

# Surfacing Rates and Surfacing Patterns of Minke Whales (*Balaenoptera acutorostrata*) off Central California, and the Probability of a Whale Surfacing Within Visual Range

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## ABSTRACT

Twenty 30-minute respiration sequences from eleven known individuals were analysed to determine surfacing rates of minke whales from the Monterey Bay area, California. The mean surfacing rate was  $38.6 \pm 9.47$  surfacings per hour (range 26–60), with no significant differences in surfacing rates among individuals. Of five individuals observed on more than one occasion, one whale exhibited a significant difference in surfacing rate between encounters. One hundred and twenty-five surfacing sequences were analysed to determine the surfacing patterns of minke whales. The general surfacing pattern consisted of about four surfacings, interspersed by short-duration dives of  $37.8 \pm 31.98$  seconds. After the fourth surfacing, there was a longer duration dive of  $4.43 \pm 2.37$  minutes. The probability of a whale surfacing on the trackline and in a 0.52 n.mile (1km) radial sighting region of the transiting vessel was estimated using a computer simulation of a moving vessel and a whale swimming in the general pattern observed. The probability of a whale on the trackline surfacing was 1.00, 0.93 and 0.78 for vessel speeds of 3.6 and 12 knots, respectively. The probability of surfacing within the sighting region was 0.96, 0.88 and 0.47. The long duration dives and movement of the survey vessel caused a whale to be 'missed' as the vessel moved through an area. The results of this simulation suggest that few whales in the present study were missed due to submergence.

KEYWORDS: MINKE WHALE; NORTH PACIFIC; RESPIRATION; BEHAVIOUR; FEEDING; MOVEMENT; PHOTO-ID; SURVEY-SHIP; NORTH ATLANTIC; SOUTHERN HEMISPHERE

## INTRODUCTION

Individual minke whales off the coast of central California were observed to determine both surfacing rates (in terms of number of surfacings per whale per hour) and surfacing patterns. The method of search was to travel slowly parallel to the general direction of travel of the whales, and there was thus the possibility of travelling past a submerged whale. This was tested using a computer simulation approach in the spirit of a suggestion by Schweder (1990).

## MATERIALS AND METHODS

Minke whales were studied off the coast of the Monterey Bay area, central California (Fig. 1). Observations were conducted from a 5m *Boston* Whaler equipped with a 70hp *Johnson* outboard motor. Searching was carried out at 2–3 knots, parallel to the coastline until a whale was sighted. Once sighted, a whale was approached as fast as possible. At a distance of 50m, the boat was slowed and turned to match the speed and direction of travel of the whale. This

distance was maintained to allow for identification photographs to be taken. After suitable photographs were taken (usually within the first few surfacings), the boat was kept to within about 100m of the whale. Whales could be followed for long periods as a result of their predictable direction of travel. Each whale was followed for as long as possible. A major concern in this type of study is whether the vessel affects the behaviour of the whale. This is difficult to determine except in extreme cases where the whale is obviously swimming towards or away from the vessel, or constantly changing direction, speed and respiration pattern. Such cases were not included in this analysis. The following data were recorded at each surfacing: time (to the nearest second); type of surfacing; direction of whale's travel; distance of whale from the boat; and any observed behaviour.

It is possible that not all surfacings in a sequence were seen. To minimise this possibility, the vessel continued in the same direction and speed as the whale during long dives in order to be close to the whale when it surfaced. In addition to keeping to within about 100m from the whale during an encounter, effort was also made to locate rings (Best, 1982) or 'footprints' of undetected surfacings after the first observed surfacing in a sequence. Sequences where it was thought that surfacings may have been missed were not included in the analysis.

