Precision of a Future Antarctic blue whales Line Transect Survey.

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Introduction

Part of the planning process for the IWC-SORP Antarctic Blue Whale Project has been testing how much effort would be required under various survey methods to return a precise estimate of circumpolar abundance for the species (Kelly *et al.* 2012; Peel *et al.* 2014; Peel *et al.* In Press). The question of performance of a mark-recapture approach to return abundance estimate for Antarctic blue whales has been dealt with elsewhere (Peel *et al.* 2014), so here we are exploring only line transect surveys.

In particular, in this short note we are considering how variance of an abundance estimate—its precision—might be predicted for varying amounts of survey effort, given the situation that the study population is, in fact, increasing. As reported by (Burnham, Anderson & Laake 1980) and (Taylor & Gerrodette 1993), for a given amount of effort of a line transect survey, the precision of a resultant abundance estimate is theoretically inversely proportional to the square root of the abundance. However, as a population increases, there may be changes in the way individuals and groups distribute themselves in their habitat. If this is the case, there might be concomitant changes in the distributional properties of sightings given a line transect survey. Here we present a method that accounts for some potential changes in the distributional properties of sightings with an increasing underlying population for Antarctic blue whales, in context of predicting the precision for a given amount of survey effort.

A model of population size

Given that the size of the Antarctic blue whale population remains at a small proportion of its original size, it is reasonable to assume any increases in abundance would still be exponential (i.e. density independent),

$$N_t = N_0(1+r)^t \quad \text{eqn 1}$$

where r is the annual rate of increase, N_0 is the abundance in the starting year of the population projection (1998), and N_t is the abundance in year t.

To demonstrate the large uncertainty for estimates of abundances of Antarctic blue whales from 1998 through to 2025, Fig. 1 shows a population projection using a simple lognormal regression with SOWER abundance estimates. In 2008, during a comprehensive assessment of Antarctic blue whales, the IWC agreed upon a conservative estimate of r of 6.4% (95% credibility interval of 2.4-8.4) (International Whaling Commission 2009). However, given the uncertainty in the population parameters, for the purposes of assessing survey methods, we examined a range of r between 0 and 10% and for N_0, we assumed three population levels for 1998 (2280, a point estimate derived by (Branch 2007) and its corresponding 90% confidence intervals, 1350 and 3450).Scenarios (with background) of circumpolar line transect surveys

To match with SOWER, two survey durations were selected, 6 and 12 years, both to start in 2013; resultant abundance estimates correspond to a mid-point of 2016 and 2019, respectively. The SOWER series (Strindberg & Burt 2004) show how much effort is possible for a single vessel in a single summer. A single vessel spent, on average, just under 38 days south of 60°S during a summer season, achieving an average of 2200 nm of primary search effort, regardless of which SOWER stratum a vessel covered in a given season (Table 1). The realised amount of primary search effort was heavily influenced by weather. Because most sightings of Antarctic blue whales are close to the sea ice boundary in summer (Branch *et al.* 2007), in this study the circumpolar region was stratified into 'northern' and 'southern' strata (see Appendix S1). The latter strata was defined as the area from the dynamic summer sea ice boundary and out to a distance of 200 km; the northern stratum is from the 200 km limit and up to 60°S, with no effort further north.

With the aim of completing a circumpolar survey in 6 or 12 years, non-overlapping blocks of either 60° or 30° of longitude, respectively, would have to be covered each summer season. To be similar to SOWER, of the 2200 nm of effort in each season for the line transect survey, 880 nm would be in the northern stratum and 1330 nm in the southern stratum (Table 1).

Owing to the conspicuous cues of blue whales (Branch 2007) it is reasonable to assume that detection on the trackline is almost certain and a single platform survey (i.e. assumption of $g(0) = 1$) would suffice. Similar to SOWER, track design would be zig-zag within given strata). However, unlike SOWER, in this design the vessel would continue along track during the night. This would ensure that 30° or 60° of longitude could be covered in the summer season (but this would result in more gaps in survey effort throughout that longitudinal range), for example see Fig. 2. In the line transect analysis, the unit of observation is the group rather than the individual whale (although 'groups' of Antarctic blue whales often consist of a single animal), so it is also necessary to estimate mean group size in order to estimate overall abundance. We applied a standard single platform, group-based distance sampling framework. Groups further from the trackline are generally harder to see. Standard distance sampling practice is therefore to truncate the dataset to include only sightings within a specified perpendicular distance d of the track-line, and to estimate the proportion missed within that perpendicular distance.

