Absolute and relative abundance estimates of Australian east coast humpback whales (*Megaptera novaeangliae*)

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ABSTRACT

The humpback whales that migrate along the east coast of Australia were hunted to near-extinction in the 1950s and early 1960s. Two independent series of land-based surveys conducted over the last 25 years during the whales' northward migration along the Australian coastline have demonstrated a rapid increase in the size of the population. In 2004 we conducted a survey of the migratory population as a continuation of these series of surveys. Two methods of data analysis were used in line with the previous surveys, both for calculation of absolute and relative abundance. We consider the best estimates for 2004 to be 7,090±660 (95% CI) whales with an annual rate of increase of 10.6±0.5% (95% CI) for 1987–2004. The rate of increase agrees with those previously obtained for this population and demonstrates the continuation of a strong post-exploitation recovery. While there are still some uncertainties concerning the absolute abundance estimate and structure of this population, the rate of annual increase should be independent of these and highly robust.

KEYWORDS: HUMPBACK WHALES; ABUNDANCE ESTIMATE; SURVEY-SHORE-BASED; TRENDS; MIGRATION

INTRODUCTION

Humpback whales undertake annual migrations between high-latitude summer feeding areas and low-latitude winter breeding areas (Chittleborough, 1965; Dawbin, 1966). Historically the western South Pacific was considered to contain one stock of humpbacks, the Group V population, that wintered around various low-latitude coastal and island areas and summered in the Southern Ocean between 130°E and 170°W (Area V). More recent work suggests, however, that the region contains several populations that inter-mingle to a variable but probably small extent (Garrigue *et al.*, 2000) and this metapopulation structure is partially reflected in the redesignation of Group V whales by the International Whaling Commission to Stocks E(i) (Australian east coast), E(ii)1 (those wintering around New Caledonia) and E(ii)2 (those wintering around Tonga) (Bannister, 2005). E(i), the Australian east coast population, is thought to be the largest of these.

Off the east coast of Australia the winter breeding area is probably dispersed inside the Great Barrier Reef (Paterson and Paterson, 1989; Simmons and Marsh, 1986) and the migration to and from these waters is along the eastern continental coastline. Off the southern coastline of Queensland the migratory corridor is narrow with most whales passing within 10km of some prominent headlands (Brown, 1996; Bryden, 1985) so the whales are available for land-based counts.

Prior to the 1950s, there was little exploitation of the east Australian humpback whale population. In 1952 industrial shore-based whaling commenced and, together with massive illegal pelagic whaling in the Southern Ocean (Mikhalev, 2000; Yablokov, 1994), took whales in such abundance that the population had collapsed by 1962. Chittleborough (1965) estimated the original Group V population to be ~10,000 whales but this has been recently revised by Jackson *et al.* (2006), in light of the only recently reported catches in the Southern Ocean, with median estimates ranging from 33,278 to 37,573. Estimates of the Group V population size in the early to mid-1960s include 104 (Bannister and Hedley, 2001) and 400 to 500 (Chittleborough, 1965). Paterson *et al.* (1994) estimated that the east Australian component of Group V was between 34 and 137. While the distribution of surviving whales was not known, the rapid recovery of east Australian whales and apparent lack of recovery of whales migrating past New Zealand suggests that most of these were of the east Australian population.

Post-whaling surveys of the east Australian population were initiated at Point Lookout, North Stradbroke Is., in 1978 and have continued most years since then (Fig. 1). At the latitude of Pt Lookout (27°30'S) in south-eastern Queensland, the northward migration peaks between mid-June and mid-July (Bryden *et al.*, 1990; Chittleborough, 1965; 1994). Surveys here have been conducted by two independent teams, the first headed by M. Bryden and then by M. Brown (Brown, 1996; 2003; Bryden, 1985; Bryden *et al.*, 1996; 1990; Bryden and Slade, 1988), hereafter known as the 'BB' (Bryden/Brown) surveys. The other series of surveys were by R. Paterson, P. Paterson and one of the current authors, DC (Paterson and Paterson, 1984; 1989; Paterson *et al.*, 1994; 2001; 2004), hereafter referred to as the 'PC' (Paterson/Cato) surveys. While both series of surveys were conducted at Pt Lookout, the BB surveys observed from a headland approximately 32m above sea level while the PC surveys were conducted from a 65m high hill approximately 300m inland from the headland. Despite some differences in survey site, survey design and data analysis, both series of surveys have been in broad agreement concerning the number of migratory whales and their rate of increase.

Recent estimates of annual rates of population increase for the Australian east coast (with 95% CI) are 12.3% (10.1–14.4%) (Bryden *et al.*, 1996) and 10.5% (10.0–11.1%) (Paterson *et al.*, 2004). These growth rates are among the

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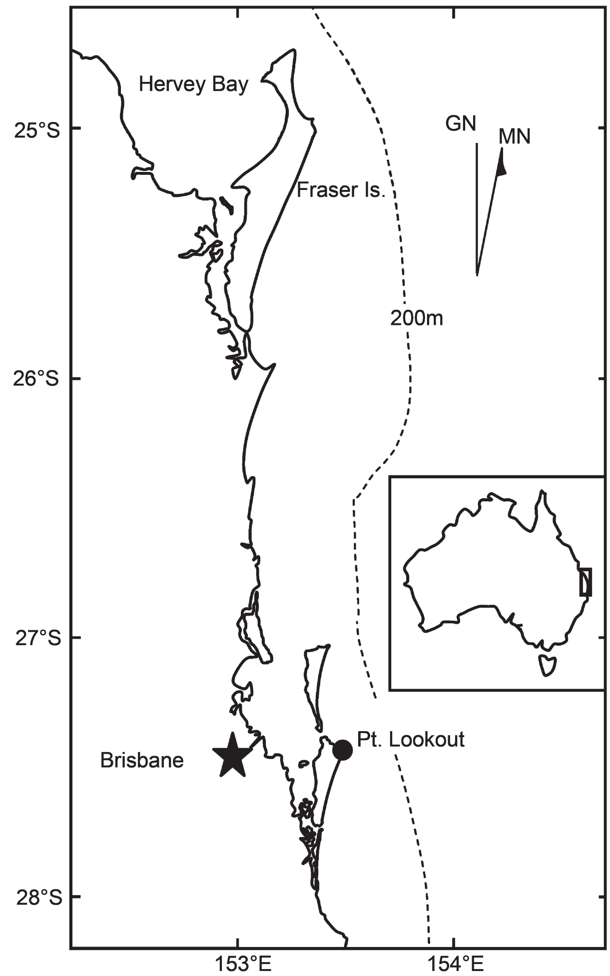

