Use of videogrammetry to estimate length to provide population demographics of dwarf minke whales in the northern Great Barrier Reef

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ABSTRACT

Commercial swim-with-whale programmes, based on the dwarf minke whale (*Balaenoptera acutorostrata*), have been conducted in Great Barrier Reef waters since 1996 and under permit since 2003. Evaluating the effectiveness of management requires information on the biology of the whales, including possible impacts on their critical life stages, such as mating or calving. In this study, length measurements have been used as the best available proxy for age and thus state of sexual maturity. Underwater videogrammetry was used to estimate the lengths of dwarf minke whales interacting with boats and swimmers during June/July 2003 and 2004. The calibrations used to correct systematic biases in distance and length estimates are presented and other sources of error associated with the methodology and the behaviour of the whales are discussed.

Mean lengths (from replicate measurements of individually identified whales) ranged 4.82-6.61m in 2003 (*n*=23, from five encounters) and 4.48-7.18m in 2004 (*n*=56, from 29 encounters). The overall mean length (2003: 5.90m; 2004: 5.73m) did not differ significantly between years. In both years, the mean lengths of the majority of whales (2003: 57%; 2004: 59%) were less than 6m, which is regarded as sexually immature based on available life history data. The size ranges within a single encounter were broad; no encounter was dominated by one size class. Segregation by size was not observed.

This paper presents the first field measurements of dwarf minke whales on their tropical wintering grounds. While most whales interacting with vessels or swimmers were immature, adult whales, including cow-calf pairs, also were involved. More information, especially on cumulative effects, is needed to assess the impact of these swim-with programmes.

KEYWORDS: AGE DISTRIBUTION; AUSTRALASIA; DWARF MINKE WHALE; MONITORING; PHOTOGRAMMETRY; PHOTO-ID; SEGREGATION; SOCIAL; WHALEWATCHING; SOUTHERN HEMISPHERE; SURVEY-VESSEL

INTRODUCTION

The dwarf minke whale, generally considered to be a subspecies of the common minke whale, *Balaenoptera acutorostrata* (Rice, 1998), has approached vessels and divers on the northern Great Barrier Reef at least since the early 1980s (Arnold, 1997). Advertised commercial swim-with-whales activities have occurred since 1996. From 2003, only operators with a specific swim-with-whales permit from the Great Barrier Reef Marine Park Authority can conduct such advertised activities, although extensive 'incidental' encounters occur from other tourist and recreational vessels. A management programme, including a code of conduct (*www.gbrmpa.gov.au*) is in place.

Swim-with programmes are a contentious issue. A review by the Scientific Committee of the International Whaling Commission (IWC) noted that 'available evidence indicated that swim-with programmes in the wild could be considered as being highly invasive' (IWC, 2001, p.57). However they further noted that impacts will vary between species and locations, thus requiring an assessment on a case by case basis. To conduct such an assessment for the dwarf minke whale swims, and to evaluate the effectiveness of management options, biological information on the target population is required.

One concern is the possible impact on critical life history stages. The swim-with programmes are conducted at low latitudes during the austral winter months. Based on life history knowledge of other Southern Hemisphere baleen whale stocks and the limited life history data on dwarf minke whales, swim-with programmes may occur at the time of mating and/or calving. In order to assess the possible impact on critical life history stages it becomes important to know to what extent mature (and thus potentially breeding) whales are involved in the programmes. Field measurements of lengths can serve as an indicator of maturity state.

The underwater videogrammetry technique developed by Spitz *et al*. (2000) was modified so that it could be combined with routine photo-identification studies that were also conducted. In this paper, the modified technique is outlined, sources of error are assessed and length data are presented from encounters with dwarf minke whales on a commercial dive vessel during the 2003 and 2004 seasons. Finally, the implications for management are discussed.

METHODS

Data were collected from *Undersea Explorer* in JuneJuly 2003 and 2004, during trips offering commercial swim-with-whale programmes along the Ribbon Reefs between Port Douglas and Lizard Island (14°39'-16°03'S and 145°35'-145°39'E). Expeditions were of six days and nights duration, departed on Saturday evenings and followed a similar cruise pattern.

Field procedures

General field procedures were as outlined in Birtles *et al*. (2002) and Valentine *et al*. (2004), which can be consulted for more details. Videogrammetry procedures are presented

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in greater detail in Sobtzick (2005) and are further refined in this paper.

Encounters depended on the initial approaches of whales. In open water, as soon as the whales approached the vessel (within approximately 30-40m) and were usually beginning to circle it in close proximity, 50m ropes were deployed from both the stern and bow, engines were turned off and the vessel was allowed to drift. Initially researchers and then passengers entered the water, hanging on to the ropes or to uninflated rubber inner tubes attached to each rope. A similar procedure occurred during reef encounters, except that often only a single rope was run from the stern if the boat was moored by the bow.

During an encounter, there was a researcher positioned at the end of each of the two ropes (usually AB and SS). They were equipped with a wetsuit, mask, snorkel and fins, and additional gear such as a digital video camera in a waterproof housing and an underwater slate for the length estimation studies.

Measurements were made during five encounters in 2003 and 29 encounters in 2004, during which whales interacted with the vessel for an average period of 148min. Many of the animals made repeated passes within the range of 5-16m from the videographer, which provided the opportunity for multiple independent size measurements to be taken. The whales' approaches and passes were below the surface, which resulted in filming of the whales at an angle ranging from approximately 15° from the surface to 90° (vertically beneath the videographer).

The videographer spent as much time as possible in the water, filming the whales with a *Sony* DCR VX 1000E digital camera in an Amphibico VH-1000 underwater housing. An underwater portable sonar rangefinder (*Hondex* PS7 from Speedtech Instruments) was attached to the camera housing to measure the distance between the camera and whale. In addition to the length estimation measurements, the videographer tried to film as many whales as possible, recording features that could be used to identify individual whales. For this it was necessary to use the zoom option on the camera to provide the clearest records of specific features like scars or colour patterns. A requirement for the size estimation method is that the field of view (FOV) of the camera is always consistent. The videographer ensured that for every length measurement the camera was zoomed out to the maximum angle of view.

