Comparison of closing and passing mode from a line-transect survey of delphinids in the eastern Tropical Pacific Ocean

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ABSTRACT

Line-transect ship surveys are the primary method used to estimate abundance of pelagic cetaceans. However, survey methods are often modified from traditional methods because observers must approach cetacean groups to identify species and estimate group size. Returning to the trackline after approaching a school dramatically reduces the amount of effective survey time, so ships often resume survey effort at the sighting but parallel to the original trackline (closing mode). Survey effort is no longer independent of group locations, and it is unclear how such methodological modifications affect overall abundance estimates. This research presents the results of a study designed to determine the effects of closing mode methods on abundance estimation for cetacean species in the eastern tropical Pacific. Species identification and group size estimation in closing mode are compared with results using survey techniques where the ship does not approach or slow down to investigate a sighting (passing mode). Both empirical data and simulations were used to compare group encounter rates in the two modes and to better understand the mechanisms that might lead to an encounter rate bias in closing mode. As seen in similar studies, observers are able to identify to the species level less frequently in passing mode (81% vs 57% of sightings), and point estimates of delphinid group size were 58% lower in passing mode than closing mode at distances between 1.0 and 5.5km from the trackline. In addition, uncertainty in group size both within and between observers was higher in passing mode. Closing mode delphinid group encounter rates were generally 20–25% lower than passing mode delphinid group encounter rates. Simulations showed the empirically lower encounter rates in closing mode are due to a loss in detection probability caused by the stop-start nature of the survey method. The closing mode encounter rate bias is greater when groups are in fewer and/or tighter clusters and when overall group density is higher. Methodological adjustments and analytical solutions to improve group size estimation and species identification in passing mode and reduce closing mode encounter rate bias are analytically complex and would also result in the loss of important additional life history data. Nevertheless, such avenues should be explored further.

KEY WORDS: SURVEY-VESSEL; SAMPLING STRATEGY; MODELLING; PACIFIC OCEAN; ABUNDANCE ESTIMATE; *g*(0); SCHOOL SIZE

INTRODUCTION

Line-transect analysis is a well-developed and widely used method of estimating density and abundance (Buckland *et al.*, 2001). Data for a line-transect analysis are collected by moving along a transect line and recording the perpendicular distances at which the objects of interest are detected. Detection probabilities are then estimated as a function of perpendicular distance from the trackline; density estimates are calculated as a function of detection probability, amount of trackline covered and overall cluster size (if objects are clustered).

Line-transect surveys are the primary method used to estimate abundance of pelagic cetaceans (e.g. Barlow, 2006; Branch, 2007; Branch and Butterworth, 2001a; 2001b; Branch *et al.*, 2004; Calambokidis and Barlow, 2004; Dolar *et al.*, 2006; Gerrodette and Forcada, 2005; Goodwin and Speedie, 2008; Hammond *et al.*, 2002; Miyashita, 1993; Mullin and Fulling, 2004). Cetacean line-transect surveys are typically conducted using one of two methods, called passing mode and closing mode. In a passing mode survey, the platform (ship or plane) moves continuously along a transect line. When a group of cetaceans is seen, visual observers determine species composition and estimate group size without leaving the transect line. In a closing mode survey, the platform stops normal searching procedures once a group of cetaceans is sighted (goes 'off-effort'), leaves the transect line and approaches the sighted group to identify the species and stock composition of the group and to make reliable estimates of group size. Once observers have recorded such information, search effort begins again (going 'on-effort'). The platform can either return to the trackline and resume effort at the point it was terminated or continue from the point of the sighting and travel along a new trajectory parallel to the original trackline. The latter is often employed during ship-based surveys since the amount of time needed to return to the original trackline would dramatically reduce overall sampling effort. Such a method also ensures the previous sighting remains 'behind' the ship and is not double counted.

When the ship does not return to the transect line but continues in a parallel direction from the point of the last sighting, the discontinuous searching effort of closing mode could bias data collection and abundance estimation in several ways. First, on-effort searching is usually carried out in the 180° arc ahead of the ship. When a sighting is made and the observers go off-effort, the area surveyed is calculated as a function of the distance travelled by the vessel from the start of effort to the point at which the observers go off effort, which does not include the area surveyed ahead of the ship (Barlow, 1997). The underestimate in area surveyed would lead to an overestimate of abundance. A second, related issue arises when observers resume scanning effort and there are schools already within visible range. Because these schools are within the search area for a shorter period

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of time, they have a lower detection probability (for the same perpendicular distance) compared to schools further down the trackline. Such an effect would lead to an underestimate of abundance. A third issue arises because the placement of the transect line is no longer random in relation to group distribution after the first sighting. If the ship is travelling through areas of non-uniform group distribution, the ship might get pulled in to high density areas on successive sightings (Haw, 1991). This non-random sampling would lead to an overestimate of abundance. Passing mode has been considered less biased when estimating school density, but closing mode is used because school size estimation and species identification are considered unreliable in passing mode.

By alternating passing and closing days during line-transect surveys, several studies have investigated differences in cetacean abundance estimates using the two survey methods. During the 1984/85 field season, the Antarctic minke whale survey alternated between passing and closing mode on successive days. Passing mode for minke whale surveys is also called independent observer (IO) mode because of the presence of an additional observer (Branch and Butterworth, 2001b). Haw (1991) found minke whale group density estimates to be 20–25% lower in closing mode than in passing mode. In addition, the overall perpendicular distance at which schools were detected appeared shorter in closing mode, leading the author to believe detection probabilities are lower in closing mode. Thus, Branch and Butterworth (2001b) applied a 17% correction factor for negative bias for closing mode surveys for minke whales. Results from the 1984/85 study also led to the incorporation of some passing mode effort during subsequent surveys (Matsuoka *et al.*, 2003). During cetacean line-transect surveys off the west coast of the USA, Barlow (1997) alternated two days in closing mode with one day in passing mode. Results showed species identification was particularly poor in passing mode, and passing mode school size estimates were often lower than closing mode estimates. He found common dolphin group encounter rates were significantly higher in closing mode than in passing mode. However, the preferred habitat for this species may have been undersampled in passing mode. Encounter rates were not significantly different for other species.

This paper reports the results of an experiment designed to compare passing and closing line-transect surveys in the eastern Tropical Pacific Ocean (ETP). Southwest Fisheries Science Center (SWFSC) has used closing mode line-transect surveys in the ETP since the 1970s to estimate abundance of several dolphin species affected by the purse-seine tuna fishing industry (Gerrodette and Forcada, 2005). Over a three month period, passing and closing mode surveys were conducted on alternate days on predetermined tracklines, repeated every 21 days. We compare the data collected in the two modes and use a simulation study to examine reasons for some of the differences.

METHODS

Field methods

To better understand the overall differences between passing and closing mode, we chose a study area thought to be rather homogeneous with respect to environment. The NOAA Ship *MacArthur II* surveyed in a region approximately 200–250 n.miles southwest of Manzanillo, Mexico from late August through late November 2007 (Fig. 1). The survey area is located in the middle of the eastern Pacific warm pool and is also far enough away from the coast to avoid coastal eddies and upwelling that lead to temporal and spatial shifts in the thermocline (Tomczak and Godfrey, 1994). The study area is also a region of relatively high cetacean abundance and is located close enough to land to allow for quick and easy resupply and exchange of personnel. The area was surveyed during four separate legs, each leg lasting three weeks. The duration of each leg was limited by ship supply needs. Timing of the survey coincided with the traditional timing of cetacean surveys conducted in the ETP. During each leg, the objective was to survey along the tracklines of two different diamond patterns twice. Each side of the diamond was to be surveyed on consecutive days, one day in passing mode and the other day in closing mode. The daily trackline distance (90 n.miles) could easily be completed in one day in passing mode but was also short enough that the ship could reach the end point of each line in time for nightly oceanographic stations even when closing mode prevented completion of the trackline. For more information on the methods and ecosystem data from the survey, see Archer *et al.* (2008).

