



Annual decrease in pulse rate and peak frequency of Southeast Pacific blue whale song types since 1970

Franck Malige, Julie Patris, Susannah Buchan, Kathleen M. Stafford, Fannie Shabangu, K.P. Findlay, R. Huckle-Gaete, Sergio Neira, Christopher Clark, Hervé Glotin

► To cite this version:

Franck Malige, Julie Patris, Susannah Buchan, Kathleen M. Stafford, Fannie Shabangu, et al.. Annual decrease in pulse rate and peak frequency of Southeast Pacific blue whale song types since 1970. 2019. hal-02073928v1

HAL Id: hal-02073928

<https://hal.science/hal-02073928v1>

Preprint submitted on 20 Mar 2019 (v1), last revised 7 Feb 2020 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Annual decrease in pulse rate and peak frequency of Southeast Pacific blue whale song types since 1970

Franck Malige (1,11), Julie Patris (1,11), Susannah J. Buchan (2,3,4,11), Kathleen M. Stafford (5), Fannie W. Shabangu (6,8), Ken P. Findlay (7,8), Rodrigo Hucke-Gaete (9), Sergio Neira (2), Christopher W. Clark (10), Hervé Glotin (1,11)

1 : AMU, Université de Toulon, CNRS, LIS, Marseille, DYNi team, France

2 : COPAS Sur-Austral, University of Concepción, Chile

3 : Centro de Estudios Avanzados en Zonas Áridas, Chile

4 : Woods Hole Oceanographic Institution, USA

5 : University of Washington, USA

6 : Fisheries Management, Department of Agriculture, Forestry and Fisheries, South Africa

7 : Cape Peninsula University of Technology, South Africa

8 : Mammal Research Institute Whale Unit, University of Pretoria, South Africa

9 : Universidad Austral, Chile

10 : Cornell University, USA

11 : BRILAAM, STICAmSud

Abstract

We examined the decrease in the frequency of the dominant southeast Pacific blue whale song type (SEP2) from 1996 to 2017, using acoustic data from five different sources ranging between the equator and Chilean Patagonia. The pulse rate of the song units as well as their peak frequency were measured using two different methods (summed auto-correlation and Fourier transform). We assess the sources of error associated with each measurement. There was a linear decline in both parameters for SEP2. A shorter comparative analysis also showed frequency decline in the scarcer southeast Pacific song type (SEP1) between 1970 to 2014, revealing that both SEP1 and SEP2 are declining at similar rates. We discuss the use of measuring both pulse rate and peak frequency to examine frequency decline. We also compare the rates of frequency decline with other song types reported in the literature.

March 20, 2019

1 Introduction

1.1 Frequency decline in whale songs

Blue whale (*Balaenoptera musculus*) songs are the repetition of one highly stereotyped low-frequency, high energy units that compose song phrases, first described in 1971 [5]. Song units and phrases have been qualified as 'remarkably consistent' within a song sequence or bout, but also between individuals [5]. Song in blue whales has been attributed to reproductive display by males [20]. Numerous, distinct songs have been identified worldwide [14], each displaying stability in the temporal and frequency characteristics of units and phrases and intervals between units or phrases. However, this global pattern has been shown to be affected by a general decreasing trend in frequency over decadal timescales [13].

This linear decline in tonal frequencies of blue whale song types is a recently described unexplained phenomena. It appears to occur worldwide, based on analyses of different regional song types, spanning five decades [13]. New studies have recently confirmed these results for Antarctic blue whale song type [7], [28], [10], for the southwest Pacific song type [18], or for different song types in the Indian ocean [8], [10]. So far, no studies have examined frequency shift in southeast Pacific blue whale songs, even though these were the first blue whales songs to be identified as such [5].

A similar inter-annual frequency decrease has been recently measured for bowhead whale *Balaena mysticetus* [26] and fin whale *Balaenoptera Physalus* populations [29], [10] and unidentified low frequency sounds attributed to baleen whales [11], [28].

1.2 Southeast Pacific blue whale song

There are two blue whale song types in the southeast Pacific known as SEP1 and SEP2. SEP1 was first described almost fifty years ago [5], while SEP2 was first recorded in 1996 [25] near the equator and described in detail as a new song type in 2014 [3]. SEP2 has been found to be the dominant song type of southeast Pacific [4], [23].

The SEP2 phrase is usually repeated every two minutes, in a sequence lasting from some minutes to a few hours (called a song).

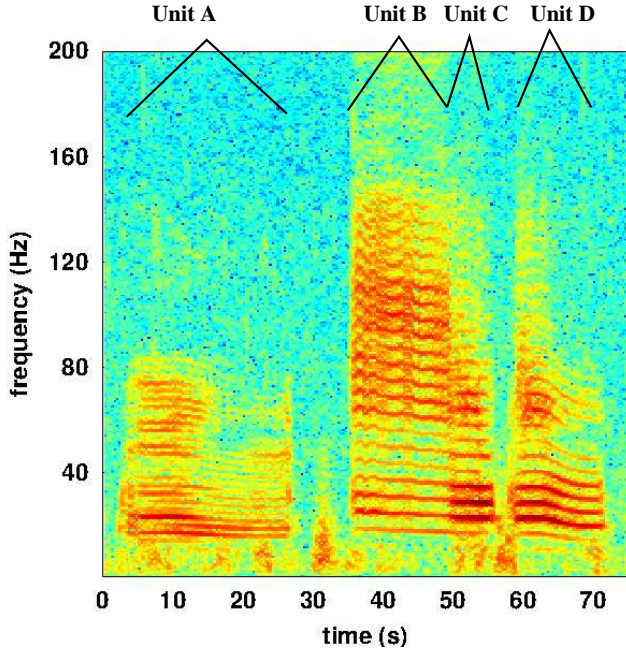


Figure 1: Time/frequency representation of a phrase of the SEP2 song, recorded off Isla Chañaral, Chile, 2nd February 2017, sample rate $f_s=48$ kHz, FFT 2^{16} points, overlap of 75%, Blackman window.

