The following supplements accompany the article

Worldwide decline in tonal frequencies of blue whale songs

Mark A. McDonald[1,*], John A. Hildebrand[2], Sarah Mesnick[3,4]

[1]WhaleAcoustics, 11430 Rist Canyon Road, Bellvue, Colorado 80512, USA
[2]Scripps Institution of Oceanography, University of California San Diego, La Jolla, California 92093-0205, USA
[3]Southwest Fisheries Science Center, National Marine Fisheries Service, NOAA, La Jolla, California 92037, USA
[4]Center for Marine Biodiversity and Conservation, Scripps Institution of Oceanography, University of California San Diego, La Jolla, California 92093-0202, USA

*Email: mark@whaleacoustics.com

Endangered Species Research 9:13–21 (2009)

Supplement 1. Data sources: recording methods, media, recording locations, archives and synopsis of related publications. Table S1 provides a numerical tabulation of the data; this is followed by a written synopsis of each data source as referenced to the index numbers in Table S1. Where the data were not available in raw form, some explanation is provided with regard to why the data is considered valid or at least worthy of plotting

Table S1. Origins of the blue whale song data used in Figs. 2 & 3 of the main article. When data sets were effectively limitless, we chose to measure 10 songs from each of 10 individual whale encounters. We show all call frequency data in an attempt to be complete and unbiased, such that the readers may judge for themselves the significance of any anomalous data, even though these points may be the result of differences in measurement methods when the raw data were not available for this study. NA: not available. Number of whales assumes each encounter separated significantly in time is a different whale, an imperfect proxy. Southern Ocean refers to the entire circum-Antarctic region. PMEL: Pacific Marine Environmental Laboratory

Index no.	Date (mo/yr)	Region	No. of calls	No. of whales	Mean freq. (Hz)	95% CI	Source
1	9/08	NE Pac.	100	10	45.5	0.21	Present study
2	8/07	NE Pac.	100	10	46.0	0.6	Present study
3	9/06	NE Pac.	100	10	46.0	1.0	Present study
4	9/05	NE Pac.	100	10	46.6	0.1	Present study
5	7/03	NE Pac.	89	10	47.0	0.4	Present study
6	7/02	NE Pac.	97	10	47.9	0.5	Present study
7	7/01	NE Pac.	85	7	48.0	0.9	Present study
8	7/00	NE Pac.	100	8	48.7	0.8	Present study
9	7/98	NE Pac.	63	2	50.5	0.6	Present study
10	10/97	NE Pac.	88	7	50.5	0.4	McDonald et al. (2001)
11	3/97	NE Pac.	318	10	50.7	2.4	Stafford et al. (1999)
12	7/96	NE Pac.	47	5	51.2	0.7	Present study
13	6/94	NE Pac.	1	1	52.5	NA	CNAWC (1994)
14	6/93	NE Pac.	1	1	52.5	NA	Dave Clark (pers. comm.)
15	9/93	NE Pac.	22	3	52.2	1.5	Rivers (1997)
16	8/93	NE Pac.	295	NA	53.7	2.0	Stafford et al. (1998)
17	9/90	NE Pac.	25	1	53.1	0.6	McDonald et al. (1995)
18	2/87	NE Pac.	23	2	53.4	2.8	Thompson et al. (1996)
19	7/85	NE Pac.	1	1	55.5	NA	Jacobson et al. (1987)
20	7/80	NE Pac.	1	1	57.6	NA	Riedesel et al. (1982)
21	8/74	NE Pac.	Many	NA	60.9	NA	Morris (1978)
22	10/71	NE Pac.	25	2	61.4	0.8	Cummings & Thompson (2002)
23	7/63	NE Pac.	24	3	65.7	0.5	Thompson (1965)
24	12/67	NW Pac.	2	1	25	NA	Northrop et al. (1971)
25	1/80	NW Pac.	8	2	23	NA	Thompson & Friedl (1982)
26	9/82	NW Pac.	43	1	22	NA	Duennebier et al. (1987)
27	1/93	NW Pac.	39	5	20.2	0.25	McDonald & Fox (1999), present study
28	1/97	NW Pac.	7	2	20.1	0.29	Present study (data near Wake Island)
29	1/01	NW Pac.	26	1	19.45	0.20	Present study (data near Hawaii)

Table S1 (continued)