Fig. 1. Southeast Queensland showing the position of Pt Lookout on North Stradbroke Is. The edge of the continental shelf is indicated by the 200m isobath (dashed line).

highest recorded for any population (but similar to those of the Australian west coast population) and are close to the theoretical reproductive limit of around 12% for the species (Bannister and Hedley, 2001; Best, 1993; Brandão *et al.*, 1999). The rates of increase are also remarkably consistent over time.

In 2004 we conducted a land-based survey of the east Australian humpback population at Pt Lookout at the same site of previous BB surveys, and the results of this survey are presented here together with long term trends in abundance using the results of the previous surveys.

METHODOLOGY

2004 survey data collection

Field methodology for the 2004 survey was at the same site as, and closely followed, BB's structured surveys of 1996, 1999 and 2000 (Brown, 1996; Brown *et al.*, 2003; Bryden *et al.*, 1996). The survey was conducted from Pt Lookout (27°26'S, 153°28'E) on North Stradbroke Island, a large island off the coast of southern Queensland near Brisbane, over a 14 week period from 25 May to 27 August 2004 (Fig. 1). Aerial surveys have demonstrated that most humpback whales migrate within 10km of the Point, a distance within which it has been assumed that most whales should be observable under average conditions (Brown, 1996; Bryden, 1985).

Survey sites

As with the BB surveys, two survey sites were used to enable a blind double count of passing whales. The primary survey site was located at 'Norm's Seat' (27°26.067'S, 153°32.770'E). This location is approximately 32m above sea level. The second location, 'Whale Rock' (27°26.152'S, 153°32.758'E), used for the double counts, was located approximately 160m south of Norm's Seat, at a similar height above sea level. The two survey locations had a similar field of view extending from the east-south-east to the north. The two survey locations were visually and acoustically isolated from each other by vegetation and the topography of the headland.

Watch structure

At Norm's Seat observations were undertaken from 0700 to 1700 each day, except during inclement weather (heavy rain, sea state >mid 5). Each 10 hour day was divided into four shifts conducted by two teams or watches. The 'early' watch observed from 0700 to 1000 and from 1200 to 1400 and the 'late' watch ran from 1000 to 1200 and from 1400 to 1700.

At Whale Rock observations were carried out most days but usually by only one watch observing every second shift in line with either the 'early' or 'late' watches at Norm's Seat. Watches alternated daily between 'early' and 'late'. Occasionally there were insufficient observers for the three watches needed to run both the primary and double counts and the double counts were not conducted at these times.

Watches consisted of three to four observers and efforts were made to balance the experience and effort of the Norm's Seat and Whale Rock teams. Norm's Seat usually had four observers due to the use of a theodolite and notebook computer. One observer operated the theodolite, while another operated the computer, reducing both their search efforts compared with Whale Rock. At each location at least one observer was 'experienced' with a minimum of one month (approx 150 hours) survey time at Pt Lookout, or several seasons of prior field experience with humpback whales at other locations. During surveys, observers were allocated a section of the survey area, which was to be scanned at all times. Observers alternated between using binoculars (generally 7 x 50) and using the naked eye to scan their allocated section.

Data collected

The notebook computer at Norm's Seat ran Cyclopes software, developed specifically for the tracking of marine mammals (Eric Kniest, University of Newcastle, Australia). The theodolite operator points the theodolite at a surfacing group of whales and sends the vertical and horizontal angles directly to the computer. Cyclopes then calculates the position of the group correcting for tides, curvature of the earth and refraction and plots it on a map of the area. Cyclopes also accepts information on the group's composition, behaviour and direction of travel and will compute the group's speed, course and distance from any user-selected reference point (e.g. the survey site, another group, a boat). Surfacings not captured by the theodolite were also entered as distance and bearing estimates so that all observed surfacings of all groups were included in the Cyclopes file.

Double counts from Whale Rock were conducted using calibrated reticle and compass binocular sightings recorded manually. These data were entered into Cyclopes each evening for group matching with the Norm's Seat data.

Most whales were sighted several times allowing ample opportunity for positive identification based on characteristics of the blow and roll of the back, flukes or pectoral fins. Single sightings of a blow only were not counted as these were too easily confused with sea spray in windy conditions and are not sufficiently diagnostic of a humpback. Single sightings of a breach were counted.

For the purpose of the census, whales were only counted if they crossed a line extending seawards at 70° from true North between 0700 and 1700. Both numbers of groups and group size were recorded. South-bound groups, though recorded, were excluded from the analysis. Negligible initially, the number of south-bound groups exceeded that of north-bound groups after mid-August. Groups with no obvious direction of travel were assigned a direction based on the ratio of definite north and south-bound groups in that week.

Weather conditions were recorded every half hour and at the beginning and end of each day. Data recorded included sea state, swell height and direction, wind speed and direction, cloud cover, glare and any other factors affecting visibility (e.g. smoke, haze, rain).

Absolute abundance estimates for 2004 – general assumptions and approaches

In line with previous Pt Lookout surveys we assumed that all whales in the migratory stream passed within 10km of the Point and that all groups within 10km were available for sighting. It is assumed that group size was accurately assessed and that travel rate did not differ between day and night (Bryden, 1985).

