Current abundance of minke whales in the northeastern Atlantic; variability in time and space

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February 21, 2003

Abstract

Spatially partial sighting surveys with two independent observers on each vessel were conducted each year from 1996 to 2001. Northern minke whales are mostly solitary animals and they are only available for observation when they surface to breath. Thus, a stochastic point process model is developed for how the data are generated. The hazard probability of initially sighting a whale that surfaces depends on relative spatial coordinates and on other covariates. The parameters of the model are estimated by maximum likelihood. To account for inter-annual variation in spatial distribution of minke whales, a random effects model is developed, and estimated by comparing current and past (1989 and 1995) survey data. A simulation approach is taken to remove bias from parameter estimates, and to assess the uncertainty in the results. For total abundance, the result is a log-normal confidence distribution with quantiles $107, 205 \cdot \exp(0.137 \cdot z)$ i.e. an abundance estimate of $107, 205$ with a $cv \approx 0.14$. Together with these and earlier survey data, past data on catch, mark-recapture, and satellite tracking are reviewed to elucidate distribution- and migration patterns in northeastern Atlantic minke whales.

1 Introduction

Minke whales are found throughout the North Atlantic although their main distribution is thought to be over continental shelf areas, particularly on its edge. They undertake feeding migrations northwards in the spring and then enter the northeast Atlantic areas. Their winter distribution in the North Atlantic is poorly known, as there are few sighting records from that time of the year. Wintering minke whales in the North Atlantic have been reported from the northern coasts, from the Gulf of Mexico and south of Bermuda (Horwood 1990).

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Schweder et al. (1997) presented two independent abundance estimates of northeastern Atlantic minke whales, one based on a shipborne sighting surveys conducted in 1988 and 1989, and one estimate based on a double platform shipborne survey carried out in 1995. They also reviewed attempts previous to 1988 to estimate minke abundance in the region. Here, we present an abundance estimate based on a series of partial sightings surveys conducted in the period 1996-2001.

The abundance estimates presented in this paper came about in the context of regulating Norwegian minke whaling. The aim has been to provide abundance estimates that, together with the catch series, are acceptable to the Scientific Committee as input to the Revised Management Procedure (RMP) of the IWC (International Whaling Commission, 1994b, 1994a). The estimates presented here are slight modifications of those in Skaug et al. (2002). These modifications are due to inclusion of additional data on surfacing rates in northern minke whales, and also to some minor changes in methodology. Thus, we present abundance estimate for each of five IWC Small Areas (Fig. 1) in addition to an estimate for the total survey area.

The surveys in 1996 to 2001 are visual line transect surveys with independent observer platforms. Northeast Atlantic minke whales are mostly solitary on their feeding grounds in the north (Øien 1989, Sigurjonsson et al. 1989), and they are only observable in the short moments (ca 2 seconds) when they surface to breathe between their dives (mean diving time ca 80 seconds). They are therefore regarded to show discrete availability in the visual survey, i.e. they are observable only at discrete points in time. Following Schweder (1974, 1977), we model the sighting process as a point process in space, representing the locations of the individual whales, and in time, representing the surfacings of the whale, and a sequence of Bernoulli experiments representing whether the animal was observed or not at the given surfacing. The success probability of these Bernoulli experiments is called the hazard probability since it is the conditional probability of sighting given that the observer previously was unaware of the animal. The hazard probability depends on the position of the whale relative to the observer, but also on other variables such as the sea state (Beaufort), visibility, glare, etc. Buckland et al. (2001) present ‘standard’ line transect methodology and its history. A key assumption for standard line transect methods is that the probability of sighting an animal located on the transect line is \( g(0) = 1 \). Due to the discrete availability, \( g(0) < 1 \) in visual line transecting of northeastern Atlantic minke whales. To estimate \( g(0) \) and the effective strip half-width, the surveys are conducted with independent observers.

The observers are placed on separate platforms without audible or visual contact. Butterworth et al. (1982) were the first to realize that data from independent observers can be used to estimate effective strip half-width when \( g(0) < 1 \). Schweder & Høst (1992) were the first to apply hazard probability methods with independent observers in animal abundance estimation. Schweder et al. (1996), Cooke (1997), Schweder et al. (1997) and Schweder et al. (1999) have further developed the methodology.

The abundance of minke whales feeding in the North Atlantic, and its temporal and spatial distribution, is of interest for ecological, fisheries management and whaling management reasons, among others. In addition to results pertinent to temporal and spatial distribution over the survey period 1996 – 2001, we present a review of what is known of the broader temporal and spatial distribution of minke whales that summer feed in
2 Material and methods

2.1 Data collection 1996-2001

2.1.1 Surveys

During the period 1996-2001 the survey has covered the northeastern Atlantic, i.e. the northern North Sea, the Norwegian Sea, the Greenland Sea and the Barents Sea (Fig. 1). While the North and Barents Seas are shelf waters with typical average depths of about 100m and 230m respectively, the Norwegian and Greenland Seas are oceans with deep basins of several thousands meter. The eastern part of the Norwegian Sea was surveyed in 1996, the western Norwegian Sea in 1997, the North Sea in 1998, the Greenland Sea with adjacent shelf areas of Svalbard in 1999, and the Barents Sea in 2000 and 2001.

The total survey area was divided into blocks (see Fig. 2) based on feasibility surveys conducted in the 1980-ies, and information extracted from catch data which have been collected since 1938 when a licence system was introduced for Norwegian small-type whaling. Areas with assumed uniform densities were defined, also taking into consideration topographical and oceanographic features. The survey effort available within a specific block was divided between two transects to ensure at least one full coverage. Transects were constructed as zig-zag tracks with a random starting point (Fig. 2). Realised track lengths in different survey blocks are given in Table 1.

The speed of the vessel was logged on a regular basis, as well as data on sighting conditions. The intended speed was 10 knots. In addition to the ordinary survey activity, distance and angle estimation experiments were conducted. In these experiments, the survey vessel was operated in the ordinary modus, while the observers were instructed to estimate distance and angle to a stationary buoy, which exact position could be determined from the vessel’s radar. Further details about the partial surveys are given in by Skaug et al. (2002).

Data on surfacing rates for minke whales have been collected by use of VHF radio tagging. The data used are the same as in previous studies (Schweder et al. 1997). In addition, surfacing data from five minke whales were collected in 2001 and 2002. Most of the tagged whales were sampled in near coastal waters within Small Areas EC and ES, in addition there is one whale from the North Sea (EN) and one whale from the Norwegian Sea (EB)

2.1.2 Observational routines

Observations of whales were made by naked eye from two platforms: A (the barrel) and platform B (the wheelhouse roof), each manned by a team consisting of two individual observers. Each vessel had 4 such observer teams working 2-hour shifts. With a few exceptions, the composition of teams did not change within a specific year. Most observers had experience from earlier surveys, and the majority of observers participated in all of
the years 1996-2001. Within a team, one of the observers was instructed to scan the port 45° sector, while the other scanned the starboard 45° sector.

The unit of observation was a track of observed surfacings, with estimated time and relative position (radial distance $r$ and sighting angle $\theta$) recorded for every sighted surfacing. Radial distances were estimated visually, while sighting angles were measured using an angle board. Time was measured automatically when a button was pushed to allow the relative position to be recorded on a tape. A track represents the sighted surfacings judged by the observer to belong to the same whale. For a certain proportion of observations the position was incompletely recorded, i.e. either the radial distance $r$ or the angle between the sighting line and the track line $\theta$ was missing. This proportion was much lower for the initial sightings than for re-sightings. Because distance estimation is uncertain at long distances, only observations for which $r \leq 2000$ meters (and $|\theta| < 90^\circ$) were included in the analysis below. Similarly, because detection probabilities at short distances may vary substantially across platforms, observations for which $r \leq 100$ meters were left out.

