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Visual-Acoustic Survey of Cetaceans during a Seismic Study in the Southeast Caribbean Sea, April–June 2004

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Abstract- **Lamont-Doherty Earth Observatory's monitoring and mitigation program during an academic seismic study in April–June 2004 was the largest cetacean survey undertaken to date in the southeast Caribbean Sea. A total of 10,007 km (904 h) of visual observations occurred from the seismic vessel R/V Maurice Ewing and from the support vessel R/V Seward Johnson II. In addition, 7375 km (846 h) of passive acoustic monitoring for vocalizing cetaceans occurred from the Ewing via a towed 250-m hydrophone array. Approximately 1293 cetaceans in 46 groups were seen from the two vessels, and 78 acoustic detections were made. Nine cetacean species were identified of which the long-beaked common dolphin (Delphinus capensis), Atlantic spotted dolphin (Stenella frontalis), and bottlenose dolphin (Tursiops truncatus) were sighted most frequently. The striped dolphin (S. coeruleoalba), spinner dolphin (S. longirostris), pantropical spotted dolphin (S. attenuata), short-finned pilot whale (Globicephala macrorhynchus), sperm whale (Physeter macrocephalus), and Bryde's whale (Balaenoptera edeni) were also identified during visual surveys. Only the sperm whale was positively identified by acoustic monitoring alone. At least 17 sperm whale detections (visual and/or acoustic) were made around the islands and atolls of the Venezuelan Archipelago near and beyond the 1000-m depth contour. Overall cetacean density in intermediate-depth water (100 to 1000 m deep) was five times greater than in deep (>1000 m) water. This study addresses previous data gaps on the occurrence of cetaceans in shelf and offshore waters across a wide area of the southeast Caribbean Sea in spring.**

Keywords- **acoustic monitoring, marine mammal, shipboard survey, Venezuela**

Introduction

For the spring 2004 marine mammal monitoring and mitigation program for Lamont-Doherty Earth Observatory's (L-DEO) academic seismic study in the southeast Caribbean Sea, biological observers monitored visually and acoustically for cetaceans. Cetacean surveys in the southern Caribbean Sea have been scarce, and abundance within the Caribbean region is mostly unknown (Roden and Mullin 2000). Prior to L-DEO's southeast Caribbean survey, only one extensive, systematic ship-based survey had occurred in the southeast Caribbean (e.g., Swartz and Burkes 2000; Swartz et al. 2001, 2003). That survey used both visual and passive acoustic monitoring (PAM) methods, focusing on the humpback whale (Megaptera novaeangliae) during winter. Other surveys in the southern Caribbean include those by Jefferson and Lynn (1994) and off the Columbian coast by Pardo and Palacios (2006) and Fraija et al. (2009). Systematic surveys in the eastern Caribbean include those by Romero et al. (2002), Boisseau et al. (2006), Jérémie et al. (2006), Rinaldi et al. (2006), Yoshida et al. (2010), and Weir et al. (2011). Numerous papers have also been published on the ecology of cetaceans in coastal waters of Venezuela (e.g., Oviedo and Silva 2005; Bermúdez-Villapol et al. 2006, 2008a,b; Oviedo et al. 2005, 2010; Silva et al. 2008) and in the Leeward Dutch Antilles (e.g., Debrot and Barros 1994; Debrot et al. 1998; Barros and Debrot 2006).

The present study was not designed as a dedicated systematic cetacean survey, but rather as part of a monitoring and mitigation program to reduce the effects of seismic study sounds on marine mammals that might occur nearby. Nonetheless, a great deal of systematically collected information on the occurrence and distribution of numerous species was obtained during the cruise in a little-studied area. This survey represents the largest cetacean survey effort undertaken to date in the southeast Caribbean Sea, and has provided, for the first time, data on the occurrence of cetaceans in that area across a wide range of longitudes during spring.

Materials and Methods

Study Area and Vessels

Two vessels were the observation platforms during the seismic study. The R/V Maurice Ewing was the source vessel used for the seismic survey from which airguns were operated. Visual observations occurred from the Ewing both during seismic acquisition and during periods without seismic; PAM occurred almost exclusively during seismic operations. In addition, the R/V Seward Johnson II, a nonseismic vessel, provided support for the Ewing and conducted additional visual monitoring for cetaceans. The Ewing was owned by the National Science Foundation (NSF) and operated by L-DEO, but has since been decommissioned. The Ewing was 70 m long and 14.1 m wide with a draft of 4.4 m. The Johnson II is part of the University-National Oceanographic Laboratory System, with a length of 62 m, a width of 11 m, and a draft of 3.7 m.