Because of the long term rise and fall in numbers over the course of the migration (Fig. 2), data analyses need to separate this source of variance from that of the day to day variation in whale counts. The PC surveys (Paterson *et al.*, 1994; 2001; 2004) used stratified random sampling theory (Cochran, 1963) to calculate the population passing during the survey period while the BB surveys (Brown, 1996; Bryden *et al.*, 1996) used a more complex Hermite polynomial modelling approach. Both techniques are used here on the 2004 data.

Absolute abundance estimate I – the Hermite polynomial modelling approach

Bryden *et al.* (1996) and Brown (1996) used a method for calculating absolute abundance from a survey of migrating whales that was developed by Buckland *et al.* (1993a; 2004; 1993b) for use on migrating Californian gray whales (*Eschrichtius robustus*). The method fits a normal curve to the number of groups passing the survey point during each shift or watch each day. The curve is then adjusted slightly through the progressive addition of Hermite polynomial terms which adjust the curve for skewness and kurtosis seeking a better fit to the data. As each term is added, the resultant curve is tested for goodness-of-fit to the data. Akaike's Information Criterion (AIC) is also calculated for each model and compared with the previous model. The model using the least number of additional Hermite polynomial terms that gives a significant improvement in fit and reduction in AIC is taken to best represent the data. The resultant curve or model is then used to calculate the number of groups that passed (a) during the survey period and (b) before and after the survey period, i.e. an estimation of the tails of the migration. It is also used to calculate a standard error for the resultant number of groups based on the variance of the observed data around the modelled curve.

We used *GWNORM* software (S. Buckland, University of St Andrews, UK) for this analysis (Buckland, 1992; Buckland *et al.*, 1993a; 1993b). For each watch the following data are required: the time of the start and end of the watch (including the day from the presumed start of the migration) and the group count for that watch. As our watches were short compared to those of the gray whale surveys, we followed Bryden *et al.* (1996) and pooled them into morning and afternoon, i.e. 0700–1200 and 1200–1700. Watches that were truncated by more than 1h were excluded and the program was run in 'grouped' mode indicating that the data

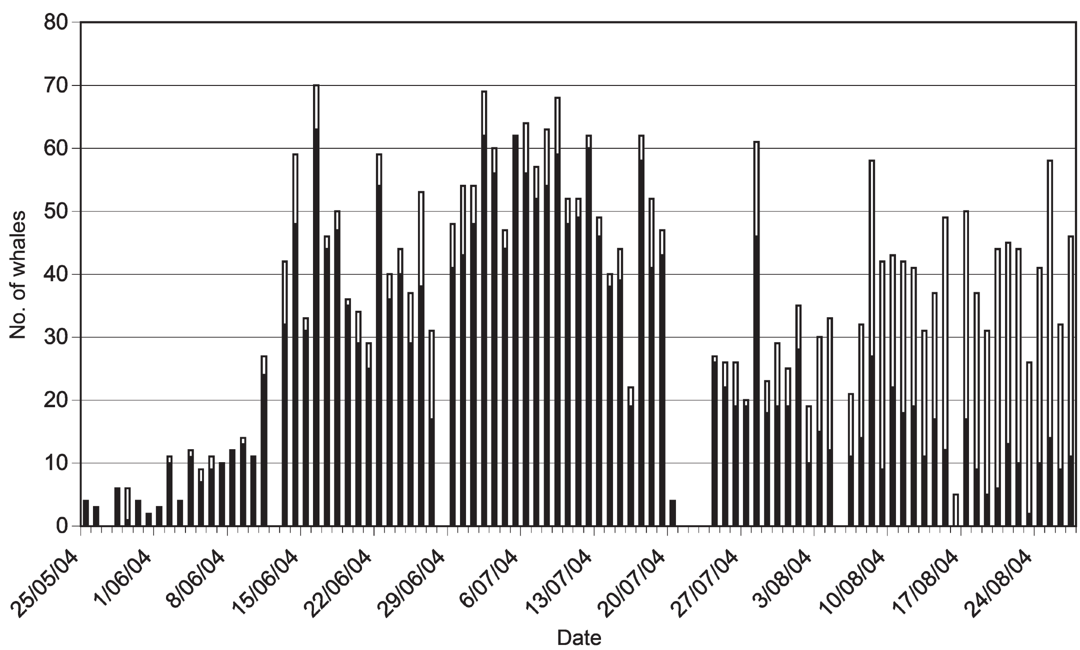

Fig. 2. Raw 2004 survey data. Confirmed northbound humpback whales passing Pt Lookout between 0700 and 1700 in solid black bars; whales southbound, unconfirmed or passing outside of survey hours shown in white bars. There were similar numbers of northbound and southbound whales in the first half of August after which southbound whales predominated. Except for 27 May when no whales were seen, gaps are days without survey (n = 6). Counts include Norm's Seat data only.

were grouped within the watch periods indicated. The output of the program gives a number of results for the normal model and for models using from one to four additional Hermite polynomial terms. For each model, the results include (with SE for each): (a) a correction factor for groups passing during the survey period (to account for unmonitored periods), (b) estimated number of groups passing during the survey period, (c) estimated numbers of groups passing before and after the survey period and (d) an estimated total number of groups passing during the migration.

The total population is calculated as:

$$N_{BB} = msf_t f_m \quad (1)$$

where N_{BB} is the total population of whales, m is the number of groups counted, s is the mean group size, f_t is the correction factor for groups passing during non-survey time (which may or may not include the tails of the migration before and after the survey period) and f_m is a correction factor for groups available for counting during survey time but missed (modified from Bryden *et al.*, 1996). The standard error of N_{BB} is then calculated as:

$$Se(N_{BB}) = N_{BB} \cdot \sqrt{\{CV(m)\}^2 + \{CV(s)\}^2 + \{CV(f_t)\}^2 + \{CV(f_m)\}^2} \quad (2)$$

Ninety-five percent confidence intervals are then calculated based on a log-normal distribution (Buckland *et al.*, 1993a).