In addition to information directly related to sightings of whales, data on environmental conditions were recorded. These were weather conditions, visibility, glare and Beaufort state. These variables were categorized as shown in Table 2. Individual observers were grouped into three categories according to their ability to detect whales at long distance. This classification was based on the general impression that the cruise leaders had gained during the surveys, and was based as little as possible on the actual data. On this basis every combination of observers into teams that had occurred in the survey was classified as either “Long” or “Short” (see Skaug et al. (2002) for further details). The proportion of realized effort time (sum over both platforms) with Long-teams was 60%.

Two teams were concurrently on watch. One team could not be seen or heard from the other platform. Both teams reported to the cruise leader, but they were not informed of sightings made by others. The two teams were thus independent.

2.2 Statistical methodology 1996–2001

The first step in the analysis is to match tracks from the two platforms that correspond to the same whale. This matching is performed by an automatic routine which mainly acts on recorded times. Then the parameters of the hazard probability function are estimated by maximizing the likelihood of the observed data, disregarding matching errors and other complications. A bias correction procedure is applied to the resulting parameter estimates to account for matching errors, measurement error in $r$ and $\theta$, etc. Finally, the effective search area is calculated from the estimated model, and abundance estimates are obtained by equating whale density in the whole survey stratum with observed whale density over the estimated effective search area. The bias correction of parameter estimates is conducted by simulating the survey under realistic assumptions, and for a sequence of parameter vectors. Simulations also provide standard errors on parameter estimates. Bias corrected abundance estimates and coefficients of variation for each of the yearly surveys are also obtained from simulations, as are confidence distributions of abundance representing confidence intervals at arbitrary levels. Finally, a combined abundance estimate for the northeast Atlantic stock of minke whales is obtained from the sequence of partial
yearly surveys. In addition to the sampling variability inherent in the partial surveys, there is a component of variation due to varying spatial minke whale distribution over the years 1996–2001, when the partial abundance estimates are combined to an abundance estimate for the entire stock. This additional variance is obtained by fitting a random effects model representing the changes in spatial distribution of the stock over the survey area and period.

2.2.1 Matching tracks

The likelihood to be developed below is based on matched pairs of tracks supposedly representing the same whale seen from the two platforms, and on single tracks without any match. Identification of matching tracks, and matching surfacings within tracks, is done by an automatic routine (Schweder et al. 1997). The reason for using an automatic routine is that it can be applied to numerous replicates of simulated survey data. The automatic routine occasionally makes mistakes that are easy to spot for the human eye, and hence it was found necessary to augment the matching results for the real data with a small number of manually judged duplicates.

Consider a matched pair or an unmatched track. The process of extracting data used in the estimation is depicted in Figure 3. A joint initial sighting is the first observed surfacing of a whale, sighted either by platform A, B, or by both platforms simultaneously. For each joint initial sighting there is an associated trinomial trial. The outcome of the trial is denoted by \( u \), and the different outcomes are \( u = A \) (seen from platform A only), \( u = B \) (seen from platform B only) or \( u = AB \) (seen from both platforms simultaneously).

Situations where one of the platforms detects the whale before the other (\( u = A \) or \( u = B \)) provide additional information on the conditional detection probability. Assume for simplicity that platform A detects the whale before platform B, as exemplified in Figure 3. Then, each subsequent surfacing detected by A sets up a Bernoulli trial with outcomes: seen/not seen by platform B. The initial sighting in the A-track does not count as a Bernoulli trial since it is included as a trinomial trial. Trials are only registered until the first success for platform B occurs.

2.2.2 Hazard probability model

The starting point for the standard line transect theory (Buckland et al. 2001) is the detection function \( g(x) \), defined as the probability that an animal located at perpendicular distance \( x \) from the transect line is detected. From an estimate of \( g(x) \) one can obtain an estimate of the effective strip half-width:

\[
    w = \int_0^\infty g(x) \, dx,
\]

which is the key parameter in the abundance estimation. For animals with discrete availability it is possible to start the modelling at a more fundamental level, that is, we can model the probability of detecting individual surfacings. Let the hazard probability function \( Q(r, \theta) \) be defined as the probability of sighting a whale that makes a surfacing at position \((r, \theta)\), given that the observer is previously unaware of the whale. The other component of the hazard probability model is the (stochastic) point process that governs
the availability of individual whales for detection, i.e. the surfacing process. As shown below, the surfacing process together with $Q$ determine $g(x)$, and hence the $w$, as well as the probability density for the position of an initial sighting of a whale.

Consider first a single platform with hazard probability function $Q$. Denote by $f(r, \theta)$ the spatial probability density of the position of an initial sighting. Mathematically it is simpler to work with Cartesian coordinates $(x, y) = (r \sin(\theta), r \cos(\theta))$, rather than with polar coordinates $(r, \theta)$. Under the assumption that dive times follow a Poisson point process with intensity $\alpha$ it may be shown (Schweder et al. 1996) that

$$f(x, y) = w^{-1} \frac{\alpha}{v} Q(r_{x,y}, \theta_{x,y}) \cdot \exp \left\{ -\frac{\alpha}{v} \int_0^\infty Q(r_{x,u}, \theta_{x,u}) \, du \right\},$$

where $v$ is the vessel speed, $w$ is the effective strip half-width, $r_{x,y} = \sqrt{x^2 + y^2}$ and $\theta_{x,y} = \arctan(x/y)$. Since $\int f(x, y) \, dxdy = 1$ it follows that

$$w = \int_0^\infty \left[ 1 - \exp \left\{ -\frac{\alpha}{v} \int_0^\infty Q(r_{x,y}, \theta_{x,y}) \, dy \right\} \right] \, dx.$$

When there are two independent platforms A and B, with separate hazard probability function $Q^A$ and $Q^B$, the hazard probability of the combined platform $A \cup B$ is

$$Q^{A \cup B}(r, \theta) = 1 - \left( 1 - Q^A(r, \theta) \right) \left( 1 - Q^B(r, \theta) \right).$$

Expressions for $f(r, \theta)$ and $w$ for the combined platform $A \cup B$ are obtained by substituting $Q^{A \cup B}$ into (1) and (2), respectively. Each whale sighted by $A \cup B$ sets up an experiment with trinomial outcome $u \in \{A, B, AB\}$, as explained above. Conditionally on the position $(r, \theta)$ the probability distribution of $u$ is

$$q(u) = \left\{ Q^{A \cup B}(r, \theta) \right\}^{-1} \cdot \begin{cases} Q^A(r, \theta) \{1 - Q^B(r, \theta)\}, & u = A; \\ Q^B(r, \theta) \{1 - Q^A(r, \theta)\}, & u = B; \\ Q^A(r, \theta) Q^B(r, \theta), & u = AB. \end{cases}$$

Assume that $Q$ belongs to a parametric class of hazard probability functions. The contribution to the likelihood function coming from a matched pair of tracks (or a track without a match) may be decomposed as follows: the probability density (1) of the position of the initial sighting, the probability (3) in the trinomial experiment, and subsequent Bernoulli trials in situations where the initial sighting is made only by one platform ($u = A$ or $u = B$). These likelihood components are conditionally independent and they are hence multiplied together. The likelihoods for different matched pairs or unmatched tracks are also independent.

A 15-point Gauss-Laguerre quadrature formula (Press et al. 1992, p. 151) is used to evaluate the integrals involved in (1) and (2). The likelihood function is maximized using the optimization software AD Model Builder (Fournier 2001).

The following parametric class of hazard probability function is inherited from Schweder et al. (1997):

$$Q(r, \theta) = \mu \cdot Q_1(r) \cdot Q_2(\theta),$$
where

\[ Q_1(r) = \frac{h(-\lambda_r(r - \rho_r))}{h(\lambda_r \rho_r)}, \]  
\[ Q_2(\theta) = \frac{h(-\lambda_\theta(\theta - \rho_\theta))}{h(\lambda_\theta \rho_\theta)}, \]  

with \( h(x) = \frac{\exp(x)}{\{\exp(x) + 1\}} \) being the logistic function. The basic parameters \( \lambda_r, \rho_r, \lambda_\theta, \rho_\theta, \mu \) of the model have the following interpretations:

- \( \mu \): is the hazard probability at the origin (where the observer is placed),
- \( \rho_r \): is the distance (in meters) at which the hazard probability has dropped to 50%,
- \( \lambda_r \): is the steepness of the hazard probability curve at distance \( \rho_r \),
- \( \rho_\theta \) and \( \lambda_\theta \): are the same as \( \rho_r \) and \( \lambda_r \), but for sighting angle rather than distance.