This often created a problem for encounters with a large number of whales present or when the whales stayed with the boat only for a short period of time. Since it was necessary to obtain the identification footage first, and this way of filming differed from the way of filming for the length estimations, it was almost impossible to obtain length measurements for every whale present in the encounter.

The passes chosen to activate the sonar were when the videographer was perpendicular to the whale's longitudinal axis, the entire length of the whale was visible in the viewfinder and the clarity of the image was sufficient to suggest identification would be possible. The distance between the camera and whale was measured with the sonar at the moment the whale's midline passed the camera. Depending on the size of the whale, this was possible from a distance of 5m or more.

If there was relative movement between the whale and videographer between measurements, then these were regarded as independent measurements. Relative movement was assessed from the video footage by monitoring whale movement and also changes in sonar distance measurements.

The sonar reading of the distance was transcribed onto an underwater slate, which was then filmed to create a permanent record of the measurement on the digital video tape. Depending on the nature of the interaction, it was nearly always possible to capture several shots of the same whale at varying distances as the whales usually made repeated passes.

In 2003, the percentage of measured whales/identified whales in an encounter ranged from 33.3-69.2% (a total of 23 whales were measured over five encounters), whereas in 2004 up to 100% of identified whales were measured (range 18.8-100%, total of 56 whales measured over 29 encounters).

The sonar has a range of 79m, a 24° beam angle and a working frequency of 200kHz (*www.speedtech.com*). Previous research on minke whale vocalisation showed that the highest frequency sound produced by dwarf minke whales had a maximum frequency of 9.4kHz (Gedamke *et al*., 2001). Hearing would be expected to be within this low frequency range from 50Hz-9.4kHz. The anatomy of mysticete whale ears also suggests that their hearing range is low frequency (Wartzok and Ketten, 1999), well below the working frequency of the sonar. The sonar should not be audible to the whales and no reaction of the whales towards the sonar was observed.

Image extraction and analysis

The video images were reviewed on a computer with speakers using the video editing software Adobe *Premiere* 6.0. An audible click sound is made by the sonar enabling the exact frame corresponding to sonar activation to be captured. Individual frames were captured with this software and then edited with Adobe *Photoshop* 5.0 LE.

The following criteria were used to ensure the identified errors (detailed below) were minimised or eliminated: (1) the picture was in focus; (2) the camera was on full wide angle; (3) the whole body length of the whale was visible; (4) the whale's midline was perpendicular to the camera axis; and (5) the body of the whale was fully extended, without the tail being bent up or down.

To estimate the size of an animal in a suitable image, the researcher first enhanced the picture if necessary by changing brightness, contrast and colour balance of the image using Adobe *Photoshop* software. Then, the size of the whale image from the tip of its rostrum to the anterior point of the notch at the centre of the tail fluke (X-Y coordinates) was marked using the Adobe *Photoshop* 'Measure Tool' as shown in Fig. 1. The ratio of the whale image length in pixels (%FOV) to the total image width in pixels (total FOV) was calculated (Eqn 2). Together with the sonar distance and the subtended camera lens angle, this enabled whale length to be calculated.

From selected images, individual whales were identified using scar and colour patterns (Arnold *et al*., 2005; Birtles *et al*., 2002). Animals were initially identified in the field. Later, the tapes for each encounter were reviewed to catalogue each time a whale was filmed in an encounter. Replicate images for individual whales were extracted using this shot list. While reviewing the video tapes, at least two researchers were present to confirm individual whale identification.

Individual whale identification codes were named in chronological order of length measurement L1, L2, L3 and onwards. An encounter code was used to identify each whale encounter (year.day.month. no. of encounter within that day). For example, 03.06.26.3 is the 3rd separate whale encounter on 26th of June 2003. There were numerous

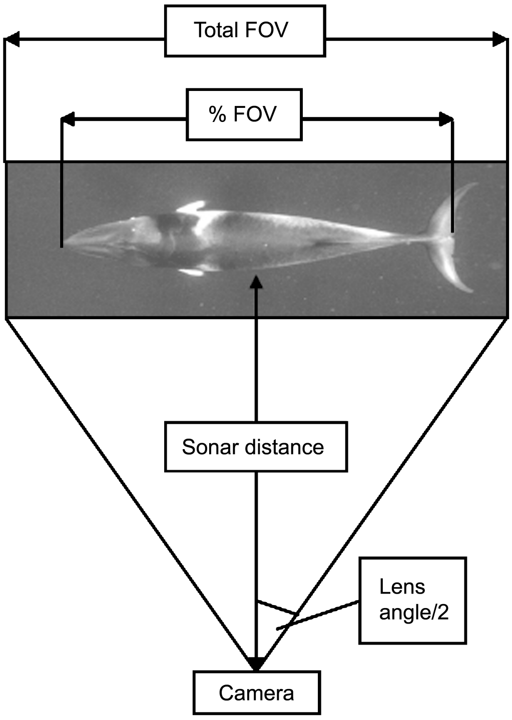

Fig. 1. Whale length determination and trigonometric background for the calculations. Dorsal shot of a dwarf minke whale with the length of the animal marked from the tip of its rostrum to the anterior point of the notch at the centre of the tail fluke

resightings of individual whales during separate encounters, however, only two resightings have resulted in length measurements. Whale L43 was measured during encounters 04.06.30.1 and 04.07.04.3 and whale L65 was measured during encounters 04.07.12.1 and 04.07.12.2 (Table 1).

