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Nonlinear features in whistles produced by the short-beaked common dolphin (*Delphinus delphis*) off southeastern Brazil

Luciana Duarte de Figueiredo,[1,a)] Israel Maciel,[2] ![ORCID] Flavio M. Viola,[3] Marcelo A. Savi,[3] and Sheila M. Simão[4]

[1]*Federal Institute of Rio de Janeiro, Rio de Janeiro, Brazil*

[2]*Department of Ecology, State University of Rio de Janeiro, Rio de Janeiro, Brazil*

[3]*Center for Nonlinear Mechanics, COPPE—Mechanical Engineering, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil*

[4]*Department of Environmental Science, Federal Rural University of Rio de Janeiro, Rio de Janeiro, Brazil*

ABSTRACT:

Animal vocalizations have nonlinear characteristics responsible for features such as subharmonics, frequency jumps, biphonation, and deterministic chaos. This study describes the whistle repertoire of a short-beaked common dolphin (*Delphinus delphis*) group at Brazilian coast and quantifies the nonlinear features of these whistles. Dolphins were recorded for a total of 67 min around Cabo Frio, Brazil. We identify 10 basic categories of whistle, with 75 different types, classified according to their contour shape. Most (45) of these 75 types had not been reported previously for the species. The duration of the whistles ranged from 0.04 to 3.67 s, with frequencies of 3.05–29.75 kHz. Overall, the whistle repertoire presented here has one of the widest frequency ranges and greatest level of frequency modulation recorded in any study of *D. delphis*. All the nonlinear features sought during the study were confirmed, with at least one feature occurring in 38.4% of the whistles. The frequency jump was the most common feature (29.75% of the whistles) and the nonlinear time series analyses confirmed the deterministic chaos in the chaotic-like segments. These results indicate that nonlinearities are a relevant characteristic of these whistles, and that are important in acoustic communication. © *2023 Acoustical Society of America*. https://doi.org/10.1121/10.0017883

I. INTRODUCTION

The common dolphin (genus *Delphinus*) is widely distributed in tropical and temperate waters (Perrin, 2018). Currently, genetic studies classified all populations of the common dolphin as one species with four recognized subspecies throughout the species' range: the common dolphin (*D. d. delphis*); eastern north Pacific long-beaked common dolphin (*D. d. bairdii*); the Black Sea common dolphin (*D. d. ponticus*); and the Indo-Pacific common dolphin (*D. d. tropicalis*) (Cunha *et al.*, 2015; Committee on Taxonomy, 2021).

The earliest descriptions of the acoustic repertoire of the common dolphin were compiled in the 1960s based on recordings obtained from both captive animals in California and free-ranging Mediterranean groups. However, these first studies do not provide any frequency or time data except for the patterns observed in the spectrograms (Caldwell and Caldwell, 1968). The first studies based on the quantitative and qualitative analyses of the repertoire of *D. delphis* emerged in the 1990s (Moore and Ridgway, 1995; Oswald 2003; Ansmann *et al.*, 2007; Petrella *et al.*, 2012; Papale *et al.*, 2014; Azzolin *et al.*, 2021; Pagliani *et al.*, 2022). The common dolphin presents a varied repertoire of whistles and some features are possible signature whistles (Ansmann *et al.*, 2007; Petrella *et al.*, 2012; Fearey *et al.*, 2019) that may transmit individual identities (Caldwell *et al.*, 1990).

While a number of studies have described the acoustic repertoire of *D. delphis* populations in the Pacific and North Atlantic oceans, little data are available for the South Atlantic Ocean, and the available studies have all focused on the analysis of linear features. It is important to note that some features of these vocalizations cannot be fully explained without taking into account nonlinear phenomena (Tyack and Miller, 2002).

Some of the bioacoustics studies conducted over the past 25 years have documented the presence of "nonlinear phenomena" or "nonlinearities" in the sounds emitted by different types of animals [e.g., Fee *et al.* (1998), Feng *et al.* (2009), Benko and Perc (2007), and Wilden *et al.* (1998)], including some cetacean species [e.g., Tyson *et al.* (2007), Mercado *et al.* (2010), and Cazau *et al.* (2016)]. The structural features of these nonlinearities may enable or facilitate individual recognition, and transmit information on parameters such as the sex, age, and physical condition of the emitter (Wilden *et al.*, 1998).

Nonlinear phenomena are characterized by the fact that small causes are not related to small effects and therefore, the perturbation of any variable does not produce a proportional change in the behavior of this or other variables, which means that cause-effect ratio is not proportional (Herzel, 1991). As phonation in mammals is produced by coupled vibratory structures (such as vocal folds and lips, air sacs, and the larynx itself) its dynamics are naturally nonlinear (Fitch *et al.*, 2002). The normal phonation of

a)Electronic mail: luciana.figueiredo@ifrj.edu.br

humans and nonhuman primates, for example, is a typical nonlinear behavior of a *stable limit cycle* type, in which the dynamic coupling between the vocal folds synchronizes their vibrations, leading to regular and periodic oscillations (Fitch *et al.*, 2002).

Purely harmonic vocalizations with a fundamental frequency (F0) and harmonics that are multiple integers of this frequency are created by the limit cycle dynamic (supplementary material[1]). A definition of each of these types of nonlinear phenomena can be found in Tyson *et al.* (2007).

Based on the need to expand the database on the acoustic repertoire of *D. delphis*, in particular, its nonlinear features, the present study describes the repertoire of whistles produced by this dolphin in the Cabo Frio region of the state of Rio de Janeiro in southeastern Brazil. The study also quantifies the proportion of whistles with nonlinear characteristics and investigates their chaotic dynamics.

II. METHODS

The area of study is located in the region of Cabo Frio ($22°50'21''$ S, $41°54'37''$ W), off the north coast of Rio de Janeiro state, in southeastern Brazil. The coastline of this region shifts from a predominantly north-south orientation to southwest-northeast, with a steep slope (Dé Leo and Pires-Vanin, 2006). Throughout the year, the waters of the Brazil Current mix with those of the central south Atlantic. This phenomenon is strongly influenced by east/north winds, which generate an upwelling phenomenon that is especially prevalent during the austral spring and summer (Carbonel, 1998). The survey area included depths ranging from 5 to 90 m.

A. Data sampling

Data were collected during four monthly surveys conducted between December 2010 and November 2012 (mean duration of daily surveys = 5.70 h, minimum = 3.25 h, maximum = 8.00 h). The surveys followed irregular routes off the coast of Cabo Frio using a 6.5 m flax boat equipped with a 150-hp engine.

