Migratory patterns and estimated population size of pygmy blue whales (*Balaenoptera musculus brevicauda)* traversing the Western Australian coast based on passive acoustics.

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ABSTRACT
Passive acoustic data sets along the Western Australian coast have revealed annual south-north migrations of pygmy blue whales. At the latitude of Exmouth (21^{o} 30' S) a sharp southerly travelling pulse of pygmy blue whales is experienced each year over October to late December, while a more protracted northerly pulse of returning animals is detected over the following April to August. It is believed the south bound pulse of animals passing Exmouth are steadily migrating. The passive acoustic detections of pygmy blue whales off Exmouth have been converted to instantaneous counts of the number of individual whales calling. By assuming a range of proportions of animals calling of from 8.5-20% of total pygmy blue whales in the area, the number of individual whales calling has been converted to estimates of the number of whales in the noise logger listening area, at 15 minute increments across the southerly migratory pulse. This curve was integrated across the migratory season. The listening range of the noise logger and the whale swim speed along a known route were used to give whale residency time in the noise logger listening area. The integrated curve of whale●*days* was divided by the residency time to give an estimate of 662-1559 pygmy blue whales passing the noise logger site during the 2004 southerly migratory pulse down the Western Australian coast. We know pygmy blue whales reside along the east Australian coast and in the southern Indian Ocean, thus the population estimate for Western Australia is a portion of the larger Indian and western Pacific pygmy blue whale population.

INTRODUCTION
A sub-population of blue whales, the pygmy blue whale (*Balaenoptera musculus brevicauda)* is known to reside in the Indian Ocean, Southern Ocean and eastern Pacific Ocean (Branch et al 2007). The migratory movements and population structure of these whales is poorly known. A number of studies and observations have revealed that pygmy blue whales migrate along the Western Australian (WA) coast (described here), into and out of coastal upwelling areas along southern Australia (Gill 2002) and south at least as far as the Antarctic convergence zone and possibly further (Gedamke et al 2007, Stafford et. al. in press). Gill (2002) has reported summer-autumn aggregations of often surface feeding pygmy blue whales along the south eastern Australian coast in a region termed the Bonney upwelling, while McCauley et al (2001) reported deep feeding pygmy blue whales in the Perth Canyon (32^{o} S on the Western Australian coast). Rennie et al (2009) reports on the biological oceanography of the Perth Canyon and related this to observations of feeding pygmy blue whales, although the large scale environmental drivers of productivity in this Canyon system are complex and not clear. Apart from animals which frequent the WA and south eastern

Australian coast we know little of the movements or numbers of pygmy blue whales which traverse east Australia and New Zealand waters or which reside in the southern Indian Ocean. The population size of any of the sub-populations of pygmy blue whales was quoted by Branch et al (2007) as ‘highly uncertain’ and not known.

Along the WA coast the primary author has been collecting sea noise data since 2000 using high storage capacity digital recording systems. Pygmy blue whales are known to produce intense and stereotypical signal types (McCauley et al 2001, McDonald et al 2006) designed to transmit well in deep ocean water or along the continental shelf break. Based on the acoustic records collected along the WA coast the pygmy blue whales seasonal migratory patterns appear to be regular and predictable. Here we use the passive acoustic detections from a site in northern WA where it is believed pygmy blues whales are focussed near the continental shelf edge during their southerly migration from Indonesian waters, to census the migratory population.

METHODS

Thirty seven sets of sea noise loggers have been set along the WA coast since 2000 and near the shelf edge where they may be expected to sample pygmy blue whale signals. Four of these sites are shown on Figure 1. The site 2664 off Exmouth has been used for the census analysis described below and the four sites shown on Figure 1 are used to give a brief display of the whales’ migratory timing as they pass along the WA coast.