Abundance estimation via line transect

The true area density of whales (i.e. per unit length of trackline multiplied by d), denoted as D, can be expressed as

$$D = \frac{\rho \bar{s}}{w d} \quad \text{eqn 2}$$

where w is the probability that a group within d of the trackline will actually be seen, $\bar{s}$ is the mean size of a group, and ρ is the expected group encounter rate (i.e. the number of groups likely to be observed within perpendicular distance t of the trackline, per unit length of trackline). Once an estimate $\widehat{D}$ is available, total abundance can be estimated simply by extrapolating $\widehat{D}$ to the total area.

To form $\widehat{D}$, estimates of the three unknowns $(\hat{\rho}, \hat{\bar{s}}, \widehat{w})$ in eqn (2) are required. As per (Buckland *et al.* 2001), it is usually reasonable to assume that these three estimates are statistically independent, and so the overall CV of $\widehat{D}$ can be approximated by the delta method as

$$CV\left(\widehat{D}\right)^2 = CV(\hat{\rho})^2 + CV(\hat{\bar{s}})^2 + CV(\widehat{w})^2 \quad \text{eqn 3}$$

In principle, all three components of eqn (2) may vary across survey strata, as may the density of survey effort, and so D should be estimated separately by stratum. Our analyses of SOWER data did show substantial variation in ρ with distance from ice edge, but not in $\bar{s}$ or w. We therefore considered a single-stratum analysis of s and w, and a multi-stratum (north and south) analysis of ρ, where overall group density was an average of the per-stratum densities ρ_i, weighted by the area of the strata A_i. For overall ρ the CV to be used in eqn (3) is then

$$CV(\hat{\rho}) = \frac{\sqrt{\sum_i (A_i \hat{\rho}_i CV(\hat{\rho}_i))^2}}{\sum A_i \hat{\rho}_i} \quad \text{eqn 4}$$

Assuming similar survey protocols to SOWER, such data provided historical estimates of ρ, $\bar{s}$ and w and their CVs (although, as SOWER was configured for smaller, less conspicuous Antarctic minke whales, the search pattern in future line transect surveys may scan further out from the trackline) , but we need to consider how these are likely to change as true abundance changes. We assumed that Antarctic blue whales will still be distributed in approximately the same way as they were during the SOWER surveys, i.e. that there will not any be major changes in terms of large-scale latitudinal and longitudinal distribution, medium-scale patchiness, or the frequency distribution of group size.

For w and $\bar{s}$, where the existing data do not show much evidence of spatial variation, each encounter constitutes an independent sample. Consequently, their CVs will scale as the inverse-square-root of the number of encounters, which, under the above assumptions, will be directly proportional to the amount of effort and to the abundance. We can therefore scale straightforwardly based on the most recent SOWER results (CPIII).

For the group encounter rate ρ, the situation is more complex. If the distribution of groups within a stratum was completely random (i.e. location of one group is independent of the location of the rest), then the number of groups encountered per transect would follow a Poisson distribution, scaled by transect length. However, it is commonly the case that there is more variability in the actual number of encounters per transect than is consistent with Poisson distributions, but without a clear enough pattern to account systematically for the variation via spatial modelling. If there is an increase in overall abundance, and therefore in the average number of encounters per transect, then the Poisson component of inter-transect variability will diminish, but the component due to patchiness will not (unless there are fundamental changes in the way that groups are distributed).

In terms of eqn (2), overdispersion in the observed number of encounters N_j between transects j corresponds to variability in the *local* expected encounter rate, ρ_j. We can therefore use the CPIII data to estimate inter-transect variability, as follows. Let N_j be the observed number of encounters in a transect of length ℓ_j, then

$$\mathbb{E}[N_j|\rho_j] = \rho_j \ell_j \text{eqn 5}$$

$$\begin{aligned} \mathbb{V}[N_j] &= \mathbb{E}_{\rho_j}[\mathbb{V}[N_j|\rho_j]] + \mathbb{V}_{\rho_j}[\mathbb{E}[N_j|\rho_j]] \\ &= \mathbb{E}_{\rho_j}[\rho_j \ell_j] + \mathbb{V}_{\rho_j}[\rho_j \ell_j] \\ &= \rho \ell_j + \omega \ell_j^2 \text{ eqn 6} \end{aligned}$$

