
Diversity of cetaceans as tool in monitoring environmental impacts of seismic surveys

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Abstract

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New information about the effects of seismic surveys on cetaceans is causing increasing concern about the impact of this type of activity on marine life. The effects described include behavioral responses and changes in vocalization patterns, diversion of migratory routes, damage to the auditory system, and an increase in strandings. Although such effects could affect the diversity of species in areas where seismic research has been carried out, there is no scientific information on this subject. This study aims to evaluate the relationship between seismic surveys, oceanographic data and diversity of cetaceans recorded in Brazil following the stepping up of seismic survey activities between 1999 and 2004. The study is based on oceanographic data from the Pilot Research Moored Array in the Tropical Atlantic (PIRATA Project), sightings made during seismic surveys, progress reports from Brazilian research projects to the International Whaling Commission, Brazilian seismic survey reports available at the Escritório de Licenciamento de Petróleo e Nuclear of the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (ELPN-Ibama) and complementary data from the webpage of the Agencia Nacional de Petróleo e Gás Natural (ANP). The results suggest a decrease in the diversity of species in the face of an increase in the number of seismic surveys during the years 2000 and 2001, even though there was no significant change in oceanographic patterns in this period, and that a relationship exists between diversity of cetaceans and intensity of seismic surveys between 1999 and 2004. It is recommended that data collection be improved in order to evaluate this hypothesis properly. The results suggest that species diversity might be used as a long-term indicator of the impact of seismic surveys on cetaceans.

Keywords: *noise impact, seismic survey, diversity of cetaceans, South America.*

Resumo

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Tem sido constante o surgimento de novas informações sobre o efeito das sísmicas marítimas em cetáceos, demonstrando uma crescente preocupação com essa atividade. Os efeitos da atividade incluem respostas comportamentais e mudanças nos padrões de vocalização, alterações nas rotas migratórias, danos no sistema auditivo e aumento dos encalhes. Embora todos esses efeitos possam afetar a diversidade de espécies nas áreas de realização de sísmicas marítimas, não existem informações acadêmicas nesse sentido. Este estudo buscou verificar as relações entre as sísmicas marítimas, dados oceanográficos e a diversidade de cetáceos registrados no Brasil após a intensificação das operações a partir de 1999 até o ano 2004. Foram utilizados dados de observações de cetáceos realizadas durante as sísmicas marítimas e complementadas por relatórios de progresso do Brasil enviados para a Comissão Internacional Baleeira, dados oceanográficos disponibilizados pelo projeto Pilot Research Moored Array in the Tropical Atlantic (PIRATA) e informações de sísmicas marítimas arquivadas no Escritório de Licenciamento de Petróleo e Nuclear do Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Sustentáveis (ELPN-Ibama) e outras disponibilizadas na página da Internet da Agencia Nacional de Petróleo e Gás Natural (ANP). Os resultados indicam decréscimo na diversidade de espécies durante os anos 2000 e 2001, enquanto uma intensificação das sísmicas marítimas foi registrada para os mesmos anos. Os dados oceanográficos não apresentaram variações significativas entre os anos estudados. Os resultados sugerem alguma relação de efeito e causa entre a diversidade de cetáceos e a intensidade de sísmicas marítimas ocorridas no Brasil entre 1999 e 2004. O aprimoramento na coleta de dados com foco mais específico para avaliar os efeitos imediatos

na diversidade é recomendado para melhor avaliação da hipótese e utilização da diversidade de espécies como indicador de longo prazo dos impactos das sísmicas marítimas nos cetáceos.

Palavras-chave: *impacto sonoro, sísmica marítima, diversidade de cetáceos, América do Sul.*

Introduction

Although new species are recorded from time to time, there are, at present, only 119 identified species of aquatic mammals throughout the world (Jefferson et al. 1994). The order Cetacea contains 84 of those species, which inhabit oceans, rivers and estuaries and, of these, 13 belong to the Mysticeti sub-order, and 71 to the Odontoceti. Brazilian waters host 43 species of cetaceans: 8 species of Mysticeti and 35 species of Odontoceti (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis - IBAMA 2001, Pinedo et al. 2002).