All noise loggers were set on the seabed with hydrophones either lying free on the seafloor or mounted to the housing (flange mounting for the GIC32 hydrophone). For set 2505 a General Instruments C-32 hydrophone connected to an impedance matching pre-amplifier which fed to system electronics provided by Greeneridge Sciences using a Tatttletale processor and 9.1 GB SCSII hard drive. This system sampled at 10 kHz on a sampling regime of a 90 s sample every10 minutes. The sets 2664 and 2672 used the same housing and hydrophone but a Curtin designed and built set of electronics (CMST-DSTO noise loggers) using a Persistor processor, with technical details to be found at www.cmst.curtin.edu.au under Products. Set 2664 sampled 123 s every 15 minutes at 5 kHz sample rate while sets 2672 and 2720 sampled 205 s every 15 minutes at 6 kHz sample rate. Set 2720 used the CMST-DSTO noise logger in a different housing with a Massa TR1025C hydrophone. All systems were calibrated using white noise of known level input with the hydrophone in series. The GIC32 hydrophone calibrations were carried out in an anechoic chamber. The system gain with frequency determined from the white noise input was then used with the hydrophone sensitivity to convert volts to Pa.

Set 2505 was deployed in 240 m depth and ran over 16-Oct-2000 to 18-Nov-2000.
Set 2664 was deployed in 305 m depth and ran over 28-Sep-2004 to 18-Mar-2005.
Set 2672 was deployed in 450 m depth and ran over 30-Dec-2004 to 08-Jul-2005.
Set 2720 was deployed in 333 m depth and ran over 21-Mar-2006 to 27-Nov-2006

All recording locations had deep ocean water on a > 180^{o} heading about the recording site.

All analysis has been carried out in the Matlab environment (MathWorks) using purpose built software for analysing the noise logger data sets.

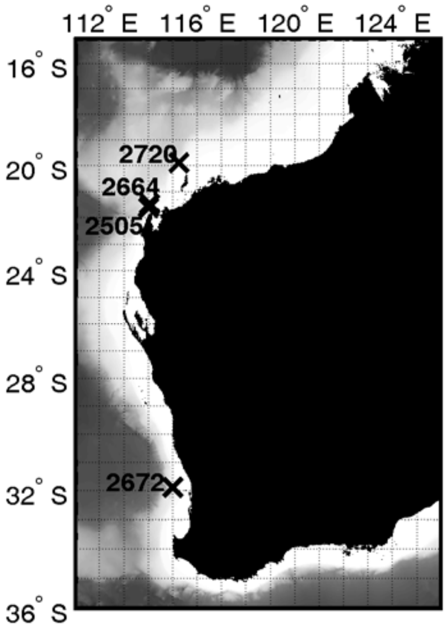

Figure 1: Locations of sites sampled for pygmy blue whale calling along the Western Australian coast. The numbers are the set or recording number. Set 2672 was perched on the edge of the Perth Canyon, sets 2505 and 2664 are off North West Cape and set 2720 was north of the Monte Bello islands.

RESULTS

An example of a high signal to noise ratio pygmy blue whale call comprised of three sets of tones as recorded from the Perth Canyon is shown on Figure 2. The call has been described in detail in McCauley et al (2001). It comprises three components, the first spread over 15-65 s on Figure 1, the second over 75-95 s and the third over 115 – 135 s. The highest level part of the call is the 18-26 Hz frequency sweep of the second component, followed by the 65-75 Hz sweep of the second component. There is some variability in the call structure and some novel forms based on the structure shown on Figure 2 and believed due to individual animals, but this issue is not explored here. The pygmy blue whales do produce other call types, notably a single down-frequency sweep which is akin to those attributed to 'true' blue whales, and a 20 Hz thump believed associated with feeding (physics of this call defined in Jones et al 2003). For this paper the call structure shown on Figure 2 can be considered the 'normal' and most consistent or common call type produced by pygmy blue whales.