The boat was manoeuvred onto the footprint of the terminal surfacing of a sequence, which was usually denoted by the whale arching its tailstock. The location was determined by triangulating off at least two known landmarks using a hand-held sighting compass. The locations were then plotted along with associated times, and from this, tracks and speeds were calculated. The direction of travel was measured relative to magnetic north, and the mean angle and angular deviation were calculated according to Batschelet (1981). The *r*-value is a measure of linearity of a track on a scale of 0 to 1, with 0

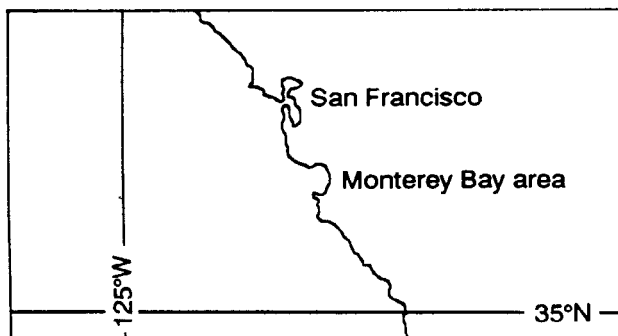


Fig. 1. A map of the west coast of the United States showing the Monterey Bay area study site.



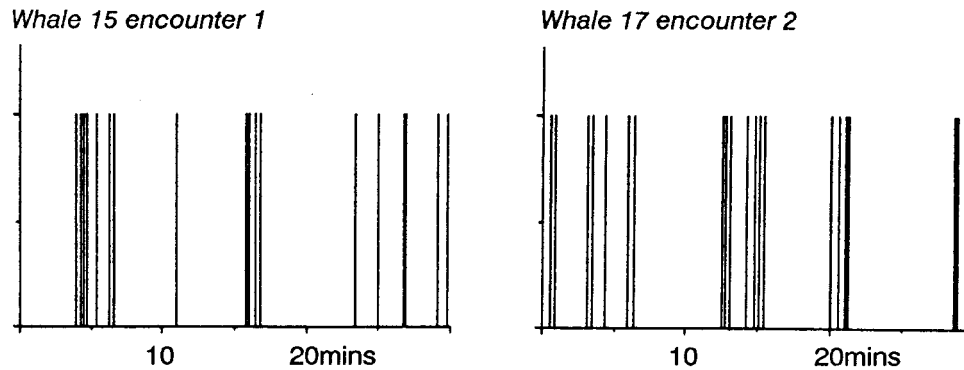


Fig. 2. The frequency distribution of surfacing rates.

corresponding to random directions, and 1 corresponding to a uniform direction.

Minke whales in the study area generally occurred singly, although groups of two animals were seen occasionally. A group was defined as two (or more) whales swimming in the same direction within two body lengths of each other. Not all animals in a group surfaced simultaneously, nor did all animals surface the same number of times within a surfacing sequence. It was not possible to time each surfacing in a surfacing sequence for each individual in a group of whales or to photograph every surfacing of every whale to document the differential surfacing rate. Therefore only data on single whales were used in this analysis.

Surfacing rate, defined as the number of surfacings per whale per hour (SPWPH) were calculated in a manner similar to Joyce (1982); Ward and Hiby (1987); Ward (1988); Joyce *et al.* (1989); Gunnlaugsson (1989); and Øien *et al.* (1990). Since whales were followed for as long as possible to determine patterns of movement as well as behaviour, some encounters lasted longer than 30 minutes. In these encounters, for comparative reasons, only the first 30 minutes were used.

Surfacing patterns were determined from 125 surfacing sequences from 48 observation periods with 14 identified individuals. The general pattern emerged when diversions were plotted as they occurred in an encounter. Only those sequences starting after the first long dive of an encounter were used, since without this marker it was not possible to determine at what point in the surfacing cycle the encounter started. The symbol '±' refers to one standard deviation.

**RESULTS OF SURFACING RATE ANALYSIS**

Twenty 30-minute respiration sequences of 11 known individuals were analysed to determine surfacing rates (Fig. 2). The mean surfacing rate was  $38.6 \pm 9.47$  SPWPH (range 26–60). The frequency distribution of surfacing rates is summarised in Fig. 3. There were no significant differences in surfacing rates between individuals. Five individuals were observed on more than one occasion. Surfacing rates were compared to test whether differences existed between encounters of a given individual. There was a significant difference in the surfacing rates between encounters of Whale 3 (chi-square = 11.89; 2 df;  $p < 0.005$ ). There were no significant differences between encounter rates of the other whales.

