

**Universidade Federal de Juiz de Fora  
Programa de Pós-Graduação em Ecologia**

FRANCIELE REZENDE DE CASTRO

**MONITORAMENTO ACÚSTICO PASSIVO ATRAVÉS DE MATRIZ DE ARRASTO:  
DETECÇÃO, LOCALIZAÇÃO, PERFIL DE MERGULHO E ESTIMATIVA DA  
DENSIDADE DE BALEIAS CACHALOTE (*Physeter macrocephalus*) NA  
PLATAFORMA CONTINENTAL EXTERNA E TALUDE SUL BRASILEIRO**

[Passive acoustic monitoring using a towed array: detection, localization and density estimation of sperm whales (*Physeter macrocephalus*) on the outer continental shelf and slope off southern Brazil]

Juiz de Fora, Minas Gerais – Brasil  
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FRANCIELE REZENDE DE CASTRO

Tese apresentada ao Programa de Pós-Graduação em Ecologia da Universidade Federal de Juiz de Fora, como parte dos requisitos necessários à obtenção do grau de Doutor em Ecologia Aplicada a Conservação e Manejo de Recursos Naturais.

Orientador: Prof. Dr. Artur Andriolo  
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“Todo mundo tem dentro de si um fragmento de boas notícias.  
A boa notícia é que você não sabe quão extraordinário você pode ser!  
O quanto você pode amar! O que você pode executar! E qual é seu potencial!”  
[Anne Frank]

POR ISSO...

“Prometa-me que você sempre lembrará: você é mais corajoso do que você acredita, mais forte do que parece e mais inteligente do que você pensa.”  
[Alan Alexander Milne]

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S4: Similar to the previous figure, PAMGuard during the click trains identifying process, each of them corresponding to an individual or group of individuals, addressed to their respective events (identified by the different colors). In (a) Bearing x time, (b) Waveform, (c) Spectrum, and (d) Wigner Plot of the selected click, and (e) automatic inter-click interval measurement (ICI).

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Table 3.1: Summary of the best fitting model for the perpendicular distance datasets assessed: original perpendicular distances dataset acoustically estimated using PAMGuard, and (b) corrected perpendicular distances based on the maximum foraging-dive depth, assessed through TDR tags attached to sperm whales in the southern Brazilian outer continental shelf and slope. Adj. term – adjustment term, Param. – number of parameters, Pa – detection probability, CV – coefficient of variation, CI – 95% confidence interval.

Table 3.2: Sperm whale abundance (N, and respective CV and CI), considering the estimated  $g(0) = 0.96$  (Castro et al. unpublished (chapter 2), and  $g(0) = 0.81$ , adopting the ESW estimated in the present study. Adj. term – adjustment term, Param. – number of parameters, CV – coefficient of variation, CI – 95% confidence interval.

S2: Table showing details on the arrays used per cruise.

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## RESUMO

Diante das novas ameaças introduzidas em todos os oceanos através do crescente desenvolvimento de atividades antropogênicas, o monitoramento de espécies marinhas, como os cachalotes, é iminente. Esta espécie geralmente gasta de 70 a 75% do seu tempo em mergulhos de forrageio, o que a torna difícil de ser observada. No entanto, os indivíduos produzem cliques de ecolocalização durante os mergulhos, tornando-se receptivos ao monitoramento acústico passivo (*Passive Acoustic Monitoring* – PAM). Nos últimos anos, o PAM vem sendo cada vez mais utilizado. Aqui, são apresentados os resultados do primeiro esforço acústico sistemático para o monitoramento de baleias cachalotes, conduzido na plataforma continental externa e talude sul brasileiro. Três cruzeiros foram realizados usando uma matriz de arrasto composta por três elementos. As cadeias de cliques de cachalote foram detectadas e localizadas através do software PAMGuard. A ocorrência e distribuição dos encontros acústicos da espécie em relação às feições estacionárias e antropogênicas foram espacialmente avaliadas, e sua abundância estimada através do método convencional de amostragem por distâncias (*Conventional distance sampling*, CDS). Adicionalmente, dados de cinco *Time-Depth Recorders* (TDR's) implantados em cachalotes em águas brasileiras foram utilizados para descrever o perfil de mergulho desta espécie e cinco *Digital Tags* (Dtags) colocados em indivíduos ao redor dos Açores foram usados para estimar diretamente a porcentagem de tempo que os indivíduos permanecem acusticamente disponíveis. A avaliação conjunta de ambos os tipos de transmissores permitiu estimar a probabilidade de detecção à distância horizontal zero,  $g(0)$ . Dos 21 encontros acústicos registrados, 57% estavam além da isóbata de 1000 metros (m), com 85,71% ( $n=18$ ) ocorrendo entre os limites do talude (200 m e 2000 m). Sete registros (33,33%) ocorreram em blocos de petróleo e gás. Em contraste, todos os encontros acústicos foram registrados em Áreas Prioritárias para Conservação (*Priority Areas for Conservation*, PACs). O modelo linear generalizado melhor ajustado (GLM) indicou a profundidade como a única covariável com relação significativamente positiva com a distribuição dos encontros acústicos de cachalotes. Um total de 139 mergulhos completos foram usados para avaliar o perfil de mergulho desta espécie. Mergulhos rasos em forma de V (40,29%) foi o tipo mais frequente, seguido por mergulhos de profundidade intermediária (29,50%), mergulhos profundos (17,27%) e mergulhos rasos em forma de U (12,95%). Vinte e sete mergulhos obtidos a partir de TDR's e 60 obtidos através dos Dtags foram identificados como de forrageio e, a partir deles, estimada uma disponibilidade acústica correspondente a 38,10 minutos (min). Com períodos de 30,58 min em silêncio e uma janela de tempo finita de 27,71 min para detecção, o  $g(0)$  foi estimado

em 0,96. Adotando-se  $g(0)=1$ , a partir dos registros acústicos obtidos durante a primavera de 2014, a densidade estimada para a área pesquisada foi de 0.0146 baleias/ km<sup>2</sup> e a abundância de 1654,35 indivíduos (CV: 0,379; IC: 778,35 – 3516,24). No entanto, este número foi subestimado em 4% em relação à abundância resultante quando considerado o  $g(0)$  estimado a partir de Dtags e TDR's. Embora as PAC's cubram toda a área de ocorrência de cachalotes, elas são apenas instrumentos que podem apoiar a implementação de futuras ações de manejo na área de estudo. Apesar de uma minoria dos eventos ter sido registrada em blocos de exploração de petróleo e gás, devido à proximidade das baleias em relação a estas áreas, recomenda-se monitorar a população de cachalotes e a condução de atividades associadas à exploração de petróleo e gás nesta região e em outras bacias sedimentares. Embora ainda em desenvolvimento, o monitoramento acústico apresenta-se como um método alternativo ou complementar ao monitoramento visual, permitindo acessar informações úteis sobre a distribuição e abundância dos cachalotes, enquanto sua aplicação contribui potencialmente para a melhoria contínua desse método.

## ABSTRACT

In face of new potential threats from anthropogenic activities introduced in all oceans worldwide, the monitoring of marine fauna species, such sperm whales, is imminent. This species typically spends 70 to 75% of its time in foraging dives, becoming difficult to be observed. However, while diving individuals produce foraging vocalizations, which make them amenable to acoustic monitoring. In recent years, Passive Acoustic Monitoring (PAM) have been increasingly applied. Results from the first sperm whale PAM effort carried out in the southern Brazilian outer continental shelf and slope are presented here. Three ship-based surveys were conducted using a 3-element towed array. Sperm whale click trains were detected and located using PAMGuard. This species acoustic encounters occurrence and distribution in relation to stationary and anthropogenic features were spatially assessed, and its abundance estimated through Conventional Distance sampling (CDS) analysis. Moreover, data from five Time-Depth Recorders (TDR's) attached in sperm whales off Brazil were used to assess this species dive profile and five Digital Tags (Dtags) placed in individuals around Azores were used to directly estimate the percentage of time individuals were acoustically available. The joint assessment of both tag types allowed to estimate the detection probability at zero horizontal distance  $g(0)$ . From 21 acoustic encounters recorded, 57% were beyond the 1000 meters (m) isobath, with 85.71% ( $n = 18$ ) occurring between the slope limits of the 200 m and 2000 m isobaths. Seven recordings (33.33%) occurred in oil and gas blocks. In contrast, all acoustic encounters were recorded in Priority Areas for Conservation (PACs). The best-fitted generalized linear model (GLM) indicated depth as the only covariate with a significantly positive relationship to sperm whale acoustic encounters distribution. A total of 139 complete dives were used to assess this species dive profile. V-shaped shallow dives (40.29%) were the most frequent dive type, followed by intermediate-depth (29.50%), deep dives (17.27%) and U-shaped shallow dives (12.95%). Twenty-seven TDR's dives were identified as foraging, from which, together with the 60 foraging dives from Dtags, were estimated an expected value of acoustical availability correspondent to 38.10 minutes (min). With a 30.58 min silent time and a finite time-window of 27.71 min, the estimated  $g(0)$  was 0.96. A density of 0.0146 whales/ km<sup>2</sup> and an abundance of 1654.35 whales (CV: 0.379, CI: 778.36 – 3516.24) for the surveyed area were estimated, from the acoustic data recorded during Spring 2014, considering a  $g(0)=1$ . The number of sperm whales was underestimated in 4% compared to the resulting abundance when considered the  $g(0)$  estimated from Dtags and TDR's. Although PACs cover the entire area of sperm whale occurrence, they are only instruments that may support the implementation of future management actions in the study area. Despite a minority of



individuals have been recorded in oil and gas exploration blocks, due to the sperm whale's proximity to such areas, monitoring this species' distribution, as well as the process associated with oil and gas activities is recommended. Although still in development, acoustic monitoring presents as an alternative or complementary method to visual monitoring, being able to access useful information on sperm whale distribution and abundance, while its applicability potentially contribute to the continuous improvement of such method.

## 1. Introdução Geral

Atividades humanas, como a pesca, navegação, extração mineral e consequente poluição química e sonora, vêm sendo continuamente desenvolvidas em todos os oceanos, potencialmente impactando a fauna marinha (Reeves et al. 2003, Whitehead 2003, Nielsen & Møhl 2006, Jewell et al. 2012). Após a moratória à caça comercial em 1986, estas atividades se tornaram a principal fonte de ameaça a estes animais (Whitehead 2003) e, para a maioria delas, é esperado um crescimento significativo durante as próximas décadas (Jewell et al. 2012).

Em resposta, as populações podem diferir em tamanho e distribuição (Whitehead 2002, Evans & Hammond 2004). Por isso, quando o objetivo de gestão for a conservação de espécies ameaçadas (Thomas & Marques 2012), conhecer a variação espaço-temporal em sua abundância, assim como em sua distribuição, é essencial para a elaboração de plano de conservação das espécies e manejo eficaz das atividades impactantes (Evans & Hammond 2004, Fais et al. 2016).

No entanto, medir mudanças populacionais representa um desafio particular para espécies móveis, como os cetáceos (Evans & Hammond 2004), em particular espécies cujo hábito e habitat as tornam pouco acessíveis à observação humana (Marques et al. 2009, Thomas & Marques 2012).

Nosso conhecimento sobre distribuição e densidade da maioria dos mamíferos marinhos vem principalmente dos métodos de monitoramento visual (Ward et al. 2012, Marques et al. 2013, Novak 2016). Os métodos tradicionais de pesquisa visual estão associados ao treinamento de equipes qualificadas, ao esforço intensivo de trabalho e a custos altos de execução (Evans & Hammond 2004, Ward et al. 2012). Seu uso permite detectar apenas uma fração dos animais presentes, tanto por poderem ser realizadas apenas durante o dia e em condições meteorológicas favoráveis, quanto pelo fato dos indivíduos estarem disponíveis à observação visual apenas durante o período que vêm à superfície para respirar (Mellinger & Barlow 2002, Mellinger et al. 2007, Ward et al. 2012, Yack et al. 2013, Verfuss et al. 2018).

Nos últimos anos, tem havido um interesse crescente no desenvolvimento e utilização de outras abordagens para o monitoramento de espécies marinhas, entre elas o monitoramento acústico passivo, *Passive Acoustic Monitoring* – PAM, buscando, com isso, lidar com as dificuldades associadas ao monitoramento visual, em particular, de espécies de difícil acesso (Jewell et al. 2012, Verfuss et al. 2018). O PAM vem sendo cada vez mais utilizado, apresentando-se como método não invasivo de monitoramento complementar ou alternativo aos tradicionais métodos de monitoramento visual, particularmente em condições de baixa avistabilidade (Nielsen

& Møhl 2006, Mellinger et al. 2007, Gillespie et al. 2009, Yack et al. 2013, McDonalds et al. 2017, Verfuss et al. 2018). Integrado ao monitoramento visual, permite uma maior cobertura espaço-temporal, além de aumentar a probabilidade de detecção (Gillespie et al. 2008, Marques et al. 2009, Novak 2016). No entanto, cada um tem vantagens e desvantagens, e sua aplicabilidade pode variar entre as espécies (Evans & Hammond 2004).

Estimativas de densidade baseadas em PAM foram calculadas para uma variedade de espécies de cetáceos (Barlow & Taylor 2005, Marques et al. 2009, 2011, Ward et al. 2012, Yack 2013, Fais et al. 2016). No ambiente marinho, dados acústicos podem ser coletados a partir de matrizes fixas ou móveis como os *gliders* e as matrizes de arrasto, adequados principalmente quando a intenção é cobrir áreas maiores (Nielsen & Møhl 2006, Marques et al. 2013, Kusel et al. 2011, 2017, Warren et al. 2017).

Entretanto, os métodos de arrasto parecem mais ajustáveis às espécies cuja vocalização apresente frequência acima da faixa de ruído potencialmente associado a estes sistemas, em particular quando o comprimento da matriz não é suficiente para minimizar o mascaramento dos sinais recebidos pelos ruídos produzidos pela cavitação da hélice e o próprio fluxo de água (Barlow & Taylor 2005, Benda-Beckmann et al. 2010, Thode et al. 2010).

As baleias cachalote (*Physeter macrocephalus* Linnaeus, 1758), espécie modelo deste estudo (Figura 1), são reconhecidas como uma das espécies mais vocalmente ativas entre os cetáceos e, portanto, detectáveis pelo monitoramento acústico (Barlow & Taylor 2005, Kandia & Stylianou 2006, Nielsen & Møhl 2006).



Figura 1: Baleia cachalote registrada na área de estudo, durante o cruzeiro de outono em 2015 (Foto: Projeto Talude, pesquisadora Elisa Seyboth).

Essa espécie, classificada como vulnerável pela *International Union for Conservation of Nature* (IUCN, 2018), é o maior representante entre os membros da subordem Odontoceti (Ordem Cetartiodactyla), considerada uma espécie de extremos e conhecida, especialmente, por habitar regiões próximas à quebra da plataforma continental, com profundidade superior a 1.000 metros (m) (Rice 1989, Whitehead & Weilgart 1991, Reeves et al. 2002, Whitehead 2003). Sua distribuição se estende a todos os oceanos até as margens de ambos polos (Rice 1989, Whitehead 2003, Reeves et al. 2002, Jefferson et al. 2008). No entanto, podem ser ocasionalmente encontradas em águas mais próximas à costa, onde a plataforma continental seja mais estreita, com ocorrência também associada à presença de *canyons* submarinos (e.g. Reeves et al. 2002, Whitehead 2009).

Machos e fêmeas têm diferentes padrões de histórias de vida e distribuição (Whitehead et al. 1992, Whitehead 2003, 2009). Enquanto as fêmeas e juvenis são observados em grupos maiores, conhecidos como unidades matrilineares, permanecendo em latitudes temperadas e tropicais; machos adultos são encontrados geralmente solitários ou em grupos menores (grupos *Bachelor*), realizando migrações sazonais para latitudes mais altas (Whitehead et al. 1992, Whitehead 2003, 2009).

A espécie é conhecida por realizar regularmente mergulhos longos e profundos que podem atingir profundidades superiores a 2000 m e durar cerca de uma hora (Watkins et al. 1985, 1993, 2002, Rice 1989, Papastavrou et al. 1989, Wahlberg 2002, Watkins et al. 2002, Amano & Yoshioka 2003, Watwood et al. 2006, Irvine et al. 2017). Os indivíduos chegam a passar aproximadamente 70 a 75% de seu tempo em mergulhos de forrageio (Whitehead 2003). Períodos em superfície ocorrem em dois contextos diferentes: (1) entre mergulhos, durante sua fase de superfície, com duração aproximada de 8-10 minutos (Amano & Yoshioka 2003, Whitehead 2003, Watwood et al. 2006, Mathias et al. 2013, Irvine et al. 2017); e (2) quando em períodos de socialização e descanso, mais longos, porém menos frequentes, sendo observados principalmente durante o dia (Whitehead 2003). Portanto, seu comportamento de mergulho, associado à sua ocorrência principalmente em águas *offshore*, contribui para tornar os cachalotes um dos mamíferos marinhos mais difíceis de ser visualmente monitorado (Nielsen & Møhl 2006, Ward et al. 2012).

Os cachalotes produzem uma variedade de tipos de cliques classificados de acordo com o intervalo entre cliques (*Inter-Click Interval*, ICI), duração, direcionalidade, nível de pressão sonora na fonte e comportamento associado à sua emissão; sendo utilizados em diferentes contextos, como no mapeamento acústico do entorno, na

busca e captura de presas e na comunicação social (Zimmer et al. 2005, Caruso et al. 2015, Amorim 2017, Stanistreet et al. 2018).

Os cliques, por ação pneumática, forçam a passagem de ar através dos lábios fônicos ("*Monkey lips*"), que são refletidos pelos sacos aéreos (*Frontal air sac*) localizados na porção posterior do espermacete – órgão preenchido por óleo, que corresponde a cerca de 1/3 o comprimento do indivíduo e opera como um gerador de som – para, então, serem emitidos (Norris & Harvey 1972, Madsen et al. 2002a, Møhl et al. 2003), funcionando como um grande "espelho sonoro" (Caruso et al. 2015). Os lábios fônicos também estão ligados ao lado direito da passagem nasal e ao saco de ar distal, outro "espelho sonoro" localizado, por sua vez, na extremidade anterior da cabeça (Caruso et al. 2015).

Durante os mergulhos de forrageio, os animais produzem cliques do tipo regular, audíveis e de curta duração (*usual clicks*) com frequências que variam de várias centenas de hertz para mais de 30kHz (Waltikins 1980, Weilgart & Whitehead 1988, Møhl et al. 2000, Wahlberg 2002), cuja energia predomina em frequências entre 5 e 15kHz (Madsen et al. 2002a, 2002b, Møhl et al. 2003). Estes sinais são pontuados periodicamente pelos *creaks* (*buzzes*), sinais com alta taxa de repetição associados à captura das presas (Miller et al. 2004), ou seja, ambos associados ao forrageio. Tais sons pulsados possuem rápido tempo de alcance (<1 milissegundos), que melhoram a precisão dos métodos de localização com base na diferença de tempo de chegada (*Time difference of Arrival* – TDOA) entre um par de hidrofones, otimizando sua localização (Barlow & Taylor 2005, Frazer & Nosal 2006). Os cliques sociais, por sua vez, correspondem aos codas, série padronizada de cliques produzidos tipicamente por fêmeas e os *slow clicks*, sinais de baixa direcionalidade e taxa de repetição e energia predominante em frequências mais baixas, produzidos por machos adultos (Weilgart & Whitehead 1988, 1993, Madsen et al. 2002, Stanistreet et al. 2018).

Uma vez que o repertório vocal dos cachalotes os mantém detectáveis por intervalos maiores do que sua disponibilidade visual, o método acústico tem sido cada vez mais utilizado, em esforços independentes ou associado ao monitoramento visual desta espécie, e sua aplicabilidade em diferentes abordagens de pesquisa tem se tornado cada vez mais certa nos últimos anos (Whitehead 2003, Mellinger et al. 2007). O monitoramento acústico de baleias cachalotes tem sido continuamente conduzido utilizando uma variedade de metodologias e a partir de diferentes plataformas: fixas ou móveis (Gillespie 1997, Gannier et al. 2002, Leaper et al. 2003, Hastie et al. 2003, Barlow & Taylor 2005, Lewis et al. 2007, Ward et al. 2012, Fais et al. 2016).

Por produzirem cliques cuja distribuição de frequência estende-se acima da faixa dominante dos ruídos produzidos pelo navio e fluxo de água, é possível que seus cliques sejam detectados por sistemas acústico passivo de arrasto (Barlow & Taylor 2005), tornando viável a associação deste sistema de monitoramento ao esforço visual de amostragem por transecção linear (Barlow & Taylor 2005, Yack et al. 2013). Whitehead (2002, 2003), considera o PAM uma crescente promessa, especialmente quando conduzido a bordo de plataformas oportunísticas móveis, como navios, uma vez que proporcionam uma ampla cobertura com um custo relativamente pequeno podendo, assim, resultar em estimativas mais precisas da abundância da espécie.

No entanto, por ser um método ainda em desenvolvimento, o PAM também apresenta limitações, as quais se espera que sejam superadas à medida que esforços sejam conduzidos, buscando melhorar os equipamentos e métodos de processamento dos sinais (Mellinger et al. 2007, Kusel et al. 2017). Por isso, a integração do monitoramento acústico e visual pode ser particularmente produtiva, fornecendo a maneira mais eficaz de preencher as lacunas atuais no conhecimento dos cachalotes e de outras espécies marinhas (Whitehead 2003, Barlow & Taylor 2005, Yack et al. 2013).

Até hoje, a caça comercial foi a maior ameaça que os cachalotes enfrentaram, pois a espécie foi fortemente explorada (Mackay et al. 2018, Whitehead 2002, 2003). De acordo com Gero et al. (2016) o status de conservação desta espécie é geralmente incerto, pois taxas muito pequenas de mudança, extremamente difíceis de serem identificadas usando a maioria dos métodos disponíveis, podem ser de grande importância. Entre os esforços mais recentes para estimar a abundância de cachalotes a nível global, Whitehead (2002) estimou que o tamanho populacional compreende apenas 32% de seu nível pré-caça.

Informações sobre estrutura populacional e abundância de cachalotes ainda são necessárias para muitas regiões (Novak 2016). No Brasil, até recentemente, apenas informações sobre ocorrência e índice de abundância da espécie (número de observação por unidade de esforço) estavam disponíveis (Pinedo et al. 2002, Zerbini et al. 2004). No entanto, um estudo de distribuição e estimativa do tamanho populacional de cachalotes para a porção externa das plataformas continentais e taludes sul e sudeste brasileiro foi conduzido recentemente através de monitoramento visual, esforço ao qual o presente estudo foi conduzido simultaneamente (Di Tullio 2016).

Apesar dos estudos já realizados, o conhecimento sobre a espécie em águas brasileiras ainda é insuficiente. Informações sobre sua ocorrência, distribuição e abundância ainda são pontuais e, pouco se sabe sobre seu comportamento acústico,

de mergulho e forrageio e, conseqüentemente, sobre sua disponibilidade visual e acústica.

Considerando as limitações associadas aos métodos de monitoramento disponíveis, integrar resultados provenientes de diferentes esforços pode contribuir de forma significativa para um melhor entendimento desta espécie, além de contribuir para o desenvolvimento prático dos métodos utilizados, permitindo ainda o acesso a informações que auxiliem na elaboração de possíveis estratégias de conservação da espécie. Isto se torna particularmente importante considerando que a área amostrada neste estudo está inserida na região correspondente à porção brasileira da bacia sedimentar de Pelotas, onde, além de transporte e navegação, atividades de prospecção e exploração de petróleo que, apesar de ainda pouco desenvolvidas se comparada à outras bacias, têm sido continuamente implementadas, com potencial crescimento esperado para os próximos anos, aumentando a ameaça e risco de conflito entre a presença da espécie e o desenvolvimento destas atividades em ambiente *offshore*.

## 2. Objetivos e estrutura da tese

### 2.1. Objetivo Geral:

Monitorar acusticamente as baleias cachalotes e determinar os padrões de distribuição e abundância desta espécie, além de descrever seu perfil de mergulho na plataforma externa e talude sul brasileiro (bacia de Pelotas).

### 2.2. Objetivos específicos:

- a. Detectar e localizar eventos correspondentes a cadeias de cliques de baleias cachalotes.
- b. Avaliar a ocorrência e distribuição de baleias cachalote de acordo com variáveis geográfica (latitude), fisiográficas (batimetria, distância às isóbatas de 200 e 2000 m e à costa) e antrópicas (Blocos de Exploração de Óleo e Gás, Agência Nacional do Petróleo – ANP, e Áreas Prioritárias para a Conservação, Ministério do Meio Ambiente – MMA).
- c. Descrever os perfis de mergulho de baleias cachalote a partir de *Time-Depth Recorders* (TDR) em águas brasileiras.
- d. Associar informações referentes ao comportamento de mergulho (obtidos a partir dos TDR's e de *Digital Tags* – Dtag) e acústico (Dtag) de baleias

cachalote para, assim, estimar sua disponibilidade acústica e probabilidade de detecção a uma distância horizontal zero,  $g(0)$ .

- e. Estimar a densidade e abundância de baleias cachalote na plataforma continental externa e talude sul brasileiro (bacia de Pelotas) a partir do registro acústicos das vocalizações de forrageio (*usual clicks* e *creak*) que produzem.

### 2.3. Estrutura da tese:

Seguindo a introdução geral, objetivos e estrutura da tese, é apresentada uma breve descrição da área de estudo e coleta dos dados.

A tese segue, então, dividida em três capítulos, em formato de manuscritos, e em preparação para serem submetidos à publicação:

- A detecção e localização dos eventos acústicos correspondentes aos cliques produzidos por baleias cachalotes, sua ocorrência e distribuição em relação a covariáveis (objetivos específicos a e b) são apresentados no capítulo I.
- Os perfis de mergulho de cachalotes em águas brasileiras, estimativas sobre sua disponibilidade acústica e probabilidade de detecção à distância horizontal zero (objetivos específicos c e d) são apresentados no capítulo II.
- Já a estimativa da densidade e abundância de baleias cachalote na região de estudo, através dos cliques que produzem durante o forrageio (objetivo específico e), é apresentada no capítulo III.

Por fim, encontram-se as considerações finais da tese.

## 3. Área de Estudo e Monitoramento Acústico

### a. Área de estudo:

O presente estudo foi conduzido na plataforma continental externa e talude sul do Brasil, do Chuí (Rio Grande do Sul, RS) ao sul da ilha de Florianópolis (Santa Catarina, SC), área onde está situada a porção brasileira da bacia de Pelotas (Figura 2).





Figura 2: Área de estudo, limitada ao norte pelo sul da ilha de Florianópolis, SC e ao sul pelo Chuí, RS, correspondendo também a porção brasileira da Bacia de Pelotas.

Reconhecida como a mais austral entre as bacias sedimentares do país (Santos 2009), Pelotas localiza-se entre os paralelos de 28° e 34° S, limitada ao norte pelo Alto de Florianópolis (Cabo de Santa Marta) e ao sul por sua fronteira com as águas territoriais Uruguaias, onde a bacia se estende até o Alto do Polônio que, geologicamente, a separa da bacia de Punta Del Este (Kowsmann et al. 1974, Rosa 2007, Anjos-Zerfass et al. 2008, Leão et al. 2009, Santos 2009, Batista 2017).

Quando limitada a leste pela isóbata de 2000 m, a porção brasileira dessa bacia possui uma área correspondente a cerca de 210.000 km<sup>2</sup> (Dias et al. 1994, Silveira & Machado 2004), com área emersa abrangendo os estados do Rio Grande

do Sul (RS) e Santa Catarina (SC). Sua plataforma continental é considerada ampla com largura média de aproximadamente 125 Km, sendo mais estreita no cabo de Santa Marta (SC) e Mostardas (RS), alargando-se ao sul, com seus contornos batimétricos acompanhando a morfologia costeira e quebra localizada próxima à isóbata de 180 m (Alves 2006, Santos 2009).

Essa região compreende a Zona de Convergência Subtropical do Atlântico Sul, caracterizada por contrastes resultantes do encontro de correntes marinhas – do Brasil e Malvinas (Leão et al. 2009, Santos 2009).

