Steady inter and intra-annual decrease in the vocalization frequency of Antarctic blue whales

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Time averaged narrow-band noise near 27 Hz produced by vocalizations of many distant Antarctic blue whales intensifies seasonally from early February to late October in the ocean off Australia's South West. Spectral characteristics of long term patterns in this noise band were analyzed using ambient noise data collected at the Comprehensive Nuclear-Test-Ban Treaty hydroacoustic station off Cape Leeuwin, Western Australia over 2002–2010. Within 7 day averaged noise spectra derived from 4096-point FFT (~0.06 Hz frequency resolution), the −3-dB width of the spectral peak from the upper tone of Antarctic blue whale vocalization was about 0.5 Hz. The spectral frequency peak of this tonal call was regularly but not gradually decreasing over the 9 years of observation from ~27.7 Hz in 2002 to ~26.6 Hz in 2010. The average frequency peak steadily decreased at a greater rate within a season at 0.4–0.5 Hz/season but then in the next year recovered to approximately the mean value of the previous season. A regression analysis showed that the interannual decrease rate of the peak frequency of the upper tonal call was 0.135 ± 0.003 Hz/year over 2002–2010 ($R^2 \approx 0.99$). Possible causes of such a decline in the whale vocalization frequency are considered.
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I. INTRODUCTION

Antarctic blue whales (*Balaenoptera musculus intermedia*), often referred to as true blue whales, reside primarily in the Southern Ocean and can also be found in some parts of the Indian and Pacific Oceans. These giant animals tend to stay on feeding grounds along the Antarctic coast in both Western and Eastern Antarctica during the austral summer and autumn months and migrate northward as the Antarctic sea ice grows in winter (Branch *et al.*, 2007). The migration routes and seasonal patterns of Antarctic blue whales are poorly known, though the ability of underwater sound to propagate over large ranges in the ocean and advances in the technology behind the collection of underwater noise data have vastly increased the ability to study these animals. For example, Antarctic blue whales have been acoustically observed widely throughout Southern Ocean waters in austral summer (e.g., Širovic *et al.*, 2009; Gedamke and Robinson, 2010) and in the southwestern, southeastern and northern Indian Ocean and in the eastern tropical Pacific in austral winter (Samaran *et al.*, 2010; Stafford *et al.*, 2004; McCauley *et al.*, 2004).

Vocal characteristics of Antarctic blue whales have been considered in several publications. Ljungblad *et al.* (1998) identified a so-called "*Z*-shaped" sound with the Antarctic subspecies of blue whales. This type of whale call begins with an 8 to 10 s tone at about 28 Hz followed by a short downsweep to approximately 20 Hz and another tonal sound with the frequency decreasing slowly to about 18 Hz over 6 to 8 s. A variant of this Antarctic blue whale call is frequently observed in Antarctica (Rankin *et al.*, 2005; Gedamke and Robinson, 2010) and in the eastern Pacific and southeastern Indian Oceans (Stafford *et al.*, 2004) consisting only of the first tonal component of the *Z*-shaped sound. The source level of Antarctic blue whale calls measured by Širović *et al.* (2007) off the Western Antarctic Peninsula was 189 ± 3 dB re 1 μPa at 1 m.

Gedamke *et al.* (2007) analyzed the spectrum level of sea noise recorded at the Comprehensive nuclear-Test-Ban Treaty (CTBT) hydroacoustic station off Cape Leeuwin, Western Australia in 2004–2006 and found that numerous remote calls from great whales, such as Antarctic and pygmy blue whales and fin whales, produced a continuous increase of noise in certain low frequency bands. In particular, a narrow band spectral peak in noise around 28 Hz was attributed to vocalizations of Antarctic blue whales. The noise from great whale vocalizations appeared to increase ambient noise yearly during different seasonal periods for different species. The authors suggested using this noise for studying seasonal patterns of whale migration in the Southern Oceans.