For noise receivers on or near the continental shelf edge or for pygmy blue whales located on the continental shelf the 65-75 Hz sweep of the second call component is the call part most commonly detected. A spectrogram correlation search algorithm has been developed to locate the 65-75 Hz sweep of the second component while allowing for some variability in the frequency range. This search algorithm has been run over all data sets to locate pygmy blue whale calls. The locations of calls (time) are then checked by viewing spectrograms, corrected if required, then all confirmed detections are bracketed by at least five samples and these checked to detect missed calls. This process is iterated until no more new calls are detected, ensuring a high confidence that all pygmy blue calls in the data set have been located correctly.

Several sets of data utilising either long samples (> 500 s) or of continual sea noise with calling pygmy blue whales (CTBTO Cape Leeuwin hydrophones, some noise logger data with long samples and drifting sets using DAT tape systems) have been used to get the minimum call repeat cycle for an individual whale. While the repeat cycle varies, for the purposes of this paper it is considered to be that an individual whale will repeat the call shown on Figure 2 at a minimum of 200 s from initiation of the first call component. Thus counting all of the 65-75 Hz upsweeps within a 200 s sea noise sample gives the number of individual pygmy blue whales calling over that 200 s. This is the metric which has been used in all analysis below. This metric differs from other published works which have used counts of whale calls per unit time (calls, not individual calling whales) to define migratory habits (ie. Stafford et al in press), have used cue counting techniques from multiple receivers to estimate abundance (ie. Marques et al 2009) or relate time averaged received levels across seasons to whale numbers (Gedamke et al 2007). It is considered that the number of individual whales calling at any point in time is a simpler and more robust proxy for relative abundance than any other metric based on counts of whales calling.

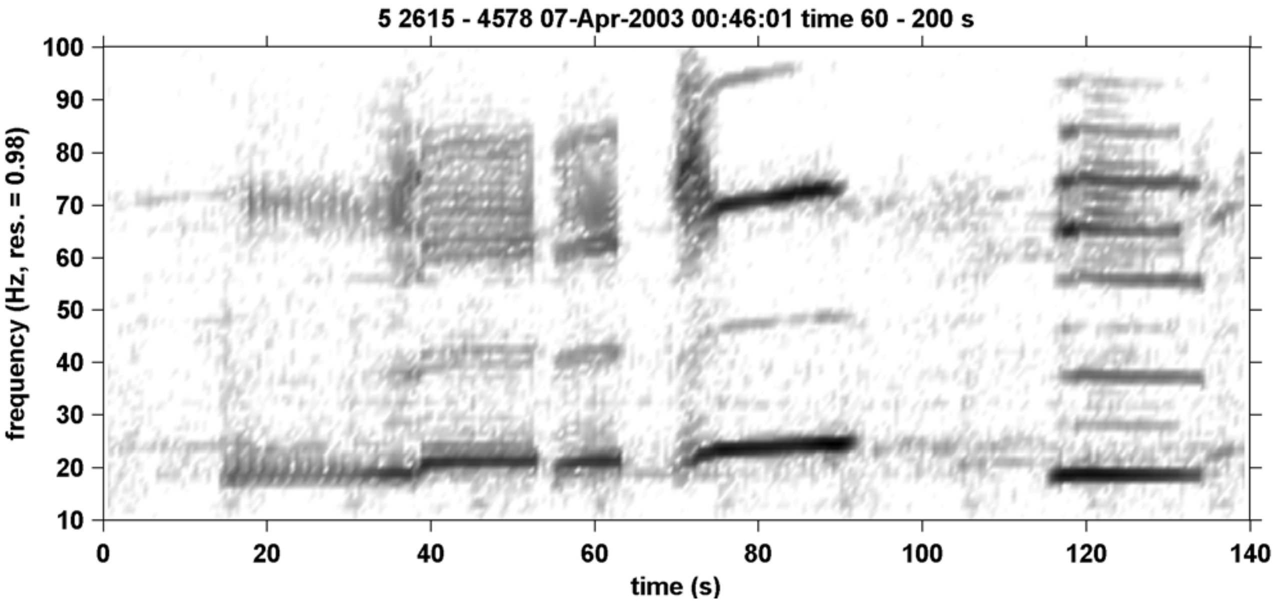

Figure 2: Spectrogram of a three part pygmy blue whale call (over 15-135 s). A weak second calling animal can be seen over 0-16 s (the second component).