O estágio de conhecimento sobre o sistema petrolífero da bacia de Pelotas ainda é incipiente (Anjos-Zerfass et al. 2008). As primeiras investigações tiveram início nas décadas de 1950/60 (Santos 2009, Batista 2017). Desde a criação da Agência Nacional do Petróleo (ANP) até o presente, blocos de exploração identificados para esta bacia foram incluídos em seis rodadas de licitação promovidos pela agência, havendo hoje quatro blocos sob concessão (Batista 2017).

Apesar dos esforços exploratórios ainda serem considerados pequenos, se comparado ao observado em outras bacias (Santos 2009), recentemente a ANP tem investido em estudos a fim de avaliar o potencial petrolífero da região (Batista 2017). Os resultados apontam para a ocorrência de micro destilações de gás, particularmente na região onde localiza-se o cone de Rio Grande, cuja composição se assemelha à de outras bacias, como a de Santos, gerando perspectivas quanto ao seu potencial comercial (Santos 2009, Batista 2017).

A ocorrência de acumulações de hidratos de gás que, segundo Santos (2009) ocorrem especialmente associados a taludes e elevações continentais, já havia sido reportada por Sad et al. (1998) para a margem continental desta bacia, em batimetrias de 1.000 a 2.500 m.

É importante considerar, no entanto, que com o possível interesse na expansão da exploração de petróleo e gás, associado, ainda, ao transporte marítimo já realizado na região, a ocorrência de conflitos resultantes da ocupação de áreas comuns por estas atividades e a biodiversidade marinha, incluindo os cetáceos, torna-se potencial (Alves 2006, Andriolo et al. 2010, Castro et al. 2014), reafirmando a importância de monitorar o possível impacto advindo destas atividades, destacando-se a oportunidade de acompanhar integralmente seu processo de implementação.

b. Monitoramento acústico passivo:

O presente estudo é resultado de uma parceria entre a Universidades Federal de Juiz de Fora (UFJF, Laboratório de Ecologia Comportamental e Bioacústica – LABEC) e a do Rio Grande (FURG, Laboratório de Ecologia e Conservação da

Megafauna Marinha – EcoMega), contando com o suporte logístico de ambas instituições e do Instituto Aqualie.

O monitoramento acústico dos cachalotes foi conduzido oportunisticamente a bordo do Navio Oceanográfico R/V Atlântico Sul, durante cinco cruzeiros (outonos de 2013, 2014 e 2015 e primaveras de 2014 e 2015) do Projeto de Monitoramento Visual de Mamíferos Marinhos (Projeto Talude – EcoMega, FURG), como um de seus subprojetos, seguindo o método de amostragem por distância através de transecção linear (Buckland et al. 2001) em zig-zag. No entanto, no presente estudo, são apresentados apenas os resultados obtidos a partir dos registros acústicos feitos durante o segundo, terceiro e quarto cruzeiros (outono e primavera de 2014 e outono de 2015, respectivamente), com qualidade e número de canais suficientes para a condução das análises.

Os sinais acústicos foram coletados de forma contínua durante o período de amostragem visual (entre 5 e 19h) e em estado do mar até 6 na escala Beaufort. O monitoramento durante a noite foi possível apenas quando, mesmo após o fim das observações, o navio manteve a navegação seguindo os transectos planejados.

Dois tipos de matrizes rebocadas (AUSSET®) foram utilizados: (a) matriz linear de 250 m composta por três elementos omnidirecionais (1.592 Hz *High pass filter* – “passa alta”) equidistantes cinco metros e dispostos cinco metros a partir da extremidade do cabo para manter a estabilidade do sistema; e (b) matriz linear de 300 m (para reduzir o ruído produzido pelo navio), também composta por três elementos omnidirecionais (0,499 Hz *High pass filter* – “passa alta”) distantes cinco e três metros, respectivamente, e dispostos cinco metros a partir da extremidade do cabo. A primeira configuração foi utilizada durante o primeiro cruzeiro e a segunda durante o segundo e terceiro.

Os sinais registrados pelos hidrofones foram transmitidos a um gravador digital (Fostex® FR-2 LE), com entrada para dois canais, a bordo do navio. Em seguida, foram gravados em arquivo digital (*arquivo .wav*) e armazenados em disco rígido para análise subsequente. A frequência de amostragem adotada para este sistema foi de 96KHz/24 bits. Quando possível, os sinais acústicos foram transmitidos a uma placa digitalizadora (modelo Iotech-Personal Daq/3000 Series) com frequência de amostragem de 200KHz/24 bits, permitindo o registro acústico pelos três canais.

Dados ambientais (velocidade e direção do vento, estado do mar) e da embarcação (coordenadas geográficas, velocidade e direção do navio) foram coletados pela equipe de observadores e registrados através do software WinCruz. Um sistema adicional de registro de coordenadas (EchoView), conectado ao mesmo GPS, também foi utilizado.

c. Monitoramento via satélite do comportamento de mergulho:

O comportamento de mergulho de baleias cachalote foi monitorado de forma remota, a partir de dados obtidos por telemetria via satélite. A colocação de transmissores do tipo *Time-depth recorders* – TDR's (MK-10, *satellite-linked tags*, *Wildlife Computers*), em configuração de baixo impacto (LIMPET, *low impact minimally percutaneous external-electronics transmitter*) foi realizada durante as atividades do Projeto Monitoramento de Cetáceos, na plataforma continental e talude sul brasileiro, entre 07 a 22 de dezembro de 2012.

O monitoramento visual da espécie foi conduzido a bordo do navio R/V Atlântico Sul de 36 metros de comprimento. Quando avistado um grupo de baleias cachalote e em condições ideais para a descida de um bote inflável de casco rígido, com 6,7 m de comprimento (estado do mar até 3-4 na escala Beaufort), a aproximação e colocação dos transmissores foram conduzidas. Os transmissores implantados na superfície dorsal do indivíduo a partir de balestra de 150 lb (Andrews et al. 2008), foram programados para registrar os dados de profundidade em intervalos de 150 a 300 segundos (devido à limitada durabilidade das baterias). Os sinais, juntamente com os dados de profundidade, foram transmitidos a satélites do sistema Argos, que classificou as posições dos indivíduos em diferentes categorias de qualidade com precisão decrescente: 3, 2, 1, 0, A, B (Argos 1990), as quais foram obtidas remotamente através de plataforma online.

Como o monitoramento acústico foi conduzido de forma passiva, não exigiu autorização de comitê de ética, assim como permissão específica do Instituto Chico Mendes (ICMBio) ou institutos estaduais do meio ambiente, uma vez que a região não inclui áreas de proteção (Di Tullio 2016). Já a colocação dos transmissores satelitais foi conduzida sob licenças emitidas pelo Instituto Chico Mendes para Conservação da Biodiversidade ao Dr. Artur Andriolo (ICMBio - licença # 27072-1).

## CAPÍTULO I

**Can you find me by just listening for my clicks? Passive acoustic monitoring of sperm whales (*Physeter macrocephalus*) and this species distribution on the outer continental shelf and slope off southern Brazil (Pelotas Basin)**

Manuscrito em preparação para submissão à revista: "*Deep Sea Research I*"

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## **Can you find me by just listening for my clicks? Passive acoustic monitoring of sperm whales (*Physeter macrocephalus*) on the outer continental shelf and slope off southern Brazil (Pelotas Basin)**

### **Abstract**

In face of new potential threats introduced in all oceans worldwide, through the development and intensification of anthropogenic activities, the sperm whales monitoring becomes imminent, especially in regions where knowledge about this species is still limited. In recent years, alternative methods, including Passive Acoustic Monitoring (PAM), have been increasingly considered. Here, results of the first sperm whale PAMs effort carried out in the southern Brazilian outer continental shelf and slope are presented. Three ship-based surveys were conducted using a 3-element towed array. Recordings were processed using PAMGuard to detect and localize sperm whale click trains. Subsequent acoustic events not separated by non-detection intervals greater than 30 minutes (min) were grouped and named as acoustic encounters. Their occurrence and distribution in relation to stationary and anthropogenic features were then assessed. A total of 178 on-effort recorded events, comprising 21 acoustic encounters were analyzed. Acoustic encounters were recorded at depths of 405 meters (m) to 2523 m with 57% occurring beyond the 1000 m isobath. Nevertheless, 85.71% (n = 18) of total recordings were between the slope limits (200 m and 2000 m isobaths). Seven recordings (33.33%) occurred in oil and gas blocks. In contrast, all acoustic encounters were recorded in Priority Areas for Conservation (PACs). The best-fitted model indicated depth as the only covariate with a significantly positive relationship to sperm whale acoustic encounters distribution. PACs are located within the entire area of sperm whale occurrence. However, they are only instruments that may support and drive the future implementation of management actions in the region. Despite a minority of acoustic records have been recorded in oil and gas exploration blocks, due to the sperm whale's proximity to such areas, monitoring this species' distribution, as well as all process associated with oil and gas activities is recommended.

Keyword: toothed whales, acoustic, towed array, distribution, oil and gas blocks.

## Introduction

To date, the greatest threat that sperm whales (*Physeter macrocephalus* Linnaeus, 1758) across the globe have faced was large-scale hunting, which occurred over two extensive periods: between the early eighteenth century, and establishment of the International Whaling Commission's moratorium in 1986 (Whitehead 2002, 2003, Novak 2016). However, new potential threats have been introduced worldwide, through the development and intensification of anthropogenic activities, particularly those carried out in offshore areas (e.g. Reeves et al. 2003, Whitehead 2003, Nielsen & Møhl 2006, Madsen et al. 2006, Miller et al. 2009, Jewell et al. 2012, Marques et al. 2013, Weilgart 2013, Isojunno 2014, Fais et al. 2016, Fleishman et al. 2016).

Marine pollution, fishing, the whale watching industry, and an increase in oil exploitation and shipping, with ship collisions and noise pollution as consequences, are potential threats, not only for sperm whales, but also for marine fauna in general (Reeves et al. 2003, Whitehead 2003, Nielsen & Møhl 2006, Oliveira 2014, Jewell et al. 2012). Many of these activities are expected to increase in the coming decades (Jewell et al. 2012). Thus, immediate monitoring of sperm whale populations, including their response to these activities, becomes imminent (Nielsen & Møhl 2006, Jewell et al. 2012, Marques et al. 2013, Fleishman et al. 2016, Novak 2016). This is especially important in regions where knowledge about this species is still limited (Jewell et al. 2012).

The species is the largest deep-diving toothed whale, widely distributed in almost all deep waters (>1000 meters, m) above and beyond the continental slope between the ice edges of both poles (Rice 1989, Jaquet & Whitehead 1996, Whitehead 2002, 2003, Reeves et al. 2003, Jefferson et al. 2008). Individuals regularly perform long, deep dives greater than 400 m, known as foraging dives, during which they can reach depths of up to 2000 m, usually between 30 and 45 minutes (min) in duration, but which can last over an hour (Watkins et al. 1993, 2002, Wahlberg 2002, Amano & Yoshioka 2003, Watwood et al. 2006, Aoki et al. 2007, Irvine et al. 2017).

A sperm whale's time at the surface occurs in two different contexts, (1) during socializing/resting periods, usually during daylight hours (Whitehead 2003), and (2) between dives, during which the surface phase lasts approximately 8-10 min (Amano & Yoshioka 2003, Whitehead 2003, Watwood et al. 2006, Mathias et al. 2013, Irvine et al. 2017). Thus, besides the logistics required to survey their deep-water preferential habitats (Rice 1989), species such as sperm whales are difficult to monitor visually (Nielsen & Møhl 2006), since individuals typically spend about 70 to 75% of their time in foraging dives (Whitehead 2003, Watwood et al. 2006, McDonald et al. 2017). This

potentially contributes to the reduced probability of detecting individuals visually (Whitehead 2003, Nielsen & Møhl 2006, Watwood et al. 2006, Ward et al. 2012, McDonald et al. 2017).

Furthermore, visual monitoring methods require training of a qualified observer team, good weather and sea conditions, and must be carried out during daylight hours, thereby reducing temporal coverage (Mellinger & Barlow 2003, Evans & Hammond 2004, Nielsen & Møhl 2006, Mellinger et al. 2007, Ward et al. 2012, Marques et al. 2013, Yack et al. 2013).

In contrast, sperm whales are well suited to acoustic monitoring, due to their vocal repertoire, which consists mainly of regular and distinctive clicks, and makes them one of the marine mammals more likely to be acoustically surveyed, even during foraging dives and while several miles away from the ship (Barlow & Taylor 2005, Kandia & Stylianou 2006, Nielsen & Møhl 2006).

Passive Acoustic Monitoring (PAM) has been increasingly applied in recent years, becoming important as either a complementary or alternative monitoring technique to the conventional visual method, particularly in low visibility conditions (Mellinger et al. 2007, Gillespie et al. 2008, 2009, Yack et al. 2013, McDonalds et al. 2017, Verfuss et al. 2018). PAM also offers a non-invasive method for studying species that are usually difficult to observe, as pointed out by McDonalds et al. (2017).

Sperm whale occurrence and distribution on the Brazilian southern and southeastern outer continental shelf and slope has already been studied using visual surveys (Zerbini et al. 2004, Di Tullio 2016, Di Tullio et al. 2016), as their distribution and density relative to environmental features (Di Tullio 2016).

Here, we present results of the first passive acoustic monitoring effort of sperm whales carried out systematically on the southern outer continental shelf and slope off of Brazil, in an area corresponding to the Brazilian portion of the Pelotas Basin. This species' occurrence and distribution in relation to stationary features were assessed using acoustic recordings. Furthermore, snapshots are presented of sperm whale occurrence in areas identified as having potential for oil and gas exploration, and in areas identified as priorities for biodiversity conservation.

## **Methods**

### *Study area and data collection:*

Three ship-based surveys were conducted aboard the 36 m-long *R/V Atlântico Sul* during fall and spring 2014 and fall 2015 on the southern continental shelf break



and slope off Brazil, from Chuí (Rio Grande do Sul State, RS – 34° S) to the south of Florianópolis (Santa Catarina State, SC – northern limit of Pelotas Basin, 28°40' S), mainly between the outermost portion of the continental shelf (100 m isobath) and the slope's lower limit (2000 m isobath) (Figure 1.1).

Sperm whale acoustic recordings were carried out opportunistically during a marine mammal visual monitoring project (Slope Project - *Projeto Talude/ EcoMega – FURG*), as one of its subprojects, following the line-transect distance sampling method (Buckland et al. 2001) (Figure 1.1a). However, as this study focuses on investigating the occurrence and distribution of this species using passive acoustic monitoring, a comparative approach between both methods (visual and acoustic) is not covered here. Visual survey results can be consulted in Di Tullio (2016) and Di Tullio et al. (2016).

The zigzag sample design, planned for the visual survey, was the same during the first two cruises (Figure 1.1b and c). However, for the third cruise, the design was modified to allow for sampling in deeper waters (up to the 3000 m isobath) (Figure 1.1d), which was required by one of the activities carried out on board. Therefore, four transects were extended to the 3000 m isobath.

Two different three-element towed array configurations (AUSSET®) were employed: (a) a 250 m three-element linear array (1.592 Hz high pass filter) with hydrophones equally spaced five meters apart (used during the first cruise), and (b) a 300 m three-element linear array (0.499 Hz high pass filter) with hydrophones spaced five and three meters apart (used during the second and third cruises). These arrays configurations had elements (hydrophones) located five meters from the end of the cable, to which a two-meter-long rope was attached to provide stability to the system (Supplementary material S1 and S2). The array was towed at an average speed of 9.95 knots, to a depth of up to 4 m, based on Thode et al. (2010).

Although 24-hour monitoring is one of the main advantages of acoustic monitoring methods, recordings were made mostly during daylight periods (since acoustic monitoring was simultaneously conducted with a visual survey), up to a rough sea state (Beaufort scale up to 6). Acoustic monitoring was also opportunistically conducted during part of the night, when the ship stayed on the trackline, even after the end of the visual effort.

Hereafter, “on effort” corresponds to acoustic monitoring conducted when on the trackline. In turn, “off effort” corresponds to acoustic recordings performed when visual sampling ceased on the transect, e.g. to approach a sighted marine mammal group for counting and photo-identification.

Daily acoustic recordings were transmitted to a Fostex® FR-2 LE digital recorder (two channels with a frequency response of 48 kHz) or an Iotech-Personal Daq/3000 Series acquisition board (three channels with a frequency response of 100 kHz) onboard the ship, and were stored on a hard drive as wave files (.wav) for post-analysis. The ship's geographic coordinates were also continuously recorded by a GPS coordinate system, connected to two storage programs: (1) WinCruz (used by the visual monitoring team) and (2) Echoview. Echoview was first adopted because it recorded the coordinates every two seconds. However, where gaps in information occurred, records from WinCruz were used if available.

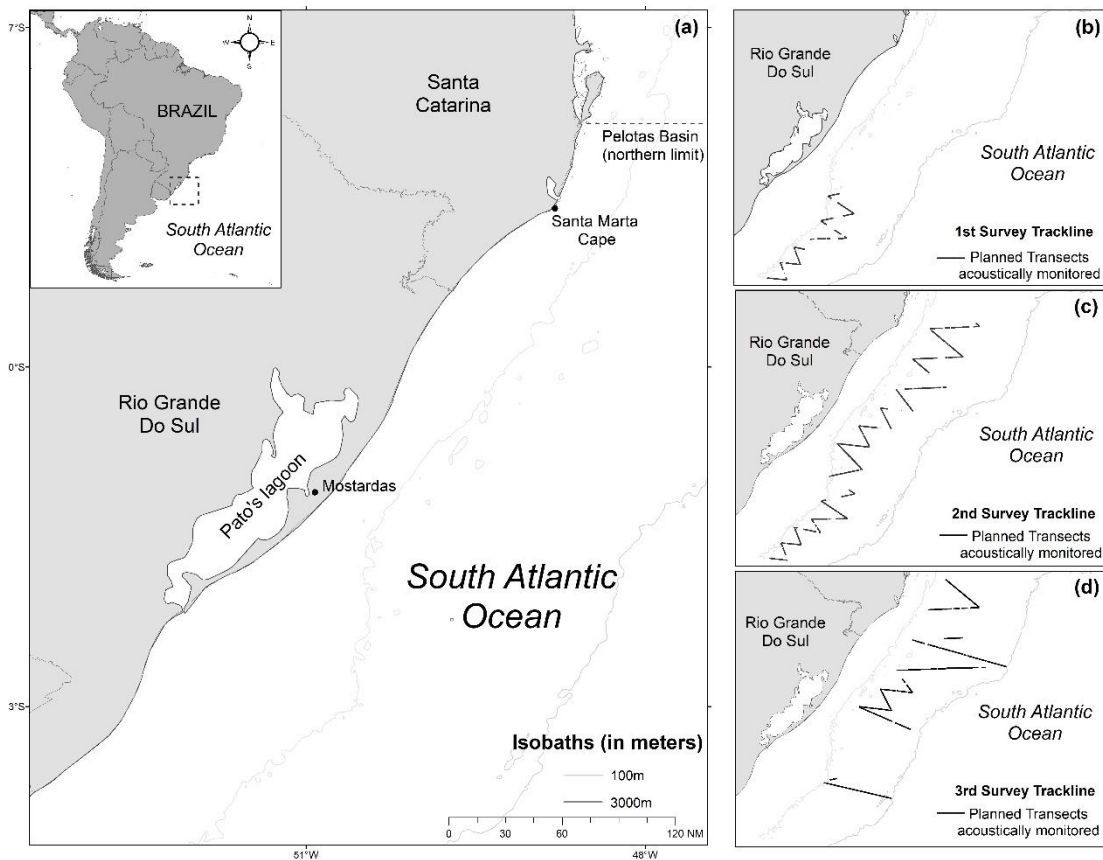


Figure 1.1: Study area on the southern outer continental shelf and slope off Brazil, from Chuí (RS) to the northern limit of the Pelotas Basin (a). During the surveys, the portion of the ship-based visual survey sample design acoustically monitored during: (b) fall 2014, (c) spring 2014 - same design, and (d) fall 2014 - with a modification to allow deeper water sampling at 3000 m isobath.

*Data processing:*

a. Acoustic data analysis:

A preliminary screening of the acoustic recordings was performed by means of long-term spectral averages (LTSA) using the custom software program Triton

(Wiggins & Hildebrand 2007) developed in MATLAB (Mathworks, MA 2014a), to search for signals of interest. Furthermore, one-minute spectrograms that were taken every three minutes from these recordings were visually inspected (Hann window of 512 points of FFT with 50% overlap) using Raven Pro 1.5 (Cornell Laboratory of Ornithology, NY 2017) to minimize the number of missed clicks (false negatives).

Two-channel acoustic files were then processed using the open-source software PAMGuard, version 1.15.11 (Gillespie et al. 2008). Following Gillespie et al. (2009), detections were carried out using this program's click detector module. First, the raw data were filtered to remove signals above 2000Hz, then passed through a 2-17 KHz band-pass filter. A threshold trigger was applied to the output data to select transient sounds, which had an intensity of at least 12 dB above background noise and were within the sperm whale frequency band (see Swift et al. 2009 and Macaulay et al. 2015).

Click length and the minimum and maximum click separations were determined based on the frequency sample adopted and the distance between the pair of hydrophones used, which varied between recordings. Two additional classifiers were applied to remove noise from the survey ship's 18 and 35 kHz echo sounders. In addition, the click detector *angle vetoe* feature was used to eliminate any detections between 88 and 92° to avoid false triggers caused by ship noise.

Detected signals were displayed as bearings against time (Isojunno 2014), which were estimated by the time difference of arrival (TDOA) of each signal to the pair of hydrophones used (Hastie et al. 2003, Lewis et al. 2007, Swift et al. 2009).

Together with the GPS data, detections were loaded and simultaneously processed (Macaulay et al. 2015) in the PAMGuard Viewer mode to visualize the ship's track while performing click train location analyses. As pointed out by Swift et al. (2009), the assignment of species clicks to their respective click trains is a manual process. Thus, detection results were visual and aurally inspected throughout the spectrogram, and additional PAMGuard displays (e.g. waveform, power spectrum, inter-click interval) were used to identify sperm whale clicks and reduce false-positive detections and echoes (Supplementary material S3 and S4).

Sperm whale click trains were identified as sequences of regularly spaced clicks displayed at bearings that shifted slowly as the ship passed by individuals or a group (Swift et al. 2009). Usual and creaks (hereafter referred as foraging vocalizations), coda and slow clicks were separated into different trains. For each sperm whale click train or for a group of the closest trains identified, a corresponding event was created (Swift et al. 2009).

Target motion analysis (TMA) was performed to estimate the location of an event (Supplementary material S5). Bearings corresponding to each event were plotted from different points along the trackline as the survey platform passed an individual or group; and an individual's or group's perpendicular distance to the trackline was estimated, assuming a slow whale swim speed relative to the ship's speed (Gillespie 1997, Leaper et al. 2000, Hastie et al. 2003, Barlow & Taylor 2005, Lewis et al. 2007).

As the trackline is rarely straight and is characterized by constant oscillations, the observed left-right ambiguities in the linear array can be potentially solved. The more the trackline deviates from a straight line, the more likely an event position can be better identified (PAMGuard guidelines). PAMGuard's TMA also calculates the Akaike's Information Criterion (AIC) for each location model, thereby supporting the selection of the best-estimated position.

Information on location and perpendicular distance to the trackline of each selected event was stored in a database and exported as a .csv file, along with the number of trains per event, click type and location quality score, all of which were identified by an acoustician.

b. Acoustic encounter spatial analysis:

Event sequences were organized into detection blocks, which were separated from each other by a 30 min interval (an interval without sperm whale click detection). Considering sperm whale diving behavior, this interval was chosen based on Gordon et al. (2000), whom adopted one-hour interval without acoustic detection to determine an independent encounter. Here, half of that interval was adopted, as the average survey speed (~10 knots) was twice that of the recorded survey speed in the Gordon et al. (2000) study.

Event locations were plotted using ArcMap (ArcGIS 9.3). For detection blocks with more than one event, the geographic center was estimated based on the position of the events using *Mean Center* (Spatial Statistical Tools, ArcToolbox). Results were merged into one-event detection-block positions (Data Management Tools, ArcToolbox), hereafter referred to as "acoustic encounters".

Each acoustic encounter was evaluated to determine whether it overlapped with (1) oil and gas blocks (already under concession or recently offered by the Brazilian National Petroleum Agency – ANP 2018, Batista 2017), and (2) Priority Areas for Conservation (PACs – areas identified by the Brazilian Ministry of the Environment – MMA 2018) located in the Pelotas Basin. *Count points in Polygon* (Hawth's Tools

extension) and *Join* analyses were used for this purpose, with each acoustic encounter position listed in a Geographic Coordinate System (GCS, WGS 84).

Likewise, the minimum distances from each acoustic encounter to (1) the coastline (shapefile from the Brazilian Institute of Geography and Statistics – IBGE 2018), (2) the 200 m isobath, (3) 2000 m isobath (shapefiles from the Mineral Resources Research Company – CPRN 2018), and (4) the oil and gas blocks were estimated using *Proximity* (Analysis Tools, ArcToolbox), adopting the Universal Transverse Mercator (UTM, WGS 84, zone 25° S) coordinate system.

The corresponding depth values of acoustic encounters were also assessed through the *Spatial Analyst Tool* (Extract, ArcToolbox), using the 1 arc minute version of ETOPO1 (Amante & Eakins 2008) bathymetry (in meters) for the Pelotas Basin.

The spatial analysis results were used in descriptive statistics of the acoustic encounters recorded in this study. On-effort acoustic tracklines were equally divided into 20 nautical miles (nm) segments (~37 km), as adopted for a sperm whale distribution assessment by Gannier et al. (2002) and Jaquet & Gendron (2002). The latter study was conducted in a region with a topographic scale similar to that sampled in the present study and corresponding to four times the average interval between two independent acoustic encounters, adopted here.

For each segment, (1) the number of acoustic encounters and (2) its midpoint were calculated. The midpoint coordinates were plotted, overlapping the same shapefiles described above, to determine the bathymetric values and the minimum distances to the coastline, the 200 m and 2000 m isobaths, and the oil and gas blocks. The results and the latitude of each segment midpoint were adopted as explanatory variables in the fitted distribution model.

#### c. Statistical analysis:

Descriptive statistics (mean, standard deviation (sd) and range - minimum to maximum, hereafter referred to as “min-max”) were used to summarize the results of the estimated minimum distances between the acoustic encounters and (1) the coastline, (2) the 200 m and 2000 m isobaths, and (3) the oil and gas blocks, along with depth values corresponding to the acoustic encounter’s mean center. The presence/absence (represented by 1 and 0, respectively) of these encounters in oil and gas blocks, and their recordings in waters deeper or shallower than 1000 m were compared using the nonparametric Wilcoxon Test. Likewise, differences in distance to the coast between recordings made to the north and south were verified using the non-parametric Mann-Whitney Test.

For distribution modelling, trackline segments were adopted as sample units. An exploratory data analysis was performed to check for normality, homoscedasticity and outliers (Zuur et al. 2007, 2009). Linearity was also verified between acoustic encounters per trackline segment (response variable) and covariates (also called explanatory variables). A Spearman's correlation test was applied to evaluate the collinearity between explanatory continuous variables (Zuur et al. 2009). Those with a correlation coefficient  $|r|$  greater than 0.6 were considered collinear and therefore were not included in the same model.

The relationship between the response variable and covariates was modeled using a Generalized Linear Model (GLM) (McCullagh & Nelder 1989, Zuur et al. 2007, 2009), with a logarithmic link function (log-link function). In addition to Poisson, a negative binomial distribution, recommended for a count response variable (Zuur et al. 2007, 2009), was tested for overdispersion. A log-link function was chosen to ensure positive counts and a linear relationship with the covariates (Dolman 2007).

The best-fitted model was chosen based on the lowest value of Akaike's Information Criterion (AIC) (Burnham & Anderson 2002), using backward stepwise selection. Among the nested models, the Chi-square Test for Goodness of Fit was also applied to support the best model choice.

All statistical analyses were performed in R (R Development Core Team 2017, version 3.4.3), using the stats and MASS packages. For all analyses, the statistical significance adopted was  $\alpha = 0.05$ .

## **Results**

### **a. Acoustic survey effort:**

Over the 29-days acoustic monitoring effort, approximately 1850nm of trackline were covered, totaling around 210 hours (h) of acoustic data recording (Table 1.1).