When a dolphin group was sighted, the boat approached to within approximately 50 m to record its size, composition, and the geographic position (Garmin E-Trex Vista CX GPS). Once the dolphins appeared to be habituated to the presence of the boat, the engine was switched off to reduce background noise for the collection of acoustic records. If the dolphins moved away from the boat ($\sim$500 m), the acoustic recording was halted, with a new approach being initiated.

The data were collected using an M-Audio MicroTrack II (sampling rate 96 kHz/24 bit) digital recorder fitted with a C54 hydrophone (Cetacean Research Technology, Inc., Seattle, WA; 0.008 to 100 kHz; -165 dB re 1 V/mPa). The hydrophone was deployed at a depth of approximately 2 m to record the dolphin vocalizations.

B. Data analyses

The sound recordings were analyzed using RAVEN 1.4 (Cornell Laboratory of Ornithology, Ithaca, NY) to digitalize and create spectrograms (Hann, window size = 5.33 ms, 3 dB bandwidth = 270 Hz, overlap coefficient = 50%, DFT = 512 samples). The analyses included only whistles for which the contour shape was defined definitively. A total of 11 acoustic parameters were measured for each whistle: duration, start frequency (SF), end frequency (EF), minimum frequency (MnF), maximum frequency (MxF), mean frequency (average frequency of all point marked along the duration of the whistle), number of inflections, number of harmonics, frequency gradient (calculated as EF $-$ SF/ duration), frequency range (calculated as MxF $-$ MnF), and the number of steps (portion of the signal without frequency modulation). Each whistle was then assigned to a basic schematic type, based on its contour shape, then grouped in basic category, as described previously for this species: constant frequency (C.F.), upsweep, downsweep, convex, concave, and sine [see Ansmann *et al.* (2007)]; prevailing C.F., prevailing up; prevailing down; prevailing convex; prevailing concave, and prevailing sine [see Petrella *et al.* (2012)].

The analyses of the nonlinear features (NLF) of the whistles was based on the approach established by Riede *et al.* (2004), Mann *et al.* (2006), and Tyson *et al.* (2007). The spectrogram of each whistle was assessed visually to determine whether it represented one of the four types of NLF: frequency jump (FJ), subharmonic (SH), biphonation (BP), or deterministic chaos (DC). As the larynx has a nonlinear dynamics, harmonic vocalizations composed by a fundamental frequency and its harmonics represent nonlinear phenomena (Riede *et al.*, 2004). In the present study, however, these harmonics are compared with all the other types of nonlinear signal. When the presence of an NLF was questionable, a conservative approach was adopted, and the feature was not scored. As it was not possible to identify individuals during the recording of the vocalizations, only sideband (SB) biphonation was scored, given that nonparallel bands may be confused with the simultaneous whistles of two dolphins.

When the segments of deterministic chaos involved no simultaneous emission of any other type of vocalization (whistles or pulsating sounds), time series demonstrating their dynamics were assembled. The four largest series were then selected and used to determine whether these emissions were due to chaotic dynamics or nondeterministic Gaussian noise, following the technique described by Facchini *et al.* (2003), with the analyses being run in the TISEAN software package (Hegger *et al.*, 1999). As the contamination of these time series with noise is unavoidable and represents a factor limiting the analyses of chaotic dynamics (Kantz and Schreiber, 2004), these segments were processed in RAVEN pro 1.4 using a 0–300 Hz band stop filter to reduce the background noise. Both types of time series (the original and the filtered version) were analyzed to detect chaotic dynamics. This comparison can be used to determine whether the

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exclusion of the background noise is sufficient to reduce the contamination of the time series.

A time series is a discrete, numerable set of values related to dynamical system states (Savi, 2017). The analyses of the system dynamics of a time series requires the reconstruction of the phase space. The reconstructed space preserves the system geometric invariants such as the attractor dimension and Lyapunov exponents (Savi, 2017). The Lyapunov exponents are an acceptable tool to quantify and diagnosis chaos (Kantz and Schreiber, 2004).

Phase space reconstruction is performed by the *time delay vector method*, where a time series is employed to reconstruct the phase space using delayed states in such a way that the reconstructed trajectory is expressed as a matrix in which each row is a phase space vector built from the delayed states (Facchini *et al.*, 2003). This procedure needs the definition of the embedding dimension, and the time delay.

The time delay represents the measure of the correlation between two consecutive components of the D_E-dimensional vectors used in the reconstruction of the trajectory, which value corresponds to the first minimum of the average mutual information function (Facchini *et al.*, 2003). The embedding dimension is the minimum dimension at which the reconstructed attractor can be considered totally revealed without overlapping in the reconstructed trajectories (Kantz and Schreiber, 2004). Therefore, D_E can be evaluated using the method of false nearest neighbors (Kennel *et al.*, 1992). As the dimension increases, the number of false neighbors decreases to zero and the first dimension that has no overlapping points is the embedding dimension (Facchini *et al.*, 2003).

The Lyapunov exponents evaluate the sensitive dependence of nearby trajectory, establishing a measure of the chaotic nature of the system. The idea is to monitor the evolution of an N-dimensional object in phase space, which means that there are N exponents, which are referred to as a spectrum of Lyapunov exponents (SLE). A chaotic trajectory has an unstable direction associated with at least one positive exponent. The value of this exponent, which is known as the maximum Lyapunov exponent (MLE), providing a good characterization of its dynamics (Facchini *et al.*, 2003). On this basis, chaotic signals can be identified due to the presence of at least one exponent greater than zero in the SLE (Kantz and Schreiber, 2004).

The nonlinear analyses were developed employing the TISEAN package. The mutual function was used to determine the appropriate time delay of each segment. The D_E of each segment was estimated using the false_nearest function. The SLE was calculated using the method of Sano and Sawada (1985), through the lyap_spec function. The MLE was calculated using the Kantz (1994) method, based on the lyap_k function of the TISEAN package, employing the linear regression taken from the exponential growth region of the curve generated in the analyzis (Kantz and Schreiber, 2004). The accuracy of the TISEAN package to identify segments as deterministic chaos were tested using an electronically generated harmonic sound segment (96 kHz sampling rate) and a known chaotic time series (De Paula *et al.*, 2006).

III. RESULTS

A total of 96 surveys were conducted during the present study, with a total of 525.4 h of sampling effort. Groups of *D. delphis* were observed during three surveys (6.3% of the total), with a total of 10.5 h of direct observation. However, adequate sampling conditions were encountered during only one of these surveys. All recordings were made with good visibility conditions (no rain or fog) and good sea conditions (beaufort 2) that allowed the dolphins to be visually followed during the recording. The recorded group consisted of 50 dolphins, including calves, who were engaged in displacement and foraging during the recordings. At these conditions, 67 min of dolphin vocalizations were recorded. A total of 473 whistles were selected from these recordings for analyses (Table I and supplementary material[1]). The majority of these whistles (71.88%) presents inflections, 49.05% have steps, and 81.13%, harmonics.

