Chapter 5
Marine Mammal Bioacustics Using Towed Array Systems in the Western South Atlantic Ocean

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Abstract Acoustic technologies have been applied in order to investigate and monitor underwater sound and have promoted achievements on the understanding of animal biology, behavior and ecology. Whales and dolphins produce sounds, which are unique, compared to other sounds in the marine environment. Passive acoustic surveys using a towed hydrophone array have become more accessible and widely used to explore patterns of occurrence, identifying critical habitats for several species of cetaceans and inferring about potential noise impacts over the populations.

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In this chapter we present characterization of acoustic signals produced by nine different cetacean species obtained form acoustic surveys. The species have species-specific qualities in their whistles and clicks. Acoustic methods can also offer population size estimates and identification of population structure.

5.1 Introduction

Acoustic technologies have been applied in order to investigate and monitor underwater sound and have promoted achievements on the understanding of animal biology, behavior and ecology. Due to physical characteristic the sound propagation is favored in the underwater environment and have contributed to evolution of acoustic features of marine life.

Whales and dolphins are top predators and are known to spend all their lives in the aquatic environment. As such, they can be considered sentinels of the ocean since they serve as indicators of the habitat health to which they are part of. Most importantly is that cetaceans produce sounds, which are unique, compared to other sounds in the marine environment.

Passive acoustic surveys have become more accessible and widely used to explore patterns of occurrence, identifying critical habitats (Risch et al. 2014) for several species of cetaceans and inferring about potential noise impacts over the populations (Rice et al. 2014; Pirotta et al. 2015). Acoustic methods can also offer population size estimates that are used to track large-scale displacement patterns (Mellinger and Barlow 2003) and long term population trends (Evans and Hammond 2004; Magera et al. 2013; Campbell et al. 2015).

The recent expansion in bioacoustics research was possible due to the development of available technologies on autonomous acoustic recorders (Passive Acoustic Monitoring – PAM), which can be fixed on the sea floor (e.g. Parks et al. 2007; Cerchio et al. 2001; Darling and Sousa-Lima 2005; Sousa-Lima et al. 2013) or

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which can be towed behind vessels (Jaquet and Whitehead 1999; Whitehead 2002; Watwood et al. 2006; Barlow et al. 2013), allowing to record sounds continuously.

Passive acoustic detection systems have been successfully used on a number of cetacean surveys (Gannier et al. 2002; Barlow and Taylor 2005; Leaper et al. 2003; Hastie et al. 2003; Lewis et al. 2007; Fais et al. 2016). Acoustic monitoring provides an opportunity to collect data in conditions unsuitable for visual observations such as darkness, poor visibility and high sea states (Evans and Hammond 2004; Mellinger et al. 2007; Ward et al. 2012). The use of simple towed hydrophones to monitor cetacean vocalizations enables quantifiable data to be collected at minimal cost (Whitehead 2002).

The implementation of acoustic survey associate to visual effort can maximize the results, knowing that a relative large amount of ship time would be lost due to bad weather or night fall, a passive acoustic towed-array device can increase search effort. Some researchers have demonstrated the advantages of acoustic towed arrays in comparison to visual survey methods specially to detect species that spend most of their time in deep divings, such as beaked whales and sperm whales (Jaquet and Whitehead 1999; Whitehead 2002; Watwood et al. 2006; Barlow et al. 2013; Yack et al. 2013; Schorr et al. 2014). On the other hand, this technique has disadvantages as the need to manage a heavy cable when the moving platform stops, loss of maneuverability of the moving platform, risk of damaging the propellers, requires an experienced crew and is a lengthy process to initiate the survey (Evans and Hammond 2004; Nielsen and Møhl 2006).

This chapter will present a general overview of the equipment which has being used to cetaceans acoustic survey in the Western South Atlantic Ocean. Also, will give a basic bioacoustic analysis introduction and will present a general description of acoustic parameters of different species registered. Recordings were obtained opportunistically from 2012 to 2015 during a survey mostly dedicated to visual monitoring of cetacean occurrence and distribution along the western South Atlantic continental shelf break. Research cruises were performed between 26°S and 38°S over the continental shelf break and slope. Acoustic tracklines comprised an average of 780 nm of effort per survey. Concurrent environmental and GPS data were logged automatically using WinCruz software. Visual positive identifications were associated to the acoustic recordings. The wave files were analyzed using partially automated detections tools complemented with visual and aural searched for species confirmation whenever possible.

5.2 Towed Array Equipment

The system consists of a three-elements hydrophone array (Fig. 5.1) on a cable towed 150–300 m behind the vessel) coupled to a recording system, configured to give a variable frequency response from 499 Hz (High Pass Filter) to 100,000 Hz (Fig. 5.2). This system is mostly used as an additional method to visual surveys commonly applied to marine mammals (Bittle and Duncan 2013), allowing real time or post data analysis. It has being used from different platforms and contexts

Fig. 5.1 Three-element hydrophone array in a 300 m cable. The *black* elements are the hydrophones covered by a polyurethane resin. (Reproduced with permission of Gustavo Miranda)

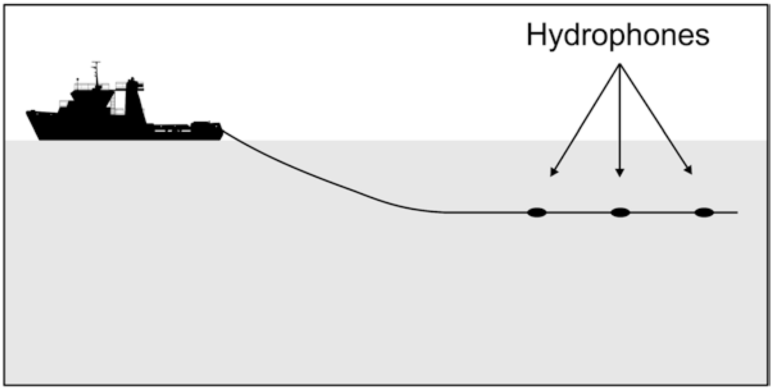

Fig. 5.2 Three-hydrophone array on a cable towed by a moving platform. (Reproduced with permission of Gustavo Miranda)

(e. g. Barlow and Taylor 2005; Lewis et al. 2007; Hastie et al. 2003; Leaper et al. 2003; Moretti et al. 2006; Swift et al. 2009).

Different types of equipment have been used over the years for different purposes. Their characteristics depend on the target species (Evans and Hammond 2004) and specific questions and analysis planned. At least two hydrophones in a linear array are necessary to apply the target motion analysis in order to define a spatial localization (Barlow and Taylor 2005; Lewis et al. 2007, Swift et al. 2009). Usually the recording system is composed by a fanless computer, a data acquisition board for frequencies higher than 192 kHz and an audio interface for frequencies below 192 kHz (Fig. 5.3). The use of a data acquisition board requires a high quality bandpass filter, given that the audio interface provides an anti-aliasing filter. The power supply of the system has to be considered with attention in order to reduce the electrical noise associated with the moving platform, but in some cases may be necessary an independent clean battery power (Rankin and Barlow 2010).

Fig. 5.3 Recording system composed by a fanless computer, a data acquisition board for frequencies higher than 192 kHz and an audio interface for frequencies below than 192 kHz. (Reproduced with permission of Franciele R. de Castro)

Regardless of the number of hydrophones in a linear array the ambiguity is present, because it is not possible to distinguish the side of the signal (Au and Hastings 2008). A greater number of hydrophones would enable the localization of the signal rather than a group of vocalizing individuals (Benda-Beckmann et al. 2013). However, this has been still discussed in the literature, especially considering the possible instability associated to towed systems.

In general the spacing between hydrophones considers the frequencies of vocalizations of the target species. The lower is the frequency, the greater will be the distance between hydrophones (Leaper et al. 1992, 2003; Benda-Beckmann et al. 2013; Gillespie 1997; Barlow and Taylor 1998, 2005; Lewis et al. 2007; Rankin and Barlow 2007; Swift et al. 2009; Gillespie et al. 2010). However, these systems are mostly indicated to species that produces signals above the noise frequency band produced by the moving platform and the flow noise of the cable, e.g. sperm whales (Barlow and Taylor 2005), beaked whales (Gillespie et al. 2010) and harbor porpoise (Sveegaard et al. 2011).

5.3 Basic Bioacoustics Data Analysis

For decades, scientists have been listening to the seas, looking forward to accurately record and understand the nature and purpose of whales and dolphins sound emissions. Marine mammals produce a variety of vocalizations, each of them suited to a particular behavior or situation. Bioacoustics is a cross-disciplinary science that is broadly concerned in understand: animal communication and associated behavior, sound production anatomy and neurophysiology, effects of human-made noise on animals, auditory capacities and auditory mechanisms of animals, effects of human-made noise on animals.