The seismic study encompassed an area from 59º to 71ºW and ~10º to 15ºN in the southeast Caribbean Sea and adjacent Atlantic Ocean, off the coasts of Venezuela, Aruba, Bonaire, Curaçao, and Trinidad and Tobago (Fig. 1). Survey effort for cetaceans also occurred during transit to and from San Juan, Puerto Rico. The Ewing and Johnson II departed San Juan on 18 and 19 April 2004, respectively, and returned to San Juan on 3 and 1 June 2004, respectively. During the survey, the two vessels were typically separated by ~50 to 100 km. The survey was generally conducted from west to east across the study area, with transect lines typically running perpendicular to the shore. Water depths in the study area ranged from ~15 to 6000 m (Fig. 1).

During the seismic survey, the Ewing towed a 20-airgun array with total discharge volume of 6947 in^3 and a source level of 255 dB re 1 μPa · m (0-pk). Seismic pulses were 200 ms in duration at the source and were emitted at intervals of ~20–60 s. Seismic operations occurred on 20–22 April, 27–30 April, 1–15 May, and 18–31 May. During seismic acquisition the Ewing traveled at 7–9 km/h, but when the vessel was not towing gear, the Ewing and the Johnson II typically cruised at 18–20 km/h.

Visual Observations

One or two experienced observers watched from each vessel for cetaceans and sea turtles during all daytime hours when the airgun array was operating, and usually when the vessel was underway but the airguns were not firing. Visual observations occurred nearly daily throughout the study from both vessels. On the Ewing, observations occurred from the flying bridge (eye level 14.4 m above sea level [asl]); during inclement weather, observations occurred from the bridge (11 m asl). On the Johnson II, observers watched from the flying bridge (~11.4 m asl), or during poor weather, from the bridge (8.5 m asl). The naked eye and 7×50 hand-held reticle binoculars were used to look for cetaceans and turtles; on the Ewing, two 25×150 big-eye binoculars were also used.

Observers systematically recorded watch data onto a datasheet every ~30 min. For each record, the date, time, vessel position (latitude and longitude), vessel operational activity, and environmental conditions (glare, visibility, Beaufort wind force [Bf], water depth) were recorded. Operational activities included the number of airguns in use and the type of ves-