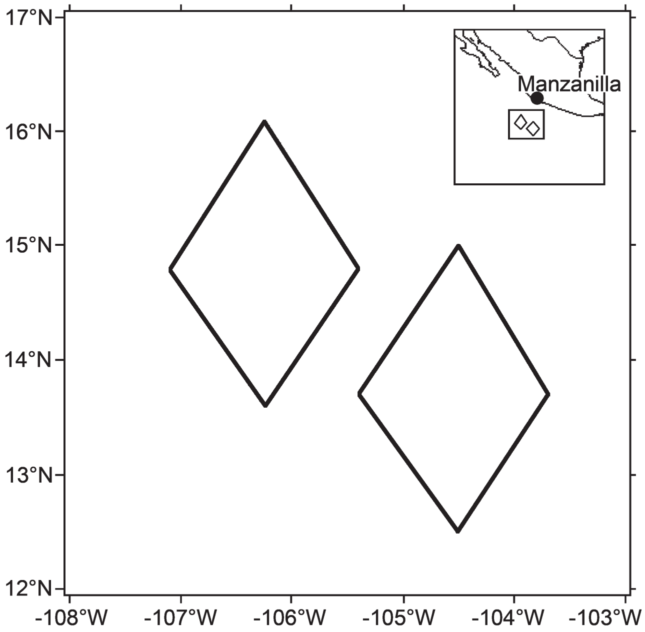

Fig. 1. Study area and tracklines.

Methods for cetacean line-transect surveys by the SWFSC have been consistent since 1986 (Kinzey *et al.*, 2000). Three observers are stationed on the flying bridge of the ship which is travelling at a constant speed of 18.5km/hr (10 knots). Two observers scan for schools using 25 × 150 binoculars mounted on each side of the ship. Each observer sweeps the area from the trackline (0°) to 90° to the left or right of the trackline. In this manner, the area 180° in front of the ship is scanned with high-powered binoculars. Prior to 2003, observers scanned an additional 10° over the trackline, so the 20° area directly in front of the ship was scanned by both observers. Such scanning overlap was not conducted in this study. A third observer in the middle, also acting as data recorder, scans for schools near the ship with the naked eye and hand-held 7× binoculars, covering the entire 180º area ahead of the ship. The searching method used in this study is exactly the same as methods used in previous studies. The difference between passing and closing mode occurs when a cetacean group is detected.

Passing mode is a form of line-transect sampling used in most non-cetacean surveys. Within the ETP, passing mode consists of the following steps. The ship travels at a constant speed (18.52km/h) along the predetermined trackline. When a cetacean school is sighted, only the observer who detected the school attempts to identify the school to species and estimate school size. Angle and binocular reticle readings are also taken for each group which are later converted to perpendicular and radial distances (Kinzey and Gerrodette, 2003). Observers do not terminate effort to investigate the school or to give an observer more time for species identification or school size estimation. The ship does not deviate from the trackline or slow down when a group is detected. Scanning effort is not continuous, since the observer must briefly stop scanning to determine school size and species. The methods are somewhat different from passing (IO) mode methods during Antarctic minke whale surveys where one group of observers continuously scans while another group is responsible for species ID and school size estimation (Haw, 1991).

Cetacean species identification and school size estimation can be difficult from a distance, so closing mode is often used in cetacean line-transect surveys. During closing mode, as in passing mode in the ETP, the ship begins on a predetermined trackline with a given bearing and constant speed. When a cetacean school is detected, the observers terminate search effort, and the ship manoeuvres to approach the school. All three observers work together to identify species within the school, and each observer makes an independent estimate of school size, recording best, high and low estimates. Additional data may be collected, such as photographs and biopsies (Jackson *et al.*, 2008). Depending on the school's distance from the ship, size and species composition, observers may spend anywhere from five minutes to several hours collecting data on a single school. When observers are finished investigating a school, the ship returns to its original bearing and speed, and scanning effort resumes. In almost all cases, the ship does not return to the original trackline before resuming effort. However, to prevent surveying too far from the original trackline, the ship bearing is altered to return to the line at a 20º angle if the ship has moved more than 18.5km (10 n.miles) from the line.

Analysis

Similar to other analyses of ETP data, we limited the data within certain sighting conditions (visibility > 5.5km and Beaufort sea state ≤ 5) and only included sightings detected within 5.5km perpendicular distance from the trackline.

Species identification

Species identification was based on a tiered system and the level of identification depends on the expert judgment of the observers. The least descriptive identification is 'Unidentified Cetacean.' Observers are often able to identify schools to a species or even sub-species level, and schools may have more than one species present. To compare the ability of observers to identify schools to the species or subspecies level, schools were tallied based on level of species identification (identified to species or subspecies level vs not identified to species or subspecies level). Using a binomial likelihood with a uniform conjugate prior distribution of $\beta eta(1,1)$, the posterior distribution of the probability a school is identified to the species or subspecies level becomes $\beta eta(n + 1, N - n + 1)$, where n is the number of schools identified to the species or subspecies level, and N is the total number of detected schools (Gelman *et al.*, 1995). The number of schools with more than one species identified were also tallied for both passing and closing mode and the same Bayesian binomial method was used to determine the probability schools were composed of more than one species (n = number of mixed-species schools, N = total number of detected schools). Comparison of passing and closing modes was done via comparison of 100,000 random samples from the respective beta distributions.

Identification during passing mode was poor, so comparison of school sizes and encounter rates in passing and closing modes on a species-by-species basis was not feasible (see Results). To create a reasonable sample size for further analyses of school size and encounter rate, several identification categories were combined in to a 'delphinid' category: unidentified dolphin, unidentified medium delphinid, unidentified small delphinid, spinner dolphin (*Stenella longirostris*; unidentified subspecies), pygmy killer whale (*Feresa attenuata*), Risso's dolphin (*Grampus griseus*), rough-toothed dolphin (*Steno bredanensis*), common bottlenose dolphin (*Tursiops truncatus*), pantropical spotted dolphin (*Stenella attenuata*; offshore), eastern spinner dolphin (*Stenella longirostris orientalis*), striped dolphin (*Stenella coeruleoalba*) and common dolphin (*Delphinus delphis*).

Delphinid school size

School size estimates were calculated using the methods described in Gerrodette and Forcada (2005). Prior to this study, each observer's school size estimates were 'calibrated' by comparing their estimates to school size counts from aerial photographs of the same school (Gilpatrick, 1993). The observers' school size raw estimates are adjusted by observer-specific regressions which include effects of year and school size (Barlow *et al.*, 1998; Gerrodette *et al.*, 2002). On occasion, observers will only record a low count if they feel they did not get a thorough look at the school. In such cases, the low count is used as an observer's best estimate. The logarithm of the point estimate on school size was:

$$\ell n\ \hat{s} = \sum_{i=1}^{n} w_i\ \ell n\ C_i \tag{1}$$

with variance

$$\operatorname{var}(\ell n\ \hat{s}) = \sum_{i=1}^{n} w_i^2 \operatorname{var}(\ell n\ C_i) \tag{2}$$

where

n = number of calibrated estimates (C) for the school

$w_i = {}^{v_i^{-1}} \big/ \sum {}^{v_i^{-1}}$

v_i = var ($\ell n\ C_i$), the residual variance of the log-log regression of school size estimates vs photo counts for the observer

The above calculations and calibrations are based on school size estimates in closing mode only, when each observer has a prolonged opportunity to estimate school size at a close distance. School size calibration has never been done for passing mode estimates; so for this analysis, the same calibration coefficients and calculation methods were used for both passing and closing modes. Variance estimates account for differences among observers and uncertainty in the calibration relationship.