Recently McDonald *et al.* (2009) revealed indications of a worldwide decline in the vocalization frequencies of blue whales. The trend is evident for the blue whale subspecies inhabiting the northeast Pacific, where passive acoustic observations have been maintained since the mid 1960s. At present, blue whales of this population make calls at a frequency about 30% lower than 45 years ago. Gavrilov *et al.*

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(2011) observed a steady interannual decrease in the call frequencies of pygmy blue whales of the eastern Indian Ocean population during 2002–2010 by analyzing from several hundred to thousands of whale calls recorded yearly at the Cape Leeuwin CTBT station and the passive acoustic observatories of the Integrated Marine Observing System in Australia. The decrease rate was estimated to be 0.35 ± 0.06 Hz/year for the third harmonic of unit 2 in the whale song theme, which corresponded to about 0.12 Hz/year at the call fundamental frequency of approximately 23 Hz. However, trends in the call frequency shift for the other blue whale subspecies are not that obvious. For example, the call frequency data available for Antarctic blue whales, used by McDonald *et al*. (2009), were collected from 1995 to 2005 and represented only from 1 to 10 animals recorded in different years. The trend observed over these years was not linear and the overall decrease was estimated to be about 1.4 Hz. The statistical sample was not large enough to accurately estimate the trend in the call frequency for the entire population, because the recorded animals could be different in age and size and consequently their calls could have slightly different pitches.

The study presented in this article analyzes continuous narrow band noise that appears seasonally at vocalization frequencies of Antarctic blue whales in sea noise recorded at the Cape Leeuwin CTBT hydroacoustic station in 2002–2010. It is inferred that this noise is formed by many frequent calls from different whales residing within a large area south and, probably, west of Australia. The upper frequency bound of this noise that corresponds to the approximate 28 Hz tonal component of Antarctic blue whale calls can be measured with high resolution. These measurements were used to analyze intra-seasonal variations and interannual trend in the blue whale call frequency, which is discussed in this article.

II. DATA COLLECTION AND PROCESSING

Sea noise data used in this study were recorded over 9 years, from 2002 to 2010, at the Cape Leeuwin CTBT hydroacoustic station deployed at approximately 34°53′S and 114°8′E. This station consists of three hydrophones moored as a triangular array of about 2-km sides. The hydrophones are placed at a depth of 1100 m below the sea surface, i.e., near the axis of the Sound Fixing And Ranging (SOFAR) or deep sound channel, maximizing the ability to receive distantly produced sounds. Sea noise from all three hydrophones is continuously recorded and sampled at a 250 Hz sampling frequency. The receiving channels are calibrated to ensure the accuracy of acoustic pressure measurements of ± 1 dB within the frequency band of 10 to 100 Hz. The seafloor around the station is gently sloping with the sea depth of about 1600 m at the array center. Sea noise data from one hydrophone were used for the analysis presented in this study.

To analyze long-term changes in spectral characteristics of sea noise, a Power Spectrum Density (PSD) was calculated for each 1 h fragment of acoustic recording using 4096-point FFT and a Hanning window with no overlap using custom written MATLAB code. This provided a relatively high frequency resolution of approximately 0.06 Hz with a relatively small variance of about 7% for PSD estimates. Long-term trends in the frequency of blue whale vocalization were estimated using weekly average PSDs, which reduced the effect of short-term variations due to the difference in the call frequency of different whales. PSDs of noise recordings containing intense low frequency signals from underwater earthquakes and ice events in Antarctica (long lasting iceberg sounds and ice breakup noise) were excluded from averaging. The mean vocalization frequency was determined at the PSD maximum in the frequency band from 25 Hz to 30 Hz. This frequency was regarded as the prevalent vocalization frequency.

Individual calls from Antarctic blue whales were automatically detected by searching for tonal signals of 6 to 12 s long at frequencies from 26 Hz to 29 Hz in sea noise spectrograms. Signals from whale calls, which had a signal-to-noise ratio (SNR) of more than 10 dB in a 26 to 29 Hz frequency band, were accepted for further analysis. PSD of individual calls was also calculated using 4096-point FFT applied to a Hanning-windowed signal.