The primordial step in understanding acoustic behavior of a species is to describe the characteristics of a specific emission, with regard to what types of sounds make up the repertoire and what are the acoustical parameters features related to such sounds. Sound emissions by odontocetes can be classified into two broad categories of frequency-varying continuous tonal sounds referred to as whistles and pulsed sounds including broadband clicks including and burst sounds (Evans 1967). Depending on the main objectives of a research, bioacousticians rely on some technologies to make measurements in each broad category. Some examples are given below.

5.3.1 Whistles

The first method consists of visual inspection of spectrograms with a particular emphasis on establishing categories in the shape of the whistle contour. Despite of being very subjective, this method can be useful to determine if a particular contour is unique within the repertoire or whether is a minor variation to another contour. In order to specify a particular category of contour in which a whistle belongs to, we have been using six general broad categories based on the slope of the whistle fundamental frequency and the number of inflection points, defined as a point at which the slope of the contour reverses in direction:

1. Constant frequency: the frequency does not really remain constant over its duration, but has a minimum amount of frequency change (Fig. 5.4a).
2. Upsweep or ascending: the frequency is modulated with the instantaneous frequency increasing over duration and do not have any marked inflection points (Fig. 5.4b).
3. Downsweep or descending: – the frequency is modulated with the instantaneous frequency decreasing over duration and do not have any marked inflection points (Fig. 5.4c).
4. Concave or ascending-descending: the frequency modulated with the instantaneous frequency initially increasing with time, followed by an inflection point and an ending with the frequency decreasing over duration (Fig. 5.4d).
5. Convex or descending-ascending: the frequency is modulated with the instantaneous frequency initially decreasing with time, followed by an inflection point and an ending with the frequency increasing over duration (Fig. 5.4e).
6. Sinusoidal or multiple: the frequency is modulated with more than one repetition of a hill or a valley and the contour appearing somewhat like a sinusoidal signal with at least two inflection points (Fig. 5.4f).

A more quantitative method involves extract various parameters of the fundamental frequency directly from the spectrogram: beginning (starting) frequency, ending frequency, minimum frequency, maximum frequency, delta frequency, peak frequency, center frequency, duration, number of inflection points, number or presence of break in contour and number or presence of harmonics.

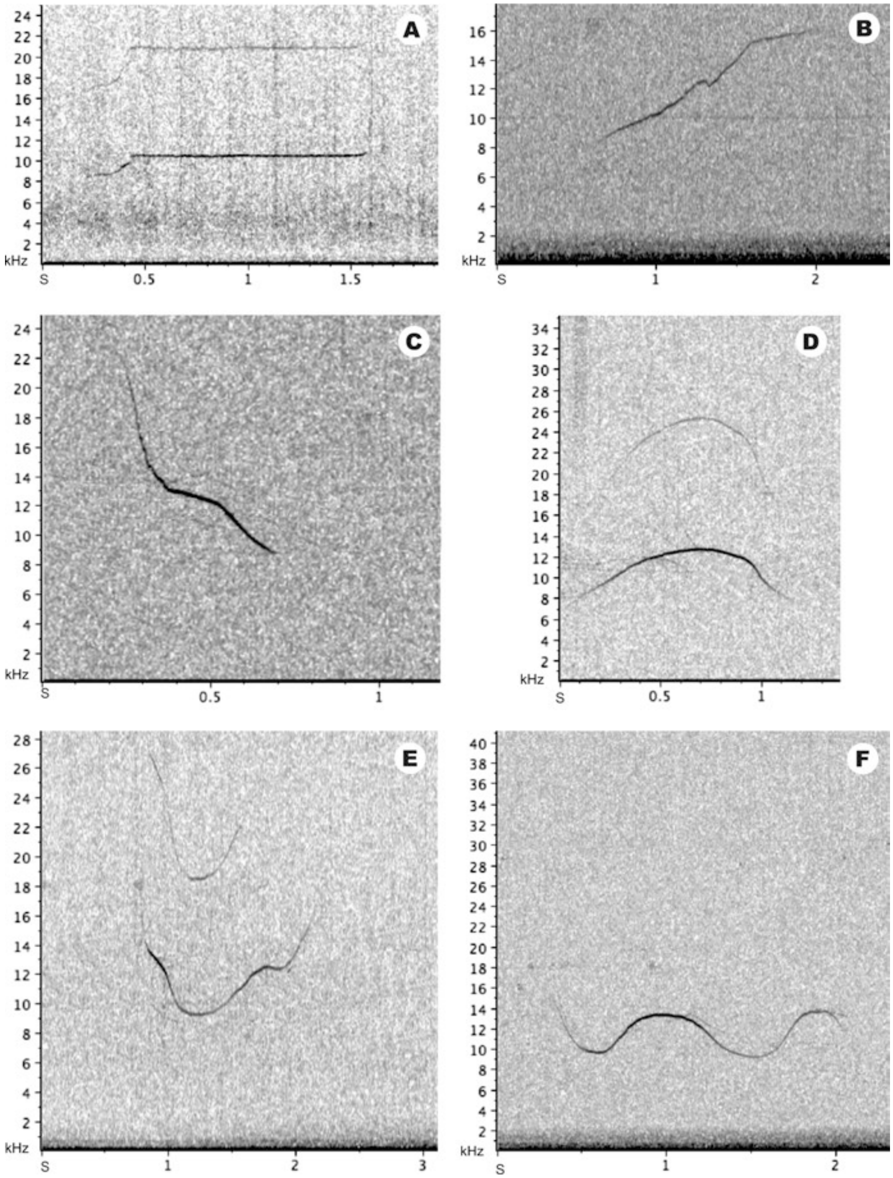

Fig. 5.4 Examples of spectrograms showing general categories of whistles contours. (**a**) Constant, (**b**) Upsweep or ascending, (**c**) Downsweep or descending, (**d**) Concave or ascending-descending, (**e**) Convex or descending-ascending and (**f**) Sinusoidal or multiple

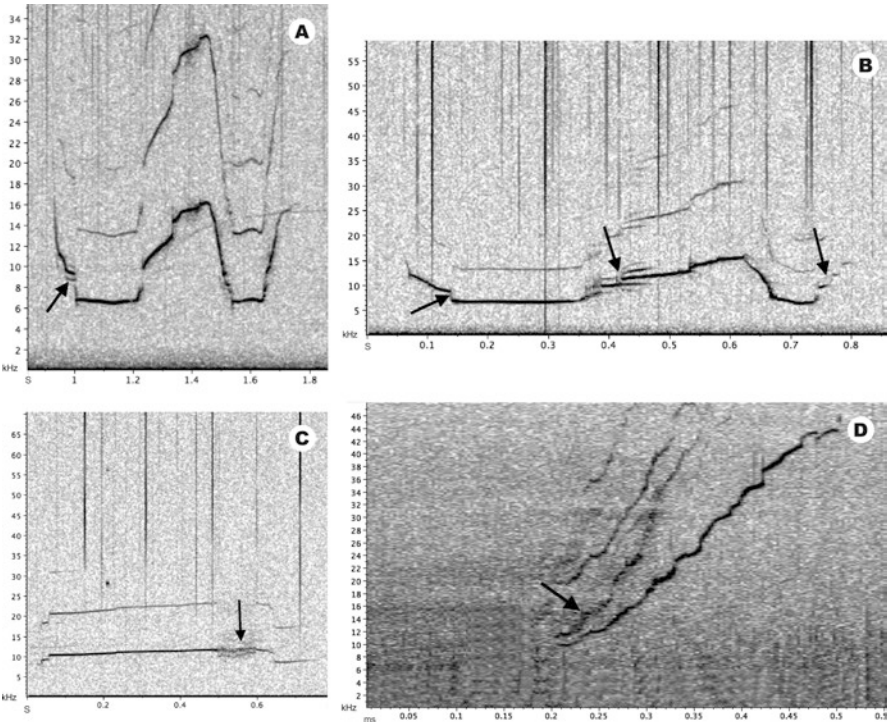

Fig. 5.5 Examples of non-linear phenomena. Arrows point to: (**a**) Subharmonics, (**b**) Frequency jump, (**c**) Deterministic chaos and (**d**) Biphonation

One set of relatively unexplored features, referred to as non-linear phenomena, can also be observed as a component of whistles emissions. This phenomenon includes subharmonics, frequencies jumps, biphonation and deterministic chaos. These complex features are produced by nonlinearities in the vocal production system, where rather simple neural commands to the system can result in highly complex and individually variable acoustic signals (Fitch et al. 2002). The spectrogram in Fig. 5.5 shows some non-linear acoustic phenomena.