To analytically compare school size estimates for the two survey methods, a Bayesian analysis was conducted using a lognormal likelihood with unknown mean and variance. Data were school size point estimates (Equation 1), grouped by survey method and perpendicular distance from the trackline (0 to 1km vs 1 to 5.5km). Comparison of passing and closing modes was done via comparison of 100,000 random samples from the respective posterior lognormal distributions. When only one observer reports a low estimate for school size, variance calculations are not possible, so uncertainty in school size point estimates was not incorporated into the Bayesian model. However, to compare additional measurement uncertainty for each school and observer, the range of high to low estimates standardised by the best estimates was calculated. In addition, standard deviations of $\ln \hat{s}$ as a function of distance from the trackline and survey method are reported when school sizes were based on more than one low estimate.

Delphinid school encounter rate

Since previous studies have shown that species identification and school size estimation were compromised in passing mode, our analytical methods focused on comparing school encounter rates (number of detected schools/km effort) between passing and closing mode. We first develop a model that assumes school placement is temporally and spatially random. However, daily encounter rates are probably not temporally random due to potential large scale movements of groups in to and out of the area, most likely due to environmental changes. Therefore, we also developed a hierarchical Bayesian model, treating each day as an independent estimate of encounter rate. Since encounter rates decline with sea state and our estimates did not adjust for such changes, data were partitioned and analysed separately by sea state.

To estimate school encounter rate, we started by assuming school location was random in relation to the trackline and each other. In that case, the number of detected schools follows a Poisson process:

$$p\ (x \mid \lambda t) = \frac{(\lambda t)^x}{x!}\ e^{-\lambda t} \tag{3}$$

where

x = count of detected schools

t = km of effort (known and constant)

λ = encounter rate

The above equation becomes the likelihood when estimating daily encounter rates. The prior on λt can be expressed differently and the data partitioned in various ways depending on how confident we are in the assumption of temporally and/or spatially random placement of schools. If we assume school placement is completely random, all survey data can be pooled and a conjugate gamma prior for λt can be used (Robert, 2001):

$$\pi\ (\lambda t) = \frac{\beta^{\alpha}}{\Gamma(\alpha)}\ (\lambda t)^{\alpha-1}\ e^{-\beta\lambda t} \tag{4}$$

where

α = gamma distribution shape parameter

β = gamma distribution inverse scale parameter.

With a conjugate prior, the posterior on λt is another gamma distribution (Robert, 2001):

$$\lambda t \mid x \sim \text{Gamma}(\alpha + x,\ \beta + 1). \tag{5}$$

By transformation, the posterior on encounter rate is also a gamma distribution:

$$\lambda \mid x,t \sim \text{Gamma}(\alpha + x,\ (\beta + 1)t). \tag{6}$$

The prior distribution becomes vague or non-informative as α and β approach zero (Robert, 2001). In this case, both parameters were set constant at 10^{-6}. Setting the constants smaller or larger by a magnitude of three did not affect the outcome of the analysis, indicating 10^{-6} was essentially zero.

A second estimate of school encounter rate relaxed the assumption that school density was the same for all days. In this region, school density may potentially change on a daily scale due to various ecosystem dynamics. So, another form of analysis used each day as an exchangeable and independent sample of encounter rate in a hierarchical Bayesian model. Daily encounter rates may not be independent because of changes in temporally correlated environmental variables. However, the experimental design randomised the environmental variables since passing and closing methods were performed in pairs of days.

We still assumed school distribution was random within any given day, so the likelihood was a product of Poisson distributions on a daily scale.

$$p(\underline{x} \mid \underline{\lambda t}) = \prod_{i=1}^{m} \frac{(\lambda_i t_i)^{x_i}}{x_i!}\ e^{-\lambda_i t_i} \tag{7}$$

where m is the total number of days of sampling. However, now we assume that each daily encounter rate is drawn from a gamma-distributed overall encounter rate, so the prior distribution for all daily encounter rates (λ) becomes a multiple of a gamma distribution.

$$p(\underline{\lambda} \mid \gamma,\phi) = \prod_{i=1}^{m} \frac{\phi^{\gamma}}{\Gamma(\gamma)}\ (\lambda_i)^{\gamma-1}\ e^{-\phi\lambda_i} \tag{8}$$

where

γ = gamma distribution shape parameter for overall encounter rate

ϕ = gamma distribution inverse scale parameter for overall encounter rate

Note the gamma prior distribution in the hierarchical analysis describes the distribution of overall encounter rates and is not the same as the conjugate gamma prior described for λt when pooling the data. In the hierarchical model, the gamma distribution was chosen for its flexibility and because values are limited above zero. We used Jeffery's hyperpriors on γ and ϕ: independent uniforms on the log of γ and ϕ (Miller, 1980).

$$\pi(\gamma,\phi) \propto \frac{1}{\gamma\phi} \tag{9}$$

Linking all probabilities together gives us the final joint posterior distribution of γ and . We also have posterior distributions for λ, but they are not relevant here since we are interested in the derived posterior distribution of overall encounter rate based on posterior distributions of γ and .

$$p(\underline{\lambda}, \gamma, \phi \mid \underline{x}, t) \propto p(\underline{\lambda} \mid \gamma, \phi) \cdot p(\underline{x} \mid \underline{\lambda t}) \cdot \pi(\gamma, \phi) \tag{10}$$

The hierarchical Bayesian analysis was done using program MTG (Metropolis within Gibbs) developed by Daniel Goodman of Montana State University (Schwarz, 2008). To maximise computer efficiency, simulations were performed on orthogonally transformed parameters when correlation between parameters was high (γ and ϕ). Simulations were set for a rejection rate near 0.7, a sub sampling (thinning) of 1 in 150 and a burn-in period of 150, continuing for a subsample size of 10,000 for each inference (see Cowles and Carlin, 1995). The resulting lag-1 autocorrelations were <0.1, and independent chains with different parameter starting values gave indistinguishable results. To verify convergence and stationarity within the final chains, we used the Heidelberger and Welch convergence diagnostic available from the CODA package in *R* using standard 10% increments and $p \leq 0.05$ (Heidelberger and Welch, 1983; Plummer *et al.*, 2006). Results are reported as the ratio of the derived posterior distributions of closing mode encounter rate over passing mode encounter rate.

In general, school detection probabilities decline with higher Beaufort sea state level (Barlow *et al.*, 2001; Gerrodette and Forcada, 2005; Teilmann, 2003), and the proportion of time spent surveying in each sea state was not equal for passing and closing modes simply due to random factors. Since encounter rates are not adjusted for changes in detection probability by sea state, data (observations and km of effort) were partitioned and analysed separately by sea state. However, Beaufort sea states 0 and 1 were combined since sample size was small for these two categories. Sighting conditions are nearly identical in such excellent weather conditions. Although data collection procedures were designed to produce pairs of days in passing and closing modes along the same trackline, data were not analysed in a pair-wise fashion for two reasons. First, we found fluctuations in encounter rates between paired days to be just as high as fluctuations between all days. Second, fluctuations in sea state were highly variable on a daily scale, making paired day comparisons inappropriate. Final 'delphinid' abundance estimates were not calculated because simulation results (see below) led us to believe we need to re-measure several variables and rethink some assumptions that go in to such a calculation.

Simulation

To understand the mechanisms that lead to differences in passing and closing mode encounter rates, a line-transect simulation was developed. The simulation exercise accounts for all known potential sources of bias in closing mode. All schools within detection range along the trackline have the potential to be detected based on the schools' radial distance from the ship, which accounts for scanning in front of the ship. With spatially clustered schools, ships in closing mode have the potential to spend more survey effort in high density areas. Lastly, the detection probability equations account for lower detection probabilities for schools closer to the ship when survey effort resumes. The simulation does not account for passing mode biases, namely school size estimates and species identification.

The simulation is based on the instantaneous probability of detecting a school as a function of radial distance from the ship (D_x).

$$p(Detected \mid D_x) = -\frac{1}{72}D_x + \frac{1}{6} \tag{11}$$

Distances are assumed to represent the distance from the bow of the ship to the centre of the schools. The exact shape of the above function for ETP dolphin schools is not known, although it most definitely varies by sea state and school size. For ease in transformation and integration, we chose a linear function. However, Equation 11 is based on some characteristics we would expect to find in the true function. The maximum possible detection distance is 12.0km, and the function assumes objects closer to the ship are easier to detect than objects further away. The overall resulting patterns in relation to school density and school clustering between the two modes hold if the true function exhibits the same characteristics but has a different shape. The simulation assumes all schools have the same number of individuals and does not allow for different Beaufort sea states. Such differences merely change the shape of the detection function.