These songs are composed of a single repeated phrase, highly stereotyped in unit composition, duration and frequency characteristics (see figure 1). The four main parts of the phrase are : **Unit A**, a clearly pulsed sound with an energy maximum around 25 Hz, lasting 20 s and decreasing in intensity, with a very slight frequency decrease at its end; **Unit B**, a clearly pulsed sound with a maximum of energy between 20 and 100 Hz, that can vary from one song occurrence to another. The duration of this unit is around 15 s and it has a slight frequency decrease; **Unit C**, a slightly pulsed sound with a maximum of energy usually around 25 Hz and a duration of 5 s; and **Unit D**, very similar to the C unit except that it lasts longer, around 10 s, and has a frequency decrease in the last five seconds. All these features are observable only in clear recordings, with high signal to noise ratio (SNR). The C and D units are usually the loudest and together have been used as a kernel for automatic detection [4]. One of the defining characteristics of this song is the pulsed nature [21] of its units, visible in figure 2. The SEP2 units have a pulse rate f_{pulse} around 6 pulses per second for B, C and D units, and 3 pulses per second for A unit.

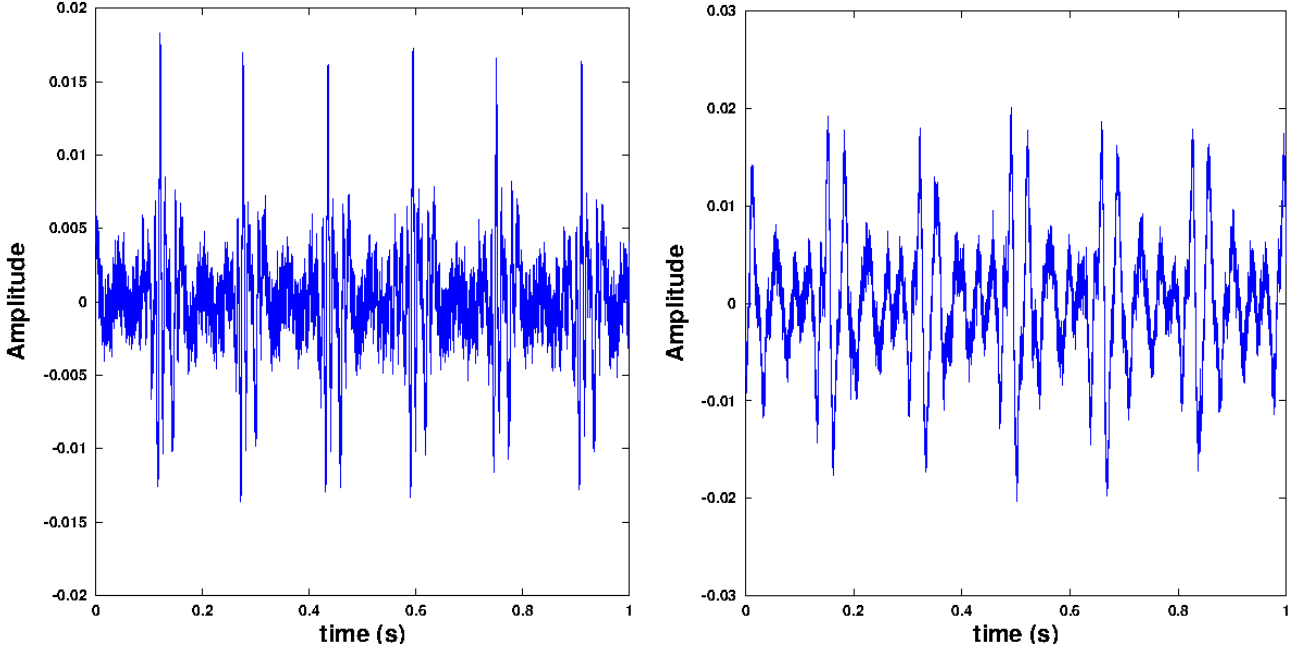


Figure 2: Extracts of units B (left) and C (right) of a SEP2 song recorded off Isla Chañaral, 2017 February the 2nd, in waveform.

The SEP2 song type has been recorded at different sites in the eastern Pacific Ocean: near the equator, in the eastern tropical Pacific (ETP) between 1996 and 2002 [25], off the north coast of Chile in 1997-1998 by International Whaling Commission's Southern Ocean Whale and Ecosystem Research (IWC SOWER) program [24], in the Corcovado Gulf in the south of Chile in 2012, 2013, 2016, 2017 [4], near the Juan Fernandez archipelago off Chile in 2005, from 2007 to 2010 and from 2014 to 2016 by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO <https://ctbto.org/>) and off Isla Chañaral, Chile, in 2017 [22].

In this paper, we examine the frequency characteristics of the SEP2 song type by computing pulse rate and peak frequency of units C and D to determine whether frequency decline has occurred between 1996 and 2017, using seven different data sets. We also discuss the sources of error associated with both pulse rate and peak frequency measurements.

We then apply this approach to assess the frequency decline of SEP1 between 1970 and 2014 using four data sets and a single data point from the literature [5].

2 Material and methods

2.1 Data collection

We analyzed 436 SEP2 song phrases spanning 21 years (1996-2017), from 5 different locations and 7 different data sets listed in Table 1.

Fifty high SNR phrases were manually selected for each year. To minimize the probability of only analyzing phrases from a single song bout, phrases were taken from five different days. In the case of the SOWER data, only 36 phrases from three different days were selected, due to the short duration of the data set.

Table 1: Characteristics of the data analyzed. Table includes name of the data set, references, place, epoch, number of phrases analyzed and sample rate of the data.

Data Set	lat (S)/ long (W)	year	Austral season	nb. phra- ses	samp. rate f_s (Hz)
ETP 1 ¹	8°/95°	1996	winter	50	100
IWC SOWER ²	29°/72°	1997	sum.	36	1000
ETP 2 ¹	8°/95°	2002	winter	50	250
CTBTO ³	34°/79°	2009	fall	50	250
Corcovado 1 ⁴	44°/74°	2012	sum.	50	2000
Corcovado 1 ⁴	44°/74°	2013	sum.	50	2000
CTBTO ³	34°/79°	2014	sum.	50	250
Corcovado 2	44°/74°	2016	sum.	50	4000
Chañaral ⁵	29°/72°	2017	sum.	50	48000

2.2 Data analysis

To estimate the frequency decrease, we measured peak frequency and pulse rate of units *C* and *D* of each phrase, since *A* and *B* usually have lower SNR and are somewhat modulated in frequency (see figure 1).