Index no.	Date (mo/yr)	Region	No. of calls	No. of whales	Mean freq. (Hz)	95% CI	Source
30	?/64	SW Pac.	1	1	25.3	NA	Kibblewhite et al. (1967), Cummings & Thompson (2002)
31	12/97	SW Pac.	20	2	20.0	0.29	McDonald (2006a), present study
32	4/59	N Atl.	Many	NA	23	NA	Weston & Black (1965)
33	?/61	N Atl.	8	1	20.7	0.16	Payne (1977)
34	9/79	N Atl.	7	1	18.95	NA	Edds (1982)
35	12/93	N Atl.	3816	?	18.4	0.27	Mellinger & Clark (2003)
36	6/97	N Atl.	12	1	18.5	NA	Clark & Charif (1998)
37	11/00	N Atl.	52	5	18.07	0.12	PMEL data, present study
38	12/02	N Atl.	33	4	17.7	0.22	PMEL data, present study
39	11/04	N Atl.	11	1	17.6	0.08	PMEL data, present study
40	1/95	S Ocean	18	2	28.4	0.12	D. Demer recordings, present study
41	1/97	S Ocean	4	1	28.5	NA	Ljungblad et al. (1998)
42	1/99	S Ocean	1	1	28.4	NA	Matsuoka et al. (2000)
43	3/01	S Ocean	100	10	27.8	0.16	Present study
44	3/02	S Ocean	100	10	27.8	0.29	Present study, Širovic et al. (2004)
45	2/03	S Ocean	100	10	27.7	0.20	Present study
46	12/03	S Ocean	20	5	27.4	0.24	Present study
47	4/05	S Ocean	48	5	26.9	0.16	Present study
48	4/93	E Indian	6	2	24.25 21.42 18.96	0.37 0.25 0.18	McDonald et al. (2006), L. Hall (pers. comm.)
49	2/00	E Indian	235 35 134	NA	23.9 21.1 18.95	NA	McCauley et al. (2001)
50	3/84	N Indian	2	NA	115.5	NA	Archival tape, British Library, J. Gordon
51	4/02	N Indian	1	1	106	NA	Present study, data near Diego Garcia

Synopsis of data sources in Table S1

Index numbers 1–9: For the years 2000 to 2008 offshore southern California, USA, the data set is practically limitless. We selected 834 blue whale calls categorically assumed to be from 77 different individuals as recorded on digital recorders custom-built by Scripps Institution of Oceanography. These digital data are archived by J.A.H. at Scripps. The recorders are described in Wiggins (2003) and Wiggins & Hildebrand (2007). All data used were recorded offshore southern California. Frequency measurement errors are negligible. These 834 calls were selected to provide a statistically valid sample of 10 calls from each of 10 assumed individuals. In some cases fewer than 100 calls were measured because the effort required to access and search more of the archived data was not deemed worth the gain achieved by adding more calls to the statistics for that year. The assumption that whales recorded on different days in different locations are different individuals can be argued statistically as we have good estimates of the population size (~2500), average travel rates (3 km h^{-1}), detection range (10s of km) and frequency of singing, but it is not a critical assumption to this study. Some of the 77 individuals reported here may be repeat recordings of the same animal, but this is not expected to bias the overall trend in frequency shift.

Index number 10: These data were collected using sonobuoys recorded by digital audio tape recorders during a cruise between San Francisco and San Diego, CA, by the lead author (M.A.M.) The focus of the cruise was to photo identify blue and humpback whales in waters further offshore than small boats are able to work; thus the sonobuoy deployments were primarily near the continental shelf, spread along the entire San Francisco to San Diego track. A further description of some of these recordings is provided in McDonald et al. (2001). The digital data are archived in the office of M.A.M.

Index number 11: This data point was reported by Stafford et al. (1999) using data recorded on autonomous digital recorders. The anomalously large confidence intervals reported here presumably relate to measuring something other than the midpoint of the B call, although it is not clear from the manuscript how the measurement was made. The data point is included for completeness and to demonstrate that no matter what measurement differences there may have been, this data point does not contradict the overall trend in frequency shift. The raw data are available at www.pmel.noaa.gov/vents/acoustics/ftp-files/GetTPDbyDays.html (Aug 24, 2009 verified), though the raw data were not used in this study because of the effort required to do so in relation to the relative importance of one more data point for this song type in this year.

Index number 12: These data were collected using sonobuoys recorded by digital audio tape recorders during a series of 3 day cruises between Santa Rosa Island and Santa Barbara California. The digital data are archived in the office of M.A.M. Frequency errors associated with sonobuoys and digital audio recorders are thought to be negligible.

Index number 13: This report describes blue whale calls recorded off San Diego with sonobuoys and a military aircraft. A spectrogram of a high signal to noise ratio blue whale call is provided. The frequency measurement reported here was measured on the paper copy of the published spectrogram. Status of the original data is unknown.

Index number 14: This raw recording was provided to the authors by Dave Clark of Space and Naval Warfare Systems Center, San Diego, from a Navy study related to ship shock testing. The recording is believed to be from a sonobuoy and a military aircraft. A copy is archived in the offices of M.A.M.