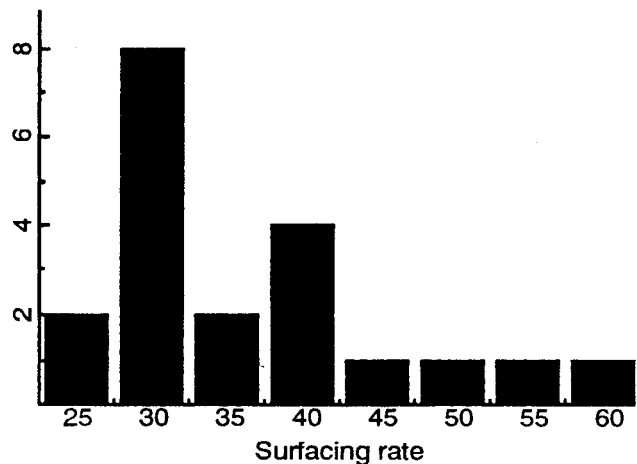


Fig. 3. Surfacing patterns of minke whales. The Y-axis corresponds to the first surfacing of the encounter.

The mean surfacing rate in the morning was  $36.33 \pm 11.55$  SPWPH ( $n=6$ ) while the mean surfacing rate in the afternoon was  $39.57 \pm 8.74$  SPWPH ( $n=14$ ); these were not significantly different (unpaired t-value =  $-0.6718$ ; 18 d.f.;  $p = 0.4985$ ).

**RESULTS OF SURFACING PATTERN ANALYSIS**

The surfacing pattern consisted of a series of short-duration dives followed by a long-duration dive. Long-duration dives were defined as those lasting longer than the upper 95% confidence limit of all dives for that particular encounter. The average number of surfacings within a surfacing sequence was  $3.74 \pm 2.08$ . The mean length of short duration dives was  $0.63 \pm 0.53$  minutes ( $n=341$ ). The mean length of the long-duration dive was  $4.43 \pm 2.37$  minutes. This pattern was not always observed and periods of consistent regularly spaced surfacings were observed on two occasions (see Fig. 2; Whale 3 encounter 1; Whale 6 encounter 3).

The mean swimming speed of the whales was  $4.5 \pm 3.45$  knots ( $n=146$ ). There were no significant differences in speed among individuals ( $F = 1.512$ ; 145 df;  $p = 0.1273$ ) or between encounters of individuals.

The mean direction of travel was  $08^{\circ}22'48'' \pm 79^{\circ}37'47''$  ( $n=146$ ) with a mean r-value of 0.46 (range 0.13–0.99). There was a bimodal distribution of mean directions of north and south moving whales, with most whales heading north. In general, whales moved in an alongshore direction

and were limited to a corridor within 1.67 n. mile of shore, in water with a mean depth of  $26.6 \pm 19.4$  fathoms ( $48.6 \pm 35.5$ m).

**SURFACING SIMULATIONS**

**Methodology**

In an attempt to determine the probability of a single whale surfacing on the trackline and within a defined sighting region, a series of simulations were run using the swimming and surfacings patterns observed. The sighting region used was a 0.52 n. mile arc sweeping from 0 to 90 degrees on the starboard quarter to the vessel. The respiratory cycle used comprised a series of four surfacings, lasting about 3 seconds in duration (Doi, 1974) interspersed by three short dives, 0.67 minutes in duration. After the fourth surfacing, there was a longer dive of 4.33 minutes. The duration of the respiratory cycle was 387 seconds or 6.43 minutes (Fig. 4).