Integrating over all possible radial distances, the overall probability of detecting the school becomes

$$p(Detected) = -\frac{1}{144}(D_{rs}^2 - D_p^2) + \frac{1}{6}(D_{rs} - D_p) \tag{12}$$

D_{rs} is the maximum possible radial distance between the ship and school at which the school can be detected. If the school is 12km or more away from the ship at the beginning of scanning effort, D_{rs} is 12.0km (distance to the horizon). Otherwise, D_{rs} is simply the distance between the ship and school at the start (or usually resumption in closing mode) of searching effort. The minimum distance at which a school can be detected is the perpendicular distance from the school to the trackline (D_p). Equation 12 would represent the 'detection function' in a standard line-transect analysis, assuming all schools are at least 12km away at the start of survey effort, and the detection probability for a school 12 or more kilometres away on the trackline ($D_{rs} = 12.0$, $D_p = 0$) is 1.0.

Because the ship travels at a constant speed, the probability of any specific distance from the ship to the perpendicular intercept is a uniform distribution from 0 to $\sqrt{D_{rs}^2 - D_p^2}$, assuming our simulated world is flat. By transformation we get:

$$p(D_x) \propto \frac{D_x}{\sqrt{D_x^2 - D_p^2}} \tag{13}$$

Combining Equations 11 and 13, Bayes' formula allows us to calculate the probability of D_x given a school was detected:

$$p(D_x \mid Detected) \propto \frac{-\frac{1}{72}D_x^2 + \frac{1}{6}D_x}{\sqrt{D_x^2 - D_p^2}} \tag{14}$$

The simulation first placed a predetermined number of schools in a survey region. Coordinates x and y were assigned to each school where $0 \leq x \leq 222$km and $-24.52 \leq y \leq 24.52$km. This region represented the area surveyed in one day (12h of effort at 18.5km/hr) in passing mode with the ship travelling through the area starting at the origin (0,0) and ending at coordinates (222,0). In closing mode, the ship starts at the origin (0,0) and can veer away from the trackline up to 10 n.miles (18.52km) in either direction. Similar to closing mode in the field, the ship did not stop to investigate schools detected further than $D_p = 6.0$ from the trackline. Nor were such schools used in encounter rate estimates.

School coordinates were generated to allow a controlled degree of spatial clustering. Since schools are the object of detection, the spatial Poisson process referred to clusters of schools, not clusters of individuals as traditionally defined in line-transect analysis. First, the coordinates for the centres of a predetermined number of clusters (1, 10 or 20) were generated randomly in the rectangle. Then each school, from a predetermined number of schools (50, 150 or 150), was randomly assigned to a cluster. The school's coordinates were generated based on a bivariate normal circular placement around the cluster centre with a known standard deviation (10, 20 or 30km). If the coordinates of the school were outside the survey region, were within 0.5km of a previous school, or were more than two standard deviations away from the cluster centre, the school coordinates were re-sampled. The process was repeated until a predetermined school density for the survey region (50, 150 or 250) was reached. Assuming school density, cluster number and cluster size are independent, there were a total of 27 different simulations. Although school density and cluster characteristics are highly variable within the ETP, the suite of simulations represents probable scenarios one would encounter in this region.

The overall spatial distribution of the schools is relatively simplistic compared to potential real spatial processes. The simulation produces circular school clusters; each cluster has the same radius, and densities of schools are highest in cluster centres. However, the spatial point process is able to illustrate the overall differences in passing and closing mode encounter rates when schools are clustered. Total number of schools in the area controls overall density, and cluster standard deviation controls how concentrated the schools are within the clusters.

In passing mode, the trackline was defined as the x-axis, and we assumed the ship travelled at a constant speed (18.52km/hr). The probability of detection was calculated for each school in relation to its perpendicular distance from the trackline and its distance from the ship when surveying began (Equation 12). Schools more than 12km from the ship at the beginning of surveying had the highest detection probability possible given their perpendicular distance from the trackline. Each school was randomly detected or not detected based on that probability. The simulation tallied the number of detected schools and calculated the encounter rate (number of detected schools/222.0km).

The encounter rate was then reassessed for the same spatial distribution of schools while the ship moved through the area in closing mode. In closing mode, the ship started at the origin (0,0) but then moved off the original trackline toward the first detected school (i) with $D_{pi} \leq$ 6km. To determine which school was detected first, the radial distance at which each school was detected (D_{ri}) was randomly drawn from its probability distribution (Equation 14), limiting values between D_{pi} and D_{rsi}. Then the distance along the trackline (D_{ti}) at which the school was detected became

$$D_{ti} = D_{start}\sqrt{D_{ti}^2 - D_{pi}^2} \tag{15}$$

where D_{start} is the total distance between the starting point and the school's perpendicular intercept. The school with the shortest D_t was the first school detected (school A). All other schools were put back in the pool to potentially be detected later.

The total amount of trackline surveyed was D_{tA}, and the amount of survey time was calculated as the sum of the time on the trackline, the time it took to approach the school and the time it took to investigate the school.

$$Time = \frac{D_{tA} + D_{rA}}{18.52} + \frac{1}{6} \tag{16}$$

We assumed the observers terminate scanning effort as soon as a school is detected. The ship then travels directly to the school, covering the radial distance between the ship and school A (D_{tA}) at the same speed as searching speed (18.52km/h). We assume the school does not move in response to the ship. Once the ship arrives at the school, the observers spend 10min determining species composition and school size. Only the first assumption affects comparisons between passing and closing modes. If observers continued to search after finding a school in closing mode, the actual amount of survey effort would be underestimated, leading to an overestimate of encounter rate. Changing the other assumptions only decreases sample effort in closing mode.

When scanning effort resumes, the ship begins at the coordinates of the last detected school (x_A, y_A) continuing along a trackline parallel to the original trackline. The process of determining the position of the next detected school and calculating the amount of accrued survey time is repeated, adjusting for the new starting point of the ship. All schools 'behind' the ship ($x_i < x_A$) are no longer available for detection, and any schools within 12km of the ship ($D_r <$ 12.0) have a lower detection probability than schools further away. The tally of number of schools detected (n_c) and sum of total surveyed trackline (D_c) continues until the ship reaches the edge of the survey area (x = 222.0), or the accrued survey time is 12.0h. If the ship moves more than 18.52km from the original trackline, the scanning trackline is angled at 20° toward the original trackline instead of running parallel to it. All distances and the definition of 'behind' the ship are adjusted for the angle change. Encounter rate for the survey day in closing mode is then calculated as n_c/D_c. Sample size was 1,000 sample 'days' for every combination of number of schools, number of clusters and cluster size.

Results are shown as the ratio of raw closing mode encounter rate over raw passing mode encounter rate. To understand potential biases in estimation of the detection function in closing mode, we also present the distribution of perpendicular distances of detected schools in closing mode for nine of the 27 simulations. They are graphically compared with the perpendicular distance distribution one would expect in passing mode given the same amount of covered trackline. Such comparisons indicate differences in detection probabilities one would estimate in the two modes if one was estimating abundance (Buckland *et al.*, 2001). A general description of perpendicular distances of sightings from the field data are then given by Beaufort sea state and survey method to compare with simulated results.

RESULTS

Survey effort

Overall, the ship spent 67 days surveying on the trackline, with a total of 9550km of effort and 765 cetacean sightings. Weather, including a hurricane, prevented completion of both diamonds on Legs 1 and 3. After limiting effort by sighting conditions (Beaufort sea state ≤5, visibility >5.5km), more days were spent in closing mode than passing mode, but distance on effort was longer in passing mode when combining days together (Table 1). Average daily distance on effort was 26% lower in closing than passing mode (113 vs 153km/day). At greater than 100km/d of effort in closing mode, the total number of daily sightings is negatively correlated with distance on effort, indicating longer distances on effort in closing mode are only achieved on days with fewer sightings (Fig. 2).