2.2.1 Fast Fourier transform to measure the peak frequency

In most studies [13], frequency decrease has been assessed by measuring the frequency of the highest energy band (peak frequency f_{peak}) of a tonal part of a song unit. However, the frequency where energy is maximum can be highly variable due to environmental effects or sensor sensitivity even though the general set of frequency peaks within a single unit is very stable at subdecadal timescales. For the SEP2 song type, we decided to call 'peak frequency' the frequency of the band that is on average the one with maximum energy, which in this case is around 25 Hz. When maximum energy is shifted to the 32 Hz frequency band, we still measured the exact frequency of the band around 25 Hz, in order to ensure a standard metric for examining the decadal trend in the song frequencies.

For all selected *C* and *D* units, we performed a FFT on the first 4s of the unit by a routine in OCTAVE [6]. We measured the peak frequency as the frequency corresponding to the maximum value (in modulus) of the FFT between 22 and 28 Hz.

Long term spectral averages [7] were not computed because of the complex nature of SEP2 songs compared to the Antarctic blue whale song type : the frequencies of different parts of the song overlap, blurring the long-term average.

2.2.2 Auto-correlation of the signal to measure the pulse rate

Units *C* and *D* are in effect periodic, or harmonic functions [21]. That is, the pulse rate is the fundamental frequency of these units and the ratio $\frac{f_{peak}}{f_{pulse}}$ is an integer. This ratio is equal to eight for unit *A* and four for units *B*, *C* and *D*. In this case, the pulse rate can be accurately measured by an summed auto-correlation of the signal when the sample rate of the recording is high (see the following section, about associated uncertainties). The auto-correlation function of a signal *s* is

$$C(\tau) = \lim_{T \rightarrow +\infty} \frac{1}{T} \int_{-T/2}^{T/2} s(t) s^*(t + \tau) dt$$

(where s^* is the complex conjugate of *s*). In practice, time *T* was limited by duration T_{signal} of the unit and our signal was sampled at a frequency f_s . We thus defined an approximation of $C(\tau)$ by

$$C_{T_{signal}, T_s}(\tau) = \sum_{n=0}^{\lfloor T_{signal}/T_s \rfloor} s(nT_s) s^*(nT_s + \tau)$$

where $T_s = \frac{1}{f_s}$ is the sampling interval and $\lfloor x \rfloor$ is the integer part of a real *x*. Here, we have $T_{signal} = 4s$. If the signal *s* is harmonic, the function $C(\tau)$ has maximums when τ is a multiple of the period. For a description of auto-correlation techniques see for example [15].

For each unit *C* and *D* we computed the approximate auto-correlation function (using an OCTAVE dedicated routine) for $\tau \in [0 : t_{correl} = 1s]$ with a step of T_s (see figure 3). A low-pass filter (fifth order Butterworth with frequency cut-off at 50 Hz) was applied before the auto-correlation to reduce high frequency noise.

To obtain a maximum likelihood of the pulse frequency detection, we performed a refinement of the auto-correlation method [30], involving the computation of the summed auto-correlation function

$$g(t) = \frac{t}{t_{\text{correl}}} \sum_{n=1}^{\lfloor t_{\text{correl}}/t \rfloor} C_{T_{\text{signal}}, T_s}(nt)$$

We computed this function for all values of t between 0 and t_{correl} with a step T_s . This function has a peak for t equal to the period. We thus measured the corresponding time T_{pulse} of the highest peak of the summed auto-correlation between $t = 0.15$ and 0.175 seconds (corresponding to frequencies between 5.71 and 6.66 Hz) which gives the frequency $f_{\text{pulse}} = \frac{1}{T_{\text{pulse}}}$.

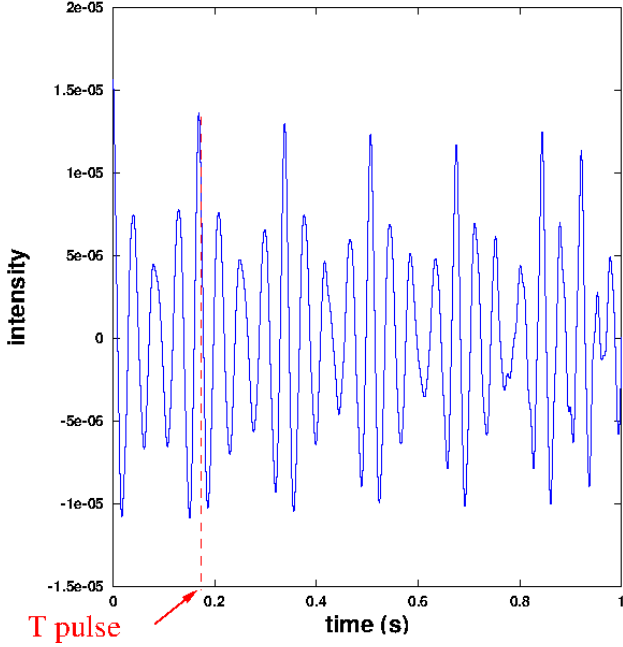


Figure 3: Graph of the auto-correlation $C_{T_{\text{signal}}, T_s}(\tau)$ of unit C : the maximum of correlation for $T_{\text{pulse}} \simeq 0.17$ s corresponds to a frequency $f_{\text{pulse}} \simeq 6$ Hz. The time T_{signal} is 4 s.

It is important to note that if the signal is not harmonic (that is if $\frac{f_{\text{peak}}}{f_{\text{pulse}}}$ is not an integer), the summed auto-correlation has a bias [21], and should not be used without first applying an envelope detection. Other methods of pitch detection can be used to measure the fundamental frequency of the signal as [2].

2.2.3 Error in frequency estimation

Uncertainties arise from three main sources : the inherent error of each method (quantification error) in measuring f_{pulse} and f_{peak} , ambient noise and the intrinsic dispersion in whale vocalizations. We assessed separately these three causes of uncertainty in the measurements.