where ω is is the inter-transect variance in ρ_j. It is convenient to assume that ρ_j follows a Gamma distribution, so that N_j is Negative Binomial, and the parameters ρ and ω can be estimated by fitting a NBGLM (Generalised Linear Model extended to include estimation of the shape parameter). The conventional notation for a NBGLM is $\mathbb{V}[X] = \mathbb{E}[X] + \mathbb{E}[X]^2/\theta$. Eqns (5) and (6) can be fitted using an NBGLM with a log-link, an offset of log ℓ_j, an intercept of ρ, and where $\theta = \rho^2/\omega$. Estimation was done separately for the northern and southern strata. Despite the limited number of Antarctic blue whale encounters in SOWER, the NBGLM does indicate substantial overdispersion, with estimated variance typically about three times higher than when overdispersion was fixed at zero.

To predict the distribution of N_j in a new survey, we assumed that there may be a change in the mean of ρ_j, but that the shape of the ρ_j-distribution will not change. This is reasonable if inter-transect variability reflects local variations in habitat quality for Antarctic blue whales, and if the habitat has not changed much since CPIII. Algebraically, this means that ω stays fixed while ρ changes. In practice, the new $\hat{\rho}$ would probably be estimated by re-fitting a NBGLM to the new data. This is essentially equivalent to an optimal inverse-variance-weighted average of the new N_j/ℓ_j using the variances from eqn (6). Assuming transects are independent (i.e. that there is no substantial large-scale spatial patterning within the northern or southern stratum), and applying standard formulae for inverse-variance-weighted means, this yields

$$\mathbb{V}[\hat{\rho}_{new}] = \left(\sum_j \left(\hat{\rho}_{new}\ell_j^{-1} + \omega\right)\right)^{-1}$$

The overall consequence of the overdispersion in N_j is that, for fixed survey effort, $CV(\hat{D})$ will still decline, but more slowly proportional to the inverse-square-root of abundance.

In this study we assumed that only one vessel would complete the line transect surveys. However, in the proposed multinational framework, more than one vessel would likely participate. Different vessels with different observing crews would operate with different detection functions. Pooling density estimates from different detection functions (beyond which could be accommodated with a multiple covariate distance sampling type approach) may impose a penalty on the ultimate precision of an abundance estimate.

Results and Discussion

The predicted precision of line transect surveys increased with larger r and N_0, and with overall duration of survey (Fig.3.).The precisions returned for the 6 year programmes, were all too low to be considered useful. Over a 12 year programme, the predicted precision (CV) for a circumpolar abundance estimate, at N_0=2280 and r=6.4% (i.e. the agreed IWC Antarctic blue whale estimates), was 0.27.

Although precision is fundamental to judging the performance of a survey method, there are satellite considerations that may influence their relative attractiveness. Line transect methods are well established and widely understood; can easily allow collection of sighting data for multiple species; the necessary distribution of transects allows for collection of environmental covariates from a broad spatial range, leading the way to extra environmental modelling; and, finally, the abundance estimates are directly comparable with those previously made with SOWER data. Conversely, line transect can be labour intensive; requires coverage of low density regions (although not necessarily at the same rate as higher density areas); and does not ordinarily facilitate the collection of data to study individual movement and population structure.

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Table 1. Amount and types of effort achievable by a single vessel as informed by CPII, CPIII and research surveys after completion of CPIII of the SOWER series. Southern stratum is defined as the area between the sea ice boundary and out to a distance of 200 km; the northern stratum is from the 200 km limit and up to 60°S.

	Total length-hours (days)	Overnight - hours	Bad weather and drift – hours	Confirming and experimental —hours	Primary search effort – hours	Primary search effort (nm)	Track length achievable (nm)
Northern stratum	360 (15)	144	133	12	70	880	3390
Southern stratum	540 (22.5)	216	171	27	122	1320	5850
All	900 (37.5)	360	304	39	192	2 200	9240