Table 1.1: Acoustic effort (in hours and nautical miles), number of sperm whale's acoustic encounters, the average acoustic encounter rate per segment recorded in each survey, in both daylight hours and nighttime.

Cruise	Daytime		Nighttime			
	Acoustic effort		Acoustic encounters	Acoustic effort		Acoustic encounters
	(hh:mm:ss)	(nm)		(hh:mm:ss)	(nm)	
Fall/ 2014	29:54:06	250.78	2	0:08:13	1.18	-
Spring/ 2014	84:02:48	749.38	17	8:13:48	73.39	1
Fall/ 2015	70:13:49	624.9	3	16:52:12	150.12	1
<b>Total</b>	<b>184:11:23</b>	<b>1625.06</b>	<b>22</b>	<b>25:14:13</b>	<b>224.69</b>	<b>2</b>

Due to logistical and acoustic equipment issues, it was not possible to acoustically sample all transects completely, which resulted in different coverages between cruises.

b. Acoustic encounters descriptive analysis:

Twenty-four sperm whale acoustic encounters were recorded in 13 recording days and were distributed throughout almost the entire study area. A gap in detections was observed in waters between northern RS and the southern end of SC, corresponding to 15.54% (29275.78 km<sup>2</sup>) of the covered area (Figure 1.3). Most recordings occurred from this gap southward, area correspondent to 86489.44 Km<sup>2</sup> (45.91% of the study area), comprising 62.5% (n = 15) of total acoustic encounters. From the gap northward (72624 km<sup>2</sup>, 38.55% of the study area), of the small number of records obtained during the three cruises, one-third of those records occurred in waters deeper than 2000 m, which were sampled only during the third cruise, at least once in both areas: north and south of the gap. The northernmost acoustic encounter was recorded near to Santa Marta Cape (SC).

A total of 285 sperm whale detection events were identified, with a mean of 8.91 events per encounter (min-max: 1-45, sd: 12.03). On average, acoustic encounters lasted  $27.52 \pm 28.92$  min (from the first to the last recorded click), with minimum and maximum durations of 0.32 min (corresponding mainly to creak and coda detections, with a known lower inter-click interval – ICI) and 98.82 min, respectively. The sum of their durations corresponded to 4.68% of the total acoustic monitoring time.

Because of hydrophone array instability due to ship maneuvers during off-effort recordings and its effect on bearing estimation, only 178 on-effort recorded events, comprising 21 acoustic encounters were analyzed. The assignment of click trains to individuals resulted in an estimated 216 individuals with a mean of 1.21 individuals per event (min-max: 1 to 4, sd: 0.43).

On average, sperm whales were observed at 31.55 degrees south latitude (min-max: 28.63° S to 34.40° S, sd: 1.91), 183.07 km from the coastline (min-max: 116.64 km to 301.26 km, sd: 49.46 km), with a significantly greater distance observed for the encounters recorded to the north of the gap (212.74 km compared to 160.81 km recorded for the encounters to the south; Mann-Whitney Test,  $W = 20$ ,  $p$ -value = 0.0148) (Figure 1.2).

Acoustic encounters were recorded at depths of 405 m to 2523 m (mean: 1208 m, sd: 628.30), with 57% occurring beyond the 1000 m isobath. Despite this, a significant difference was not observed between the inshore recordings and those beyond the 1000 m-depth (Wilcoxon Test,  $V = 99$ ,  $p$ -value = 0.5255).

Nevertheless, 85.71% ( $n = 18$ ) of total recordings were between the slope limits of the 200 m and 2000 m isobaths. The average distances from these recordings to the 200 m and 2000 m isobaths were 50.55 km (min-max: 1.18 km to 195.38 km, sd: 54 km) and 40.17 km (min-max: 9.24 km to 73.77 km, sd: 16.65 km), respectively (Figure 1.2).

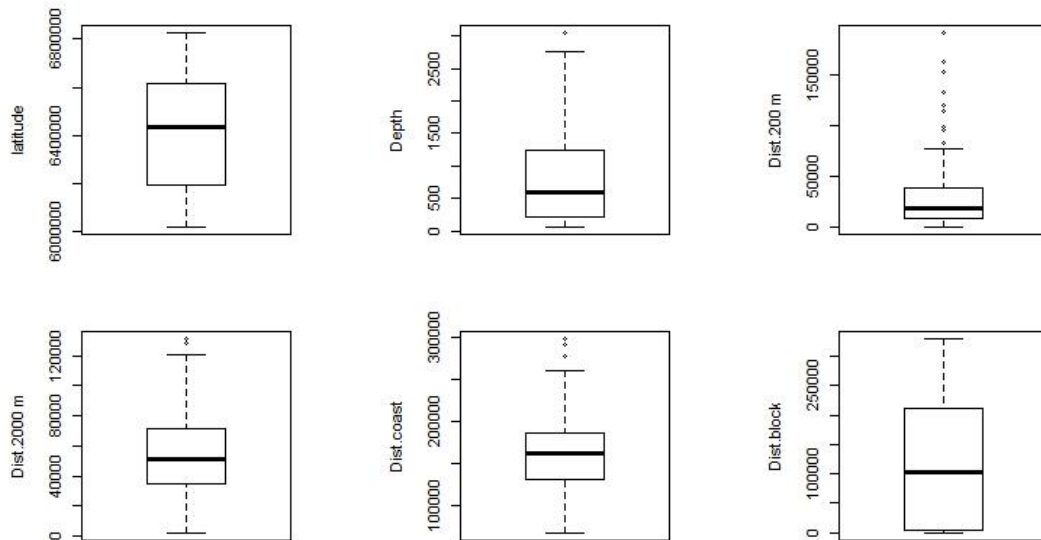


Figure 1.2: Mean center of acoustic encounters occurrence in relation to (a) latitude (in Universal Transverse Mercator, corresponding to the 34.6823°S to 27.8155°S latitude interval), (b) depth, (c) distance to 200 m isobath, (d) distance to 2000 m isobath, (e) distance to the coastline, and (f) distance to the oil and gas blocks, all in meters.

Acoustic encounter occurrences were also evaluated in oil and gas blocks, as petroleum activity is of major importance and in constant development in offshore areas. According to the Brazilian National Petroleum Agency, there are 39 oil and gas blocks, divided into three sectors, in the Pelotas Basin. The first sector has 33 blocks (areas ranging from 641.40 km<sup>2</sup> to 654 km<sup>2</sup>), which were offered in the sixth bidding



round promoted by the Agency. Of these, only four blocks were granted for exploration. The second and third sectors have four and two blocks (areas ranging from 2546.98 km<sup>2</sup> to 2561.88 Km<sup>2</sup>), respectively, which were offered in the 14th bidding round, but without concession. A 1924.20 km<sup>2</sup> overlap area was observed between blocks of the first and second sectors (Figure 1.3).

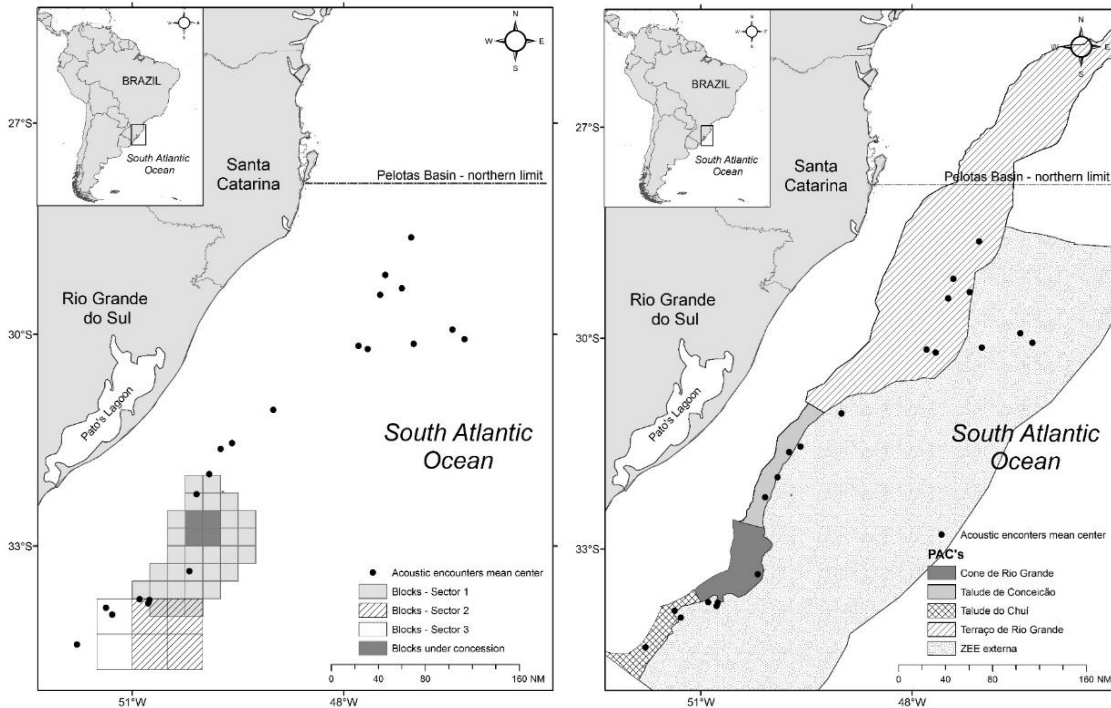


Figure 1.3: Mean center of acoustic encounters occurrence, considering on-effort events, in (a) oil and gas exploration blocks/sectors and (b) Priority Areas for Conservation (PACs).

Two acoustic encounters were observed in blocks of the first sector, while there were three and two encounters in blocks of the second and third sectors, respectively. There were no encounters in the mentioned overlap area. This totals seven recordings (33.33%) in oil and gas blocks. Nevertheless, no significant difference was observed between the number of recordings within and all those outside of these blocks (Wilcoxon Test,  $V = 77$ ,  $p\text{-value} = 0.1316$ ). In contrast, all acoustic encounters were recorded in areas identified by the government as priorities for conservation (PACs). These areas correspond to five PACs, which are shown as polygons (Figure 1.3), namely Cone do Rio Grande PAC, Talude de Conceição PAC, Talude do Chuí PAC, Terraço do Rio Grande PAC and ZEE external PAC.

c. Distribution modeling:

In addition to the descriptive analysis, the relationships between the acoustic encounters recorded per trackline segment and the covariates were modeled. Due to the small number of segments with acoustic encounters, the modeling was performed using the combined datasets of the three surveys. As the response variable and the model residuals presented a non-normal distribution in the exploratory analysis step, sixteen GLMs (Poisson and negative binomial distribution) were fitted, considering only non-correlated explanatory variables (Table 1.2). Collinearity (Spearman's correlation coefficient greater than  $|r| > 0.6$ ) was observed between four of the five covariates evaluated (Table 1.2). Latitude and distance to the oil and gas blocks presented the highest coefficient, being positively correlated. Depth, in turn, was both negatively and positively correlated to minimum distance to 2000 m and 200 m isobaths, respectively.

Table 1.2: Spearman's correlation coefficients for the explanatory variables. Values of  $|r| > 0.6$  are highlighted.

	Latitude	Depth	200 m isobath	2000 m isobath	Coastline
Latitude	1	0.0287	0.3004	0.1645	-0.2053
Depth	0.0287	1	0.7022	-0.7143	0.6422
200 m isobath	0.3004	0.7022	1	-0.3802	0.6040
2000 m isobath	0.1645	-0.7143	-0.3802	1	-0.3864
Coastline	-0.2053	0.6422	0.6040	-0.3864	1

Since there was no overdispersion, only the Poisson regression model results are presented. The eight models developed show goodness of fit (Table 1.3). However, comparing the simplest to the most complex models, the inclusion of additional explanatory variables was not relevant to justify their adoption.

Table 1.3: Poisson regression models fitted to investigate the relationship between covariates, the response variable and their respective: Residual degree of freedom (Df), Residual deviance, Akaike's Information Criterion (AIC) and Anova (Chi-square) test among nested models. Distance to the coast: dist.coast, Distance to the 200 and 2000m isobath: dist.200 m and dist.2000 m, respectively.

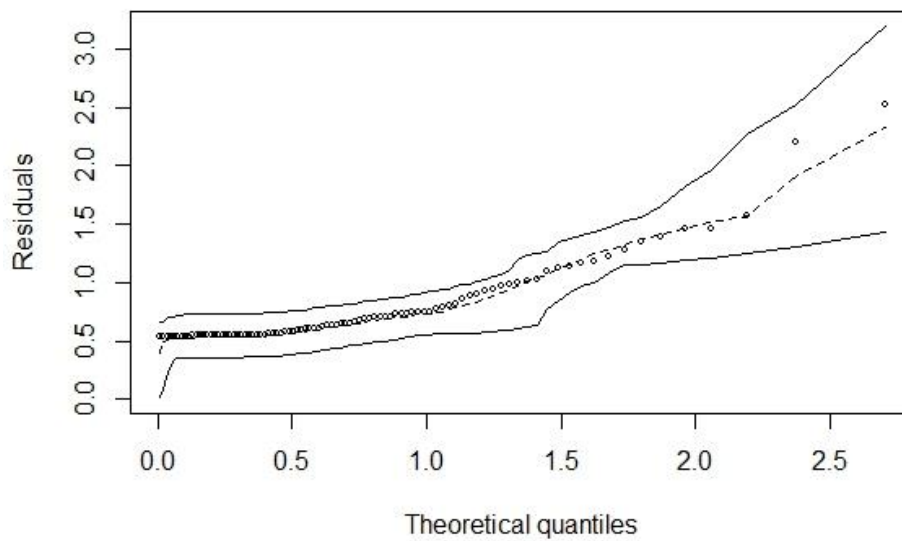
Model	Residual Df	Residual Deviance	Step AIC	Goodness of fit test	Anova Pr(>Chi)
acoustic encounter ~ depth + latitude	88	65.630	110.19	0.9643	-
acoustic encounter ~ depth	90	66.534	<b>108.38</b>	0.9698	0.4917*
acoustic encounter ~ latitude + dist.200 m + dist.2000 m	88	65.631	111.47	0.9643	-
acoustic encounter ~ latitude + dist.200 m	89	66.723	110.56	0.9627	0.4851*
acoustic encounter ~ dist.200 m	90	67.372	<b>109.21</b>	0.9642	0.4626**
acoustic encounter ~ dist.coast + dist.2000 m + latitude	88	65.906	111.75	0.9623	-
acoustic encounter ~ dist.coast + dist.2000 m	89	67.052	110.89	0.9602	0.4833*
acoustic encounter ~ dist.coast	90	67.056	<b>108.90</b>	0.9664	0.4832**

- \* Lack of fit test between the nested models 1 and 2
- \*\* Lack of fit test between the nested models 1 and 3

According to the backward stepwise selection, the best-fitted model (based on AIC: 108.38) indicated depth as the only covariate with a significantly positive relationship to sperm whale acoustic encounters (Table 1.4, Figure 1.4a). Its residual deviance was smaller than the null (null deviance: 70.36, null Df: 91), indicating model improvement (Table 1.4). Alternative candidate models presented the distance to the coast (AIC: 108.90) and 200 m isobath (AIC: 109.21), respectively, as the only covariates, although both with no significant trend observed in their relationship to the response variable (Table 1.4, Figure 1.4b). However, as both were correlated to depth, their relationship with the acoustic encounters was already expected.

Table 1.4: The best fit and alternative candidate models, with respective estimates, standard error, z and p-value.

<b>Explanatory variable</b>	<b>Estimate</b>	<b>Std. Error</b>	<b>Z value</b>	<b>p-value</b>
Depth	0.0005	0.0003	2.053	0.0401
Distance to the coast	7.974e-06	4.238e-06	1.882	0.0599
Distance to 200 m isobath	8.015e-06	4.217e-06	1.901	0.0574



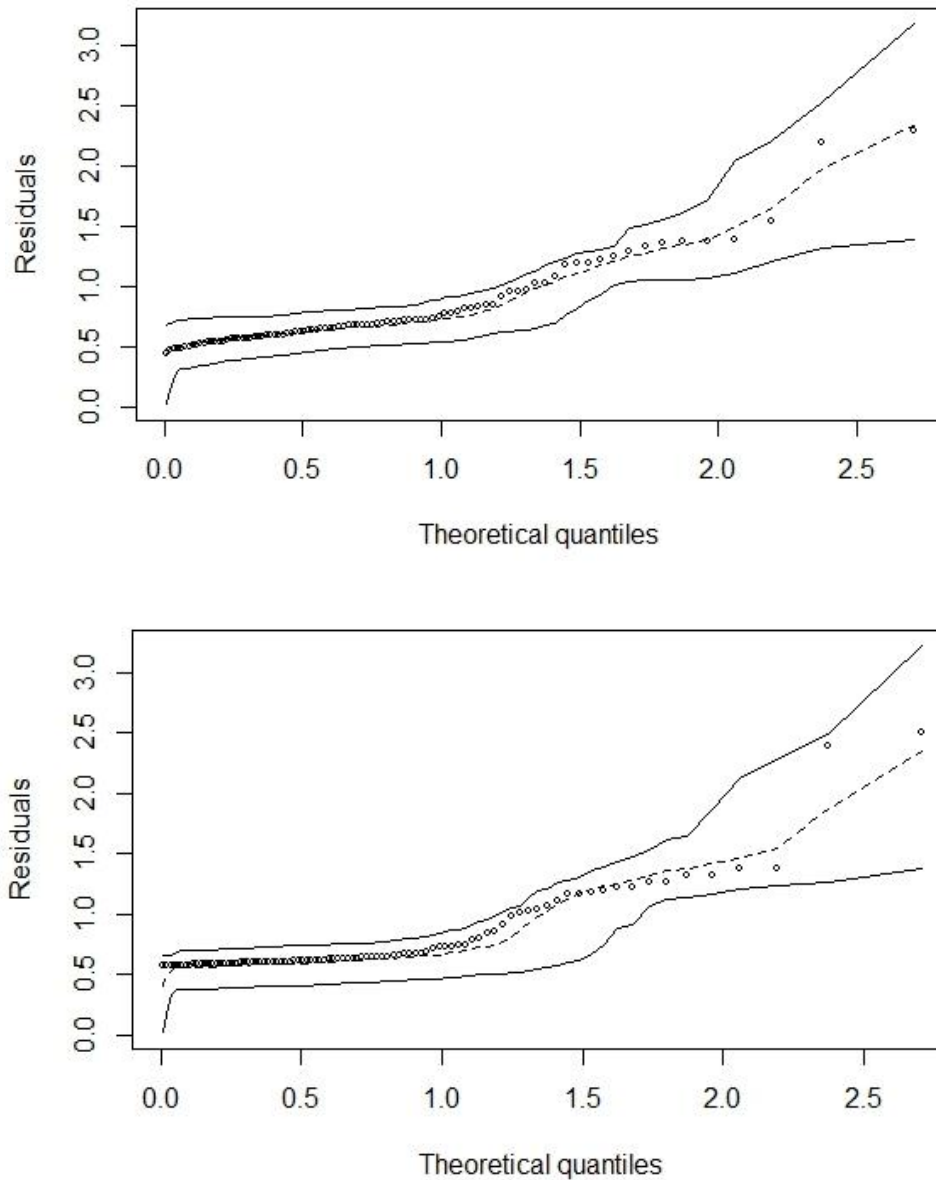


Figure 1.4: Quantile-quantile plot with simulated envelope, indicating a good fit of (a) depth, the best-fitted model, (b) distance to the coast, and (c) distance to the 200m isobath, the alternative candidate models.

## Discussion

### a. Acoustic monitoring effort:

This study represents the first sperm whale passive acoustic monitoring effort on the southern Brazilian outer continental shelf and slope. Although opportunistic, it was simultaneously conducted during an ongoing visual monitoring effort, using the Distance Sampling method (DS, Buckland et al. 2001). DS has been widely applied in PAM efforts in both fixed (point transects) and towed arrays (line transects) (Thomas et

al. 2006, Mellinger et al. 2007, Marques et al. 2009, 2013). Thus, even on a non-dedicated platform, it was possible to perform systematic acoustic coverage of the study area.

It could be considered that PAM fulfilled its role well, not only because it was well adjusted to the activities onboard, not interfering with their execution, but also, as it was less limited by sea and weather conditions that negatively impact visual sampling (see Hastie et al. 2003). Likewise, the hydrophone array deployment and towing did not present any major difficulties, as was also reported by Hastie et al. (2003).

Complete trackline acoustic coverage was not possible, mainly due to equipment malfunctions, but also because both visual and acoustic methods were occasionally affected by logistical problems. Anticipating some of the difficulties that could contribute to lower spatial and temporal acoustic coverage of the study area, one of this effort goals (not address here) was to evaluate the performance of the specially constructed hydrophone arrays, so as to allow for future equipment improvements through feedback from their use in the course of fieldwork.

Furthermore, 24-hour continuous acoustic monitoring was not possible, since fieldwork was conducted on a non-dedicated platform, and conducted only during the day. Although PAM can be conducted continuously over 24 hours for sperm whale day-night foraging cycles (Smith & Whitehead 1993, Gannier et al. 2002, Watkins et al. 2002), visual monitoring is limited to daylight hours (Mellinger & Barlow 2003, Evans & Hammond 2004, Mellinger et al. 2007, Marques et al. 2013).

During part of the night, acoustic monitoring was carried out sporadically, when the ship followed the planned transects, resulting in some of the acoustic detections presented here. An appropriate comparison between daylight and nighttime monitoring as well as an assessment of whether continuous monitoring provides an additional opportunity to increase detection, as already reported in other studies (e.g. Gannier et al. 2002, Barlow & Taylor 2005, Yack et al. 2013), was not possible so far. Other advantages of PAM are that it can be kept in use, even in low visibility conditions and under rough sea conditions (Beaufort up to 6), when visual monitoring is no longer possible. Therefore, any PAM limitations on opportunistic platforms are small when compared to its advantages. Opportunistic platforms permit a wide-ranging survey of species, such as sperm whales, and significantly reduce associated costs (Whitehead 2003). Additionally, multiple activities can be conducted on the same platform, thereby optimizing its use.

Acoustic monitoring was not conducted in sea states beyond 6 on the Beaufort scale, since the rougher the sea, the greater the array instability. A similar situation was observed in off-effort recordings during maneuvers performed by the ship when

approaching sighted groups. In these situations, array instability justified the exclusion of the acoustic encounters.

Benda-Beckmann et al. (2013) stated that hydrophone positioning is generally an issue for towed arrays, since uncertainties in the position of elements may result in less reliable estimates of the marine mammal's location. According to these authors, array stability probably depends on the ship's speed and towing depth. This is difficult to quantify as it can vary between systems used. Nielsen and Møhl (2006) further state that towed arrays, besides being difficult to handle, can limit maneuverability and ship speed.

Barlow and Taylor (2005) adopted a thin cable system that, according to them, reduces drag, resulting in greater depth and speed of the array. They also fixed the hydrophones to a 120 kg depressor at 100 m depth and attached a 30 m nylon rope to the cable tail, which maintained system stability. Akamatsu (2016) added a small weight to the end of the towed system to prevent rope vibration and its possible effects when conducting line transects.

A weight was not added to the end of the rope because of the type of cable used and its difficult manual recovery. The short rope was not sufficient to minimize system instability, allowing periodic exposure of the cable to the surface, particularly in rough sea conditions. These issues and the relatively short length of the array cable led to an increase in background noise, already produced by the towing ship and cavitation, contributing to the masking of the recordings (Thode et al. 2010, Akamatsu 2016).

Despite the adoption of the built-in high pass filter, use of additional filters, *angle vetoe*, and sounder noise elimination during analysis, the background noise was still the main issue, making the detection process less automatic and more labor intensive. Thus, for further acoustic efforts, alternative measures may need to be adopted, such as longer cables, mechanisms to stabilize the array system, built-in high-pass filter adjustment, and use of the same array configuration. This may minimize signal masking by background noise, allowing data post-processing to be more reliable and automatic.

PAM can be associated with a variety of methodologies, such as tagging operations and tracking individuals during foraging dives, increasing its effectiveness (Evans & Hammond, 2003, Mellinger et al. 2007, Marques et al. 2009, Nosal 2013, Yack 2013, Kimura et al. 2014). Possibly, the integration of acoustic and visual monitoring into a single approach offers the most effective way to fill in current gaps in the knowledge of marine species (Barlow & Taylor 2005, Yack et al. 2013), including sperm whales. This could reduce the limitations of each method and allow for an

appropriate assessment of the benefits of one method over another, and potential for complementarity.

b. Descriptive analysis and an acoustic encounters' model of distribution:

Incorporating acoustic records into spatial analysis may provide valuable additional information about the characteristics of marine habitats, as well as on the acoustic interactions of marine mammals and their environments (Moore et al. 2006, Novak 2016). A preliminary descriptive analysis was performed to evaluate which spatial: fixed (latitude, depth, distance to the coastline, to the 200 m and 2,000 m isobaths) and anthropogenic features (oil and gas blocks and Priority Areas for Conservation) are associated with sperm whale distribution, independent of a significant relationship.

Despite sperm whales being distributed across almost the entire study area, most acoustic records occurred to the south of the gap. This represents an area where the continental shelf seems to be wider (Santos 2009). However, despite the fact that most of the tracklines have been surveyed twice, a considerable part of these encounters occurred in a single sampled area during the second cruise. This supports the finds of Di Tullio et al. (2016), whose reported that a higher concentration of the species occurs in this basin region, at least in spring, when sperm whale records are more numerous.

The continental shelf is 125 km wide, on average (Santos 2009), with the shelf break occurring near the 180 m isobath (Alves 2006). A narrowing of the continental shelf is observed in Santa Marta Cape, SC and Mostardas, RS (Santos 2009, Figure 1.1). The observed gap occurred to the north of the latter site. A third of the acoustic encounters recorded to the north occurred beyond the 2000 m isobath, which was not observed to the gap southward, even also sampling deep waters in this area. This may indicate a larger offshore species distribution compared to that found in continental or slope waters in this region, especially when considering the average distance of these records to the coast. These findings corroborate results from visual efforts that encompass the same region surveyed in this study. Zerbini et al. (2004) recorded seven sperm whales, all sighted to the south of Santa Marta Cape, between 850 and 1550m depth. The sperm whale was the most sighted species during the visual survey, which was conducted simultaneously with this study, and was mainly sighted at high latitudes and beyond the isobath of 1500m (Di Tullio 2016, Di Tullio et al. 2016).

The potential significance of these relationships was evaluated using a Poisson regression model, considering, however, only fixed variables. Fixed spatial features

had already been identified as essential predictors of deep-diving cetacean habitat such as that of sperm whales (Cañadas et al. 2002, Pirodda et al. 2011, Novak 2016) and beaked whales (MacLeod 2000, MacLeod & Zuur 2005, Yack 2013).

Spatial modeling has been increasingly applied to better understand factors influencing the distribution of cetaceans (Evans & Hammond 2004). GLM, in particular, has been traditionally used to adjust species distribution models (Zurell et al. 2009), inducing linearity between response and explanatory variables (Novak 2016), being applied alone (Cañadas et al. 2002, Baumann-Pickering et al. 2016), or in combination with other models (Stanistreet et al. 2018).

Depth selection as a significant predictor of the sperm whale's distribution is also consistent with results of previous studies conducted in different regions worldwide, many of them applying PAM. In these studies, depth has also been positively correlated with sperm whale encounters and is among the most predictable variables of this species' habitat (Davis et al. 2000, Cañadas et al. 2002, Pirodda et al. 2011, Frantzis et al. 2014, Di Tullio 2016, Novak 2016).

Stanistreet et al. (2018) reported the detection of sperm whale clicks along the continental slope in the western North Atlantic Ocean, rarely occurring off the coast of Florida, where the slope descends to only approximately 800 m to 1000 m, in contrast to deeper waters northward. According to the authors, sperm whale density off the Florida coast had already been described as low.

Although not common, an apparently broad distribution of sperm whales was observed in the deep waters of the Ligurian Sea (Gordon 2000). Jaquet & Gendron (2002), in turn, reported a uniform distribution of sperm whales relative to mean depth and slope in the Gulf of California; they were found in both deeper and shallower waters relative to 1000 m.

Likewise, Gannier et al. (2002) indicated an apparent, but not significant, preference of the distribution of this species for the Mediterranean's continental slope, due to its proximity to the 200 m isobath, one of the alternative models in this study.

