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Year-round acoustic presence of sperm whales (*Physeter macrocephalus*) and baseline ambient ocean sound levels in the Greek Seas

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Abstract

The sperm whale (*Physeter macrocephalus*) is the largest odontocete occurring in the Greek Seas. However, monitoring the species' spatiotemporal distribution patterns is especially difficult during the winter months when unfavorable weather conditions often hinder survey efforts. In the Greek Seas, visual cetacean surveys are typically not conducted between November and March. In a first attempt to collect year-round baseline information on sperm whale occurrence patterns in Greek waters, two Passive Aquatic Listeners (PALs) were deployed for 19 months, at Pylos Station (36.8 N, 21.6º E) in the Hellenic Trench, and at Athos Station (40.0 N, 24.7º E) in the North Aegean Trough. Results revealed the year-round presence of sperm whales at Pylos Station with a higher number of detections observed during late spring and throughout the summer. No sperm whale vocalizations were detected at Athos Station. An ambient sound level analysis revealed higher winter and lower summer levels at both sites largely driven by local weather conditions. Results showed that marine life in the Hellenic Trench area was exposed to higher low frequency (< 1 kHz) sound levels (by up to 10 dB re 1 μPa^2/Hz). Ambient noise below 1 kHz is frequently dominated by anthropogenic sources including shipping. Ship strikes and noise disturbance constitute major threats for the small, genetically isolated, endangered sperm whale population. The results of this study are useful for sperm whale conservation efforts in the region and may help policymakers in prioritizing mitigation measures, including the establishment of speed limits and rerouting of ship traffic.

Keywords: Sperm whale; Passive Acoustic Monitoring; year-round presence; Hellenic Trench; Greek Seas; Ambient Sound Levels.

Introduction

Sperm whales (*Physeter macrocephalus*) inhabiting the Greek Seas are part of the Mediterranean Sea population, which is genetically isolated from its adjacent Atlantic population (Engelhaupt *et al.*, 2009) and listed as 'Endangered' by the International Union for Conservation of Nature (Notarbartolo-di-Sciara *et al.,* 2012). The sperm whale population in the Greek Seas is very small and believed to consist of less than 250 individuals (Frantzis *et al.*, 2014a); about 12% of the entire Mediterranean Sea population (Rendell & Frantzis, 2016). The Hellenic Trench, located in the Ionian Sea (Fig. 1), concentrates the majority of those 250 individuals and has been described as a sperm whale hot spot in eastern Mediterranean Sea (Boisseau *et al.*, 2010; Frantzis *et al.*, 2014a). Consequently, under the Agreement for the Conservation of Cetaceans of the Black and Mediterranean Seas, this area has been assigned as an *Important Marine Mammal Area* and is being considered as a designated *Marine Protected Area (MPA;* IUCN-MMPATF, 2017). Information on sperm whales in the Aegean Sea is sparse and largely limited to reports of opportunistic sightings for the North Aegean and the Ikarian Troughs (Frantzis, 2009).

In the Hellenic Trench, the sperm whale population consists of both mature males and social units of adult females with their young indicating that this area is an important nursing and breeding ground (Frantzis *et al.*, 2014a; Frantzis *et al.*, 1999; Rendell & Frantzis, 2016). Even though their only natural predator, the killer whale (*Orcinus orca*), is not abundant (Notarbartolo Di Sciara, 1987) and whaling never occurred within the Mediterranean Sea, other anthropogenic activities (e.g., ship strikes) threaten the sperm whale population in this area