5.3.2 *Echolocation Clicks*

As well as in whistles, we have been firstly categorizing echolocation into categories based on the visual inspection of spectrogram. The first category consists on clicks that can be aurally assigned to one vocalizing animal and does not show any other clicks belonging to a different train (Fig. 5.6A). The second category gathers clicks produced by more than one animal, and therefore it is possible to visualize many overlapped clicks (Fig. 5.6b). Again, depending on the main objective, both

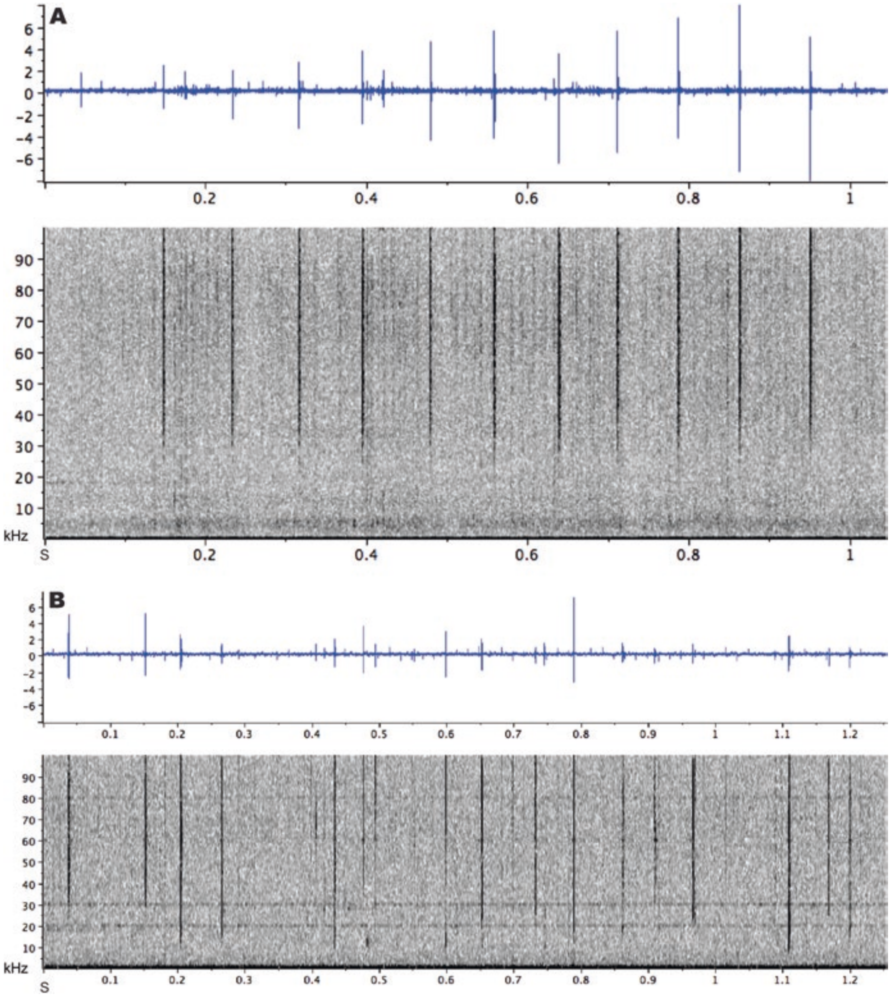

Fig. 5.6 Click trains. (**a**) Clicks can be aurally assigned to one vocalizing animal and do not show any other clicks belonging to a different train and (**b**) Overlapped clicks produced by more than one animal

types of trains can be used to investigate the general echolocation behavior. For example, the automatic measurement of inter-click interval (ICI) is greatly underestimated in overlapped clicks, but apart from that, other spectral and time parameters can be extracted using such clicks sequences without any inaccurate result.

For a general quantitative approach, some acoustical parameters can be automatically extracted: peak frequency, 3 dB bandwidth, 10 dB bandwidth, inter-click interval (ICI), sound pressure level (peak to peak), root mean square amplitude (rms) and number of clicks in train.

5.3.3 Burst Sounds

Burst pulse sounds are another major category of sound emissions by odontocetes. For dolphins and small whales, burst pulse sounds are characterized by a high repetition rate (greater than about 300 pulses per second) or low inter-pulse intervals (less than about 3 ms) (Au and Hastings 2008).

The great emphasis on studying whistles has led many to suppose that whistles are the primary mode of communication in odontocetes. It is likely that the reason for this relies on the wide band nature of burst pulse sounds compared to the frequency of the fundamental components of whistles, given that burst pulses can have frequencies components that extend beyond 100 kHz (Lammers and Au 1996). The Fig. 5.7 shows burst vocalizations with frequency components in the ultrasonic range. So far, our data set allows basic measurements as duration, peak frequency, center frequency and delta frequency. In addition, we have been observing the sequential and time patterns in which burst sounds appear in the spectrograms. Apparently, some burst sounds are emitted continuously to clicks trains (Fig. 5.7a) or they are discrete in time (Fig. 5.7b).

The basic description of sounds produced by marine mammals in South Atlantic Ocean, allows further investigations on geographical variation, signals classification systems, social structure, behavior and so many other science fields that reflect on acoustic communication. The next species sections in this chapter will present some acoustical parameters for whistles, clicks and burst sounds of delphinid species recorded in the South Atlantic continental shelf break.

5.4 Cetaceans Species Recorded and Identified in the Western South Atlantic

5.4.1 Risso's Dolphin (**Grampus griseus***)*

Rissos dolphin (Fig. 5.8) is a small cetacean that can reach up to four meters long and is distributed in temperate and tropical waters worldwide (Jefferson et al. 2014). This species is distributed along the Brazilian continental shelfbreak and slope from northeast to south region (Bastida et al. 2007; Di Tullio et al. 2016).

The acoustic repertoire of the Risso's dolphin has not been fully detailed and examples of whistles and clicks are preseted in Fig. 5.9. Neves (2013) described the acoustic parameters of whistles and clicks in different regions (Australia, Azores, California, Egypt and Gran Canaria). Gannier et al. (2008) and Rendell et al. (1999) studied whistles in the waters of the western Mediterranean Sea and Azores, respectively. Philips et al. (2003) described the clicks emitted by the Risso's dolphin in captivity, and Madsen et al. (2004) studied click emissions of free-ranging animals in Sri Lanka. Corkeron and Van Parjis (2001), in addition, describing the acoustic parameters of pulsed sounds and whistles in Newcastle, Australia. Andriolo et al.