The basic parameters are allowed to depend on covariates through exponential and logistic link functions:

\[ \rho_r = \exp(\eta_r), \]  
\[ \rho_\theta = \exp(\eta_\theta), \]  
\[ \mu = \frac{\exp(\eta_\mu)}{\{1 + \exp(\eta_\mu)\}}, \]

where \( \eta_r, \eta_\theta \) and \( \eta_\mu \) are linear predictors (linear combinations of covariate effects). To allow platform A and B to have different hazard probability functions (\( Q^A \) and \( Q^B \)), the intercept term in the linear predictors may be platform-specific. The vector of all parameters in the model (\( \lambda_r, \lambda_\theta \) and the parameters associated with \( \eta_r, \eta_\theta \) and \( \eta_\mu \)) is denoted by \( \beta \).

### 2.2.3 Abundance estimation

For the purpose of abundance estimation the subareas EN, EC, EN, EC and CM are split into survey blocks, which are believed to be homogeneous with respect to whale density. The geographical definition of survey blocks is shown in Figure 1.

Changes in the values of covariates will cause \( w \) to vary along the transect line. Let \( w(l) \) denote the effective strip half-width at position \( l \), and denote by \( L \) the total survey length. The average effective strip half-width in the survey block is given as

\[ \bar{w} = \frac{1}{L} \int_0^L w(l)dl. \]

The abundance estimate \( \hat{N} \) for the survey block is obtained by equating whale density in the survey block with observed whale density over the effective search area:

\[ \hat{N} = \frac{n^{(A)} + n^{(B)}}{2L(\bar{w}^{(A)} + \bar{w}^{(B)})} \text{AREA}, \]

where
• \(n^{(A)}\) and \(n^{(B)}\) are the total number of sighted whales for platform A and B, respectively.
• \(L\) is total transect length.
• \(\bar{w}^{(A)}\) and \(\bar{w}^{(B)}\) are platform specific averages of \(w\).
• AREA is the area of the survey block.

Note that a common hazard probability model is fitted for all survey blocks. This causes estimates of \(\bar{w}\), and hence \(\hat{N}\), from different survey blocks to be correlated.

### 2.2.4 Simulation model

The presence of measurement errors in the spatial and temporal data (related to observed surfacings), matching errors, spatial clustering of whales and other difficulties has made it impossible for us to obtain unbiased estimates and valid standard errors without recourse to simulation. Models for these various components of the data generating process have been estimated, as detailed below, and they combine to a more realistic model for the surveys. An implementation of this model as a computer program is used to simulate artificial data in the same format as collected in the surveys.

The program simulates a virtual sighting vessel with two independent observer platforms moving through an ‘ocean’ of pre-distributed whales. The virtual whales are available for detection at discrete time points determined by dive time series obtained from radio tagging of minke whales. Every surfacing that an individual makes is detected by the observers according to the hazard probability \(Q(r, \theta)\). The spatial distribution of whales is determined by a Neyman-Scott clustered point process (Hagen & Schweder 1994). The Neyman-Scott process is characterized by the following three parameters:

- \(\gamma^{\text{NS}}\) the intensity of clusters (pr square meter).
- \(\mu^{\text{NS}}\) the average number of whales in each cluster,
- \(\rho^{\text{NS}}\) the radius (in meters) for each cluster, that is, the standard deviation in the bivariate Gaussian distribution of whales belonging to the cluster.

In addition, we simulate measurement errors in radial distance \(r\), sighting angle \(\theta\) and time point of observation (see below); incomplete tracking (the observer fails to report information about subsequent surfacings); and missing values in \(r\) and \(\theta\).

A model for measurement error was developed by Schweder (1997). This model has been modified and fitted to data from the survey period 1996–2001, yielding:

\[
\begin{align*}
    r &= 0.898 \cdot r' \exp \left[ N(0, 1) \cdot 1.371 \cdot (r')^{-0.2375} \right], \\
    \theta &= 1.057 \cdot \theta' + N(0, 1) \cdot 4.826 \cdot \exp [0.0117 \cdot \min (|\theta'|, 55)]
\end{align*}
\]

(11) (12)

where \(r'\) and \(\theta'\) are the true quantities, and the \(N(0, 1)\) denote standard normal random variables. The following error model for time has been adopted from Schweder (1997):

\[
t = t' + \max [0, 7 + 3.4 \cdot N(0, 1)],
\]

(13)

where \(t'\) denotes true time.
2.2.5 Simulation-based inference for separate surveys

Computer simulation of a parametric model for inferential purposes is often called parametric bootstrapping (Efron & Tibshirani 1993). We use simulation to remove bias from parameter estimates obtained under the hazard probability model, to estimate standard errors, and to establish a confidence distribution (Schweder & Hjort 2002) for the abundance of minke whales. The main source of bias in the maximum likelihood estimation is the measurement error added in the simulation model, but not accounted for in the pure hazard probability model of Section 2.2.2. As noted earlier, measurement error in distance and angle estimates leads to errors in the track-matching procedure, which in turn affect the estimate of the hazard probability.

Schweder et al. (1999) used the simulation model of the previous section to remove bias from the Bernoulli part of the likelihood. Here, our aim is to obtain asymptotically unbiased inference under the assumptions of the simulation model. We thus apply bias correction to the full likelihood in the pure hazard probability model. This is done by correcting the maximum likelihood estimate $\beta$ by $\Delta$, to

$$\hat{\beta} = \tilde{\beta} - \Delta.$$  (14)

The correction $\Delta$ is calculated iteratively. Start with $\beta_1 = \tilde{\beta}$. At the i-th step, simulate a large data set $D_i^*$ (we use 30 times the size of the real survey data) using $\beta = \beta_i$. This leads to a maximum likelihood estimate $\tilde{\beta}_i^*$ based on $D_i^*$. The bias estimate at this stage is $\Delta_i = \tilde{\beta}_i^* - \beta_i$. The next large data set to simulate is based on $\beta_{i+1} = \tilde{\beta} - \Delta_i$. We have found this process to converge fairly rapidly. The process leads to an asymptotic bias correction in the sense that $\hat{\beta}$ given by (14) converges to the true value of $\beta$ as the amount of data becomes large (Kuk 1995).

To study the sampling distribution of the abundance estimator, 1,000 data sets of the same size as the observed data set are simulated at $\beta = \tilde{\beta}$. The simulations are set up with effort at covariate levels as in the real survey. (The large data sets used to evaluate $\Delta$ do also have effort similarly distributed.) For each simulated dataset we first evaluate $\hat{\beta}$ through (14), then we calculate the effective strip half-width $w$, and finally we calculate $\hat{N}$ from the abundance formula (10). The number of sightings $n^{(A)} + n^{(B)}$ in the abundance formula is also generated using the simulation model, but from a different (independent) simulation replica than used to estimate $\hat{\beta}$. For the purpose of simulating the variance of $\hat{N}$, separate Neyman-Scott parameters are used for each survey block (see Table 7), while in evaluating the bias correction factor $\Delta$ the same set of Neyman-Scott parameters is used for all survey blocks.

To obtain a confidence distribution for total abundance, a few additional bootstrap runs are carried out. A confidence distribution represents confidence intervals by its quantiles. The interval between the confidence quantiles at 2.5% and 97.5% is for example the 95% confidence interval. The confidence density provides a graphical representation of confidence intervals at all conceivable levels of confidence, and might be regarded as the frequentist analogue to the Bayesian posterior density (Schweder & Hjort 2002). The bootstrap runs are carried out at various levels of abundance around $\hat{N}$. To simplify matters, we only vary the intensity of clusters in the Neyman-Scott process. The degree of clustering and the other parameters ($\beta$) are fixed at their estimated values. For each
parametric bootstrap sample, a bootstrap estimate of abundance, $\hat{N}$, is obtained as the estimate (10). From the series of these, an approximate pivot $p(\hat{N}, N)$ with cumulative distribution function $F$ is constructed. From Schweder & Hjort (2002) the approximate confidence distribution will then simply have cumulative distribution function $C(N) = F\left(p\left(\hat{N}, N\right)\right)$.