Uncertainties due to the method : quantification errors Measuring peak frequency by means of a FFT cannot be more precise than the frequency step of the FFT (quantification of the frequency). Given that units C and D are around $T_{\text{signal}} = 4$ seconds long, the highest resolution FFT that can be computed is $f_s \times T_{\text{signal}}$ points. This results in a precision in frequency of $\frac{f_s}{f_s \times T_{\text{signal}}} = \frac{1}{4} = 0.25$ Hz. We note that this uncertainty is $1/T_{\text{signal}}$ and thus does not depend on the sample rate f_s .

On the other hand, the quantification error of the summed auto-correlation method depends strongly on f_s . To estimate f_{pulse} , assuming that the recording device has a sample rate f_s , the uncertainty in time when we measure T_{pulse} is thus at least of the order of $1/f_s$. We have $f_{\text{pulse}} = 1/T_{\text{pulse}}$ so $\Delta f_{\text{pulse}} = \Delta T_{\text{pulse}}/T_{\text{pulse}}^2 = f_{\text{pulse}}^2 \Delta T_{\text{pulse}} \simeq f_{\text{pulse}}^2/f_s$. In the case of a sample rate of 48 kHz and for a measured frequency f_{pulse} around 6 Hz, the quantification error is $\Delta f_{\text{pulse}} \simeq 10^{-3}$ Hz. But for $f_s = 2$ kHz, we have $\Delta f_{\text{pulse}} \simeq 0.05$ Hz and for $f_s = 100$ Hz, we have $\Delta f_{\text{pulse}} \simeq 0.2$ Hz.

We can also compute (and compare) the relative quantification error $\Delta f/f$. For our signals, we have $f_{\text{pulse}} \simeq 6$ Hz and $f_{\text{peak}} \simeq 24$ Hz. The relative error of f_{peak} measurement is thus $\Delta f_{\text{peak}}/f_{\text{peak}} = 1/(t_{\text{signal}} \times f_{\text{peak}}) \simeq 1\%$ for each recording. The relative error of f_{pulse} measurement depends on the sample rate: $\Delta f_{\text{pulse}}/f_{\text{pulse}} = f_{\text{pulse}}/f_s$. It becomes smaller than 1% for f_s greater than 400 Hz ($f_s = 100$ Hz leads to $\Delta f_{\text{pulse}}/f_{\text{pulse}} \simeq 6\%$, $f_s = 2000$ Hz leads to $\Delta f_{\text{pulse}}/f_{\text{pulse}} \simeq 0.3\%$). Thus, pulse rate measurement has a smaller systematic relative uncertainty than peak frequency measurement for f_s greater than 400 Hz.

Uncertainty due to noise To compute SNR, the following approach was used: The energy of a unit of duration T_{signal} is proportional to $\int_0^{T_{\text{signal}}} |s(t)|^2 dt$ [1]. We computed an approximation of the energy (where the coefficient A depends on the sampling rate but is constant for a given signal and will not appear in the SNR) :

$$E_{\text{SEP2}} = A \sum_{n=0}^{\lfloor T_{\text{signal}}/T_s \rfloor} |s(nT_s)|^2$$

We measured the energy of each unit C and D by computing the energy E of the signal during 4s. A band-pass filter (fifth order Butterworth with frequency band 5-50 Hz) was applied before the computation of energy. We then calculated the SNR by estimating the energy E_N of the background noise at a time selected manually before or after each SEP2 phrase, using the same formula and during the same T_{signal} . We compute $\text{SNR}_{(\text{dB})} = 10 \log_{10}(\frac{E_{\text{SEP2}}}{E_N})$ for each SEP2 song phrase. The SNR varied from 1 dB to 40 dB in the 436 selected SEP2 phrases.

To check each method's resistance to noise, we selected one song from the 14th of February 2012 in Corcovado with high SNR (around 40 dB) and we added background noise (taken from the same recording) with increasing level, resulting in a deterioration of the SNR. We then measured the peak frequency and pulse rate.

The measurement of peak frequency by means of a FFT is robust despite increasing background noise: for all levels of noise measured, the main error in the measurement comes from the quantification error. The main noises in the recordings are: Gaussian white noise, short-duration (less than 1s) low frequency (less than 20-30 Hz) sounds from surface waves and constant frequency bands (from ship motors). As the FFT is a linear process, these sounds did not generally prevent us from accurately measuring peak frequency. As for the measurement of the pulse rate, these noises seemed to have a higher influence on measurement, probably given that auto-correlation is a non-linear process. By performing several measurements of f_{pulse} for different noise levels, we estimated the uncertainties, which were on the order of 0.05 Hz or less, and shown as error bars in figures 4 and 5.

Intrinsic dispersion of frequencies In theory, intrinsic dispersion is due to the difference between two different sounds emitted by two different whales; two different sounds emitted by the same whale; or two sounds emitted by the same whale but affected differently by propagation effects. For example, in the latter case, the Doppler effect changes the received frequency by $f_{\text{received}} = \frac{1}{1-v/c} \times f_{\text{emitted}}$ where c is the sound speed and v is the radial speed of the whale relative to the recording device. For a typical value of $v/c \simeq 1/1000$, the difference in the frequency estimation is of the order of 0.1%. That is, for a frequency of 25Hz, a difference of 0.025 Hz is obtained. Dispersion uniquely caused by sound production (the former two cases) is extremely difficult to estimate and seems very small [9].

To estimate the intrinsic dispersion, regardless of its cause, we computed the standard deviation of results obtained for each year for f_{peak} and f_{pulse} . This standard deviation can also be affected by background noise or by quantification of measurements.

Representation of uncertainties For each year, we computed the quantification error, the error due to noise and the standard deviation of measured values, and we chose the greater of the three values to represent error graphically (see figures 4 and 5).

3 Results

3.1 Shift in peak frequency

Figure 4 clearly shows the decrease in peak frequency for the two units C and D between 1996 and 2017. As found for other blue whale song types [13], the shift in frequency seems to be linear over time.

The peak frequency of unit C dropped from 25.8 ± 0.25 Hz in 1996 to 23.6 ± 0.25 Hz in 2017, an average decrease of 0.10 ± 0.03 Hz per year. For unit D , peak frequency dropped from 25.8 ± 0.25 Hz in 1996 to 23.5 ± 0.25 Hz in 2017, resulting in a decrease of 0.11 ± 0.03 Hz per year. For almost all years, the main source of uncertainty was quantification error. This means that this method has reached its intrinsic limit of precision for analyzing this type of sound.