Index number 15: This measurement is as reported by Rivers (1997). Status of the original data is unknown. The data point is included for completeness and to demonstrate that no matter what measurement differences there may have been, this data point does not contradict the overall trend in frequency shift.

Index number 16: This measurement is as reported by Stafford et al. (1998). The recordings were made with a dipping hydrophone and digital audio tape recorder over a range of locations off California from 37 degrees north to 38 degrees north. The raw data were not available to the authors.

Index number 17: These recordings are described in McDonald et al. (1995) several hundred miles offshore the Oregon coast. Custom-built digital recorders were used, thus there is no frequency measurement error. Copies are archived in the offices of M.A.M.

Index number 18: These recordings are described in Thompson et al. (1996) in the Gulf of California with a dipping hydrophone and analog tape recorder. It is unclear why the confidence intervals reported for these frequency measurements are much larger than seen in other data. Status of the original data is unknown.

Index number 19: These recordings are described in Jacobson et al. (1987) several hundred miles offshore Oregon. Jacobsen recognized these sounds to have been produced by whales, though the species was unclear at this time. The published paper provides waveform displays of the blue whale calls which allowed clear identification and precise frequency measurement of one call, from the image of the waveform. A digital autonomous hydrophone system was used to make the recordings and is expected to have had negligible frequency error. The raw data was only available to the authors in the paper form as published.

Index number 20: These recordings are described in Riedesel et al. (1982) near the southern tip of Baja California, Mexico. These sounds were only recognized as coming from blue whales after publication of the paper (Mark Riedesel pers. comm.). The instruments used were digital seismographs, expected to have negligible frequency error. The blue whale calls were plotted in the published paper with both spectra and waveform displays which is effectively as good as raw data for the one call published. Status of the original data is unknown.

Index number 21: These recordings are described in Morris (1978) several hundred miles offshore San Diego. A vertical hydrophone array was recorded with commercial analog scientific recorders. A prominent frequency line corresponding to that known to be from whales was recognized and reported, though the whale species was not recognized in this publication. We now recognized this frequency peak to be very near the midpoint of the B call of the blue whale. In this case, Morris is reporting the average of many blue whale calls. Status of the original data is unknown.

Index number 22–23: These data are in the form of raw analog tapes at the Hubbs Sea World acoustic library, as donated by William Cummings. The recordings were made with various seafloor cabled hydrophones described in a long list of now declassified Navy reports, including Wenz (1968) and Thompson (1965). For this study we relied entirely on the raw analog data for which each tape contained frequency calibration tones. The frequency corrections applied were on the order of 1 % based on the tones on the tapes. The spectrograms presented by Wenz, Thompson and others in the now declassified reports serve to confirm the frequency measurements made from the raw analog tapes. Each tape contains a voice introduction describing each recording. Copies are archived in the offices of M.A.M.

Index number 24: These recordings are described in Northrop et al. (1971) several hundred miles offshore Midway Island. A cabled hydrophone and analog recorders would have been used. The sounds were recognized as probable whales, though the species was unclear. The paper provides a study of call frequencies, complete with example waveforms. Status of the original data is unknown.

Index number 25: These recordings are described in Thompson & Friedl (1982) off the north coast of Oahu, Hawaii with a cabled hydrophone and analog tape recorders. The frequencies of the blue whale calls are described in the paper along with example spectrograms. Status of the original data is unknown.

Index number 26: These recordings are described in Duennebier et al. (1987) from a location several hundred miles northeast of Japan. Whale sounds, now recognized as blue whales are well described in the publication, and spectra are presented showing the dominant peaks associated with the 2 whale calls from this song type. Status of the original data is unknown.

Index number 27: These recordings are described in McDonald & Fox 1999 from one of the same hydrophones used by Thompson & Friedl (1982) off the north coast of Oahu, Hawaii. A digital recording system was used and copies of the data are archived in the offices of M.A.M.

Index number 28: These recordings were acquired from the Comprehensive Test Ban Treaty Organization along with the data described in McDonald (2006) from cabled hydrophones as described in McCreery & Duennebier (1993) near Wake Island. These are digitally recorded at 320 samples s^{-1}. Copies of the data are archived in the offices of M.A.M. The data are available on the internet at www.rdss.info.

Index number 29: These data were digitally recorded on a seafloor recorder (Wiggins 2003) north of the big island of Hawaii. The data are archived at Scripps Institution of Oceanography.

Index number 30: These data are described in Kibblewhite et al. (1967) and raw analog tapes of these recordings are available from the Hubbs Sea World acoustic library, as donated by William Cummings. For this study we relied entirely on the raw analog data, each tape of which contained frequency calibration tones. The frequency corrections applied were on the order of 1% based on the tones on the tape. The spectra presented by Kibblewhite serve to confirm the frequency measurements made from the analog tapes. The tape contains a voice introduction describing the recording. Copies are archived in the offices of M.A.M.