III. RESULTS

A. Individual calls

Between 800 to 1500 individual calls from Antarctic blue whales were detected yearly at the Cape Leeuwin station except for 2004 when only 65 signals from whale calls were received with an SNR of 10 dB or greater. The detected calls were not uniformly distributed across any season, as illustrated in Fig. 1. Similarly sparse distributions were observed in the other years. Based on a constant call repetition interval and gradual changes in the signal amplitude, it is most likely that whale calls detected frequently during several hours on each day of multiple detections have been from one animal in most cases. Consequently, the number of

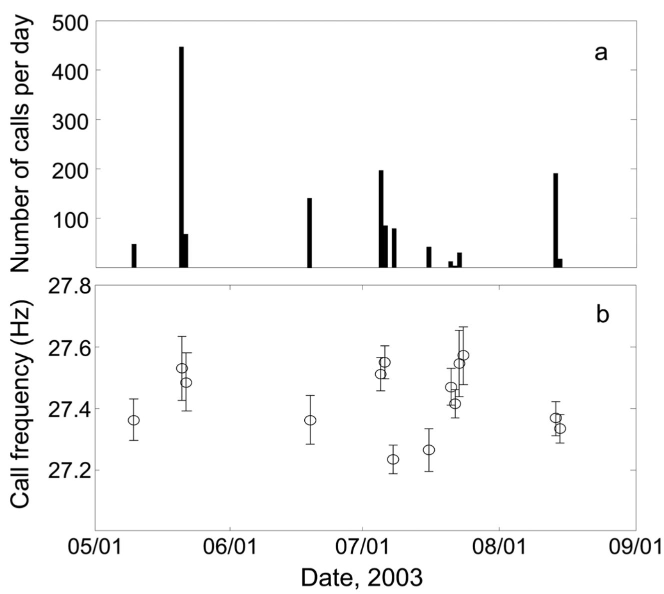

FIG. 1. Number of individual calls from Antarctic blue whales detected daily in 2003 (a) and the mean value and standard deviation of call frequencies detected daily (b). The signal frequency was determined at the PSD maximum in the frequency band from 25 Hz to 30 Hz.

different animals sampled every year was not large. For example, considering the temporal distribution of calls and variations in the call frequency shown in Fig. 1, one can conclude that the total number of animals recorded in 2003 most likely was not greater than 10. The majority of variations in the call frequency of an individual whale were within approximately ±0.1 Hz, which is smaller than or comparable to the difference in the mean vocalization frequency of different animals (bottom panel of Fig. 1). Thus measuring frequencies of individual calls or the mean frequency of calls from one or a few animals is not adequate for assessing potential long-term changes in the vocal characteristics of the whole population.

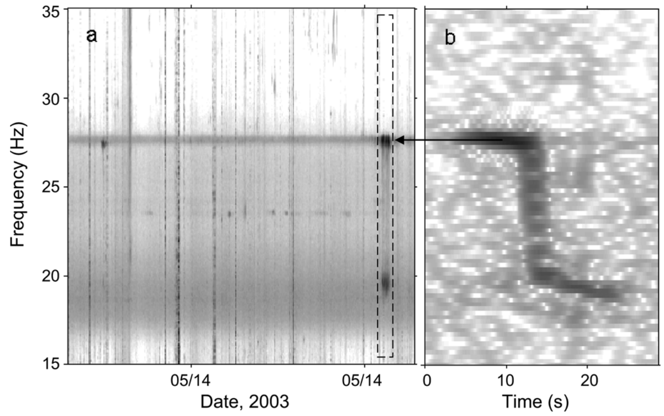

FIG. 3. Variations of the power spectrum density of sea noise during two weeks in 2003 (a) and a spectrogram of one of the calls recorded from an Antarctic blue whale on 22 May (b). The dashed rectangle indicates the time period when nearly 300 individual calls of high intensity were detected.

B. Noise from whale calls

Figure 2 shows long-term variations in the spectral level of sea noise observed at the Cape Leeuwin station in the frequency band from 15 Hz to 30 Hz over 9 years. The narrow band noise at 26–28 Hz is evident every year from early March to late November. This noise is accompanied with a broader band of noise at frequencies from about 17 Hz to 21 Hz. According to Gedamke *et al.* (2007), this low frequency noise is comprised of a combination of fin whale impulsive calls at low frequencies and the second tonal part of the *Z*-shaped sound from Antarctic blue whales. The narrow band noise at about 28 Hz corresponds to the vocalization frequency of Antarctic blue whales as illustrated in Fig. 3.

The frequency of the spectral peak in noise produced by Antarctic blue whales decreases regularly over years, as clearly seen in Fig. 2. To assess this decrease in a more accurate way, the weekly average PSD of sea noise was compared in Fig. 4 for the same week (week 21 from 21 to 27 May) in different years, when the level of noise from whale vocalizations was high. A frequency shift by about 1 Hz, from 27.7 Hz in 2002 to 26.6 Hz in 2010, is evident from this plot. Another important observation from the averaged PSD is that the full width of the noise frequency band is as narrow as approximately 0.5 Hz at a -3-dB level, so the overall change over 8 years was distinctly larger than call frequency variation within a short-term period of one week.