Table 1

	Survey method	
Resulting effort	Closing	Passing
Days	34	31
Km effort	3,832.5	4,741.8
Delphinid sightings	186	288

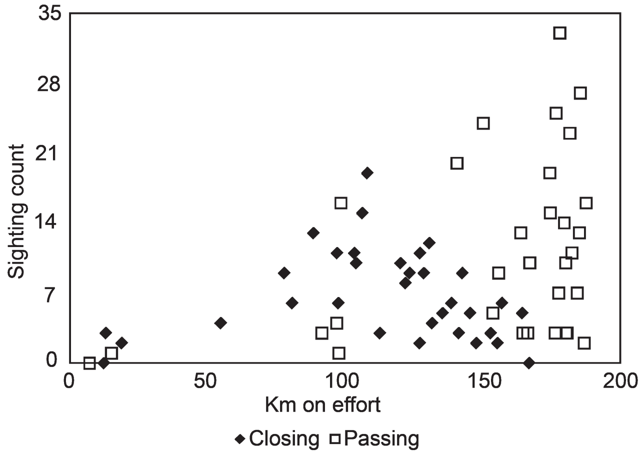

Fig. 2. Daily sighting counts and kilometers of effort for closing and passing modes (all cetacean species). Sighting conditions limited to Beaufort ≤5 and visibility >5.5km. Perpendicular distances of all sightings are limited to ≤5.5km.

Species identification

After filtering the data for visibility, Beaufort and distance, results indicated observers were able to identify cetaceans to the species or subspecies level 81% (±2% SD) of the time in closing mode and 57% (±3% SD) of the time in passing mode. The probability that the proportion of groups identified to the species or subspecies level in passing mode is equal to or greater than the proportion of groups identified to the species or subspecies level in closing mode is zero. In addition, the observers' abilities to identify to the species or subspecies level declined with distance in passing mode (Fig. 3). Mixed-species schools were identified 22% (±3% SD) of the time in closing mode and 7% (±1% SD) of the time in passing mode. The probability that the proportion of mixed species schools identified in passing mode is equal to or greater than the proportion of mixed-species schools identified in closing mode is zero. In closing mode, observers determined four schools that consisted of three different species. No schools with three or more species were identified in passing mode. The observers' ability to identify schools with more than one species was generally poor in passing mode regardless of distance (Fig. 4). The combined 'delphinid' category made up 79% of all sightings in closing mode and 84% of all sightings in passing mode. Only one mixed-species school contained both delphinids and non-delphinids. In general, species identification was poor in passing mode compared to closing mode. Only schools identified as delphinids were used in further analyses.

Delphinid school size

When using closing-mode calibration techniques for both passing and closing survey methods, passing mode delphinid school size estimates tended to be lower for schools further than 1.0km from the trackline (Fig. 5). Estimates of delphinid school size were 58% lower in passing mode than closing mode at distances between 1.0 and 5.5km from the trackline. The probability that passing mode school sizes were less than

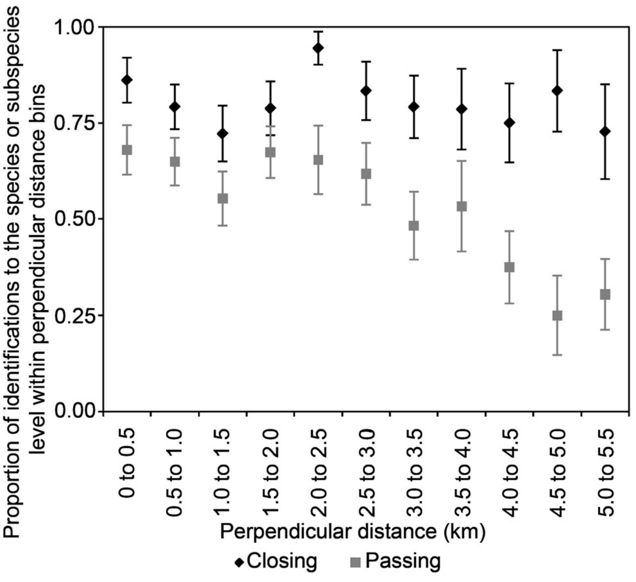

Fig. 3. The proportion of identifications to the species or subspecies level for all sightings as a function of perpendicular distance from the trackline and survey method. Bars are ± one standard deviation. Sighting conditions limited to Beaufort ≤5 and visibility >5.5km.

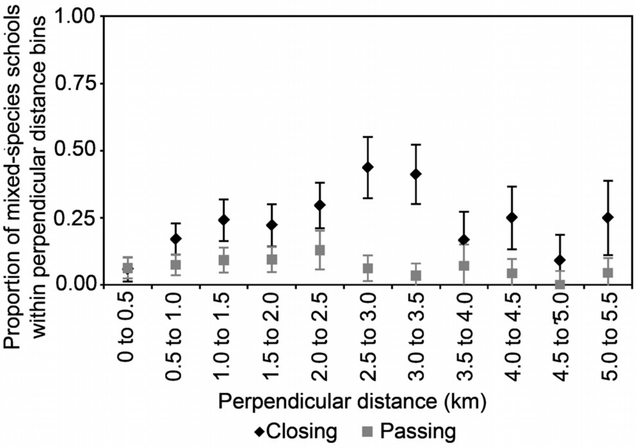

Fig. 4. The proportion of schools with two or more species for all sightings as a function of 0.5km perpendicular distance bins from the trackline and survey method. Bars are ± one standard deviation. Sighting conditions limited to Beaufort ≤5 and visibility >5.5km.

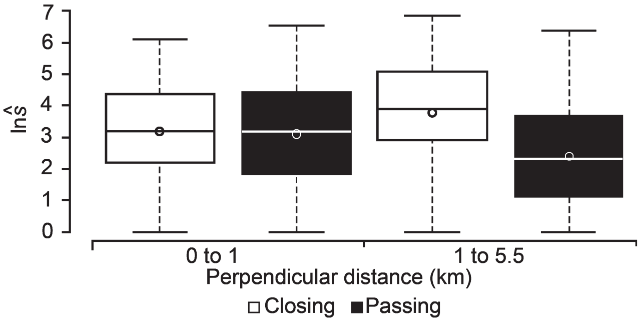

Fig. 5. Distributions of log of school size estimates in relation to perpendicular distance from the trackline and survey mode for delphinid sightings. Open circles are means. Boxes are 1st and 3rd quartiles, and lines within the boxes are medians. Whiskers are minimum and maximum values. Sighting conditions limited to Beaufort ≤5 and visibility >5.5km.