The mean number of length estimation measurements per whale varied considerably between individual encounters on different days (e.g. mean of 6.2 and 2.7 shots per measured whale in encounters 04.06.30.1 and 04.07.06.2 respectively) (Table 1). However, the overall mean number of measurements per whale was 4.6 in 2003 (23 whales measured) and 5.3 in 2004 (56 whales measured).

Camera lens angle determination

A 6.0m long white polyvinylchloride (PVC) pipe with a diameter of 90mm was placed on a flat sandy bottom on a sheltered dive site. To ensure minimal water movements, calm days were picked and locations that were mostly protected from currents. The PVC pipe was marked in 1m intervals with black PVC tape. From the centre of the pipe a measuring tape and a rope were attached that were both suspended vertically by a float to a few metres below the surface while the pipe was weighted down with dive weights.

Five consecutive measurements were taken at each metre interval, 5-10m from the pipe. This range covered the distances to the whales for most measurements taken in previous years. Measurements from both the sonar and tape measure were recorded by an observer as the videographer recorded images. This process was done twice, while divers were ascending and descending.

The sonar activation frames were captured using the same method as for the whale images (see later). Out of the five measurements per distance, the three best images were selected, i.e. where the pipe was clearly visible, not angled and the picture was in focus; these images were used for further calculations.

From these frames individual images of the pipe in 1m increments were cropped, starting at 4m (smaller than smallest whale in the sample). The size of the pipe segment was measured using the Adobe *Photoshop* 'Measure Tool'. The %FOV of these pipe segments was calculated and was used, together with their known true length to calculate the full field of view at this sonar distance. This FOV measure was used to calculate the subtended angle of the camera lens when zoomed out to its widest angle.

Length determination theory

The sonar distance and the widest angle of view of the camera lens provide the trigonometric values necessary to calculate the length of individual whales. Sonar ranges were determined to be synonymous with range to the object. The errors pertaining to this assumption are dealt with in the treatment of sonar calibration errors.

The camera lens angle was calculated through field calibrations based on previous underwater videogrammetry studies (Spitz *et al*., 2000). In this case a pipe of known length marked in metre increments was filmed from a range of known distances. The resulting linear relationship between camera field of view (FOV) and sonar distance allowed the lens angle to be calculated as 54.25°.

Using this lens angle ($\acute{Ø}$) enabled the field of view to be calculated in metres for each sonar distance measurement (SD),

$$\text{FOV(metres)} = 2 \times \tan\acute{Ø} \times \text{SD}$$

As $\acute{Ø} = 54.25°$ then

$$\text{FOV(metres)} = 1.019 \times \text{SD} \quad (1)$$

Through analysis of images in Adobe *Photoshop* it was possible to calculate the %FOV taken up by the whale as described in the section on image extraction and analysis and hence to calculate the length of the whale (Fig. 1).

$$L = 1.019 \times \text{SD} \times \text{\%FOV of whale} \quad (2)$$

Treatment of errors

Image selection and whale body flexure

Body flexure can result in underestimates of length measurement. Minke whales flex dorsoventrally much more than laterally as this is their main locomotory movement. Within an individual frame it is possible to assess the level of dorsoventral flexure from the side orientation (dvfS) and level of lateral flexure from a top orientation (latfT). It is not possible to assess dorsoventral flex from the top (dvfT) nor is it possible to assess lateral flex from the side (latfS) in a still image. Using the video footage, head and tail movement were obvious if the whale was actively swimming (dorsoventral flex) or changing direction (lateral flex). It was possible to assess levels of body flexure in these orientations in the period before, during and after the captured frame.

To quantify error levels, only high quality still images were used and classified as: (1) straight; (2) minor flex; or (3) major flex. The whales in these images were measured in two ways: (1) in a straight midline from snout to tail notch; and (2) following the convex outline of the body. This procedure was carried out for the two orientations where this was possible, to quantify both dorsoventral and lateral flexure. For dvfS, the ratio of straight line to outline was, straight = 0.99, minor flex = 0.95 and major flex = 0.92. LatfT ratios were straight = 0.98, minor flex = 0.95. Whale flexure in this orientation is restricted so major flex was not an issue.

Table 1

Summary of dwarf minke whale encounters and length data taken during 2003 and 2004.