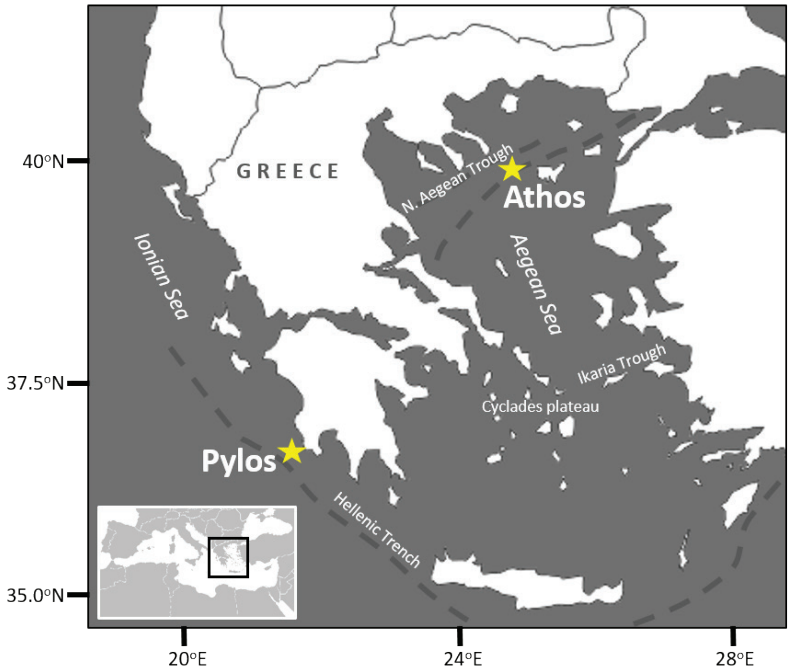

Fig. 1: Location of the POSEIDON buoys where the Passive Acoustic Listeners (PALs) were deployed and the acoustic sampling was implemented. The Hellenic Trench and the North Aegean Trough are shown in dashed lines in the main map and the position of the Greek Seas in the Mediterranean is shown in the inset on the bottom left.

(Notarbartolo-Di-Sciara, 2014; Rendell & Frantzis, 2016). In the Greek Seas, levels of marine traffic are especially high along the Hellenic Trench (Frantzis *et al.*, 2014a; Frantzis *et al.*, 2015). In addition to ship strikes (Frantzis *et al.*, 2015; Campana *et al.*, 2015), further concerns exists about potential negative impacts of increased vessel noise on the whales (Weilgart, 2007, Erbe *et al.*, 2015). The Greek government's recent plan for offshore oil and gas exploration in the Hellenic Trench area (YPEKA, 2018) constitutes another potential threat to sperm whales and marine life in general.

To establish effective conservation measures for sperm whales, year-round studies and knowledge on habitat use are essential (Levin *et al.*, 2014; Mannocci *et al.*, 2018). For many parts of the Greek Seas, information on sperm whale spatiotemporal distribution patterns are still lacking (Rendell & Frantzis, 2016). The Aegean Sea has been monitored the least for cetaceans among the Greek Seas (Mannocci *et al.*, 2018). Mannocci *et al.* (2018) also highlighted the need to relate patterns of cetacean presence to local levels of ship traffic and underwater noise.

Obtaining a long-term time series of cetacean presence using traditional visual surveys is a difficult task, especially for deep-diving, offshore species such as sperm whales. Due to the deep (up to 1800 m; Oliveira *et al.*, 2013) and long dives (up to 50 min; Aoki *et al.*, 2012) of sperm whales, it is difficult to detect them visually even in good weather conditions. The high costs associated with offshore research cruises also contribute to the lack of data in the eastern Mediterranean Sea. However, sperm whales are highly vocal animals which can be readily monitored using passive acoustic monitoring (PAM) techniques (Mellinger *et al.*, 2004). Sperm whale clicks (left panel, Fig. 2) are broadband, impulsive signals which are about 30 ms in duration and highly directional featuring peak frequencies between 10 and 15 kHz (Møhl *et al.*, 2003). The clicks also feature a nearly omnidirectional low frequency (1-4 kHz) component (Zimmer *et al.*, 2005). This part of the click can be acoustically detected independently of the orientation of the animal towards the acoustic sensor. Sperm whales produce different patterns of clicks with distinct inter click intervals (ICIs). 'Usual clicks' with an ICI of 0.5-1.0 s are the most common signals and primarily used for prey detection. 'Creaks' with an ICI between 0.01-0.4 s are used to follow prey at close distances and are indicative of prey catching attempts (Wahlberg, 2002). 'Slow clicks' with an ICI of 5-8 s are mostly produced by males at breeding grounds and thought to be used for communication and advertisement. 'Codas' exhibit irregular ICI but stereotyped patterns of clicks that are repetitive and linked to communication and social interactions (Teloni *et al.*, 2008).