Figure 1 presented the contour types of whistles of *D.delphis* identified from Cabo Frio. All six of the basic categories of whistle described by Ansmann *et al.* (2007) from UK waters were observed in the present study, although some of the whistle types described by these authors were not found in the repertoire of the studied group. Similarly, while contours consistent with the six basic categories described by Petrella *et al.* (2012) from New Zealand waters, were also observed in the repertoire, only nine of the 45 types described by these authors were observed here. On the other hand, a total of 54 new whistle contour types were observed and classified in the categories proposed by Petrella *et al.* (2012).

In general, the quantitative parameters of the whistles of the Cabo Frio group were similar to those recorded in other populations. However, the Cabo Frio population has a wider frequency range and more frequency modulation than the dolphins in the Hauraki Golf, Celtic Sea, and the English Channel, although this pattern is less clear in comparison with southern Brazil, the Mediterranean, the Azores and Canary Islands, and the Bay of Biscay (Table II).

TABLE I. Quantitative characterization of the parameters analysed in whistles of *D. delphis*, in the Cabo Frio region (N = 473).

Parameter	Avarage	Minimum	Maximum	SD
Start frequency (kHz)	13.11	3.05	27.80	4.55
End frequency (kHz)	12.82	4.80	23.03	3.95
Minimum frequency (kHz)	8.73	3.05	16.76	1.75
Maximum frequency (kHz)	16.45	4.91	28.04	3.72
Mean frequency (kHz)	12.78	3.98	19.28	2.39
Frequency gradient (kHz/s)	2.34	−39.09	84.75	15.94
Frequency range (kHz)	7.74	0	23.45	3.93
Duration (s)	0.71	0.04	3.67	0.46
Number of inflections	1.1	0	8	1.07
Number of steps	0.7	0	4	0.86
Number of harmonics	1.4	0	5	1.01

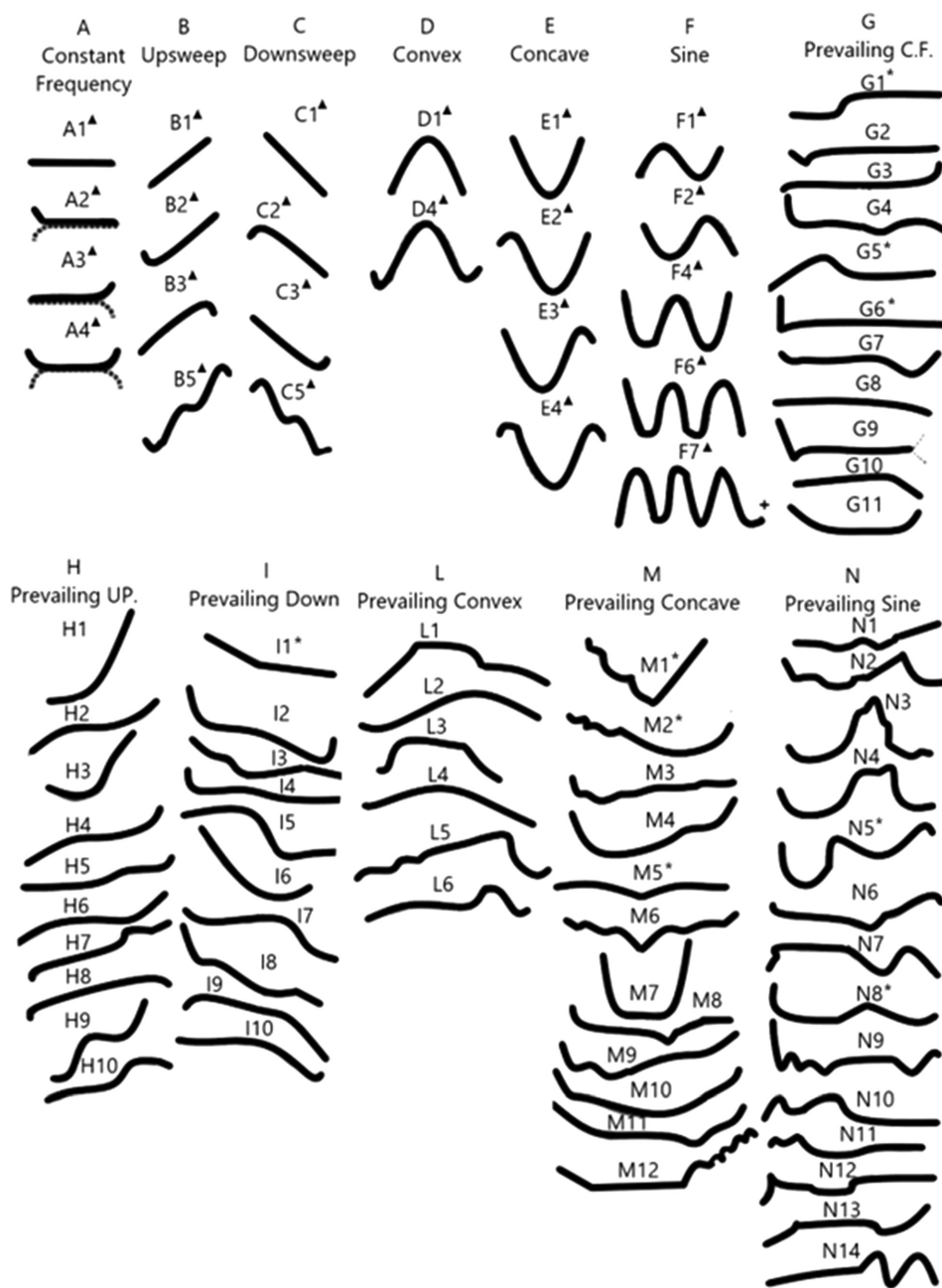2438   J. Acoust. Soc. Am. **153** (4), April 2023

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FIG. 1. Cassification of basic categories and contour types of whistles of *D. delphis* identified in Cabo Frio, south-eastern Brazil. Classification based on Ansmann *et al.* (2007) and Petrella *et al.* (2012). Types marked with triangle were also reported by Ansmann *et al.* (2007) and marked with asterisk were also reported by Petrella *et al.* (2012).

The concave (24.62% of the whistles) and upsweep (22.20%) were the most frequent contours observed in the 473 *D. delphis* whistles analyzed from Cabo Frio, followed by the downsweep (17.76%) and constant frequency contours (15.64%). The convex (9.94%) and sine contours (9.94%) were observed much less often. In all the categories of whistle identified in the present study, those with the lowest frequency modulation (the lowest number of inflection points and steps) were invariably the most frequent.