Encounter	No. of measured whales/no. of whales present	Whale ID	Calculated length (m)			Stdev. (m)	Whale ID	Calculated length (m)			Stdev. (m)
			Mean	Range	Rep.			Mean	Range	Rep.	
2003											
03.06.26.3	1/3 (33%)	L1	6.28	5.86-6.52	3	0.368	L2	6.39	6.00-6.82	6	0.329
03.07.07.2	1/3 (33%)	L3	5.6	5.52-5.68	2						
03.07.08.2	9/13 (69%)	L4	6.17	5.94-6.45	4	0.239	L5	5.67	5.45-5.83	4	0.181
		L6	5.62	5.35-5.85	6	0.212	L7	6.02	5.73-6.53	5	0.301
		L8	5.8	5.67-5.94	3	0.139	L9	4.82	4.80-4.83	2	
		L10	5.9	5.54-6.25	5	0.293	L11	5.2	5.15-5.27	3	0.063
		L12	5.87	5.66-6.22	3	0.306					
03.07.09.2	5/10 (50%)	L13	5.68	5.50-5.94	6	0.156	L14	6.18	6.15-6.22	2	
		L15	6.4	6.37-6.44	2		L16	5.77	5.72-5.89	5	0.074
		L17	6.03	5.94-6.11	2		L18	6.55	6.37-6.82	5	0.171
03.07.10.2	5/10 (50%)	L19	6.11	5.87-6.42	6	0.262	L20	6.61	6.30-6.85	14	0.18
		L21	5.56	5.41-5.71	2		L22	5.68	5.58-5.80	7	0.08
		L23	5.66	5.35-5.97	8	0.19					
2004											
04.06.07.1	1/1 (100%)	L24	6.09	5.81-6.26	4	0.195					
04.06.09.1	2/3 (66.7%)	L25	5.68	5.36-6.04	34	0.204	L26	7.18	7.07-7.36	7	0.127
04.06.15.2	1/1 (100%)	L27	6.17	6.02-6.35	7	0.127					
04.06.15.3	1/3 (33.3%)	L28	6.34	6.23-6.52	4	0.125					
04.06.20.2	2/10 (20%)	L29	5.44	5.25-5.68	4	0.18	L30	5.07	4.95-5.13	4	0.086
04.06.21.1	1/1 (100%)	L31	6.13	5.96-6.35	9	0.117					
04.06.21.2	1/1 (100%)	L32	6.59	6.40-6.70	6	0.115					
04.06.22.1	3/16 (18.8%)	L33	4.98	4.91-5.06	2		L34	5.88	5.82-5.95	3	0.065
		L35	5.86	5.81-5.92	2						
04.06.23.2	2/4 (50%)	L36	5.27	5.20-5.34	2		L37	6.23	5.97-6.36	8	0.137
04.06.25.2	1/2 (50%)	L38	6.72	6.54-6.83	7	0.129					
04.06.27.1	3/3 (100%)	L39	6.18	6.03-6.39	5	0.144	L40	5.95	5.92-5.99	2	
		L41	5.44	5.26-5.56	3	0.154					
04.06.30.1	5/7 (71.4%)	L42	4.79	4.58-4.98	12	0.134	L43	6.22	6.19-6.25	2	
		L44	6.36	6.21-6.57	6	0.123	L45	5.89	5.64-6.08	5	0.191
		L46	6.52	6.16-6.71	6	0.216					
04.07.01.1	2/2 (100%)	L47	6	5.84-6.14	6	0.11	L48	5.15	5.06-5.25	2	
04.07.01.2	3/3 (100%)	L49	4.76	4.63-4.83	3	0.108	L50	6.61	6.49-6.87	7	0.147
		L51	5.54	5.52-5.56	2						
04.07.02.1	2/3 (66.7%)	L52	6.18	6.06-6.30	3	0.123	L53	5.58	5.50-5.79	4	0.142
04.07.04.2	2/2 (100%)	L54	5.3	5.07-5.53	7	0.148	L55	5.69	5.40-5.97	6	0.229
04.07.04.3	3/8 (39.5%)	L43	5.99	5.80-6.14	4	0.152	L56	4.97	4.83-5.03	4	0.093
		L57	4.48	4.43-4.53	3	0.052					
04.07.06.1	1/3 (33.3%)	L58	6.13	5.90-6.25	3	0.198					
04.07.06.2	3/6 (50%)	L59	5.56	5.49-5.66	4	0.071	L60	6.1	6.07-6.14	2	
		L61	5.87	5.84-5.89	2						
04.07.11.1	1/2 (50%)	L62	4.89	4.77-5.24	7	0.164					
04.07.11.2	2/3 (66.7%)	L63	4.67	4.57-4.75	6	0.075	L64	6.19	6.00-6.44	8	0.144
04.07.12.1	2/4 (50%)	L65	5.63	5.48-5.74	7	0.107	L66	6.65	6.42-6.84	3	0.215
04.07.12.2	4/11 (36.4%)	L65	5.41	5.32-5.51	8	0.091	L67	5.15	4.94-5.30	7	0.125
		L68	4.74	4.66-4.80	3	0.072	L69	6.1	5.99-6.21	4	0.104
04.07.14.1	1/3 (33.3%)	L70	6.25	6.24-6.27	3	0.015					
04.07.14.2	1/2 (50%)	L71	6.03	5.85-6.20	2						
04.07.15.2	1/1 (100%)	L72	5.04	4.94-5.23	4	0.138					
04.07.21.1	3/3 (100%)	L73	5.62	5.55-5.67	5	0.056	L74	5.35	5.27-5.43	2	
		L75	4.99	4.94-5.05	2						
04.07.23.1	1/4 (25%)	L76	5.68	5.56-5.81	9	0.093					
04.07.30.1	3/3 (100%)	L77	4.78	4.73-4.83	2		L78	5.33	5.23-5.45	4	0.102
		L79	7.11	7.08-7.14	2						

Maximum errors arise from image angles where the flexure is not easily identified (dvfT and latfS). In a top shot major dorsoventral flex is obvious from the video footage and such images were rejected. This leaves the maximum error as being −5% for both images of laterally flexed animals viewed from the side and also images of dorsoventrally flexed animals viewed from the top.

Image selection and whale perpendicularity

Accurate length determination requires that the whale axis is perpendicular to the camera. To quantify the angle of images accepted or rejected, a 3D minke whale model was rotated on a protractor template. Both videographers (SS and AD) were asked to class the angle of the whale as perpendicular (1), slightly off (2) or greatly off perpendicular (3). This test showed situations where the angle was greater than 10° were classed as (3) and were rejected on all occasions. At a 10° angle (the greatest angle of acceptance) this equates to a length estimation error of −1.5%.

Whale pixel measurement (%FOV)

Whales were measured (pixel count) using the Adobe *Photoshop* 'Measure Tool'. Two factors contributed to errors in these measurements: (1) low image resolution blurring the accurate identification of the extreme ends of the measure, snout and tail notch; and (2) inaccurate placement of the end cursor of the 'Measure Tool'. To quantify this error the two main videographers independently measured 10 separate images to compare results. Applying the Mann-Whitney test showed no significant difference between videographer's results at the 95% confidence level.