In Brazil, as in other parts of the world, these aquatic mammals are negatively impacted by a number of human activities, such as fishing (e.g. Monteiro-Neto et al. 2000, Pizzorno et al. 1998, Siciliano 1994), tourism (e.g. Lodi et al. 1996, Silva Jr. 1996) and industrial activities. More recently, it has been suggested that the stranding of adult male humpback whales is associated with seismic surveys in the Northeast region of Brazil (Engel et al. 2004). Concern as to the effects of seismic surveys on marine mammals is not recent (e.g. Green et al. 1994, Popper et al. 2000, Richardson et al. 1995). Some studies have demonstrated that noise emitted by seismic survey air-guns causes differing effects on different species of cetaceans due to: hearing sensitivity, behavior, habituation or desensitization, age, sex, location of exposure, and proximity to a shoreline (e.g. Dolman & Simmonds 2003, Evans et al. 1993, Gordon et al. 2004, Madsen et al. 2002). Recently, a study off Scotland has suggested that the absence of certain whale species from one sea area surveyed in 1998, where they might be expected to have been found, may have resulted from the incidence of seismic survey work there, although other potentially confounding variables are also noted (MacLeod et al., in press). Nonetheless, the available information focuses only on a small number of species that are observed in the course of a seismic survey or that are already undergoing observation (e.g. Goold 1996, Mate et al. 1994, McCauley et al. 2000) and it is not acceptable to extrapolate the results obtained for some species to others due to the variation in the acoustic characteristics of the environment and the potential differences in sensitivity between the animals.

Species diversity has proven to be an excellent tool for the analysis of environmental impacts (e.g. Myers 1989, Gaston 2000, Weitzman 1993). However, variation in cetacean diversity measured using diversity indexes in the light of oceanographic patterns and the presence of seismic surveys in the area has not yet been verified. There are a number of explanations for the lack of such studies, including: 1) the difficulty of undertaking a long-term series of observations of marine mammals using standardized procedures, and 2) the fact that research into cetaceans normally focuses on the most common species in certain areas. Given the variations in cetacean behavior responses to seismic surveys, it is possible that the diversity of species in a certain area could be altered because of the oceanographic patterns or the presence of seismic surveys over large areas. This research aims to evaluate the potentiality to use the diversity of cetaceans as tool to indicate effects of the seismic surveys in this group of animals recorded in the Brazilian ocean shelf between 1999 and 2004.

Materials and Methods

1. Data sources

Information on the diversity of cetaceans in Brazil was obtained from two sources: the Brazilian progress reports published by the International Whaling Commission (IWC) between 1999 and 2004 (IWC 2005), which are compiled annually by the Brazilian government on the basis of the results of those involved in research into and conservation of cetaceans in the country, and from reports of sightings during seismic surveys over the same period and available in the archives of the ELPN (Escritório de Licenciamento de Petróleo e Gás Natural). Cetacean records were obtained by researchers by way of sightings surveys and monitoring along the whole coastline of Brazil. As data originated from different institutions and researchers lacked standardized procedures and sampling methods, the study was restricted to the presence or absence of species in Brazil to cluster analyses, and number of specimens to diversity analyses. Even though this methodology is uncommon in studies of cetaceans, it is recommended by biologists as an effective tool for ecological studies (Legendre & Legendre 1998). The period interval of data between 1999 and 2004 was selected because it coincides with recent seismic surveys and research on cetaceans has increased since 1997, when the Brazilian government published the first Action Plan about Marine Mammals (IBAMA 1997), insuring that changes in diversity were not the result of changes in research efforts.

The data on seismic surveys carried out between 1999 and 2004 were taken from annual reports of the ANP (Agência Nacional do Petróleo e Gás Natural 2005) and supplemented with reports from the ELPN. The information on 2-dimensional (2D) and 3-dimensional (3D) seismic surveys was organized in an electronic database - allowing for evaluation of the evolution of seismic surveys during the period in terms of the technology used.

The information concerning oceanographic parameters (temperature, salinity and density) was obtained during seismic surveys and from the PIRATA (Pilot Research Moored Array in the Tropical Atlantic) which was downloaded from the website of the TAO Project (Tropical Atmosphere Ocean project). Data from this project was used to calculate the monthly mean temperature (°C), salinity (PSU) and density (kg/m³) to a depth of 1 m from the buoy sited at 10° S-10° W.