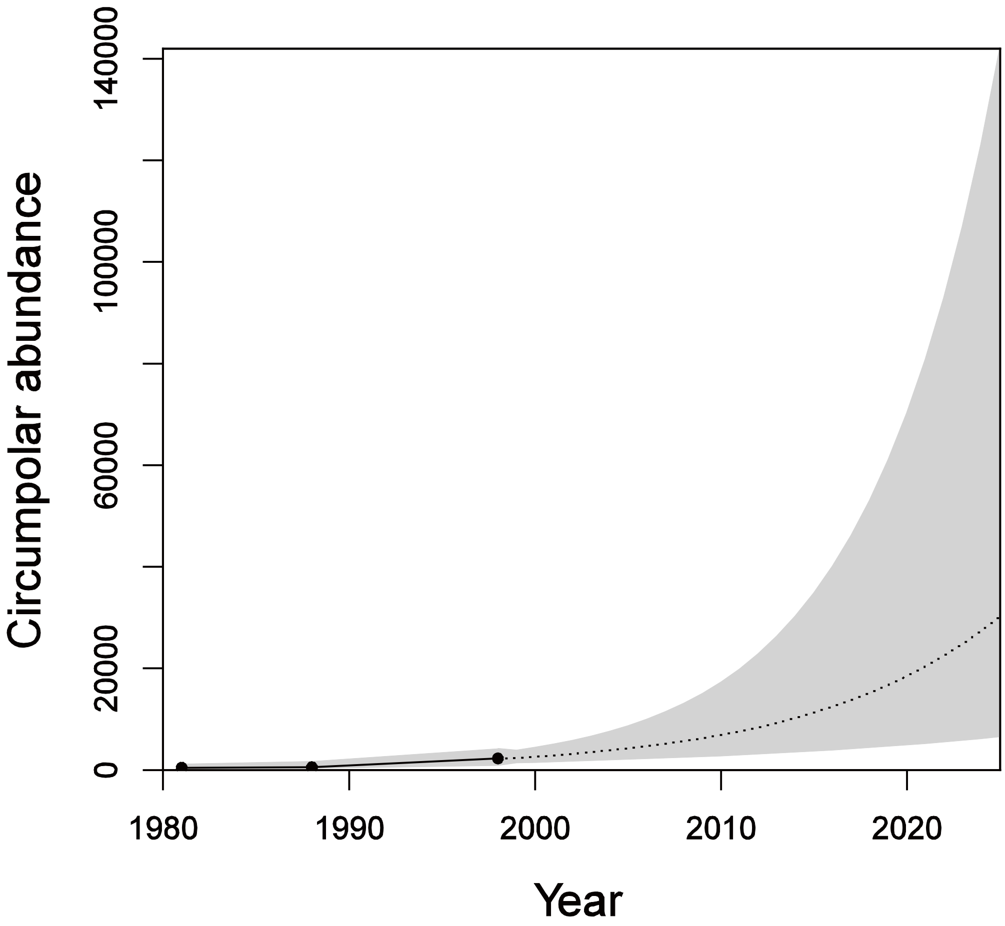

Fig. 1. Estimated and projected circumpolar abundance estimate for Antarctic blue whales. Circles and joining solid line represent circumpolar abundance estimates for CPI (1978/79-1983/84), CPII (1985/86-1990/91) and CPIII (1991/92-2003/04), with associated 95% confidence intervals in grey (from (Branch 2007)). Dotted line beyond 1998 represents projected abundance, with 90% confidence interval in grey.