Sonar calibration

The sonar measurement was consistently less than the tape measurement by a mean of 2.2%. The ratio was consistent across the different distances and the standard deviations were also sufficiently small (<0.022) to indicate that this difference is a systematic error. Underestimation could be a precautionary safety feature in the design of the sonar device. It could also be an overestimate in the tape measurements as a result of slight tape curvature due to water movement. In 2004 a second sonar unit was also used which showed a variation of 0.5% in measurements.

While the sonar has a consistent error related to 'real distance' this did not affect the accuracy of whale length determination. The camera lens angle determination and subsequent whale length calculations relied solely on sonar distance readings and known pipe lengths for calibration. These are consistent and show a linear relationship between distance to object and %FOV.

Sonar error and depth

The depth of the whale at the time it was filmed could potentially produce errors due to difference in sound (sonar) transmission speeds at different depths. Transmission speed varies due to effects of changes in salinity, temperature or pressure with depth. In the outer reef areas of this study the water is well mixed and temperature and salinity are constant across the range of depths (3-16m) where whale measurements were taken. Maximum pressure effects over this 13m depth variation are approximately 0.2m sec^{-1}, or a 0.013% difference in speed of sound transmission (Jensen *et al*., 1994) and therefore sonar error.

Curvature of the lens

The effects of the curvature of the wide angle lens with regards to a possible distortion existing at the edges of the field of view was examined. A black and white grid (40×56cm) consisting of 2cm squares was filmed underwater at a set distance (38.85cm) from the nodal point of the camera's wide angle lens, as in Spitz *et al*. (2000).

Each square within the grid was measured using the Adobe *Photoshop* 'Measure Tool'. This produced a pixel count per square (observed) which could be graphed against mean pixel count per square (expected) across the full field of view to show lens distortion. The general principles and calculation of the curvature regression equation are the same as used in Spitz *et al*. (2000) and produced the quadratic regression equation (r^2=1.000).

$$y = 0.00007x^2 + 1.0532x - 2.002.$$

This equation was applied to all whale pixel measurements (%FOV) to eliminate error due to lens curvature.

The same camera and underwater housing were used in each field season; therefore it was not necessary to retest the curvature of the lens or the lens subtended angle.

RESULTS

Summary of encounters during 2003 and 2004

Overview of length estimations 2003 and 2004

Fig. 2 shows the mean body lengths and standard deviation of all whales measured in 2003 and 2004 for which replicates were available. This shows there is no discontinuity in size and also demonstrates the variation in measurements in relation to the size of the whole group.

In 2003, the mean lengths of whales varied from 4.82m to 6.61m (n=23, from five encounters). In 2004, the sample size (n=56, from 29 encounters) was larger and the size range (4.48m-7.18m) was greater (Fig. 3).

The overall mean size of all whales measured was 5.90m in 2003 and 5.73m in 2004. Testing the data for normal distribution by applying the Levene's Test for Equality of Variances indicated that the data were normally distributed (F=6.064, p=0.016). Therefore a parametric t-test was used; which showed that the mean lengths of the whales in 2003 and 2004 were not significantly different (p=0.243). All statistical analyses were conducted with *SPSS* for Windows, version 14.0.1.

Kato and Fujise (2000) suggested that females were likely to attain maturity at a length of 6-6.5m; the smallest mature female in their study was 6.6m in length. A study of 13 whales by Best (1985) showed the smallest mature female was 6.4m. Male baleen whales are generally about 5% smaller than females (Boyd *et al*., 1999) suggesting that males ⩾6m would also be mature. As the gender of many of the measured animals was not able to be determined, all animals <6m were assumed to be definitely immature and all those ⩾6m as mature or maturing.

In both 2003 and 2004 most of the whales measured were smaller than 6m (2003: 13/23=56.5%; 2004: 33/56=58.9%) and can therefore be regarded as sexually immature (see Discussion).

The size classes 5.50-5.99m and 6.00-6.49m were the most frequent classes in both years with the difference that in 2003 47.8% of the measured whales belonged to the 5.50-5.99m class, whereas in 2004 only 23.2% of the examined animals belonged to that group. Mature or maturing whales (6m or more in length) comprised a sizable proportion of the total in both years (43.5% in 2003, 41.1 % in 2004).

Size classes in individual encounters for 2003 and 2004

To examine whether the size structure of whales in individual encounters varied between years, all encounters from 2003 (Fig. 4) were compared with encounters in 2004 with three or more whales (Fig. 5). The encounters were in weeks 3-5 in 2003 and 4-8 in 2004.

The group composition was similar in both years. The size range covered in all of the encounters was similar and included the size classes '<6m' and '≥6m' whales. No encounter was clearly dominated by one size class.

Size segregation within season

To examine whether dwarf minke whales show a size segregation over the season, the length data were grouped into the two size classes '<6m' and '≥6m' by week for 2004 (Fig. 6). Data from 2003 were excluded because they were taken in only three weeks of the eight week season.