A whale was generated ahead of the vessel at the maximum sighting radius of 0.52 n.miles. Since a whale could enter the sighting region at any point in its surfacing pattern, the initial condition of the simulations was varied to include each second of the respiratory cycle as the initial starting condition. The pattern of swimming was continued from that point in the cycle. The whale swam in a straight line parallel to the trackline of the survey vessel, either in the same or in the opposite direction as the vessel. The speed of 3.5 knots was used since it was the mean speed of the whales analysed for the surfacing pattern analysis rather than the 4.5 knots calculated as the mean for all whales. Angular variance was not incorporated into the simulation since only slight changes in the direction of travel were observed between two successive surfacing sequences in the majority of cases. At every second, the location of the whale relative to the vessel was evaluated to determine (1) if the whale was in the sighting area and (2) if the whale was 'at the surface'. If during a simulation run, the whale surfaced at least once within the sighting range of the vessel, that run was counted as a sighting. Simulations were run for a vessel travelling in a straight line, at speeds of 0 to 12 knots and at 100m increments from the trackline. A run was terminated when the whale passed abeam of the vessel (Fig. 5).

The proportion of respiratory cycles (P) resulting in at least one surfacing within the sighting area (one potential sighting) for each 100m increment from the trackline and for speeds of 0 to 12 knots for convergent and parallel whales is:

$$P_{(y,v)} = C_{(y,v)} / N_{(y,v)} \tag{1}$$

where C is the number of cycles resulting in at least one surfacing; N is the total number of cycles (387); y is the distance from the trackline; and v is the vessel velocity.

The total probability of a whale surfacing in the sighting region for each vessel velocity and distance from the trackline was calculated by multiplying each distance from trackline and velocity probability for opposite direction values by 0.5 and same direction values by 0.5, since a whale at the periphery of the sighting region had a probability of 0.5 of the whale heading one way or the other. These were then summed to give the total probability for each velocity and distance from the trackline:

$$s_{(y,v)} = (OP_{(y,v)} \times P_s) + (SP_{(y,v)} \times P_s) \tag{2}$$

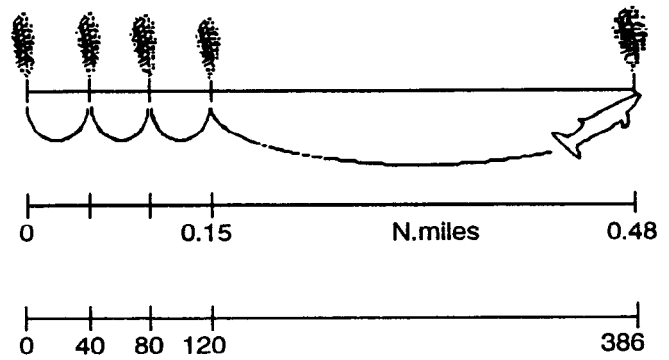


Fig. 4. Diagrammatic representation of the surfacing sequence of minke whales used for the simulation.

where OP is the probability for opposite direction whales; SP is the probability for same direction whales; and  $P_s$  is the probability of a given whale surfacing in either the opposite or same direction (0.5).

The probability of a whale surfacing at each speed was then calculated by multiplying the probability of surfacing at each distance from the trackline and each speed by the probability of a whale being at one of the 10 distance intervals. These values for each distance were then summed for each vessel velocity to give the probability of surfacing in the sighting area for each vessel velocity:

$$s(v) = \sum_{i=1}^{100} ((OP_y \times P_m) + (SP_y \times P_m)) \tag{3}$$

where:  $P_m$  = probability of a whale surfacing at a given distance from the trackline (0.1).