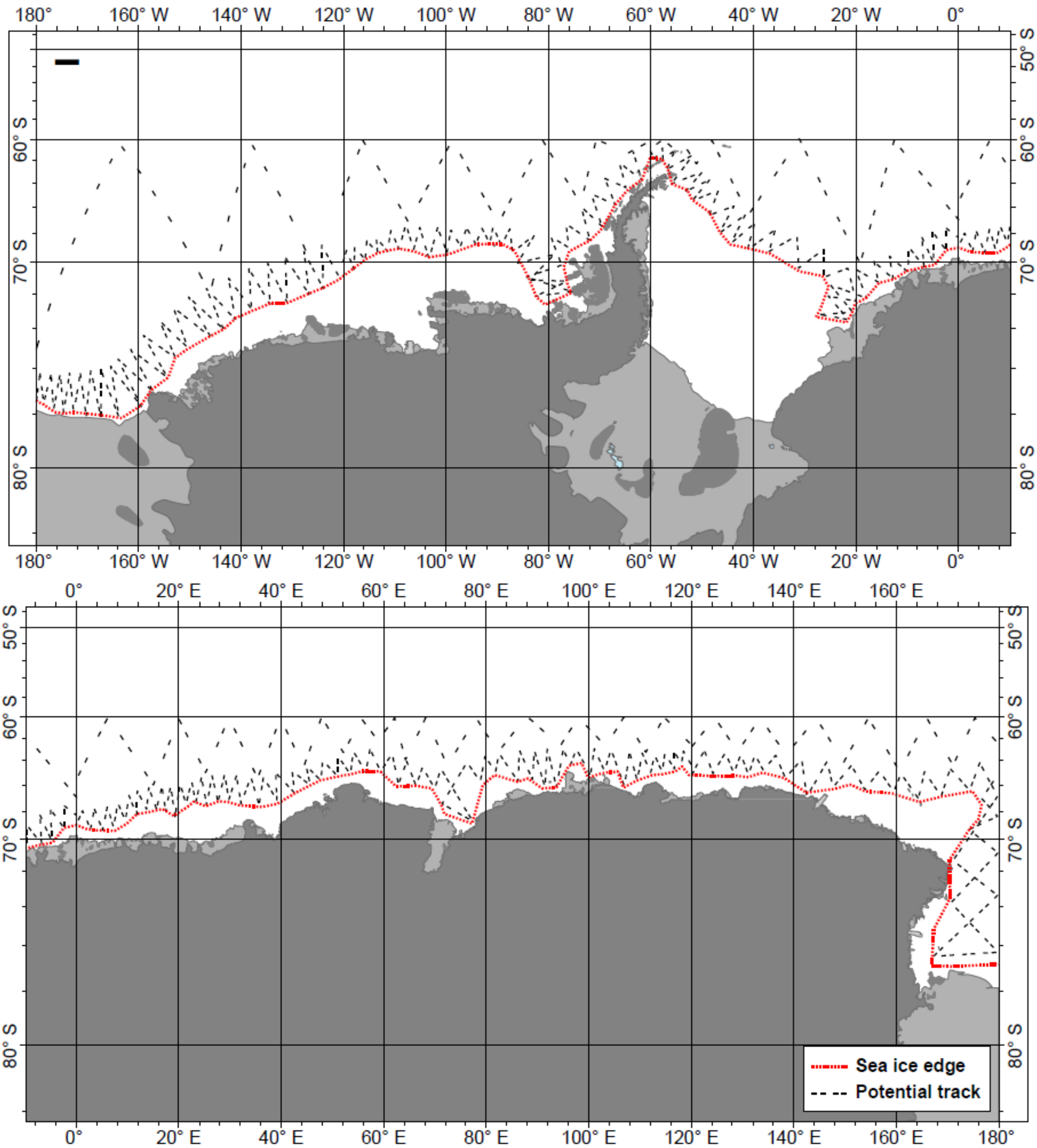

Fig. 2. Demonstration line transect survey ‘outcomes’ from a 6 year programme (i.e. surveying 60° of longitude in each survey year).