Calculation of f_t – the Hermite polynomial model

Although *GWNORM*'s output includes a correction factor, it is only for groups missed during the survey period. The BB surveys have, however, used the model to calculate several types of f_t depending on whether one includes the tails outside the survey period, the limits of the dates on these tails and other constraints that might be placed on the model. The various correction factors (all termed f_t) used by the BB surveys for groups missed therefore include:

(a) During the period of the survey only, where there are no assumptions about the start and end of the migration and the polynomial is fitted only to the data without constraint.

(b) During the nominated migration period with the curve fitted to the data without constraint. The pre- and post-survey estimates of passing groups are made based on the area under the curve outside the survey period but within the nominated migratory start and end dates (the values of which only matter if the model does not reach 0 within these dates). For our analysis we chose the 15 May and 30 September as the reasonable limits of the northward migration.

(c) During the nominated migration but for a curve recalculated so that it is constrained by zero counts added at the nominated start and end of migration taken (in the BB surveys) as 15 May (day 0) and 23 August (day 100) and with data after day 99 truncated. In other words counts before 16 May and after 22 August were assumed to be zero.

To be clear, we have renamed these $f_{t(s)}$ for 'survey', $f_{t(m)}$ for 'migration' and $f_{t(c)}$ for 'constrained', respectively. Depending on whether or not the input data include the zero constraints mentioned in (c), *GWNORM* will produce $f_{t(s)}$ and $f_{t(c)}$ as part of its output. The correction factor $f_{t(m)}$ has to be derived by dividing the estimate for groups passing during the migration (which includes groups passing before and after the survey) by the number of groups observed. Alternatively *GWNORM*'s estimate of total groups passing during the migratory period (with its associated SE) can be used to replace terms mf_t in equation 1.

Correction for groups available but missed (f_m)

A correction factor f_m for groups available for counting but missed is calculated using the double count data. The first step is to attempt to match groups seen from Norm's Seat with those from Whale Rock. Matching was performed daily using the Cyclopes files and checked again post-fieldwork. Most of the time group matches were obvious from similar group tracks at similar times. During busy or confused periods, however, sightings were considered individually to prevent incorrect assumptions concerning group identity. A match required at least two sightings matched in time and space from the two survey sites. Matching of individual sightings depended on estimated bearing and distance, time and group size. Some flexibility was necessary to account for differences in data capture techniques, differences in survey site positions and recording error. Times had to match to within 30sec and group size could vary by one. Distance estimates had to agree to within 500m for groups within 2km of shore, to within 1km for groups 2–5km from shore, and to within 2km for groups 5–10km from shore. Bearings had to agree to within 10° for groups more than 1km from shore and to within 20° for groups less than 1km from shore. We assumed that the sightings from each survey site were independent of each other and that matches were made without error.

These matched data were then analysed using mark-recapture techniques. The BB surveys used a logistic regression model summarised by Buckland *et al*. (1993a; 1993b) which incorporates co-variates to allow for heterogeneity in mark-recapture experiments. An alternative approach is to use the simple Petersen estimate (Seber, 1982) which calculates P, the size of a population as:

$$P = \frac{MC}{R} \quad (3)$$

where M is the number of animals 'marked' during the first capture episode, C is the number of animals 'captured' during a second capture episode and R is the number of those caught in the second episode that had been marked in the first. Both were used by Bryden *et al*. (1996) who calculated $f_m s$ of 1.111 and 1.104 using the logistic regression and Petersen methods, respectively. They concluded that the effects of heterogeneity were small. We therefore elected to use the simpler Petersen estimate.

When applied to our survey, M can be taken as the number of groups observed from Norm's Seat, C is the number observed from Whale Rock, and R is the number observed by both. The correction factor to be applied to M will therefore be given by C/R. In theory M and C are reversible depending on which survey point is considered to be the marker and which the capturer and so M/R is also a valid correction factor for groups seen from Whale Rock. However, Norm's Seat was our primary survey site and generated the data used for the population estimates while Whale Rock was only a part-time survey. Therefore, for the purposes of this study, C/R was the appropriate correction factor for the count data. In any case C/R and M/R were not significantly different.

To calculate C/R with a standard error, C/R was calculated by grouping consecutive days of data until R was approximately 40 in each group. These measures were averaged and a standard error calculated. C/R daily or weekly was not calculated, as early measures of daily or weekly C/R (using far fewer groups), had a much higher variance than estimates using more groups, causing an overestimate of the standard error. There was no significant difference between the mean C/R for early in the season and the peak of the migration.

Mean group size (s)
Mean group size s was calculated using the initial size of the group as assessed at Norm's Seat. Subsequent splits into small groups or joins with other groups to create larger groups were ignored. As with the count of groups, only groups passing a line seaward between 0700 and 1700 and heading north were included.

As with previous Pt Lookout surveys, we assumed that the group sizes recorded were correct. Bryden *et al*. (1990) found no difference between group sizes observed from the land and air at Pt Lookout and Findlay and Best (1996) found no significant difference between group size as estimated by land-based observers of humpbacks off South Africa and confirmed by boat, providing the group had been sighted at least twice.

The standard error of the number of passing groups (m)
This is given by Buckland *et al.* (1993b) by first calculating a dispersion parameter estimate (the appropriate Hermite polynomial model's χ^2 goodness-of-fit statistic divided by its degrees of freedom), then taking the square root of this multiplied by the original number of groups seen.