3.2 Shift in pulse rate

Figure 5 displays the pulse rate for SEP2 blue whale song type over 20 years, from 1997 to 2017. The results for 1996 were not plotted because auto-correlation methods produced unreasonable values due to the very low sample rate of these recordings, ($f_s = 100$ Hz).

In general, the relative error for pulse rate measurements was higher than for peak frequency measurements, although quantification errors can be reduced (typically with a higher sample rate of recording) for pulse rate measurement but not for peak frequency. Recordings with a high sample rate and high SNR usually had lower associated uncertainty (eg. years 2012 and 2013). Moreover, calculating an average reduces the uncertainty when error is introduced due to noise or intrinsic dispersion, but it usually does not reduce the error due to quantification.

The decrease also appears linear for the pulse rate. This is consistent with a harmonic signal and the fixed ratio $\frac{f_{\text{peak}}}{f_{\text{pulse}}}$. The pulse rate of unit C dropped from 6.44 ± 0.06 Hz in 1997 to 5.87 ± 0.10 Hz in 2017, an average decrease of 0.03 ± 0.01 Hz per

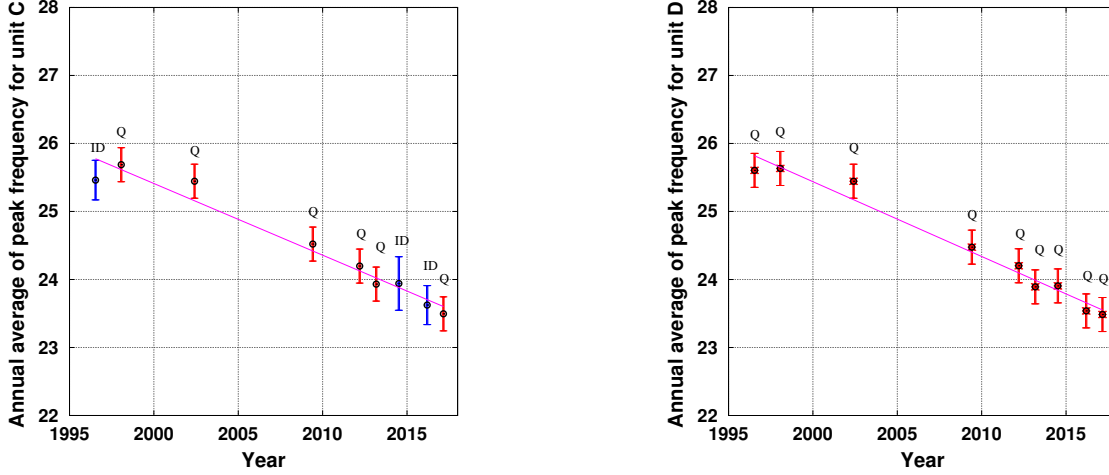


Figure 4: Temporal evolution of the peak frequency of units *C* (top panel) and *D* (bottom panel), computed by a Fast Fourier transform of the signal. The error bars color code is : red when quantification error is the greatest source of error, blue when intrinsic dispersion is the greatest source of error. A letter corresponding to the largest source of error is given on top of each error bar. The line correspond to the linear interpolation by least-square error of the points displayed in the graph (the coefficient of determination R^2 being close to 0.95).

year. For unit *D*, the pulse frequency dropped from 6.45 ± 0.06 Hz in 1997 to 5.87 ± 0.10 Hz in 2017, resulting in a decrease of 0.03 ± 0.01 Hz per year.

4 Discussion

4.1 Frequency decrease of SEP2 units

The decrease in frequency measured both from peak frequency and pulse rate is shown in figures 4 and 5 for the SEP2 units.

We also note that depending on the data, either peak frequency or pulse rate measurements can be used for these units. Error analysis shows that for data with a high sample rate (higher than 400 Hz), the pulse rate measurement with summed auto-correlation method has the best precision.

4.2 Application of this method to the SEP1 frequency shift

The oldest data point for SEP2 is 1996, however for the SEP1 song type, there is a data point as far back as 1970 [5]. Cummings and Thompson (1971) only reported pulse rate, but not peak frequency. Also, over all available data bases, there are fewer examples of SEP1, given that SEP2 is predominant as found in recent studies [3], [4], [23]. With these limitations, we applied the same approach for SEP2 to SEP1 examples to compute the pulse rate and examine whether SEP1 suffers the same rate of decrease as SEP2. This allow us to examine SEP frequency shift over 44 years (1970-2014), which is double the time period available for SEP2.

SEP1 is composed of 3 units [5] called A, B, C and shown in figure 6. First, we checked if SEP1 units were harmonic or not by computing the values of f_{peak} and f_{pulse} for forty SEP1 phrases with high SNR selected from the 2012 and 2014 data sets. We found that $\frac{f_{peak}}{f_{pulse}} = 6.23 \pm 0.50$ for unit A, 3.06 ± 0.09 for unit B and 4.07 ± 0.09 for unit C. We thus assumed that the peak frequency is an integer multiple of the pulse rate (as for units C and D of SEP2) and therefore SEP1 units B and C are also harmonic.

We then measured both pulse rate (by summed auto-correlation of the signal as in section 2.2.2) and peak frequency of 107 high SNR units B and C of SEP1 selected from four years of data (1996 from the ETP, 2012 from Corcovado gulf and 2007 and 2014 from CTBTO data off Juan Fernandez Island). We also took the value of the pulse rate for 1970 given in [5]. We did not have access to the precise values of peak frequencies for 1970 because in this paper peak frequencies are given only at a precision of 1/3 octave. For 1996, the low sampling rate (100 Hz) did not enable us to make a precise measure of the pulse rate.

Considering than $\frac{f_{peak}}{f_{pulse}} = 3$ for unit B and $\frac{f_{peak}}{f_{pulse}} = 4$ for unit C, we estimated the long term decline of f_{pulse} combining both methods (see figure 7).