In contrast to individual calls from Antarctic blue whales detected at the Cape Leeuwin station, the narrow band noise produced by vocalizations of many remote Antarctic blue whales was nearly persistent over the whole period from February to October every year. This allowed us to analyze changes in the whale vocalization frequency over each season in addition to interannual changes. Variations in the prevalent vocalization frequency of Antarctic blue whales measured from 5 March (first day of week 9) to 4 November (last day of week 43) over the 9 years of observation are shown in the top panel of Fig. 5. The plot reveals a gradual decrease of the prevalent vocalization frequency during each season of the whale presence in the area in addition to a steady decline over years.

To estimate the interannual trend, a regression analysis was applied to the samples of the prevalent vocalization frequency taken from week 21 in each year (small circles in the top panel of Fig. 5). It resulted in a decrease rate of 0.135 Hz/year, demonstrated by the dashed line in Fig. 5,

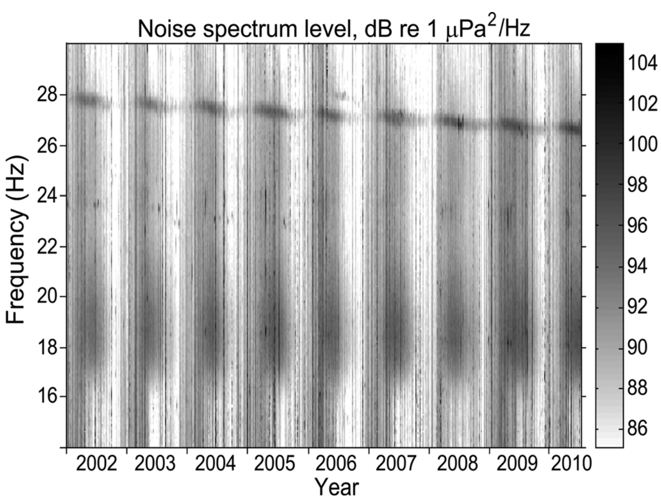

FIG. 2. Variations of the power spectrum density of sea noise in a frequency band from 15 Hz to 30 Hz recorded at the Cape Leeuwin CTBT hydroacoustic station in 2002–2010.

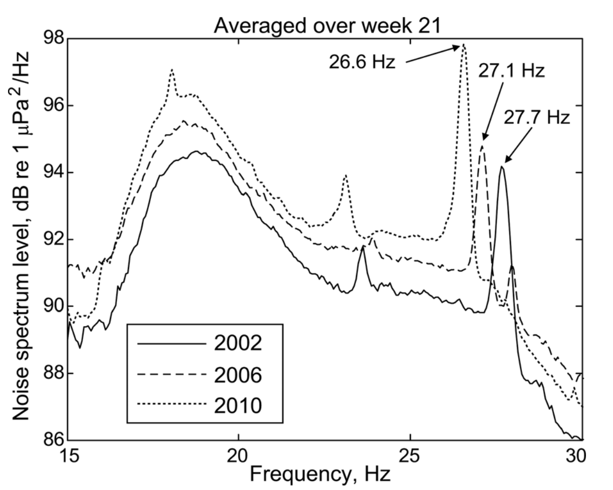

FIG. 4. Power spectrum density of sea noise averaged over 7 days during week 21 (21 to 27 of May) in 2002, 2006, and 2010. The sharp spectral peaks correspond to the tonal component of Antarctic blue whale calls.