1.2. Analysis of data

The information about cetaceans was organized in an electronic database in order to draw up an annual table of presence and absence of cetacean species in Brazilian waters. This table enabled quantification of the number of cetacean species recorded throughout the period studied, and application of the Shannon-Wiener diversity index (H'), based on Log₂ (Shannon 1948).

The tables with the annual list of species (presence/absence), oceanographic data and annual seismic surveys were submitted to cluster analyses using the weighted pair-group method, and arithmetic average (WPGMA) in Q modules to verify levels of similarity across the years studied (Legendre & Legendre 1998). The Dice coefficient was used for the cetacean species tables and the Euclidean distances coefficient was applied to the seismic surveys and oceanographic data tables. A cophenetic analysis was also carried out to test the

goodness of fit of clustering to the set of data (Dice 1945, Legendre & Legendre 1998, Rohlf & Fisher 1968).

The Kruskal-Wallis non-parametric statistical test was applied to the number of seismic surveys being carried out by month to verify significant differences over the years as well as to analyze the differences in the oceanographic parameters over the same period. To compare the variance of the oceanographic data, the ANOVA test was applied to the matrix of each parameter (temperature, salinity, and density).

The means of seismic surveys/month and the diversity indexes of cetaceans by years were submitted to the non-parametric statistical test of Spearman to verify their level of correlation. Results of $p \leq 0.05$ were taken to be statistically significant for the tests as a whole.

Results

2.1. Seismic surveys

A total of 103 seismic surveys were carried out over the period, corresponding to 21 seismic programs using the technology for 2-dimensions (2D), covering 300,388.7 km, and 82 using technology for 3-dimensions (3D), covering 162,494.1 km². The number of seismic surveys in operation/month was highest in 2000 with 43 programs (mean = 15.2 survey/month; SD = 3.4), followed by 2001 (n = 27;

mean = 9.6; SD = 7.1), 2002 (n = 24; mean = 6.0; SD = 1.1), 2003 (n = 20; mean = 2.8; SD = 1.4), 1999 (n = 13; mean = 6.7; SD = 5.9) and 2004 (n = 13; mean = 2.1; SD = 1.4). (Figure 1) shows the distribution of the seismic surveys over the years.

The cluster analysis of the number of seismic surveys in operation/month in each year showed a great similarity between the years 2000 and 2001 compared to other years studied (Figure 2), further confirming the intensification of seismic surveys in those years. The cophenetic analysis showed a good fit of the data, explaining more than 90% of possible variations ($\lambda = 0.90372$). The Kruskal-Whallis statistical test also showed very significant differences between the years 2000 and 2001 and the others ($H = 35.74$; $p = 0.000000$).

2.2. Diversity of cetaceans

Of the 43 species of cetaceans occurring in Brazil, 33 (76.7%) were recorded between the years 1999 and 2004 (Table 1). These included the following families: Balaenidae, Balaenopteridae, Delphinidae, Kogiidae, Phocoenidae, Physeteridae, Pontoporiidae, and Ziphiidae. The cetaceans that were not identified to the taxonomic level of species were not considered.

The number of species varied over the years and among regions as can be observed in Figure 1. The Delphinidae family was mainly