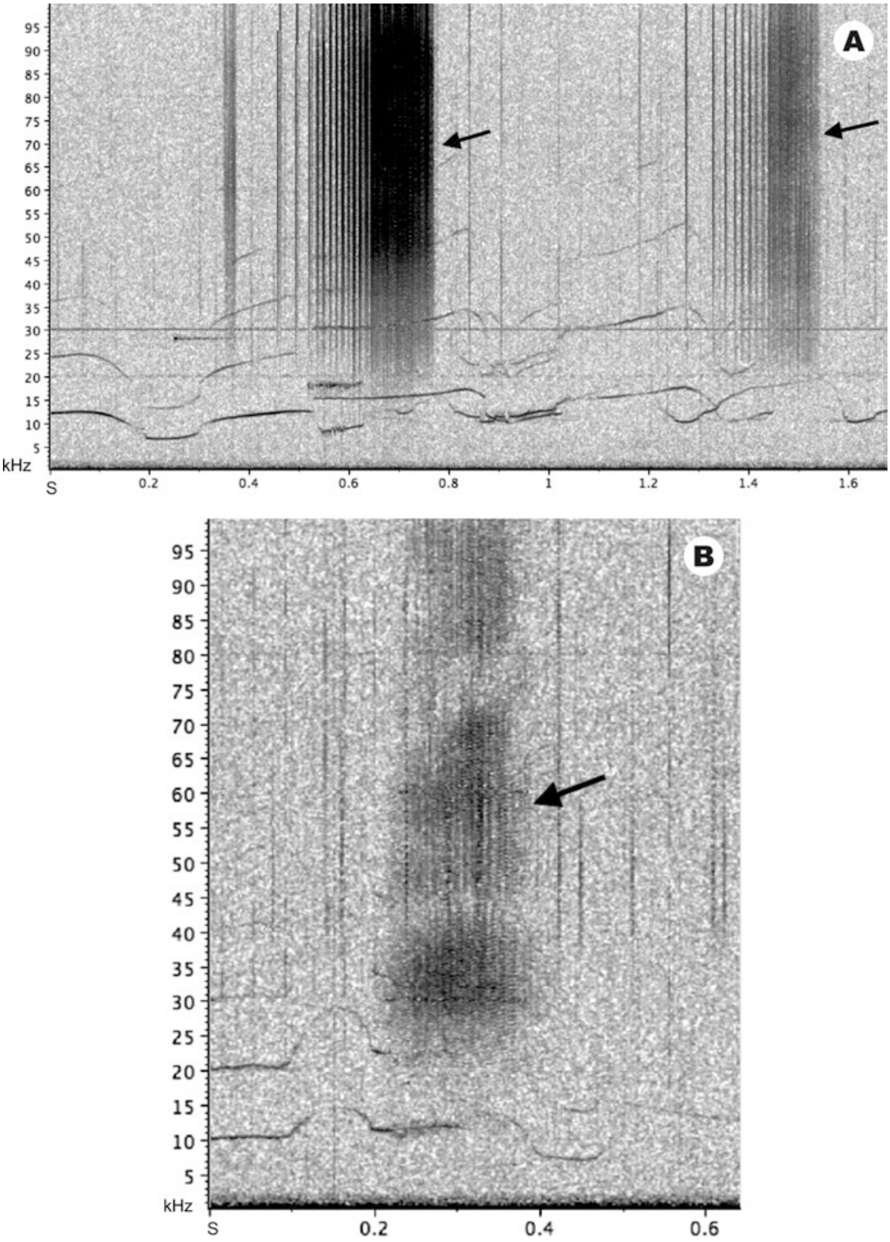

Fig. 5.7 Spectrogram of burst sounds. (**a**) Burst sounds emitted continuously to clicks trains and (**b**) Burst sounds emitted discrete in time

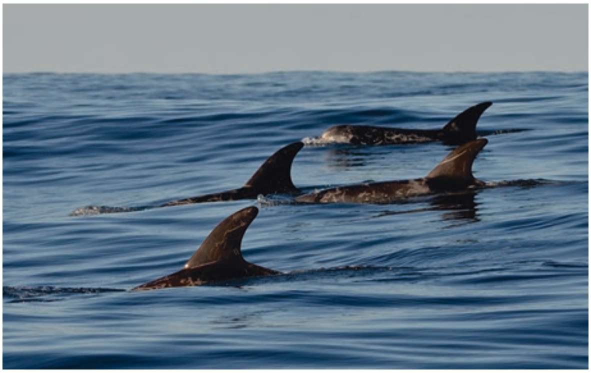

Fig. 5.8 Risso's dolphin photographed off the Brazilian coast (Reproduced with permission of Rodrigo Genoves)

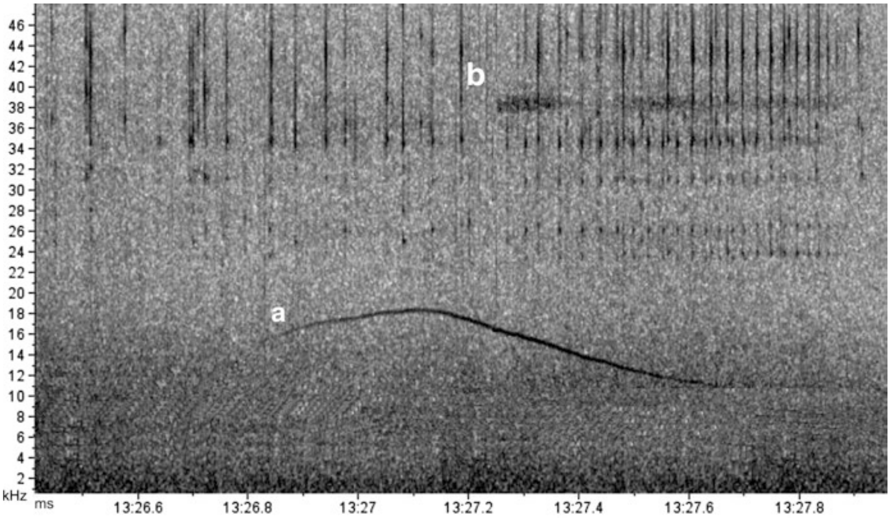

Fig. 5.9 Examples of Risso's dolphin whistles (**a**) and clicks (**b**)

(2013) conducted a study in Brazil describing the acoustic parameters of the tonal sounds of this dolphin.

*5.4.2 Rough-Toothed Dolphin (*Steno bredanesis*)*

The rough-toothed dolphin is a small delphinidae that can reach up to 2.85 ms long and is distributed in tropical and temperate warm waters worldwide (Bastida et al. 2007). In Brazilian waters this species can be found over the continental shelf shallow and deep waters from the northeast to south regions, whereas in Rio de Janeiro

Fig. 5.10 Rough-toothed dolphin photographed off the Brazilian coast (Reproduced with permission of Pedro Fruet)

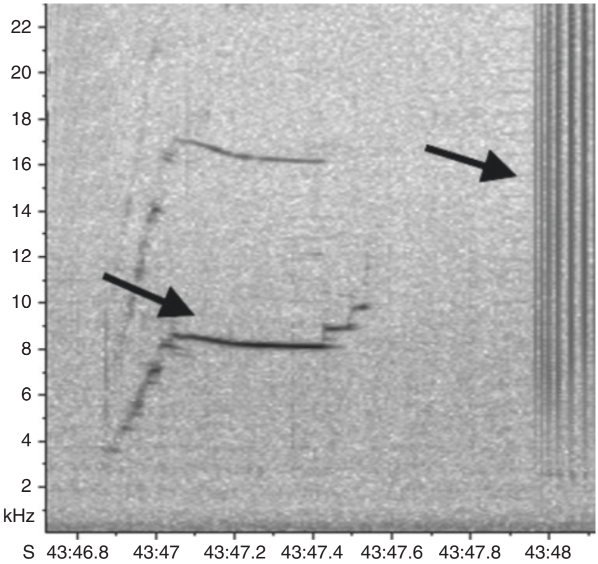

Fig. 5.11 *Steno bredanensis* acoustic signal presented in a spectrogram (Whistles and clicks, respectively)

state it is commonly sighted near the coast (Ott and Danilewicz 1996; Meirelles et al. 2009; Lodi and Hetzel 2012; Bastida et al. 2007) (Fig. 5.10).

As the majority of the delphinids species, the rough-toothed dolphin produces tonal (whistles) and pulsed sounds (echolocation clicks and burst pulses – broad-band emissions) (Tyack and Clark 2000; Oswald et al. 2003, 2007; Rankin et al. 2008a, 2015; Hoelzel 2009; Baumann-Pickering et al. 2010; Corrêa 2012; Lima et al. 2012; Amorim et al. submitted) (Fig. 5.11). The acoustic signals produced by this species have been discussed in the literature through different approaches such as: acoustic repertoire characterization (Busnell and Dziedzic 1966; Watkins et al.

Fig. 5.12 Spinner dolphin photographed off the Brazilian coast (Reproduced with permission of Pedro Fruet)

1987; Oswald et al. 2003, 2007; Rankin et al. 2015), preliminary acoustic behavior description (Rankin et al. 2008a), including possible eavesdropping recording during synchronized swimming (Gotz et al. 2006), acoustic monitoring (Rankin et al. 2008b), and species identification (Oswald et al. 2003, 2007).

In Brazil, the rough-toothed dolphin acoustic signals have been recorded on the southeastern (Guanabara Bay, Rio de Janeiro state), northeastern (Abrolhos Bank) coast (Bezerra Filho 2012; Corrêa 2012; Lima et al. 2012) and, in a most recent effort, on the southern (Rio Grande do Sul state) coast (Amorim et al. submitted). Except for Bezerra Filho (2012), the others have described spectral and temporal whistles parameters for this species (Amorim et al. submitted; Corrêa 2012; Lima et al. 2012).

5.4.3 *Spinner Dolphin (*Stenella longirostris*) and Atlantic Spotted Dolphin (*Stenella frontalis*)*

Spinner dolphin is a small delphinidae, which can reach up to 2.30 m long and is considered to have a pantropical distribution. This species has been described to occur beyond the outer continental shelf in tropical waters of the Southwestern Atlantic Ocean and near oceanic islands (Bastida et al. 2007; Danilewicz et al. 2013; Amaral et al. 2015), however, a few sightings exist south of 31°S, in spring (Di Tullio et al. 2016) (Fig. 5.12).

The acoustic investigation of the whistles emitted by the spinner dolphin already presented some geographical variation (e.g. Bazúa-Durán and Au 2002; 2004; Moron et al. 2015; Bonato et al. 2015). However, so far the geographical isolation indicates no relation to whether spinner dolphin whistles. Thus is necessary to

Fig. 5.13 *Stenella frontalis* photographed off the Brazilian coast. (Reproduced with permission of Pedro Fruet)

investigate other factors handling those geographical differences (Moron et al. 2015) and even extend the comparison to pulsed signals. Therefore, more studies and partnerships between researchers studying other populations are important to be better explore and recognize the results found so far.