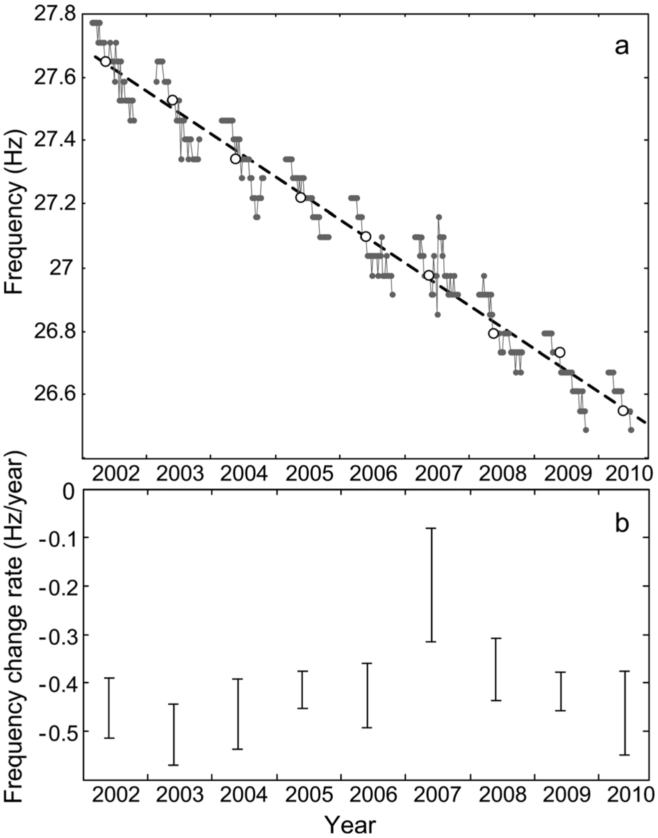

FIG. 5. (a) Variations of the prevalent vocalization frequency of Antarctic blue whales observed in 2002–2010 (dots). The vocalization frequency was determined from the PSD of sea noise averaged for each week of observation. The small circles are the vocalization frequency measured in week 21 and the dashed line shows the best linear fit to their values. (b) Estimates of the linear decrease rate of the call frequency in each season and their 95% confidence intervals.

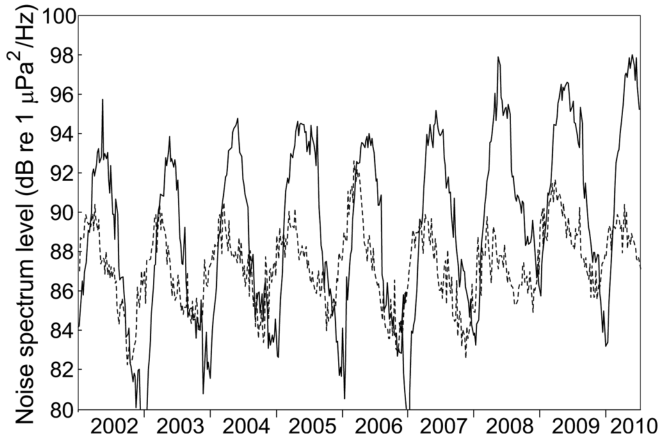

FIG. 6. Variations in the maximum spectrum level of noise in a frequency band from 26 to 28 Hz containing acoustic energy from blue whale vocalization (solid line) corrected for the PSD of ambient noise averaged in a frequency band from 28 to 30 Hz (its level shown by the dashed line), showing seasonal changes in the noise intensity from blue whale calls. The noise spectrum levels were estimated from weekly average PSDs of ambient noise.

with a 95% confidence interval of 0.003 Hz/year (R^2 statistics value of approximately 0.99 and *t*-statistics *p*-value less than 0.001 at $n = 7$ degrees of freedom). The intra-seasonal trends were also estimated using the regression analysis. The linear decrease rate of the vocalization frequency with its 95% confidence interval is shown for each year in the bottom panel of Fig. 5. The decrease rate of about 0.4–0.5 Hz/year was similar in different years and the estimation errors were relatively small ($R^2 > 0.8$ and p-values < 0.001 at $n = 34$) except for 2007 when fluctuations were considerably larger resulting in a noticeably larger error ($R^2 \approx 0.26$ and p-value ≈ 0.002 at $n = 34$).

Another important observation from these measurements is that the prevalent vocalization frequency at the beginning of each season recovers to approximately the mean value of the previous season and then decreases gradually to a value that is noticeably lower than the vocalization frequency at the end of the previous season.