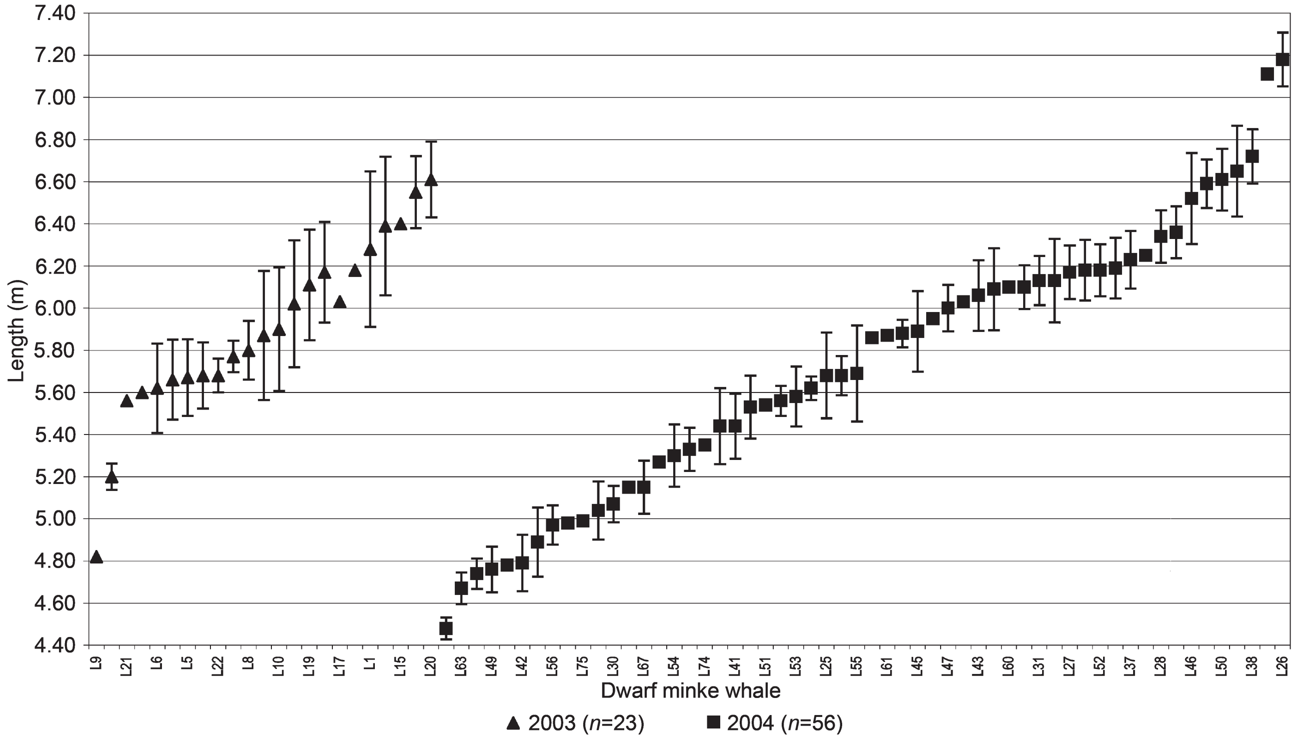

Fig. 2. Mean body length and standard deviation of 79 whales measured in 2003 and 2004.

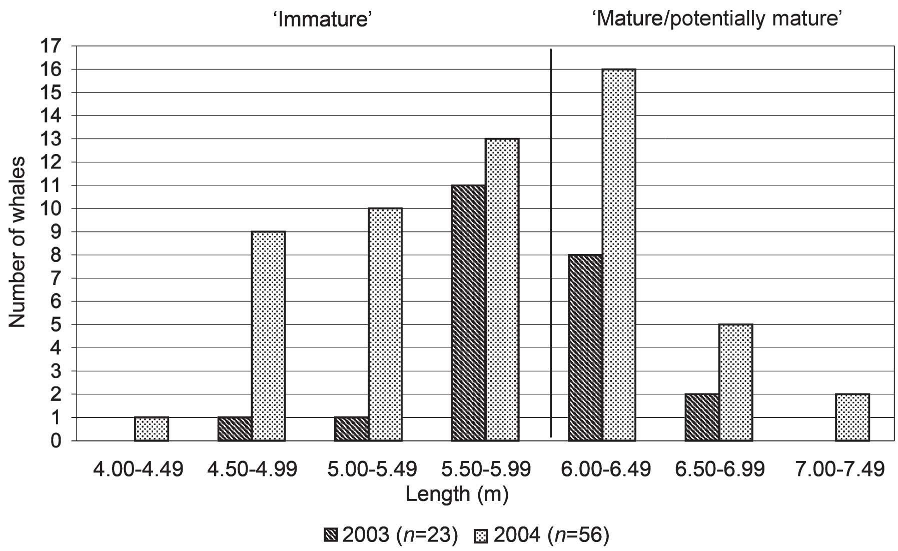

Fig. 3. Number of individual whales in half metre size classes in 2003 and 2004. The thick black line separates the immature whales (<6m), from the mature or potentially mature whales in Figs 3, 4 and 5.

Fig. 6 clearly shows that dwarf minke whales approaching the boat over the period of eight weeks were not clearly segregated by size. In weeks 3-6, which were the ones best sampled, both size classes were present. Both size classes were not represented in weeks 2 and 7, which could have been caused by the small sample size.

DISCUSSION

Sources of error

Underwater videogrammetry has proved to be a relatively robust method to measure dwarf minke whales. There are systematic errors, resulting especially from inaccuracies in the distance measured by sonar and with different sonar units, which emphasises the need for routine calibration. There was no correlation between extent of variation in size measurements and distance to the whale, nor was precision increased with a larger sample size within the range of our measurements. The major sources of error may thus be non-systematic and attention should be directed at more rigorous identification of flexure and perpendicularity of whales in the image selection process. Improving clarity of images to more accurately identify the snout and tail notch for pixel measurement should be possible with future use of high definition video for this procedure.

Overview of data

Only 50 size measurements of dwarf minke whales have been published (Table 2), with an additional eight whales from the sub-Antarctic reported by Kato and Fujise (2000).