### 2.2.6 Combination of partial surveys

Due to inter-annual variations in spatial prey distribution, the proportion of whales present in the different survey strata will vary between years. For the purpose of estimating the total minke whale abundance in the northeastern Atlantic, this variation has no effect when the total area used by the stock is covered in a synoptic survey (such as assumed for the years 1989 and 1995). The surveys in 1996-2001 all had partial coverage. The IWC Small Areas in Fig. 1 constitute areas with synoptic survey coverage in single years, except for EB which was covered during three years. Below, the index $a$ refers to these Small Areas, together with the three parts of EB.

To assess the level of additional variance in the combined estimate due to temporal-spatial variability, we also use data from 1989 and 1995. Let $N_y$ be the true abundance in year $y$ in the total survey area (Fig. 1). We let $N_{1989}$ and $N_{1995}$ be free parameters in the model, but for the period $1996 \leq y \leq 2001$ it is assumed that the population grows exponentially, i.e.

$$\log(N_y) = \log(N_{y-1}) + \omega,$$

where $\omega$ is the unknown rate of growth (or decline). Denote by $p_{a,y}$ the proportion of whales present in the small area $a$ in year $y$, so that the number of whales present in the small area is $p_{a,y}N_y$. The following random effects model for the $p$’s is assumed

$$p_{a,y} = \exp(\mu_a + \xi_{a,y})/c(y),$$

where $c(y) = \sum_a \exp(\mu_a + \xi_{a,y})$ is a normalizing factor ensuring that $\sum_a p_{a,y} = 1$ for all $y$. The fixed effect parameter $\mu_a$ account for time invariant differences in abundance between small areas, and the random effects $\xi_{a,y}$ account for inter-annual changes in whale distribution. These random effects are assumed to be independent and normally distributed with zero mean and variance $\sigma^2$. The parameter $\sigma$ will be referred to as the additional variance parameter.

Denote by $\hat{N}_{a,y}$ the abundance estimate for small area $a$ in year $y$. Assuming that $\hat{N}_{a,y}$ is conditionally log-normally distributed (given the true abundance that year) we have

$$\log\left(\hat{N}_{a,y}\right) = \log(N_y) + \log(p_{a,y}) + e_{a,y},$$

where the survey error terms $e_{a,y}$ are assumed to be zero mean normally distributed random variables. Equation (17) shows how the total error in $\hat{N}_{a,y}$ can be decomposed into additional variance (variation in $p_{a,y}$) and survey error ($e_{a,y}$). There are three survey periods: 1989, 1995 and 1996-2001. The terms $e_{a,y}$ are correlated within survey period due to the use of a common estimated model for the effective strip half-width. The terms $p_{a,y}$ are correlated within year due to the normalization factor $c$ in (16), but are uncorrelated across years.
To obtain an estimate of $\sigma$, the method of restricted maximum likelihood (Punt et al. 1997) is used. Denote by $L(N, \omega, \sigma, \mu, \xi)$ the likelihood function based on the small area estimates from 1989, 1995, 1996-2001, where $\mu$ and $\xi$ are vectors, and $N = (N_{1989}, N_{1995}, N_{1996})$. When evaluating $L$ we use the assumption of conditional normality (17) together with the assumptions (15) and (16). The restricted maximum likelihood estimate of $\sigma$ is obtained by maximizing

$$L(\sigma) = \int L(N, \omega, \sigma, \mu, \xi) \, dN \, d\omega \, d\mu \, d\xi,$$

where the numerical integration is done by Laplace’s method (Tierney & Kadane 1986). Because data are sparse with respect to information about $\sigma$, the resulting estimate can be expected to be biased (in addition to having a large variance). Thus, we use parametric bootstrapping, and an equivalent to 14, to remove bias. In the present setting, the equations (15), (16) and 17 constitute the simulation model.

In order to sample from (16) we also need an estimate of $\mu$. This estimate is based only on data from 1996-2001, and is taken to be $\log(\hat{N})$ for the respective small areas.

3 Results

Figure 2 shows the geographical distribution of sightings, while the number of sightings in each survey block is shown in Table 1. Figure 4 shows histograms of radial distances and sighting angles to detected whales. In the analysis below, tracks with missing positional information (either $r$ or $\theta$ missing) for all surfacings were left out. The proportion of tracks left out for this reason was approximately 1%. The track matching routine identified 200 duplicate whales. Manual judgment identified additional 2 duplicate whales. The resulting number of joint initial sightings, after applying the data truncation rules, was 870 and the number of Bernoulli trials was 623.

3.1 Likelihood analysis

Initial attempts to fit the model showed that it was not possible to simultaneously estimate the two sighting angle parameters $\rho$ and $\lambda$. Thus, we fixed the slope at $\lambda = 0.1$, while $\rho$ was estimated as a free parameter. Table 3 shows deviances for a set of selected covariate models, ranging from the model without covariates (bottom line) to the full covariate model (first line). A backwards model selecting scheme was used to eliminate covariates from the full model. The likelihood ratio test was used to compare nested models. It was only the covariate “Weather” that could be removed from the full model (p-value 0.065), leaving a model with the linear predictor $\eta_r = B+V+G+P+T$ (see Table 2 for covariate abbreviations). This model selection was carried out within the pure hazard probability model (no bias correction). A similar analysis was attempted to identify covariates affecting the level parameter $\mu$. Here, none of the covariates yielded a significantly increase in the likelihood value, and hence only the intercept term was included in the linear predictor for $\mu$.

For the chosen model the maximum likelihood estimate $\hat{\beta}$ was bias corrected using (14). Table 4 shows both uncorrected and bias corrected parameter estimates, together
with estimates of average effective strip half-width. Sum-to-zero constraints were imposed on the parameters associated with the different levels of categorical covariates, except for the platform covariate P. For instance, the constraint \( \beta_{\text{BI}} + \beta_{\text{BII}} + \beta_{\text{BIII}} = 0 \) was imposed for the Beaufort covariate, and hence Table 4 only shows the values of \( \beta_{\text{BI}} \) and \( \beta_{\text{BII}} \). The platform effect \( \beta_{\text{P}} \) was added only to the linear predictor of platform B. Thus a negative value of \( \beta_{\text{P}} \) means that platform B looked at shorter range than platform A.

During the survey, 39 different combination of covariate levels occurred. Table 5 shows effective strip half-width and \( g(0) \) for a selected subset of these.

### 3.2 Externally determined parameters

There are several parameters in the hazard probability model that were not estimated from the likelihood function. The mean surfacing rate \( \alpha \) was estimated from 10 VHF-tagged whales to be \( \alpha = 0.0129 \) surfacings per second. The Neyman-Scott parameters (used in the simulation model) were estimated by matching the theoretical K-function (Ripley 1977) to its empirical counterpart. Table 7 shows parameter estimates obtained by fitting a separate Neyman-Scott model to each survey block. In four survey blocks (VSN, NON, BJ, JMC) the estimated Neyman-Scott model is consistent with a homogenous Poisson process (which is a special case of the Neyman-Scott model).

As seen from the table, the estimates for the survey block NS deviated strongly from those of the other survey blocks. A comparison of the empirical and the theoretical K-function indicated that the Neyman-Scott model did not fit data well for NS. To resolve this problem the survey block NS was split into two more homogenous sub-areas (the coast off Aberdeen and the rest of NS), and the method of Skaug (2002) was used to estimate the coefficient of overdispersion \( \tau \) (see Table 7) for each sub-area. From these estimates an effort-weighted average \( \tau = 8.96 \) was calculated, and the Neyman-Scott parameters for NS was chosen to yield this level of overdispersion (under the constraint that \( \gamma_{\text{NS}} \cdot \mu_{\text{NS}} \) was equal to the observed whale density in NS), yielding \( \gamma_{\text{NS}} = 4.34e - 11 \), \( \mu_{\text{NS}} = 1079 \), \( \rho_{\text{NS}} = 25,563 \). (Note that the superscript ‘NS’ refers to the term Neyman-Scott, and not to the survey block NS.) These estimates replace those in Table 7.