Absolute abundance estimate II – the stratified random sampling approach
A detailed explanation of the stratified random sampling approach, as applied to the Pt Lookout humpback surveys, can be found in Paterson *et al*. (1994). Sampling was carried out every day, weather permitting, during the survey period and was well distributed over the full 14 weeks of the migration (Fig. 2). One full 10h day of observations is taken to represent one sample unit. On this basis the sampling is considered to be a reasonable approximation to random sampling of the stream of humpback whales passing Pt Lookout. Days with less than 10h of observations (truncated by rain or wind) were normalised to a 10h day based on the sighting rate of the surveyed part of that day. This method does not estimate the contribution from whales passing outside the survey period, so requires the survey period to extend over as much of the migration as possible to obtain an estimate of the population. Previous PC surveys extended to the end of October rather than the end of August as in this survey.

The sample was split into seven strata each comprising two weeks of observations, the first stratum being the fortnight starting 25 May and the seventh being the slightly truncated fortnight starting 17 August. The number of humpback whales seen per 10h in an equivalent 10h observation period is considered to be a sample unit. Over the total period of 95 days (which includes all strata), there were 228 10h periods. The sample can then be considered to be the selection of those 10h periods when observations were actually made. This gives a total of 89 sample units.

From Cochran's equation (5.14), the estimate of the total population from which the sample was drawn, with 95% confidence interval, is

$$N\bar{y}_{st} \pm tNs(\bar{y}_{st}) \tag{4}$$

Here N = 228 is the number of equivalent 10h units in the total period of 95 days over which the observations were made and

$$\bar{y}_{st} = \sum_{h=1}^{7} N_h \bar{y}_h / N \tag{5}$$

is the weighted mean (Cochran's equation 5.1) where $\bar{y}_{st}$ is the sample mean and N_h the total number of units in stratum h. Also, from Cochran's equation (5.11),

$$s^2(\bar{y}_{st}) = \sum_{h=1}^{7} N_h(N_h - n_h)s_h^2 / (N^2 n_h) \tag{6}$$

is the estimate of the variance of $\bar{y}_{st}$, where s_h^2 is the sample variance of stratum h, n_h is the number of samples in stratum h and t is Student's t for the effective number of degrees of freedom given by Cochran's equation (5.15).

Correction for groups available but missed
Although the PC estimates did not use a correction factor for groups available but missed, we included this to improve the accuracy of the estimate. This was identical to f_m as calculated above.

Population estimate
The final population estimate is given by

$$N_p = N\bar{y}_{st} \cdot f_m \tag{7}$$

The standard error for N_P was calculated by combining the standard errors of its contributing factors in a manner similar to that used in equation 2. Ninety-five percent confidence intervals were then calculated based on a log-normal distribution.

Rate of population increase I – relative abundance estimate method
The BB surveys use a measure of 'relative abundance' to calculate the annual rate of increase. In the early surveys (pre-1991) data were sparse and zero counts at the presumed start and end of migration had to be added to constrain the Hermite polynomial model and prevent it predicting unrealistically large tails (Buckland *et al.*, 1993b). The dates chosen, based on data at the time, were 15 May and 23 August (days 0 and 100, assumed to be the start and end of migration, respectively). Although subsequent surveys with increased whale numbers have shown that the migration extends as a long tail until around the end of September, the addition of 0 values at these dates and truncation of data collected after 23 August was continued to maintain continuity and enable the calculation of a comparable 'relative abundance' measure. Doing this fundamentally alters the shape of the Hermite polynomial model and results in a new constrained correction factor for groups missed $f_{t(c)}$ (described above). The other feature of the calculation of the BB 'relative abundance' measure was the omission of f_m (as no double counts were performed in earlier surveys). Using this methodology, the relative population size P_{RA} is given by:

$$P_{RA} = msf_{t(c)} \tag{8}$$

The rate of increase was calculated from the simple logarithmic regression of the relative abundance estimates produced against year. Later surveys produced a range of estimates for various time spans (Brown, 1996; Bryden *et al.*, 1996).

Rate of population increase II – the rate of whales passing method
The difficulties and limitations of estimating the rate of increase of this stock have been discussed by Paterson and Paterson (1989) and Paterson *et al*. (1994). The PC surveys use a procedure in which the index chosen for the calculation of relative abundance is the number of humpback whales observed per 10h averaged over the four, eight and ten consecutive weeks with the highest counts across the survey period. This is effectively the four, eight and ten weeks

around the peak of the northward migration. Fixed dates were not used as the peak of the migration shifts by up to two weeks from year to year (Chittleborough, 1965; Paterson *et al.*, 2004). Data are available for the 19 years from 1984 to 2002 except 1993, 1995, 1997 and 2000 (Paterson *et al.*, 1994; 2001; 2004). In all years a rate of increase based on the four weeks around the peak was possible, however the survey period was not of sufficient length to allow eight and ten week comparisons for all years surveyed, so there are fewer data points for these indices.

This technique requires the assumption that the proportion of the stock passing in the period chosen at the peak of the northern migration is constant from year to year. This assumption was tested by Paterson *et al.* (2001) using the data of 1987, 1992 and 1999 when the observation period covered almost the full migration and was shown to be reasonable as the proportion of the population estimated to be passing during these periods varied by no more than 2% between years.

RESULTS

Data collected

The 2004 survey was conducted from 25 May to 27 August (95 days). Surveys were cancelled completely on six days and were truncated on a further 13 days, seven of these by less than two hours. Excluding southbound groups, single blows and other unconfirmed sightings, and groups not passing between 0700 and 1700, 1,250 groups containing 2,239 whales were observed passing the Pt Lookout during the survey (Fig. 2).

Mean group size (s)

The mean group size s of northbound groups was 1.80 (SE 0.023). The largest group seen contained nine whales (Fig. 3).

Correction for groups available but missed (f_m)

Double count data were used from 43 days (26 May–9 July) to calculate the correction factor for groups available but missed by the primary survey site, Norm's Seat. On the watches when both Norm's Seat and Whale Rock surveys were operating Norm's Seat observed 451 groups (M) and Whale Rock observed 464 groups (C). Of these 423 groups were observed from both survey points (R). The correction factor for groups available but missed by Norm's Seat is 1.10 (SE 0.021).