The Atlantic spotted dolphin is small, reaching approximately two meters long, and is restricted to the tropical and temperate warm waters of the Atlantic Ocean (Bastida et al. 2007). In Brazilian waters this species is found over the shallow continental shelf waters (20 m) and slope in southeastern and southern regiosn; however it appears to have a discontinuous distribution, with no records occurring between 6°S and 18°S (Moreno et al. 2005; Danilewicz et al. 2013). The Atlantic spotted dolphin is the only member of the genus *Stenella* that is commonly observed close to shore in Brazil (Moreno et al. 2005) (Fig. 5.13).

There are few published works about this species acoustic signals in the South Atlantic (Azevedo et al. 2010; Lima et al. 2016), being mostly studied in a few localities of the North Atlantic Ocean (e.g. Ding et al. 1995, Lammers et al. 2003, Herzing 2015). Previous acoustic studies were taken especially in the Bahama Islands, where a local population exists (e.g. Dudzinski 1996; Herzing 1996, 2015).

Both species presented several repeated contours, especially *S. frontalis*, indicating not only the existence of the so-called signature whistles (Moron and Andriolo 2015) but also indicating its importance. Nonlinear events were also identified, mostly on spotted dolphins' vocalizations (Moron and Andriolo 2016) in the form of different types of biphonation.

Overall, *S. longirostris* and *S. frontalis* emit complex whistles. Despite having many features in common, acoustic analysis is pointing on how to differentiate both species on the Western South Atlantic Ocean. Examples of both species acoustic behavior are presented in the Fig. 5.14.

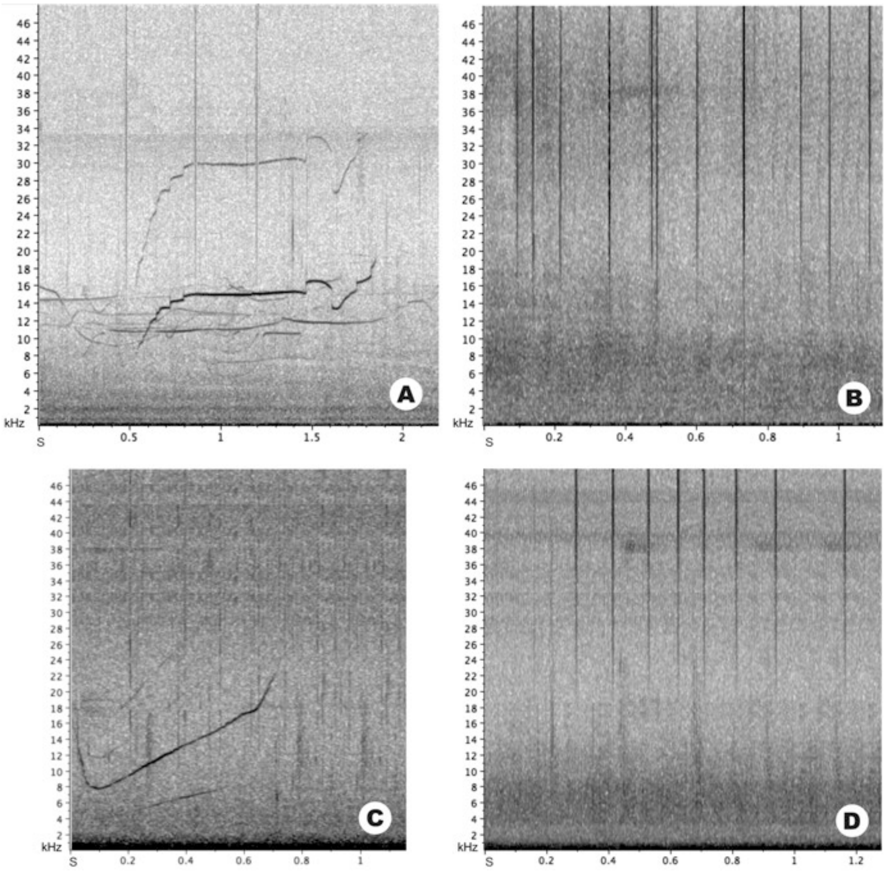

Fig. 5.14 Examples of spectrograms of spinner dolphins whistles (**a**) and (**b**) clicks. Examples of Atlantic spotted dolphins whistles (**c**) and clicks (**d**)

*5.4.4 Bottlenose Dolphin (*Tursiops truncatus*)*

The bottlenose dolphin are found in tropical and temperate waters worldwide and show a high variation in morphology according to geographical location, where adult lengths range between 2.5 and four meters approximately (Wells and Scott 2009). The distribution of bottlenose dolphins is spread along the Southwestern Atlantic at both nearshore (coastal ecotype) and offshore (oceanic ecotype) waters (Bastida et al. 2007). The coastal ecotype concentrates in areas near river discharge, estuaries and bays of Argentina, Uruguay and southern Brazil (Fruet et al. 2014). The oceanic ecotype, on the other hand, seems to be widely distributed in tropical and subtropical deep waters along the outer continental shelf and beyond and in association with oceanic islands (Bastida et al. 2007) (Fig. 5.15).

Fig. 5.15 *Tursiops truncates* photographed off the Brazilian coast. (Reproduced with permission of Rodrigo Genoves)

The bottlenose dolphin is probably one of the most studied cetacean species, therefore responsible for much of the knowledge about the dolphins sound emissions. Bottlenose dolphin acoustic repertoire consists of narrowband and modulated whistles; broadband clicks and pulsed calls (Tyack and Clark 2000). Efforts have been substantially focused in researches with whistles, mainly that named as signature whistles (e.g. Caldwell and Caldwell 1965; McCowan and Reiss 1995, 2001; Tyack 1997; Janik and Slater 1998; Sayigh et al. 2007; Harley 2008; Esch et al. 2009; Janik and Sayigh 2013; Kriesell et al. 2014).

So far, little is known about the acoustic of South Atlantic bottlenose dolphin populations. Azevedo et al. (2007) recorded bottlenose dolphins at Patos Lagoon estuary, southern Brazil. Lima et al. (2016) described and made a comparison among whistles emitted by four delphinid species, in the Rio de Janeiro State Coast, Brazil: *Sotalia guianensis*, *Stenella frontalis*, *Steno bredanensis* and *Tursiops truncatus* (Fig. 5.16).

*5.4.5 Short Beaked Common Dolphin (*Delphinus delphis*)*

The short beaked common dolphin is a small delphinidae, reaching up to approximately 2.60 m, and presents a warm-temperate distribution along the Atlantic and Pacific oceans (Bastida et al. 2007; Perrin 2009). Along the Brazilian water this species appears to have an isolated population in northern Brazil; however in the southeast this species is frequently sighted in shallower waters (18–70 m) and between southern Brazil and central Argentina this species is commonly found from the outer continental shelf to upper slope (100–1500 m) (Tavares et al. 2010; Cunha et al. 2015; Di Tullio et al. 2016) (Fig. 5.17).

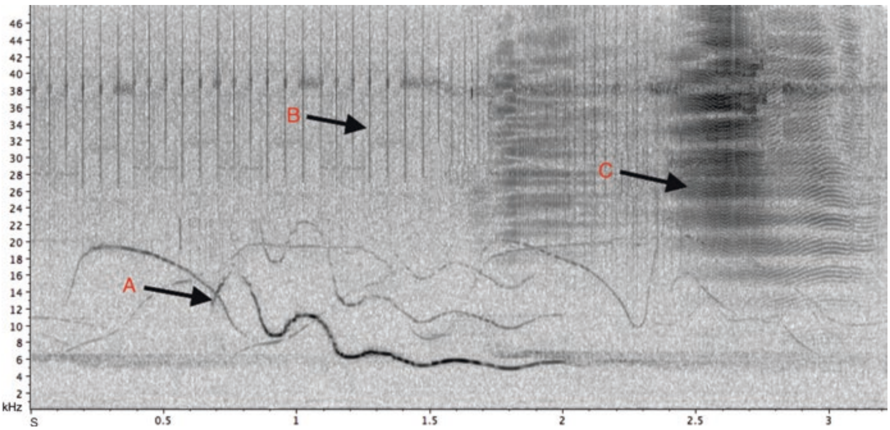

Fig. 5.16 Examples of spectrograms of (**a**) whistle, (**b**) clicks and (**c**) burst sound of bottlenose dolphin

Fig. 5.17 *Delphinus delphis* photographed off the Brazilian coast (Reproduced with permission of Pedro Fruet)

The common dolphin whistles are emitted usually between 3 and 23.51 kHz and duration between 0.01 and 2.1 s (Ansmann et al. 2007; Petrella et al. 2012). Whistles recorded in the western South Atlantic presented frequency range between 4.07 and 31.46 kHz and duration between 0.11 and 1.73 s (Fig. 5.18).