Index number 31: These data were acquired from the Comprehensive Test Ban Treaty Organization and are described in McDonald (2006). These data are digital recordings at 160 samples per second from a cabled near seafloor hydrophone. Copies of the data are archived in the offices of M.A.M. These data are available on the internet at www.rdss.info.

Index number 32: These data are described in Weston & Black (1965) from the southern Norwegian Sea. The paper provides a thorough description of the sounds now known as North Atlantic type blue whale songs, though at the time these sounds were termed simply whale moans. The frequencies of the multipart songs are described, but no raw waveforms or spectra are presented. There is little description of the tape recorders or analysis systems and the whereabouts of the original data is unknown.

Index number 33: These data are available as a compact disk (Payne 1977), with liner notes providing the only documentation available to us. The blue whale songs are pitch shifted by a factor of 10 to be better heard by human ears, but these are Atlantic blue whale songs from a recording location unknown to us.

Index number 34: These data are described in Edds (1982) as recorded in the St. Lawrence River with analog tape. The frequencies of individual calls are tabulated in the publication. Status of the original data is unknown.

Index number 35: These data are described in Mellinger & Clark (2003), a subset of which is available in raw digital form on CD with an increased playback speed as Clark (1996). The data were recorded on restricted access military hydrophone arrays. The frequency data presented in the published paper are used here.

Index number 36: The report by Clark & Charif (1998) provides a spectrogram of blue whale song recorded on restricted access military hydrophone arrays. The frequency reported here was scaled off that published image. We presume the raw data are not available without special permission and clearances.

Index number 37–39: The raw digital data used is available on the internet at www.pmel.noaa.gov/vents/acoustics/ftp-files/GetTPDbyDays.html (Aug 24, 2009 verified), The recordings are from custom-built digital autonomous hydrophones and are further described in Nieukirk et al. (2004).

Index number 40: These recordings were made with sonobuoys and digital audio tape recorders by Dave Demer while working with the Census of Antarctic Marine Life project near Elephant Island Antarctica. The original audio tapes were made available to the lead author (M.A.M.) and copies of these data are archived in the offices of M.A.M.

Index number 41: These data were measured from the published spectrograms in Ljungblad et al. (1998). The data were recorded with sonobuoys and digital audio tape. The archival status of the original data is unknown to us.

Index number 42: This frequency measurement was taken from the image of the spectrogram in Matsuoka et al. (2000). The recording was made with an autonomous digital hydrophone system. The archival status of the original data is unknown.

Index numbers 43–47: These data were recorded on autonomous digital systems as described by Wiggins (2003). Publications which further describe these data include Širovic et al. (2004, 2007, 2009).

These data are archived at Scripps Institution of Oceanography.

Index number 48: These data were recorded on a military towed array in the Timor Sea and provided to the authors by Lindsey Hall, then of the New Zealand Defence Research Establishment. The recordings are further described in McDonald et al. (2006). The data are archived in the offices M.A.M.

Index number 49: The report by McCauley et al. (2001) provides spectrogram examples of blue whale songs for which the frequencies were picked from the paper prints. Rob McCauley & Chandra Salgado (pers. comm.) provided a digital example of a high signal to noise ratio blue whale song. The recordings were made with custom-built digital recorders and are presumed to be archived at Curtin University.

Index number 50: These recordings are from an archival tape contributed to the British Library by Jonathan Gordon. These are believed to have been made with a dipping hydrophone and an analog tape recorder near Trincomalee, Sri Lanka. A digital copy was obtained directly from the British Library, London for this study.

Index number 51: These data were recorded by the Comprehensive Test Ban Treaty Organization near Diego Garcia and are available on the internet at www.rdss.info

Note that only the earliest few years of data are available without a password, while the later data are being held confidential except to researchers of the nation within which it was collected and/or by special permission. The data are all from cabled hydrophones and digital recorders.

Supplement 2. Population recovery from whaling: assumptions, calculations and tests

Assumptions used in calculating relative population density and change in density

(1) Although songs occur year around, there is some relationship assumed between singing and breeding success, where all singers in a population must sing the same song at the same pitch to be successful.

(2) Male blue whales that live in areas with lower population densities sing louder songs. This could be in order to be heard by a greater number of animals or to be better heard in some form of mate competition.

Producing a blue whale call (song phrase) may require nearly all of the whale's total respiratory volume (Aroyan et al. 2000), with the lowest or fundamental frequency requiring more than 90 % of the air volume (McDonald et al. 2001). The frequency of the most demanding call and the maximum possible sound pressure level are directly related. Given that song frequency is fixed within any given singing season for each song type, whales with greater air volume (larger whales) will potentially be heard at greater distance and be louder at lesser distances.