Some studies have considered dynamic oceanographic variables, such as sea surface temperature and chlorophyll concentration, to evaluate indirectly the density of the sperm whale's prey and how it can potentially drive this species' distribution (Jaquet & Whitehead 1996, Jaquet & Gendron 2002, Gannier et al. 2002, Praca et al. 2009). Jaquet (1996), based on the findings of Jaquet & Whitehead (1996), reported a possible spatial and temporal lag between chlorophyll concentration and sperm whale distribution. However, when considered in association with climatic components (e.g. season, temperature), chlorophyll may be useful in identifying areas of higher concentrations of sperm whales (Jaquet 1996, Praca et al. 2009, Di Tullio 2016). Still



other studies have suggested that this species' occurrence in continental-slope waters and in areas with bathymetric contrasts could be driven by the presence of prey and improved prey capture efficiency (Di Tullio 2016, Novak 2016).

Marine mammals have faced rapid changes in their habitats, including noise pollution (Reeves et al. 2003, Isojunno 2014, Pastor et al. 2015), resulting from anthropogenic activities that are of increasing concern. According to Anjos-Zerfass (2008), knowledge about oil in the Pelotas Basin is still at an incipient stage. Until recently, studies in regions of the basin have suggested low economic potential for oil exploration (Santos 2009). Moreover, blocks recently offered by ANP are located in deeper waters, potentially inhibiting investment in the region (Santos 2009, Batista 2017).

However, despite continued low commercial interest in the Pelotas Basin, studies to evaluate its oil and gas exploration potential have been conducted. Thus, evidence of concentrations of gas hydrates and associated estimates of methane occurrence have been identified; this potentially increases interest in the region and could stimulate further studies for future offers (Santos 2009, Batista 2017).

As the occurrence of hydrates appears to be particularly associated with the slope and areas with high sedimentation rates (Santo 2009), it is expected that oil and gas exploration activities will be implemented in potential sperm whale habitats. The highest gas concentration was recorded in the Cone do Rio Grande, an area also identified as a PAC, which overlapped with only one of the recorded sperm whale encounters.

While PACs are proposed as a useful approach in guiding future public policies, they do not correspond to legally protected areas, or to where any management activity is being conducted (MMA 2007, Castro et al. 2014). For the PACs assessed in this study, as well as for the other PACs identified for this region (within which other acoustic encounters were recorded), priorities for PAC management are fisheries management and protection of stocks (MMA 2007).

When considering oil and gas exploration and production activities, it is also important to consider all associated steps, from seismic surveys to the transport of end products. Such activities can generate, among other impacts, an increase in noise pollution, to which cetaceans are especially vulnerable (Mackay et al. 2018, Tyack et al. 2004, Isojunno 2014).

Seismic surveys have raised concerns about their potential negative effects on marine wildlife (Madsen et al. 2006, Parente et al. 2007, Miller et al. 2009, Weilgart 2013). Even though the short-term and long-term impacts of such activities are difficult to evaluate (Engel et al. 2004), some research has been conducted to assess the

possible influence of noise resulting from these activities on the behavior of odontocetes (Madsen et al. 2006, Miller et al. 2009, Jewell et al. 2012, Isojunno 2014).

In an experiment of exposure of sperm whales to air guns in the Gulf of Mexico, Madsen et al. (2006) reported that, while relative pulse strength from different paths varied with the range and depth of diving whales, the absolute received air-gun noise levels can be as high as at 12 km as they are at 2 km. Miller et al. (2009) also evaluated the behavior and acoustic response of eight sperm whales to controlled air-gun sounds in the Gulf of Mexico, using acoustic and movement recording tags. Although individuals did not exhibit major changes in either behavioral state or movement direction, lower pitching effort and buzz rates during air-gun array exposure suggest that feeding rates may be impacted by seismic surveys.

Sperm whales may also be affected indirectly through the impact of offshore activities on their prey. An increase in fish and squid alarm response, along with an avoidance response, particularly observed in fish, was reported by Fewtrell & McCauley (2012) from results obtained during a controlled exposure of these animals to gun noise. According to the authors, other factors can be associated with the effect of such noise in wild marine fish and invertebrates; however, they assert that consistency in the types of behavior observed can provide support to predict the behavioral response of these animals to such noise and hence, seismic surveys.

Due to concerns about the potential effects of offshore activities on deep-diving marine mammals, such as sperm whales, the PAM system has been implemented as part of mitigation procedures during mobile anthropogenic activities (Thode et al. 2005, 2010). Some countries, including Australia, the UK and the USA, have recently established guidelines for oil exploitation, including seismic operations (Vilardo & Barbosa 2018). In Brazil, the Brazilian national mitigation guidelines developed by the Environmental Federal Agency (IBAMA 2005), based on international practices, has been improved through feedback from fieldwork, adding to global efforts to fill gaps in knowledge about the impacts of offshore activities on biodiversity (Vilardo & Barbosa 2018).

In light of rapid changes in the Brazilian marine environment, a possible increase in interest by the oil and gas industry in the Pelotas Basin region, and the possible influence of their activities on the local marine fauna require continuous monitoring of the entire process associated with the implementation and development of such activities. Additionally, the identification of important management areas and research on the best way to reconcile economic development and conservation of such species should be a priority (Andriolo et al. 2010, Castro et al. 2014).

It is important to emphasize, however, that when sperm whales move to waters beyond Brazilian jurisdiction, their monitoring and management becomes an international issue, such that collaboration among various research and management groups is expected.

This study constitutes the first systematic continuous passive acoustic monitoring effort of sperm whales along the southern outer continental shelf and slope off Brazil, encompassing the Brazilian portion of the Pelotas Basin. The results demonstrate that the species occurs throughout almost the entire study area, with an apparent higher concentration to the south, almost entirely within the slope limits. Results also show concentrations of sperm whales increasing with depth.

Furthermore, a snapshot of the species' occurrence in oil and gas blocks shows that the species does not significantly use those areas, particularly those under concession. However, due to the sperm whale proximity to such areas, and the large-scale nature of oil and gas exploration, production and associated operations, monitoring the species' distribution and habitat use as well as the entire process associated with oil and gas activities is recommended. This is especially urgent, given a possible increase in interest for oil exploitation in this region.

Areas identified as priorities for biodiversity conservation are located within the entire area of sperm whale occurrence as evaluated by this study. However, PACs are the only instruments that may support and drive the future implementation of management actions in the region. Such actions may not adequately address the impacts associated with the oil and gas industry and other offshore activities that have the potential to change the marine environment as PACs only refer to fisheries management.

In future studies, implementing different monitoring methods simultaneously, such as PAM and visual monitoring, can improve mitigation activities due to overall improved detection performance. By drawing on the strengths of different methods, such an approach can decrease the probability of false alarms and represents the most effective monitoring approach to aid in the management and conservation of marine species, particularly those that are difficult to observe, such as the sperm whales (Barlow & Taylor 2005, Yack et al. 2013, Verfuss et al. 2018).

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## CAPÍTULO II

### **Am I available when underwater? Sperm whale (*Physeter macrocephalus*) diving behavior and a snapshot of the species' acoustic availability in the subtropical western South Atlantic Ocean**

Manuscrito em preparação para submissão à revista: "*Marine Ecology Progress Series*"

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## **Am I available when underwater? Sperm whale diving behavior and a snapshot of the species' acoustic availability in the subtropical western South Atlantic Ocean**

Running page head: Sperm whale dive profiles and acoustic availability in Brazil

### **Abstract**

Sperm whales typically spend 70 to 75% of their time in foraging dives. While diving they produce usual clicks and creaks, which make them one of the most amenable species to acoustic monitoring. In many regions worldwide, this species diving and acoustic behavior has already been studied using different methods. However, in Brazilian waters, information on both is still unknown. Thus, this study is divided in two sections: (1) sperm whale dive profile descriptive analysis using time-depth recorders (TDRs) data from Brazil, and (2) the joint assessment of both tag types, TDR and Digital tags (Dtag), to estimate acoustic availability and the detection probability at zero horizontal distance  $g(0)$ . Data from five TDR's attached in sperm whales off Brazil and five Dtags placed in individuals around the Azores were adopted. A total of 139 complete dives were used to assess this species dive profile in Brazilian waters, which was apparently dominated by shallow dives classified as V-shaped (40.29%) and U-shaped (12.95%). Intermediate depth (29.50%) and deep dives (17.27%) were also identified, from which 26 were classified as foraging dives using the 'time\*depth criteria' of 17,500 m-min. The percentage of time individuals produce foraging clicks were directly estimated from Dtag acoustic data. Foraging dives of both tag types were, then used to estimate the acoustic availability time correspondent to 38.10 minutes (sd: 8.11 min), while spent 30.58 min (sd: 3.64) silent. For a time-window of 27.71 min, the estimated  $g(0)$  were then equal to 0.96, which can be applied to line transect surveys.

Keyword: marine mammals, deep divers, dive profile,  $g(0)$ , Brazilian waters.

### **Introduction**

Sperm whales (*Physeter macrocephalus* Linnaeus, 1758), the largest of the odontocetes, are distributed worldwide, up to the edges of both poles, and are generally found in waters deeper than 1000 meters (m) (Rice 1989, Jaquet & Whitehead 1996, Whitehead 2002, 2003, Reeves et al. 2002, Jefferson et al. 2008). This species performs long, deep dives, which last about 30 to 45 minutes (min), but

which can exceed one hour, occasionally reaching depths of up to 2000m (e.g. Watkins et al. 1993, 2002, Wahlberg 2002, Amano & Yoshioka 2003, Whitehead 2003, Watwood et al. 2006, Aoki et al. 2007, 2012, Davis et al. 2007, Irvine et al. 2017).

Surface periods, when individuals become visually available, occur in two different contexts, (1) between dives, during which the surface phase lasts roughly 8 to 10 min (Amano & Yoshioka 2003, Whitehead 2003, Watwood et al. 2006, Mathias et al. 2013, Irvine et al. 2017), and (2) when individuals are socializing/resting, which are periods that last longer and occur mainly during daylight hours, but are less frequent than the surface phase between dives (Whitehead 2003, Barlow & Taylor 2005).

Sperm whales typically spend 70 to 75% of their time executing foraging dives (Whitehead 2003, Watwood et al. 2006, Irvine et al. 2017, McDonald et al. 2017), which has generated interest in this species' diving behavior over the years (Amano & Yoshioka 2003). In many regions worldwide, such a behavior has already been studied using different methods, more recently using sonar transponders (Watkins et al 1993) and radio- and/or satellite-linked tags, including time-depth recorders (TDRs) (e.g. Watkins et al. 2002, Amano and Yoshioka 2003, Aoki et al. 2007, 2012, Davis et al. 2007, Mathias et al. 2013, Irvine et al. 2017), and digital tags (Dtags) (Johnson & Tyack 2003, Watwood et al. 2006, Teloni et al. 2008, Mathias et al. 2012), as also reviewed by Oliveira (2014) (Supplementary material S6).

Dtags, which record acoustic signals produced during an individual's dive, allow access to information about a species' foraging (Miller et al. 2004a, Watwood et al. 2006, Teloni et al. 2008, Mathias et al. 2012). This behavioral assessment has shown that, although sperm whale males at high latitudes seem to present a different foraging behavior (possibly because they prey in epipelagic waters; Teloni et al. 2008) from that of individuals at lower latitudes, a close relationship exists between their diving and acoustic behaviors, which attributes an apparent stereotyped pattern (Watwood et al. 2006) to this species' foraging dives.

As this species' habitat and behavior are difficult to assess only through conventional visual methods, relatively recent efforts to estimate sperm whale abundance have been using acoustic methods as an alternative or complementary approach (Gannier et al. 2003, Hastie et al. 2003, Barlow & Taylor 2005, Lewis et al. 2007, Fais et al. 2016). This potentially increases detections that would not have been obtained using only visual methods (Marques et al. 2011).

An important assumption of conventional distance sampling (CDS), the most widely used method for estimating a marine mammal's population size, is that the probability of acoustically or visually detecting an animal (or group) on the survey trackline, i.e., at a zero-horizontal distance, is certain. For cetaceans, this assumption

is usually violated because the individuals may not be available for detection (availability bias), or even when available they may not be detected (perception bias) (Marsh & Sinclair 1989, Buckland et al. 2001).

During passive acoustic surveys, animals may be unavailable because they may not be vocalizing at certain times. However, when sperm whales vocalize during a foraging dive, they produce usual clicks with inter-click intervals (ICI) of 0.5 to 1 second, and creaks at even smaller ICIs on the order of milliseconds (Madsen et al. 2002a, Whitehead 2003). Additionally, these echolocation clicks (also referred as foraging vocalization) are highly directional broadband signals, which contain energy predominantly at frequencies above the background noise range (Weilgart & Whitehead 1998, Madsen et al. 2002a, 2002b, Møhl et al. 2003, Zimmer et al. 2005), contributing to reduce masking, particularly by towed systems typically used in abundance estimation efforts (Barlow & Taylor 2005). Thus, in this study, the acoustic perception was simplified by assuming that it would be certain, and that there would be a high detection probability of vocalizing animals within a finite time window (e.g. Barlow et al. 2013, Fais et al. 2016). Therefore, the  $g(0)$  estimation was only dependent on the individuals being acoustically available.

In most studies that estimate sperm whales abundance, this species acoustic availability was assumed to be certain; consequently,  $g(0)$  was considered equal to or very close to 1 (Barlow & Taylor 2005, Leaper et al. 2003, Swift et al. 2003, Lewis et al. 2007). However, some studies recognize that individuals do spend periods in silence (Barlow & Taylor 2005, Lewis et al. 2007).

Although sperm whales may produce codas and slow clicks when involved in social activities at the surface, they often do not echolocate (Lewis et al. 2007, Fais et al. 2016). Since in this study, individuals were assumed to be only available when they produce foraging vocalizations, based on these signals' characteristics, surface time was considered silent periods. Fais et al. (2016) recognized that this species spends a fraction of their dives in silence before start vocalizing and returning to the surface (Madsen et al. 2002a, Watwood et al. 2006, Teloni et al. 2008); therefore, silent periods were incorporated to estimate a  $g(0)$  equal to 0.92 for this species' line transect survey.

In Brazilian waters, information on both diving and acoustic behavior of sperm whales during a dive is still unknown. This study presents the first effort to describe the sperm whale's dive profile for this region. Barlow et al. (2013) present an approach to estimate the acoustic availability of two species of beaked whales from Dtag data. Due to the close relationship observed between beaked whale dives and their acoustic behaviors, these authors assumed this method was applicable to other geographic regions where only dive behavior data were available. Thus, following the Barlow et al.



(2013) approach, the Azores Dtag dataset was applied to this study by assuming stereotypical sperm whale foraging behavior, as suggested by Watwood et al. (2006). Foraging dives were identified for individuals tagged with TDRs in Brazilian waters using the time\*depth criteria (Barlow et al. 2013). Additionally, using the percentages of total sample time in which a sperm whale spent both clicking and in silence, its acoustic availability and  $g(0)$  were estimated for potential use in line transect surveys carried out in Brazilian waters.

## Methods

This study is divided into two sections. The first section corresponds to the sperm whale dive profile descriptive analysis using TDR data from Brazil. The second presents the joint assessment of both tag types, TDR and Dtag, to estimate acoustic availability and the detection probability at zero-horizontal distance  $g(0)$ , which is the probability of detecting an animal or group at distance zero from the trackline (Buckland et al. 2015), based on the approach used by Barlow et al. (2013).

### 1- Sperm whale dive profile analysis

#### a. Study area and tagging operations:

TDR tagging operations were conducted over the Brazilian continental shelf and slope, off of Rio Grande do Sul State (RS), from 7 to 20 December, 2012 (Figure 2.1). Sperm whales were tracked from the 36 meter-long *R/V Atlântico Sul*. Deployments were undertaken when weather conditions were appropriate for launching a 6.7 meter-long rigid-hulled inflatable boat (Beaufort Sea State 3-4). Time-depth recorders (TDRs, MK-10 satellite-linked tags, Wildlife Computers), which had a low-impact, minimally percutaneous external-electronics transmitter (Limpet) configuration (Andrews et al. 2008), were deployed on the dorsal surface of five sperm whales using a 150-lb crossbow (Andrews et al. 2008).

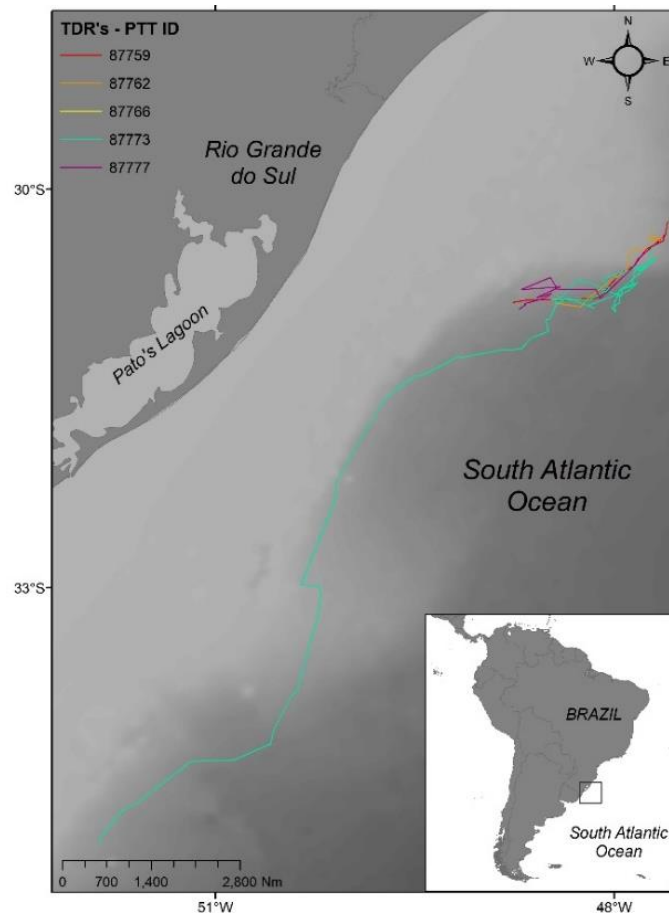


Figure 2.1: This study surveyed area, which includes the tagging operation region and the five tagged-animal tracks, with the longer route performed by a possible male # 87773 in light blue.

The TDRs were programmed to collect sensor data (dive depth) using a low-resolution time series, corresponding to a 2.5-min interval (also adopted in Mathias et al. 2013), considering the limited battery durability. In addition, considering the restricted number of satellite overpasses, which was expected, not all dives and surface times were represented. However, due to this tag's longer duration (Barlow et al. 2013), greater temporal coverage was obtained.

In the field, four individuals were thought to be female, given their body length and the presence of calves in close proximity. However, using an 80 lb crossbow, biopsy samples were also collected for sex determination. A summary of information about the deployments is presented in Table 2.1. Depth and location data were received via the Argos Service while individuals were at the surface. Each location was classified into different quality categories of decreasing accuracy, as follows: 3, 2, 1, 0, A, and B (Argos 1990).

Table 2.1: Information about the five deployed time-depth recorders (TDRs) and the respective tagged animals. Sampling interval in seconds (s) and dive threshold in meters (m).

Animal ID	Deployment coordinates		Sampling interval (s)	N. of samples	Sampling beginning	Sampling end	Dive threshold (m)
	Lat	Long					
87759	-30.218	-47.604	150	248	12/16/2012 13:40	12/17/2012 09:57	10
87762	-30.240	-47.628	300	75	12/16/2012 14:45	12/17/2012 04:55	10
87766	-30.490	-47.651	150	60	12/18/2012 11:30	12/18/2012 13:57	10
87773	-30.315	-47.665	150	1677	12/16/2012 16:07	12/25/2012 21:57	10
87777	-30.220	-47.617	150	248	12/16/2012 13:12	12/17/2012 17:55	10

b. TDR data processing:

TDR raw data were analyzed in R (R Development Core Team 2017, version 3.4.3), using the `diveMove` package (Luque 2007, 2017) and custom-written programming routines.

Before any analyses were performed, Greenwich Mean Time (GMT) was converted to local time. Data calibration was then performed, along with a correction for shifts in the pressure-sensor was applied to the depth data (Luque 2007) using the “offset” method, assuming three meters as an offset value. Dives were defined as starting when a whale's depth was greater than the adopted dive threshold of 10 m, which considers an individual's body length (Watwood et al. 2006, Mathias et al. 2012, Irvine et al. 2017). The dive phases (ascent-, bottom- and descent phases) were identified during the same process using the unimodal regression cubic spline model, which is appropriate for research on air-breathing animals (Luque 2017). The critical quantiles of the vertical velocity threshold (which define the end and beginning of the descent and ascent phases, respectively ) and the knot factor varied between TDRs (for more details about the script `diveMove`, see Supplementary Material S7).

Each dive was visually reviewed to evaluate the performance of the adopted settings and to correct any phase misclassifications (Vila Pouca 2012). To assist in correct phase identification and to adopt the same time scale used in the manual correction of misclassifications (Vila Pouca 2012), dive profiles were reviewed individually, as well as in groups of up to five consecutive dives.

c. Statistical analysis:

Due to the possible effect of tagging operations on sperm whale acoustic and diving behaviors, the first dive cycle (which includes a dive and its respective post-dive interval that preceded the next dive, also called the surface phase), immediately after tagging were removed from further analyses (Amano and Yoshioka 2003, Miller et al. 2004a, 2004b, Watwood et al. 2006, Aoki et al. 2007, Barlow et al. 2013). Only complete dive cycles were considered, removing those with incomplete recordings due to either tag release or absence of satellite coverage (Arranz et al. 2011, Barlow et al. 2013).

For each sperm whale dive, the mean ( $\pm$  standard deviation, sd) was calculated for the following parameters: dive duration, post-dive duration, the duration of each phase (descent, ascent and bottom), bottom/dive duration ratio, maximum dive depth, bottom depth, mean and SD bottom depth, and descent and ascent velocities.

Dives were classified into different types using Principal Component and Hierarchical Cluster Analysis, following the same analytical process presented by Irvine et al. (2017), and by visual inspection of each dive profile, considering sperm whale dive types already described in the literature as a basis (see Amano & Yoshioka 2003, DeRuiter et al. 2013, Isojunno 2014, Irvine et al. 2007). Each dive was identified as occurring either during the day (between dawn and dusk) or at night (Augé 2010).

Local bathymetry corresponding to each available TDR position was assessed through the Spatial Analyst Tool (ArcGIS 9.3), using the 1 arc minute version of ETOPO 1 bathymetry (Amante & Eakins 2008). A profile comparing animal depths and local bathymetry corresponding to a given time was plotted to assess the animals' distances from the bottom, and whether their proximity to the bottom limited their maximum depth.

The statistical difference among mean number of dives for each type was tested by the nonparametric Kruskal-Wallis test, followed by Dunn's test, in order to perform multiple comparisons among the observed categories. Regardless of dive type or category, the frequencies at which these dives occurred during the day and at night were tested using the Mann-Whitney test. Statistical analyses were performed in R, adopting  $p < 0.05$  as significant.

## *2- Estimation of acoustic availability and detection probability at zero-horizontal distance, $g(0)$ :*

According to Barlow et al. (2013), the percentage of time during which sperm whales are producing echolocation clicks in a foraging dive can be estimated directly from Dtags.

To date, the only information on sperm whale dive profiles for Brazilian waters corresponds to the temporal series of depths obtained from the TDR's presented in this study and a recent effort, which described an adult sperm whale dive profile using data from a Splash-10 tag (Wildlife Computers) (Baracho-Neto et al. 2018). Therefore, no information is available on the acoustic behavior of this species during foraging dives. Thus, in order to estimate this species' acoustic availability in Brazilian waters, applying the same approach used in Barlow et al. (2013), information on the acoustic behavior of sperm whales during foraging dives was obtained from five of the 11 Dtags (Dtags: pm10\_211b, pm10\_222a, pm10\_222b, pm10\_226a, pm10\_228a), dataset provided by Dr. Cláudia Oliveira and her collaborators) attached to individuals around the Azores archipelago (38°N, 28°W) during the summer of 2010 (Oliveira, 2014). Although located in the opposite hemisphere and at a latitude north of the Equator, this region is in a temperate zone with a climate defined as subtropical, similar to our study area. This dataset has already been described by Oliveira (2015) and, through a different approach, by Fais et al. (2016), where this species' foraging behavior was described using a subset ( $n = 7$ ) of the Oliveira (2015) data.

Acoustic signals were recorded by two channels, using a sampling frequency of 96 kHz and a 16-bit resolution. In addition, Dtags sampled pressure and temperature and used three-axes accelerometers and magnetometers at a 50-Hz sampling rate and 16-bits. After a Dtag detached from a whale, it was recovered with the aid of internal VHF transmitters while floating. The data were then downloaded and stored for further analysis (consult Oliveira 2014 for more detailed information on the field work and Dtags).

Dtag datasets had already been corrected/calibrated (pitch, roll and heading) for foraging dives, and had been passed through a click detection process. For these data, the first dive cycle (composed of a dive and its subsequent post-dive interval, also called the surface phase of a dive) was excluded. Only complete dive cycles were considered, using the same dive parameters as for TDRs.

A routine analysis was developed in R, using functions already available, to identify each dive, its duration and whether it was shallow or deep (<150 m and >300 m, respectively, Watwood et al. 2006). Depth, pitch and sampling frequency data were used to divide each dive profile into dive cycles.

Individual dives were then subdivided into three phases: descent (starting immediately after the animal exceeded 10m depth and ending when the pitch became positive), ascent (from when the pitch became positive, after the last negative pitch, until the animal was 10 m from the surface), and bottom (a period when an individual

usually wiggles, delimited by the descent and ascent phases) (Miller et al. 2004a, 2004b, Watwood et al. 2006).

To estimate acoustic availability, only foraging dives were considered (Barlow et al. 2013, Fais et al. 2016). Here, as in other studies of sperm whale acoustic behavior during diving, the focus was on foraging vocalization signals: usual clicks, which were produced during the search phase, and creaks (buzzes), which were apparently produced during the final stage of foraging (Madsen et al. 2002b, Miller et al. 2004a, Watwood et al. 2006, Teloni et al. 2008).

For Dtags, foraging dives were identified by their depth and presence of foraging vocalization (as adopted by Barlow et al. 2013 for beaked whales, also see Miller et al. 2004a). Echolocation periods were estimated by identifying the beginning and end of usual click production (Watwood et al. 2006, Barlow et al. 2013, Oliveira 2014, Fais et al. 2016). Where pauses were observed, unlike that presented by Fais et al. (2016), their total duration was subtracted from the echolocation period, thus assessing the total time that an animal actually spent foraging within a dive (Barlow et al. 2013). A scheme of a foraging dive is shown in the Supplementary Material S8.

For TDRs, these dives were identified following the "time\*depth criteria" proposed by Barlow et al. (2013), corresponding to the multiplicative product of the maximum depth of a foraging dive recorded from a Dtag and its duration. According to these authors, this allows the separation of dives into two modes, which are foraging and non-foraging dives. In addition to a visual inspection of the generated product histogram, a hierarchical cluster analysis was performed in R in order to confirm whether only two diving modes could be identified.

As in Barlow et al. (2013), for both tag types, the total sample period of a tagged animal was estimated by summing the duration of its foraging dive cycles (comprising only the complete foraging dive and subsequent post-dive interval). The percentages of dive cycle time that an animal spent in a foraging dive and in the post-dive interval were estimated by dividing the dive and surface phase duration, respectively, by the corresponding dive cycle duration.

The percentage of the dive time that an animal spent foraging was estimated by dividing the total time spent clicking by the dive duration. During foraging dives, sperm whales were silent in the earlier descent phase before starting to click, and for most of the ascent phase after the last click (Watwood et al. 2006, Douglas et al. 2005, Fais et al. 2016). Thus, the total time of a dive spent in silence was estimated by summing this silent period before and after usual click production and vocalization pauses, and the percentage of foraging dive time spent in silence was estimated by dividing the total silent period by the dive duration.

Finally, the percentages of the total sample period in which a whale spent actively foraging and in silence were estimated respectively as follows: (1) by multiplying the average percentage of foraging dive time that an individual spent clicking by its total sample time, and (2) by summing the average percentage of the dive time a whale spent in silence and the average percentage of the dive cycle that it spent in the post-dive interval (Barlow et al. 2013).