Nonlinearities were found in 38.4% of the 473 whistles analyzed. All types of nonlinear features were observed in these whistles (Fig. 2), with 9.94% of the whistles including more than one feature. The most frequent nonlinearity observed in the present study was the frequency jump, including both upper and lower frequency jumps, which

occurred in 29.75% of the whistles. Multiple jumps were observed in a single whistle. Sideband-type biphonation was observed in 11.06% of the whistles and deterministic chaos in 4.64%. Subharmonics were observed in only 3.16% of the whistles analyzed.

In general, nonlinearities were widely distributed among the different types of whistles, but in particular, type L1, which presented frequency jumps in all 10 of the samples analyzed. This appears to be a defining feature of this type of whistle. The analyze of the chaotic dynamics of the harmonic sound and the chaotic series presented results consistent with the expected pattern (Table III, Fig. 3, and Fig. 4), which indicates that the employed algorithms (TISEAN package) are able to reliably identify the periodic features of the chaotic dynamics.

TABLE II. Quantitative parameters of whistles of *Delphinus delphis* in Cabo Frio compared to the Hauraki Gulf, New Zealand (Petrella *et al.*, 2012); Celtic Sea and English Channel, United Kingdom (Ansmann *et al.*, 2007); South of Brazil (Pagliani *et al.*, 2022); Mediterranean Sea, Azores, Canary Island and Biscay Bay (Papale *et al.*, 2014).

Parameter	Cabo Frio ($\mu \pm$SD)	Hauraki Golf ($\mu \pm$SD)	Celtic Sea ($\mu \pm$SD)	English Channel ($\mu \pm$SD)	South of Brazil ($\mu \pm$SD)	Mediterranean Sea ($\mu \pm$SD)	Azores, Canary Island, and Biscay Bay ($\mu \pm$SD)
Start frequency (kHz)	13.1 ± 4.6	12.6 ± 4.1	12.0 ± 3.5	12.6 ± 4.0	11.7	11.1 ± 4.3	13.0 ± 5.0
End frequency (kHz)	12.8 ± 4.0	12.3 ± 4.1	12.0 ± 3.3	12.5 ± 4.0	12.1	12.6 ± 3.5	11.8 ± 4.0
Minimum frequency (kHz)	8.7 ± 1.8	11.4 ± 3.9	9.5 ± 2.1	9.8 ± 2.5	10.1	8.2 ± 2.3	8.1 ± 1.8
Maximum frequency (kHz)	16.4 ± 3.7	13.6 ± 4.1	14.7 ± 3.1	15.8 ± 3.3	13.6	15.7 ± 3.0	16.7 ± 3.6
Mean frequency (kHz)	12.8 ± 2.4	12.5 ± 3.8	11.9 ± 2.1	12.7 ± 2.4	—	—	—
Frequency gradient (kHz/s)	2.3 ± 15.9	-0.9 ± 14.4	0.4 ± 9.7	0.5 ± 11.6	—	—	—
Frequency range (kHz)	7.7 ± 3.9	2.2 ± 2.6	5.2 ± 3.3	6.0 ± 3.4	3.5	7.5 ± 3.1	8.6 ± 3.4
Duration (s)	0.7 ± 0.5	0.3 ± 0.3	0.7 ± 0.3	0.6 ± 0.3	0.7	0.85 ± 0.43	1.0 ± 0.4
Number of inflections	1.1 ± 1.1	0.6 ± 0.9	0.6 ± 1.0	0.6 ± 0.9	1.3	2.1 ± 1.7	1.1 ± 1.2
Number of steps	0.7 ± 0.9	0.1 ± 0.4	0.1 ± 0.4	1.1 ± 0.3	—	1.5 ± 2.9	1.8 ± 2.9
Sampling rate	96 kHz	44 kHz	44 kHz	44 kHz	48 and 192 kHz	48 kHz	48 and 192 kHz
N	473	2663	1835	435	2761	193	514

An embedding dimension of 6 was found for all the segments tested (Table III and Figs. 3 and 4), which means that these segments are not purely Gaussian noise, which would present a high immersion dimension on the order of 102 or 103 (Tyson *et al.*, 2007). The SLEs of the whistle segments presented positive exponents (Fig. 5). Nevertheless, the Kantz approach did not confirm this result through the estimation of the MLE, given that exponential growth is not
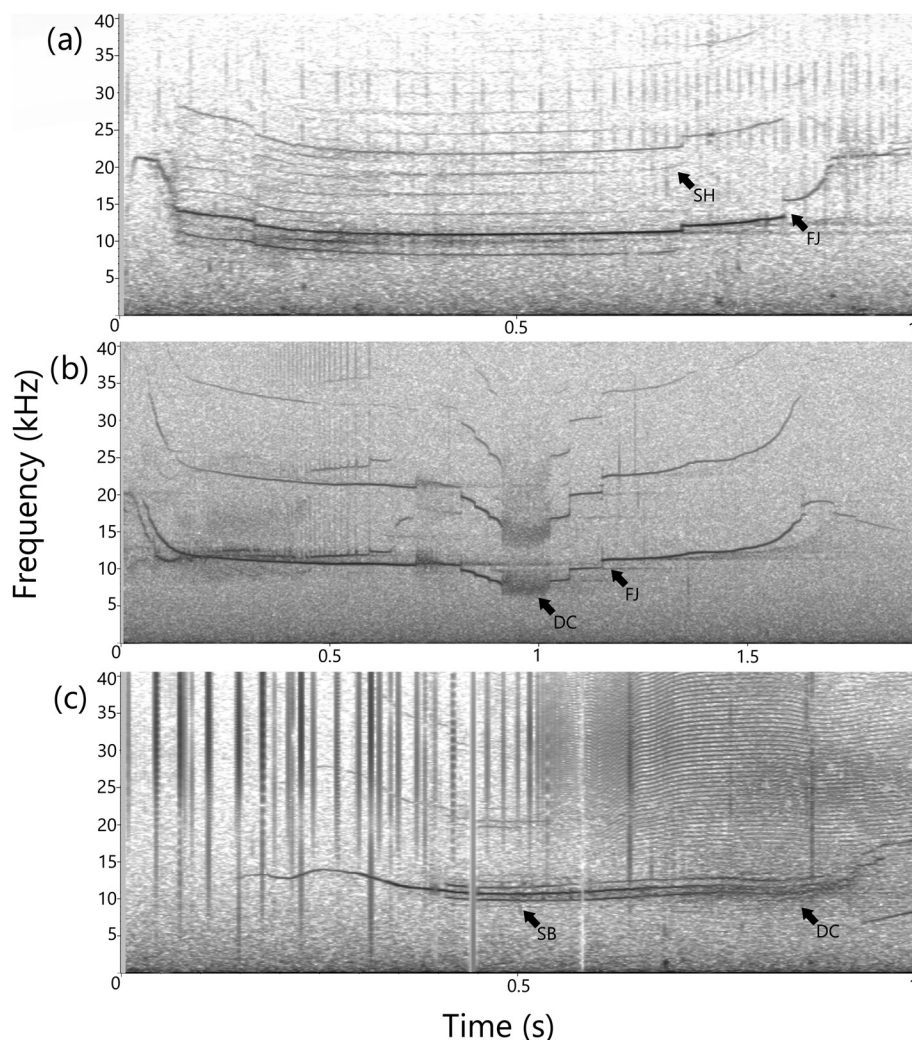