While sound intensity allows calculation of maximum communication range, loudness, a measure of hearing perception, is typically not linearly related. It is unclear whether loudness or maximum communication range is more relevant, but maximum communication range is certainly the more easily calculated. To achieve lower (more desirable?) frequencies, the physical constraints of fixed lung volume force blue whales into a trade-off with sound intensity. However, because populations are growing, these whales may still be reaching the same or even a greater number of individuals (Fig. S1).

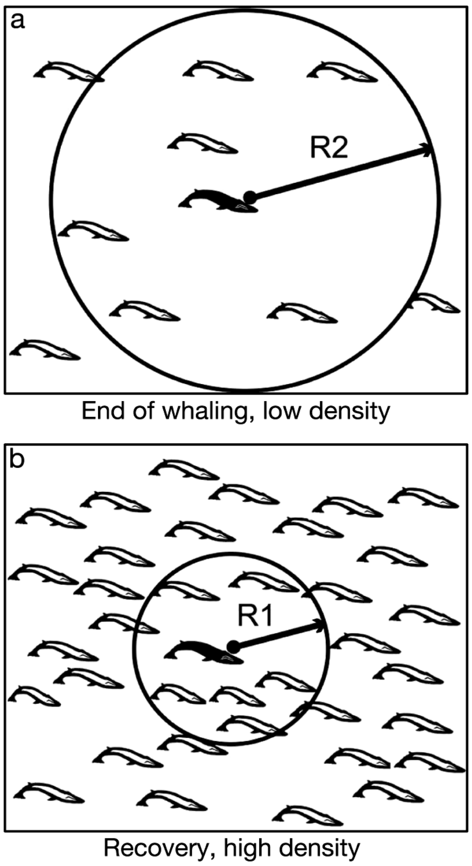

Fig. S1. As the number of whales increases after the cessation of commercial whaling, the intensity of selection on the various aspects of song may change. (a) When whales were scarce, a higher sound pressure level song is received over a larger radius (R2). (b) As the number of whales increases, a lower sound pressure level song at lower frequency is associated with a smaller radius (R1)

Calculations

From this rate of frequency shift, a population density increase or population growth rate within some geographic region where song is most important could theoretically be calculated, except for the confounding effect of increasing ocean noise. The calculations follow:

(1) Assuming a typical propagation loss, call frequency (f) is related to change in ensonified area, a proxy for change in population density (ΔD) by Eq. S4, which is derived in Supplement 3.

$$\Delta f = \left(\frac{1}{\Delta D}\right)^{0.4375} \qquad \text{(Eq. S4)}$$

(2) The pitch shift calculation: The Hz yr^{-1} shifts for each song type are translated to an index of population density increases (Table S2), ignoring small corrections for differences in acoustic propagation. Acoustic propagation between near surface whales is expected to be good at high latitudes due to the surface sound channel, good at low latitudes due to the surface sound duct and poorer at temperate latitudes due to a downward refracting environment (Urick 1983). In the Antarctic, Širovic et al. (2007) found losses to be 17.8 × log (range). Acoustic absorption is negligible at these distances (0–1000 km) and frequencies (15–150 Hz). The relevant ranges are those at which a listener might practically swim to the caller in a reasonable time, rather than the maximum distance at which a call could be detected in ideal conditions.

(3) Predictions of population density based on source levels: The 4 factors which set the maximum source level of sound which a blue whale can produce throughout a continuous tonal call are (1) call duration (s), 2) fundamental frequency (Hz) of the longest duration tonal song phrase, (3) lung volume and (4) resonance factor. We assume a fixed combined lung volume and resonance factor for all blue whales worldwide based on 186 dB re 1 µPa @ 1 m source level for the California blue whale calls in 1997 (McDonald et al. 2001). The lung volume/resonance factor can be treated as a percentage of lung volume. Given this lung volume/resonance factor, the call duration and call frequency determine the theoretical maximum call source level. Potential differences in lung volume based on average size differences between whale populations may provide a second order correction (Branch et al. 2007).

Given the sound production capacity, we can predict with the theoretical model what the maximum call source level should be for 7 of the 9 song types which have been observed worldwide. Our definition of a continuous tonal call for the purpose of this calculation means the whale would not have time between calls to re-circulate the air, a different definition than may be used when dividing blue whale song into units. When 2 frequencies are present as 2 continuous phrases in the call, we use the weighted mean frequency for the calculation. We apply our calculation to the fundamental tonal frequency when harmonics are present.