It is also interesting to consider how the level of noise from Antarctic blue whale calls was changing within seasons and over years. To estimate the noise level only from whale calls, it is necessary to take into account the contribution of ambient noise in the same frequency band and its temporal variations. To make such correction, one can assume that the ambient noise level at adjacent frequencies is similar to that at the call frequency. The solid line in Fig. 6 shows variations in the peak level of weekly average PSDs in a frequency band from 26 to 28 Hz, which spans the whale call frequency with its variations, corrected for the PSD of ambient noise averaged in an adjacent frequency band from 28 to 30 Hz, which does not contain acoustic energy from whale vocalization. The spectral level of ambient noise at the whale vocalization frequency reveals an obvious seasonal component that has the maximum of 90–92 dB re 1 μPa^2/Hz in late March to early April and the minimum of 82–85 dB in late October to early November. The level of noise from whale calls noticeably exceeds the ambient noise level every year from about early March to September and reaches its maximum from mid to late May. Although a slight increase in the maximum noise level from whale calls can be noticed in 2006–2010, there is as yet no clear evidence of any significant interannual trend that could be determined in this time series of 9 years.

IV. CONCLUDING REMARKS

The analysis of narrow-band noise from Antarctic blue whale vocalizations reveals that their prevalent frequency was decreasing in 2002–2010 with the rate of -0.135 ± 0.003 Hz per year. This interannual decrease is slightly slower than that estimated from the measurements by McDonald *et al.* (2009) who found a frequency decline from 28.5 Hz in 1995 to 26.9 Hz in 2005 using recordings of calls from individual blue whales of the northeast Pacific population. In contrast to the analysis of individual whale calls, the approach implemented in this study was based on measuring the frequency of the maximum intensity of noise produced simultaneously by calls from many remote whales. In essence, this much broader survey of the population permitted us to more closely examine and determine population level changes in vocalization characteristics than extrapolating from calls recorded from a few individual whales. This approach allowed us to detect a gradual decrease in the call frequency within each season in addition to an obvious interannual trend. The rate of the intra-seasonal frequency decrease varied mainly within 0.3–0.5 Hz/year and was considerably higher than that of the average interannual shift. The whale population reset the mean call frequency at the beginning of each season to about the mean value in the middle of the previous season and then reduced it gradually to a value that was noticeably lower than the minimum frequency in the previous season.

The combined intra-seasonal and interannual pattern of these trends is particularly informative when considering possible causes and mechanism behind this change. If considered in isolation, each of these patterns could lead to different hypotheses as to why it is occurring. For example, McDonald *et al.* (2009) discussed a number of hypotheses that could potentially explain the long-term interannual decline and suggested an increasing population density to be the most likely cause of the observed trend. On the other hand, the pattern of a more rapid intra-seasonal decline with a partial frequency reset at the beginning of each subsequent season further indicates that some other underlying mechanism is likely to be at work. A gradual decrease in the mean vocalization depth discussed in Gavrilov *et al.* (2011) as one of possible causes of frequency change could potentially explain the intra-seasonal decrease with the annual reset, if considered in isolation from the long-term interannual trend. Slight changes in the dive behavior over the length of each breeding season could be due various factors, such as variations in the water temperature or change in the blubber mass resulting in the diving depth. However, when considering the steady and long-term interannual trend, such a consistent change in the dive behavior does not have any reasonable justification or validation by direct measurements. There are no obvious reasons which would make blue whales produce their calls at depths decreasing over years, apart from some form of change in whale singing behavior.

Although a simplistic sound production model of blue whales has been suggested by Aroyan *et al.* (2000), a better understanding of the physics of their vocal system and potential impacts of external factors, such as the water temperature, vocalization depth, etc., might help explain short-term fluctuations and long-term trends in the vocal characteristics of blue whales.

If the frequency decline we described here is simply a longer term evolution [e.g., compared to more rapidly changing humpback whale song discussed in Noad *et al.* (2000)] of the Antarctic blue whale song consisting of repetitive calls, the structural components of individual calls could also be changing. The lower frequency component of the *Z*-shaped calls around 20 Hz may be becoming less prevalent over the years as its frequency decreases, leading to the increased prevalence of the one-component tonal calls at about 27 Hz. As the 27 Hz component drops further in frequency, it will be interesting to see if a new higher frequency component is eventually introduced.

Finally, the intensity of noise produced by many remote blue whales during the same time period of their maximum presence in different years may serve as an indicator of the population size migrating in astral winter from Antarctica to temperate waters. Some interannual variations were observed in the data collected from 2002 to 2010 and some trends may be contained within the data. However, with this approach, the time series is not long enough to unambiguously detect any interannual trend in the noise intensity and, consequently, in the population size.

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