In the bias correction procedure of Section 2.2.5 a common set of Neyman-Scott parameters was used for all survey blocks. This estimate was obtained by ranking the survey blocks according to their value of the quantity

\[
\kappa = 0.5\mu_{\text{NS}} \left( \gamma_{\text{NS}} + 4\pi \left( \rho_{\text{NS}} \right)^2 \right)^{-1},
\]

which is proportional to the error rate in the track matching algorithm (Schweder et al. 1997). It was found, by excluding blocks where the fitted Neyman-Scott process was consistent with a Poisson process, and using the median value of \( \kappa \) as the criterion, that a representative set of Neyman-Scott parameters was that of the survey block SV (\( \gamma_{\text{NS}} = 4.50e - 09 \), \( \mu_{\text{NS}} = 12.0 \), \( \rho_{\text{NS}} = 2130 \)).

### 3.3 Abundance estimates 1996-2001

Table 1 contains abundance estimates for each survey block. All quantities needed to evaluate the abundance formula (10) are also given in the table. Table 6 contains estimates...
for IWC Small Areas obtained by summing the contribution from the constituting survey blocks. In the variance calculations, intra-block correlation was automatically accounted for by the parametric bootstrap approach. Table 6 also contains estimates for the total survey area (TOTAL), and for the total area apart from Small Area CM (TOTAL$_E$). The latter forms the 'Eastern North Atlantic Medium Area' in the IWC terminology. In the estimation of the additional variance parameter $\sigma$ it was necessary to exclude the survey block NVS which was not covered in 1989 and 1995. Based on data from 1989, 1995 and 1996-2001 we obtained the estimate $\hat{\sigma} = 0.28$ (SD 0.15), but when the bias correction explained earlier the estimate became $\hat{\sigma} = 0.22$. When ignoring additional variance (putting $\sigma = 0$) the corresponding estimates of standard error for the total area (TOTAL) was 10.821.

Parametric bootstrapping was carried out at 90%, 100% and 110% of the total abundance estimate $\hat{N} = 107,205$ in order to study the sampling distribution of the estimator of total abundance and to obtain a confidence distribution for this parameter. The number of bootstrap replicates were 1000, 1000 and 636, respectively. It turns out that the abundance estimator is practically normally distributed on the log scale (Figure 5), with standard deviations 0.134, 0.145, and 0.129 respectively. These standard deviations are significantly different (p-value 0.003, Bartlett test). Due to the lack of linear pattern in the standard deviations, we base our pivot on the assumption that the standard deviation is constant on the log scale in the neighbourhood of $\hat{N}$. On the log scale, there is no significant bias in $\hat{N}$, see Figure 5. In the notation of Section 2.2.5, the pivot is $p(\hat{N}, N) = \left( \log(N) - \log(\hat{N}) \right) / 0.137$, while $F$ is the cumulative normal distribution function. The confidence distribution for total abundance is thus log-normal with median $\hat{N}$, and with a scale parameter of 0.137. The confidence intervals for $N$ are thus $\hat{N} \cdot [\exp(-1.37z), \exp(1.37z)]$ for appropriate normal quantiles $z$. The confidence density is shown in Figure 6.

3.4 Distribution of Northeastern Atlantic minke whales; a comparative review

Although many aspects of minke whale distribution have been revealed in recent years, virtually no progress has been made on knowledge of migration behaviour necessary to understand why these distributions occur and eventually change. The general belief is that minke whales migrate to polar regions in summer to feed and return to warmer waters in winter to breed, but details about the factors governing the migrations and thus distributional patterns are not known. Available data to elucidate distribution and migration are catch data, strandings, sightings data, mark-recapture data, and in recent years, data from instrumentation with radio and satellite tags. The survey data, used here to estimate abundance, could be combined with mark-recapture data, satellite tracking data, and possibly other data to describe migration behaviour in northeastern Atlantic minke whales. Such an integrative study is, however, outside the scope of the present paper.
3.4.1 Distribution

In 1938 a compulsory logbook system was introduced in Norwegian small type whaling (Christensen & Øien 1990), including detailed information on each whale caught and all participating vessels. Modern minke whaling started off the coast of Møre in western Norway in the 1920ies and spread quickly along the Norwegian coast. After the Second World War the minke whaling expanded northwards to Spitsbergen and westwards to the northern areas of the British Isles and Faroe Islands. In the 1960ies the minke whaling by Norwegians also included East and West Greenland waters. From 1976 onwards total quotas were introduced to Norwegian whalers that resulted in movement of virtually all the whaling effort on the Northeastern stock of minke whales to the Barents Sea, north of 70°N. Nevertheless, it is reasonable to assume that the geographical distribution of catches reflects the distribution, and changes in distribution, of whales. The general pattern in the Northeastern stock area is that catches have been taken in the North Sea, on shelf areas along the Norwegian coast, in the Barents Sea and on the shelf area off Spitsbergen. This picture has since been extended by the sightings surveys conducted over the period from 1987 to date, which show that minke whales also have large offshore distributions in the Norwegian and Greenland Seas (see for example Schweder et al. 1997). The catch distributions indicate that within the Barents Sea changes have taken place over the years between eastern distributions (for example in 1952, see Fig. 7) and western distributions (for example in 1980, see Fig. 7). Also within the recent sightings surveys changes of distributions have occurred, for example the high concentrations of minke whales off Kola in 1988 and 1989 (Øien 1990, Øien 1991) were succeeded by a remarkable low concentration in that area in 1995 (Schweder et al. 1997). Presumably these changes in minke whale distributions are related to changes in abundance and distribution of possible prey species, although this has not yet been demonstrated. Minke whales feed on a variety of fish and pelagic crustaceans. Haug et al. (1996) found that given the opportunity to choose prey items, minke whales will generally favour herring and capelin before other species such as krill and gadoid fishes.

3.4.2 Migration

According to Jonsgård (1951) minke whales migrate into Norwegian and Arctic waters in the spring, are most frequent there in the summer, and leave these northern waters again more or less completely in the autumn. Immigration in the spring begins apparently in the southern and western areas and continues along the coast. On basis of stranding records around the British Isles, Jonsgård (1951) concluded that minke whales enter the North Sea from the north. The majority of minke whales frequenting Norwegian fjords and inlets on the west coast are pregnant females migrating alone, while males have seldom been reported in the fjords. The whales found outside Vesterålen in October, mostly males, are migrating in a general southwesterly direction. There is segregation both with respect to length and sex (Jonsgård 1951, Øien 1988). Large females dominate in Skagerak and in the main Barents Sea and off Spitsbergen, while large males dominate in the North Sea and at the Shetland-Faeroe Islands. Off the coast of mid-Norway (Møre to Lofoten) small animals, interpreted by Jonsgård (1955) to be recently weaned yearlings, about six months old, dominated the catches, but this changed during the 1960ies when the catches...
in that area gradually included larger animals.

From markings of minke whales, mainly in the period 1974-78 within the Barents Sea, there is at least indication that a regional fidelity exists. Most of the markings mentioned were made near Bear Island in fall, while the recaptures were made in the following years in the area of marking, off the coast of northern Norway and Kola, in the eastern and central Barents Sea, and west off Spitsbergen (International Whaling Commission 1991). Whales marked at Spitsbergen have been recaptured at Bear Island and off the Kola coast.

So far, instrumentation with radio and satellite tags have not given answers to large-scale movements of minke whales in the Northeast Atlantic, but tracking over periods of approximately one-month duration indicate regional fidelities. Satellite tagging of two minke whales in the Lofoten area (northern Norway) which could be followed over approximately one month in early fall (Heide-Jørgensen et al. 2001), showed that they can move considerable distances on a daily basis while the overall movement during the observation period was regional. One of the whales apparently moved between two feeding areas while the other one stayed within the Vestfjord. Both probably fed on herring, which is particularly abundant in this area at this time of the year.