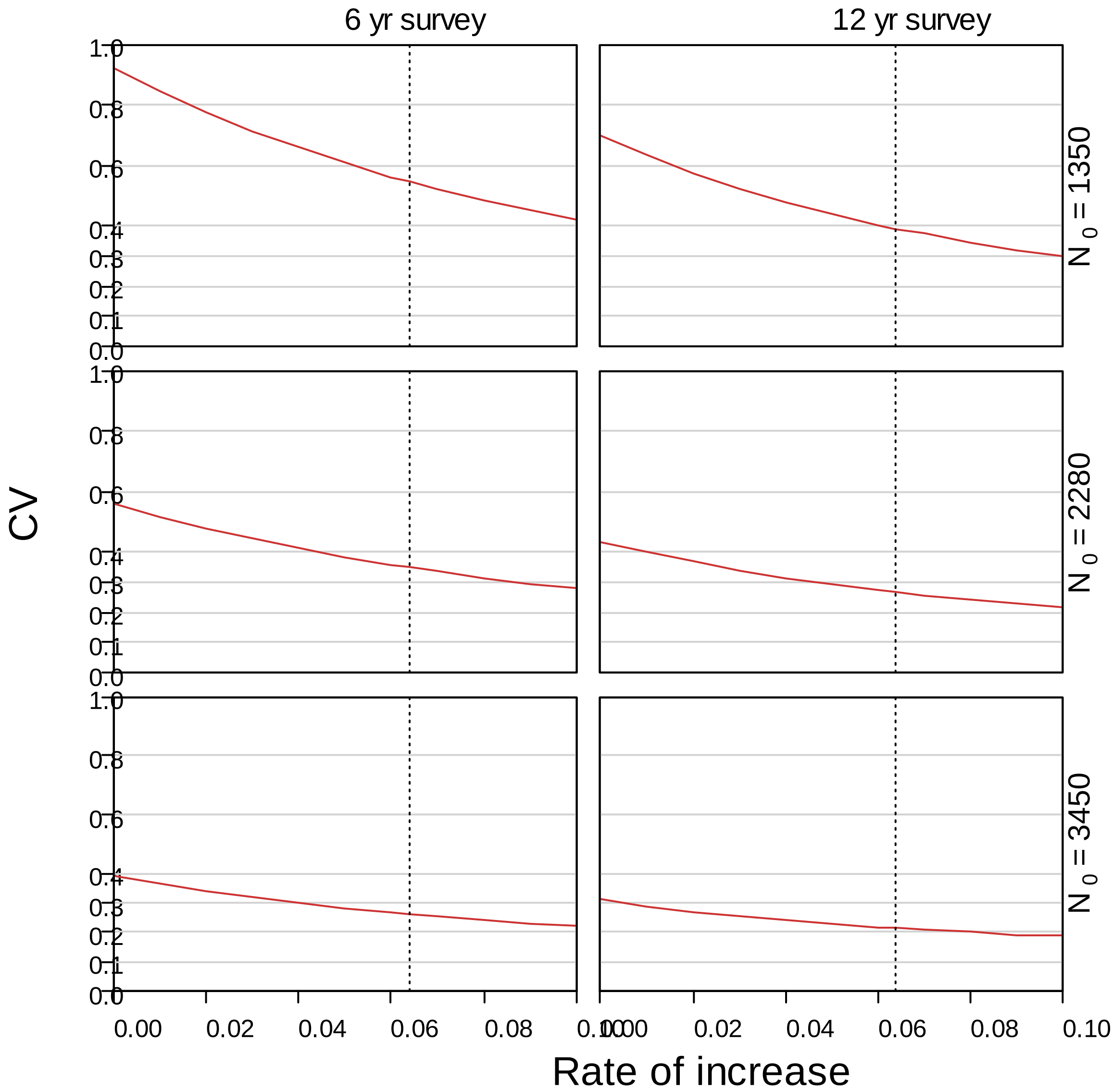

Fig 3. Predicted CV of a circumpolar line transect survey (assumed circumpolar abundance in 1998 of N_0 = 1350, 2280 and 3450), for both 6 and 12 year circumpolar survey lengths, across three different underlying annual rates of increase (0.00, 0.064 and 0.1).

Appendix S1 Finding an approximately optimal stratification of the circumpolar region

Stratifying the survey region is helpful when there are broad-scale and predictable gradients in animal densities (Thomas, Williams & Sandilands 2007). As only within-stratum variation contributes to variance of estimators, dividing the survey region up into areas of homogeneous densities, so the within-stratum variation is minimised, and the between-stratum variation is maximised, will increase the precision of the overall abundance (Thomson 2012).

Suppose for some survey region there are two strata, the first with N_1 whales in a total area A_1 to which effort E_1 will be applied, and similarly N_2, A_2, and E_2 for the second. Assume the total effort is constrained to sum to 1, so that E_2=1-E_1 (with some simplifying assumptions the optimal split is independent of the total amount of effort, so it is assumed total effort E=1). We want to choose E_1 to get the lowest overall variance in the estimated total number of whales $\widehat{N}$. The dominant term in the variance of an abundance estimate $\mathbb{V}(\widehat{N})$ is almost always the variance in the encounter rate bits, not the uncertainty in $\bar{s}$ and w, so the latter can be treated as known (i.e. they are assumed to have no variance for the purposes of this exercise).

Let M_1 be the number of encounters in stratum 1. We have

$$\mathbb{E}[M_1] = k\frac{N_1 E_1}{A_1}$$

for some constant k that is related to w and $\bar{s}$. Setting k=1 for convenience, our estimate of N_1 will be

$$\widehat{N}_1 = \frac{M_1 A_1}{E_1}$$

This has expected value $\mathbb{E}[M_1]A_1/E_1 = N_1$ and variance $\mathbb{V}[M_1]A_1^2/E_1^2$. Assuming, for this exercise, quasi-Poisson-type variability for N_1 we have $\mathbb{V}[M_1] \propto \mathbb{E}[M_1]$ so that

$$\mathbb{V}[\widehat{N}_1] = \frac{N_1 E_1}{A_1}\left(\frac{A_1}{E_1}\right)^2$$

$$= \frac{N_1 A_1}{E_1}$$

The combined abundance estimate is $\widehat{N} = \widehat{N}_1 + \widehat{N}_2$ with variance