Testing the model

The proposed model could be tested and/or modified by future studies which correlate blue whale song acoustic source level maximum with fundamental song frequency. Maximum blue whale song source level and call frequency are expected to be directly related while lower call frequencies are expected to correlate to higher population densities. Direct measures of call source levels are uncommon (Cummings & Thompson 1971, McDonald et al. 2001, Širovic et al. 2007) and care should be taken with such correlations, as not every song a whale produces must be at the maximum level possible. For instance, limited data suggests that males in male/female pairs sing at a lower source level than single traveling males (Thode et al. 2000, Oleson 2005). Antarctic blue whale song maximum sound pressure levels have been measured near 195 dB at 27 Hz (Širovic et al. 2007), while eastern North Pacific blue whale song has been measured at a maximum level near 186 dB at 16.8 Hz (McDonald et al. 2001), consistent with the model presented here, both in the frequency-source level correlation and in the relative density index correlation.

Some of the best known blue whale densities are in the northeast Pacific and Antarctica (Calambokidis & Barlow 2004, Branch et al. 2004). The eastern North Pacific density during the summer is approximately 2500 animals per 2 000 000 km^{-2} or 1.25 animals per 1000 km^{-2} and in Antarctica, density during the summer, is approximately 1900 animals per 20 000 000 km^{2} or 0.1 animals per 1000 km^{-2}, close to the predicted relative densities calculated from song frequencies (Table 1 in article). A review of worldwide blue whale densities and seasonal variability is beyond the scope of this study and differences in site-specific background noise levels and average lung volume differences in the whale populations could be applied as correction factors.

Another test of the proposed hypothesis would be to compare computed relative growth rates from the hypothesis for each song type with growth rates estimated from demographic models. Initial analyses show that the growth rates calculated here are in the same direction and are similar to, but lower than the more or less 5 % growth rates anticipated from blue whale biol-

Table S2. Theoretical source levels in dB re 1 µPa @ 1 m are calculated for the earliest (initial) and most recent (final) data points for each song type and the dB per year change is calculated between these 2 points. Population density index is derived from the change in area ensonified at equal dB level assuming 17.5 log (range) losses. When 2 song units are directly adjacent, the calculation uses the combined durations and frequencies; thus pairs of values are given. The percent change in population density index over time is a proxy for population growth rate. Relative density index is referenced to the NE Pacific song type because this source level was used as a basis for the calculations. Southern Ocean refers to the entire circum-Antarctic region

Song type (region)	Duration (s)	Initial Year	Initial Freq.	Initial dB	Final Year	Final Freq.	Final dB	Change yr^{-1} dB	Change yr^{-1} Density (%)	Relative density (%)
NE Pacific	19	1960	22.2	188.4	2003	15.9	185.5	0.067	1.8	100
SW Pacific	6 + 12	1964	30.8/25.3	190.7	1998	25.8/20.1	188.8	0.027	0.8	47
NW Pacific	12 + 12	1968	25/23	187.1	2001	19.45/17.9	184.9	0.066	1.8	126
N Atlantic	8	1959	23	196.3	2004	17.6	193.9	0.053	1.4	11
S Ocean	10	1995	28.5	196.2	2005	26.9	195.7	0.050	1.3	7
N Indian Ocean	27	1984	116	199.8	2002	106	199.0	0.044	1.2	3
SE Indian Ocean	20	1993	19.5	186.9	2000	19.0	186.6	0.043	1.2	82

ogy models (Branch et al. 2004). The difference may be because of increases in ambient noise worldwide. Masking noise from increased commercial shipping is expected to result in blue whale songs needing to have higher source levels to be detected by the same number of conspecifics, a topic which needs further development before making quantitative predictions of the ambient noise change effect.

Lastly, analysis of yet-to-be discovered historical recordings of blue whale song may provide additional data points for comparison with our recordings. Additional early recordings of blue whale song in Antarctica and elsewhere may enable determination of whether the turning point of the song frequency shift corresponds with the end of whaling.

At least 1 other species, the three wattled bellbird, is known to have a long-term linear downward shift in its song frequency and is known to be decreasing in abundance (Kroodsma 2005). This is the opposite trend, however; given the jungle environment of this species and the frequencies involved, frequency-dependent attenuation may be the dominant factor in how far the song can be heard, in an environment where lower frequencies are being heard further. While the calculations for this species will be different, the concept may still be applicable.

Supplement 3. Derivation of relationship between call frequency and source level

Assuming a call of fixed duration, the call frequency (f) and sound pressure level at the source (P_0) are limited by the animals' respiratory system volume (V) as follows:

$$V = \frac{P_0}{\rho\pi(f)^2} \qquad \text{(Eq. S1)}$$

where, ρ is the density of seawater (Aroyan et al. 2000).