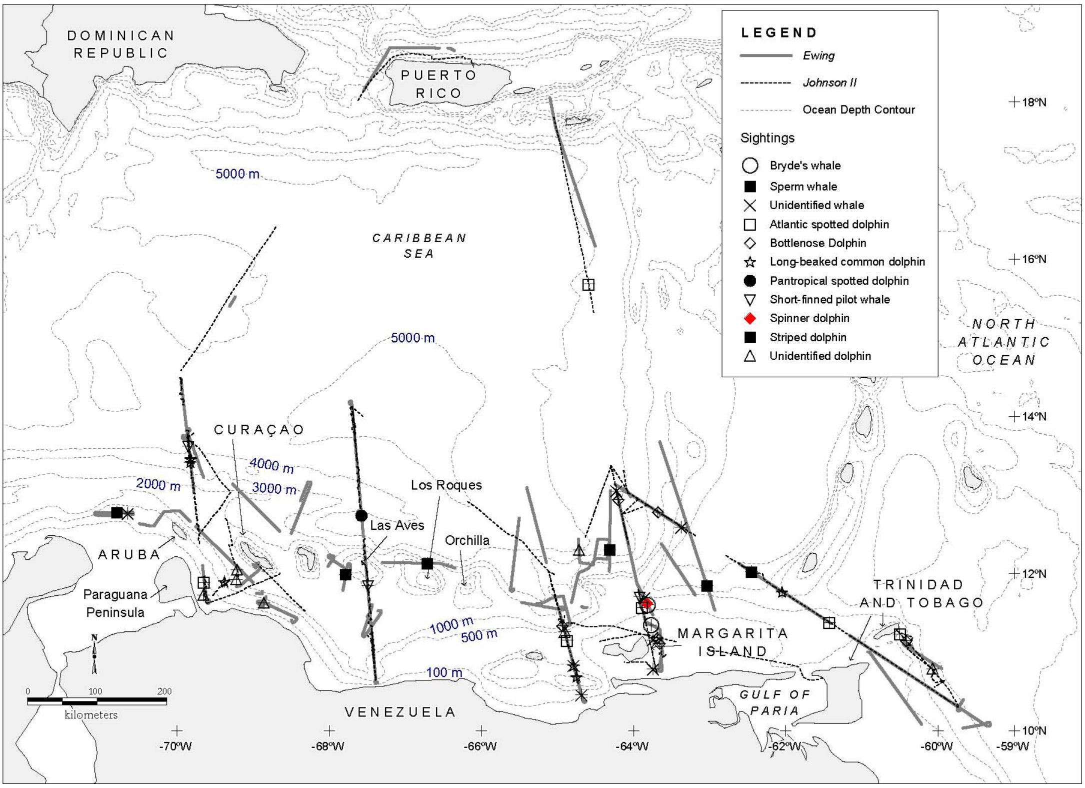

FIG 1. Map of visual survey effort and sightings made from both the Ewing seismic source vessel and the non-seismic Johnson II support vessel during L-DEO's Southeast Caribbean and adjacent Atlantic seismic survey, 18 April–3 June 2004.

sel/seismic activity. For each sighting, species, number of individuals, direction of movement, sighting cue, behavior, sighting distance, species identification reliability, vessel position and activity, and environmental conditions were recorded.

Passive Acoustic Monitoring

PAM occurred nearly 24-h per day from the Ewing. The main purpose of PAM was to aid visual observers by alerting them to the presence of vocalizing cetaceans. SEAMAP software (version 1.525, Houston, TX) was used for acoustic monitoring. This program was limited to a bandwidth of ~0.5–24 kHz. Two of four hydrophones in the active section of the array were monitored at one time. The length of the lead-in from the hydrophone array was 240 m; the active part of the array was 56 m long. The array was towed at a depth of ~20 m or less, depending on bottom depth in the study area. The acoustic detection system was monitored via headphones and/or speakers by one observer. Vocalizations were shown on a spectrographic display (SeaPro, CIBRA, University of Pavia, Italy).

Cetacean Density Calculations

Only cetacean sightings and survey effort during non-seismic periods were used to calculate animal densities (#/1000 km^2). Non-seismic periods included all data collected from the non-seismic vessel Johnson II and from the Ewing before or over 6 h after seismic operations had ceased. The 6-h time period was used to distinguish seismic periods from those periods where seismic surveys were sufficiently far in the past that it can be assumed that they had no effect on current cetacean behavior and distribution. In 6 h, the vessel travelled at least 45 km which is beyond the distance where earlier sounds might have caused cetacean responses. Only data obtained during Bf≤5 and when the vessel was traveling at speeds over 3.7 km/h were used for density calculations. Densities were determined for two water depth categories — intermediate (100 to 1000 m) and deep (>1000 m) water; densities could not be calculated for shallow (<100 m) water as effort was too low.

Density calculations were based on Distance sampling methods (Buckland et al. 2001). Densities were corrected for g(0), a measure of detection bias, and f(0), the reduced probability of detecting an animal with increasing distance from the trackline. The g(0) and f(0) factors used in this study were taken from results of previous work for corresponding species and sea states. Sightings were also subjected to species-specific truncation criteria per Koski et al. (1998) and Barlow (1999).

Results

Visual Survey Effort

Aboard the Ewing, total effort was 510 h of visual observations along 4920 km from 18 April to 3 June 2004; 3662 km and 1258 km occurred during seismic and non-seismic operations, respectively. Most of the non-seismic effort occurred during transit to and from Puerto Rico. One observer was on visual watch aboard the Ewing during 2787 km, with at least two observers on watch during the remaining 2133 km. Aboard the Johnson II, total effort was 394 h of visual observations along 5087 km from 19 April to 1 June 2004; this included 813 km during transit to and from Puerto Rico. All effort on the Johnson II was non-seismic. One observer was on visual watch aboard the Johnson II during 3078 km, with two or more observers on watch during the remaining 2009 km. Bf during observations on both the Ewing and Johnson II ranged from 1 to 7. Aboard the Ewing, most (74%) of the 4920 km of observation effort occurred with Bf ≥ 4. Aboard the Johnson II most of the 5087 km of observation effort was split fairly evenly across Bf 2 (27%), 3 (29%) and 4 (25%), with only 4% of effort occurring during Bf ≥ 5.