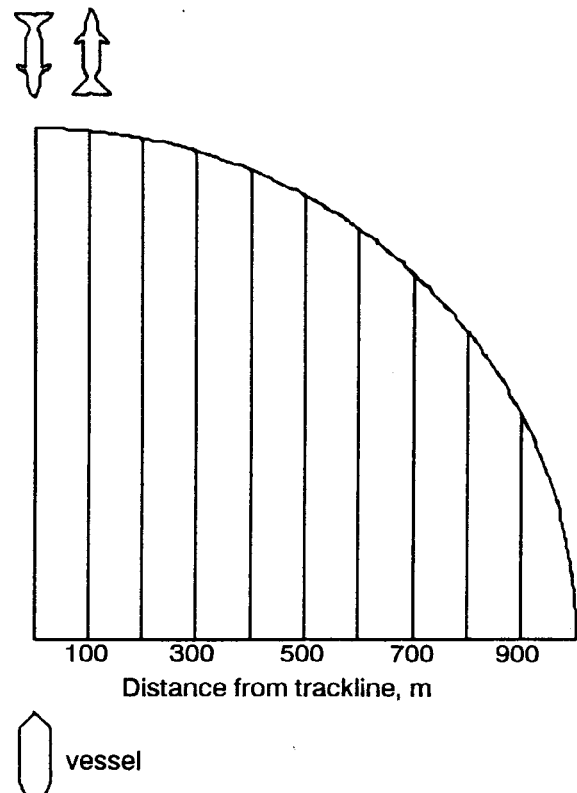


Fig. 5. Initial conditions of the simulation with the vessel generated at 0 and simulations run for the whale heading on convergent or parallel courses at 1km and for 100m increments from the trackline.

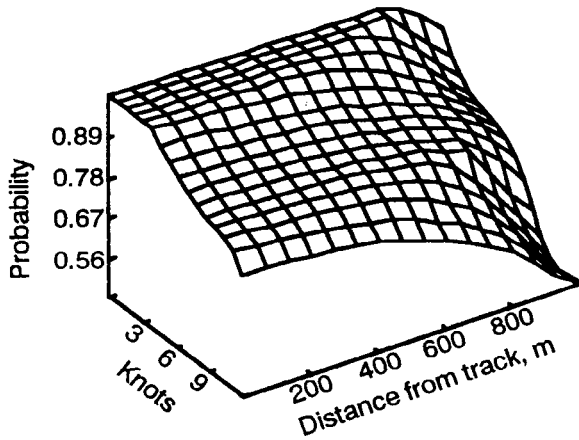


Fig. 6. The results of the simulation with distance from the trackline on the x-axis, speed of the vessel in knots on the y-axis, and probability of the whale surfacing on the z-axis.

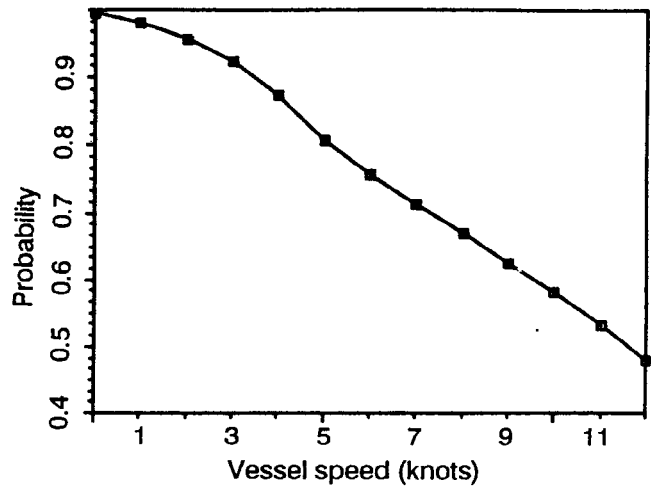


Fig. 8. The probability of a whale surfacing in the sighting region as a function of vessel speed.

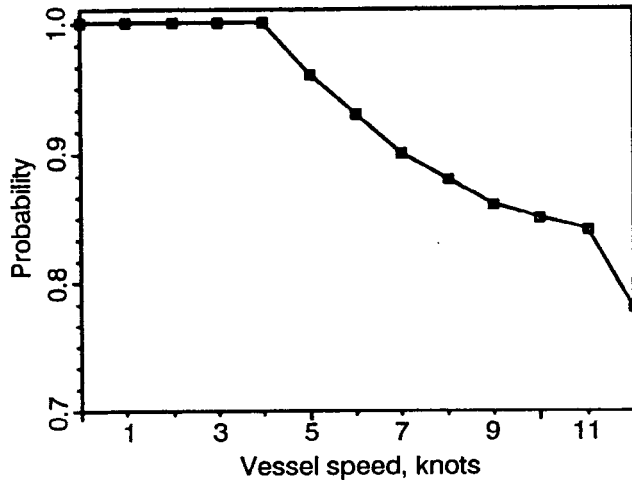


Fig. 7. The probability of a whale surfacing on the trackline as a function of vessel speed.