As for TDRs, the percentage of foraging dives with echolocation clicks cannot be directly assessed; nevertheless, the percentage of the total sample period with active foraging was estimated by multiplying the average foraging dive time for individuals monitored through Dtags by the total sample period for individuals monitored using TDRs (Barlow et al. 2013).

For each tag type and, consequently, for each location where individuals were tagged, the mean values of each estimated parameter were calculated from the individual's average values. The overall parameter average of the pooled tags was defined from the estimated average value for each tag type.

For acoustic line-transect surveys, Barlow et al. (2013) stated that the percentage of time actually spent foraging and then echolocating can be an instantaneous estimation of  $g(0)$ , when the detections are restricted to individuals that are acoustically available at the time of close proximity to the observation platform (difficult to estimate). They also observed that whales directly under the trackline may be detected within a range ahead of or behind the ship, which means that acoustic detections can be made over a finite time window. This time window is directly dependent on the range considered, as well as and survey speed, which should be greater than the typical animal's swimming speed (Barlow et al. 2013, Fais et al. 2016).

In this study, a distance of approximately 4 km was adopted as the sperm whale detection range (Barlow & Taylor 2005, Fais et al. 2016) and an average survey speed of 9.35 knots (17.32 km) was used to calculate the finite time window as follows:  $w = 2 * k/v$ , with  $k$  corresponding to the detection range and  $v$  to the survey speed (Barlow et al. 2013).

Considering that an individual's silent time (when a whale is acoustically unavailable) may be greater than the finite time window,  $g(0)$  was estimated by applying the same equation used in Barlow et al. (2013), which was based on Laake et al. (1997). Using this equation,  $g(0)$ , was estimated from the sum of the expected acoustically available time (mean time spent clicking) and the estimated finite time window, divided by the sum of the acoustically available time and unavailable time (mean time spent in silence), i.e., the total sample time.

## Results

### *Sperm whale dive profile in southern Brazilian waters:*

TDR tags were attached to five sperm whale individuals, totaling on average 57.41 hours (2.4-221.76 h) of monitoring. As it was not possible to collect enough skin sample for two of the tagged animals (# 87773 and # 87777) for sex identification, they were identified during field work as a possible male and female, respectively, based on their body sizes and behavior, so thereafter they were referred to as such. The other three individuals, all identified as females, had their sex genetically determined.

Because one female (# 87766) did not perform dives deeper than the adopted 10m-threshold, while monitored for only 2.4 h, the results presented here refer to the dives performed by four of the five-tagged animals. Complete dive cycles, excluding the first dive and post-dive interval for all TDR datasets, corresponded to 91.45% of the 152 dives studied (Table 2.2). Therefore, the analyses were based on 139 complete dives from four animals.



Table 2.2: Sperm whale dive parameters, mean (min-max), on the southern Brazilian outer continental shelf and slope, considering the time period (day or night) in which the dives were performed, as well as the statistical significance between them (1). Also presented are (2) loadings for the first two components resulting from the PCA of the seven dive parameters considered, and (3) parameters of the four identified dive categories. Duration in minutes (min), depth in meters (m) and velocity m/s.

	Dive Dur	Maximum Dive Depth	Bottom Duration	Bottom Depth (mean)	Bottom Depth (SD)	Bottom/dive duration	Descent velocity	Ascent velocity	Post-dive Duration
<b>Dive parameters</b>									
<b>Total (n=139)</b>	12.50 (2.5-85)	105.00 (10.5-683.5)	20.00 (0-55)	170.50 (10.5-554.4)	6.02 (0-89.98)	0.57 (0-0.89)	0.31 (0.05-1.53)	0.41 (0.05-1.05)	20.00 (0-180)
<b>Day (n=90)</b>	11.25 (2.5-72.5)	104.50 (11.5-683.5)	25.00 (2.5-55)	191.00 (13-554.4)	17.13 (0-89.98)	0.58 (0.17-0.76)	0.37 (0.05-1.53)	0.41 (0.05-1.05)	20.00 (0-180)
<b>Night (=49)</b>	22.50 (2.5-85)	156.50 (10.5-403.5)	15.00 (0-50)	163.39 (10.5-263)	0.00 (0-77.32)	0.56 (0-0.89)	0.22 (0.07-0.65)	0.32 (0.06-0.79)	20.00 (0-157.5)
<b>Mann-Whitney (day x night)</b>	W = 2420, p = 0.341	W = 2724, p = 0.022	W = 1111, p = 0.010	W = 1162.50, p = 0.002	W = 1082.50, p = 0.003	W = 913.50, p = 0.458	W = 3170.50, p < 0.001	W = 2686, p = 0.034	W = 2132, p = 0.748
<b>Principal components that explain most of the variance</b>									
<b>PC1</b>	0.425	0.394	0.257	-0.334	-0.406	-0.407	0.221	0.328	-
<b>PC2</b>	-0.172	-0.278	-0.503	-0.501	-0.33	-0.347	-0.371	-0.148	-
<b>Dive types identified</b>									
<b>Shallow U-shaped</b>	7.50 (2.5-22.5)	20.25 (10.50-123)	2.50 (0-20)	20.25 (10.5-123)	0.00 (0-15.91)	0.33 (0-0.89)	0.16 (0.05-0.55)	0.17 (0.09-0.71)	15.00 (2.5-70)
<b>Shallow V-shaped</b>	2.50 (2.5-15)	17.25 (10.5-114.5)	no bottom	no bottom	no bottom	no bottom	0.20 (0.05-1.53)	0.17 (0.05-1.05)	10.00 (0-180)
<b>Intermediate depth</b>	32.50 (12.5-575)	170.50 (79-520.5)	20.00 (2.5-32.5)	164.50 (51.12-453.89)	0.00 (0-72.70)	58.00 (0.20-0.76)	0.34 (0.17-0.71)	0.55 (0.32-0.85)	7.50 (2.5-157.5)
<b>Deep</b>	60.00 (37.5-85)	512.50 (277-683.5)	37.50 (15-55)	422.70 (244.3-554.4)	48.06 (0-89.98)	0.59 (0.35-0.76)	0.57 (0.20-0.92)	0.65 (0.32-0.85)	10.00 (0-120)

In general, the assessed dive profiles were apparently dominated by shallow dives, presenting both shallow depths and short durations (Table 2.2). Maximum depths, however, were not limited by the proximity to the bottom, since individuals reached depths that were on average 1529.98 m from the seafloor (median: 1436.5 m, range: 643 m to 2441 m, Figure 2.2).

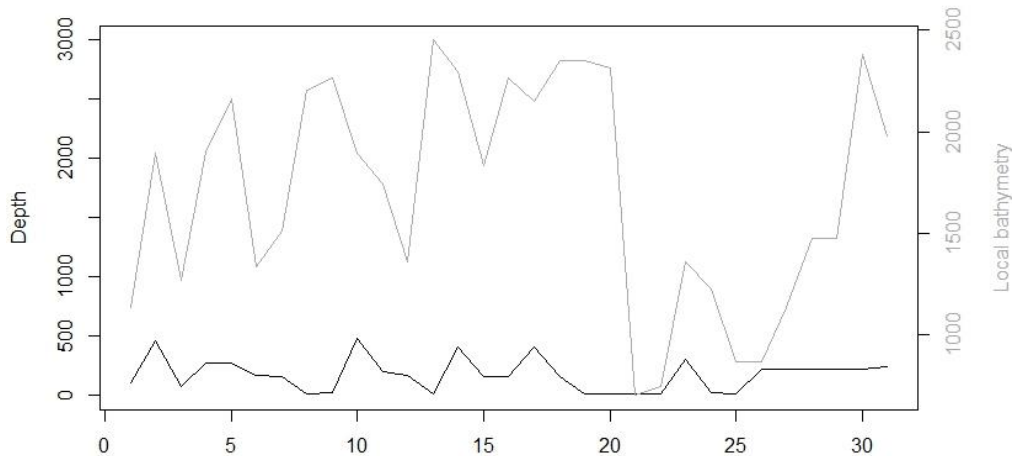


Figure 2.2: Sperm whale depths and the corresponding local bathymetry (represented here as depths relative to the animals' positions).

Forty-nine dives (35.25%) were performed during the night, having a significantly greater maximum dive depth compared to those reached during the daylight hours. In contrast, the bottom phase duration was significantly lower at night (Table 2.2).

Based on the sperm whale dive types already described in the literature, dive categories were. The post-dive interval parameter was not considered at this stage of the analysis due to its apparently general representation of surface time, which included not only the surface phase of a dive cycle, but also this species' resting/socialization periods.

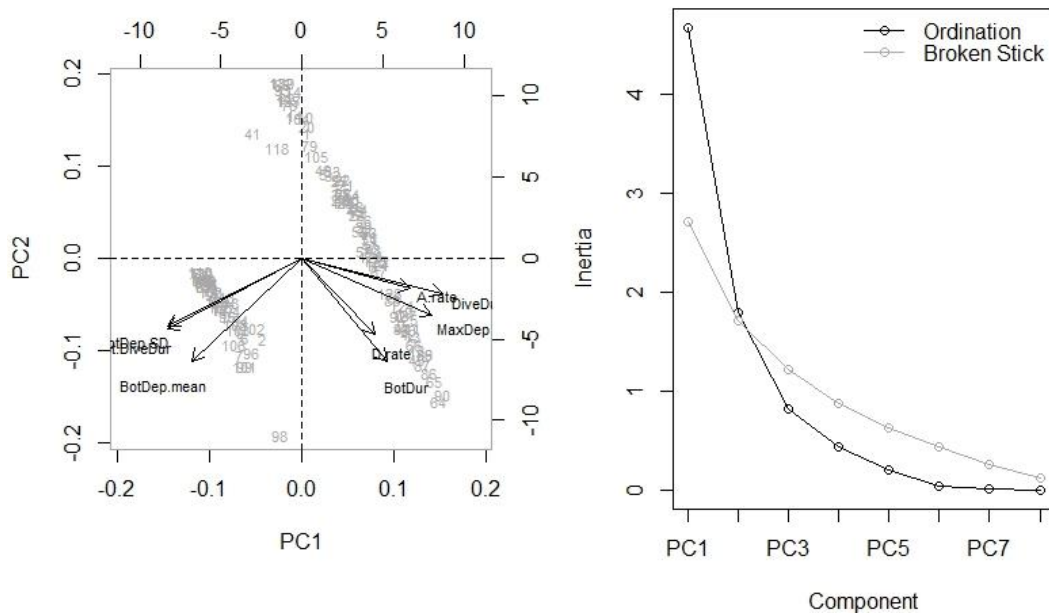


Figure 2.3: Biplot showing PC1 and 2 and related parameters (a), and the broken stick screen plot showing the number of retained PCs.

The first two principal components, also indicated by the Broken Stick values of the screen plot, explain 81% of the variance in the assessed sperm whale dives (Figure 2.3, Table 2.2). The higher values of PC1 refer to parameters associated with maximum dive depth and duration, as well as the bottom phase duration, which indicate contrasts between shallow dives and deep dives and whether the bottom phase was active (U-shaped) or inactive (V-shaped). PC2 shows higher values associated with the bottom phase duration and variation in depth, highlighting even more active and inactive bottom phases.

The PCA score outcomes were used as inputs in a hierarchical cluster analysis, resulting in four different dive categories: shallow U-shaped, shallow V-shaped, deep, and a fourth category referred to here as “intermediate-depth dives”. The cophenetic correlation value of 0.81 indicated a good fit of clustering. The summary of the four dive types is presented in Table 2.2 (also see Figure 2.4 and Supplementary material S9).

The V-shaped shallow dives (40.29%) were significantly more frequent, followed by intermediate-depth dives (29.50%), deep dives (17.27%) and U-shaped shallow dives (12.95%) (Kruskal-Wallis  $X^2 = 33.963$ ,  $p < 0.001$ ). However, a pairwise post-hoc test indicated statistical significance between U-shaped dives and both V-shaped shallow dives ( $Z = -5.2586$ ,  $p < 0.001$ ) and intermediate-depth dives ( $Z = -3.1828$ ,  $p < 0.001$ ), as well as between V-shaped shallow dives and intermediate-depth dives ( $Z = 4.4283$ ,  $p < 0.001$ ).

U-shaped shallow dives were performed equally during the day and night (6.47%). At night, sperm whales dove more frequently to intermediate depths (16.55%,

W = 1611,  $p < 0.001$ ). V-shaped shallow dives (29.50%) and deep dives (15.83%) were more frequent during the day, although statistical significance was only observed for the latter case (W = 2654,  $p = 0.002$ ).

When analyzed individually, sperm whale # 87773 had almost the same number of dives recorded during the day and at night (36 and 38, respectively). This individual presented the highest mean maximum dive depth and duration values (187.4 m and 30 min, respectively), as well as the highest bottom/dive duration ratio (0.59, Table 2.3). Moreover, it dove more often to intermediate depths, instead of going to shallow and deep depths.

There was a statistically significant difference between this individual and the other sperm whales for dive duration, bottom/dive duration ratio, and the most frequently performed dive type (Table 2.3). However, a *Dunn's* post-hoc test showed that this difference occurred only between whales # 87773 and # 87777 (Dive duration,  $Z = 3.298$ ,  $p = 0.006$ ; bottom/ dive duration,  $Z = 2.994$ ,  $p = 0.016$ ; and dive category,  $Z = 3.692$ ,  $p = 0.001$ ). The other evaluated pairs did not present significant differences for any of these parameters.

Table 2.3: Tagged animals' dive parameters, mean (min-max), and the frequency with which each individual performed each dive type. Duration in minutes (min), depth in meters (m) and velocity m/s.

TDR		87759	87762	87773	87777	Kruskal-Wallis test p-value
Number of Dives	Day	13	5	36	36	-
	Night	0	1	38	10	-
Dive duration		7.5 (2.5-57.5)	10 (5-85)	30 (2.5 - 72.5)	7.5 (2.5-50)	$p = 0.012$
Maximum Depth		87 (14-534.5)	62.5 (46.5-277)	162.5 (10.5-683.5)	52.25 (11-624)	$p = 0.354$
No bottom phase		7	4	18	27	-
Bottom duration		17.5 (2.5-30)	27.5 (5 - 50)	20 (0-55)	12.5 (0-27.5)	$p = 0.097$
Bottom Depth (mean)		308.5 (51.12-534.5)	162.4 (80.5-244.3)	169.2 (10.5-526.9)	218.67 (13-554.39)	$p = 0.934$
Bottom Depth (SD)		10.94 (0-50.74)	13.39 (10.61-16.18)	3.10 (0-89.98)	16.97 (0-73.24)	$p = 0.889$
Bottom/dive duration		0.52 (0.17-0.60)	0.46 (0.33-0.59)	0.59 (0-0.89)	0.42 (0-0.67)	$p = 0.007$
Descent velocity		0.46 (0.17-0.83)	0.26 (0.16-0.38)	0.31 (0.07-0.74)	0.31 (0.05-1.53)	$p = 0.220$
Ascent velocity		0.46 (0.17-0.83)	0.31 (0.09-0.49)	0.45 (0.06-0.85)	0.31 (0.05-0.92)	$p = 0.120$
Post-dive duration		7.5 (0-180)	5 (0-10)	10 (0-157.5)	10 (0-120)	$p = 0.105$
Dive Category	1	0.15	1.17	0.09	0.17	$p = 0.001$
	2	0.54	0.67	0.24	0.59	
	3	0.08	0	0.46	0.13	
	4	0.23	0.17	0.2	0.11	

### Sperm whale dive data from Dtags:

Only five of the 11 tagged individuals in the Azores were considered to access the sperm whales foraging behavior (Figure 2.4).

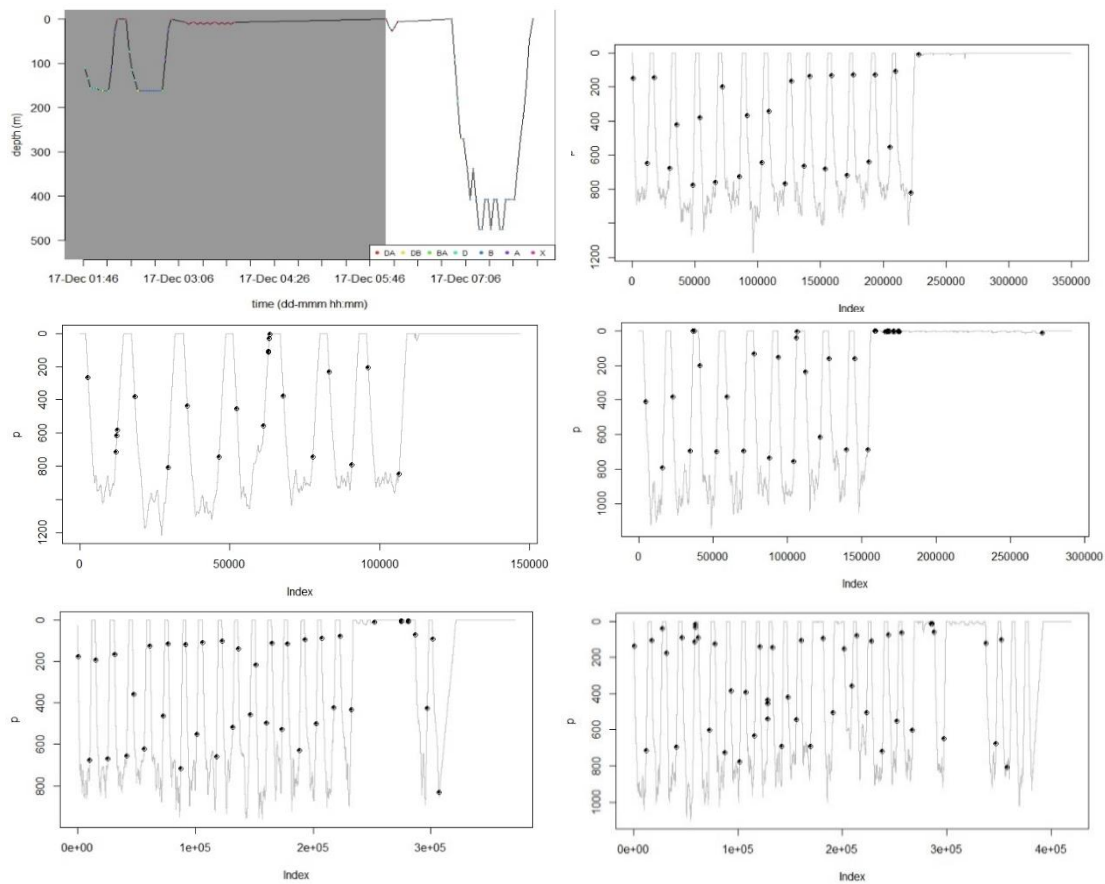


Figure 2.4: Dive profile of a whale tagged with TDR, shows all dive types (first plot). Dive profile (grey lines) of the Azores Dtags (pm10\_211b, pm10\_222a, pm10\_222b, pm10\_2226a and pm10\_228a, respectively) and points (black dots) that represent the start and end of usual click production per dive.

A total of 60 complete foraging dives from Dtags were identified, considering both the maximum-depth dive and presence of echolocation clicks. Based on these dives, 26 of the 139 complete TDR dives were recognized as foraging dives using the 'time\*depth criteria' of 17500 m-min (Supplementary material S10), which clearly separated the multiplicative products of maximum-dive depth and dive duration into two different groups. This was also obtained from cluster analysis with a cophenetic correlation of 0.93, indicating a good clustering.

In addition, the following is presented: the percentage of total sample period in foraging dives and in the surface phase, the percentages of foraging dive time and the total sampled period in echolocation and silent periods.

Due to the absence of acoustic data, the percentage of the dive time in which individuals spent clicking was not estimated (referred to as “not estimated”, i.e. “ne” in Table 2.4) for the foraging dives recorded by TDRs. This information was only available for the dive data from Dtags, from which the average percentage of total sample time corresponding to the time actively foraging, i.e. producing usual clicks and creaks, was estimated for TDRs. This was also carried out to estimate the percentage of foraging-dive time spent by individuals not echolocating, including pauses in usual click production and time spent by a whale in silence, before and after clicking (Table 2.4).

For Dtags, individuals presented on average 3.67-min pauses in vocalization between the first and last click produced and remained in silence for 8.68 min (mean), during the beginning of the descent phase (before they started clicking) and after the last click produced, usually at the beginning of the ascent phase. Therefore, the mean, total silent time was 12.35 min without echolocation during a dive.

Whales spent an average of 55.28% of their time (the total sample period) producing clicks, 22.16% in silence during a dive, and 22.56% in the surface phase. Therefore, the time in which the sperm whales were acoustically available was estimated as 32.37 min and 43.84 min for Dtags and TDR, respectively, with a mean of 38.10 min (sd: 8.11 min). In turn, the estimated time during which this species was acoustically unavailable corresponded to 28.01min for Dtags and 33.15 min for TDR, with a mean value of 30.58 min (sd:3.64).

To estimate the probability of detecting sperm whale echolocation clicks at zero-horizontal distance,  $g(0)$ , for line-transect surveys, the calculated time window was 27.71 min, adopting an average survey speed of 9.35 knots (17.32 km) and 4 km as the limit of the detection range. This time window was added to the mean acoustic available time and divided by the sum of the time that this species spent being acoustically available and unavailable, which resulted in an estimated  $g(0)$  of 0.96.

Table 2.4: TDR and Dtag foraging dive parameters, mean (standard error), applied to estimate sperm whale acoustic availability and  $g(0)$ , ne – not estimated/ na not available. Information on sperm whale foraging dives is also presented, described in other studies for other regions. Duration in minutes (min), depth in meters (m) and velocity m/s.

Parameters	TDR (Brazilian waters)					Dtag (Azores archipelago)					
	87759	87762	87773	87777	Mean	211b	222a	222b	226a	228a	Mean
Mean foraging dive cycle time (min)	59.1 (3.63)	95 (na)	73.82 (1.42)	80 (20.86)	76.99 (7.42)	58.95 (1.20)	50.76 (6.05)	94.56 (35.87)	49.02 (0.70)	48.62 (1.44)	60.38 (8.75)
Mean foraging dive depth (m)	534.5 (0)	277 (na)	477.2 (21.60)	564.5 (26.72)	463.31 (64.69)	984.73 (24.04)	1042.53 (536.74)	1036.83 (17.17)	899.04 (11.70)	930.94 (18.64)	978.81 (14.19)
Mean foraging dive time (min)	53.3 (2.20)	85 (na)	62.06 (1.47)	44.5 (1.46)	61.22 (8.70)	50.03 (1.02)	43.39 (6.37)	45.85 (1.12)	39.2 (0.72)	37.19 (0.72)	43.13 (2.30)
Mean surface phase time (min)	5.8 (3)	10 (na)	11.76 (1.47)	35.5 (21.22)	15.77 (6.69)	8.92 (1.06)	7.38 (0.32)	48.71 (36.12)	9.82 (0.26)	11.44 (1.17)	17.25 (7.89)
% foraging dive cycle in foraging dive	90.60 (4.92)	89.47 (na)	66.27 (10.27)	84.23 (1.68)	82.64 (5.63)	84.87 (0.14)	85.47 (0.02)	48.49 (0.15)	79.97 (0.10)	76.48 (0.07)	75.06 (6.84)
% foraging dive clicking	ne	ne	ne	Ne	Ne	72.91 (0.49)	66.53 (1.31)	69.75 (2.11)	75.52 (0.57)	72 (1.45)	71.34 (1.48)
% foraging dive in silence	ne	ne	ne	Ne	Ne	27.09 (0.49)	33.39 (1.24)	30.25 (2.11)	24.48 (0.57)	28 (1.45)	28.64 (1.50)
% foraging dive cycle clicking	0.64 (na)	0.64 (na)	0.6 (na)	0.4 (na)	0.57 (0.06)	61.88 (0.11)	56.86 (1.60)	33.87 (0)	60.37 (0.07)	55.08 (0.08)	56.59 (2.35)
% foraging dive cycle in silence	0.26 (na)	0.26 (na)	0.24 (na)	0.16 (na)	0.23 (0.02)	38.11 (0.08)	43.14 (0.33)	66.12 (0.15)	39.63 (0.03)	44.81 (0.13)	46.36 (5.08)
Literature											
Study	Location	Tag-type	Number of attachment	Sex gender	Mean foraging dive depth	Mean foraging dive time	Search phase duration	% dive in searching	Mean Post-dive duration		
Watwood et al. 2006	North Atlantic Ocean	Dtag	8	Mostly Female and immature	985.2	45.7	37	80.7	9.3		
	Gulf of Mexico		29		643.6	45.5	37.4	81.2	8.1		
	Ligurian Sea		12		827	44.2	36	81.4	9.9		
Teloni et al. 2008	Norway	Dtag	5	Male	492	32.3	29.2	91	14.5		

## Discussion

### *Sperm whale dive profile in southern Brazilian waters:*

This study was one of the first efforts to describe sperm whale dive profiles in Brazilian waters using data from time-depth recorders (see also Baracho-Neto et al. 2018). Due to the limited durability of the batteries used, TDRs were programmed to collect dive depth data in low-resolution, which possibly resulted in less information about dives. This tag type usually allows for longer remote monitoring and therefore more dive information on tagged whales, which could compensate for the low durability of the batteries (Barlow et al. 2013). However, successive dives performed by the same individual over a short period are potentially more similar than dives made by different individuals, or by the same individual several days apart (Barlow et al. 2013).

In this study, an individual was monitored for a maximum of nine days (# 87773). Accordingly, dives performed by this individual in the first days of monitoring may be independent of those performed toward the end of the monitoring period, which in turn does not apply to the three other individuals that were monitored for a shorter period (see Barlow et al. 2013).

Other studies have also dealt with a short battery life, and a reduced number of days monitoring tagged whales (Amano & Yoshioka 2003, Davis et al. 2007). However, a recent satellite monitoring effort was conducted to record dives of different whale species, including sperm whales, using an updated version of the same tag type used in this study (Advanced Dive Behavior (ADB) tag) (Mate et al. 2016). Dives were recorded at a sample resolution of 1 Hz, while staying attached for intermediate time periods (several weeks to less than a month) (Mate et al. 2016, Irvine et al. 2017). Thus, a next step for research would be to obtain more refined information on the underwater behavior of species that perform longer dives, such as sperm whales, in different regions worldwide.

Two tagged whales, the possible male (# 87773) and female (# 87777), performed most dives, accounting for approximately 86% of assessed dives. The former was monitored for 1.19 days, performing 46 dives (1.61 dives/h), which due to the potential similarity between dives (Barlow et al. 2013) may not have contributed substantially to the description of diving parameters. In turn, the possible male was monitored for 9.24 days and performed 74 dives (0.33 dives/h). Although a greater number of dives were expected, this was not possible due to recording failures, resulting in incomplete dives being removed from the analysis. However, the analyzed dives were recorded throughout the monitoring period and along the southern Brazilian



slope, which as already mentioned may have resulted in independent dives performed by the same individual.

Variation between studies exists regarding the threshold adopted to separate deep and shallow dives of sperm whales (Amano & Yoshioka 2003, Watwood et al. 2006, Aoki et al. 2007, Isojunno & Miller 2015). The present study adopted the values found in Watwood et al. (2006), which seemed to fit the thresholds already presented: shallow dives of < 150 m and deep dives of > 300 m.

The mean maximum dive depth observed in this study was lower than the threshold adopted for shallow dives. In Davis et al. (2007), 74% of dives were shallower than 100 m. According to these authors, these dives could be associated with the period of resting and socialization. Since the aim was to evaluate sperm whale foraging behavior, these were removed from the analyses, evaluating only those whose depth exceeded 100 m. Even among those dives, the majority did not exceed 500 m (Davis et al. (2007). Teloni et al. (2008) recorded an average maximum depth of 175 m, and Irvine et al. (2017) observed a bimodal pattern in the depths recorded, with peaks at < 50 m and between 300 and 500 m. As in the present study, those studies calculated the overall mean of the dive parameters from all the assembled dives, including shallow dives, which potentially contributed to the lower values.

The difference between the present findings in relation to those of studies previously mentioned is in the maximum recorded depth value, which exceeded 1000 m for all of those studies, reaching in the Teloni et al. (2008) study a depth almost three times that recorded here. In those studies, the mean dive duration was around 25-30 min, whereas in the present study it was half that. The previously mentioned studies were conducted in temperate and tropical regions, except for that of Teloni et al. (2008), who studied adult male dives at high latitudes. In all of those studies, average maximum depth and duration of dives were generally smaller than that described in regions that are also at lower latitudes (Papastavrou et al. 1989, Watkins et al. 2002, Amano & Yoshioka 2003, Watwood et al. 2006, Aoki et al. 2007).