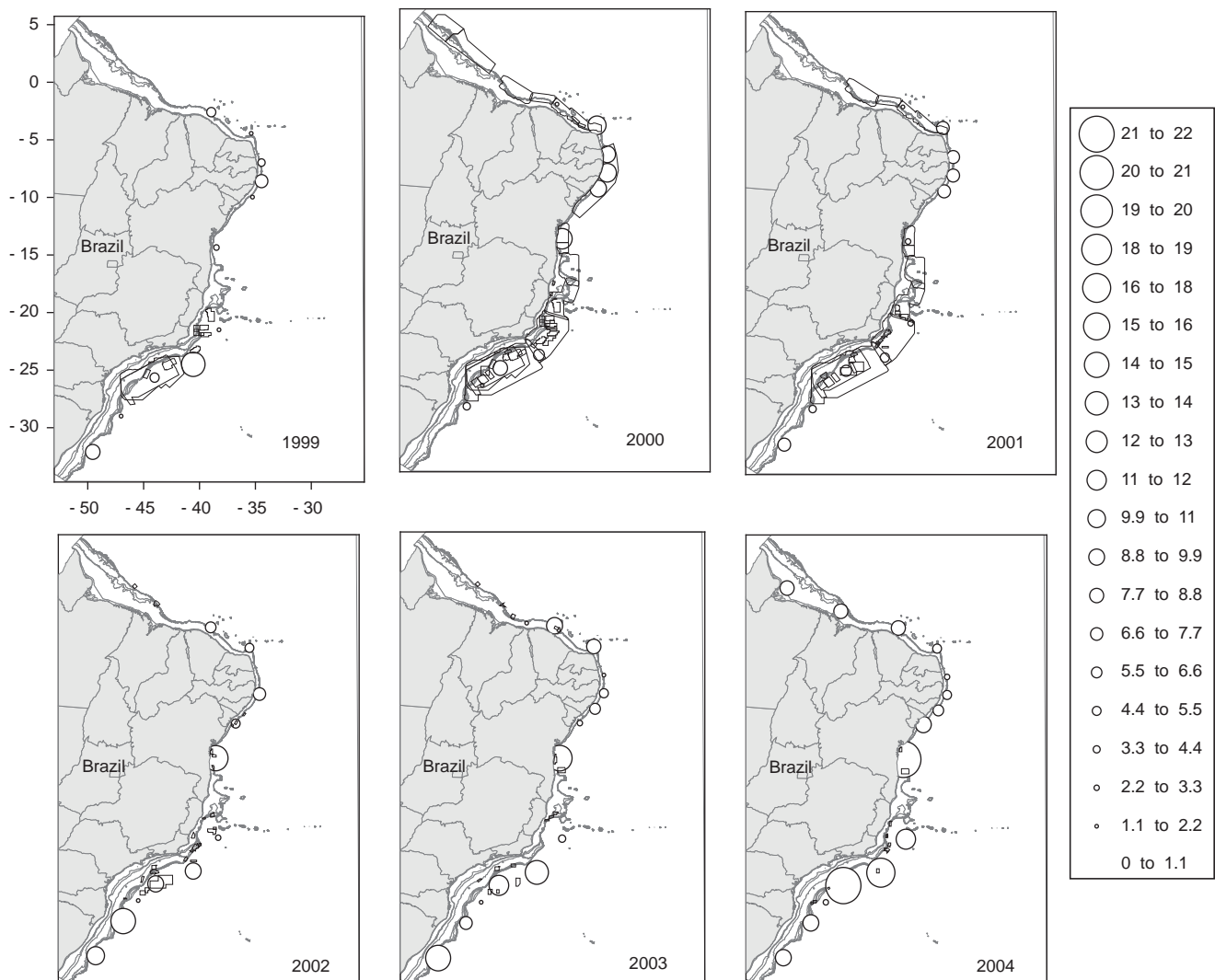


Figure 1. Areas where seismic surveys (black) were carried out in Brazil between 1999 to 2004 and volume of diversity of cetaceans (white).

Figura 1. Áreas de ocorrência de sísmicas marítimas (preto) entre 1999 e 2004 e quantidade de diversidade de cetáceos (branco).

responsible for the reduction in the total number of species recorded during the years 2000 and 2001. The cluster analysis of the species present and absent for each year, including species identified at genus level, showed a great similarity between the years 2000 and 2001 compared to the other years studied (Figure 3), as was the case with the analysis of seismic surveys. The cophenetic analysis showed a good fit of the data ($\lambda = 0.83396$) (Rohlf & Fisher 1968).

The Shannon-Wiener diversity indexes for the studied period were: $H' = 3.178$ bits.indiv.⁻¹ in 1999, $H' = 2.996$ bits.indiv.⁻¹ in 2000, $H' = 2.565$ bits.indiv.⁻¹ in 2001, $H' = 3.296$ bits.indiv.⁻¹ in 2002, $H' = 3.401$ bits.indiv.⁻¹ in 2003, and $H' = 3.497$ bits.indiv.⁻¹ in 2004. These indexes showed a slight variation in the diversity of species over the years with a reduction in the years 2000 and 2001. When those diversity indexes were submitted to Spearman test together the means of seismic surveys/month of each year the result was significant ($r_s = -0.9429$; $t = -5.9565$; $p = 0.0048$) and shown a negative correlation.