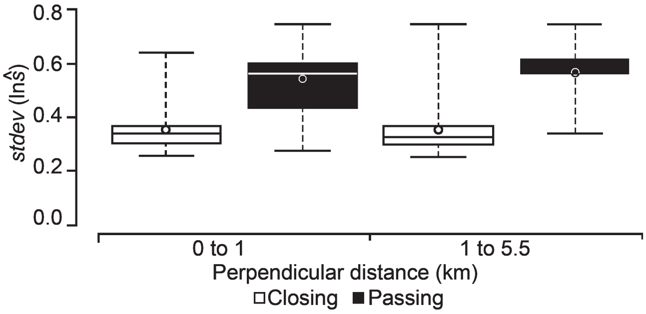

Fig. 6. Distributions of standard deviation of the log of school size given perpendicular distance from the trackline and survey mode for delphinid sightings. Each data point represents multiple observer estimates of the same group (Equation 2). Open circles are means. Boxes are 1st and 3rd quartiles, and lines within the boxes are medians. Whiskers are minimum and maximum values. Sighting conditions limited to Beaufort ≤5 and visibility >5.5km.

closing mode school sizes was 0.51 between 0 and 1.0km from the trackline and 0.73 between 1.0 and 5.5km from the trackline. The standard deviation of school size estimates was higher in passing mode than in closing mode (Fig. 6). The better precision in closing mode school size estimates is due to lower within-observer variability as well as a larger sample size since more than one observer estimates school size in closing mode. Delphinid school size estimates were based on one observer's low estimate 6.5% of the time in closing mode and 36.1% of the time in passing mode. Differences between school size estimates in passing vs closing mode at greater distances are not as pronounced when estimates based on one low count are removed. Without low-count school size estimates, the probability that passing mode school sizes were less than closing mode school sizes was 0.47 between 0 and 1.0km from the trackline and 0.61 between 1.0 and 5.5km from the trackline. The standardised range between low and high school size estimates implies that within-observer uncertainty was generally higher in passing mode than closing mode, particularly with delphinid schools further from the trackline (Fig. 7). No changes in the difference between passing and

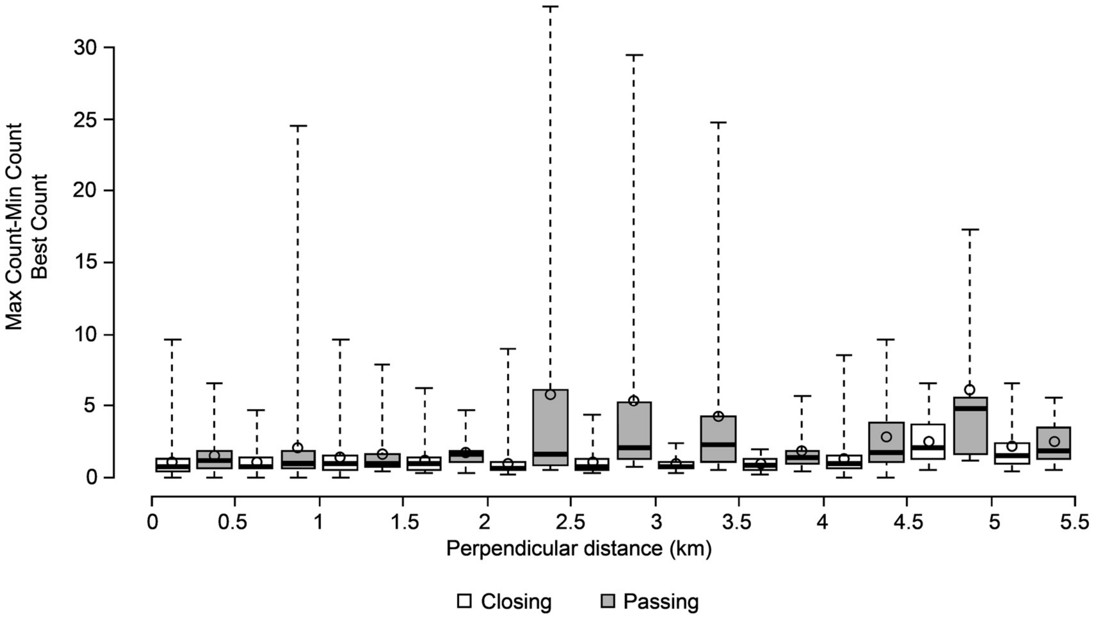

Fig. 7. Range of observer delphinid counts (maximum count-minimum count) standardised by the best count in relation to survey method and distance from the trackline (0.5km bins). Open circles are means. Boxes are 1st and 3rd quartiles, and lines within the boxes are medians. Whiskers are minimum and maximum values. Sighting conditions limited to Beaufort ≤5 and visibility >5.5km.

closing mode school size estimates were seen in relation to sea state (not shown). Overall, delphinid school size estimates were lower in passing mode with a higher level of uncertainty compared to closing mode. However, if estimates are biased low, they could be recalibrated using new aerial survey data.

Delphinid encounter rates

Without adjusting for different levels of effort in different Beaufort states, the simple aggregate delphinid encounter rate was 20% lower in closing than passing mode (0.049 vs 0.061schools/km). When pooling data within each Beaufort state, encounter rate in closing mode is more likely to be lower than encounter rate in passing mode, except in Beaufort 5 conditions (Fig. 8). However, the posterior distribution of the ratio of closing mode encounter rate over passing mode encounter rate is much more variable in Beaufort 5 conditions due to small sample size. With the assumption that schools are randomly located in our survey area, the results indicate a 95% probability that the encounter rate bias is roughly between 40% and 120% of passing mode encounter rate, which would result in an underestimate of abundance in closing mode. Variability in the posterior of the encounter rate ratio is higher when treating days as exchangeable samples of an overall encounter rate (Fig. 9). When we incorporate temporal variability in to our bias estimates, there is a 95% probability the bias is around 25% to 400% of passing mode encounter rates.

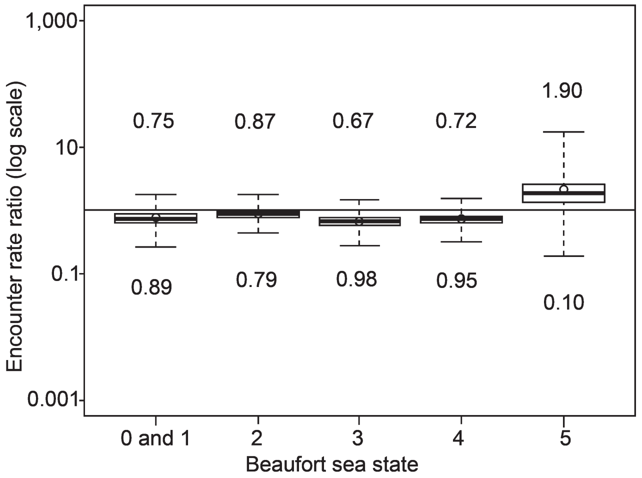

Fig. 8. Derived posterior distribution of the ratio of closing mode encounter rate over passing mode encounter rate by Beaufort sea state when days are pooled. Boxes are 1st and 3rd quartiles. Bars within the boxes are medians, and points are means. Whiskers are minimum and maximum values. Top numbers are medians. Bottom numbers are proportions of distribution <1.0. Sighting conditions limited to Beaufort ≤5 and visibility >5.5km. Perpendicular distances of sightings are limited to ≤5.5km.

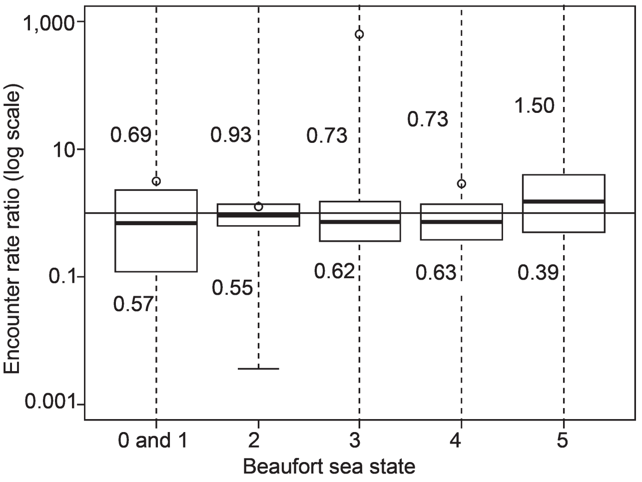

Fig. 9. Derived posterior distribution of the ratio of closing mode encounter rate over passing mode encounter rate by Beaufort sea state using a hierarchical model with days as exchangeable estimates of encounter rate. Boxes are 1st and 3rd quartiles. Bars within the boxes are medians, and points are means. Whiskers are minimum and maximum values (mostly off scale). Top numbers are medians. Bottom numbers are proportions of distribution <1.0. Sighting conditions limited to Beaufort ≤5 and visibility >5.5km. Perpendicular distances of sightings are limited to ≤5.5km.