In this study, the proximity to the bottom was not a limiting factor to the depths reached during sperm whale dives, which was also observed by Davis et al. (2007). Teloni et al. (2008) also showed that individuals, although closer to the bottom during deep dives, did not explore 100% of the water column, indicating that the bottom did not limit their dive depths; rather, the distribution of prey limited such depths.

When separated into dive types, V-shaped shallow dives, for which the bottom phase was absent, were the most frequent type and had the lowest mean maximum dive depth and duration.

The mean duration of dives of Intermediate-depth was comparable to those recorded by Davis et al. (2007), Teloni et al. (2008) and Irvine et al. (2017), although Davis et al. (2007) excluded shallow dives from the analysis. Deep dives in this study, which were even shallower than foraging dives described in Watwood et al. (2006), in turn had a mean dive duration of an hour. These had a marked bottom phase characterized by a greater mean depth and depth variation, as observed by Aoki et al. (2007) for deep dives generally.

When only considering dives deeper than 150 m (classified as 'Intermediate' and 'Deep' dives), mean dive duration increased to 42.69 min, similar to those described by Watwood et al. (2006) for temperate and tropical latitudes, but which had a lower mean maximum dive depth of 305.55 m, which was similar to that recorded by Irvine et al. (2017) for all dives they evaluated.

The predominance of shallower dives observed in the present study could be related to the fact that they were mostly performed by the possible male. According to Teloni et al. (2008), adult males at high latitudes tend to make shallower dives. Another possibility is that, since this is a generalist species (Whitehead 2003), shallow dives are a response to prey availability in these regions, as observed by Davis et al. (2007) for females and immatures in the Gulf of California.

In the Irvine et al. (2007) study, dive time and depth were not coordinated between individuals, suggesting mesopelagic vertically heterogeneous prey field foraging. Variation at an individual level had already been observed within a given region in Watwood et al. (2006), but not over the temporal and spatial scales reached in the Irvine et al. (2017) study. Evans & Hindell (2004) found variability in the composition of cephalopods in sperm whale diet in southern Australia, according to stranding site and sex, but not with age. According to the authors, this may reflect individual variability in foraging success, and perhaps of foraging groups.

Whales performed most dives during the day. However, nocturnal dives, representing one-third of the dives, had a greater mean maximum depth, but a lower mean and variation in bottom depth, which tended to also be shorter than for bottom phases performed during the day. Therefore, even in deeper waters, dives performed at night did not reach great depths, being between 10.5 and 403.5 m, which is a smaller range than that observed during the day (10.5 to 685.5 m).

Davis et al. (2007) observed that both whales and squid were found at depths of 300 to 400 m during the day, when dives were on average deeper than those performed at night, when jumbo squid moved to shallower depths. These authors also stated that even though the whale dive-depth distribution was shallower and broader at night than during the day, it did not match the notable shift in the distribution of squid.

The same vertical migration pattern was observed by Moiseev (1991), who through an underwater vehicle expedition conducted in open oceans worldwide, including in the southwestern Atlantic, showed that short-finned squid occurred at depths of 125-850 m during the day and migrated to 200 m and the surface at night. This may explain the average maximum depth reached by the whales in the present study. Vertical migration was also partially described by Moiseev (1991) for nine other species in the Atlantic Ocean, most of which occurred in deeper waters during the day and migrated to shallower waters at night.

Aoki et al. (2007) also reported diel dive patterns for sperm whales tagged off the Ogasawara Islands, where individuals dove deeper during the day than at night. However, no diel pattern was observed by the author off the Kumano Coast, suggesting that differences in this species' diel pattern, which is in turn mediated by the diel behavior of its prey, could be related to environmental differences between the two areas surveyed.

Dives classified as deep and V-shaped shallow were more frequently performed during the day, which may explain an overall mean maximum dive depth that was lower than those observed at night. However, considering only deep dives, most likely involved in foraging, the variation between daytime and nocturnal dive depths may be explained by the vertical migration of squid species.

Thus, although the data presented here are limited both by monitoring time and by the number of individuals, the overall dive behavior is apparently not uncommon in often studies in tropical and temperate latitudes (Davis et al. 2007, Teloni et al. 2008).

*Sperm whale acoustic availability and detection probability at zero horizontal distance,  $g(0)$ :*

Passive acoustic monitoring has been gaining popularity in marine mammal surveys, proving that it can be a valuable and widely applied tool in association with different approaches, such as density and abundance estimation efforts (Barlow & Taylor 2005, Thomas et al. 2006, Gillespie et al. 2009, Marques et al. 2013, Yack et al. 2013).

Among marine mammals, sperm whales are one of the most well-suited to acoustic monitoring, due to their vocal repertory, in particular the regular, audible and short-duration usual clicks typically produced during a dive (Weilgart & Whitehead 1988, Madsen et al. 2002a, 2002b, Barlow & Taylor 2005)

Density estimates are based on the estimated probability of detecting an animal as a function of its perpendicular distance from the transect line (Fais et al. 2016). An

important assumption for the Conventional Distance Sampling (CDS) is that individuals at the zero-horizontal distance,  $g(0)$ , either under or above the trackline, will be detected with certainty (Buckland et al. 2001). However, this assumption is typically not met by either visual or acoustic monitoring. Even allowing for detection when individuals are unavailable for observation, using PAM for density estimation needs to deal with an individual's acoustic availability and, once vocally active, the probability that their signals are detected by the acoustic monitoring system (i.e., a perception issue).

In this study, as in Douglas et al. (2005) and Fais et al. (2016), acoustic availability was based on the likelihood of the individual producing foraging vocalizations, particularly usual clicks produced by both males and females (Stanistreet et al. 2018). This was due to the high directionality and short duration particularly of usual clicks, making sperm whales ideal research candidates for Time Difference of Arrival (TOAD) methods (Frazer & Nosal 2006). In addition to the powerfulness and frequency band at which these signals are produced, they contain energy predominantly at frequencies above the background noise range (Weilgart & Whitehead 1998, Madsen et al. 2002a, Møhl et al. 2003, Zimmer et al. 2005).

Thus, the estimation of  $g(0)$  relies only on the probability that individuals are vocalizing within a finite time window for detection. There are three contexts in which individuals may not produce echolocation clicks, contributing to  $g(0)$  being smaller than one (Douglas et al. 2005, Barlow & Taylor 2005, Barlow et al. 2013, Fais et al. 2016). The first corresponds to occasional resting and/or socializing periods spent at the surface, in addition to the post-dive intervals. During these longer periods, whales typically do not produce echolocation clicks (Barlow & Taylor 2005, Lewis et al. 2007, Fais et al. 2016). The second is related to periods before and after the production of echolocation clicks, in which individuals are silent during a dive, and which appear to vary locally and between age/sex classes (Watwood et al. 2006, Davis et al. 2007, Teloni et al. 2008). The third refers to the regular interruptions in the production of usual click trains by small intervals of apparent silence, as well as the production of creaks (Madsen et al. 2002a).

In the present study, pauses in vocalizations were also counted as silent periods, generating an expected time when whales were unavailable for detection (silent periods), which exceeded the finite time window when they were available for detection, resulting in a  $g(0)$  equal to 0.96. Basing their estimation on the same acoustic data used here, Fais et al. (2016) accounted for only the surface phase and the silent periods before and after the production of usual clicks, not considering pauses in the production of these clicks. Even when doing so, the time window in their

study was greater than the estimated period of silence. Therefore, they adopted another method to estimate the  $g(0)$  that they found, which was equal to 0.92 ( $\sigma = 0.031$ ).

The sperm whale dive parameters described for the Azores (Oliveira 2014) were similar to those described by Watwood et al. (2006) and Madsen et al. (2002a) for whales in tropical and temperate latitudes. Therefore, they are also different from those found in the present study, if considered the overall mean of the dive parameters. In turn, if only deep dives -- particularly those identified as foraging dives by the criteria adopted in Barlow et al. (2013) -- are considered, the dive and bottom phase durations resembled those observed in those studies. Nevertheless, the dive depth remains shallower, even in relation to that observed for males at high latitudes, as well as that observed for females and immatures in tropical and temperate waters (e.g., Davis et al. 2007, Irvine et al. 2017).

It is worth mentioning that variation in the duration of active foraging periods was also reported in Teloni et al. (2008) for adult males at high latitudes, which apparently forage across a wide range of depths and in all dive phases, echolocating during approximately 91% of dive.

However, despite such apparent differences already observed in this species' behavior, as most of the individuals monitored were females, it was decided to assume the stereotyped pattern suggested by Watwood et al. (2006) in foraging behaviors as possibly applicable to dives performed in Brazilian waters, where individuals would then follow a similar pattern of acoustic availability, even if generalizations are not encouraged.

Although, given the possible evidence that sperm whales are also not at all identical in their foraging behavior between regions, the collection of larger samples of this species' diving and acoustic behaviors at a higher resolution and across different regions is required to provide an overview of these behaviors, therefore allowing generalizations. Notably, Barlow et al. (2013) state that generalizing the results obtained from the approach presented here depends on the assumption that the behavior of both marked whales and the population in general is the same.

Another important issue reported by Barlow et al. (2013) corresponds to the fact that not always the hypothesis of the vocalizing individuals within a finite-time window would be detected with certainty, can be satisfied. If this is disregarded,  $g(0)$  will be overestimated and abundance will be underestimated. Although the sperm whale's foraging clicks characteristics make them amenable to detection, background noise can potentially mask acoustic signals produced by relatively close, but off-axis vocal whales, or those produced by distant individuals due to signal attenuation (Zimmer

2011). Additionally, clicks produced during the descent phase and directed downwards are less likely to be detected by a towed hydrophone (Barlow et al. 2013).

Finally, based on the potential synchronism between vocalizations of individuals in a group that dives synchronously, the detection of a group was assumed to be the same as that of an individual (Barlow et al. 2013). However, considering that foraging vocalizations are likely to be a source of information for conspecifics about foraging conditions, Madsen et al. (2002b) and Whitehead (1989) have suggested the possibility of individuals eavesdropping on their conspecifics' acoustic emissions in search of a potential foraging location. Additionally, the chance of detecting at least one individual in a group that is vocalizing asynchronously tends to be greater than that of a single whale, which would increase the likelihood of acoustic detection (Barlow et al. 2013); therefore, abundance estimates need to account for this possibility and include it as a covariate in analyses.

Despite the limitations presented above, particularly the assumptions associated with the approach adopted here to estimate  $g(0)$ , efforts to consider and estimate this important parameter are essential for producing more reliable estimates.

Therefore, further studies are strongly suggested to understand the diving and acoustic behavior of sperm whales in different regions, addressing their behavioral variations, including the synchronicity of their vocalizations and the potential influence of group size on detections (see Barlow et al. 2013). Additionally, research to assess the perception bias associated with acoustic detections is strongly encouraged.

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### **CAPÍTULO III**

**I cannot see you, but I am listening to you: Acoustic density estimation of Sperm whales (*Physeter macrocephalus*) on the outer continental shelf and slope off southern Brazil**

Manuscrito em preparação para submissão à revista: "*Marine Ecology Progress Series*"

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## **I cannot see you, but I am listening to you: Acoustic density estimation of Sperm whales (*Physeter macrocephalus*) on the outer continental shelf and slope off southern Brazil**

### **Abstract**

In recent decades, the conservation of marine mammals has become increasingly important particularly considering the continuous development of anthropogenic activities in their habitats. Whereas information on population abundance is essential to determine effective management efforts. Information on sperm whale's population structure and abundance is still limited for many regions, including Brazil. Here it is presented the first effort to acoustically estimate the sperm whale's population size in the southern Brazilian outer continental shelf and slope. An opportunistic ship-based survey was conducted using towed array. Recordings were processed using PAMGuard for sperm whales click trains detection and localization. This species density and abundance were estimated using the Conventional Distance sampling (CDS) analysis. A mean foraging dive maximum depth of 492 meters (m) was adopted to correct the perpendicular distances acoustically estimated. Both original and corrected perpendicular distances dataset were used to estimate the detection function and  $g(0)$  values: 1, 0.96 and 0.83 were adopted as multipliers. The best fitting model was the Half-normal with no adjustment terms. For the corrected distances it was defined an effective strip half-width (ESW) of 1523.81 m, allowing to reach a density of 0.0146 whales/ km<sup>2</sup> and an abundance of 1654.35 (CV 0.379, CI 778.36-3516.24) whales for the surveyed area, which was underestimated in 4% and 17% if compared to the abundance estimated considering  $g(0)$  equal to 0.96 and 0.83, respectively. Compared to the original perpendicular distances, the abundance was underestimated in only 2.31%. Although still in development, acoustic monitoring presents as an alternative or complementary method to visual monitoring, being able to access reliable information on sperm whale population size, as well as contribute to the continuous improvement of such method.

Keyword: marine mammals, deep divers, TDR tags, dive cycle, dive phases, Brazilian waters.

## Introduction

In recent decades, conservation of marine mammals has become increasingly important (Nielsen & Møhl 2006), particularly because of continuous implementation of anthropogenic activities in their habitats (e.g. fishing, shipping, oil exploitation, chemical and noise pollution), which have potentially affected marine mammals in all oceans worldwide (Reeves et al. 2003, Whitehead 2003, Jewell et al. 2012, Fleishman et al. 2016). Since the International Whale Commission established the moratorium in 1988, such activities have become the most important threat to marine species.

Therefore, to conserve a potentially threatened species, information on spatial and temporal variations of their distribution and abundance is essential to determine if management actions are necessary, and if taken, whether they are effective (Evans & Hammond 2004, Thomas & Marques, 2012, Fais et al. 2016).

Measuring changes in a mobile population, such as marine mammals, is a challenge. According to Thomas & Marques (2012), despite the seemingly simple question, "How many whales are there?", answering it is often not easy because some populations are spread over large areas and their habits can make them difficult to observe. This problem is applicable when attempting to estimate the population size of sperm whales (*Physeter macrocephalus* Linnaeus, 1758). This species, listed as vulnerable by the International Union for the Conservation of Nature (IUCN 2018), inhabits all ocean basins, only avoiding the polar regions, and is mainly found over the continental slope (Rice 1989, Jaquet & Whitehead 1996, Whitehead 2003, Reeves et al. 2003, Jefferson et al. 2008). Individuals typically spend 70 to 75% of their time submerged, performing long and deep foraging dives (Whitehead 2003, Watwood et al. 2006, McDonald et al. 2017), which means that they are unavailable for visual observation (Ward et al. 2012).

However, due to sperm whale's vocal repertory, in particular the regular, audible and short-duration usual clicks typically produced during a dive (Weilgart & Whitehead 1988, Madsen et al. 2002), it is one of the most amenable species to monitor acoustically (Barlow & Taylor 2005). Because these species click have rapid rise times (< 1 ms), they contribute to better accuracy of location methods based on arrival time difference (Swift et al. 2003, Barlow & Taylor 2005, Frazer & Nosal 2006).

Passive Acoustic Monitoring (PAM) is a growing area of research (Kusel et al. 2017) and is becoming either a complementary or alternative monitoring method to conventional visual surveys, which have known limitations (Mellinger et al. 2007, Gillespie et al. 2008, 2009, Jewel et al. 2012, Yack et al. 2013, Marques et al. 2013, McDonalds et al. 2017, Verfuss et al. 2018). PAM offers a non-invasive method to

study species such as sperm whales, which are usually difficult to observe (McDonalds et al. 2017).

Density estimates from PAM have been performed using a variety of equipment and from different platforms (Gillespie 1997, Barlow & Taylor 2005, Gannier et al. 2002, Hastie et al. 2003, Leaper et al. 2003, Lewis et al. 2007, Swift et al. 2009, Ward et al. 2012, Fais et al. 2016, Andriolo et al. 2018). By producing clicks whose frequency band (100 Hz to 30 kHz, Watkins, 1980) extends above the dominant range of ship and water flow noise, sperm whales are well suited to be studied using towed PAM systems (Barlow & Taylor 2005). Towed during dedicated research surveys or opportunistically, PAM allows wide-ranging sample coverage, collecting qualitative and quantitative vocalization data, often at relatively low costs (Whitehead 2003, Swift et al. 2003).

In many regions, research is still needed on the population structure and abundance of sperm whales (Novak 2016). Despite monitoring efforts already carried out in Brazil, information on this species is still limited. Until recently, only information on this species' occurrence and abundance index (number of sightings per unit effort) had been available in this study area (Pinedo et al. 2002, Zerbini et al. 2004). However, sperm whale population estimates have been recently assessed through a visual monitoring survey, to which this study was simultaneously conducted (Di Tullio 2016).

From this species' acoustic data, which were collected opportunistically but systematically, this study presents the first effort to acoustically estimate sperm whale population size in the southern Brazilian outer continental shelf and slope. Although conducted simultaneously with a visual survey, we do not present results from the two monitoring methods because observations were part of an ongoing project (see Di Tullio 2016 for further details), and temporal coverage varied between them. However, results presented here corroborate Di Tullio findings (2016), showing that both methods, despite their limitations, are useful approaches for monitoring sperm whales, especially when conducted in an integrated way, but also independently.

## **Methods**

### *Study area and data collection:*

During Spring 2014, an opportunistic ship-based survey was conducted aboard the 36 m-long *R/V Atlântico Sul*, from Chuí (Rio Grande do Sul State, RS 34° S) to south of Florianópolis (Santa Catarina State, SC – the northern limit of Pelotas Basin, 28°40' S), between the 100 and 2000 meters (m) isobaths. This area covers the outer



continental shelf and slope of southern Brazil and corresponds to the Brazilian portion of the Pelotas Basin (Figure 3.1a).

Acoustic recordings of sperm whales' usual clicks and creaks (hereafter referred to as foraging vocalizations, but also known as echolocation clicks), along with slow clicks and codas were continuously collected by a towed array, used during a marine mammal visual monitoring project (Slope Project/EcoMega – FURG). The line-transect distance sampling method was applied (Buckland et al. 2001), using a zigzag sample design that was planned for the visual survey (Figure 3.1b).

An array (AUSSET<sup>®</sup>), composed of three omnidirectional elements (hydrophones, high pass filter of 1592 Hz) was used. The distances between hydrophones were five and three meters apart. The furthest element was located five meters from the end of the cable, to which a two-meter-long rope was attached in order to provide system stability (Supplementary Material S1 and S2). The array was towed at the vessel's steering speed of approximately 9.35 knots, at an estimated depth of up to 4 m, based on Thode et al. (2010).

Recordings were made mostly during the day, as they were conducted simultaneously with a visual survey, and were carried out in rough seas (Beaufort scale up to 6). After the visual effort ended, occasional monitoring was possible during part of the night when the ship stayed on the trackline. Recordings were transmitted onboard to a Fostex<sup>®</sup> FR-2 LE digital recorder (2 channels, frequency response of 48 kHz) or an Iotech-Personal Daq/3000 Series acquisition board (3 channels, frequency response of 100 kHz), stored as a digital file (.wav) on a hard drive for post-analysis.

The ship's geographic coordinates were also continuously recorded by a GPS coordinate system, connected to two storage programs: (1) WinCruz (used by the visual monitoring team) and (2) Echoview. Echoview, which was first adopted because it recorded the coordinates every two seconds. However, where gaps in information occurred, WinCruz records were used, if available.

To increase the location quality of the events, only acoustic records made 'on effort', e.g. when on the trackline, were considered. 'Off effort' recordings, performed when visual sampling ceased on the transect, were disregarded.

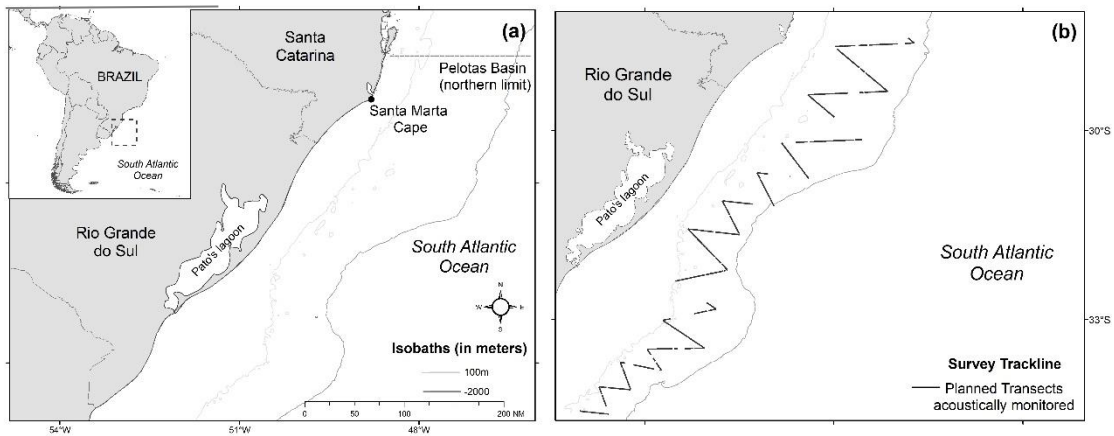


Figure 3.1: Study area on the outer continental shelf and slope off southern Brazil, from Chui (RS) to south of Florianopolis (SC) – Pelotas Basin (a). Acoustic monitoring tracklines covered during the Spring 2014 (b).

#### Acoustic data analysis:

The raw acoustic data was preliminarily inspected: (1) for signals of interest using Long-term Spectral Averages (LTSA) through the custom software program Triton (Wiggins & Hildebrand 2007), and (2) to minimize the number of missed clicks, through visual inspection of one-minute spectrograms (Hann window of 512-point FFT with 50% overlap), which were taken every three minutes using Raven Pro 1.5 (Cornell Laboratory of Ornithology, NY).

Open source software, PAMGuard version 1.15.11 (Gillespie et al. 2008) processed the two-channel acoustic files using two steps: detection and location, following Gillespie et al. (2009). Candidate clicks were detected by applying the program's click detector module to the raw data, which was first filtered to remove signals above 2000 Hz, and then passed through a 2-17 KHz band-pass filter. Additionally, a 12dB trigger threshold was adopted, as well as the detector *angle veto* feature to avoid false triggers caused by background noise (also see Swift et al. 2009 and Macaulay et al. 2015). Noise from the survey ship's 18 and 35 kHz echo sounders were removed using specific classifiers. As the frequency sample and the distance used between the pair of hydrophones differ among recordings, the click length and the minimum and maximum click separations were also different for each processed recording. Detected signal bearings were estimated by the time difference of arrival (TDOA) of each signal to the pair of hydrophones (Hastie et al. 2003, Lewis et al. 2007, Swift et al. 2009), then displayed as bearings against time (Isojunno 2014).

The detection-step outcomes, together with the GPS data, were loaded and simultaneously processed (Macaulay et al. 2015) in the PAMGuard Viewer mode. Candidate clicks were visually and aurally inspected using the PAMGuard

spectrogram, which provides additional displays such as waveform, power spectrum, and inter-click interval to identify sperm whale clicks and reduce false-positive detections and echoes.

Usual clicks, creaks, codas and slow clicks were separated into different click trains, which in turn were defined as events (Swift et al. 2009). Whenever possible, each event included a single click train, corresponding to acoustic signals from an individual. However, when two or more trains were close together, these were regarded as one event which had the number of click trains visually defined, thus allowing for an estimate of group size (Swift et al. 2009).

Event locations were estimated using Target Motion Analysis (TMA), assuming a slow whale swim speed relative to the ship's speed (Gillespie 1997, Leaper et al. 2000, Hastie et al. 2003, Barlow & Taylor 2005, Lewis et al. 2007). Along with the event locations, the Akaike's Information Criterion (AIC) was also calculated for each location model to support the selection of the best estimated position. The more the trackline deviated from a straight line, the more likely an event position could be better identified, solving left-right ambiguities (PAMGuard guidelines).

Information about location and distance of each event to the trackline was stored in a database and exported as a .csv file, along with the number of trains per event, click type and location quality score, as defined by an acoustician. Only estimated location and perpendicular distance to the trackline of foraging vocalization events were considered in the density estimation analysis.

#### *Density estimation analysis:*

The density and abundance estimates of whales in the surveyed area were determined using the Conventional Distance Sampling (CDS) analysis (Buckland et al. 2001).

Information regarding the location of acoustic events, corresponding to usual clicks and creaks, their perpendicular distances from the trackline, and number of click trains per event (estimated group size) were accessed from the .csv file, resulting from the location step.

As acoustic location is determined in a three-dimensional environment, the estimated perpendicular distance from the trackline does not correspond to that estimated in two dimensions (at the surface) using distance sampling (Figure 3.2). Furthermore, information on detected group depth is not available to allow estimation of the horizontal distance at the surface. Thus, an average maximum depth of ~492 m, recorded for sperm whales monitored with time-depth recorders (TDRs) in Brazilian

waters during foraging dives (Castro et al. unpublished, chapter 2) was adopted as the general depth of the detected groups to correct the perpendicular distances acoustically estimated through PAMGuard (hereafter referred to as “original perpendicular distance”), using basic trigonometric rules (Barlow & Taylor 2005). However, when the original perpendicular distance was smaller than the assumed depth value, it was adopted without correction.

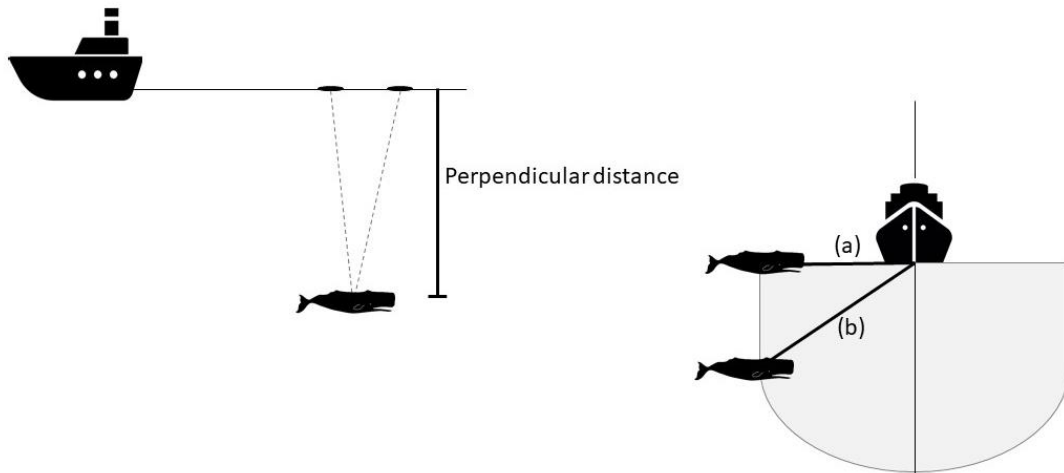


Figure 3.2: Scheme of the acoustically estimated perpendicular distance, which may correspond to (a) if the group is near the surface or at the same depth as the array (approximately 4 m for this study) or (b) when the individual is most likely at a greater depth.

For original and corrected perpendicular distance datasets, detection distances and respective group size (observations), along with information about acoustic effort (surveyed area and trackline length) were uploaded in R (R Development Core Team 2017, version 3.4.3) to estimate the detection function, i.e. the probability of detecting an individual or group as a function of its perpendicular distance using the Distance package.

First, an exploratory data analysis of the perpendicular distances histogram was performed to evaluate whether adopting a right truncation distance was necessary (see Buckland et al. 2001). The uniform, half-normal and hazard-rate key functions available for CDS were tested to determine which one would best fit the perpendicular distances distribution. However, preliminary tests were run to support adopting the right truncation distance.

Second, a stepwise model selection was conducted, starting with simple models, then adding an adjustment term (cosine and simple polynomial for uniform and hazard rate, and cosine and hermite polynomial for half normal), selecting the best model based on the lowest value of Akaike’s Information Criterion (AIC and delta AIC) (e.g. Burnham & Anderson 2002). If the data provided good support for more than one

model, the simplest model (with the fewest parameters) was chosen (as adopted by Bortolotto et al. 2017).