The long time series of calling pygmy blue whales were used to develop a correlation between shorter sampling periods than the 200 s call repeat cycle (noting that set 2505 sampled 90 s only and set 2664 sampled 123 s), with a linear correlation found between the proportion of calling animals counted and the sample length, up to a 200 s sample. The linear relationship derived was:

$$proportion\_counted = 0.004 \times Length + 0.1155 \quad \text{with} \quad r^2 = 0.992$$

Where *Length* is the sample length (s) and the proportion counted considered to be one for a sample length of 200 s or greater. This relationship was used to correct all pygmy blue whale counts where samples were < 200 s in length, to give the number of individual pygmy blue whales calling (IPBWC) at a point (200 s sample) in time.

To display seasonal patterns in calling the 24 hour averaged counts of IPBWC (12:00 to 12:00) have been displayed for the four sites on Figure 3. The 24 hour averages are used to remove diurnal trends (animals call more at dusk and dawn, McCauley et al 2001). The migratory trend, described below, is clear and has been supported by visual observations (data of Jenner).

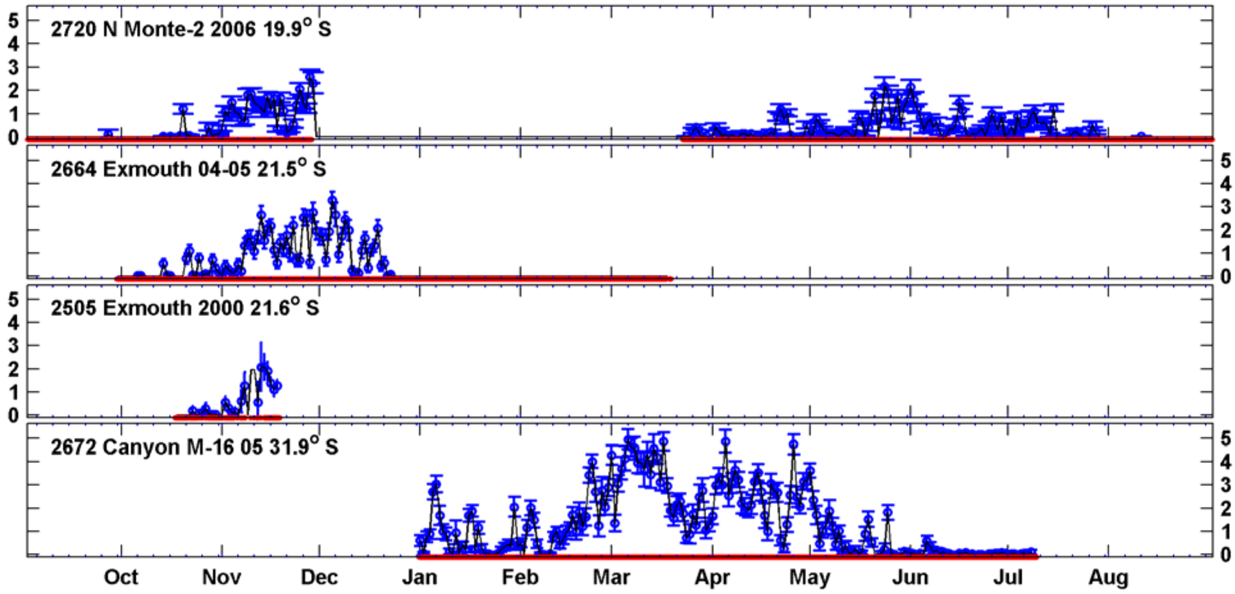

Figure 3: 24 hour averaged counts of pygmy blue whales in the Perth Canyon, off North West Cape and north of the Monte Bello Islands along the WA coast. The daily means are given with error bars and a smoothed curve fitted through the data. The heavy line at the bottom of each plot is the noise logger sampling period. The different years are aligned by Julian day. The latitude of each site is shown.