Acoustic studies with common dolphin whistles parameters are still rare and punctual. In Brazilian waters, this was the first effort to investigate common dolphin whistles repertoire. Moreover, in the current scenario of the taxonomic genus, the bioacoustics is a tool to help the classification of these dolphins and their phylogenetic relationships.

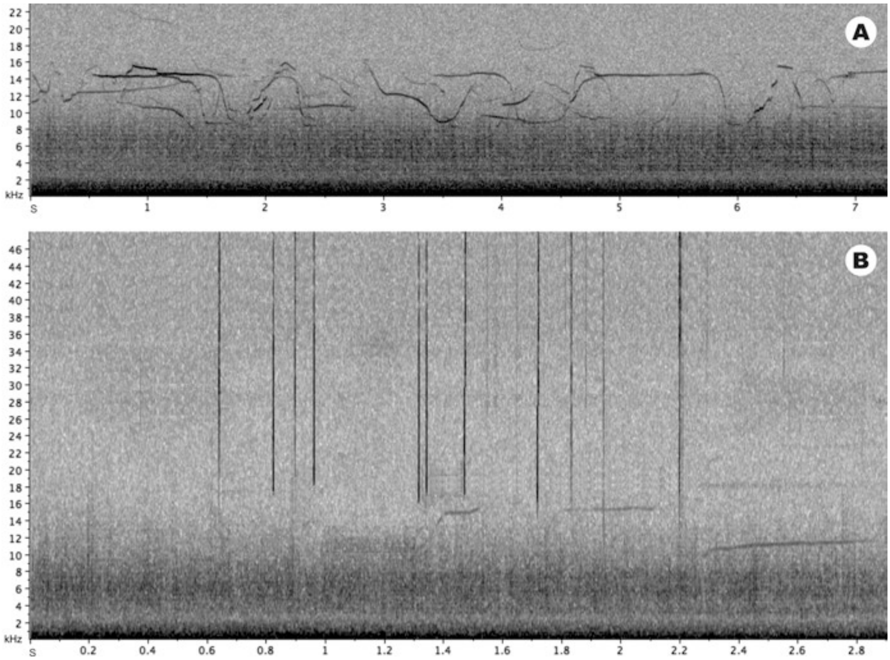

Fig. 5.18 Example of spectrogram of whistle (**a**) and clicks (**b**) of common dolphin

5.4.6 *Long Finned Pilot Whale* (**Globicephala melas**)

The long-finned pilot whale is a large delphinidae presenting a robust body and a slightly sexual dimorphism, which adult males are larger reaching up to six meters long (Olson 2009; Bastida et al. 2007). This species inhabits cold-temperate waters of the North Atlantic and southern Ocean and along Brazilian waters is sighted mainly south of 30°S and over depths between 500 and 1000 m (Pinedo et al. 2002; Zerbini et al. 2004; Bastida et al. 2007; Di Tullio et al. 2016) (Fig. 5.19).

The long finned pilot whales vocalizations have been still little described. The first studies reported whistles, pulsed calls (Busnel and Bziedzic 1966) and clicks (Busnel and Bziedzic 1966; Busnel et al., 1971) (Fig. 5.20) as part of their vocal repertoire. Taruski (1979) classified long finned pilot whales' whistles in seven broad categories, ranging from simple to complex types. Weilgart and Whitehead (1990) showed a strong relationship between the type and complexity of vocalization and the behavior displayed by animals.

Long finned pilot whale whistles recorded in the western South Atlantic presented frequency range between 2.77 and 7.50 kHz and duration between 0.23 and 0.58 s (Fig. 5.20).

Fig. 5.19 Long-finned pilot whale photographed off the Brazilian coast (Reproduced with permission of Rodrigo Genoves)

Fig. 5.20 Spectrogram of whistles (**a**) and clicks (**b**) of the long finned pilot whales

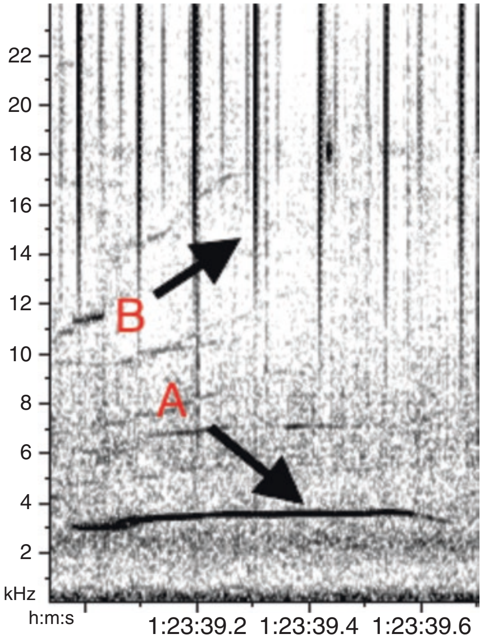

Fig. 5.21 Killer whale photographed in the western South Atlantic Ocean off the Brazilian coast (Reproduced with permission of Rodrigo Genoves)

*5.4.7 Killer Whale (*Orcinus orca*)*

Killer whales are widely distributed throughout all ocean basins, especially in areas of high ocean productivity (Ford 2009). This species presents a sexual dimorphism, which males develop larger total length (nine meters) and appendages than females (seven meters) (Bastida et al. 2007; Ford 2009). In Brazilian waters sightings of killer whale are more frequent in coastal waters of the southeast; however this species is known to frequently depredate the catch of longline fisheries near the shelf break and beyond in southern Brazil (Secchi and Vaske 1998; Dalla Rosa and Secchi 2007) (Fig. 5.21).

Killer whales have complex communication strategies (Filatova et al. 2012). Signals, such as whistles and pulsed calls, are probably culturally transmitted through vocal learning (Ford 1991; Deecke et al. 2002; Foote et al. 2006), and are highly stereotyped (Ford 1991; Riesch et al. 2006). When compared to pulsed calls, whistles are highly modulated signals and have lower sound pressure levels and higher fundamental frequencies (Ford 1989; Thomsen et al. 2001; Riesch et al. 2006). Discussions on the ecological role and possible ecological function of high frequency whistles (HFWs) produced by killer whales have recently emerged in the literature (Samarra et al. 2010, 2015; Simonis et al. 2012; Filatova et al. 2012; Trickey et al. 2014). This signal could be used for navigation (Simonis et al. 2012) or for private communication (Filatova et al. 2012).

Recent study on the western south Atlantic have described the acoustic parameters of killer whale whistles and highlighted the occurrence of high frequency whistles (Andriolo et al. 2015). The high frequency whistles (Fig. 5.22A) were highly stereotyped and were modulated mostly at ultrasonic frequencies. Compared to other contour types (Fig. 5.22B), the high frequency whistles are characterized by higher bandwidths, shorter durations, fewer harmonics, and higher sweep rates (Andriolo et al. 2015) (Table 5.1).

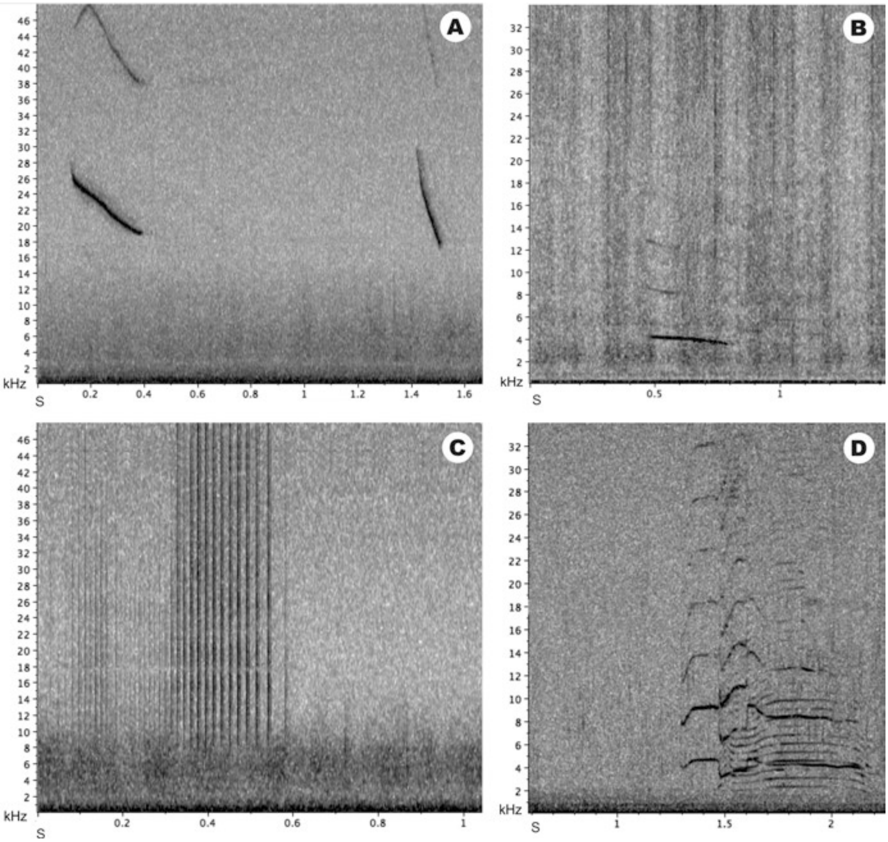

Fig. 5.22 Spectrograms of killer whale (A) high frequency whistle (HFW) (B) whistle contour, (C) clicks and (D) calls recorded in the western South Atlantic Ocean