Sightings

Approximately 1293 individual cetaceans were seen in 46 groups during the survey from both vessels (Table 1); the majority of groups (28 of 46) were observed when the airguns were off. All cetaceans were seen in the southeast Caribbean Sea or adjacent waters except one group of Atlantic spotted dolphins (Stenella frontalis) seen during the transit to Puerto Rico (Fig. 1). Nine cetacean species were documented visually from the Johnson II or Ewing during the survey (Table 1). Unidentified whales and unidentified dolphins (n = 7 of each) were the most commonly seen categories, followed by six groups each of bottlenose (Tursiops truncatus), Atlantic spotted, and long-beaked common dolphins (Delphinus capensis) (Table 1). Four groups of sperm whales (Physeter macrocephalus), three groups of short-finned pilot whales (Globicephala macrorhynchus), and two groups of Bryde's whales (Balaenoptera edeni) were seen. The long-beaked common dolphin was the most abundant cetacean, accounting for ~734 individuals in six groups, including one group of ~600 (Table 1). Sperm whales (n = 4) were seen (as well as detected acoustically) only from the Ewing in deep water. Striped dolphins (S. coeruleoalba, n = 2), spinner dolphins (S. longirostris, n = 1), and pantropical spotted dolphins (S. attenuata, n = 1) were also observed only from the Ewing, whereas short-finned pilot whales (n = 3) were observed only from the Johnson II. The overall cetacean density in intermediate-depth water (82.4/1000 km^2; Table 2) was five times greater compared to that in deep water (15.9/1000 km^2; Table 3). Densities of individual species were also greater in intermediate depths compared with deep water.

In addition to the cetacean sightings, four sea turtles were observed: one leatherback turtle (Dermochelys coriacea), one hawksbill turtle (Eretmochelys imbricata), and two unidentified turtles.

TABLE 1. Number of visual and acoustic detections of cetacean groups from the Ewing and Johnson II during the Southeast Caribbean survey, 18 April–3 June 2004. Numbers in parentheses are number of individuals. For acoustic encounters (encount.), group size was unknown unless there was a concurrent visually matched sighting.

Species	*Johnson II* Visual Sightings (# indiv)	*Ewing* Visual-Only Sightings (# indiv)	*Ewing* Acoustic -Only Encount.	Matched *Ewing* Visual/ Acoustic Detections (# indiv)	Total Visual Sightings (# indiv)	Total Acoustic Encount.
Sperm whale *Physeter macrocephalus*	0	0	5	4 (12)	**4 (12)**	**9**
Bottlenose dolphin *Tursiops truncatus*	5 (30)	0	0	1 (20)	**6 (50)**	**1**
Pantropical spotted dolphin *Stenella attenuata*	0	0	0	1 (30)	**1 (30)**	**1**
Atlantic spotted dolphin *S. frontalis*	5 (174)	0	0	1 (55)	**6 (229)**	**1**
Spinner dolphin *S. longirostris*	0	0	0	1 (80)	**1 (80)**	**1**
Striped dolphin *S. coeruleoalba*	0	1 (60)	0	1 (7)	**2 (67)**	**1**
Long-beaked common dolphin *Delphinus capensis*	5 (684)	0	0	1 (50)	**6 (734)**	**1**
Unidentified dolphin	4 (18)	1 (4)	61	2(38)	**7 (60)**	**63**
Short-finned pilot whale *Globicephala macrorhynchus*	3 (17)	0	0	0	**3 (17)**	**0**
Bryde's whale *Balaenoptera edeni*	0	2 (3)	0	0	**2 (3)**	**0**
Unidentified whale	3 (3)	5 (8)	0	0	**8 (11)**	**0**
Total	**25 (926)**	**9 (75)**	**66**	**12 (292)**	**46 (1293)**	**78**

Acoustic Survey Effort and Detections

A total of 846 h of acoustic monitoring along 7375 km occurred from the Ewing. Acoustic effort was nearly equally divided between daytime (3787 km) and nighttime (3562 km) periods; nearly all effort (95%) occurred during seismic periods. Seventy-eight detections of vocalizing cetaceans were recorded from the Ewing (Fig. 2; Table 1), of which 31 detections were made concurrent with daytime visual monitoring. All 66 acoustic-only detections were unidentified dolphins (n = 61) or sperm whales (n = 5). All acoustic sperm whale detections occurred in offshore waters. Acoustic encounters of delphinids were nearly twice as common at night (13.0/1000 km) as during the day (7.5/1000 km) (n = 69, including 63 unidentified dolphin encounters and six dolphin groups identified to species based on visual/acoustic matches). Twelve of the 21 cetacean groups sighted from the Ewing were concurrently matched with acoustic encounters involving seven different odontocete species (Table 1). No baleen whale vocalizations were detected.