Current monitoring efforts in the eastern Mediterranean Sea are largely based on visual surveys, which at times include the use of towed acoustic arrays (Frantzis *et al.*, 2014). However, to be able to monitor both cetaceans and ambient sound levels over extended periods (months to years) at locations of interest, the use of stationary autonomous recorders is a more effective method. Two autonomous acoustic recorders, Passive Aquatic Listeners (PALs), were deployed at Stations Pylos and Athos to investigate occurrence patterns of sperm whales and ocean sound levels in the Greek Seas between 2008 and 2010.

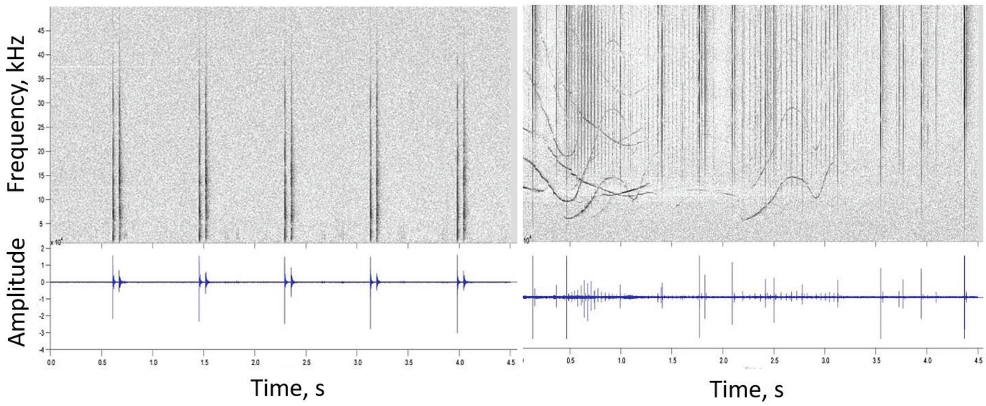

Fig. 2: Spectrogram (1024 Fast-Fourier Transform, Hamming window, 50% overlap) (top panels) and waveform (bottom panels) of sperm whale usual clicks (on the left; showing clicks and their surface reflection) and delphinid clicks and whistles (on the right) recorded by a Passive Aquatic Listener (PAL) (duration: 4.5 s, sampled at 100 kHz) at Pylos and Athos Stations, respectively.

Methods

Data collection and analysis

To assess sperm whale occurrence patterns, two Passive Aquatic Listeners (PALs) were deployed on oceanographic moorings as part of the POSEIDON II project (Nittis *et al.*, 2002). The first PAL was deployed at Pylos Station (36.8 N, 21.6º E; 1680 m water depth) in the Ionian Sea. The second PAL was deployed at Athos Station (40.0 N, 24.7º E; 400 m water depth) in the North Aegean Sea (Fig.1). The PAL at Pylos Station (hereafter referred to as Pylos) was deployed at a depth of 500 m, approximately 10 km off the west Peloponnese coast and operated between 11 November 2008 and 8 July 2010. A 72-day gap in the acoustic data occurred from 19 September until 28 November 2009 due to a delay in the mooring maintenance cruise. The PAL at Athos Station (hereafter referred to as Athos) was deployed at 200 m depth, approximately 30 km offshore between the Athos Peninsula and the island of Limnos. The sampling period at Athos lasted 9 months, from 5 November 2008 to 8 July 2009.