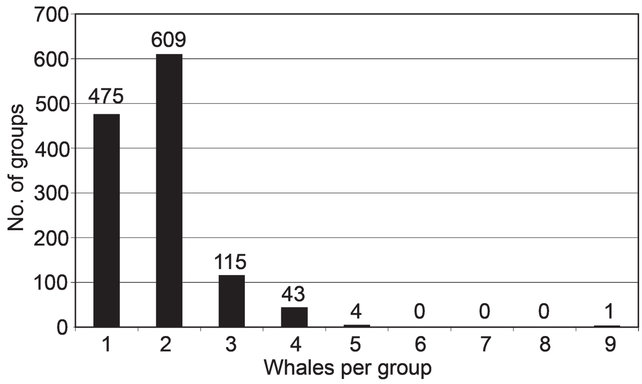

Fig. 3. Numbers of groups seen by size. The number of groups is also displayed above each bar

Absolute abundance estimate I – the Hermite polynomial modelling approach

Of the 1,250 confirmed, northbound groups sighted, 1,212 were seen during complete (or nearly complete) pooled morning and afternoon shifts and were input into *GWNORM*. The model was run for 'grouped' data with migration start and end dates as 15 May and 30 September, respectively. This produced five models corresponding to a normal model plus four Hermite polynomial models with from one to four additional polynomial terms. The one-term (or 'third-order') polynomial model was significantly better than the normal model at explaining the underlying trend in the number of passing groups (AIC = 747.6 and 796.8, respectively), but

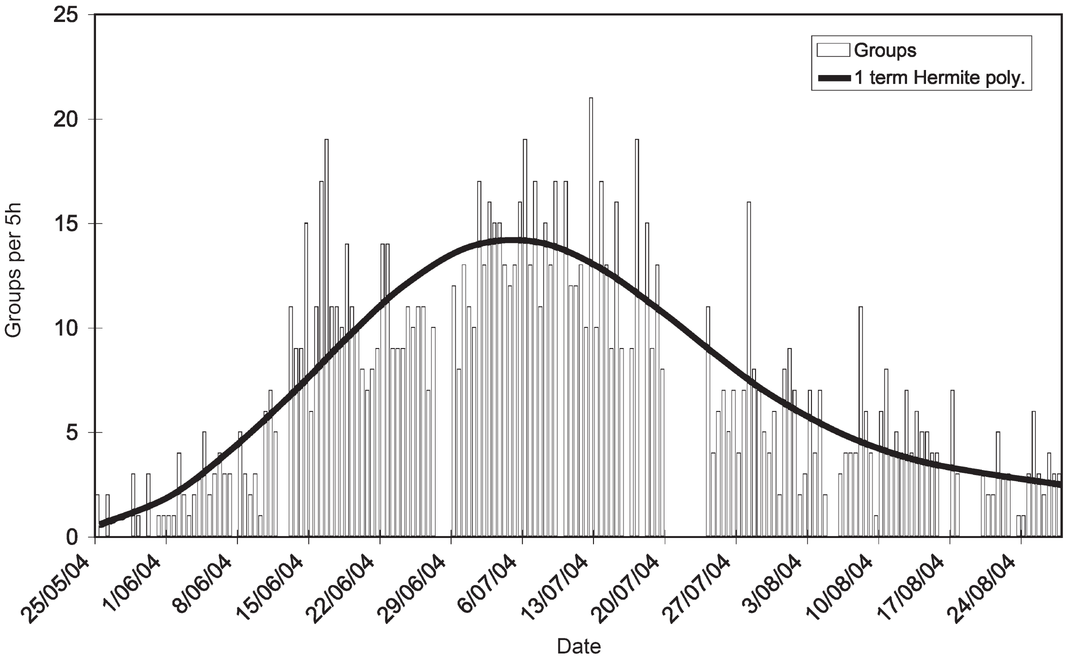

Fig. 4. The one-term Hermite polynomial model produced by *GWNORM* superimposed on the morning and afternoon group counts used as input.