2.3. Oceanographic parameters

The mean of temperature, salinity and density of water at the point analyzed did not show great variation over the years (Figure 4). The temperature varied from 23.13 °C to 27.35 °C, salin-

ity from 36.0 to 36.6 PSU, and density from 23.5 to 25.0 kg/m³. The ANOVA Statistical test showed that variations were not significant for the three parameters: temperature ($F = 0.1385$; $p = 0.9807$), salinity ($F = 2.2347$; $p = 0.0604$), and density ($F = 0.3261$; $p = 0.8954$). The cluster analyses of the oceanographic parameters are presented in the (Figure 5). As the other information analyzed in this study, the cophenetic analysis of density, salinity and temperature showed a good fit

Table 1. List of cetacean species registered in Brazil between 1999 and 2004

| Taxonomy |
|--|
| Mysticeti |
| Balaenopteridae |
| <i>Balaenoptera acutorostrata</i> Lacépède (1804) |
| <i>Balaenoptera bonaerensis</i> Burmeister (1867) |
| <i>Balaenoptera borealis</i> Lesson (1828) |
| <i>Balaenoptera edeni</i> Anderson (1879) |
| <i>Balaenoptera physalus</i> (Linnaeus 1758) |
| <i>Megaptera novaeangliae</i> (Borowski 1781) |
| Balaenidae |
| <i>Eubalaena australis</i> Desmoulins 1822 |
| Odontoceti |
| Delphinidae |
| <i>Delphinus capensis</i> Gray (1828) |
| <i>Delphinus delphis</i> Linnaeus (1758) |
| <i>Feresa attenuata</i> Gray (1874) |
| <i>Globicephala macrorhynchus</i> Gray (1846) |
| <i>Globicephala melas</i> (Traill 1809) |
| <i>Grampus griseus</i> (Cuvier 1812) |
| <i>Lagenodelphis hosei</i> Fraser (1956) |
| <i>Orcinus orca</i> (Linnaeus 1758) |
| <i>Peponocephala electra</i> (Gray 1846) |
| <i>Pseudorca crassidens</i> (Owen 1846) |
| <i>Sotalia guianensis</i> (van Bénédén 1864) |
| <i>Stenella attenuata</i> (Gray 1846) |
| <i>Stenella clymene</i> (Gray 1850) |
| <i>Stenella coeruleoalba</i> (Meyer 1833) |
| <i>Stenella frontalis</i> (Cuvier 1829) |
| <i>Stenella longirostris</i> (Gray 1828) |
| <i>Steno bredanensis</i> (Cuvier in Lesson 1828) |
| <i>Tursiops truncatus</i> (Montagu 1821) |
| Kogiidae |
| <i>Kogia breviceps</i> (Blainville 1838) |
| <i>Kogia sima</i> (Owen 1866) |
| Pontoporidae |
| <i>Pontoporia blainvillei</i> (Gervais & d'Orbigny 1844) |
| Phocoenidae |
| <i>Phocoena spinipinnis</i> Burmeister (1865) |
| Physeteridae |
| <i>Physeter macrocephalus</i> Linnaeus (1758) |
| Ziphiidae |
| <i>Berardius arnuxii</i> Duvernoy (1851) |
| <i>Mesoplodon europaeus</i> (Gervais 1855) |
| <i>Ziphius cavirostris</i> Cuvier (1823) |

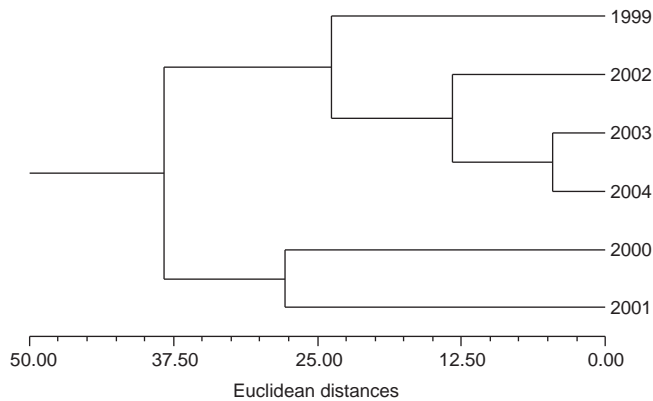


Figure 2. Tree data structure of the clustering analyses of the years by number of seismic surveys carried out ($\lambda = 0.90372$).