Two minke whales tracked with satellite tags put on in a fjord in northern Iceland in fall 2001 showed a clear coastal affinity and they were apparently stationary for the tracking periods, which were 16 and 60 days (Heide-Jørgensen and Vikingsson 2002, unpublished). These minke whales were also probably feeding on high abundance of small herring in the area.

3.4.3 Abundance

Prior to the introduction of sightings surveys to estimate abundance of whales in the Northeastern Atlantic, some attempts had been made to estimate the stock size of Northeastern minke whales. Based on catch-effort analysis and population modelling Ugland (1976) arrives at an estimate of current population size of about 30,000 minke whales. Further, based on two recaptures from 15 minke whales marked in 1964 and 1965 he estimates 40,700 minke whales. Over the period 1974-78 333 minke whales were tagged in the Barents Sea and Christensen & Rørvik (1981) calculated a best estimate of the total stock of 113,000 animals when taking availability into account. Of these, the number of whales recruited to the areas north of 70°N was estimated to be 55,000 animals.

Based on the same marking experiment conducted 1974-78, but with more years with recaptures, Beddington et al. (1984) found point estimates of the Northeast Atlantic stock of minke whales in the range 81,500 to 121,000 based on multi-year recaptures, and 66,000 based on next year recaptures only. IWC concluded in 1983 that the multi-year recapture estimates should be discarded and therefore that a best estimate for total stock then would be 60,000 corrected for age distribution bias.

3.4.4 Trends

For evaluating trends in abundance of minke whales we have no other information than the catch data besides the recent series of sighting survey estimates. In their analysis of relative abundance series for minke whales in the Barents Sea 1952-1983, Schweder &
Volden (1994) found that the estimated density of clusters of whales and the mean cluster area showed little variation over the 32 year period, however the estimated whale density within clusters showed a roughly 20 year cycle around an almost stationary level, with declines in the 1950ies and the 1970ies.

4 Discussion

Our abundance estimate at the stock level is lower for the period 1996-2001 than it was for 1995, but higher than for 1989 (Table 6). The p-value for a change in abundance since 1995 is 0.18 (excluding the survey block in CM that was not covered in 1995 in the comparison). Is this evidence for a decline in the northeastern Atlantic stock of minke whales? As Schweder et al. (1997) found it difficult to ascribe the more dramatic increase in the abundance estimate from 1989 to 1995 to population growth alone, we find it difficult to ascribe the decline in estimates to a decline in the stock. One possible explanation for a decline in the TOTALE-stock is that the E and C stocks are less separated than previously believed, at least on the feeding grounds. Alternatively, the migration patterns of minke whales may vary because of yet not identified factors. Shifts in spatial distribution of catches have been revealed (Figure 7). According to the estimated random effects model of Section 2.2.6, the proportion of the total stock (CM and E-areas) being present in CM each year varies randomly between 18% and 33% (lower and upper 5% prediction intervals). The increase in the estimate for the CM-area from 1996-2001 is quite marked, and could be due to more whales from the E-stock being present in CM when it was surveyed in 1997, than was the case in 1995. With more contact between the E- and C-stocks, it might be misleading to focus on the abundance of the E-area in isolation.

Although it is possible to find alternative explanations for a possible decline in abundance estimates from 1995 to 1996-2001, the possibility of a decline should not be ruled out. Seen over the whole period 1989 - 2001, the impression is, however, that there might have been some growth in the population. This latter effect could be due to a component of the stock staying outside the surveyed area during the survey, and to variation in the size of this unsurveyed component.

From Table 4 it is seen that the directions of the covariate effects were as would be expected. For the Beaufort covariate, the effective strip half-width was highest for Beaufort state ’0–1’ (covariate level BI), while it was lowest for Beaufort state ’3–4’(covariate level BIII). For the Team covariate, the effective strip half-width for the Long category was higher than for the Short category, showing that the classification of teams that was done prior to the analysis was meaningful. Also, the effective strip half-width was higher for platform A than for platform B, in concordance with the findings in Schweder et al. (1997) and with prior belief.

The bias corrected abundance estimate for the total area is 107,205 (Table 6), while the corresponding uncorrected estimate is 110,000 (Table 3). Thus, the bias correction has little effect on the total abundance estimate. This could be due to cancellation of biases of different sign in the uncorrected estimate. One example of this is done deliberately for the automatic track-matching routine, which was tuned (on simulated data) so that the number of duplicate pair missed approximately equaled the number of erroneously judged
duplicate pairs.

The measurement error models (11) and (12) were estimated from the data collected in the distance and sighting angle experiments conducted during the survey. For radial distance ($r$) it was concluded that the variability in the experimental data was representative for the variability in the real survey data. Schweder (1997), however, recommended that the variability should be estimated from the survey data. For sighting angle ($\theta$) it was found that a higher variability was observed in the survey data than was seen in the buoy experiments. The chosen measurement error model captures this higher level of variability. The model (13) for the difference between true and reported surfacing times was adopted from Schweder et al. (1997) without modification. A priori, one expects more accurate time points in the present data than in the 1995 data, because the observers on average were more experienced than those participating in 1995.

Figure 4 in Skaug et al. (2002) shows diagnostic plots for each covariate stratum for their best fitting model. Similar plots have been produced for the model chosen in the present paper, but are not shown here due to lack of space and the fact that they are very similar to those in Skaug et al. (2002). The diagnostic plots compare model predicted histograms to the corresponding empirical histograms of radial distances and sighting angles. We also have diagnostics plots for success probabilities in Bernoulli trials as a function of radial distance. Chi-square goodness of fit tests to the radial distance data (by covariate stratum) show that the model fits reasonably well, except that there are some sightings at large distances that the model is not able to explain. For the Bernoulli trials there are more successes at large distances than predicted by the model, especially for teams in the Long-category. The explanation for this might be unmodeled heterogeneity in cue strength, due to the angle at which the whale shows its back when surfacing.

4.1 Potential sources of additional bias in point estimates

The transect design was non-adaptive and the survey was conducted in passing mode. Transects were planned to give a uniform coverage and not to correlate with expected whale density within survey blocks. To make full use of the available effort, two uniform layers of tracks were planned. The first layer was mandatory, and the second layer was to be covered as extensively as possible, subject to weather conditions and practicalities. The second layer was only incompletely covered. Selectivity of tracks in the second layer could lead to bias in the coverage, as would also temptation to move to regions of expected high whale density. However, the protocol specified that secondary tracks should be selected exclusively on logistic and weather considerations and they should be discussed with the survey leader. Since weather and Beaufort sea state is accommodated as a covariate in the analysis model, no bias should thus follow from the lack of uniform coverage that resulted from the selection of secondary tracks.

Effort was also allocated to gather more data on diving behavior in minke whales by means of satellite and VHF-radio tracking. These experiments were not very successful and resulted in only three new series of VHF tracking data in addition to the eight dive time-series used in earlier analyses (Schweder et al. 1996). All these series were obtained in near coastal waters, and they might not be fully representative of dive patterns in
minke whales within sighting distance throughout the survey. The sign and size of any such bias, should it occur, is not known.

In the analysis, whales are assumed to be immobile except for diving. Random motion between surfacings has been found to bias abundance estimates positively when not accounted for (Schweder et al. 1996). Responsive behavior could bias abundance estimates even more. From an analysis of recorded swim directions in the 1995 data, Palka & Hammond (2001) found evidence for northeastern Atlantic minke whales avoiding the vessel when the radial distance is less than approximately 700 meters. Based on the evidence available in 1995, Schweder et al. (1997) concluded that “the direction and size of a potential bias due to random or responsive whale behavior is unknown, but if the bias is positive, its size is likely to be small in the abundance estimates”. We believe that this conclusion is valid also today.