**Results**

The probability of a whale surfacing for each distance from the trackline and vessel speed tested is given in Fig. 6. The probability of a whale that was present on the trackline surfaced within range decreased from 1.00 to 0.93 and 0.78 for vessel speeds of 3, 6 and 12 knots respectively (Fig. 7). In all cases where the whale did not surface, the initial conditions began at a time corresponding to some point during a long-duration dive. As one would expect, the probability of a whale surfacing in the sighting region decreased as vessel velocity and distance from the trackline increased (Fig. 8). The probability that a whale present in the search area surfaced was 0.96, 0.88 and 0.47 at cruise speeds of 3, 6 and 12 knots, respectively.

**DISCUSSION**

The two objectives of this analysis were to: (1) describe the surfacing patterns of minke whales in the Monterey Bay area; and (2) determine how the movement of the vessel and the surfacing behaviour of the whale affected the probability of a whale surfacing on the trackline and within the sighting region of the research vessel.

In his review of surfacing rate experiments for minke whales in the Antarctic, Ward (1988) obtained a mean rate of 36.74 SPWPH, which, when corrected for missed blows, gave an estimate of 48 (95% CI 36–59) SPWPH. These values are not inconsistent with the rate of  $38.6 \pm 9.47$  SPWPH observed in this study. Reported mean surfacing rates for minke whales in Norwegian waters are 42 SPWPH (Øien *et al.*, 1990) and  $52.4 \pm 9.4$  (SE) SPWPH (Joyce *et al.*, 1989), while Gunnlaugsson (1989) reported a surfacing rate of 52.7 SPWPH for minke whales off Iceland. A radio-tagged minke whale off Iceland had an overall surfacing rate of 66.59 SPWPH, with a rate of 60.35 during the day and 74.44 during the night (Joyce *et al.*, 1990). The authors suggested that surfacing rates based on visual observations may be negatively biased since as sample size increases, more surfacings will be missed during an observation period. These North Atlantic rates are higher than those for the Antarctic and North Pacific. This suggests there may be an actual difference in surfacing rates between minke whales in the North Atlantic and those in the North Pacific and Antarctic.

Two types of surfacing patterns were observed. The most prevalent was the clumped surfacing pattern, similar to that observed in the Antarctic (Joyce, 1982; Ward, 1988) and in the North Atlantic (Gunnlaugsson, 1989; Joyce *et al.*, 1989). Given this similarity, the differences in surfacing rates between Antarctic and North Pacific whales and those in the North Atlantic are probably due to differences in long-duration dives. The second pattern of uniform surfacings (observed twice) corresponded to high rates of 60 and 56 SPWPH, respectively. These were similar to some surfacing patterns observed by Joyce *et al.* (1990). However, higher surfacing rates are not confined to the latter pattern; encounter 4 with Whale 3 for example, had a clumped surfacing pattern but a high surfacing rate of 52 SPWPH.

As shown in Figs 9a and b, two different surfacing patterns can have similar surfacing rates. Although both have surfacing rates of 42 SPWPH, the uniform pattern would yield a lesser chance of missed whales due to submergence. Clearly surfacing pattern as well as surfacing rate is important in determining the probability of sighting a whale.