Figura 2. Dendrograma em modo Q do número de sísmicas marítimas realizadas por ano ($\lambda = 0.90372$).

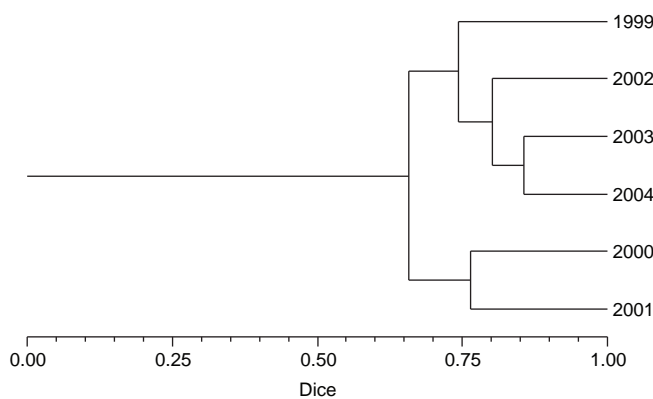


Figure 3. Tree data structure of the cluster analyses grouping the years studied by similarity in terms of the presence and absence of cetacean species ($\lambda = 0.83396$).

Figura 3. Dendrograma em modo Q da presença e ausência de espécies de cetáceos por ano ($\lambda = 0.83396$).

of the data, explaining more than 80% of possible variations (Density $\lambda = 0.85788$; Salinity $\lambda = 0.86262$; Temperature $\lambda = 0.84486$).

Discussion

The pattern of seismic surveys occurring in Brazil agrees with the analyses carried out by Parente & Araujo (2005), which recorded a rapid increase up to 2001, and a drop in the following years. The 2004 seismic surveys were similar those of 2002 and 2003 in terms of both their number and the technology used. The seismic surveys were widely spread out along Brazilian coast during 2000 and 2001. The predominant technology used in this period was the 2D-technology that covers large areas, while 3-D technology came to predominate after 2002 in restricted areas. The decline in activity in the last few

years resulted from a stricter policy being introduced by IBAMA and the end of the long period of exploration surveys using 2D-technology (Parente & Araujo 2005).

The environmental control exercised by the Brazilian government includes defined periods and exclusion zones, as well as the requirement to carry out specific environmental studies according to the environmental sensitivity of each area (Vilardo et al. 2003). The first exclusion period/zone defined by IBAMA was the Abrolhos Bank during the winter, owing to its importance for the conservation of the humpback whale (Engel et al. 2004). This decision has been widely criticized by seismic contractors who believe it could reduce the development of the oil industry in Brazil. As petroleum accumulates in basins, the areas near the Abrolhos Bank may constitute a large reserve of this resource. This situation will require IBAMA and the