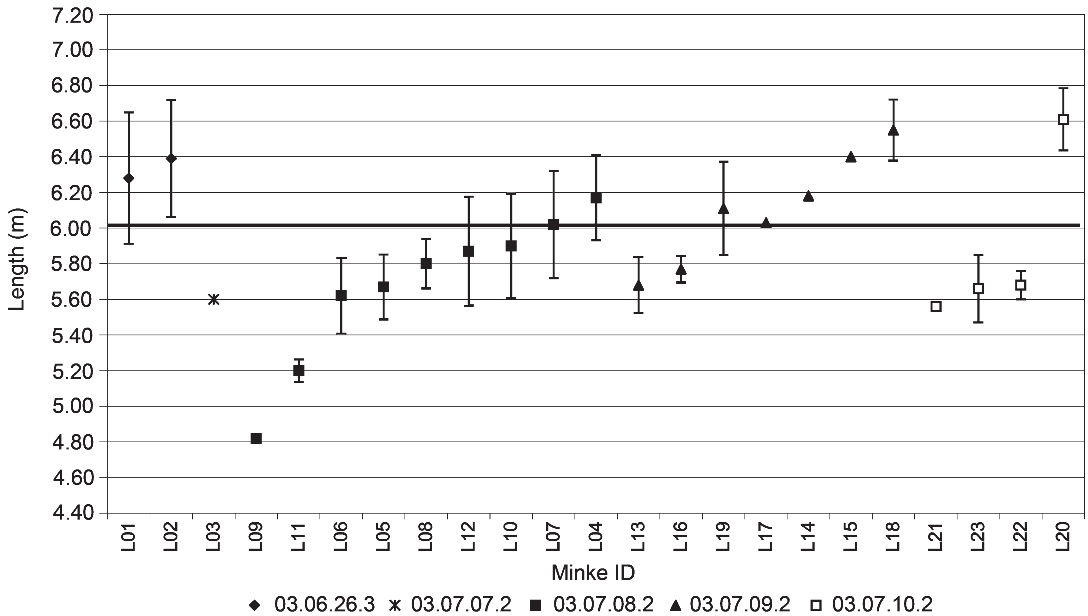

Fig. 4. Mean lengths (plus standard deviation) of minke whales in 2003 grouped by encounter.

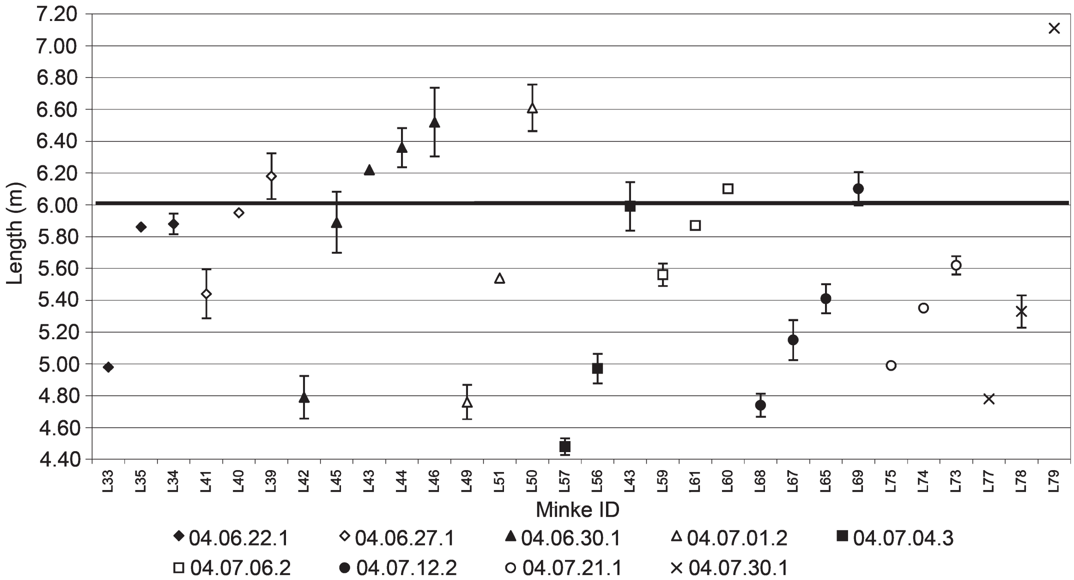

Fig. 5. Mean lengths (plus standard deviation) of minke whales from nine selected encounters in 2004 grouped by encounter.

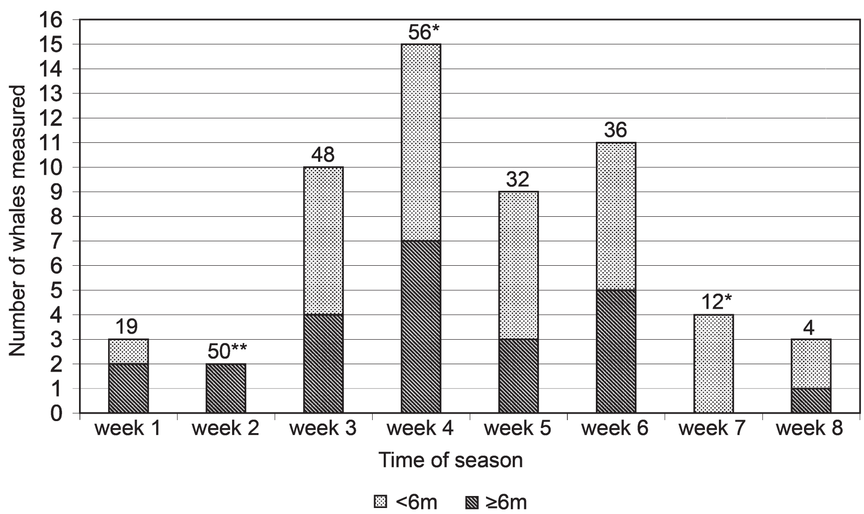

Fig. 6. Number of whales in the size classes '<6m' and '⩾6m' over the length of the field season 2004 and occurrence of cow and calf pairs (asterisk). The total sample size is 57, since one whale appears twice in the figure (L43 was allocated to two different size classes). (See text for details).

The length estimates of 79 dwarf minke whales presented in this paper thus considerably extends the sample size of length measurements; moreover they are the first data from the low latitude wintering grounds where mating and reproduction may take place and they were obtained by non-lethal methods.