After fitting a model to the detection function, as in Buckland et al. (2001) and Thomas et al. (2006), sperm whale density ( $\hat{D}$ ) was estimated using the following equation:

$$\hat{D} = \frac{n \cdot \hat{f}(0) \cdot \hat{E}(s)}{2L}$$

where  $n$  is the number of acoustic encounters detected,  $\hat{f}(0)$  is the probability density function for zero distance,  $\hat{E}(s)$  is the group size, and  $L$  is the total surveyed trackline length. The abundance ( $\hat{N}$ ) was then estimated considering:  $\hat{N} = A \cdot \hat{D}$ , where  $A$  is the surveyed area.

A multiplier was selected to account for  $g(0) < 1$ . Although sperm whales spend most of their time performing foraging dives, producing usual clicks and creaks for most of a dive period, individuals also spend some time without producing foraging vocalizations (during a dive and when on the surface). Assuming that, for line transect surveys, all individuals vocalizing within a finite time window will be detected (Barlow et al. 2013), the estimated  $g(0)$ , as per the parameter estimation method used in Castro et al. (unpublished, chapter 2), based on the approach presented by Barlow et al. (2013) (also see Fais et al. 2016), was adopted here. Thus, both datasets of perpendicular distances were analyzed by adopting  $g(0) = 1$ ;  $g(0) = 0.96$ , as estimated in Castro et al. (unpublished, chapter 2), in which a finite time window – time during which all individuals were assumed to be detected – was calculated based in a detection range of 4 km and an average survey speed of 9.35 Knots; and a  $g(0)$  estimated in this study, assuming as detection range the average Effective Strip Width (ESW) resulted from modeling the detection function.

Variance, coefficients of variation (CVs), 95% confidence intervals (CI) were also estimated in R.

## Results

During the cruise, the surveyed area was almost completely sampled. Covering 1523.81 km along tracklines during the survey, acoustic monitoring detected and located 104 sperm whale acoustic events, which correspond to foraging vocalizations. The perpendicular distance of each event location from the trackline was then acoustically estimated at an average of 2622.81 m (standard deviation, sd: 5107.22 m). After correction, the mean acoustical perpendicular distance was 2550.03 m (sd: 5123.85 m).

The number of acoustic events was slightly reduced after adoption of a distance truncation of 7 km, resulting in perpendicular distances for 100 sperm whales' groups, which were used to adjust the detection function. Detection functions were then adjusted to the distribution of both sets of perpendicular distances, which were those originally estimated (from PAMGuard) and those that were corrected based on the maximum-depth foraging dives from TDR tag data adopted in this study, with  $g(0) = 1$  being initially assumed.

From the AIC stepwise selection, the key function selected was the half-normal model with no adjustment terms, which resulted in average detection probabilities ( $\hat{P}_a$ ) of 0.40 and 0.39, and an effective half-strip width (ESW) of 2799.91 m (CV = 0.08) and 2736.56 m (CV = 0.08) for the original and corrected perpendicular distances, respectively. This model presented a good fit to the evaluated perpendicular distance distribution, which was further confirmed by the Kolmogorov-Smirnov and Cramer-von Mises goodness-of-fit tests.

The summary of the best supported detection function for both sets of data are presented in Table 3.1 (also see Figure 3.3), as well as the respective density estimate, abundance estimate (CV and 95% confidence intervals), group size (CV) estimate, and goodness-of-fit test p-values.

Table 3.1: Summary of the best fitting model for the perpendicular distance datasets assessed: original perpendicular distances dataset acoustically estimated using PAMGuard, and (b) corrected perpendicular distances based on the maximum foraging-dive depth, assessed through TDR tags attached to sperm whales in the southern Brazilian outer continental shelf and slope. Adj. term – adjustment term, Param. – number of parameters, Pa – detection probability, CV – coefficient of variation, CI – 95% confidence interval.

Dataset	Model	Adj. Term	Param.	AIC	Pa	CV (Pa)	ESW	D	N	CV (N)	CI (N)	Group size	CV(E)	GOF (K-S), p-value
Original	Half-normal	-	1	1687.59	0.399	0.080	2799.91	0.014	1616.93	0.379	760.05 – 3439.84	1.22	0.025	0.512
Corrected	Half-normal	-	1	1683.37	0.391	0.077	2736.56	0.015	1654.35	0.379	778.36 – 3516.24	1.22	0.025	0.852

Table 3.2: Sperm whale abundance (N, and respective CV and CI), considering the estimated  $g(0) = 0.96$  (Castro et al. unpublished (chapter 2), and  $g(0) = 0.81$ , adopting the ESW estimated in the present study. Adj. term – adjustment term, Param. – number of parameters, CV – coefficient of variation, CI – 95% confidence interval.

$g(0)$	Dataset	Model	Adj. Term	Param.	N	CV (N)	CI (N)
0.96	Original	Half-normal	-	1	1684.30	0.379	791.72 – 3583.17
	Corrected	Half-normal	-	1	1723.29	0.379	810.79 – 3662.75
0.83	Original	Half-normal	-	1	1948.11	0.379	915.72 – 4144.39
	Corrected	Half-normal	-	1	1993.20	0.379	937.78 – 4236.43

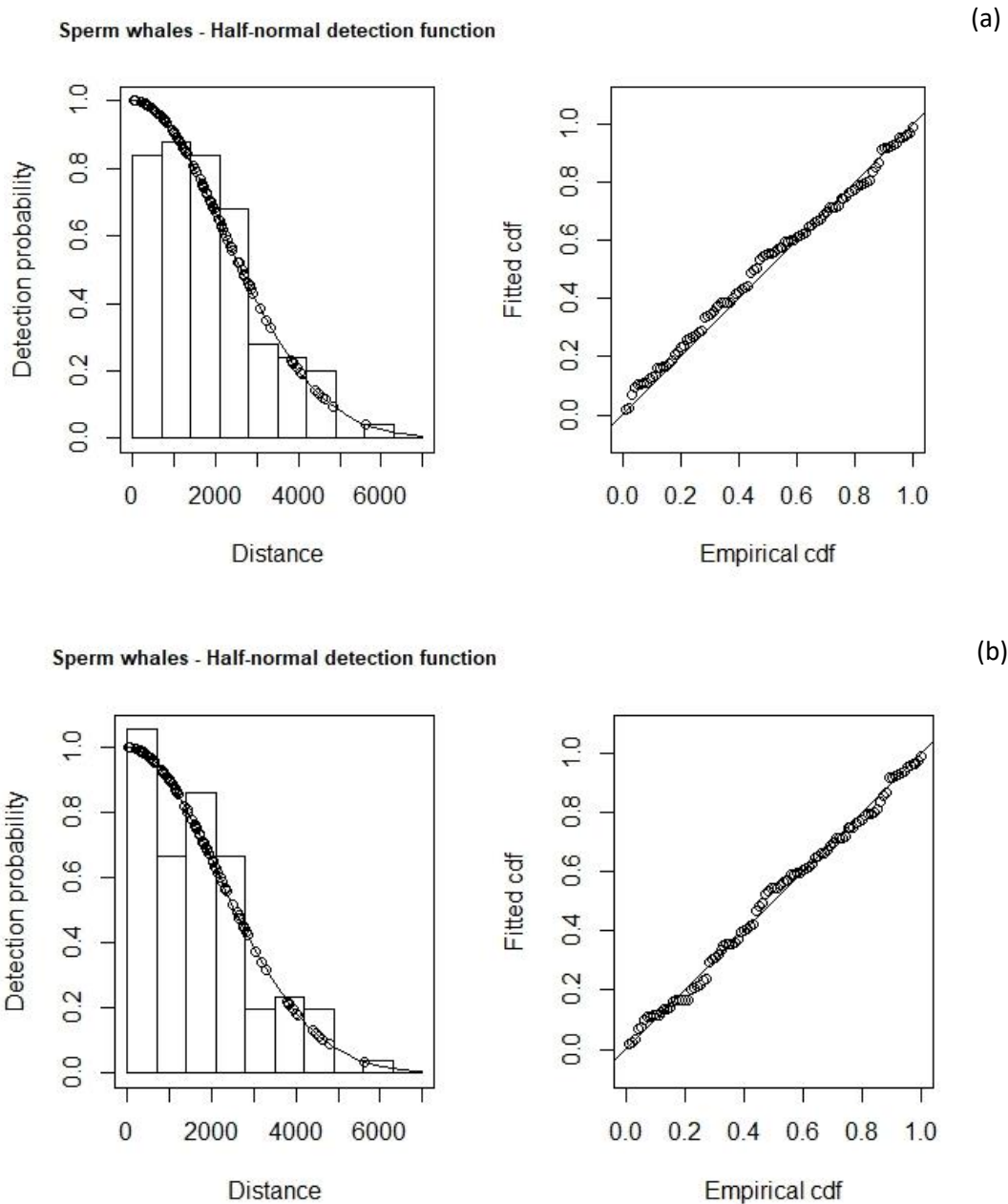


Figure 3.3: Detection probability and QQ plots of fitted model (half-normal) for (a) the original perpendicular distances dataset and (b) the corrected perpendicular distances dataset.

Applying the estimated  $g(0)=0.96$  for sperm whales, the estimated abundance, based on both the original and corrected perpendicular distances, increased by 4.17% (see abundance values for each adopted  $g(0)$  and respective variance in Table 3.2).

As the average ESW in this study was 2768.23 m, assuming an average survey speed of 9.35 Knots (17.32 km/ hour, h), the finite time window was 19.18 min for sperm whale acoustic detection, defined as  $w = 2 *k/v$ , where  $k$  corresponds to the detection range and  $v$  to the average survey speed (Barlow et al. 2013). The multiplication of such a time window by the species' time spent acoustically available,



divided by the sum of the time spent acoustically available and silent, both estimated from time-depth recorders (TDRs) and digital tags (Dtags), resulted in a  $g(0) = 0.83$ . Based on this value, the estimated number of sperm whales for the study area from the original and corrected perpendicular distances dataset was 17% greater than when considering detection at the zero horizontal line as certain.

## Discussion

Sperm whales are among the most vocally active marine mammals and thus are one of the species most likely to be acoustically monitored (Barlow & Taylor 2005, Kandia & Stylianos 2006). Given the difficulties in accessing and monitoring this species, particularly faced by visual methods (Evans & Hammond 2004, Marques et al. 2009, Jewell et al. 2012, Ward et al. 2012), developing additional and/or alternative methods, such as acoustic monitoring, is essential to access reliable data and this adopting tangible conservation measures for marine species (Fais et al. 2016).

Based on the dataset of corrected perpendicular distances and the best-fit detection function, sperm whale density within the surveyed area was estimated at 14.63 whales/1000 km<sup>2</sup> (CI 6.88 – 31.09), resulting in a relative abundance (based on  $g(0) = 1$ ) of 1654.35 whales (CI 778.35 – 3516.24 whales), which was close to the highest abundance visually estimated in Di Tullio (2016), value corresponding to Spring 2012 (density 13.3 whales/ km<sup>2</sup>, abundance 1253.08 whales). The present study was conducted during the last visual monitoring cruise (Spring 2014), which had estimated density of 4.50 whales/ 1000 km<sup>2</sup> and abundance of 320.33 whales.

It is worth noting that, in Di Tullio (2016), the area covered acoustically corresponds only to the southern portion of the area that was visually monitored, which extended further north and included the southeastern Brazilian outer continental shelf and slope (up to 22.9° S). Di Tullio et al. (2016) state that the largest concentration of sperm whales occurred throughout the southern area with few records in the southeast. Despite the effort put into the southeastern outer continental shelf and slope, density and abundance estimates are mostly based on sightings in the southern portion, which was also sampled in this study (Di Tullio 2016).

The use of acoustically estimated perpendicular distances (original distances) resulted in approximately 2.31% underestimated abundance when compared to that obtained from corrected distances based on the average maximum-depth foraging dive, which was performed by animals tagged with TDRs in Brazilian waters (Castro et al. unpublished – chapter 2). Barlow & Taylor (2005) also assume the average foraging dive depth (~600 m), as described in the literature, as a basis for correcting

perpendicular distances obtained in their study, subtracting only the array tow depth (100 m). If the individuals were deeper than the array tow depth, their abundance could be further underestimated.

Potential underestimation of abundance is related to the fact that it was estimated from the perpendicular distances of vocally active individuals. Thus, the estimated group size corresponds to the number of click trains identified per event. If one or more individuals from a group are silent in the hydrophones vicinity and do not vocalize within the finite time window, they are not detected. This is observed in groups, e.g. when adult females and immature sperm whales dive synchronously during foraging (Oliveira 2014). In these cases, they can potentially eavesdrop to locate prey by listening to the clicks of a conspecific, as suggested by Madsen et al. (2002b).

As larger groups are expected in temperate and tropical latitudes, Leaper et al. (2003) pointed out that a visual detection method together with acoustic effort is needed, as visual monitoring in closing mode allows the group size to be visually estimated. Lewis et al. (2007) indicated that manual assignment of clicks to individual whales could be subject to error, especially when individuals are close together, their clicks have similar characteristics and they do not vocalize at the same time. Thus, as in Swift et al. (2009), whenever possible, only one individual was included per event. Only when two or more click trains are so close together that their separation would be subject to more errors than when they are assigned to the same event can an event comprise more than one individual.

Most efforts to estimate abundance of sperm whales from acoustic data have adopted a  $g(0)$  that is equal to or close to 1, assuming that the time spent by the whales in silence is short (Hastie et al. 2003, Leaper et al. 2003, Barlow & Taylor 2005, Lewis et al. 2007, Swift et al. 2009). However, Barlow & Taylor (2005) and Lewis et al. (2007) recognized that individuals spend more time at the surface resting and socializing than when they are between foraging dives, as described in Whitehead (2003). While at the surface, they typically do not produce foraging clicks, though, according to Lewis et al. (2007), Teloni (2005) did not observe individuals in silence for more than 40 min.

In light of possible sperm whale silent periods exceeding the detection time window, as in Barlow et al. (2013), Castro et al. (unpublished, chapter 2) estimate a  $g(0)$  based on the mean time spent by individuals acoustically available and in silence within a finite time window, using a survey speed of 9.35 knots and a detection range of 4 km. From Castro et al. (unpublished, chapter 2), using  $g(0) = 0.96$  and  $g(0) = 0.83$  estimated by assuming the present study mean ESW as the adopted detection range, the number of sperm whales available for detection in the surveyed area was

underestimated by approximately 4% and 17%, respectively, since individuals did not echolocate for periods that exceeded their respective time windows: 27.71 min and 19.18 min.

Therefore, when the finite time window increases by using a lower survey speed or when a larger detection range is possible, and it becomes larger than the estimated average silent period, as stated by Lewis et al. (2007), the potential bias introduced by assuming  $g(0) = 1$  is small.

The  $g(0)$  is then also conditioned by the energy which clicks arrive at the hydrophones, given the signal degradation through the distance traveled and the ship's speed. Thus, the greater the ship speed, the greater the noise produced by the vessel, contributing to the masking of acoustic signals, which has a substantial but predictable effect on the detection range (Leaper et al. 2003).

The estimated ESW in the present study was greater than ESW equal to 1.69km, obtained visually by Di Tullio (2016), which was already expected from acoustic surveys (Leaper et al. 2003, Fais et al. 2016). However, the estimated ESW of approximately 2768.23 m in the present survey was significantly less than that estimated by previous sperm whale acoustic surveys at similar latitudes. Barlow & Taylor estimated an ESW of 7.99 km for the northeastern temperate Pacific, which is similar to that found in Gillespie & Lewis (1997) for the Azores archipelago and Leaper et al. (2000) for South Georgia Island. Lewis et al. (2007) estimated an ESW of 10 km for the Ionian Sea and Straits of Sicily, while Fais et al. (2016) found an ESW of 4.2 km for the Canary Islands. Therefore,  $g(0) = 0.96$ , based on a detection range equal to 4 km, is potentially more conservative than that estimated from the ESW obtained in this study. Since the lower the value of  $g(0)$ , the greater the estimated abundance. This could lead to a possible misclassification of the conservation status of a given species at a threat level that is possibly greater than assumed.

Acoustic availability and silent periods as adopted in Castro et al. (unpublished, chapter 2) are estimated based on data obtained in the Azores. Despite the Azores and this study's surveyed area being located in a subtropical region, and the stereotyped pattern of diving and vocal behaviors of sperm whales in warm and temperate regions as observed by Watwood et al. (2006), differences exist in this species' foraging behavior between regions, including in Brazilian waters.

Moreover, Watwood et al. (2006) emphasized that their findings were most relevant to adult females and immatures. The Azores tag data are from two tagged whales, identified as females, and three other whales of unknown sex (Oliveira 2014). Adult male foraging behavior at high latitudes is quite different from that of individuals at low latitudes, probably due to the prey distribution within the water column (Teloni et

al. 2008). However, it is still unclear whether males observed at lower latitudes would behave the same in higher latitudes, or if females in other regions would behave similarly, depending on the distribution of their prey.

Davis et al. (2007) evaluated the foraging behavior of five female/immature sperm whales and the diving behavior of three jumbo squid, which were all tagged in the Gulf of California. The dive maximum depth and duration of those sperm whales were different when compared to females and immatures that were tagged in other tropical and temperate regions (Amano & Yoshioka 2003, Watwood et al. 2006, Aoki et al. 2012). The same difference was observed in Castro et al. (unpublished, chapter 2) for whales tagged with TDRs in southern Brazil, including a suspected male that was monitored the longest and performed the most assessed dives, including those which were identified as foraging dives. Therefore, such behavioral differences are not only associated with sex and age classes, but also with the sampled region, since the distribution of the species is related to its prey distribution (Jaquet & Gendron 2002, Di Tullio 2016) and their diving and vocal behaviors (Watwood et al. 2006, Davis et al. 2007, Teloni et al. 2008).

A generalized view can lead to misinterpretations. Although important interpretations or insights can be reached for different regions (Barlow et al. 2013), acoustic data obtained at a dive site and/or broader knowledge on this species' vocal and diving behaviors, considering all age and sex classes and different regions that sperm whales inhabit, must be evaluated to determine if variations in vocal behavior during dives can lead to variations in the amount of time that whales are available for acoustic detection. Consequently, variations in estimated abundance can arise, based on the  $g(0)$  obtained. This highlights how closely linked each approach is, how important an overall understanding of this species is, including accessible reliable information about population status and potentially threatening activities, and how to conduct effective management actions.

In addition to some efforts to estimate sperm whale abundance through their vocalizations (Fais et al. 2016), this study uses perpendicular distances to foraging vocalizations. Echolocation clicks are regularly produced in a broadband frequency, generally above the range of background noise, and are highly directional, which make them suitable for detection, even at large distances, using towed arrays (Whitehead & Weilgart 1991, Madsen et al. 2002, Whitehead 2003, Barlow & Taylor 2005). Social vocalizations such as codas and slow clicks are usually produced by females and adult males, respectively, when at or near the surface. When these are detected and reliably located and, therefore, considered for the detection function model, even if different truncation distances are required (see Barlow & Taylor 2005), they will potentially

contribute to increase the acoustic availability of this species and make  $g(0)$  even closer to 1.

This study provides the first systematic acoustic effort to estimate the sperm whale's abundance in the southern Brazilian outer continental shelf and slope, a region corresponding to the Brazilian portion of the Pelotas basin. It was also an opportunity to show that PAM can be an effective method, even when conducted from an opportunistic platform with limited resources and during acoustic equipment testing. PAM adjusts well to different methodologies, allows access to a relatively reliable acoustic dataset that includes abundance estimates, and is applicable to different research approaches.

In light of the advantages and disadvantages of visual and acoustic methods (Evans & Hammond 2004), the integration of such different monitoring methods in the research, mitigation, and conservation of marine mammals is possibly the most effective approach to filling current knowledge gaps of these species, particularly those that are hard to access, such as sperm whales (Whitehead 2003, Gillespie et al. 2008, 2009, Yack et al. 2013, Verfuss et al. 2018). However, as acoustic monitoring techniques are still under development and continuous refinement of methods for estimating abundance is an ongoing effort, not only do they provide information on population trends, they also contribute to method improvements to estimate population status, thereby promoting their conservation. These outcomes and the estimates already visually obtained, as suggested by Di Tullio (2016), can assist monitoring efforts by identifying which adjustments are necessary to improve estimates and ultimately provide more reliable information.

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## Considerações Finais

O presente estudo traz os resultados do primeiro esforço de monitoramento acústico de baleias cachalote conduzido ao longo da plataforma continental externa e talude sul brasileiro, bem como um dos primeiros esforços para o monitoramento remoto de mergulhos desta espécie em águas brasileiras a partir de *Time-Depth Recorders* (TDR).

Apesar de oportunístico, o PAM pode ser conduzido de forma sistemática, seguindo o método de amostragem por distâncias (Buckland et al. 2001), também adotado pelo monitoramento visual. Sua realização não interferiu nas demais atividades conduzidas a bordo, ajustando-se bem à logística empregada pelo projeto Talude.

Apesar das limitações, em sua maioria relacionadas ao mal funcionamento do equipamento acústico, algo já esperado de um sistema em processo de desenvolvimento e ainda em teste, foi possível coletar uma base de dados acústico útil a diferentes abordagens como: o estudo da ocorrência e distribuição dos cachalotes, incluindo *insights* sobre sua presença em áreas também ocupadas por atividades *offshore*.

O esforço acústico pode ser conduzido em condições de tempo e mar consideradas adversas ao monitoramento visual, sendo mantido até estado do mar 6 na escala Beaufort. Entretanto, acredita-se que a adoção de matrizes mais resistentes e de maior comprimento, além do controle de sua profundidade, permita que o monitoramento acústico seja mantido em mares ainda mais agitados, reduzindo potencialmente o mascaramento dos sinais pelos ruídos da embarcação e fluxo de água.

Neste estudo, foi possível observar que a espécie ocorre em quase toda a área amostrada, com concentração aparentemente maior ao sul, geralmente entre os limites do talude (isóbatas de 200 a 2000 m). Os resultados também mostram um maior registro de encontros acústico com o aumento da profundidade. Além disso, a espécie não pareceu utilizar de forma significativa áreas onde também estão localizados os blocos de exploração de óleo e gás, particularmente aqueles sob concessão. No entanto, diante do possível aumento no interesse do setor de petróleo e gás na região ocupada pela bacia de Pelotas e o potencial impacto, direto e indireto, que esta e outras atividades associadas podem causar à fauna marinha local, o monitoramento contínuo de todo o processo intrínseco à sua implementação e desenvolvimento, simultâneo ao monitoramento das populações de mamíferos marinhos, incluindo os cachalotes, que ocupam áreas comuns é iminente.

É importante ressaltar que estes esforços devem se estender às diferentes atividades antrópicas reconhecidas como de potencial ameaça às populações, bem como às demais bacias sedimentares onde tais atividades já vêm sendo desenvolvidas e, para muitas delas, de forma ainda mais intensa.

Apesar dos encontros acústicos terem sido, em sua totalidade, registrados em áreas identificadas como prioritárias para a conservação, as PAC's são apenas instrumentos que podem apoiar e orientar a implementação de futuras ações de gestão na região. As ações atualmente identificadas para estas áreas, principalmente direcionadas ao manejo da atividade pesqueira, não abordam os impactos associados à indústria de petróleo e gás e à outras atividades *offshore*.

Informações sobre o perfil de mergulho da espécie em águas brasileiras foram obtidas a partir de TDR's implantados em cinco indivíduos em 2012. Os mergulhos avaliados, de forma geral, mostraram variações em relação aos parâmetros de mergulhos descrito para outras regiões temperadas e tropicais. Porém, particularmente os mergulhos de profundidade intermediária e profundos se aproximaram do que já foi descrito para machos adultos em altas latitudes, e para fêmeas e imaturos no Golfo da Califórnia.

No entanto, supõe-se que estas variações também possam ser observadas no comportamento acústico e, conseqüentemente, de forrageio da espécie, uma vez que estariam condicionadas à distribuição de suas presas na coluna d'água.

Apesar disto possivelmente limitar a utilização de informações advindas de outras regiões como base para inferências sobre o comportamento da espécie, neste estudo, optou-se por assumir que o padrão estereotipado observado entre mergulhos de forrageio amostrados em baixas latitudes (Watwood et al. 2006), poderiam ser estendidas aos mergulhos de forrageio em águas brasileiras.

Portanto, a estimativa da disponibilidade acústica da espécie para a região estudada foi obtida a partir da associação de informações sobre seu comportamento acústico durante o mergulho, provenientes dos Açores, e aquelas obtidas também neste estudo sobre o comportamento de mergulho da espécie.

Porém, reconhece-se o possível viés associado à disponibilidade acústica estimada, em particular resultante do conjunto de dados utilizado (limitado a poucos indivíduos amostrados em diferentes regiões) e das variações comportamentais que este pode refletir. Além disso, foi assumido que, uma vez vocalizando em uma janela de tempo finito, com base nas características dos cliques que produzem, particularmente os de ecolocalização (alta direcionalidade, curta duração, sinais de banda larga e com energia predominantemente em frequências acima da banda de ruído produzidos pelos navios e fluxo de água), os indivíduos seriam certamente

detectados (percepção) pelos sistemas de gravação. No entanto, mesmo estes cliques podem ser mascarados pelo ruído de fundo e, portanto, assumir a percepção como certa nem sempre será verdadeiro.

As estimativas de densidade e abundância obtidas foram baseadas em dois conjuntos de dados de distância perpendicular: aquele estimado acusticamente e as mesmas distâncias corrigidas, assumindo uma profundidade média de forrageio (~492 m) para sua correção. Três valores de  $g(0)$  foram utilizados, sendo incluídos na análise como multiplicadores. Além de  $g(0) = 1$ , foram adotados:  $g(0) = 0,96$  estimado através do método proposto por Barlow et al. (2013), considerando uma faixa de detecção acústica igual a 4 km e a velocidade da embarcação igual a 10 nós para estimar a janela finita de tempo; e  $g(0) = 0,83$  assumindo, neste caso, o ESW (*Effective Strip Width*) estimado neste estudo (faixa efetiva de detecção) como limite de detecção.

Apesar de importante, a correção das distâncias resultou em uma estimativa apenas 2.31% maior do que aquela obtida a partir das distâncias originalmente estimadas. Já quando adotados os valores de  $g(0)$  adotados neste estudo (0,96 e 0,83), o número de baleias cachalote estimado foi 4 e 17% maior, respectivamente, que o estimado com  $g(0) = 1$ .

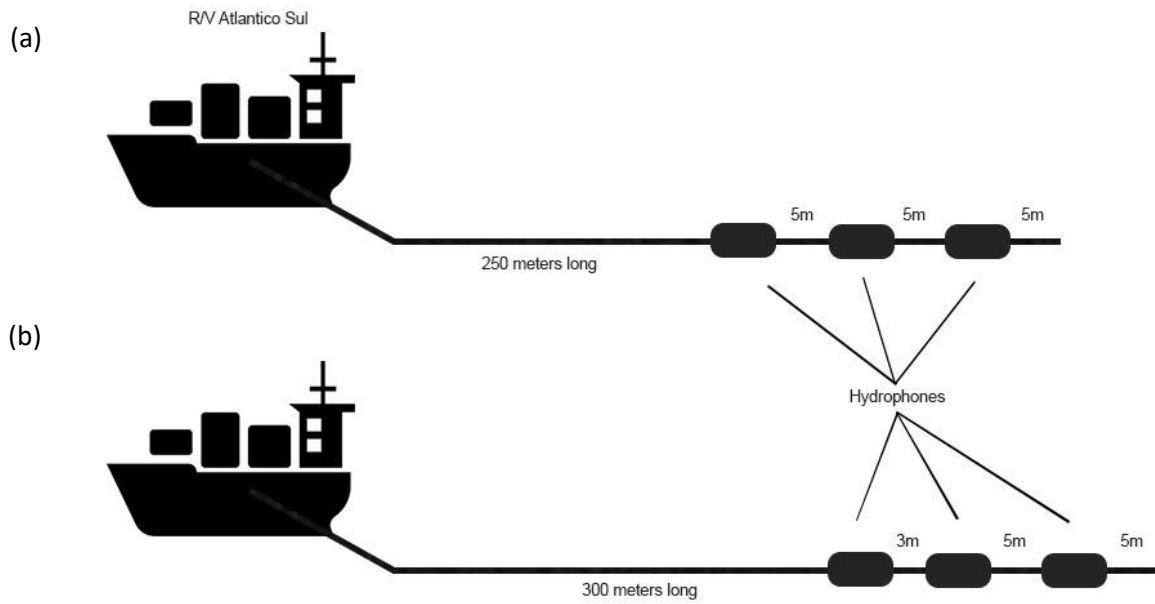
Porém, é importante reconhecer algumas potenciais fontes de enviesamento. A densidade e abundância obtidas podem ainda ter sido subestimadas, uma vez que a disponibilidade acústica não tenha sido corretamente calculada pelo método utilizado, considerando as aparentes variações no comportamento da espécie; e assumir a percepção como certa nem sempre será aplicável. Variações na profundidade dos indivíduos e/ou grupos detectados, em relação ao valor médio adotado para a correção, levariam a variações na distância perpendicular corrigida e, conseqüentemente, na abundância estimada. Grupos que mergulham sincronicamente, podem vocalizar de forma independente, tornando sua detecção mais provável que de indivíduos solitários. Além disso, estimativas obtidas acusticamente estão condicionadas aos indivíduos vocalmente ativos. Uma vez que haja indivíduos nas proximidades dos hidrofones, se em silêncio, estes não serão detectados.