The PAL, an autonomous passive acoustic recording system, collects data at a low duty cycle (1.5%) to achieve year-long deployment durations (Anagnostou *et al.*, 2011). For this study, the PAL was configured to wake up from sleep mode every 5 min to collect 4.5 s of acoustic data sampled at 100 kHz. The 4.5 s snippet (hereafter referred to as sound bite) was analyzed with an onboard energy detector for acoustic signals of interests and the sound bite was stored when a non-stationary (transient) acoustic signal, typically representing biological sound sources, was recognized. In order for the algorithm to detect a signal, the energy level in the 1-20 kHz band had to exceed a detection threshold of 12 dB. The specific triggering frequency band was chosen to cover the omnidirectional part and peak frequency of the sperm whale clicks (1-4 kHz [Zimmer *et al.*, 2005] and 10-15 kHz [Møhl *et al.*, 2003], respectively). If a signal of interest was detected, the wakeup time was reduced from 5 min to 2 min until (a) no additional detection occurred, or (b) a daily quota of stored sound bites was reached (typically 6 per day). The decrease in sampling interval allowed more sound bites to be stored during the presence of signals of interest. If the quota at any given day was not reached, the following day's quota was increased by the number of remaining sound bites. Due to limitations in data storage capacity (~2 GB), the PAL's total per-deployment quota was 2200 sound bites, resulting in a total of 165 min of acoustic recordings during a one-year deployment. If no signal of interest was detected or the daily quota was reached, the PAL calculated and stored eight spectrum level curves (0.5-50 kHz) based on 10.24 ms of data separated by 0.6-0.7 s. While these spectrum levels could not be used to reliably detect sperm whale clicks, they provided valuable and continuous information on ambient sound levels in the sampling areas.

The PAL's subsampling strategy did not limit the detectability of sperm whale or other odontocete echolocation signals. Given that sperm whales vocalize continuously for 30-45 minutes during each dive, with an average ICI of 0.6 s, a 4.5 s sound bite contains seven echolocation clicks. Under these conditions, the probability of detection is nearly 100%. However, the detectability of sperm whale clicks is limited with regards to the available daily quota of sound bites. This is of particular concern when other vocal species occur frequently at the deployment sites. When acoustic signals emitted by these species are present early in the day, the daily quota can be exhausted within the first hour of the day.

Sperm whale detections

The collected sound bites were converted to WAVE (.wav) audio files and manually screened by an experienced analyst (ND) for sperm whale and other marine mammal vocalizations. For this purpose, the Matlab-based program Osprey (Mellinger, 1995) was used to create spectrograms (Fig. 2) using a Fast Fourier Transform size of 1024 points (Hamming window) with 50% overlap.

The data were used to report the daily presence or absence of sperm whale clicks, and high frequency delphinid clicks and whistles or pulsed calls (or 'burst-pulses') for each station. At least two clicks were required to confirm a sperm whale acoustic encounter. The manually annotated daily presence/absence of sperm whale and delphinid calls was binned by month and analyzed for temporal patterns. Each monthly time series was normalized by the number of sampling days within each bin. The data was used to assess seasonal and annual variability in the sperm whale and delphinid occurrence patterns.

Because of the PAL's sampling scheme, more common species in the deployment area typically take up most of the available sound bites and thus reducing the detection likelihood of lesser common species. Therefore, the relationship between sperm whale and other odontocete detections was investigated. All detections were grouped into three categories: (a) only sperm whale signals present in the sound bite, (b) only delphinid signals present in the sound bite, and (c) both sperm whale and delphinid signals present in the sound bite. In a second step, the occurrence of each category throughout the entire sampling effort was investigated.

In addition, the number of vocalizing sperm whales was estimated for each sound bite containing sperm whale vocalizations. Discriminating individual sperm whales involved manually grouping at least two similar usual clicks into single click trains. Clicks were grouped based on ICI, amplitude, and frequency characteristics (Fig. A1; Appendix) (Ward, 2002). Vocalizing sperm whales were classified into three categories: (a) 1, (b) 2, and (C) 3+ animals.

Operator error at Pylos, assessment of biases

At Pylos, an operator error occurred when the unit was programmed which resulted in a reduced sound bite duration of 2.5 s (instead of 4.5 s) for data recorded during the first 9 months of the deployment (November 2008 – July 2009). With an average ICI of about 0.7 s, at least two sperm whale usual clicks should have been recorded in the shorter sound bites still allowing for the identification and classification of the species. However, to evaluate the potential reduction in the analyst's ability to detect sperm whales in the shorter sound bites, a resampling experiment was conducted using 103 sound bites of 4.5 s duration containing sperm whale signals that were recorded in 2010. From each of these 103 sound bites, 2.5 s of continuous data were randomly extracted and re-analyzed. Results were compared to infer potential biases in detection performance.