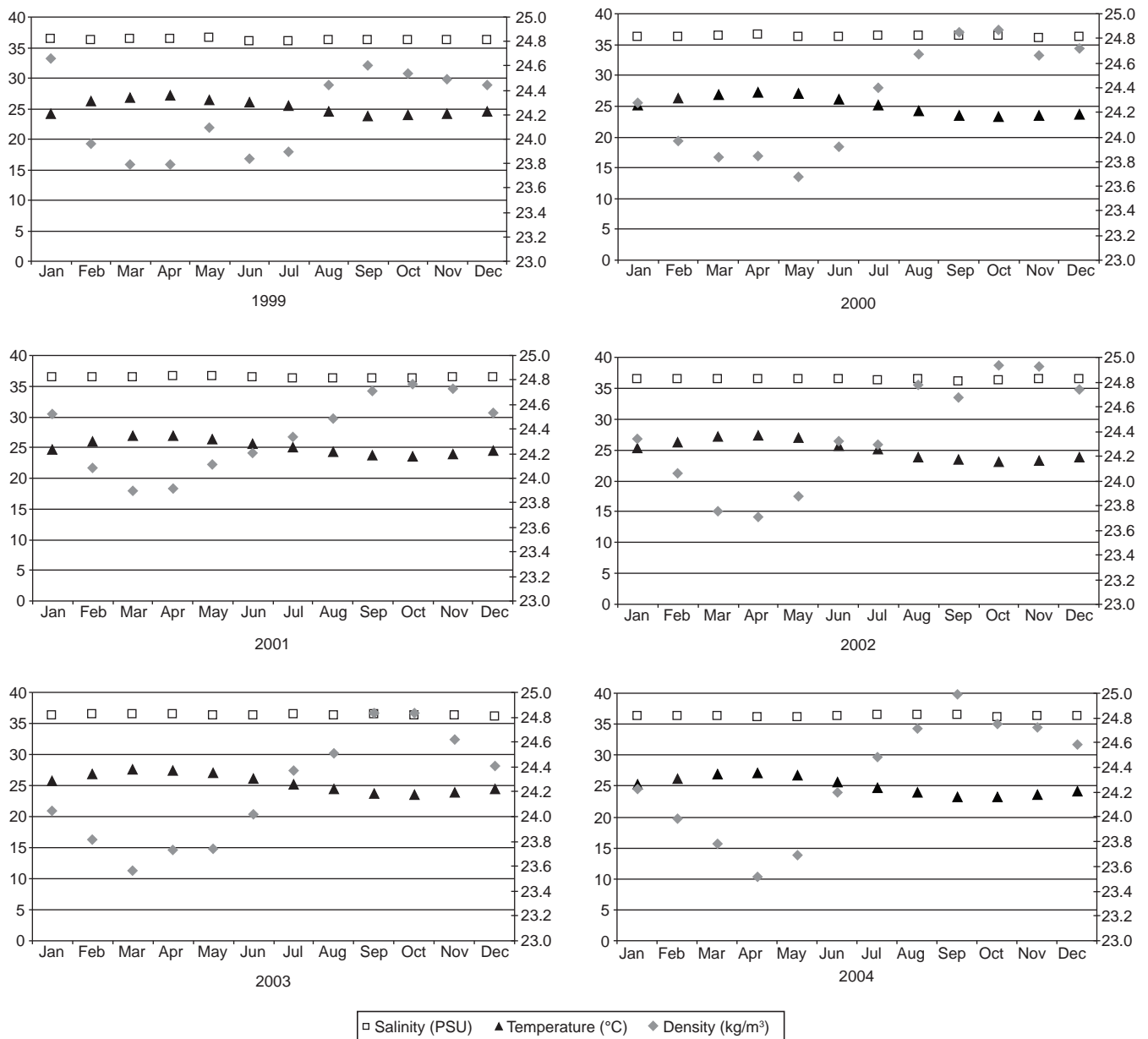


Figure 4. Means for oceanographic parameters during seismic surveys and on the western rim of the Atlantic Ocean (10° S-10° W) between 1999 and 2004 (Salinity – left, Temperature and Density – right).

Figura 4. Média dos parâmetros oceanográficos durante as sísmicas marítimas e na margem oeste do Oceano Atlântico (10° S-10° W) entre 1999 e 2004 (Salinidade – esquerda, Temperatura e Densidade - direita).

oil industry to develop environmental management tools to exploit the area without interfering in the habitat of the humpback whale.

At present, IBAMA requires that observation of aquatic mammals be carried out during the seismic surveys turning off guns when the animals are within 500 meters of the seismic vessel (IBAMA 2003). These observations have contributed little to knowledge of cetaceans or their conservation (i.e. Gurjão et al. 2004). Although efforts have been made to standardize the monitoring procedures, results regarding the occurrence, distribution and behavior of the species observed during these surveys in Brazil have not been made widely available for the scientific community, as discussed by Parente & Araujo (2005).

As to the species recorded during the period of this study, the consistency of the information was improved with the use of data from observations carried out during seismic surveys, to supplement the data obtained from the IWC Progress reports. The latter provide good information on the occurrence of cetaceans in Brazilian waters. The cluster analyses group the years of study into two different blocks of diversity of cetaceans similar to those shown by the analyses of seismic surveys. The first of these covering 2000 and 2001 has the lowest diversity and the other covers the years with the highest diversity.