Embora importantes interpretações ou *insights* possam ser obtidos a partir de dados advindos de outras regiões, uma visão generalizada pode levar a interpretações erradas (Barlow et al. 2013). Por isso, esforços contínuos que permitam acessar informações sobre os comportamentos vocal e de mergulho dos cachalotes e suas variações em diferentes regiões, enquanto métodos de amostragem e processamento dos sinais acústicos sejam progressivamente desenvolvidas é essencial para que tão

logo seja possível acessar informações confiáveis que permitam preencher as lacunas no conhecimento desta espécie.

Acredita-se, ainda, que a integração de diferentes métodos de monitoramento, como o visual e acústico, em uma abordagem única, possivelmente ofereça a maneira mais eficaz de preencher as lacunas atuais no conhecimento das espécies marinhas (Barlow & Taylor 2005, Yack et al. 2013), contribuindo, assim, de forma mais eficaz no desenvolvimento de ações de manejo e conservação destas espécies em um ambiente continuamente modificado por ações humanas.

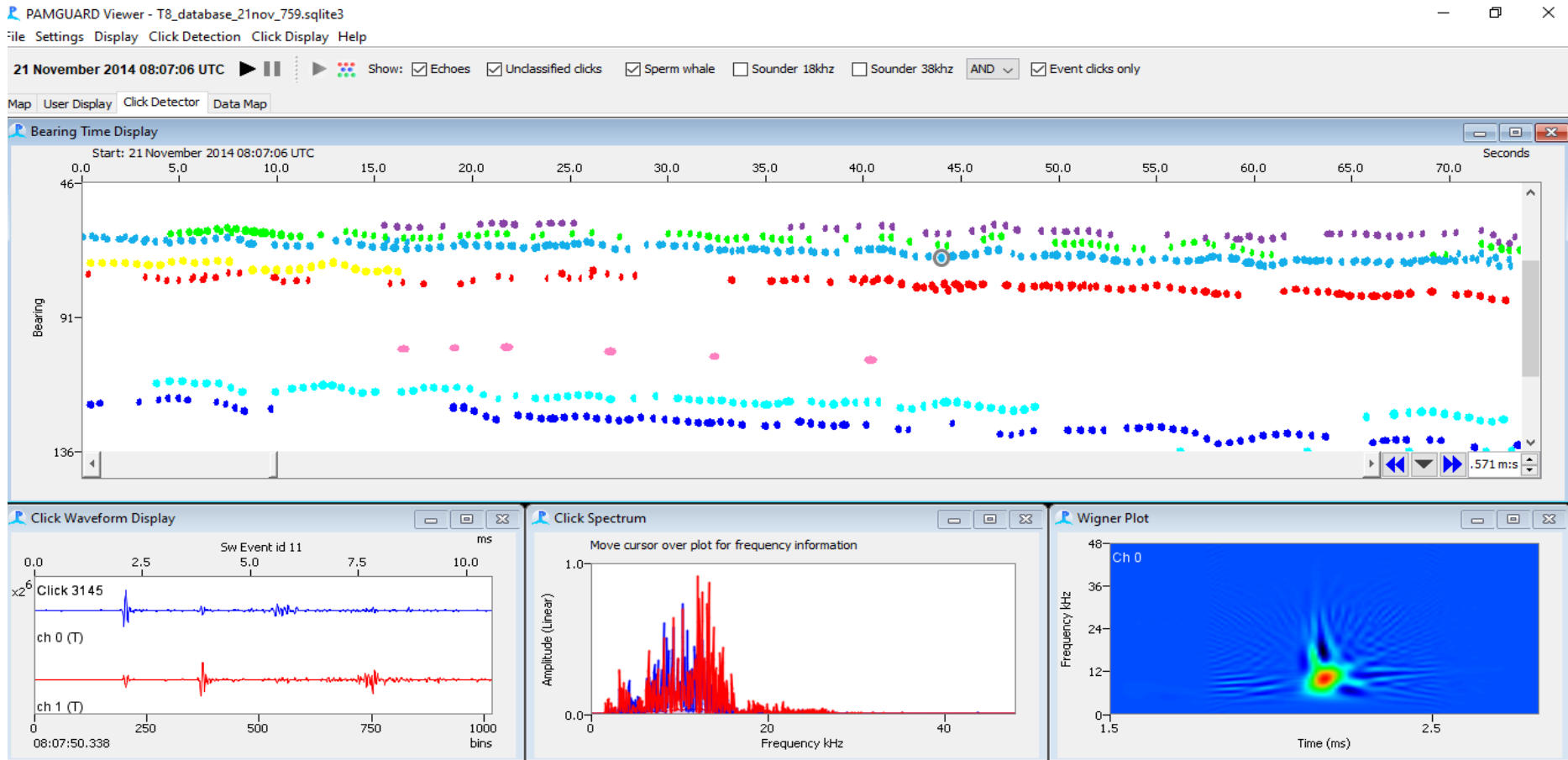
**MATERIAL SUPPLEMENTAR [Supplementary Material]**



S1: Scheme of the two linear array configurations used for acoustic recording.

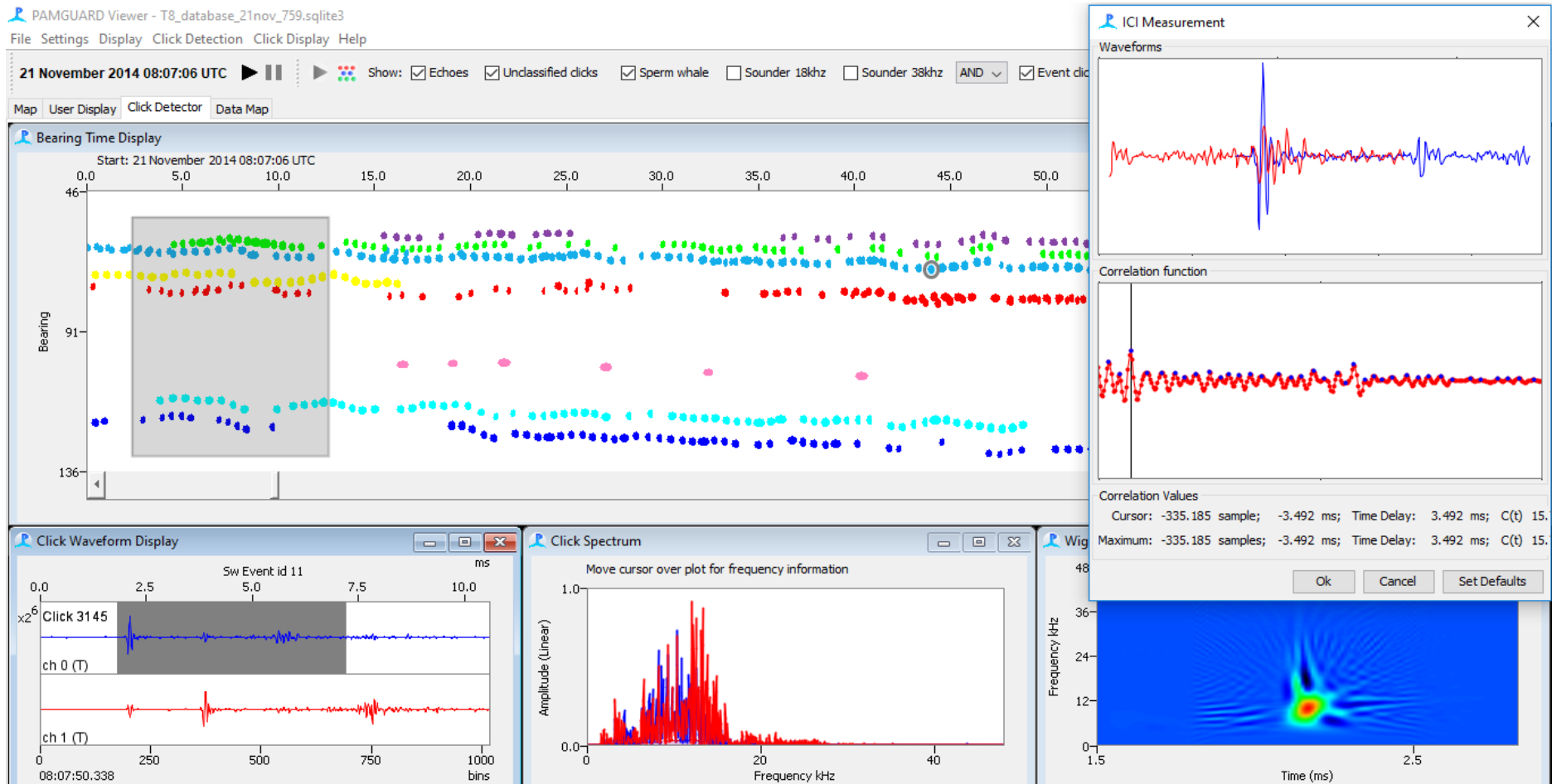
S2: Table showing details on the arrays used per cruise.

Array	Cable length (m)	N. of elements	Distance between elements (m)	Distance to the cable end (m)	High-pass filter (Hz)	N. of elements used	Cruise
(a)	250	3	5	5	1952	2	1
(b)	300	3	5 e 3	5	0.499	2 and 3	2 e 3

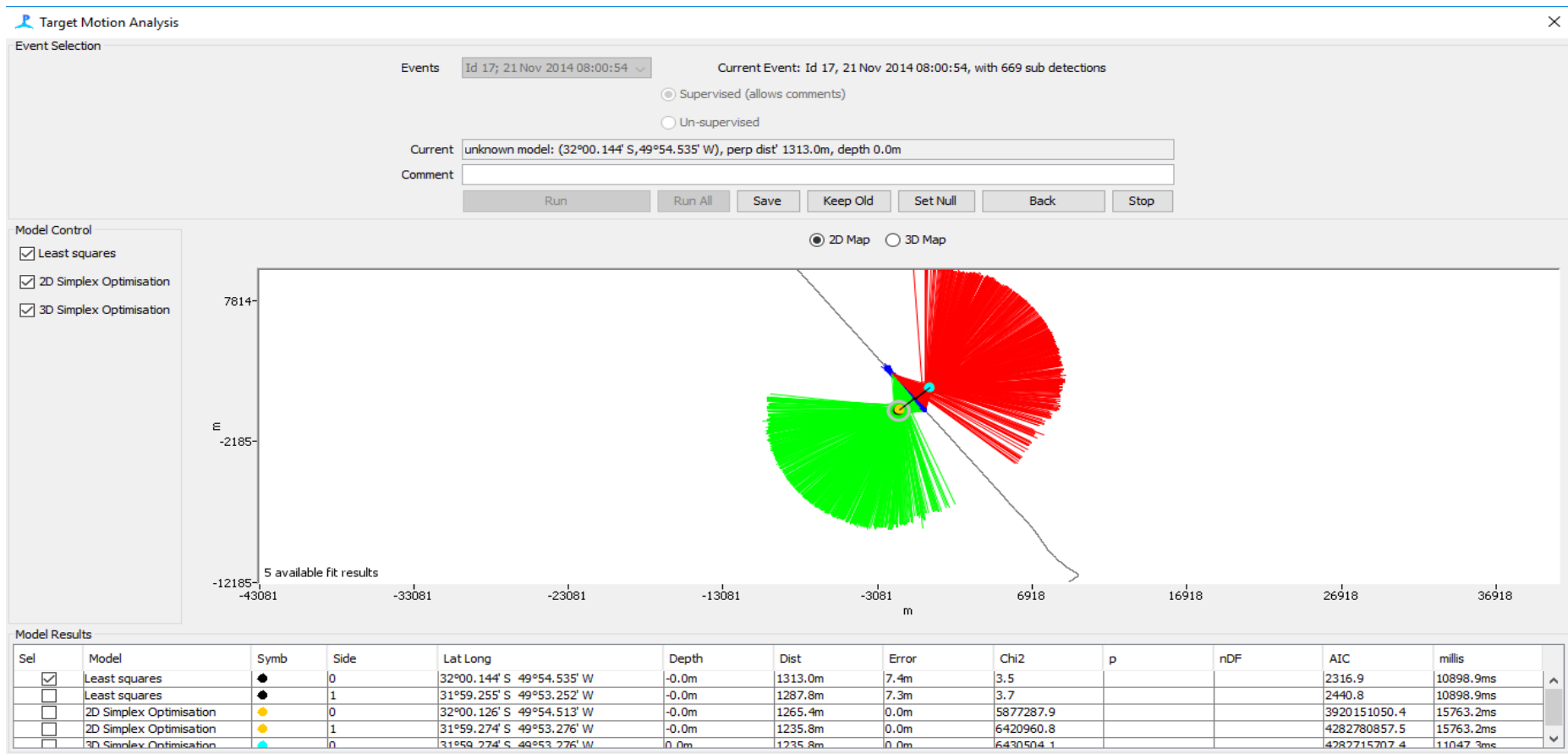


S3: PAMGuard during the click trains identifying process, each of them corresponding to an individual or group of individuals, addressed to their respective events (identified by the different colors). In (a) Bearing x time, (b) Waveform, (c) Spectrum, and (d) Wigner Plot of the selected click.





S4: Similar to the previous figure, PAMGuard during the click trains identifying process, each of them corresponding to an individual or group of individuals, addressed to their respective events (identified by the different colors). In (a) Bearing x time, (b) Waveform, (c) Spectrum, and (d) Wigner Plot of the selected click., and (e) automatic inter-click interval measurement (ICI).



S5: PAMGuard during the 'Target Motion Analysis' (TMA) used to localize the acoustic events and estimate their perpendicular distance to the trackline. Green and red lines represent the estimated bearings to the left and right, respectively. The highlighted position corresponds to the one estimated by the best model (> AIC).

S6: Some studies already conducted to investigate sperm whales dive profiles

Study	Goal	Local	Type of tag	N. of Individuals	Mean maximum depth (sd) and/or depth range (m)	Mean duration (sd) and/or duration range (min)	Inter-dive duration (min)
Amano and Yoshioka 2003	Description of a female dive profile	Kumano coast, Japan	Suction-cup attached TDR (Wildlife Computers, Mk6) tag + VHF radio Transmitter - ATS	1 female	400 to 1200	6.2 (5.89) 13.2 to 46.2	3.6 to 18.2
Watwood et al 2006	Deep dive foraging behavior of Sperm whales	Atlantic Ocean, Gulf of Mexico and Linguria Sea	Digital archival recording tag (Dtag)	45 females/immature	985 (124.3), 644 (123.4) and 827 (60.3)	45.7 (5.6), 45.5 (7.4) and 44.2 (4.7)	9.3 (2.8), 8.1 (2.6) and 9.9 (2.1)
Aoki et al 2007	Diel diving behavior of sperm whales	Kumano coast and Ogasawara Island, Japan	MK6 (Wildlife Computers) and Little Leonard - suction cup + VHF radio Transmitter - ATS	10	716.4 (83.9)	35.1 (3.0)	-
Aoki et al 2012	Sperm whale hunting behavior	Ogasawara Island, Japan	Data logger Little Leonard suction cup	12	694 (247) 270 to 1422	33.1(5.7)	10.7(5.0)
Davis et al 2007	Dive behavior of sperm whale x behavior of Jumbo squid	Gulf of California, Mexico	Satellite-linked dive recorders (SDR-T16, Wildlife Computers) + VHF radio Transmitter - ATS	5 females/immature	100 to 500	15 to 35	8.0 (1.20) 4.6 to 9.2
Teloni et al 2008	Male sperm whale foraging behavior in high latitude habitats	Andoya Canyon, Norway	Digital archival recording tag (Dtag)	4 males	492 (593)	32.3±10.1	14.5 (25.4)
Irvine et al 2017	Detailed sperm whale dive profile description	Central Gulf of California	Generation 1 of ADB tags (Implantable, novel configuration of Wildlife Computers time depth recorder MK-10)	27	325(239)	25.4 (14.2)	-

## S7: Script used to run the diveMove package in this study.

---

```
1- Call directory;
2- Loading diveMove package and linked packages;
library(stats4)
library(caTools)
library(RColorBrewer)
library(diveMove)

3- Change from GMT to local time:
srcfn <- basename("TAG time series data.csv") # inform each transmitter's time-series file name
tdrXcsv=read.csv("TAG time series data.csv")
ddtt.str <- paste(tdrXcsv$Day, tdrXcsv$Time)
ddtt=strptime(ddtt.str, format="%m/%d/%y %H:%M:%S")
time.posixct <- as.POSIXct(ddtt, tz="GMT")
tz_local<- format(time.posixct, tz="local name",usetz=TRUE) # inform the local name, e.g.
America/Sao_Paulo.
# To convert to POSIXct:
time.posixct <- as.POSIXct(tz_local, tz="")
# To check the local time:
head(time.posixct)

4- Create a TDR object:
tdrX <- createTDR(time=time.posixct,depth=tdrXcsv$Depth,
                 concurrentData=tdrXcsv[, -c(6:11)],dtime= sampling interval, file=srcfn) # inform the
sampling interval, e.g. 150 (150 seconds).
plotTDR(tdrX)

5- Calibrating the dive data:
dcalib <- calibrateDepth(tdrX)
# Defining ZOC ( here defined as 3m).
dcalib <- calibrateDepth(tdrX, zoc.method="offset", offset=3)
dcalib <- calibrateDepth(tdrX, dive.thr=10, zoc.method="offset",
                        offset=3, interp.wet= FALSE, dive.model="unimodal",
                        descent.crit.q=0.2, ascent.crit.q=0, knot.factor=55)

# In this study, the descent.crit.q and ascent.crit.q values adopted varied among transmitters.

6- Potting the dive phases:
plotTDR(dcalib, diveNo=range of dives,what="phases") # range of dives: 1:5 (when we want to
check the phases from the first to the fifth dive).

To access the misclassification index:
dcalib@dive.phases
df.misID<-data.frame(dcalib@dive.phases)

7- To incorporate possible phases's correction to 'dcalib':

dcalib@dive.phases <- as.factor(df.misID$dcalib.dive.phases)

8- To plotting the dive model:

plotDiveModel(dcalib, diveNo=x) # x = n. of a dive, e.g. : 3
```

---

---

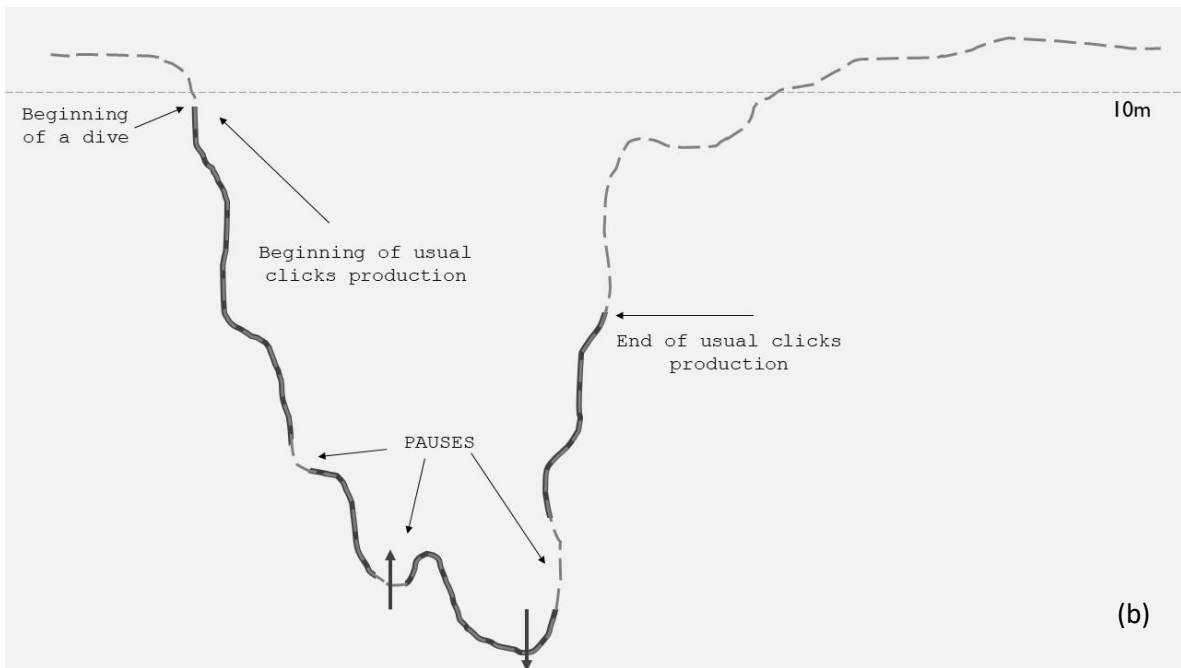
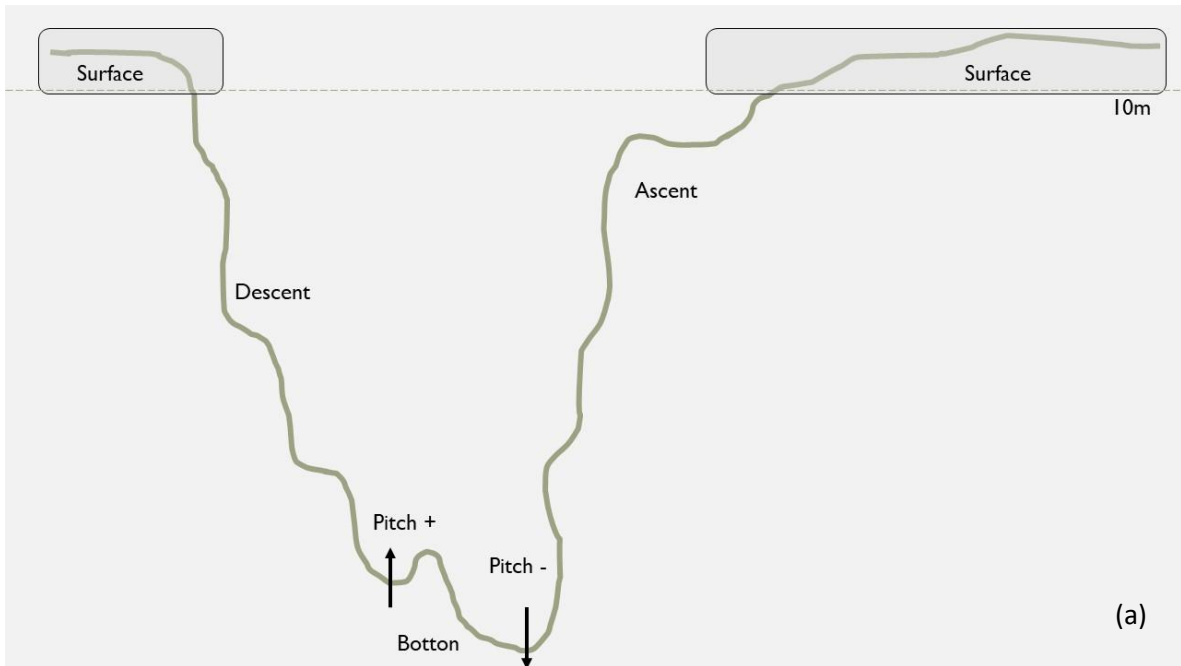
# Stats:

```
results <- diveStats(dcalib)
results
```

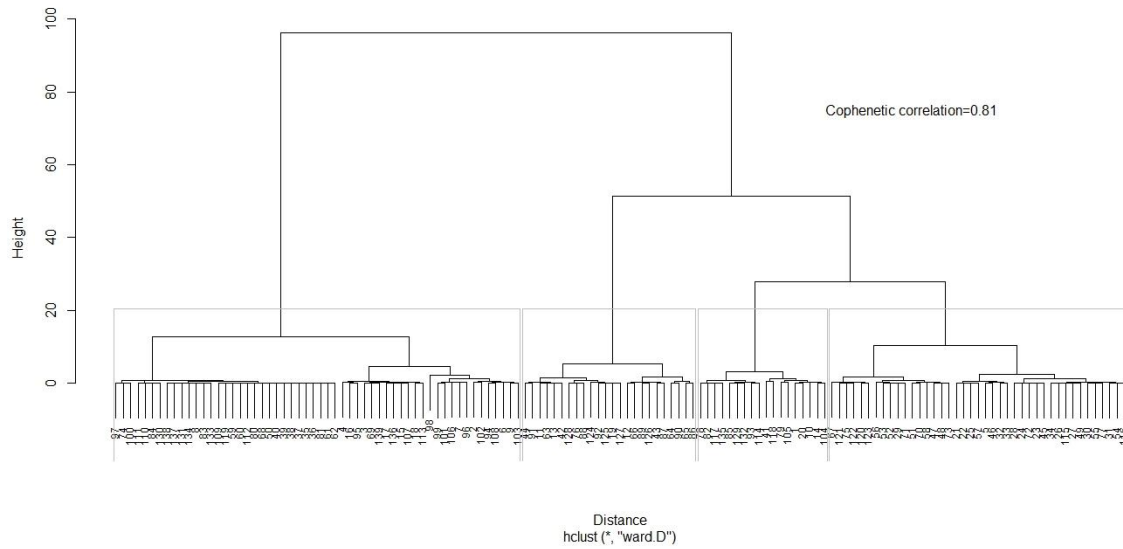
# Exporting results in .csv:

```
write.csv(results, "name of the results file.csv", row.names = FALSE)
```

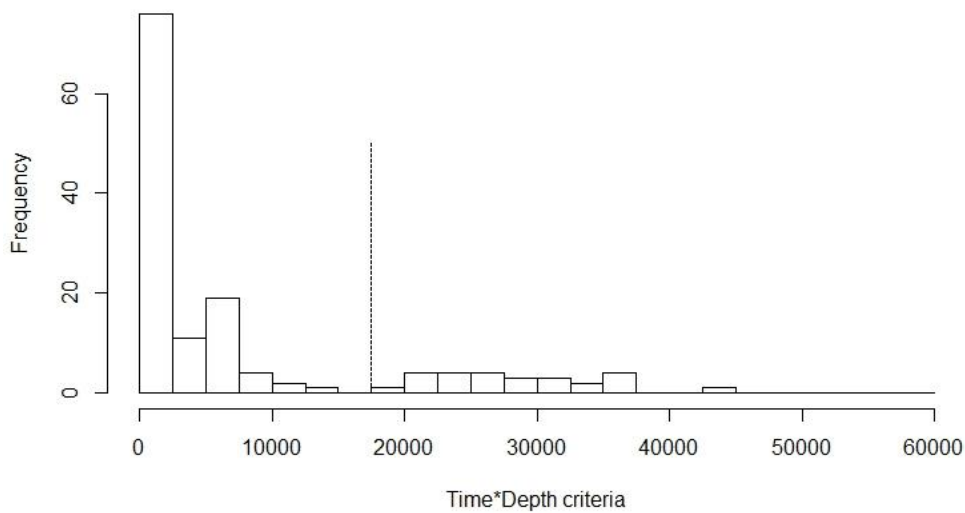
---



S8: A dive profile scheme (a), showing the beginning and end of the usual click production, as well as the pauses in vocalization (b).



S9: Dendrogram resulting from hierarchical cluster analysis applied to the dive types identification, performed by sperm whales in Brazilian waters (Cophenetic correlation = 0.81). The four types identified are delimited by gray polygons.



S10: Histogram indicating the point of separation (vertical dotted line) between foraging and non-foraging dives recorded by the TDRs and identified from the time \* depth criteria proposed by Barlow et al. (2013).

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