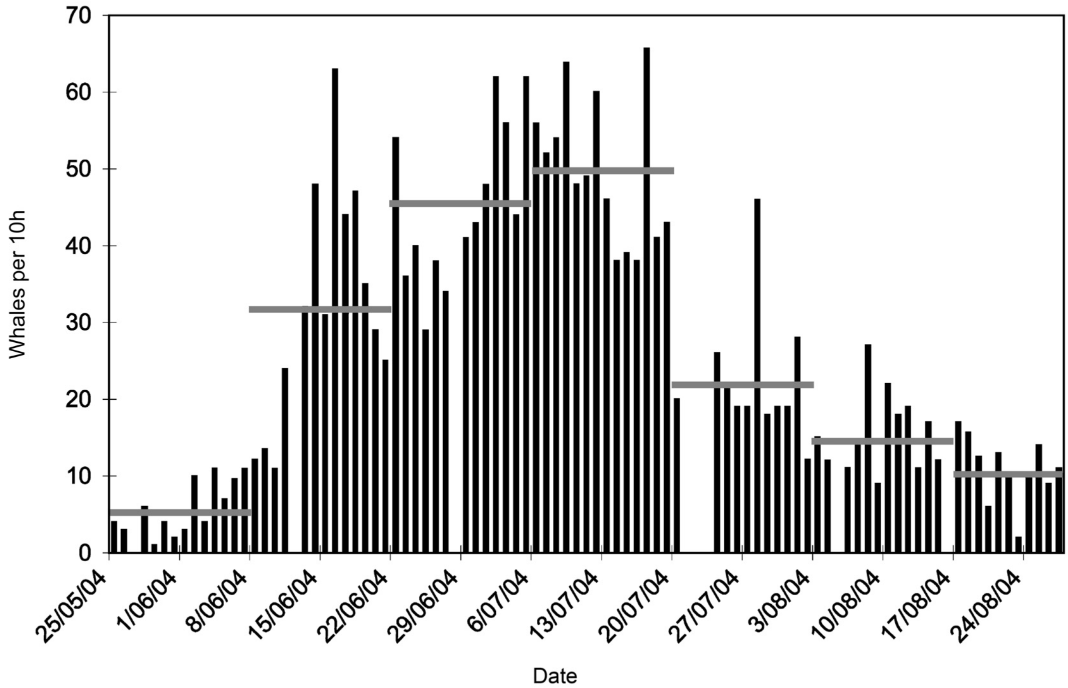

Fig. 5. Confirmed, northbound whales passing per 10h together with strata means (horizontal bars). Except for 27 May and 16 August when no confirmed, northbound whales were seen, gaps are days without survey (n = 6). Counts include Norm's Seat data only.

there was no significant improvement using the two-term model (AIC = 747.5). Results for the one-term model are given in Table 1 and the model is shown in Fig. 4.

From this the estimated population passing within the survey period (25 May–27 August) is 6,699 (CV = 3.9%; 95% CI = 6,209–7,226). The estimated population size passing during the entire estimated migratory period (15 May–30 September) was 7,090 (CV = 4.8%; 95% CI = 6,459–7,782).

Absolute abundance estimate II – the stratified random sampling approach

Using stratified random sampling theory, the resulting estimate of the passing population during the survey period (uncorrected for groups available but missed or those passing outside the period of the survey) is 5,965 (CV = 2.6%; 95% CI = 5,668–6,278) (Fig. 5). If f_m is applied to this result to correct for groups available but missed, the population estimate is 6,555 (CV = 3.0%; 95% CI = 6,177–6,956).

Rate of population increase I – relative abundance estimate method

Between the start of the survey and 22 August (inclusive) 1,186 groups were seen passing Pt Lookout. Zero values were added to day 0 (15 May) and day 100 (23 August) and the model run again. The resultant $f_{t(c)}$ was 2.82. This produced a relative abundance estimate P_{RA} of 6,011 whales (SE 200) (Table 2).

Logarithmic regression of P_{RA} from 1981–2004 yields an annual rate of increase of 12.17 ± 1.52% (95% CI) (Fig. 6). As methodology, particularly survey effort, changed considerably in 1991, excluding years prior to 1991 may produce a more realistic estimate: 10.91 ± 2.67% (95% CI) for 1991–2004. Yet another, and probably superior, estimate

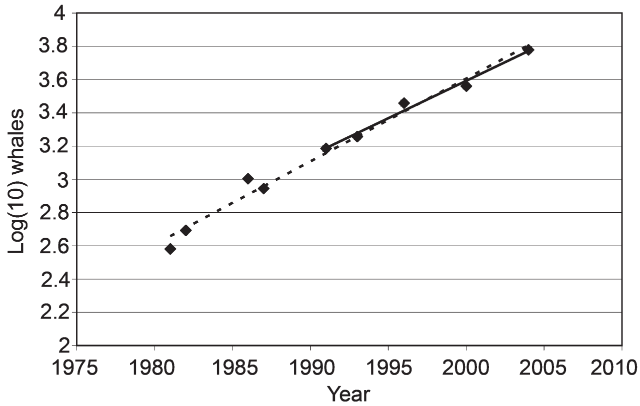

Fig. 6. Linear regression of $\log_{10}$ of relative abundance population estimates from Table 2 against year for all years 1981–2004 (dashed grey line) and for 1991–2004 (solid black line). A constant annual rate of increase will appear as a straight line. Correlation coefficient r is >0.99 for both.

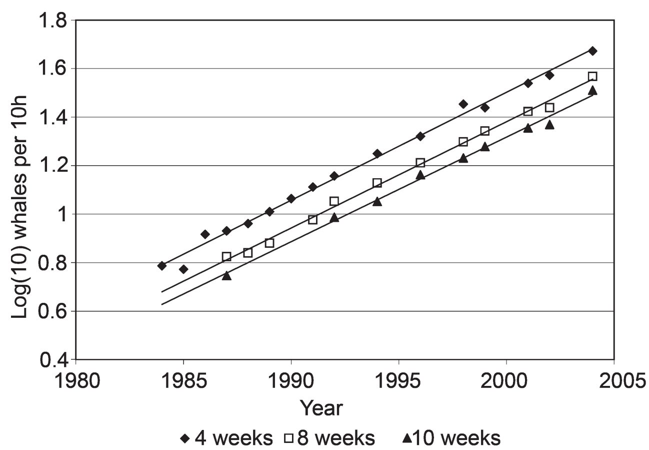

Fig. 7. Log_{10} of the average number of northbound whales passing Pt Lookout per 10h over the four, eight and ten weeks around the peak of migration. All data except for 2004 from Paterson *et al.* (1994, 2001, 2004). Correlation coefficient r is >0.99 for all three data sets.

Table 1

Results of unconstrained Hermite polynomial model. The migratory period was taken as 15 May to 30 September. The skewness of the 1-term polynomial model used produced small pre-survey and large post-survey estimates compared with the normal model. Results in italics were not produced directly by *GWNORM*, but were calculated separately.

Parameter	Value (SE)
No. of groups seen during complete survey shifts (m)	1,212 (*37*)
Multiplier to estimate number of groups passing during survey period ($f_{t(s)}$) (25 May–27 August)	2.800 (0.0051)
Estimated number of groups passing during survey period	3,394 (104)
Estimated number of groups passing before survey	4 (3)
Estimated number of groups passing after survey	194 (100)
Estimated total number of groups passing during migration	3,592 (149)
Multiplier to estimate groups passing during the migration ($f_{t(m)}$)	*2.964* (*0.0823*)

Table 2

Relative abundance estimates 1981–2004. Data 1981–2000 from Brown *et al.* (2003).