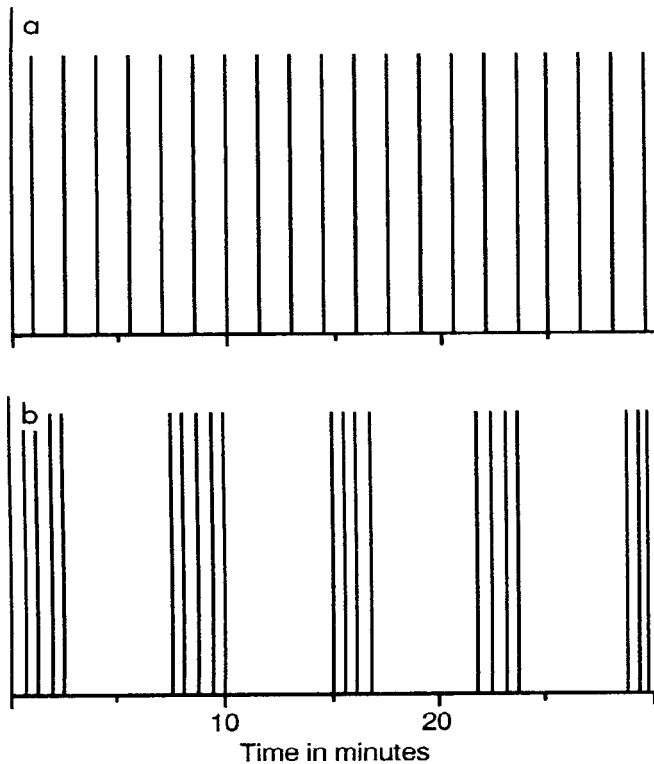


Fig. 9. Uniform (a) and Clumped (b) surfacing patterns. Both patterns have a surfacing rate of 42 surfacings per hour.

Whale 3 showed a significant difference in surfacing rates between encounters suggesting that variation occurs in surfacing rate for individuals over time. Encounter 10 was characterised by a low surfacing rate (28 SPWPH) with a clumped surfacing pattern, whereas encounter 1 had a high rate of 60 SPWPH and a uniform surfacing pattern, except for one long-duration dive. The surfacing pattern of encounter 4 was initially clumped and then changed after about 24 minutes to a more uniform surfacing pattern with seven surfacings in five minutes and an overall rate of 52 SPWPH.

Gunnlaugsson (1989) suggested that surfacing patterns may be influenced by some physical aspect of the area or distribution of prey in an area. Since all of the studies undertaken to date have been on feeding grounds, the long-duration dives may represent searching for food. Differences in the length of long-duration dives could represent differences in foraging behaviour or the distribution of prey. The mean duration of dives of minke whales immediately preceding a feeding event in the waters of the San Juan Islands, WA, were significantly different (3.87 minutes vs 1.48 minutes) between two types of observed feeding behaviours, lunge feeding and 'bird-association' feeding, respectively (Hoelzel *et al.*, 1989). The former requires the whale to locate its prey on its own while in latter the presence of birds that have located and concentrated prey is used. Whales may detect feeding birds audibly and would not therefore need to undertake a long underwater search for prey. Bird-association feeding was not observed in the Monterey Bay area, (Stern, 1990) and this may explain the occurrence of the long dives that were also found for the lunge feeders of the San Juan Islands. A similar pattern was observed between 1500–1800 hrs and 0700–1000 hrs for the radio-tagged whale in the North

Atlantic (Joyce *et al.*, 1990). They found periods of uniform surfacing patterns between 2100 and 0100 hours when foraging might be expected to be minimal due to reduced light-levels. However, gray whales off the coast of California exhibit a clumped surfacing pattern when migrating, so there may be several reasons why a clumped surfacing pattern may be advantageous.

The results of the simulation, using the observed surfacing and swimming patterns from this study, showed a decreased probability with increased vessel speed that a whale present on the trackline would surface within visual range. There was also a decrease in probability of a whale surfacing in the search area with an increase in vessel speed and distance from the trackline. Whales were missed due to long dives occurring in the surfacing pattern, and occurring as the whale came into sighting range of the vessel. Dive times may exceed the time a whale is within the visible range of a moving vessel (Joyce, 1982; Hiby, 1985), and the simulation revealed that movements of a whale may further compound this effect. This has implications for estimating population size using line transect techniques, which, for example, assume that all animals on the trackline are seen; all sighting surveys of whales violate this assumption to some degree (see review by Hiby and Hammond, 1989). The extent of the violation will depend on the behaviour of the whales being surveyed and the sighting conditions. The present simulations used an 'average' minke whale from the Monterey Bay area, and thus results cannot be used for whales in other areas. The intent was to estimate the magnitude of variability in the probability of sighting a whale based upon the observed clumped surfacing pattern, the relatively predictable travelling directions of the whales and the sighting conditions of the present study.