FIG. 2. Spectrograms of *D. delphis* whistles showing non-linear features (indicated by arrows). Frequency jump (FJ) can be seen in whistles (a) and (b); deterministic chaos (DC) can be seen in whistles (b) and (c); Subharmonics (SH) are present in whistle (b); and sidebands (SB) in whistle (c).

TABLE III. Results of the chaotic dynamics analysis for the selected segments in the whistles (wst), the filtered whistles segments, the generated harmonic tone and the chaotic series known.

Analyzed Segment	Delay time	Embedding Dimension	Positive exponent value (SLE)	Maximum Lyapunov exponent (MLE)	Number of points sampled
wst94	6	6	0.048	N/A	12 833
wst 94 filtered	7	6	0.086	N/A	12 833
wst 128	5	6	0.030	N/A	11 594
wst 128 filtered	5	8	1.081	N/A	11 594
wst 151	4	6	0.061	N/A	10 537
wst 151 filtered	4	9	1.281	N/A	10 537
wst 225	6	6	0.033	N/A	16 102
wst 225 filtered	4	10	1.292	N/A	16 102
Harmonic	2	2	0.249	0	96 000
Chaotic	32	3	0.056	0.185	576 001
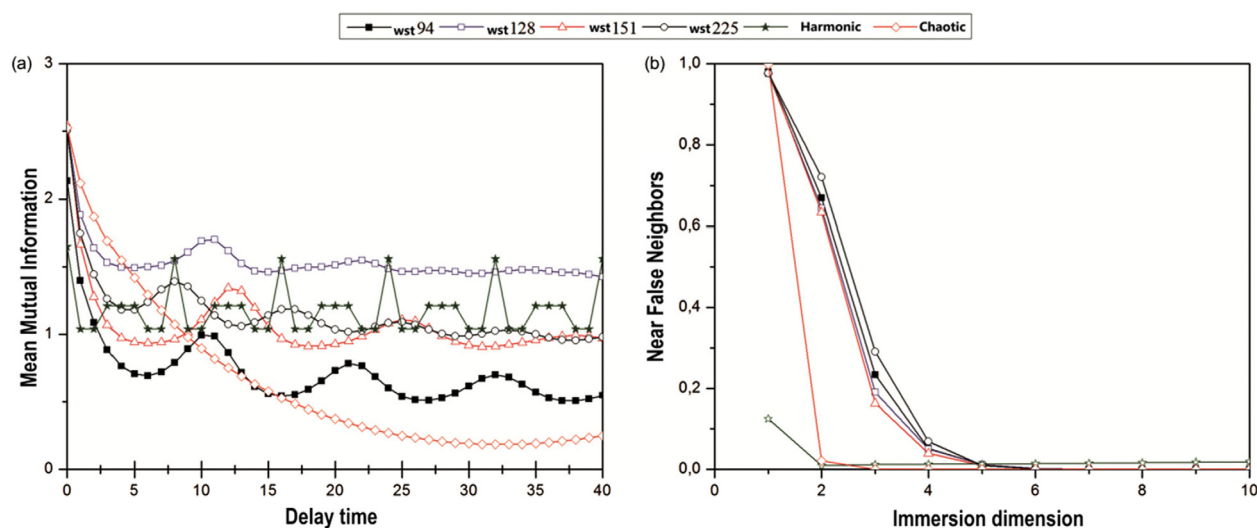
FIG. 3. (Color online) Stages of the attractor reconstruction for the series tested. (a) Analysis of the mean mutual information to determine the lag time. (b) Analysis of the near false neighbors to determine the immersion dimension. Colored lines represent each segment of whistle (wst) tested.
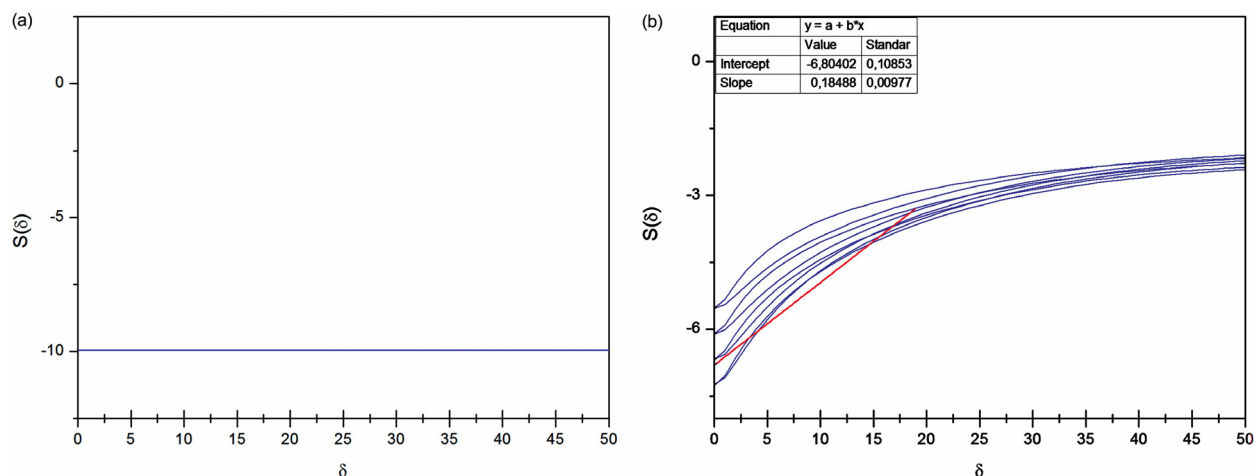