Modelling sperm whale detections

Temporal patterns in sperm whale acoustic occurrence, and effects of both non-target species detections and the shorter duration sound bites, were evaluated using a generalized linear model (GLM) in R software (R Core Team, 2017). Logistic regression with a logit link function was used with the 'glm' function in the R package 'stats' to model sperm whale acoustic presence in each sound bite throughout the sampling period as a function of four predictor variables. The presence/absence of sperm whale clicks in each recording was used as the response variable (SW). To investigate seasonal patterns, month or season, defined as winter (December-February), spring (March-May), summer (June-August), and fall (September-November), were included as categorical explanatory variables in different models. In each GLM model, the presence/absence of delphinid signals (DELPH) was included as categorical explanatory variable. A binary dummy variable (SB) indicating the duration of the sound bite (0: 4.5 s, 1: 2.5 s) was included as a predictor to test potential effects of the reduced recording effort on the sperm whale detectability. The Akaike Information Criterion (AIC) was used for model selection.

Ambient sound levels

To assess baseline ambient sound levels for both study areas, calibrated spectrum levels stored by the PAL were analyzed. To assess the geographic variation in ambient sound levels, spectral probability density plots (SPD) were generated for both locations (Merchant *et al.* 2013). The PAL spectral data provided location-specific information on typical sound level distributions for the monitored frequency band (0.5 – 50 kHz). The 1^{st}, 5^{th}, 50^{th}, 95^{th}, 99^{th} percentiles were computed for the available data sets. In addition, median daily values of ambient sound levels at 0.9 kHz and 3 kHz were compared between the two study areas and analyzed for seasonal patterns.

Median daily wind speed values from the POSEIDON buoys (http://env1.hcmr.gr/db_poseidon/) at Pylos and Athos were used to relate ambient sound levels to prevailing weather conditions. As the wind speed data from the Athos buoy were only available for the first 50 days of the deployment, additional data collected by the Hellenic National Meteorological Service (EMY; http://www.hnms.gr/emy) on Limnos Island (39.92º N, 25.24º E; closest anemometer to Athos) was included in the analysis. Cross-correlation function (CCF) plots of the wind speed and the 0.9 kHz and 3 kHz sound levels at each site were examined to assess the relationship between ambient sound levels and weather conditions. For Athos, a CCF plot of the wind-speed time series from the two data sources (POSEIDON buoy and EMY) was examined to evaluate the similarity of the data sets.

Detection range

An important consideration when interpreting the results of PAM studies is the effective monitoring radius. The detection distance of a target signal depends on factors such as the source level, the ambient sound levels, bathymetry, the water column properties, and the detection threshold (Au and Hastings, 2008; Helble et al., 2013). The average detection range of sperm whale clicks (specifically the low-frequency omnidirectional part) was modeled for both locations and investigated for temporal and spatial variability. For this purpose, the variation of sperm whale usual clicks' detection range between seasons at each location was assessed and compared among sites. Seasonal sound speed profiles for both station locations were downloaded from the World Ocean Database 2009 (WOD09, 2018). A BELLHOP model (Porter & Bucker, 1987) was applied to the data to estimate the propagation range of the omni-directional, low-frequency part of the sperm whale usual clicks. Detection distances were modeled for sperm whales vocalizing at 300 m and 900 m depth at Pylos, and 300 m depth at Athos. The usual clicks' source level was assumed to be 155 dB re 1 μPa^2/Hz at 3 kHz (Zimmer *et al.*, 2005). The required ambient sound levels at 3 kHz for each season and location were extracted from the spectrum level data collected by each PAL (see previous section). The PAL's detection threshold of 12 dB was added to the ambient sound levels to estimate the detection distance.