TABLE 2. Sightings and densities of cetaceans during non-seismic periods in water depths 100 to 1000 m in the Southeast Caribbean Sea and adjacent North Atlantic waters. Non-seismic periods are periods before seismic started or periods >6 h after seismic ended. Densities were calculated from 16 sightings of 852 cetaceans during 2184 km of survey effort in water depths 100–1000 m and were corrected for f(0) and g(0). Only data obtained during Bf≤5 and vessel speeds >3.7 km/h were used in the calculations.

Species	Number of Sightings	Mean group size	Average density (# / 1000 km^2)	
			Density	**CV[a]**
Bottlenose dolphin *Tursiops truncatus*	3	7.7	8.20	0.76
Atlantic spotted dolphin *Stenella frontalis*	4	40.8	20.64	0.72
Long-beaked common dolphin *Delphinus capensis*	2	320.0	44.84	0.83
Unidentified dolphin	2	6.0	4.28	0.83
Short-finned pilot whale *Globicephala macrorhynchus*	1	8.0	2.85	0.94
Unidentified toothed whale	1	3.0	1.07	0.94
Unidentified whale	3	1.0	0.53	0.76
			82.41	0.94

[a]CV (coefficient of variation) was estimated by the equation $0.94 - 0.162\log_e n$ from Koski et al. (1998), but likely underestimates the true variability

DISCUSSION

L-DEO's 2004 Caribbean cetacean monitoring program is the largest marine mammal survey conducted to date in the southeast Caribbean Sea. Prior to this study few large-scale surveys for cetaceans had occurred in the area, particularly in the western portion. Nine cetacean species were sighted during the survey. One of these species, the striped dolphin has been recorded only rarely in the area (e.g., Jefferson and Lynn 1994; Debrot et al. 1998; Romero et al. 2001). As noted by Romero et al. (2001), Atlantic spotted dolphins were more common off Venezuela than pantropical spotted dolphins.

No beaked whales were seen during the surveys in the Caribbean Sea. It is more difficult to see cryptic whales like beaked whales in rough seas. Aboard the Ewing, most (74%) of the 4920 km of observation effort occurred with Bf ≥ 4; the Johnson II had better sighting conditions but spent more time in nearshore waters. Although it is possible that beaked whales actively avoided the operating airguns more than the other cetacean species, northern bottlenose whales (Hyperoodon ampullatus) have been detected visually and acoustically during other seismic surveys (e.g., Lee et al. 2005; Moulton and Holst 2010).

In the Caribbean Sea, long-beaked common dolphins are known to occur off Venezuela and Trinidad, and may also occur off Grenada (Jefferson et al. 2009). During the L-DEO survey, one sighting occurred to the southeast of Grenada. Romero et al. (2002) also noted the occurrence of long-beaked common dolphins in Grenada; however, they were not sighted there by Boisseau et al. (2006). The long-beaked common dolphin was the most frequently sighted odontocete during the southeast Caribbean survey as has been previously reported for Venezuelan marine waters (Romero et al. 2001). Our sightings east of Paraguana Peninsula and north of Aruba are the western-most reported sightings of this species in the southern Caribbean

TABLE 3. Sightings and densities of cetaceans during non-seismic periods in water depths >1000 m in the Southeast Caribbean Sea and adjacent North Atlantic waters. Non-seismic periods are periods before seismic started or periods >6 h after seismic operations ended. Densities were calculated from 11 sightings of 132 cetaceans during 3841 km of survey in waters >1000 m and were corrected for $f(0)$ and $g(0)$. Only data obtained during Bf ≤ 5 and vessel speeds >3.7 km/h were used in the calculations.