Each data set has biases. The mean length of dwarf minke whales taken by commercial whalers (Best, 1985) was 6.9m, however Best (1982) noted that small whales were generally avoided by whalers. The mean length of dwarf minke whales taken in the sub-Antarctic during the Japanese scientific whaling programme (Table 2), in which there was no such selection against smaller whales, was 5.2m. The mean lengths of stranded dwarf minke whales from South Africa, eastern Australia and New Zealand, and eastern South America were 2.9m, 4.4m and 3.9m respectively, suggesting a bias towards younger animals.

Table 2
Previously published size measurements of dwarf minke whales.

Size range, sample size	Location	Sources
1.9 -7.8, *n*=17	South Africa	Best (1985)
2.2 -7.1, *n*=11	E Australia, New Zealand	Arnold *et al.* (1987); Dawson and Slooten (1990); Arnold (1997); Paterson *et al.* (2000)
2.6 -7.0, *n*=14	Brazil	Zerbini *et al.* (1997)
3.8 -7.0, *n*=8	Sub Antarctic	Kato *et al.* (1990); Kasamatsu *et al.* (1993)
4.5 -7.2, *n*=79	Northern GBR, Australia	This paper

The data set obtained represents animals that interact with vessels and swimmers during commercial swim-with-whales programmes. It is possible that those animals that approached closely enough underwater to be filmed repeatedly were not representative of the whole group around the vessel. However there were no indications from continuous surface observations (by PA) maintained throughout the encounters of any whales remaining at a distance from the vessel. The data set was dominated by animals under 6m in length (mean length 5.66m in 2003, 5.73m in 2004). Although calves estimated as being 2-3m were seen (during three encounters in 2003 and four encounters in 2004), none were measured. Thus the smallest whales are under-represented in the data set and larger whales may also have been, although the largest length estimate (7.18m) was comparable to the largest measured animals reported in the literature (7.0-7.8m) (Table 2). Despite all the biases noted here, a wide range of sizes (4.82-6.61m in 2003, 4.48-7.18m in 2004) were recorded throughout the season and within individual encounters in both 2003 and 2004 (Figs 4 and 5).

As discussed previously the selection of 6m as the length of maturity is based on low sample numbers in studies by Best (1985) and Kato and Fujise (2000). There will not be an absolute separation of mature and immature animals at 6m; males, which mature at a smaller length than females in baleen whales (Boyd *et al*., 1999), in particular might be mature at under 6m. There is a marked lack of animals >6.5m in the data set while Best and Kato and Fujise both reported a number of whales exceeding 6.5m and even 7m in their small datasets. This may indicate a lack of interaction by larger animals in this study. It could also signify a smaller mean size (and therefore size at maturity) of individuals within this population. So little is known about dwarf minke whales that this must be considered, with observed courtship and previously identified females returning with calves as evidence of mature animals within the observed population. Moreover, the error margin within the mean estimates of lengths could lead to an inconsistent classification as potentially mature/mature or immature. This happened in one case in which the mean estimate for the same whale was 6.22m and 5.99m (L43 in encounter 04.06.30.1 and 04.07.04.3, respectively) (see Table 1). Despite such sources of error, there was a similar pattern for 2003 and 2004, with 56.5% and 58.9% of the whales having a mean length under 6m and thus probably being immature.

Northern Hemisphere minke whales have been reported to segregate by age and gender (e.g. Jonsgård, 1951; Omura and Sakiura, 1956; Williamson, 1975). There was no evidence of segregation by length during the eight week field season in 2004, however no length measurements were taken when whales were first seen (April-May) or later in the season (September-October).

Management implications

Assessment of the structure of whale populations is difficult. Often juveniles interact with vessels (Constantine, 2001) and commercial whaling selects for larger animals. An even more marked factor is the depletion of populations by whaling and lack of 'normal' whale populations. These factors along with the inherent data deficiency have a significant effect on the ability for population structure to be accurately determined.

Although it is possible that the data set presented here may not fully represent the larger population of dwarf minke whales present in the region during the winter months, the length estimates do reflect those animals that most regularly interact with vessels and swimmers during commercial swim-with-whales activities. These whales thus represent the segment of the population that is most subject to potential impacts from such swim-with programmes and are the management unit that the Great Barrier Reef Marine Park Authority is most concerned with.

In both years, more than half of the whales measured had a mean length of under 6m and thus were probably immature. This is similar to the situation with bottlenose dolphins subject to swim-with activities in the Bay of Islands, New Zealand (Constantine, 2001). As noted by that author, the interactions may represent play activity of younger animals as part of developing their social and behavioural skills. In both years, the whales from 5.0-5.9m were the dominant size class (58% in 2003, 45% in 2004) and were probably immature.

Constantine (2001) reported that, on average, only 19.3% of the dolphins in an encounter interacted directly with swimmers. There was no such apparent segregation noted in dwarf minke whale interactions, with a size range from 4.79-6.52m in single encounters (Fig. 5). The measured animals (79) represented 51.3% of the 154 whales which approached the boat and were identified as individuals. The latter represented 87.5% of the total number of whales seen anywhere around the boat either underwater or from the constant surface watch (*n*=176). From 9-13% of the measured whales exceeded a mean length of 6.5m in 2003 and 2004 and thus were most probably mature; less than half of the interacting whales were 6m or above in length and thus were likely to be mature or maturing. Only a small number of cow-calf pairs were encountered (see Fig. 6), however mature animals may have been engaged in socialising activities associated with mating. The presence of mixed gender groups, observed courtship behaviour (Birtles, unpubl. data) and recordings of vocalisations that may act as reproductive advertisement displays (Gedamke *et al*., 2001) all suggest that mating activities occur on these wintering grounds. Individual whales return to the same area from year to year (Birtles *et al*., 2002); (Birtles, unpubl. data), underlining the need for more data on cumulative impacts, particularly on mature whales which may be engaged in courtship or nursing behaviour.

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