Tracking has been assumed unbiased in the sense that the number of tracks recorded from one platform is an unbiased estimate of the number of whales actually seen. Since it is possible to break up tracks (count a whale twice) or to merge different tracks into one recorded track (count two whales as one), unbiased tracking is not self-evident. Incorrect tracking can be detected in cases where the whale has been seen by both platforms, although it is usually difficult to determine in retrospect which platform made the mistake. However, during the manual validation of the duplicate pairs only a few such instances were discovered.

4.2 Potential sources of bias in variance estimates

No attempt has been made to incorporate the inherent uncertainty in model selection into the estimates of variance for abundance. The variance estimates are calculated conditionally on the third row in Table 3 being the true model, and do not reflect the fact that the other models in the table might have been chosen. However, as long as the Beaufort covariate is included in the model, the abundance estimate is relatively insensitive to model choice.

The additional variance parameter \( \sigma \) was weakly determined (CV approximately 0.5 for uncorrected estimate). If \( \sigma \) has been under-estimated, the variance estimate for the total abundance estimate (Table 6) will be too low.

The measurement error model is used without taking the sampling uncertainty in the estimates of that model into account. The most sensitive parameter is the relative bias in radial distance estimates. Schweder (1997) estimated the standard deviation of this parameter to be, at most, 0.02. There is thus some negative bias in the variance estimates for abundance when disregarding sampling uncertainty in measurement error model estimates.

In the iterative Monte Carlo scheme used to evaluate the bias correction \( \Delta \) introduces some error. This source of variation has not been accounted for in Table 6, but has been shown to be ignorable compared to the level of variation reported in the table.
5 Conclusion

Based on the discussion of possible biases in the estimation procedure, we conclude that the abundance estimate for the survey period 1996-2001 is practically unbiased or possibly negatively biased. The main factors pointing towards a negative bias are the effects of whale angle and other random heterogeneities, and responsive behavior with avoidance rather than attraction. It is difficult to assess the balance of potential sources of bias in the variance estimates.

In 1995 and in 1988/1989 the surveys were synoptic with nearly complete coverage. In 1996-2001, the survey design could be characterized as a sequence of partial designs. Except for this difference, the survey methodology and the method of data analysis are similar for the three surveys. That the 1996-2001 is non-synoptic is reflected in larger variances in abundance estimates. It should not cause other biases than in the previous surveys. Differences between abundance estimates for 1989, 1995 and 1996-2001 should thus be approximately unbiased. These differences seem to indicate that the stock has increased from 1989 to 1995 and then decreased. In the period 1996-2001, Norwegian whalers have harvested 3,144 minke whales. The estimated decline since 1995 is larger than the cumulated catch over the period. This picture, at least for the increase in the first period, prevails, even when taking the standard errors in the abundance estimates into account. The variability in true stock abundance is likely to be less than estimated. A potential explanation is that the fraction of the stock that is present in the survey area varies from year to year, either because there is substantial contact between the central and the eastern stocks, or because a variable stock component keeps to more southern latitudes at a varying degree.

6 Acknowledgments

This work has been generously funded by the Norwegian Government and the Norwegian Research Council (Grant number 111043/120). We are grateful to Kjell Arne Fagerheim and Siri Hartvedt at the Institute of Marine Research for their work with preparing the data. We are also grateful to Magne Aldrin, Marit Holden, Ingunn Friede Tvette and Gro Hagen at the Norwegian Computing Center. They performed the data analysis leading to the models (11) and (12), and to Table 7 (see Skaug et al. (2002) for further details). We will also like to thank all of the team leaders and observers who have participated in the surveys during the six year period, and finally our active discussion colleagues in the Scientific Committee of the IWC are gratefully acknowledged.

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<td>2158.87</td>
<td>859.82</td>
</tr>
</tbody>
</table>

Table 1: Summary of results by survey block: area of survey block, survey year, transect length (L), total number of sightings (n_A + n_B), effective strip half-width (w_A + w_B), abundance estimate (\( \hat{N} \)) with associated estimate of standard deviation (SD).
<table>
<thead>
<tr>
<th>Covariate</th>
<th>Description</th>
<th>Abbr.</th>
<th>Levels</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform</td>
<td>Platform indicator</td>
<td>P</td>
<td>A, B</td>
<td></td>
</tr>
<tr>
<td>Weather</td>
<td>12 categories</td>
<td>W</td>
<td>W0, W1</td>
<td>W0: Clear sky, W1: Cloudy</td>
</tr>
<tr>
<td>Visibility</td>
<td>Numerical, given in m</td>
<td>V</td>
<td>High, Low</td>
<td>High: larger than 3000m</td>
</tr>
<tr>
<td>Glare</td>
<td>4 categories</td>
<td>G</td>
<td>G0, G1</td>
<td>G0: No glare, G1: Glare</td>
</tr>
<tr>
<td>Beaufort</td>
<td>0-12 scale</td>
<td>B</td>
<td>BI, BII, BIII</td>
<td>BI: 0-1, BII: 2, BIII: 3-4</td>
</tr>
<tr>
<td>Observer/Team</td>
<td>Individual obs. codes</td>
<td>T</td>
<td>Short, Long</td>
<td>See Section 3</td>
</tr>
</tbody>
</table>

Table 2: Covariates recorded during the survey on an hourly basis.

<table>
<thead>
<tr>
<th>Covariate</th>
<th>Description</th>
<th>Abbr.</th>
<th>Levels</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform</td>
<td>Platform indicator</td>
<td>P</td>
<td>A, B</td>
<td></td>
</tr>
<tr>
<td>Weather</td>
<td>12 categories</td>
<td>W</td>
<td>W0, W1</td>
<td>W0: Clear sky, W1: Cloudy</td>
</tr>
<tr>
<td>Visibility</td>
<td>Numerical, given in m</td>
<td>V</td>
<td>High, Low</td>
<td>High: larger than 3000m</td>
</tr>
<tr>
<td>Glare</td>
<td>4 categories</td>
<td>G</td>
<td>G0, G1</td>
<td>G0: No glare, G1: Glare</td>
</tr>
<tr>
<td>Beaufort</td>
<td>0-12 scale</td>
<td>B</td>
<td>BI, BII, BIII</td>
<td>BI: 0-1, BII: 2, BIII: 3-4</td>
</tr>
<tr>
<td>Observer/Team</td>
<td>Individual obs. codes</td>
<td>T</td>
<td>Short, Long</td>
<td>See Section 3</td>
</tr>
</tbody>
</table>

Table 3: Comparison of different covariate models, with selected model printed with bold types. Deviance is two times the log-likelihood ratio relative to the full model (first row), and DF is the degrees of freedom to use in a likelihood ratio test. Abundance estimates (last column) are given for the total survey area without bias correction.

Table 4: Regression parameters for the chosen hazard probability model. Parameter estimates are given both with bias correction ($\hat{\beta}$) and without bias correction ($\hat{\beta}$). Estimates of standard deviation (SD) are given for the bias corrected estimate. Effort weighted effective strip half-widths ($w_A$ and $w_B$) are also given.
Table 5: Effective strip half-width $w$ (in meters) and $g(0)$ for selected combinations of covariate levels. The last column gives the proportion of realized survey time. The first and last row shows the lowest and highest effective strip half-width, respectively, that occurred during the survey.

