** | **81,088** | **236,503** | **116,118** | 720,526 |
| | Density | 0.083 | 0.108 | 0.189 | 0.165 | 0.286 | 0.156 | 0.166 |
| | CV | 0.157 | 0.231 | 0.136 | 0.392 | 0.094 | 0.144 | 0.088 |

| With CNB | Area | I | II | III | IV | V | VI | Total |
|---|---|---|---|---|---|---|---|---|
| CP II | Area size | 429,512 | 478,848 | 479,731 | 472,924 | 924,798 | 557,424 | 3,343,235 |
| | Abundance | **148,336** | **146,082** | **122,427** | **107,929** | **465,490** | **96,324** | 1,086,588 |
| | Density | 0.345 | 0.305 | 0.255 | 0.228 | 0.503 | 0.173 | 0.325 |
| | CV | 0.192 | 0.108 | 0.197 | 0.210 | 0.109 | 0.219 | 0.071 |
| CP III | Area size | 400,280 | 569,019 | 451,690 | 455,522 | 828,260 | 698,565 | 3,403,337 |
| | Abundance | **57,215** | **70,132** | **116,706** | **74,213** | **228,731** | **118,076** | 665,074 |
| | Density | 0.143 | 0.123 | 0.258 | 0.163 | 0.276 | 0.169 | 0.195 |
| | CV | 0.148 | 0.188 | 0.133 | 0.330 | 0.105 | 0.147 | 0.072 |