Species	Number of Sightings	Mean group size	Average density (# / 1000 km^2)	
			Density	CV[a]
Bottlenose dolphin *Tursiops truncatus*	2	3.5	1.42	0.83
Atlantic spotted dolphin *Stenella frontalis*	1	11.0	2.23	0.94
Striped dolphin *S. coeruleoalba*	1	60.0	4.03	0.94
Long-beaked common dolphin *Delphinus capensis*	3	12.7	5.00	0.76
Unidentified dolphin	3	3.3	2.03	0.76
Short-finned pilot whale *Globicephala macrorhynchus*	1	6.0	1.22	0.94
			15.93	0.55

[a] CV (coefficient of variation) was estimated by the equation $0.94 - 0.162\log_e n$ from Koski et al. (1998), but likely underestimates the true variability

Sea, except for one stranding of a long-beaked common dolphin in the Gulf of Venezuela (Jefferson et al. 2009). Although Delphinus sp. and Stenella sp. may be misidentified in the field, the experienced observers (including one cetacean specialist from Venezuela) were certain based on diagnostic characters that all sightings of Delphinus capensis were identified correctly. The use of 25×150 big-eye binoculars was also instrumental in obtaining positive identifications of species. There is no indication that short-beaked common dolphins (D. delphis) occur in the area (Jefferson et al. 2009).

Romero et al. (2001) suggested that the occurrence of cetaceans probably increased from west to east in the Venezuelan Caribbean, coinciding with higher biological productivity between 63°07'W and 65°26'W associated with increased runoff from major rivers such as the Orinoco (Monente 1997). During our survey, cetaceans were distributed throughout much of the study area, with notable concentrations in some areas. From west to east, visual sightings of cetaceans were concentrated to the east of Paraguana Peninsula, near Isla de Margarita, and near Trinidad and Tobago.

Sperm whales were detected both visually and acoustically around islands and atolls of the Venezuelan Archipelago, in waters deeper than ~1000 m, including Los Roques, Orchilla, and Las Aves. Sperm whales have been commonly sighted during surveys in the Lesser Antilles (e.g., Watkins et al. 1985; Gordon et al. 1998; Swartz and Burks 2000; Swartz et al. 2001, 2003; Yoshida et al. 2010). Bryde's whale sightings occurred in water <500 m deep north of Isla de Margarita; this species is the most commonly sighted mysticete in the area (Debrot 1998; Romero et al. 2001; Swartz et al. 2003). Similar to findings by Yoshida et al. (2010), densities of cetaceans were higher in shelf waters of the southeast Caribbean than in offshore waters.

Our density estimates are likely biased low because poor sighting conditions likely reduced the detectability of cetaceans during the survey. Most survey effort from the Ewing occurred during Bf ≥ 4, which appears to be typical of conditions in the area during spring/summer (e.g., Boisseau et al. 2006; Yoshida et al. 2010). Most survey effort from the Johnson II occurred during calmer conditions. The differences in Bf recorded during observations aboard the Ewing and Johnson II may be attributable to the fact that the Ewing remained in the open sea, whereas the Johnson II spent considerable time in the lee of various southeast Caribbean Islands while transiting to island ports to conduct crew changes, repair equipment, or layover until the Ewing finished surveying seismic lines.

The acoustic detection rate of delphinids during the daytime was three times greater than the visual detection rate (31 vs. 10 delphinids detected from the Ewing). Boisseau et al. (2006) also reported that acoustic detection rates were greater than visual detection rates during surveys in the eastern Caribbean. Greater acoustic detection rates are typical for joint visual/acoustic surveys, particularly during poor conditions (e.g., Thomas et al. 1988; Fristrup and Clark 1997; Norris et al. 1999; Swartz et al. 2003; Barlow and Taylor 2005). Goold (2000) also noted the benefit of conducting combined visual and acoustic surveys. The combined use of the two methods increased the likelihood of detecting cetaceans during this survey. However, results suggest that baleen whales were unlikely to be detected by PAM under the conditions of this study, even though at least three Bryde's whales were seen. The reduced signal to noise ratio did not allow for detection of low frequencies on the towed array. Acoustic detection rates are also known to be affected by seasonal, geographic, and diurnal variability in vocalization rates and call intensity (e.g., Stafford et al. 1999a,b; Stienessen 1998; Moore et al. 1999). Acoustic encounters with delphinids during the L-DEO survey occurred nearly twice as frequently at night as during the day. Delphinids may call more frequently at night to coordinate foraging strategies associated with nocturnal vertical-migrating