$$\mathbb{V}[\widehat{N}] = \frac{N_1 A_1}{E_1} + \frac{N_2 A_2}{E_2}$$

$$= \frac{N_1 A_1}{E_1} + \frac{N_2 A_2}{1 - E_1} \qquad \text{(eqn 1)}$$

and we choose E_1 to minimise this variance. To do this, we differentiate with respect to E_1 and set the derivative to zero at the optimum, $\tilde{E}_1$:

$$-\frac{N_1 A_1}{\tilde{E}_1{}^2} + \frac{N_2 A_2}{\left(1 - \tilde{E}_1\right)^2} = 0$$

$$\Rightarrow \left(1 - \tilde{E}_1\right)^2 = \Delta \tilde{E}_1{}^2$$

where $\Delta = N_2 A_2 / N_1 A_1$. Then solving the quadratic

$$1 - 2\tilde{E}_1 + \tilde{E}_1{}^2(1 - \Delta) = 0$$

$$\tilde{E}_1 = \frac{2 \pm \sqrt{4 - 4(1 - \Delta)}}{2(1 - \Delta)}$$

$$= \frac{1 \pm \sqrt{\Delta}}{1 - \Delta}$$

As we need $0 < \tilde{E}_1 < 1$, the following solution is required

$$E_1^{opt} = \tilde{E}_1 = \frac{1 - \sqrt{\Delta}}{1 - \Delta}$$

Having obtained E_1^{opt}, we substitute back into eqn 1 to get the best possible variance for that stratification (i.e. with the best possible effort split). We can then change the stratum boundaries (i.e. N_1, N_2, A_1, A_2) and repeat the exercise, searching for the best stratum boundary (choosing the best effort split for each boundary we are considering).

Throughout the SOWER series, higher densities of Antarctic blue whales were observed near the sea ice boundary, as compared to regions further north. We used encounter rates of Antarctic blue whales from the third (CPIII; 1991/92-2003/04) SOWER survey as a proxy for densities south of 60°S (i.e. all things remaining equal, regions with larger encounter rates would indicate a larger local density) in order to define a strata for testing survey methods to estimate a circumpolar abundance estimate. Encounter rate is defined by the number of sightings of a target species per unit of distance (say, nautical miles or kilometres) of primary search effort. The density gradient we considered was perpendicular to the circumpolar sea ice edge, which runs, generally speaking, north-south in the Southern Ocean.

For simplicity, encounter rates were pooled across all longitudes (as there was no intention of stratifying longitudinally into east and west areas). To summarise encounter rates, at the CPIII level, as a function of distance from the sea ice edge, transects were assigned to 50 km wide bins, out to a distance of around 1200 km; the distance of a given transect from the sea ice edge was defined as its mean the great-circle distance from this feature. The position of the sea ice edge was estimated either from observations during SOWER surveys, or from remotely sensed sea ice data (AMSR-E; Spreen, Kaleschke & Heygster 2005; Spreen, Kaleschke & Heygster 2008) when vessels were too far north for local observations.

Within the *k*th distance bin, a mean encounter rate, ρ_k was estimated as a weighted-mean across the T_k transects within the bin,

$$\hat{\rho}_k = \frac{\sum_{i=1}^{T_k} \left(\rho_{k,i} \cdot w_{k,i}\right)}{\sum_{i=1}^{T_k} w_{k,i}}$$

where the encounter rate, $\rho_{k,i} = \frac{n_{k,i}}{l_{k,i}}$ from the *i*th transect of the *k*th distance bin, is given by dividing the number of encounters and $n_{k,i}$ by the transect length $l_{k,i}$, and the weights w_{i_k} are given by

$$w_{i_k} = \frac{l_{k,i}}{\sum_{i=1}^{T_k} (l_{k,i})}.$$

Encounter rates for CPIII, as a function of distance from the summer sea ice edge is given in Fig. S1. Generally speaking, encounter rate is highest nearest to the sea ice edge, decreasing to close to zero further out (with the exception of a small spike at 850 km, which represents a single sighting with little associated effort; therefore, local encounter rate was high).

The results of substituting in estimated abundances (estimated to scale roughly with the encounter rate and the stratum area, A_1 or A_2), N_1 and N_2, into eqn 1, are given in Table S1. The lowest variance is associated with a stratum boundary at around 200 km from the summer sea ice boundary.