The decrease is clearly linear for pulse rate of units B and C and is of 0.029 ± 0.005 Hz/year and 0.037 ± 0.005 Hz/year respectively, which compares well with SEP2 (unit C: 0.03 ± 0.01 Hz/year and unit D: 0.03 ± 0.01 Hz/year). Interestingly, the two units B and C of the SEP1 song types are not decreasing at the same rate. In 1970, these two units were quite similar

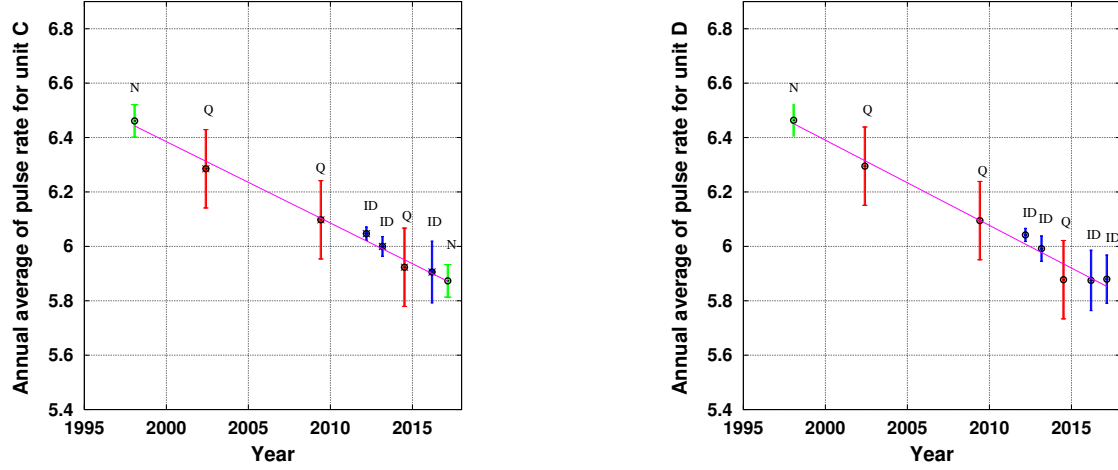


Figure 5: Evolution of the pulse rate of units C (up) and D (down). Error bars are red when quantification error is the greatest source of error, green when error due to the noise is the greatest source of error, blue when intrinsic dispersion is the greatest source of error. A letter corresponding to the largest source of error is given on top of each error bar. The line correspond to the linear interpolation by least-square error of the points displayed in the graph (the coefficient of determination R^2 being close to 0.98).

in term of frequencies [5]. Since then, the two fundamental frequencies have decreased at a different rate and each unit appear nowadays quite different in time-frequency representation, see figure 6.

Although $SEP1$ and $SEP2$ have similar time and frequency characteristics, and appear to occur with the same temporal distribution [4], it remains unclear whether these songs types indicate the presence of one or two acoustic groups. The fact that the frequency shift over decadal timescales occurs at a similar rate, may provide further support for both song types being produced by the same acoustic population.

4.3 Comparison with frequency shifts in other regional song types

To compare our results with other frequency shifts that have been reported, we extracted data from published papers (See Table 2). For the different song types, the values of the peak frequencies are very different (many of them are around 20Hz but other are around 30Hz and, in the north of Indian Ocean, it is near 100Hz). Thus, to compare different data, we computed the absolute values of the average decrease of the peak frequency during one year as % of the value estimated in a reference year. We chose the year 2000 as reference year and calculated, for each song type, the mean value of the peak frequency during this year, by linear interpolation. The results are presented in table 2.

Table 2: Comparison of our results to other works

Song type	Period studied	Frequency (Hz)	decrease in % of 2000's value / year
NE Pac. ¹	1963-2008	21.9 to 15.2	0.91
SW Pac. ¹⁴	1964-2013	25.3 to 17.5	0.81
NW Pac. ¹	1968-2001	23 to 17.9	0.86
N Atl. ¹	1959-2004	23 to 17.6	0.66
S Ocean ¹³⁵	1995-2014	28.5 to 25.8	0.51
N Indian ¹⁶	1984-2012	116 to 100	0.53
SE Indian ¹²	1993-2000	19.5 to 19.0	0.38
W Indian ⁷	2007-2015	34.7 to 33.7	0.35
SEP 1 (unit B)	1970-2014	23.1 to 19.3	0.42
SEP 1 (unit C)	1970-2014	30.8 to 24.3	0.56
SEP 2 (unit C)	1996-2017	26.5 to 23.5	0.44
SEP 2 (unit D)	1996-2017	26.5 to 23.4	0.45

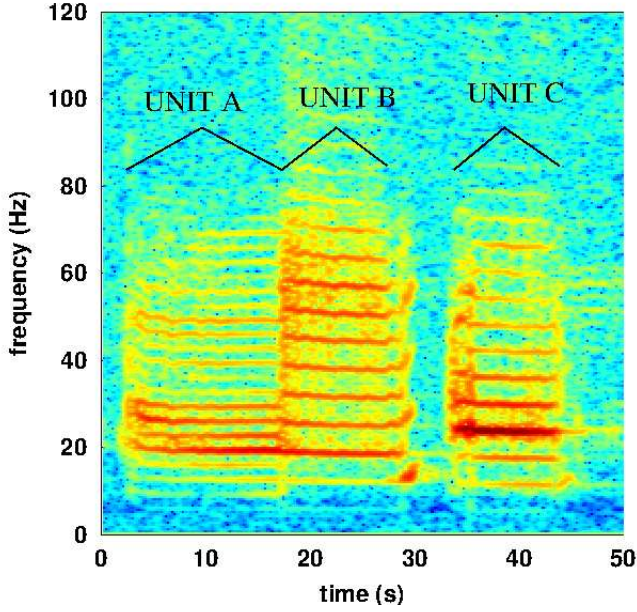


Figure 6: Time/frequency representation of a phrase of the SEP1 song, recorded in the Corcovado gulf, Chile, 2012 March 1st, sample rate $f_s=2$ kHz, FFT 2^{12} points, overlap of 90%, Blackman window.