Considering there was no reduction in effort of research during the period studied, the variation in the diversity of cetaceans seems to be influenced primarily by the number of non-resident species such as *Globicephala melas*, *Grampus griseus* and *Peponocephala electra*. Most of the species recorded in this study are described in specialist literature as cosmopolitan and pan-tropical species (Reeves et al. 2002). The number of coastal and resident species along the Brazilian coast is small. *Sotalia guianensis* and *Tursiops truncatus* being two examples of species with resident populations with great difference in group sizes according to latitude. Both species are found in small groups in lower latitudes. The use of indexes of diversity of cetaceans would not, therefore, be effective in verifying the influence of seismic surveys on such species in shallow waters between 0-100 meters of depth.

The main group of cetaceans that influenced the difference in diversity in this study was the Delphinidae family. Published information about this group and its reaction to seismic surveys currently only relates to two: species *Delphinus delphis* (Goold 1996) and *Tursiops truncatus* (Evans et al. 1993) and indicates that a portion of these populations moved to other areas during the seismic surveys. Another review suggests that such movements may result not exclusively as a direct effect on these species but potentially also indirectly, as a result of a decline in prey in the area being explored (Simmonds et al. 2003). Avoidance and changes in migratory routes have also been observed in other species of cetaceans, such as *Physeter macrocephalus* (Mate et al. 1994), *Eschritius robustus* (Malme et al. 1983, 1984 in Richardson et al. 1995), *Balaena mysticetus* (Koski & Johnson 1987 in Richardson et al. 1995), and *Megaptera novaeangliae* (McCauley et al. 2000). The possible displacement of fin (*Balaenoptera physalus*) and sei whales (*Balaenoptera borealis*) is discussed in MacLeod et al. (in press).

Many other biological and oceanographic features are known to affect the diversity of species in the oceans. Here we were only able to consider data relating to seismic surveys and oceanographic parameters. The cluster analysis of the oceanographic parameters did not show similarity with the two other cluster analyses. The statistical analyses of the oceanographic data did not show significant differences in the patterns of temperature, salinity and density, and this suggest that these parameters did not influence the diversity of cetaceans in the Brazilian shelf basin during the period of study. The possibility of other environmental or anthropogenic factors having affected diversity cannot be entirely ruled out, although the only

anthropogenic activity believed to have significantly changed during the period was the seismic surveys.

Considering the small amount of information available on the effects of sound pulses emitted by air-guns used in seismic surveys on the vast majority of cetacean species, and the possibility that these pulses cause avoidance and changes in migratory routes in some species of cetaceans, it is possible that the observed reduction in the diversity of cetacean during the period was brought about by the intensification in seismic surveys between 2000 and 2001.

In areas next to 22° S it was possible to verify a considerable increase in the number of species during periods when there are few or no seismic surveys while next to the equator this pattern was not observed. A study conducted in the mid-Atlantic Ocean between 1999 and 2000 clearly detected sound pulses from seismic surveys carried out in the northeast of Brazil, often at a distance of 3000 km or more from their hydrophone array (Nieukirk et al. 2004). Noting this and the analyses presented here, it is possible that the seismic surveys occurring along the whole of the Brazilian coast during 2000 and 2001 could have led non-resident species to avoid the Brazilian continental shelf. This proposition was supported by the result of the Spearman test applied in this study that showed significant negative correlation between diversity of cetaceans and means of seismic surveys.

Nevertheless, it is not possible to conclusively state that seismic surveys can directly result in reduction of diversity. The monitoring of cetaceans carried out during seismic surveys in the northeast region of Brazil between 2000 and 2001 increased information about the diversity of cetaceans. Further acoustic and bioacoustics studies of the Brazilian continental shelf as well as a program of cetacean survey should be carried out to deepen the knowledge on the dispersion of the sounds emitted during seismic surveys and the occurrence of cetaceans in the neighboring areas.

With the exception of the study conducted by Parente & Araujo (2005), there is no previous research focusing on the relationship between seismic surveys and the diversity of cetaceans. The absence of previous data concerning variation in the diversity of cetaceans makes it impossible to compare the results found in this study and highlights the need to extend this kind of analysis to other areas of the world. These results indicate that the diversity of cetaceans has potential as a good tool for evaluating the influence of seismic surveys over large areas and for long periods. For this reason, it is recommended that a national database be built up in Brazil to monitor marine mammals during the seismic surveys in order to provide accurate information on diversity, abundance and distribution. This database would aid with research and drawing up of alternative proposals for the management of seismic surveys in such a way as to reduce impact on marine mammals.

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