Simulation

Overall, daily closing mode school encounter rate is lower than passing mode encounter rate when schools are in fewer clusters and when clusters are more concentrated (Fig. 10). The difference is more pronounced when there are more schools in the area, i.e. overall school density is larger (Fig. 10). There is a threshold at which school clustering becomes random, and, on average, the closing mode encounter rate is no longer biassed. Again, the threshold is dependent on the number and size of clusters as well as the true school density in the area.

Even when the overall difference between passing and closing mode is minimal, variability in the encounter rate ratio can be quite high simply due to random movement patterns of the ship in closing mode as well as random detection of each school. Variability is highest when schools

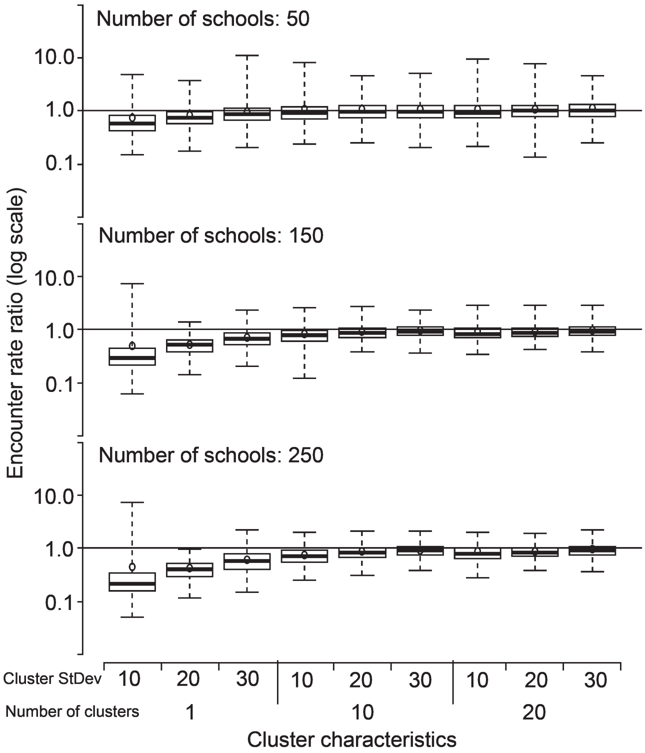

Fig. 10. Distribution of the ratio of closing mode encounter rate over passing mode encounter rate from simulations with differing overall school density and different clustering characteristics (most patchy to least patchy along the x-axis). Boxes are 1st and 3rd quartiles. Bars within the boxes are medians, and points are means. Whiskers are minimum and maximum values.

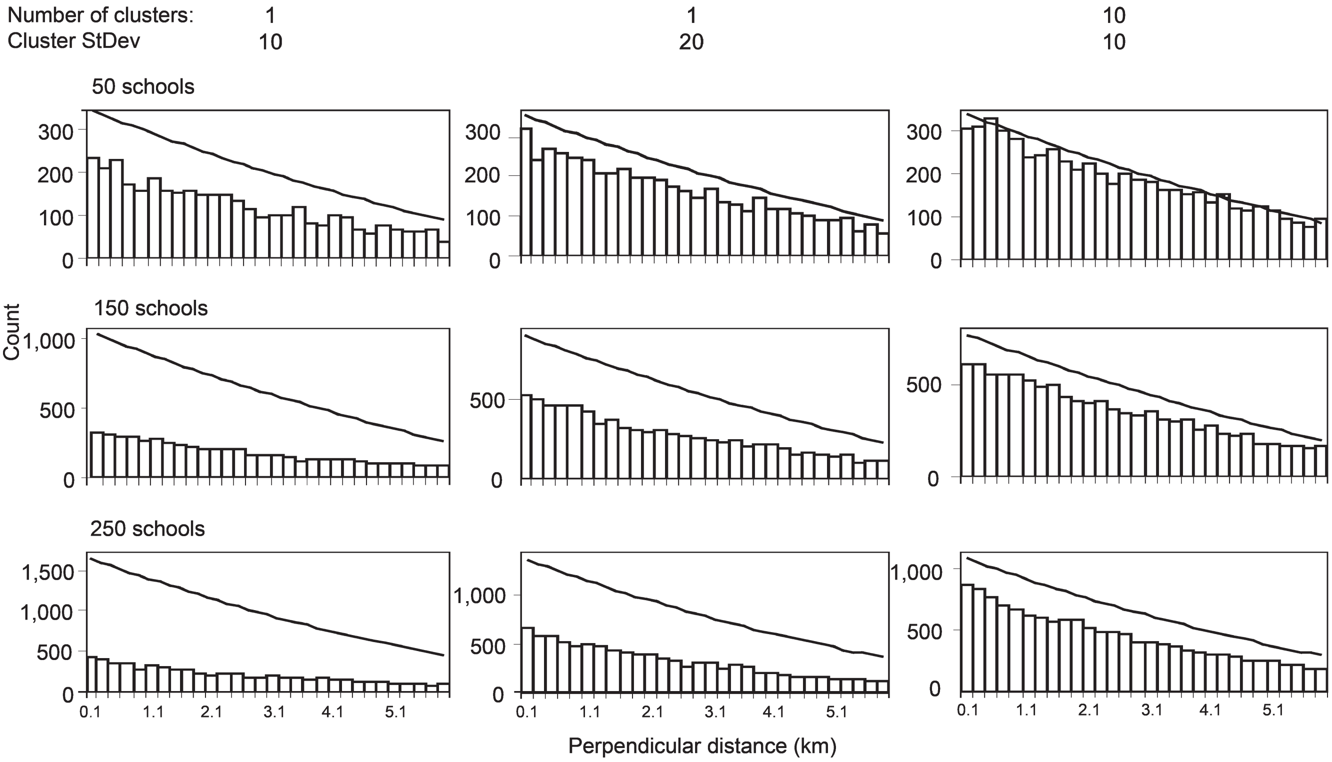

Fig. 11. Count of perpendicular distance of detected objects in closing mode simulation with differing overall school density and different clustering characteristics. Histogram bars are counts by 0.2km distances, so numbers on x-axis represent perpendicular distance midpoints for each bin. Curve represents the counts one would expect from a passing mode line-transect survey. Maximum counts are different for each scenario based on the amount of trackline covered in closing mode. One thousand simulations conducted for each density and clustering combination.

are located in one relatively tight cluster. Variability becomes more stable with more and larger clusters.

Distribution of detected sightings by perpendicular distance indicates detection probabilities by perpendicular distance are lower in closing mode than in passing mode when schools are in fewer clusters and when clusters are more concentrated (Fig. 11). The difference is more pronounced when there are more schools in the area (overall school density is larger) and for schools closer to the trackline (shorter perpendicular distances) (Fig. 11). One would expect from the simulation results that the overall distribution of perpendicular distance for detected sightings would be higher in closing mode than in passing mode, and the disparity would be larger when the encounter rate ratio is smaller. Overall, the differences in perpendicular distances of delphinid sightings are not very different by survey method (Fig. 12).

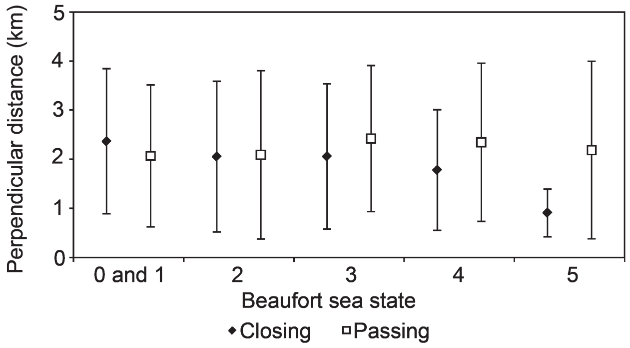

Fig. 12. Perpendicular distance as a function of sea state and survey method for delphinid sightings. Points are means and whiskers are ± 1 std. Sighting conditions limited to Beaufort ≤ 5 and visibility >5.5km. Perpendicular distances of sightings are limited to ≤ 5.5km.