For a fixed respiratory volume, call sound pressure level is increased by increasing the call frequency. Call sound pressure level is physically related to the range at which these calls will be detected by conspecifics. The number of animals which can hear the song, N, can be calculated as:

$$N = \pi(r)^2 D \qquad \text{(Eq. S2)}$$

where r is the range at which the song can be heard and D is the population density index of the animals. The received sound pressure level of the song, P_R declines with range per Eq. (S3)

$$P_R = \frac{P_0}{r^{1.75}} \qquad \text{(Eq. S3)}$$

The propagation loss coefficient used here (1.75) is an approximation which will vary geographically. Combining Eqs. (S1) through (S3), and eliminating the constants, the relationship between change in frequency and change in population density is:

$$\Delta f = \left\{\left[\left(\frac{1}{\Delta D}\right)^{1/2}\right]^{1.75}\right\}^{1/2} = \left(\frac{1}{\Delta D}\right)^{0.4375} \qquad \text{(Eq. S4)}$$

Eq. (S4) is used to calculate the change in area per year over which a blue whale call could be heard, given the shift in frequency per year.

LITERATURE CITED

Aroyan JL, McDonald MA, Webb SC, Hildebrand JA, Clark D, Reidenberg JS, Laitman JT (2000) Acoustic models of sound production and propagation. In: Au WWL, Popper AN, Fay RR (eds) Hearing by whales and dolphins. Springer handbook of auditory research Vol 12. Springer, New York, p 409–469

Branch TA, Matsuoka K, Miyashita T (2004) Evidence for increases in Antarctic blue whales based on Bayesian modeling. Mar Mamm Sci 20:726–754

Branch TA, Stafford KM, Palacios DM, Allison C and others(2007) Past and present distribution, densities and movements of blue whales *Balaenoptera musculus* in the Southern Hemisphere and northern Indian Ocean. Mammal Rev 37:116–175

Calambokidis J, Barlow J (2004) Abundance of blue and humpback whales in the eastern North Pacific estimated by capture-recapture and line-transect methods. Mar Mamm Sci 20:63–85

Clark CW (1996) Whales '93: hot tracks and greatest hits. CD available from Cornell Laboratory of Ornithology, Bioacoustics Research Program, Ithaca, NY

Clark CW, Charif RA (1998) Acoustic monitoring of large whales to the west of Britain and Ireland using bottom-mounted hydrophone arrays, October 1996–September 1997. Joint Nature Conservation Committee (Aberdeen, Scotland) Report No. 281

CNAWC (Commander Naval Air Warfare Center) (1994) Marine mammal protection/mitigation and results summary for the shock trial of the USS John Paul Jones (DDG 53). Naval Air Warfare Center, Point Mugu, CA, p 26

Cummings WC, Thompson PO (1971) Underwater sounds from the blue whale, *Balaenoptera musculus.* J Acoust Soc Am 50:1193–1198

Cummings WC, Thompson PO (2002) Marine mammal recordings archived at the library of the Hubbs SeaWorld Research Institute, San Diego, CA

Duennebier FK, McCreery CS, Harris D, Cessaro RK, Fisher C, Anderson P (1987) OSS IV: Noise levels, signal to noise ratios, and noise sources. In: Duennebier FK, Stephen RA, Gettrust JF, Avedik F and others (eds) Init Repts DSDP, Vol. LXXXVIII. US Government Printing Office, Washington, DC, p 89–103

Edds PL (1982) Vocalizations of the blue whale, *Balaenoptera musculus*, in the St. Lawrence River. J Mammal 63:345–347

Jacobson RS, Bibee LD, Embley RW, Hammond SR (1987) A microseismicity survey of Axial Seamount, Juan de Fuca Ridge. Bull Seismol Soc Am 77:160–172

Kibblewhite AC, Denham RN, Barnes DJ (1967) Unusual low-frequency signals observed in New Zealand waters. J Acoust Soc Am 41:644–655

Kroodsma DE (2005) The singing life of birds: the art and science of listening to birdsong. Houghton-Mifflin, New York

Ljungblad DK, Clark CW, Shimada HA (1998) A comparison of sounds attributed to pygmy blue whales (*B. m. brevicauda*) south of the Madagascar Plateau and those attributed to 'true' blue whales (*B. musculus*) recorded off Antarctica. Rep Int Whal Comm 48:431–437

Matsuoka K, Murase H, Nishiwaki S, Fukuchi T, Shimada H (2000) Development of a retrievable sonobuoy system for whale sounds recording in polar region. Paper SC/52/O7 presented to the IWC Scientific Committee, June 2000, in Adelaide

McCauley RD, Jenner C, Bannister JL, Burton CLK, Cato DH, Duncan A (2001) Blue whale calling in the Rottnest Trench–2000, Western Australia. Report R2001-6, Centre for Marine Science and Technology, Curtin University of Technology, Perth