The proportion of whales missed in sighting surveys may be more accurately estimated by modelling whales with a variety of swimming characteristics. Simulations such as those suggested by Schweder (1990) should be carried out. For example, whales in the present study moved in a straight line, while Hiby (1982) simulated whales swimming in random initial directions. This may more accurately reflect the behaviour of minke whales in other areas. The reaction of whales to the research vessel may also confound the results of sighting surveys but this is difficult to document and to quantify (Leatherwood *et al.*, 1982; Borchers and Haw, 1990). Surfacing patterns of minke whales may apparently differ among areas and between and within individuals, especially with respect to the distribution of long dives. Long dives are only one source of variation in the probability of whales surfacing in the sighting region of survey vessels.

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## REFERENCES

- Batschelet, E. 1981. *Circular Statistics in Biology*. Academic Press, London. 371pp.
- Best, P.B. 1982. Whales as target animals for sighting surveys. *Rep. int. Whal. Commn* 32:551-3.
- Borchers, D.L. and Haw, M.D. 1990. Determination of minke whale response to a transiting survey vessel from visual tracking of sightings. *Rep. int. Whal. Commn* 40:257-69.
- Doi, T. 1974. Further development of sighting theory on whales. pp. 359-68. In: W.E. Schevill (ed.) *The Whale Problem: A Status Report*. Harvard University Press, Cambridge, Mass. Paper presented to the IWC Scientific Committee, June 1971.
- Gunnlaugsson, T. 1989. Report on Icelandic minke whale surfacing rate experiments in 1987. *Rep. int. Whal. Commn* 39:435-6.
- Hiby, A.R. 1982. The effect of random whale movement on density estimates obtained from whale sighting surveys. *Rep. int. Whal. Commn* 32:791-3.
- Hiby, A.R. 1985. An approach to estimating population densities of great whales from sighting surveys. *IMA Journal of Mathematics Applied in Medicine and Biology* 2:201-20.
- Hiby, A.R. and Hammond, P.S. 1989. Survey techniques for estimating abundance of cetaceans. *Rep. int. Whal. Commn* (special issue 11):47-80.
- Hoelzel, A.R., Dorsey, E.M. and Stern, S.J. 1989. The foraging specializations of individual minke whales. *Anim. Behav.* 38:786-94.
- Joyce, G.C. 1982. Blow patterns as sighting cues for censusing minke whales in Antarctic waters. *Rep. int. Whal. Commn* 32:787-90.
- Joyce, G.C., Øien, N., Calambokidis, J. and Cabbage, J.C. 1989. Surfacing rates of minke whales in Norwegian waters. *Rep. int. Whal. Commn* 39:431-4.
- Joyce, G.C., Sigurjónsson, J. and Víkingsson, G. 1990. Radio tracking a Minke whale *Balaenoptera acutorostrata* in Icelandic waters for examination of dive-time patterns. *Rep. int. Whal. Commn* 40:357-61.
- Leatherwood, S., Awbrey, F.T. and Thomas, J.A. 1982. Minke whale response to a transiting survey vessel. *Rep. int. Whal. Commn* 32:795-802.
- Øien, N., Folkow, L. and Lydersen, C. 1990. Dive time experiments on minke whales in Norwegian waters during the 1988 season. *Rep. int. Whal. Commn* 40:337-41.
- Schweder, T. 1990. Independent observer experiments to estimate the detection function in line transect surveys of whales. *Rep. int. Whal. Commn* 40:349-55.
- Stern, S.J. 1990. Minke whales (*Balaenoptera acutorostrata*) of the Monterey Bay area. Master's Thesis, San Francisco State University, San Francisco, CA. 289pp.
- Ward, A.J. 1988. Accounting for the effect of pod size in the estimation of blow rates: analysis of data from the 1984/85, 85/86 and 86/87 IDCR minke whale assessment cruises. *Rep. int. Whal. Commn* 38:265-8.
- Ward, A.J. and Hiby, A.R. 1987. Analysis of cue-counting and blow rate estimation experiments carried out during the 1985/86 IWC/IDCR minke whale assessment cruise. *Rep. int. Whal. Commn* 37:259-62.