Results

Acoustic detections

In total, 4711 sound bites (4114 from Pylos and 597 from Athos) were collected during the 503-day observation period between 5 November 2008 and 8 July 2010.

Pylos Station

Sperm whales were present at Pylos during all months of the year except October (no data was collected for this month) (Fig. 3). Sound bites were recorded during 479 out of 497 deployment days. Out of the 4114 total sound bites recorded at Pylos, 235 contained sperm whale vocalizations (5.7%). Sperm whale acoustic signals were recorded on 62 days (13%) and 17 out of the 19 months with observations (Fig. 3). Most sperm whale detections were of usual clicks, but creaks and codas were also detected. It was not possible to verify the occurrence of slow clicks because the ICI associated with this signal type exceeded the duration of the recorded sound bites. Two types of codas were recorded: the 'progressive' or 'expanding' coda type (Weir *et al.*, 2007; Frantzis & Alexiadou, 2008) were detected in September 2009, and the typical '3+1' type (Pavan *et al.*, 2000; Frantzis & Alexiadou, 2008) in March, April, and May 2010. The sperm whale detections did not show any obvious seasonal pattern over the course of the study (Fig. 3). However, slightly increased detection rates occurred during the spring and early summer months (March until July) in both 2009 and 2010. No sperm whales were detected in December 2009 and July 2010, but their presence was confirmed in December 2008 and July 2009.

The delphinid detections included click trains, burst-pulse calls and whistles. At Pylos, delphinid vocalizations were detected consistently throughout the sampling period during 390 of 479 days (81.4%). Whistles were detected during only 78 out of 479 days with recordings (16.3%) (Fig. A2; Appendix). Out of the 4114 total sound bites recorded at Pylos, 2123 contained delphinid vocalizations (51.6%) and most of the remaining recordings contained anthropogenic noise attributed largely to nearby vessels. Of the 2123 sound bites with delphinid detections, 1995 contained exclusively clicks (94 %) and 128 contained whistles with and without clicks (6%). Delphinid calls did not show a consistent seasonal pattern, but the number of detections dropped by almost 40% from January to March 2009. The lowest detection rates were noted for September 2009. Detection rates remained consistently high throughout 2010 (Fig. 3).

In many cases, sperm whale clicks and delphinid signals were detected within the same sound bites (Fig. A3; Appendix). Specifically, of the 235 sperm whale detections, 45% contained both sperm whale and delphinid signals (55% contained exclusively sperm whale vocalizations). The recordings were also analyzed for sperm whale group sizes. Results indicated that groups of at least three sperm whales were detected in March, April, June, July, and September 2009, and from February through June 2010; while individuals and groups of two animals were detected during all months of the year (Fig. 4). Most detections with more than one individual occurred during the spring and summer months, while fall and winter exhibited mostly detections of individuals (Fig. 4).

Athos Station

Between November 2008 and July 2009, 597 sound bites were recorded at Athos. Detections occurred on 139 days out of 192 sampling days. Even though many odontocete acoustic signals (not classified to species level) were recorded throughout the deployment period, no sperm whale acoustic presence could be confirmed. Delphinid clicks, burst pulse calls, and whistles were identified in 373 sound bites (63% of the recorded sound bites). Exclusively delphinid clicks were recorded in 266 sound bites (71% of the sound bites containing delphinid signals) while pulsed calls with and without clicks were detected in 107 sound bites (29%). The remaining sound bites contained anthropogenic noise, most frequently cavitation noise emitted by nearby vessels. The click detections corresponded to 108 days of delphinid presence (78% of the sampling days), and the whistle detections (often recorded with clicks) were noted on 58 days (41.7%). Because of the shorter observation period, information on seasonality of delphinid occurrence patterns at Athos is limited. However, results indicated that for the observation period, the number of detections was increased during the winter months December and January. (Fig. 3 top panel).