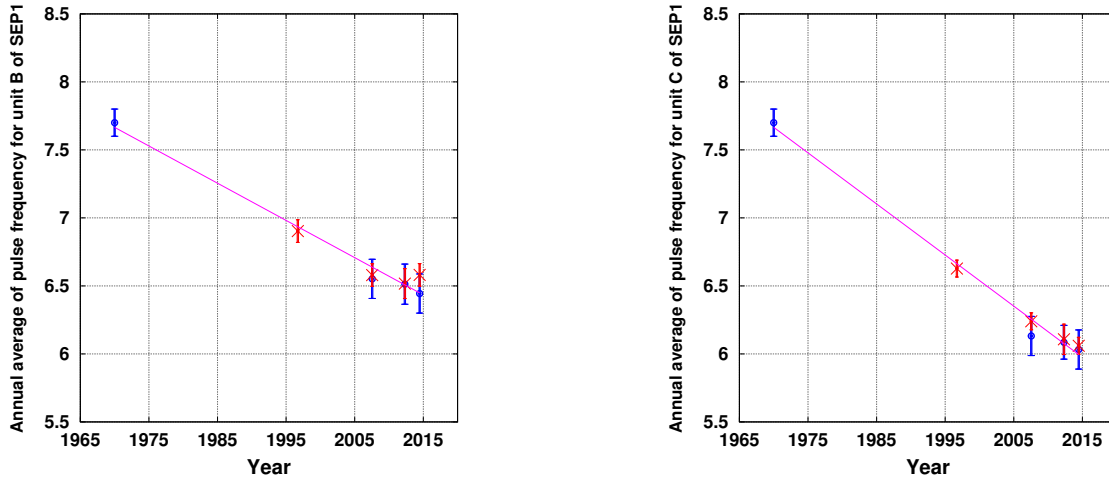


Figure 7: Pulse rate decrease in SEP1 phrases units. In blue (circles) the measures of pulse rate by mean of a summed auto-correlation method except the value of 1970 which is taken from literature [5]. In red (crosses), the points are computed by estimation of the frequency peak (by a FFT) divided by 3 and 4 for units *B* and *C* respectively. the errors bars are computed as for SEP2 . The line correspond to the linear interpolation by least-square error of the points displayed in the graph.

The frequency decrease observed here in SEP2 song types is comparable to that of other song types reported in the table 2. Interestingly, all song types from the north and west Pacific Ocean have a greater decrease than songs from other oceans and song types from the Indian Ocean have a smaller decrease than in other oceans.

4.4 Pulse rate and peak frequency decrease in other species

Another example of joint decrease of pulse rate and peak frequency has been recently noticed for fin whales songs in the northeast Pacific Ocean [29]. Other examples of different trends of pulse rate can be seen for fin whales in north Atlantic Ocean [19] or in northeast Pacific Ocean [27]. In all these cases, for fin whales, the pulse rate and peak frequency are very different (f_{pulse} being around 0.1 Hz and f_{peak} around 20 Hz) and seem not linked by an integer ratio.

Interestingly in these three studies, the pulse rate of fin whales is found to be globally decreasing over years in spite of yearly

sudden increases (for some populations) as for the peak frequency of Antarctic blue whales [7]. A similar pattern of change is found in an unidentified baleen whale “spot call” [28], with sudden increase of peak frequency after some years of constant decrease. This unidentified baleen whale may be a southern right whale [28].

This similarity of trends in frequencies of blue whale song types and other species sound emission (pulse rate and peak frequency decrease over years) has to be addressed and can be a clue to understand the reason of such trends present in the whole world and in different species of baleen whales.

5 Conclusions

We observed a linear frequency shift that is very similar to other blue whale song frequency shifts in both SEP1 and SEP2 song types.

Future studies of frequency trends of song types of baleen whales should measure both peak frequency and pulse rate. A precise value of pulse rate can be obtained whenever the signal is harmonic, the sampling rate is high enough and the SNR good and it is specially relevant to measure it when the sound is low frequency and not very long, as in most of blue whale song types.

The authors thank the help of Explorasub diving center (Chile), Agrupación turística Chañaral de Aceituno (Chile), ONG Eutropia (Chile), Valparaíso university (Chile), the international institutions and research programs CTBTO, IWC, BRILAM STIC AmSud 17-STIC-01. We are grateful to colleagues at DCLDE 2018 and SOLAMAC 2018 conferences for useful comments on the preliminary version of this work. In this work we used only the free and open-source softwares Latex, Audacity and OCTAVE.