Along the WA coast pygmy blue whales migrate south from Indonesian waters passing by the Exmouth area through November to late December each year with a comparatively short burst of animals passing. Observations suggest most pygmy blue whales pass along the shelf edge out to water depths of 1000 m but centred near the 500 m depth contour. After spending summer in southern waters animals head north, this beginning early in the New Year for some animals. In the Perth Canyon animals stop in on their northern migratory leg and pass through over an extended period with animals staying if the food supply is sufficient or leaving if not. The pygmy blue whales then head north along the WA coast passing the Exmouth-Monte Bello Islands area over an extended period ranging from April to August before heading back to Indonesian waters.

The southern migratory period for pygmy blue whales off Exmouth (51 days for set 2664 for 90% of animals to pass) is comparatively short compared to the northern migration period (83 days for set 2720 for 90% of animals to pass) suggesting southbound animals are swimming purposefully through the area in their desire to reach southern feeding areas. This short southerly migratory pulse off Exmouth, which is shown in detail on Figure 4, is ideal for estimating abundance from the acoustic counts as if most animals are swimming purposefully through the area then the probability of detecting the same individual on more than one times [the time required by a pygmy blue whale to traverse the listening range of the noise logger], is low. This assumption of animals swimming steadily past the noise logger means that the 'residency time' of an individual whale in the listening range of the noise logger is the swim time across its listening area and is not confounded by animals lingering.

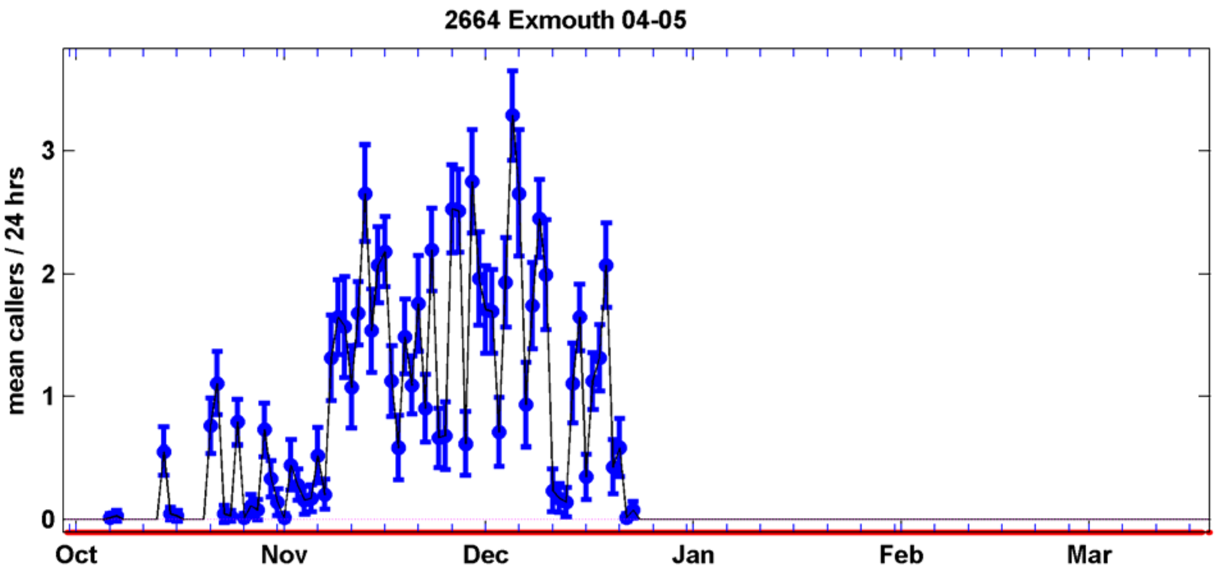

Figure 4: Passage of pygmy blue whales past site 2664, as shown by the 24 hour mean of the IPBWC. The 24 hour mean with 95% confidence limits is shown, with the black line a curve fitted through the mean, the heavy lower line the sampling period.