FIG. 4. (Color online) Curves of calculating the maximum Lyapunov exponent (MLE) method by Kantz formed to (a) generated harmonic sound and to (b) known chaotic series. Note in (b) the exponential slope between iterations 0 and 20 that allows the calculation of the MLE through linear regression.
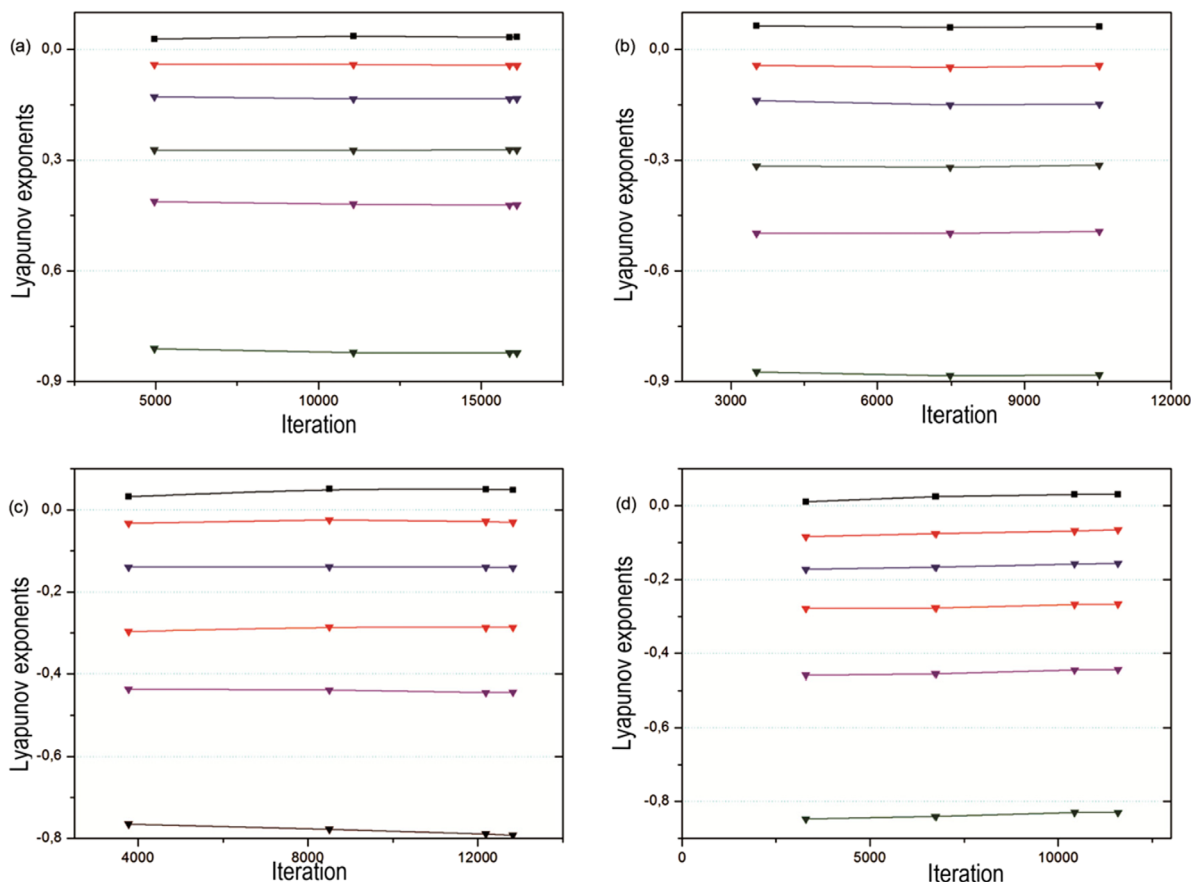
FIG. 5. (Color online) The spectrum of Lyapunov exponents for tested whistle segments. Note presence of a positive exponent in all spectra. Each line represents the segment of the whistles: (a) wst225, (b) wst151, (c) wst94, (d) wst128.

clearly defined (Fig. 6). The analyses of the filtered segments had similar results to those of the unfiltered segments [Table III and Figs. 6(c) and 6(d)], which indicates that the removal of background noise does not interfere noticeably with results.

IV. DISCUSSION

The data presented here represent the first description of the acoustic repertoire of *Delphinus delphis* from southeastern Brazil and the first study to test deterministic chaos on dolphins. Our results indicate a broad repertoire of whistles, with characteristics that differentiate them from the populations previously studied. In general lines, whistles reported here present a higher frequency range, maximum, start, and end frequencies in comparison with whistles recorded off southern Brazil (Pagliani *et al.*, 2022), as well as present a much broader range and a higher frequency modulation when compared with the data published for the Celtic Sea and the English Channel (Ansmann *et al.*, 2007), and the Gulf of Hauraki (Petrella *et al.*, 2012). The relatively higher frequency modulation of the whistles from Cabo Frio is also clear from the comparison of the contours types observed most often on different studies. In Cabo Frio, the concave, convex, and sine contours, which necessarily have inflection points (Fig. 1), contributed 44.4% of the

repertoire, whereas these contour types composed only 18.5% of the repertoire in UK waters and 19.2% in the Gulf of Hauraki.

These results, however, were obtained during a single daily survey; it seems likely that they do not represent the full repertoire of the local *D. delphis* population (Oswald *et al.*, 2003). In addition, the sampling rates used in different studies need to be considered (Table II). Given that 4.9% of the whistles recorded in the present study had a maximum frequency of over 22 kHz, differences in maximum frequency may be biased. On the other hand, higher sampling rates (192 kHz) do not appear to affect this comparison, given that no emission exceeds 30 kHz. Future studies, with a larger sample of this population, are needed to confirm these observed differences.