References

- [1] W.W.L. Au and M.C. Hastings. Principles of marine bioacoustics. Springer, 2008.
- [2] Frédéric Berthommier and Hervé Glotin. A measure of speech and pitch reliability from voicing. In Proc. Int. Joint Conf. on Artificial Intelligence (IJCAI), number EPFL-CONF-82549, pages 61–70. Scandinavian AI Society, 1999.
- [3] Susannah Buchan, Rodrigo Huckle-Gaete, Luke Rendell, and Kathleen Stafford. A new song recorded from blue whales in the corcovado gulf, southern chile, and an acoustic link to the eastern tropical pacific. *Endangered Species Research*, 23:241–252, 2014.
- [4] Susannah Buchan, Kathleen Stafford, and Rodrigo Huckle-Gaete. Seasonal occurrence of southeast pacific blue whale songs in southern chile and the eastern tropical pacific. *Marine Mammal Science*, 31(2):440–458, 2015.
- [5] W.C. Cummings and P.O. Thompson. Underwater sounds from the blue whale, *balaenoptera musculus*. *Journal of the Acoustical Society of America*, (50):1193–1198, 1971.
- [6] John W. Eaton, David Bateman, and Soren Hauberg. GNU Octave version 3.0.1 manual: a high-level interactive language for numerical computations. CreateSpace Independent Publishing Platform, 2009. ISBN 1441413006.
- [7] A.N. Gavrilov, R.D. McCauley, and J. Gedamke. Steady inter and intra-annual decrease in the vocalization frequency of antarctic blue whales. *J. Acoust. Soc. Am.*, 131(6):4476–4480, June 2012.
- [8] A.N. Gavrilov, R.D. McCauley, C. Salgado-Kent, J. Tripovitch, and C. Burton Wester. Vocal characteristics of pygmy blue whales and their change over time. . *Acoust. Soc. Am.* 130 (6), December 2011, 130(6):3651–3660, December 2011.
- [9] M.D. Hoffman, N. Garfield, and R.W. Bland. Frequency synchronization of blue whale calls near pioneer seamount. *The Journal of the Acoustical Society of America*, 128(1):490–494, 2010. doi:10.1121/1.3446099.
- [10] E. Leroy. Surveillance acoustique des baleines bleues Antarctique dans l’océan Indien austral : traitement, analyse et interprétation. *PhD thesis, Université de Bretagne occidentale*, 2017a.
- [11] E. C. Leroy, F. Samaran, J. Bonnel, and J.-Y. Royer. Identification of two potential whale calls in the southern indian ocean, and their geographic and seasonal occurrence. *The Journal of the Acoustical Society of America*, 142:1413–1427, 2017b.
- [12] E.C. Leroy, F. Samaran, J. Bonnel, and J-Y. Royer. Seasonal and diel vocalization patterns of antarctic blue whale (*balaenoptera musculus intermedia*) in the southern indian ocean: A multi-year and multi-site study. *PLoS ONE* 11(11): e0163587. doi:10.1371/journal.pone.0163587, 2016.
- [13] M.A. McDonald, J.A. Hildebrand, and S.Mesnick. Worldwide decline in tonal frequencies of blue whale songs. *Endangered species research*, 9:13–21, 2009.
- [14] M.A. McDonald, S.L. Mesnik, and J.A. Hildebrand. Biogeographic characterisation of blue whale song worldwide: using song to identify populations. *J. Cetacean Res. Manage.*, 2006.
- [15] D.K. Mellinger and C. W. Clark. Methods for automatic detection of mysticete sounds. *Marine and Freshwater Behaviour and Physiology*, 29: 1-4:163–181, 1997.
- [16] J.L. Miskis-Olds and S. Nieuwkerk. Relating the decreasing frequency of sri lankan pygmy blue whale calls to the local soundscape. *The Journal of the Acoustical Society of America*, 139, 2016.

- [17] B. S. Miller, K. Collins, J. Barlow, S. Calderan, R. Leaper, M. McDonald, P. Ensor, P.A. Olson, C. Olavarria, and M.C. Double. Blue whale vocalizations recorded around new zealand : 1964-2013. *J. Acoust. Soc. Am.*, 135(3):1616–1623, March 2014a.
- [18] B.S. Miller, R. Leaper, S. Calderan, and J. Gedamke. Red shift, blue shift : Doppler shifts and seasonal variation in the tonality of antarctic blue whale song. *PLoS ONE* 9(9): e107740. doi:10.1371/journal.pone.0107740, 2014b.
- [19] J.L. Morano, D.P. Salisbury, A.N. Rice, K.L. Conklin, K.L. Falk, and C.W. Clark. Seasonal and geographical patterns of fin whale song in the western north atlantic ocean. *J. Acoust. Soc. Am.*, 132(2):1207–1212, 2012. <http://dx.doi.org/10.1121/1.4730890>.
- [20] Erin M. Oleson, John Calambokidis, William C. Burgess, Mark A. McDonald, Carrie A. LeDuc, and John A. Hildebrand. Behavioral context of call production by eastern north pacific blue whales. *Mar Ecol Prog Ser*, 330:269–284, 2007.
- [21] J. Patris, F. Malige, H. Glotin, M. Asch, and S.J. Buchan. A case study of biological pulsed sound : the blue whale’s southeast pacific song unit, models and properties. submitted to *JASA*, 2019.
- [22] Julie Patris, Franck Malige, and Hervé Glotin. Construction et mise en place d’un système fixe d’enregistrement à large bande pour les cétacés “bombyx 2” isla de chañaral, été austral 2017. Technical Report 2017-03, *LSIS CNRS*, march 2017.
- [23] M.R. Saddler, A. Bocconcelli, L. S. Hickmott, G. Chiang, R. Landea-Briones, P. A. Bahamonde, G. Howes, P. S. Segre, and L. S. Sayigh. Characterizing chilean blue whale vocalizations with dtags : a test of using tag accelerometers for caller identification. *Journal of Experimental Biology*, 220:4119–4129, 2017. doi:10.1242/jeb.151498.
- [24] F.W. Shabangu, K.M. Stafford, K.P. Findlay, S. Rankin, D. Ljungblad, Y. Tsuda, L. Morse, C.W. Clark, H. Kato, and P. Ensor. Overview of the iwc sower cruise circumpolar acoustic survey data and analyses of antarctic blue whale calls within the dataset. Unpublished, 2018.
- [25] Kathleen M. Stafford, Sharon L. Nieukirk, and Christopher G. Fox. Low-frequency whale sounds recorded on hydrophones moored in the eastern tropical pacific. *J. Acoust. Soc. Am.*, 106(6):3687–3698, 1999.
- [26] A. M. Thode, S. B. Blackwell, A. S. Conrad, K. H. Kim, and A. M. Macrander. Decadal-scale frequency shift of migrating bowhead whale calls in the shallow beaufort sea. *J. Acoust. Soc. Am.*, 142(3), September 2017.
- [27] A. Širović, E.M. Oleson, J. Buccowich, A. Rice, and A. R. Bayless. Fin whale song variability in southern california and the gulf of california. *Scientific reports*, 7, 2017. DOI:10.1038/s41598-017-09979-4.
- [28] R. Ward, A.N. Gavrilov, and R. McCauley. “spot” call: A common sound from an unidentified great whale in australian temperate waters. *J. Acoust. Soc. Am. Express Letters*, 142, 2017. <http://dx.doi.org/10.1121/1.4998608>.
- [29] M. J. Weirathmueller, K. M. Stafford, W. S. D. Wilcock, R. S. Hilmo, R. P. Dziak, and A. M. Trehu. Spatial and temporal trends in fin whale vocalizations recorded in the ne pacific ocean between 2003-2013. *PLOS ONE*, 12(10), 2017. <https://doi.org/10.1371/journal.pone.018612>.
- [30] J.D. Wise, J.R. Caprio, and T.W. Parks. Maximum likelihood pitch estimation. In *IEEE, editor, Transactions on acoustics, speech and signal processing, volume ASSP-24*, 1976.