5.5 Ecological Approaches of Bioacoustics Using Towed Array

5.5.1 Acoustic Discrimination Between Species

The extensive use of Passive Acoustic Monitoring for detecting and monitoring marine mammals has generated huge volumes of data (Mellinger and Barlow 2003). Species identification from acoustic recordings of marine mammal vocalizations can be challenging due to the high variability in many of the characteristics of sounds that can be easily measured or extracted from spectrograms, both within species and among species (e.g. Oswald et al. 2003, 2004; Roch et al. 2007; Soldevilla et al. 2010; Baumann-Pickering et al. 2015).

The analysis of cetacean sounds to the species level is an important step in processing long-term passive acoustic recordings made in a marine environment (Baumann-Pickering et al. 2010). Most of works on acoustic classification of odon-

Table 5.1 Spectral and temporal parameters of whistles and clicks for all species given as the median with the 10th and 90th percentile in parentheses. *MinF* minimum frequency, *MaxF* maximum frequency, *DeltaF* delta frequency, *PeakF* peak frequency, *CenterF* center frequency, *BeginF* beginning frequency, *EndF* ending frequency, Duration, *ICI* inter-click interval, *3dB bw* 3dB bandwidth, *10dB bw* 10dB bandwidth. Number of analysed vocalisations is given as N: number of whistles/number of clicks

	Whitles								Clicks		
Species	MinF (kHz)	MaxF (kHz)	DeltaF (kHz)	PeakF (kHz)	CenterF (kHz)	BeginF (kHz)	EndF (kHz)	Duration (ms)	ICI (ms)	3 dB bandwidth (kHz)	lOdB bandwidth (kHz)
Delphinus delphis	8.6	15.3	5.5	11.6	12.4	11.7	13.0	735.0	0.6	24.2	6.3
(N:397/202)	(5.6–12.9)	(10.7–20.2)	(1.8–10.3)	(8.3–17.4)	(8.4–17.9)	(7.5–17.1)	(6.8–17.0)	(303.0–1270.0)	(0.1–54.3)	(11.2–35.5)	(6.1–6.5)
Globicephala melas	3.6	4.8	1.1	4.3	4.2	4.0	4.5	390.0	30.8	28.1	12.3
(N:271/117)	(2.2–6.8)	(3.3–9.6)	(0.4–3.3)	(2.6–8.5)	(2.7–8.0)	(2.6–7.4)	(2.4–9.3)	(140.0–740.0)	(0.3–392.9)	(13.5–37.7)	(8.3–33.4)
Grampus griseus	7.1	15.4	7.7	11.1	11.0	10.7	9.7	690.0	0.1	25.7	9.6
(N:340/247)	(1.8–11.2)	(3.1–18.7)	(1.0–11.7)	(2.6–15.5)	(2.2–14.5)	(2.6–14.8)	(2.1–15.9)	(220.0–1390.0)	(0.08–0.2)	(15.8–38.7)	(7.2–15.3)
Orcinus orca	3.9	8.2	4.1	5.6	7.1	4.3	8.0	295.0	19.5	14.8	16.0
(N: 187/70)	(1.9–15.1)	(3.8–24.6)	(1.6–9.3)	(2.7–17.8)	(3.3–20.3)	(1.9–24.5)	(3.4–16.9)	(110.0–838.0)	(0.4–33.2)	(11.5–32.3)	(8.2–31.6)
Stenellafrontalis	9.6	16.9	7.7	15.4	14.5	9.9	16.8	320.0	37.0	31.1	12.9
(N: 892/98)	(5.4–11.9)	(15.8–19.6)	(4.5–12.9)	(12.2–17.1)	(13.3–15.5)	(5.7–12.7)	(15.4–19.4)	(212.8–499.5)	(3.5–63.3)	(18.7–38.6)	(9.4–30.0)
Stenella longirostris	9.9	15.9	4.6	13.8	13.5	11.8	13.7	690.0	86.4	26.2	19.4
(N:768/147)	(6.5–15.1)	(10.5–20.9)	(1.3–9.4)	(9.1–16.7)	(9.4–16.3)	(6.8–17.3)	(8.6–18.7)	(200.0–1416.0)	(16.1–166.8)	(20.4–34.2)	(10.9–37.5)
,SYe«0 *bredanensis*	5.8	8.1	2.2	7.4	6.9	6.3	7.6	409.0	8.9	32.0	19.0
(N:470/113)	(4.0–8.3)	(6.7–10.1)	(0.5–4.9)	(5.6–8.8)	(5.5–8.9)	(4.1–8.8)	(5.8–9.9)	(126.6–974.4)	(0.1–28.2)	(20.8–39.1)	(9.3–35.7)
Turstops truncatus	9.6	15.6	5.1	12.5	12.1	11.9	12.8	350.0	25.4	24.5	30.5
(N:1005/301)	(7.2–13.8)	(11.7–19.9)	(1.7–9.2)	(8.7–18.0)	(9.2–17.9)	(7.9–16.7)	(8.6–18.1)	(140.0–840.0)	(4.1–56.5)	(22.4–29.4)	(13.4–34.4)

tocetes have considered the acoustical emissions separately, examining only click trains (Verfub et al. 2007, 2013; Roch et al., 2011), or whistle sequences (Oswald et al. 2007). Lu et al. (2013) integrated features from both whistles and clicks for classification of bottlenose dolphin, spinner dolphin, melon-headed whale, short-beaked common dolphin and long-beaked common dolphin.

Proposing an integrative bioacoustics approach – combining whistles and clicks - we classified eight delphinid species: spinner (*Stenella longirostris*), Atlantic spotted (*Stenella frontalis*), rough-toothed (*Steno bredanensis*), Risso's (*Grampus griseus*), bottlenose (*Tursiops truncatus*), short-beaked common (*Delphinus delphis*) dolphins, killer (*Orcinus orca*) and long-finned pilot (*Globicephala melas*) whales from the Southwest Atlantic Ocean, at the Brazilian shelf break (Amorim et al. submitted). For that, we extract whistles acoustic parameters: maximum frequency, minimum frequency, frequency range, peak frequency, center frequency, beginning frequency, ending frequency and duration; and clicks parameters: inter-click interval, sound pressure level peak-to-peak (SPL), rms (root mean square) amplitude, 3 dB bandwidth and 10 dB bandwidth. The sequential classification analysis consisted of two methodological techniques, Discriminant Function Analysis (DFA) and Classification Tree Analysis.

The discriminant function showed that the overall whistle classification had the highest number of false classifications (40.7%, N = 475, Wilks' λ = 0.18), these numbers decrease when only clicks were analyzed (25.0%, N = 158, Wilks' λ = 0.14). The discrimination result improved with the combined analysis of whis-tles and clicks, given that the misclassification percentage was only of 5.8% (N = 30, Wilks' λ = 0.01). In classification tree analysis, the optimal classification whistle tree consisted of 28 splits and misclassification rates of 0.606. Click opti-mal tree consisted of 60 splits and misclassification of 0.260. When whistles and clicks were combined, optimal tree consisted of 90 splits and a false classification of 0.188.

In summary, the eight delphinid species showed species-specific qualities in their whistles and clicks. When taken individually, echolocation clicks presented greater efficiency in distinguishing species; this might be related to the behavioural context encoded in whistles and the relationship between echolocation signals features and animals' head morphology, which makes feasible to accurately determine a species from their clicks. Otherwise, analysing both signals in combination enhanced the correct classification scores. An integrati ve bioacoustics approach potentially presents a higher contribution in the classification process, once it considers the different signals produced by the species as part of a whole communication system employed in different ecological contexts.