The translation of the IPBWC measurements shown on Figure 4 to an estimate of the number of whales passing over the southbound migratory season was carried out by the following steps:

- The curve of IPBWC measurements was integrated across the full season (first to last pygmy blue whale detection) to give units of *IPBWC●days*. This step used data from each sample (not the 24 hour means as shown on Figure 3 and Figure 4).
- The number of singing individual whales detected was assumed to reflect the total number of pygmy blue whales in the listening range of the receiver. A range of proportions of calling whales was used to give error bounds. The unit *IPBWC●days* was multiplied by the inverse of the proportion of whales calling, to give *whales●days* across the migratory pulse.
- The time taken for whales to traverse the listening range of the noise logger was calculated, assuming the whales followed a path close to the 500 m depth contour and using sound transmission modelling and the call source level estimates to delineate the receiver detection bounds.
- The measure of *whales●days* was divided by the whale transit time across the noise logger listening range (0.54 days) to give an estimate of the total number of whales which had traversed the logger listening range over that migratory pulse. This assumed whales travelled straight through the logger listening range and did not linger which is what the migratory trend data and observations suggest.

The first assumption was that the number of individual pygmy blue whales calling at any point in time was related to the total number of pygmy blue whales in the listening range of the receiver. While this will not hold for point samples it can be expected to be a reasonable assumption when averaged across the season of a migratory pulse at a single point in space. Estimates of the proportion of pygmy blue whales in the listening range of a receiver compared with the number of whales calling have not been derived accurately. McCauley et al (2001) related acoustic counts of pygmy blue whales calling in the Perth Canyon to concurrent aerial survey data. Using the raw aerial survey data only (no corrections for observer bias, whale downtime etc) they stated that the proportion of whales singing must have been < 28% of the number of whales in the listening range of the receiver and speculated that it was more like < 20%. The only other data on the proportion of whales calling is given by Cato et al (2001) of 8.5% for northbound humpback whales and 12.7% for southbound humpbacks off the east Australian coast. Given the uncertainty in pygmy blue whale calling rates two estimates are given here, 8.5% as the lower rate based on the observations of Cato et al (2001) for northbound humpbacks and 20% based on the maximum speculated level for pygmy blue whales based on point observations in the Perth Canyon.

The time taken for a pygmy blue whale to traverse the listening range of the noise logger was estimated by: 1) calculating the listening range of the noise logger on five azimuths around the receiver location and using this to calculate the distance along the 500 m depth contour across the noise logger listening range; and 2) dividing this by an estimated pygmy blue whale swimming speed during the southbound migratory phase. The transmission of pygmy blue whale calls along the five azimuths were calculated across the frequency band 20-25 Hz using: real bathymetry paths; a limestone seabed profile derived by comparing measured and modelled air gun signals in the area; representative water column sound speed profiles; a source depth of 20-30 m; the RAMS sound transmission model run out to 70 km; and assuming a 183 dB re 1μPa source level for the 18-26 Hz sweep of the second component of Figure 2. The curves of estimated transmission of blue whale calls were used to give detection ranges along the five azimuths for signals to be > 3 dB above an ambient noise level using a probability approach (McCauley et al 2001). The outside detection ranges derived along each azimuth were then used to measure the distance along the 500 m depth contour which encompassed the listening range of the noise logger (120 km). The average swimming speed of the southbound pygmy blue whales was assumed to be five knots (9.26 km/hr), to give a transit time of 0.54 days.

The integrated measure of *IPBWC●days* across the 2004 southbound pygmy blue whale migratory pulse off Exmouth was calculated to be:

71.54 *IPBWC●days*

When adjusted for the proportion of whales singing (8.5% and 20%) and divided by the transit time across the logger listening range (0.54 days) the estimated total number of whales traversing the noise logger listening area ranged over:

662 – 1559 pygmy blue whales passing by on the 2004 south bound migratory pulse.