Table S1 Distribution of variance estimates on an abundance estimate for various positions of the boundary between the southern and northern strata. Distance is km from the summer sea ice boundary.

Possible strata boundary (km)	50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	50
Overall variance estimate	371.0	373.3	378.2	**364.8**	374.3	378.4	383.8	383.9	382.3	383.8	379.9	384.8	387.8	388.5	386.8	382.0	371.0
E_1^{opt}	0.086	0.14	0.18	0.27	0.3	0.34	0.36	0.41	0.47	0.52	0.59	0.61	0.64	0.66	0.69	0.72	0.086

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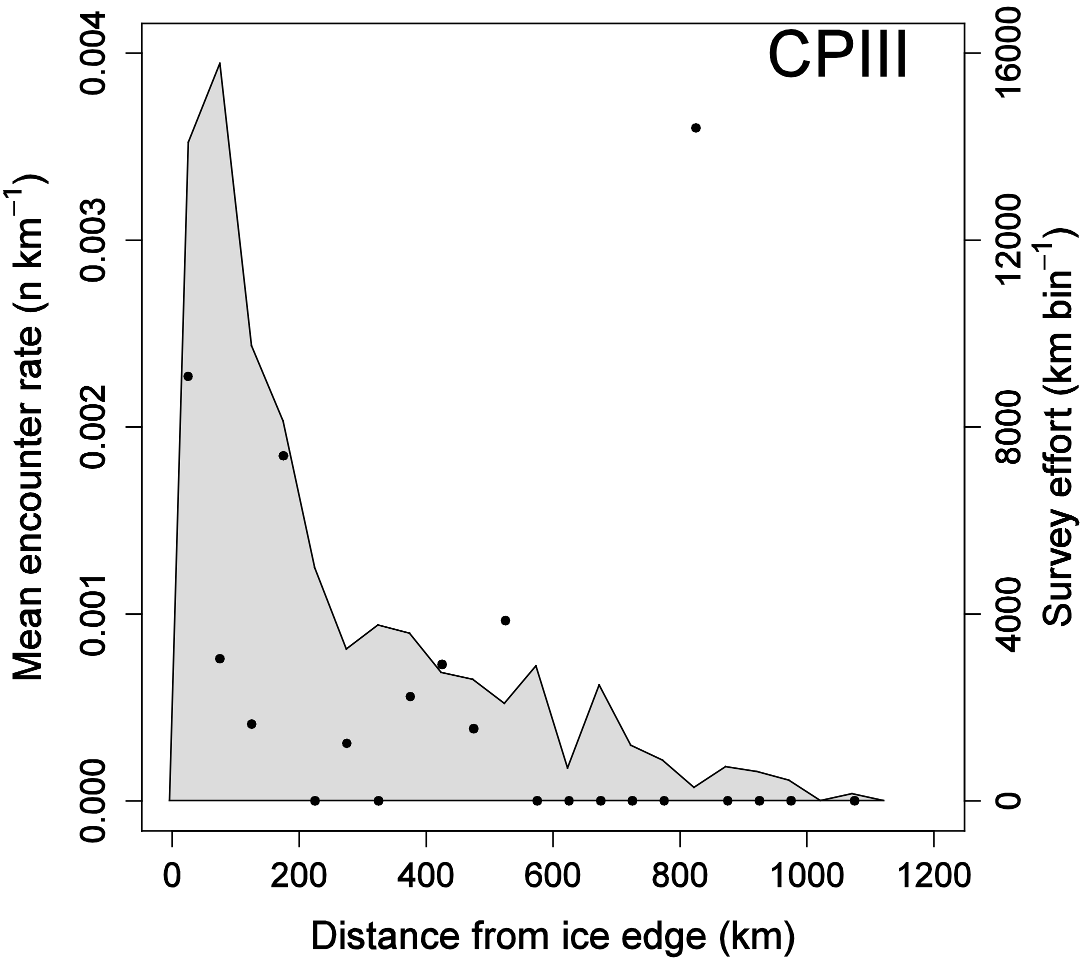

Fig. S1 Distribution of encounter rate (sightings of Antarctic blue whales per km of primary search effort) and total primary search effort with distance from sea ice edge, for CPIII. Encounter rate, given in black circles, is a weighted average per 50 km bin, representing distance from the sea ice edge; weights were derived from the length of each survey segment. The grey shaded area represents the total survey effort in each 50 km distance bin; scale for this survey length is given on the right-most y-axis.