<table>
<thead>
<tr>
<th>Beaufort</th>
<th>Visibility</th>
<th>Glare</th>
<th>Team A</th>
<th>Team B</th>
<th>$w_A$</th>
<th>$w_B$</th>
<th>$g_A(0)$</th>
<th>$g_B(0)$</th>
<th>Time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIII</td>
<td>Low</td>
<td>G1</td>
<td>Short</td>
<td>Short</td>
<td>118</td>
<td>104</td>
<td>0.264</td>
<td>0.2468</td>
<td>0.9</td>
</tr>
<tr>
<td>BIII</td>
<td>Low</td>
<td>G0</td>
<td>Short</td>
<td>Long</td>
<td>153</td>
<td>178</td>
<td>0.304</td>
<td>0.3295</td>
<td>12.5</td>
</tr>
<tr>
<td>BIII</td>
<td>Low</td>
<td>G0</td>
<td>Long</td>
<td>Short</td>
<td>212</td>
<td>132</td>
<td>0.360</td>
<td>0.2807</td>
<td>12.9</td>
</tr>
<tr>
<td>BIII</td>
<td>Low</td>
<td>G0</td>
<td>Long</td>
<td>Long</td>
<td>212</td>
<td>178</td>
<td>0.360</td>
<td>0.3295</td>
<td>14.0</td>
</tr>
<tr>
<td>BII</td>
<td>High</td>
<td>G1</td>
<td>Short</td>
<td>Long</td>
<td>320</td>
<td>388</td>
<td>0.440</td>
<td>0.4801</td>
<td>0.1</td>
</tr>
<tr>
<td>BII</td>
<td>High</td>
<td>G0</td>
<td>Short</td>
<td>Long</td>
<td>465</td>
<td>566</td>
<td>0.520</td>
<td>0.5640</td>
<td>0.4</td>
</tr>
<tr>
<td>BI</td>
<td>High</td>
<td>G0</td>
<td>Long</td>
<td>Long</td>
<td>1078</td>
<td>879</td>
<td>0.715</td>
<td>0.6669</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 6: Abundance estimates for IWC Small Areas with comparison to estimates for 1989 and 1995 taken from Schweder et al. (1997). (*) In 1989 and 1995 the estimates for CM did not include the survey block NVS. The last row (TOTAL$_E$) refers to the total area without Small Area CM.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\hat{N}$</td>
<td>SD</td>
<td>CV</td>
</tr>
<tr>
<td>EB</td>
<td>34,712</td>
<td>7,044</td>
<td>0.203</td>
</tr>
<tr>
<td>ES</td>
<td>13,370</td>
<td>2,565</td>
<td>0.192</td>
</tr>
<tr>
<td>EC</td>
<td>2,602</td>
<td>647</td>
<td>0.249</td>
</tr>
<tr>
<td>EN</td>
<td>14,046</td>
<td>3,875</td>
<td>0.276</td>
</tr>
<tr>
<td>CM</td>
<td>2,650*</td>
<td>1,283</td>
<td>0.484</td>
</tr>
<tr>
<td>TOTAL</td>
<td>67,380</td>
<td>12,811</td>
<td>0.190</td>
</tr>
<tr>
<td>TOTAL$_E$</td>
<td>64,730</td>
<td>12,444</td>
<td>0.192</td>
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</table>
Table 7: Estimates of Neyman-Scott parameters based on Ripley’s K-function. The parameter $\kappa$ defined in Equation (19) is a measure of “average whale density within clusters”. The overdispersion coefficient $\tau$ is defined as $\tau = \frac{Var(n^{(A)} + n^{(B)})}{E(n^{(A)} + n^{(B)})}$, where both the variance and the expectation are calculated under the Neyman-Scott model.

<table>
<thead>
<tr>
<th></th>
<th>$\lambda^{NS}$</th>
<th>$\mu^{NS}$</th>
<th>$\rho^{NS}$</th>
<th>$\kappa$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAE</td>
<td>6.153e-10</td>
<td>41.4</td>
<td>1213</td>
<td>1.13e-06</td>
<td>10.9</td>
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<tr>
<td>GA</td>
<td>3.387e-09</td>
<td>22.9</td>
<td>848</td>
<td>1.31e-06</td>
<td>7.64</td>
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<tr>
<td>KO</td>
<td>1.086e-09</td>
<td>26.5</td>
<td>7029</td>
<td>3.58e-08</td>
<td>2.70</td>
</tr>
<tr>
<td>FI</td>
<td>2.938e-09</td>
<td>23.3</td>
<td>1677</td>
<td>3.64e-07</td>
<td>6.01</td>
</tr>
<tr>
<td>NOS</td>
<td>3.484e-10</td>
<td>97.0</td>
<td>13218</td>
<td>3.90e-08</td>
<td>3.44</td>
</tr>
<tr>
<td>VSI</td>
<td>1.252e-09</td>
<td>25.9</td>
<td>2484</td>
<td>1.83e-07</td>
<td>7.28</td>
</tr>
<tr>
<td>VSN</td>
<td>Poisson point process</td>
<td></td>
<td></td>
<td>2.53</td>
<td></td>
</tr>
<tr>
<td>VSS</td>
<td>4.631e-10</td>
<td>169</td>
<td>8199</td>
<td>1.39e-07</td>
<td>8.79</td>
</tr>
<tr>
<td>SV</td>
<td>4.501e-09</td>
<td>12.0</td>
<td>2130</td>
<td>1.32e-07</td>
<td>3.39</td>
</tr>
<tr>
<td>NON</td>
<td>Poisson point process</td>
<td></td>
<td></td>
<td>2.30</td>
<td></td>
</tr>
<tr>
<td>BJ</td>
<td>Poisson point process</td>
<td></td>
<td></td>
<td>2.85</td>
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<tr>
<td>BAW</td>
<td>9.425e-10</td>
<td>26.8</td>
<td>2485</td>
<td>1.85e-07</td>
<td>5.99</td>
</tr>
<tr>
<td>JMC</td>
<td>Poisson point process</td>
<td></td>
<td></td>
<td>2.36</td>
<td></td>
</tr>
<tr>
<td>NVN</td>
<td>2.149e-08</td>
<td>1.57</td>
<td>1154</td>
<td>2.65e-06</td>
<td>2.76</td>
</tr>
<tr>
<td>NVS</td>
<td>7.093e-10</td>
<td>73.4</td>
<td>7277</td>
<td>8.12e-08</td>
<td>4.41</td>
</tr>
<tr>
<td>NSC</td>
<td>5.981e-09</td>
<td>3.48</td>
<td>1549</td>
<td>6.81e-08</td>
<td>1.98</td>
</tr>
<tr>
<td>NS</td>
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<td>11004</td>
<td>51126</td>
<td>1.91e-07</td>
<td>57.4</td>
</tr>
<tr>
<td>SVI</td>
<td>4.631e-10</td>
<td>82.3</td>
<td>8199</td>
<td>6.78e-08</td>
<td>4.29</td>
</tr>
<tr>
<td>LOC96</td>
<td>4.133e-11</td>
<td>883</td>
<td>27058</td>
<td>6.62e-08</td>
<td>9.86</td>
</tr>
<tr>
<td>LOC00</td>
<td>4.133e-11</td>
<td>883</td>
<td>27058</td>
<td>6.62e-08</td>
<td>11.3</td>
</tr>
</tbody>
</table>
Figures

Figure 1: Survey area split (by solid lines) into five IWC Small Areas: CM, EB, EC, EN and ES. Small Area EC was covered twice, while dashed lines in EB indicate parts that were covered in different years. The ice edge was read from ice charts (Norwegian Meteorological Institute) for mid-July for the year when the adjacent survey blocks were covered.
Figure 2: Survey block definitions (red lines), transect lines (black lines) and minke whale sightings made while on primary search effort (black diamonds).
Figure 3: Extraction of trinomial and Bernoulli trials from a pair of matching tracks. Platform A has detected three surfacings (A1, A2, A3), while platform B has detected only one surfacing (B1). The dashed line joining A3 and B1 indicates that these are judged to be the same surfacing. The difference in the location of A1, A2 and A3 is caused by vessel movement, while the differences in the location of A3 and B1 are mainly caused by error in distance and angle measurements.
Relative position of sightings

Data extraction

Trinomial trail: \( u=A \)

Bernoulli trail: failure

Bernoulli trail: success
Figure 4: Observed radial distances and sighting angles to initial sightings, pooled over both platforms.
Figure 5: Normal probability plots of bootstrapped logged total abundance estimates. The panel to the left refers to simulation at $N = 0.9\bar{N}$, etc.
Figure 6: Confidence density for total abundance. The median of the confidence distribution (vertical solid line) is nearly equal to $\hat{N} = 107,205$ (vertical dotted line).
Figure 7: Geographical positions of caught minke whales for the selected years 1952 (green) and 1980 (red). The gradient in background blue color reflects the change from several thousand meters depth in the Norwegian Sea to the shallow Barents Sea proper.