DISCUSSION

The only current estimate of the pygmy blue whale population passing along the WA coast is an un-published estimate based on photo-ID resights and mark-recapture techniques, made in the Perth Canyon. This technique is believed to return a similar population estimate, of near 1000 pygmy blue whales forming the pool of animals using the Perth Canyon, which is essentially the mean of the range given for the 2004 acoustic estimate off Exmouth of south bound pygmy blue whales (662-1559 whales or mean of 1,110).

No estimate of an increase or decrease in numbers of pygmy blue whales following the WA coast is available for comparison. Acoustic relative abundance estimates are available for the Perth Canyon over a ten year span but the number of whales present in the area in any season are believed confounded by local productivity causing large variability in the time whales spend in the Canyon system, confusing any abundance measure through repeat measurements of the same individual. The pygmy blue whale acoustically derived relative abundance estimates in the Perth Canyon do appear highly variable and with the limited analysis carried out to date, do not appear to follow any clear up or downward trend.

The estimate of 662-1559 pygmy blue whales passing along the WA coast can be considered to be only a fraction of the total pool of pygmy blue whales. We believe pygmy blue whales traverse the east Australian coast in a similar fashion to off the west coast, based on at least two pygmy blue whale stranding in recent years, an adult off Townsville in 2007 and a young calf off Rockhampton in June 2003, plus strandings late in recent summers in Bass Strait and a noise logger in Bass Strait picking up pulses of pygmy blue whales in May-June, indicative of animals heading east (too late in the season for these animals to head up the WA coast). Additionally the range of pygmy blue whales is known to cross the southern Indian Ocean (Branch et al 2007). Thus the estimate of the numbers of whales using the WA coast given here needs to be considered in context of the larger population pool of pygmy blue whales and the currently unknown movements of animals across the full (and unknown) geographic extent of the population.

The acoustic abundance estimate given here can be considered to be first estimates, given the host of unknown factors required to convert the measure of the number of individual whales calling at any point in time to the number of whales passing. We have deliberately used a wide range of the largest unknown assumption, the proportion of animals singing, in order to give a reasonable error estimate for the derived abundance. All abundance estimates contain assumptions and require the derivation of multiple factors to convert the measures to numbers of whales. Some of the factors required here are simple to obtain (ie. whale swimming speed), can be easily verified (ie. signal transmission), can be derived from the noise logger records themselves (ie. mean length of singing bouts, whale call source levels, whale tracks), while some will require considerable effort to derive (for example the proportion of whales calling). The placement of the receiver in what is believed to be a steady stream of south bound pygmy blue whales simplifies the calculations and gives greater confidence in the abundance estimate, as the whale residency time is that taken to cross the listening range of the noise logger only. One of the advantages of the acoustic counts is the ease and safety involved in data collection - strategically place a suitable receiver system in the migratory stream and one can collect a full season of whale passage data.

The migratory habits of pygmy blue whales along the WA coast are now reasonably well established: animals stream south late in the year from northern waters, with many animals known to frequent Indonesian waters; many of these animals close the WA coast in the Exmouth-Monte Bello Islands area where they stream steadily south along the continental shelf break then pass around Cape Naturaliste to fan out across southern Australia. On the return northern migratory leg, which appears to be more staggered in time than the southern migratory phase, pygmy blue whales pass north into the Perth Canyon over January to May then head up the coast passing Exmouth over April to August before continuing north. We do not know if and how many pygmy blue whales leave the WA coast and head westwards into the Indian Ocean.

In summary the migratory habits of pygmy blue whales along the WA coast involves a short sharp pulse of southbound animals and a more protracted pulse of northbound animals. The southbound pulse was sampled acoustically for calling pygmy blue whales in late 2004 and found to have somewhere between 662 to1559 whales passing.

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