McCreery CS, Duennebier FK (1993) Correlation of deep ocean noise (0.4–30 Hz) with wind, and the Holu spectrum — a worldwide constant. J Acoust Soc Am 93:2639–2648

McDonald MA, Hildebrand JA, Webb SC (1995) Blue and fin whales observed on a seafloor array in the northeast pacific. J Acoust Soc Am 98:712–721

McDonald MA (2006) An acoustic survey of baleen whales off Great Barrier Island, New Zealand. NZ J Mar Freshw Sci 40:519–529

McDonald MA, Calambokidis J, Teranishi AM, Hildebrand JA (2001) The acoustic calls of blue whales off California with gender data. J Acoust Soc Am 109:1728–1735

McDonald MA, Mesnick SL, Hildebrand JA (2006) Biogeographic characterisation of blue whale song worldwide: using song to identify populations. J Cetacean Res Manag 8:55–65

Mellinger DK, Clark CW (2003) Blue whale (*Balaenoptera musculus*) sounds from the North Atlantic. J Acoust Soc Am 114:1108–1119

Morris GB (1978) Depth dependence of ambient noise in the northeastern Pacific Ocean. J Acoust Soc Am 64:581–590

Nieukirk SL, Stafford KM, Mellinger DK, Dziak RP, Fox CG (2004) Low-frequency whale and seismic airgun sounds recorded in the mid-Atlantic Ocean. J Acoust Soc Am 115:1832–1843

Northrop J, Cummings WC, Morrison MF (1971) Underwater 20-Hz signals recorded near Midway Island. J Acoust Soc Am 49:1909–1910

Oleson EM (2005) Calling behavior of blue and fin whales off California. PhD dissertation, University of California, San Diego, CA

Payne R (1977) Deep voices: recordings of humpback, blue and right whales. Living music records, compact disk recording re-released in 1991

Riedesel M, Orcutt JA, MacDonald KC, McClain JS (1982) Microearthquakes in the Black Smoker Hydrothermal Field, East Pacific Rise at 21° N. J Geophys Res 87: 10613–10623

Rivers JA (1997) Blue whale, *Balaenoptera musculus*, vocalizations from the waters off central California. Mar Mamm Sci 13:186–195

Širovic A, Hildebrand JA, Wiggins SM, McDonald MA, Moore SM, Thiele D (2004) Seasonality of blue and fin whale calls west of the Antarctic Peninsula. Deep-Sea Res II 51:2327–2344

Širovic A, Hildebrand JA, Wiggins SM (2007) Blue and fin whale call source levels and propagation range in the Southern Ocean. J Acoust Soc Am 122:1208–1215

Širovic A, Hildebrand JA, Wiggins SM, Thiele D (2009) Blue and fin whale acoustic presence around Antarctica during 2003 and 2004. Mar Mamm Sci 25:125–136

Stafford KM, Fox CG, Clark DS (1998) Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean. J Acoust Soc Am 104:3616–3625

Stafford KM, Nieukirk SL, Fox CG (1999) An acoustic link between blue whales in the Eastern Tropical Pacific and the Northeast Pacific. Mar Mamm Sci 15:1258–1268

Thode AM, D'Spain GL, Kuperman WA (2000) Matched-field processing, source signature recovery, and geoacoustic inversion of blue whale vocalizations. J Acoust Soc Am 107:1286–1300

Thompson PO (1965) Marine biological sound west of San Clemente Island: diurnal distributions and effects on ambient noise level during July 1963. US Navy Electronics Laboratory Report 1290, San Diego, CA

Thompson PO, Friedl WA (1982) A long term study of low frequency sounds from several species of whales off Oahu, Hawaii. Cetology 45:1–19

Thompson P, Findley LT, Cummings WC (1996) Underwater sounds of blue whales, *Balaenoptera musculus*, in the Gulf of California, Mexico. Mar Mamm Sci 12:288–293

Urick RJ (1983) Principles of underwater sound. McGraw-Hill, New York

Wenz GM (1968) Properties of low-frequency, deep-water ambient noise west of San Diego, California. Navy Undersea Warfare Center Tech Publ TP-39, declassified, p 48

Weston DE, Black RI (1965) Some unusual low-frequency biological noises underwater. Deep-Sea Res 12: 295–298

Wiggins SM (2003) Autonomous acoustic recording package (ARPs) for long-term monitoring of whale sounds. Mar Technol Soc J 37:13–22

Wiggins SM, Hildebrand JA (2007) High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring. International Symposium on Underwater Technology 2007 and International Workshop on Scientific Use of Submarine Cables & Related Technologies, Tokyo, 17–20 April 2007. Institute of Electrical and Electronics Engineers, Tokyo, p 551–557