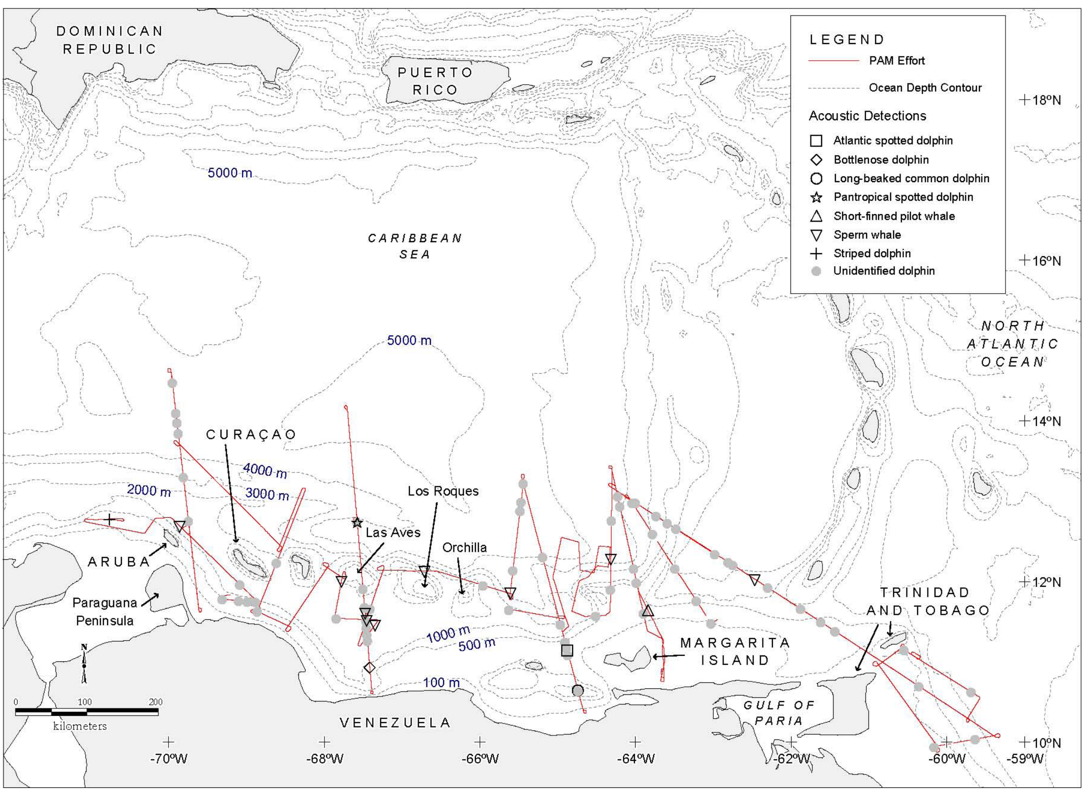

FIGURE 2. Map of passive acoustic monitoring effort and detections made from the Ewing seismic source vessel during L-DEO's Southeast Caribbean and adjacent Atlantic seismic survey, 18 April–3 June 2004.

prey (e.g., Notarbartolo Di Sciara and Gordon 1997; Stienessen 1998; Goold 2000).

Data collected during this study were part of a monitoring and mitigation program during a marine seismic survey. The density data presented are based only on effort and observations during periods when airguns were not operating or had not been operating for the previous 6 h. As such, they provide the first comparison of relative abundance of common species in shelf versus offshore waters in the southern Caribbean Sea. When interpreting the data on general occurrence of species in the survey area, it is important to remember that data collected during seismic periods were likely influenced by the Ewing's seismic operations. Cetaceans may have exhibited some localized and short-term behavioral disturbance in response to the seismic survey (e.g., Richardson et al. 1995; Gordon et al. 2004; Nowacek et al. 2007; Southall et al. 2007). For example, it is possible that beaked whales were not seen during the survey as they may have been displaced further by the seismic survey compared to other cetaceans, making them unavailable to visual observers. While such avoidance of seismic per se has not been documented in the literature (e.g., Lee et al. 2005; Moulton and Holst 2010), beaked whales are known to avoid large vessels in general (e.g., Würsig et al. 1998). Nonetheless, the general information presented on the presence of cetaceans in a little-described area of the southeast Caribbean Sea during spring is an important contribution to our understanding of the species and their distribution there.

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