The present study is the first to analyze the presence of nonlinearities in the whistle repertoire of *D. delphis*. Results indicate that these features are common in the whistles of this species from Cabo Frio. Studies of mammalian vocalizations indicate that these features are consequence of the functional dynamics of the vocal folds, which can be understood as a system of coupled vibratory structures (Wilden *et al.*, 1998; Fitch *et al.*, 2002). Even the simplest of these systems, which have only two vibratory structures, can generate complex patterns of movement that can produce harmonics, sub-harmonics, biphonation, and deterministic
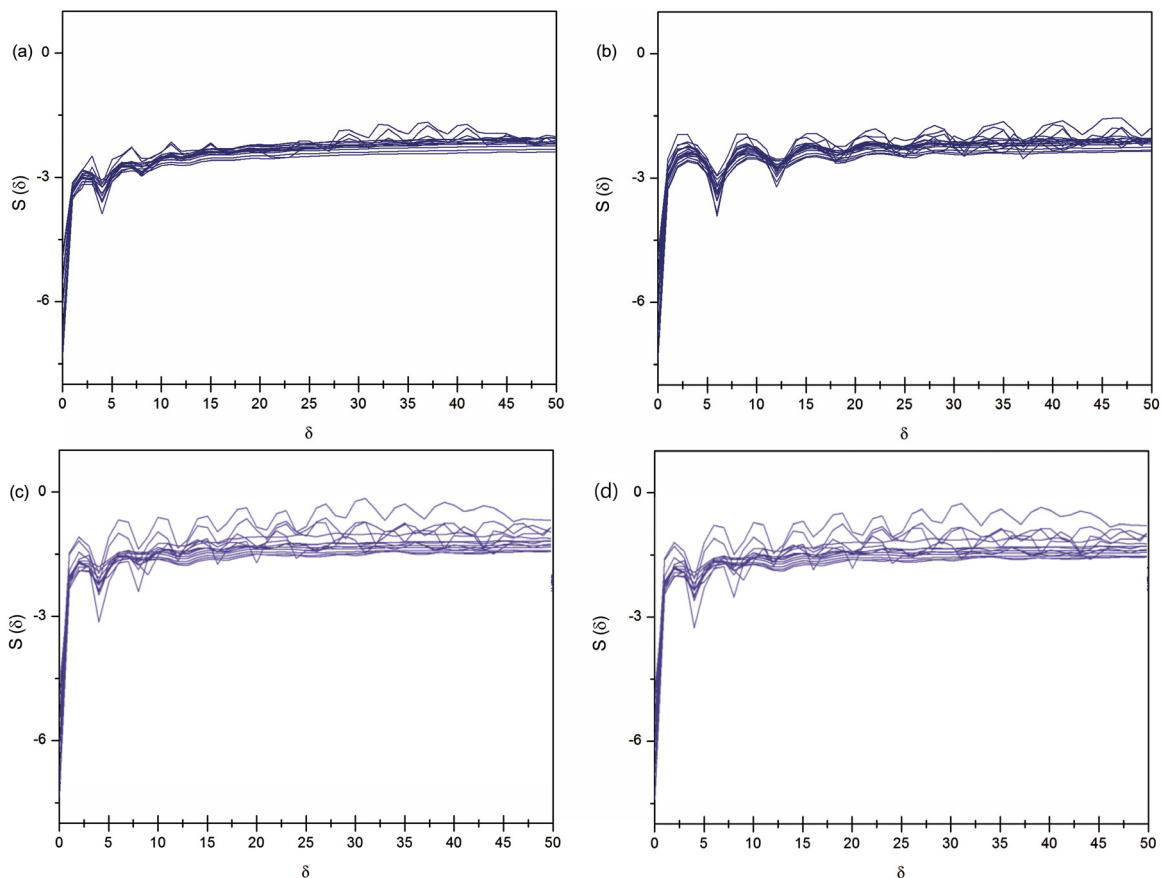
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FIG. 6. (Color online) Curves of calculating the maximum Lyapunov exponent (MLE) by the Kantz method, formed for each tested whistle segment (wst). Note the rapid exponential growth in the first two iterations and the "planning" of the curve after that point. The boxes refer to (a) wst225 (filtered segment), (b) wst151 (filtered segment), (c) wst94filtered (unfiltered segment), (d) wst128filtered (unfiltered segment).

chaos (Fitch *et al.*, 2002). Unlike the other mammals, however, cetaceans do not have vocal folds, and it is unclear which structure generates some kind of sounds, especially in the mysticetes (Au, 2000). The evidence available for the odontocetes indicates that the sound-generating center is a complex formed by two structures, the phonic lips and the dorsal bursae, which is known as the MLDB complex (Cranford, 2000). All the odontocetes, except the sperm whale (*Physeter macrocephalus*), have two MLBD complexes located at the anterior extremity of the left and right nasal passages (Cranford, 2011). Each complex is composed of a pair of phonic lips containing a pair of dorsal bursae (Cranford, 2000). It has been hypothesized that, to generate clicks, air is forced between the phonic lips, making the MLBD complex vibrate, with the rapid opening and closing of the lips interrupting the airflow to create the pulse structure (Cranford, 2000). The two MLBD complexes may be functionally separated, operating either independently or synchronously. Whistles may also be produced by the passage of air through one of the MLDB complexes (Cranford *et al.*, 2011). In this case, whistles may also be generated by the vibration of coupled oscillating structures, which are similar to the vocal folds, and would be intrinsically a nonlinear dynamical system.

Nonlinear features were found in more than a third of the whistles analyzed in the present study. Frequency jumps were the feature observed most often. A predominance of these features has also been recorded in the repertoires of other mammalian species. For example, Riede *et al.* (2004) found that 52% of the climax emissions of the pant-hoot calls produced by common chimpanzees (*Pan troglodytes*) in Uganda had some nonlinear features, with biphonation being the most frequent. In cetacean studies, Tyson *et al.* (2007) investigated possible nonlinearities in the repertoire of orcas (*Orcinus orca*) on the coast of British Columbia (Canada) and the North Atlantic right whale (*Eubalaena glacialis*) off Nova Scotia (Canada). They recorded these features in 92.4% of the *O. orca* vocalizations and 65% of those of *E. glacialis*, with biphonation and sub-harmonic being the most frequent features, respectively (Tyson *et al.*, 2007). However, these authors emphasized that the high proportion of nonlinearities in the orca vocalizations may not be representative, given that they analyzed only high energy vocalizations in which biphonation is more frequent. In humpback whale (*Megaptera novaeangliae*) songs recorded off Madagascar, Cazau *et al.* (2016) observed frequency jumps in 35% of all the detected vocalizations and chaos in 41%, which indicates that they may have a communicative function, although more studies will be necessary to assure, in particular, in combination with behavioral data.

As they are inherent phenomenon of the vocalization dynamics, nonlinear features may not have any adaptive

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role (Fitch *et al.*, 2002), however, some adaptive functions are possible, such as (1) the allowing/facilitating individual recognition (Fitch *et al.*, 2002; Wilden *et al.*, 1998), (2) the communication of data on body size and health, which may influence mating choices or dominance disputes (Fitch *et al.*, 2002; Blumstein *et al.*, 2008; Wilden *et al.*, 1998), (3) mimicking of the tone of the adult vocalization to deceive potential predators (Blumstein *et al.*, 2008), and (4) emphasizing the urgency of the vocalizer, by making sounds harder to be ignored (Fitch *et al.*, 2002; Blumstein *et al.*, 2008).