5.5.2 Sperm Whale Social Structure

Sperm whales (*Physeter macrocephalus*) are the largest and long-lived odontocete, reaching between 8.3 and 20.5 m long and with lifespan of over 50 years old (Chivers 2009; Whitehead 2009). There is a marked sexual dimorphism in body

Fig. 5.23 Sperm whale photographed off the Brazilian coast (Reproduced with permission of Luciano Dalla Rosa)

length between adults; females reach reproductive maturity about nine meters long while males at approximately 16 m long. Although they are considered cosmopolitan, the distribution of females and young individuals are restricted to tropical and temperate deep waters and differs from adult male, which extends their distribution to polar waters (Whitehead 2009). Few records of sperm whales stranding occur along the Brazilian coast, however sightings in deep waters are more frequent, especially in southern Brazil at depths over 1000 m (Di Tullio et al. 2016) (Fig. 5.23).

Hinde in 1976 stated that social structure is the quality and nature of the interactions among individuals, and the relationships between them. Considering that, to study animal's societies, we must investigate interactions and describe relationships in order to achieve a model of social organization. Some methods are used and complement each other in studies of social structure: photo identification, molecular techniques, observation of behavior, visual and photographic estimates of length and genetic sexing and, passive acoustics monitoring and vocalizations descriptions (Whitehead 2003).

The sperm whale's long life span allows the formation of long-term social bonds among individuals (Christal et al. 1998). Within sperm whale social units, individuals prefer associations and avoidances. Such preferences suggest that sperm whales have individualized relationships within units and, as a consequence, the animals may rely on strategies to recognize individuals in order to adjust their behavior (Whitehead 2003).

Within the types of clicks that sperm whales emit, a series of stereotyped patter of clicks called codas stand out. Codas have been associated to communication and identification of a specific unit membership, besides of being used for individual recognition and identification (Watkins and Schevill 1977; Whitehead and Weilgart 1991) and consequently reflects family relationships (Weilgart and Whitehead 1997).

Sperm whales social units in the Pacific were grouped into vocal clans based on their coda repertoires (Rendell and Whitehead 2003a). Besides that, within vocal clans, unit members share elements of their coda repertoire, and eventually engage in codas exchanges in order to share a signal code (Whitehead 2003; Rendell and Whitehead 2004). It is know that codas repertoire varies geographically (Weilgart and Whitehead 1997) and are learnt within matrilineal social groups. Rendell and Whitehead (2005) found that similarities among repertoires showed a negative correlation with increasing distance of clans.

Codas were mostly studied in the Island of Dominica (Schulz et al. 2008; Antunes et al. 2011; Schulz et al. 2011; Gero et al. 2015; Gero et al. 2016), in the Mediterranean (Borsani et al. 1997; Pavan et al. 2000), in the Caribean (Moore et al. 1993), in Azores (Oliveira et al. 2016), in the Galápagos (Weilgart and Whitehead 1993; Rendell and Whitehead 2003b, 2004, 2005), in the Pacific (Rendell and Whitehead 2003a, Marcoux et al. 2006) and in the North western Atlantic (Watkins and Schevill 1977). As a first effort in studying codas and social structure of sperm whales in South Atlantic (Fig. 5.24), we have been making recordings since 2011 in the South, Southeast of Brazil. In collaboration with researchers of University of St. Andrews, the vocal clans and its dialects will be investigated. So far, a total of 939 codas were marked up using a custom-written software for analyzing sperm whale sounds called Rainbow Click (see Gillespie 1997; Leaper et al. 2000).

5.5.3 Abundance Estimation of Sperm Whales

Information on distribution and density of most marine mammals have been primarily obtained from visual surveys (Ward et al. 2012; Marques et al. 2013). However, the traditional methods of visual monitoring have been associated with: (1) training of qualified staff, (2) an intensive work effort, (3) a high implementation costs (Evans and Hammond 2004; Ward et al. 2012; Marques et al. 2011, 2013). They can be undertaken merely during daylight and in good weather conditions and, as the individuals are available for visual observation only when at the surface, just part of the animals present can be detected (Mellinger and Barlow 2003; Mellinger et al. 2007; Vallarta-Hernandez 2009; Ward et al. 2012; Yack et al. 2013).

PAM has been increasingly used in study of marine mammals, especially because many of them are more acoustically than visually available (Barlow and Taylor 2005; Zimmer 2013; Yack et al. 2013). Whether simultaneously conducted, the abundance estimates obtained through these methods are possibly more reliable

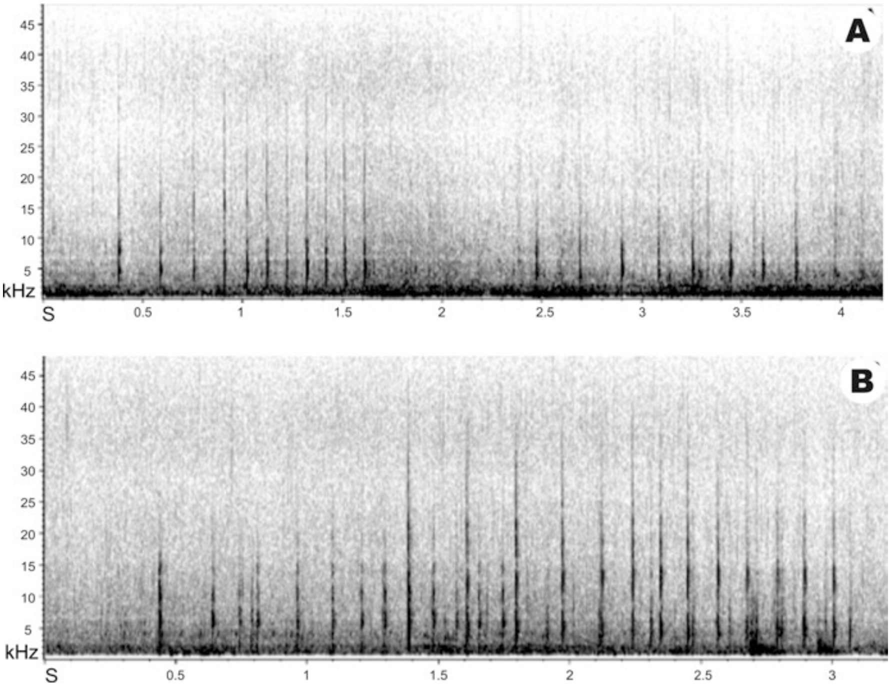

Fig. 5.24 Examples of codas from South/Southeast Brazilian continental shelf break. (**a**) Two different codas patterns and (**b**) Overlapped codas

(Whitehead 2002; Mellinger and Barlow 2003) as they tend to increase the probability of detecting individuals (Barlow and Taylor 1998, 2005; McDonald and Moore 2002; Whitehead 2003; Rankin et al. 2008c).

The long and deep dives performed by sperm whales can last approximately 1 h (Leatherwood et al. 1982; Barlow and Taylor 2005; Watwood et al. 2006). Thus, individuals spend short periods at the surface, reducing the probability of being visually detected (Whitehead 2003; Watwood et al. 2006; Ward et al. 2012). However, this species produces a variety of types of clicks (usual and slow clicks, creaks and coda), which are used in different contexts such as echolocation and communication (Zimmer et al. 2005).

According to Barlow and Taylor (2005), sperm whales are most likely to be acoustically detected among others cetacean's species. During their foraging dives, produce regular, audible and short duration clicks ('usual' clicks and creaks) with frequencies ranging from several hundred hertz to over 30 kHz (Watkins 1980; Gillespie 1997; Weilgart and Whitehead 1988; Madsen et al. 2002; Barlow and Taylor 2005). Several studies have been increasingly applied passive acoustic monitoring, some of which combined with visual surveys, trying to improve the methods of localization and density estimation of marine mammals, using sperm whales as a model (Gillespie 1997; Barlow and Taylor 1998, 2005; Gannier et al. 2002; Hastie et al. 2003; Leaper et al. 2003; Lewis et al. 2007; Swift et al. 2009; Whitehead 2009;

Ward et al. 2012; Von Benda-Beckmann et al. 2013; Tran et al. 2014; Fais et al. 2016). They have being carried out using a variety of methods and from different platforms. However, as the frequency of sperm whale clicks extends above the dominant range of the ship and water flow noise, it makes possible the use of towed passive acoustic system (Gillespie 1997; Barlow and Taylor 1998, 2005; Gannier et al. 2002; Hastie et al. 2003; Leaper et al. 2003; Lewis et al. 2007; Swift et al. 2009; Whitehead 2009; Fais et al. 2016). Once conducted opportunistically, it provides, as highlighted by Whitehead (2002), the coverage of large areas with relatively low cost resulting, additionally, in a more accurate abundance estimate for this species.

In Brazil, a recent effort has been conducted using this system, in association with a visual survey (Di Tullio et al. 2016), aiming to detect, localize and estimate the sperm whales population size in the south and southeast continental shelf break region through their acoustic signals. This study has being conducted as a partnership between the research groups of Federal Universities of Juiz de Fora and Rio Grande, as well as with the Centre for Research into Ecological & Environmental Modelling at the University of St. Andrews.

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