DISCUSSION

The results of this study confirm observers' abilities to determine species composition and estimate school size are poor in passing mode. Results are similar to those seen in Barlow (1997) and Haw (1991). In addition, uncertainty in school size estimates both within and between observers was higher in passing mode. In general, we expect a positive correlation between detection distance and group size, since larger schools are easier to detect at distance than smaller schools. Such a correlation could explain higher school size estimates with distance in closing mode. However, the ships may also influence group behaviour, and multiple smaller schools may coalesce in to larger schools as the ship approaches an area. In passing mode, school size estimates actually declined with distance, implying poorer school size estimation at distance. Once a school is detected in passing mode, observers could miss individual animals when schools are further away. Even when data were filtered to only include sightings where the observer was able to give best, high and low estimates of school size, school sizes were lower in passing mode. The school size differences occur well within the 6.0km perpendicular distance commonly used in detection functions for delphinid species in the ETP. Another possible explanation for lower school sizes in passing mode is that observers may see different parts of a large school and may record it as multiple small schools rather than a single large one. Such an effect would contribute to smaller estimated school sizes, as well as to higher school encounter rates in passing mode. To eliminate any potential bias, passing mode school size estimates would need to be recalibrated (Barlow *et al.*, 1998). However, higher uncertainty in school size estimates in passing mode would still carry over as higher uncertainty in abundance estimates compared to closing mode.

As Haw (1991) found with Antarctic minke whales, overall our delphinid school encounter rates were 20–25% lower in closing mode than in passing mode. Results show the variability in encounter rates due to random movements of schools appears to be much larger than the bias one would see in closing mode on a daily scale. One result was not consistent with general findings. Beaufort 5 encounter rate ratios had a high probability of falling above one, meaning encounter rates were actually higher in closing mode than passing mode. However, the result may be due to a small sample size, with only four days and 126km of effort in closing mode and five days and 392km of effort in passing mode.

Empirical comparisons of overall abundance estimates would not be very informative at this point because of potential biases using both methods, particularly at longer distances. If groups simply coalesce when the ship approaches in closing mode or if observers detect large groups as several smaller groups in passing mode, neither survey method produces an inherent bias in abundance estimates. Otherwise, passing mode may produce lower abundance estimates due to smaller school size estimates while closing mode also leads to an underestimate in abundance because of lower encounter rates. In any case, passing mode abundance estimates would have higher variability due to higher uncertainty in school size estimates, and passing mode methods reduce the ability to identify groups to the species level.

However, simulations confirm the suspicions of Haw (1991), showing that the reduction in detection probabilities at the beginning of each segment of search effort contributes to a bias towards lower encounter rates in closing mode. Although closing mode vessels may get 'trapped' in high density areas, the loss in detection probability from stopping and re-starting effort in those areas overall makes up for a positive bias one might get in such a situation. The degree to which detection probability is affected in closing mode is a function of school clustering and overall school density in the sampling area.

The simulations also provide insight in to differences in detection probability on the trackline, $g(0)$, in the two modes. Closing mode $g(0)$ is always less than or equal to $g(0)$ in passing mode. If one assumes $g(0)$ is the same in both modes (which is often the case), detection probability in closing mode will be overestimated further from the trackline, which in the long run leads to an even larger underestimation bias in abundance estimates. The magnitude of the bias is also dependent on school clustering characteristics, the number of schools in the area and presumably the shape of the underlying radial detection function (Equation 11 is just one theoretical example). Therefore, the magnitude of the bias needs to be calculated on a case-by-case basis and is beyond the scope of this paper.

Variability in the ratio of daily closing mode encounter rate and passing mode encounter rate can be quite high even when school density in the area does not change and without complex hierarchical modeling. The random placement of clusters, random detection and random movement of the ship in relation to detected schools creates such variability. For example, if school density ranges from high to low along the planned daily trackline, a closing mode ship will undersample areas of low density since it will spend a higher proportion of time sampling in the high density area, leading to a higher encounter rate ratio. If school density ranges from low to high, the opposite occurs (undersampling of high density areas and a lower encounter rate ratio). If planned daily tracklines are randomly placed in relation to school density, such over- and under-sampling will be reflected in the distribution of the encounter rate ratio.

Direct comparisons of results from the empirical data and the simulations should be done with caution for several reasons. First, we do not know the detection probability in relation to radial distance (Equation 11) for the empirical data. Although the general patterns seen in the simulated results would be similar to the empirical results, the absolute quantities in the encounter rate ratio could be quite different depending on the shape of Equation 11. Second, the clustering characteristics of delphinid schools are unknown, which again play a role in the absolute quantities of the encounter rate ratios. Although the simulations were created to mimic as closely as possible potential clustering scenarios and closing and passing mode data collection techniques, the simulations only function as a method to understand the underlying mechanisms that would lead to different encounter rate ratios. They are not meant to be used, at this point, to quantify any sort of correction factor or determine the type of school clustering.

There are several analytical and methodological techniques that could adjust for the overall lower encounter rate in closing mode. If we have an accurate measurement of $g(0)$ and the correct form of the perpendicular distance detection function in closing mode, we have the appropriate correction factor. In addition, we could potentially derive an analytical correction factor for closing mode using the simulation techniques presented in this paper if we knew the correct form of Equation 11 and the level of school clustering in the data. As with Antarctic minke whale surveys, one could also adjust data collection protocols to include some passing mode effort. Then we could empirically estimate a correction factor, similar to Branch and Butterworth (2001b).

However, several aspects of the current data collection methods make such analytical and methodological adjustments difficult in the ETP. First, $g(0)$ in closing mode is not easy to measure without some sort of comparison in passing mode. Second, the cluster characteristics of data collected in closing mode are difficult to determine since the measured distance between sightings is a function of (1) the non-random movements of the ship potentially in response to clustering; and (2) the changes in detection probabilities that occur with such stop-start searching effort. In addition, the ship moves in response to almost all cetacean sightings, not just the species of interest. So, different species may have differing cluster patterns that could affect the movement of the ship and thus encounter rate estimates of all species. Determination of school patchiness with such analytical complexities is a topic in need of further study. In addition, school clustering is likely to be highly variable in space and time considering the very large area and variable ecosystem traits of the ETP. Lastly, detection probability as a function of radial distance from the ship is most certainly different for different school sizes.

The benefits of incorporating passing mode in to the protocol to remove closing mode bias need to be compared with any disadvantages. In addition to a loss in precision for species ID and school size estimates, passing mode days would lead to the loss of some additional, highly-valuable data from photographs and tissue samples that can only be collected in closing mode. Such data are important for population, genetics, contaminant, diet and life history studies (André *et al.*, 1990; Archer, 1996; Borrell *et al.*, 2004; Escorza-Treviño *et al.*, 2005; Kane *et al.*, 2008; Kellar, 2008; Kellar *et al.*, 2009; Kellar *et al.*, 2006; Olson and Gerrodette, 2008; Smith and Worthy, 2006).

In summary, the study confirms observers' abilities to identify species and estimate school size are improved using closing mode methods. However, both empirical data and simulations indicate closing mode methods produce an underestimate in encounter rates, potentially leading to an underestimate in abundance. The cause of the underestimation is due to the stop-start nature of the method, which results in lower detection probabilities of schools already within the 12km visual range when effort begins or resumes. On a daily scale, variability in abundance and changing spatial distributions of schools in the area produce a high level of uncertainty in encounter rate ratios. Adjustments to field methods in the ETP could remove the bias but result in higher levels of uncertainty in the overall abundance estimate and the loss of other important data. While difficult to implement, analytical and methodological methods to remove or reduce the bias should be explored further.

ACKNOWLEDGEMENTS

We would like to thank the officers and crew of the *MacArthur II* as well as the talented marine mammal observers who collected the data. Annette Henry provided logistical support. Alan Jackson checked and edited the data. Reviews from NOAA researchers Jim Carretta and Jay Barlow greatly improved this manuscript.

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Date received: September 2009
Date accepted: May 2010