Year	1981	1982	1986	1987	1991	1993	1996	2000	2004
Groups observed passing 15 May–23 Aug. (m)	40	58	107	131	346	345	395	566	1,186
Mean group size (s)	1.55	1.67	1.83	1.70	1.64	1.80	1.53	1.61	1.80
$f_{t(c)}$	6.16	5.09	5.15	3.94	2.70	2.91	4.76	3.99	2.82
P_{RA}	381	493	1,008	879	1,533	1,807	2,872	3,634	6,011

would be possible using the survey period absolute abundance estimates for these years as the survey period was similar for all years and variability in estimation of the pre- and post-survey tails would not be included. The $f_{t(s)}$ for the 2000 survey has not yet been published, however.

Rate of population increase II – rate of whales passing method

Fig. 7 is a plot of the logarithm of the number of humpback whales per 10 hour averaged over the four, eight and ten weeks at the peak during the northern migration for each year from 1984 to 2004. Annual rates of increase are shown in Table 3.

Summary of humpback whale survey results

Table 4 presents a summary of the results using the two different methodologies.

DISCUSSION

The results of the 2004 survey support the results of the BB and PC series of surveys conducted previously at Pt Lookout. Despite differences in survey site height and outlook, number and experience of observers, numbers of days surveyed per migration, number of years surveyed and analysis of data, the similarity in relative and absolute abundance estimates of these survey series is remarkable and underlines the robustness of the results previously obtained. The current survey's results again support these results by demonstrating a continuing strong growth in the east Australian humpback population at close to their theoretically maximal rate.

Table 3

Apparent rates of population increase for the east Australian humpback whale population including data from Paterson *et al.* (1994, 2001, 2004).

	Four weeks	Eight weeks	Ten weeks
No. of data points	16	12	9
Annual rate of increase	10.80%	10.62%	10.44%
95% confidence interval	± 0.54%	± 0.48%	± 0.72%
Correlation coefficient (r)	0.997	0.998	0.997

For absolute abundance we consider the best estimate to be 7,090 (CV = 4.8%; 95% CI = 6,459, 7,782) as the Hermite polynomial method allows for the tails of the migration to be included. Its slightly larger confidence interval compared with the results of the stratified random sampling theory approach is probably a consequence of modelling a curve to the data rather than allowing the data to shape the strata means more freely. The best estimate of rate of change is 10.6% ± 0.5% (95% CI) using the PC methodology with the eight-weeks-around-the-peak-of-migration index. This gives the smallest CI, combining a large number of data points with slightly less fluctuation around the regression line than the four week data, probably due to its greater spread over the migration. While the BB relative abundance estimate approach has merit and delivers a similar central value estimate, fewer data points have resulted in a much larger CI.

The population remains much lower than estimated pre-exploitation levels with Jackson *et al*. (2006) estimating a median recovery level of around 21% of pre-exploitation levels. Another issue though is whether the pre-exploitation levels can be expected to provide a reasonable expectation of post-recovery carrying capacity. With the removal of huge numbers of predators from the Southern Ocean in the 20th Century, it would be unrealistic to expect no change to the ecosystem. How this might affect a new status quo for whale populations is unknown and only continued monitoring of population levels will allow us to measure this.

While the population trend is strong and robust, the absolute abundance estimates can still be improved upon. Brown *et al.* (1995) biopsied whales during the northward and southward migration in 1992 and found that the sex ratio was skewed with 2.4 males to every female (180 whales sampled). They suggest that not all females migrate along the east Australian coast every year, instead remaining in the southern feeding areas. Dawbin (1997), in an analysis of thousands of humpback whales caught at 11 whaling stations between latitudes of 1° and 41° in the Southern Hemisphere, noted that an average of 1.4 males were caught for every female but considered that the imbalance was probably due to temporal segregation and sampling bias. Dawbin (1997) also showed that the number of immature females migrating was approximately the same as the number of males, so does

Table 4

Summary of results. No result is given for the population estimate over the entire migration for the PC methodology as this does not estimate the contribution outside the survey period. Only the best estimates of the rate of increase are included: that with the smallest 95% confidence interval (PC results) and that which included previous surveys with a standardised methodology (BB results).

Parameter	BB methodology	PC methodology
2004 population estimate over the surveyed period (95% CI)	6,699 (6,209–7,226)	6,555 (6,177– 6,956)
2004 population estimate over the full migration (95% CI)	7,090 (6,459–7,782)	–
Best estimate of rate of population increase (95% CI)	10.91% (± 2.67%) (years 1991–2004)	10.62% (± 0.48%) (years 1987–2004)

not support the Brown *et al*. (1995) hypothesis that it might be immature females that do not migrate. This also seems unlikley as the non-migration of immature females would produce a sex ratio of around 1.7:1 males to females, not the 2.4:1 sex bias reported, and it is not clear why immature females should not migrate while immature males do. Some mature females may not migrate, but with the high reproductive rate requiring an average calving interval of two years, this also seems unlikely as females would, theoretically at least, need to migrate each year to alternately calve and mate. Therefore while there may be more males than females migrating, the ratio is likely to be less than 2.4:1. Further, carefully designed studies need to be directed towards determining the sex bias in the migratory population. If not all females migrate, this would lead to a downward bias in our population assessments.

The other main possible cause of underestimation of absolute abundance (but not relative abundance) is the underlying assumption that most whales pass within 10km of land and that all whales within that range are counted. This is akin to a strip sampling approach that is likely not to be accurate. The difficulty with developing a more robust line transect approach, however, is that the distribution of the whales is not random with a higher density of whales passing through the inshore area. Thus shore-based observations will not provide a robust detection function and future aerial surveys, providing an unbiased measure of distribution, will be required to address this issue.

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