Few studies have attempted to clarify the function of vocal nonlinearities. Volodina *et al.* (2006) concluded that biphonal emissions increase individual discrimination in the dhole (*Cuon alpinus*). Blumstein and Recapet (2009) reported a shift from a harmonic to a noisy regime in yellow-bellied marmot (*Marmota flaviventris*) alarm calls. Similar to deterministic chaos, this leads to the rapid interruption of foraging and the initiation anti-predator behavior by the marmots (Blumstein and Recapet, 2009). Aubin *et al.* (2000) proposed that biphonation in the emissions of the emperor penguin (*Aptenodytes forsteri*) provides additional features for the recognition of parents and reproductive partners. In amphibians, Feng *et al.* (2009) proposed that nonlinearity in the vocalizations of the frog *Odorrana tormota* plays a role in individual vocal recognition. Filatova *et al.* (2009) concluded that biphonal emissions are emitted by orcas as markers of each pod and matrilineal affiliation and are used mainly to ensure group cohesion.

As the orca vocalizations analyzed by Tyson *et al.* (2007) were primarily of the pulsating emission type, the present study is the first to analyze the proportion of nonlinear features in the whistles of a dolphin species. The significant presence of these features suggests that they may play an important role in the communication of this species. The most common nonlinearity observed in the present study was the frequency jump, which is much rarer in the orca and right whale (Tyson *et al.*, 2007) and other mammalian species [e.g., Riede *et al.* (2004) and Mann *et al.* (2006)]. This may be a characteristic feature of dolphin whistles, given that is the nonlinearity recorded most frequently in the whistle spectrograms published in previous studies of other dolphin species [*Stenela coeroleoalba*: see Fig. 2 in Oswald *et al.* (2004); *Sotalia guianensis*: see Fig. 2 in Rossi-Santos and Podos (2006); *Steno bredanensis*: see Figs. 2 and 3 in Seabra de Lima *et al.* (2012)]. Frequency jumps have also been observed in some of the spectrograms published on the most studied dolphin, the bottlenose (*Tursiops truncatus*)—see Fig. 2 in Cook *et al.* (2004), for example. It is interesting to note that Wang *et al.* (1995) described a parameter of the *T. truncatus* whistle as a "break of contour" which may in fact represent a frequency jump, given the configuration of Fig. 2 in Morisaka *et al.* (2005), who used this same parameter for the whistles of *Tursiops aduncus*. In the genus *Delphinus*, the presence of frequency jumps can be observed in spectrogram B of Fig. 1 in Caldwell and Caldwell (1968). Unfortunately, spectrograms have not been provided in the

more recent studies of the repertoire of the whistles of this genus, such as Ansmann *et al.* (2007), Petrella *et al.* (2012), and Papale *et al.* (2014). As frequency jumps represent oscillatory instability in the phonatory structures (Brown *et al.*, 2003), the predominance of these jumps in dolphin whistles may be related to the fact that this type of vocalization is typically a continuous signal, with a narrow band and modulated frequency, in which case, the emission range may exceed the ultrasound range in many species (Au and Hastings, 2008). Modulation under these conditions of the vibration of the phonatory structures would require much greater control by the animal, which would, in turn, increase the possible occurrence of instabilities.

Other types of nonlinear features can be observed in the whistle spectrograms published for different dolphin species. For example, sidebands can be seen in a *T. truncatus* whistle, in Fig. 3 of dos Santos *et al.* (2005). Subharmonics can be seen in the whistles of *Grampus griseus* [see Fig. 2 in Corkeron and Van Parijs (2001)], *T. truncatus* [Fig. 1 in Kershenbaum *et al.* (2013)], and *S. guianensis* [see Fig. 2 in Figueiredo and Simão (2009)]. It seems that these features are significant component of the structure of dolphin whistles. Further research is needed to detect and quantify the contribution of nonlinear characteristics to the whistles of other dolphin species, to ensure a better understanding of the role they may play in this type of vocalization.

The nonlinear analyses indicate low embedding dimensions (Table III), and the SLE values with one positive exponent in all the analyzed whistles (Table III), which is a characteristic of chaotic dynamics (Kantz and Schreiber, 2004). Therefore, nonlinearity is preponderant when compared with Gaussian noise. The maximum Lyapunov exponent could not be calculated by the Kantz method were not conclusive. This outcome may be related to the sampling rate used on the recordings. On average, the analyzed segments had a fundamental frequency of approximately 9.22 kHz. As all the sounds were recorded at a 96 kHz sampling rate, these segments have around 10 sample points per vibration cycle [see Smith (1997) for a review of digital signal sampling], which may be insufficient for the detection of chaotic dynamics by considering this algorithm (Kantz and Schreiber, 2004). As a matter of fact, the first analysis of the chaotic dynamics of animal vocalization segments involved sounds with a fundamental frequency of 70 Hz and a sampling rate of 22 kHz (Facchini *et al.*, 2003), which produces around 31 sample points per vibration cycle. Another potential problem for this analysis is the unavoidable time series noise contamination from natural surroundings. Au and Hastings (2008) pointed out that the ocean and other bodies of water are quite noisy environments, with sound being generated by a range of different sources. In this regard, time series formed from sound segments tend to be contaminated extensively by noise. Kantz and Schreiber (2004) pointed out that noise is one of the most significant factors limiting the predictability of deterministic systems. In the present study, the filtering of low-frequency background noise was insufficient to eliminate this contamination from

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the segments (see Table III and Fig. 6). High frequency filtering was not attempted because it could have excluded components of the vocalization, given that the frequencies of chaotic segments are scattered over a wide range (Fitch *et al.*, 2002). Therefore, the combination of these two factors, that is, low sampling resolution and strong noise contamination, limits the capacity of some algorithms.

The whistles segments can be considered to be deterministic chaos based on the positive Lyapunov exponent, and for present the same characteristics used for Wilden *et al.* (1998) and Fitch *et al.* (2002) to differentiate this feature from turbulent noise: (a) extremely abrupt changes at both the beginning and the end of the chaotic segment, (b) the existence of some residual harmonic structure within the chaotic episode, (c) the occurrence of periodic windows, i.e., inserted harmonic structures, and (d) the adjacent occurrence of other non-linear features. Some of these characteristics can be observed in the spectrograms in Fig. 4.

Overall, the whistles of *D. delphis* from Cabo Frio have an exceptionally broad frequency range, being more modulated than the whistles recorded in previous studies. The novel contours found in the repertoire of the Cabo Frio group reinforce the wide variability of the acoustic repertoire of this species. Nonlinear features were recorded in a high proportion of the whistles and may play an important role in the acoustic communication of these animals. The nonlinear analyses indicated chaotic dynamics associated with the signal. Some other approaches can be applied to assure the conclusions about the presence of chaos in dolphin whistles. Either Poincaré section or recurrence plots can be employed for this aim. In addition, new acoustic recordings using a higher sampling rate can be employed, which would allow a better resolution of approximately 20 points per cycle of vibration at the mean target frequency of 9 kHz.

[1]See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0017883 for a schematic spectrogram representing the nonlinear vocal phenomena and histograms of acoustic parameter of whistles of *Delphinus delphis*.

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