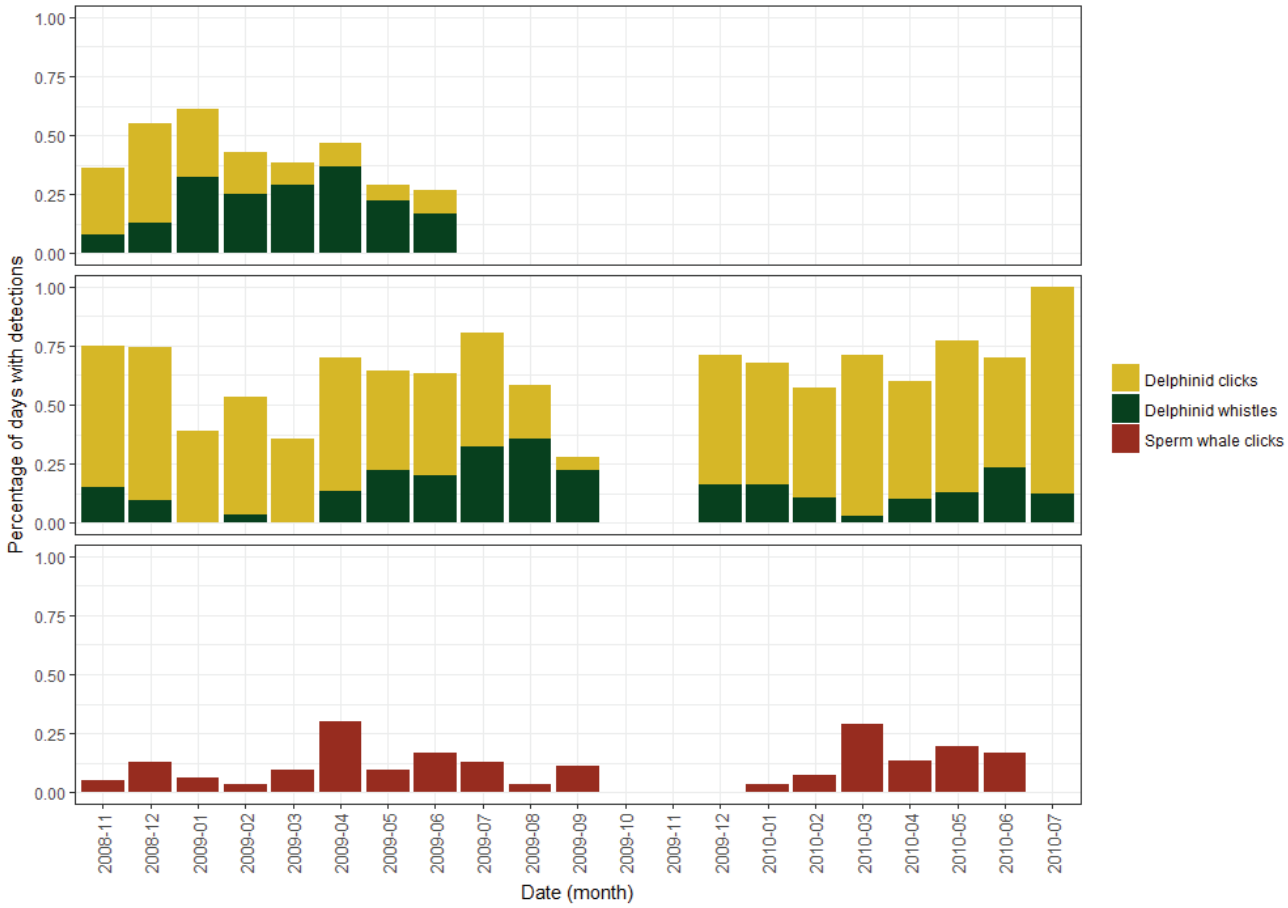

Fig. 3: The normalized monthly sperm whale and delphinid (clicks and whistles) acoustic detections at both Athos (panel on the top) and Pylos Station (middle and bottom panels), in the Eastern Ionian and the North Aegean Seas. Sperm whale clicks were only detected at Pylos. The percentage of days with sperm whale detections per month are shown for the sampling period, November 2008 - July 2010. The highest number of days with sperm whale detections at Pylos was recorded in April 2008 (0.3).

Investigations of detection biases due to shorter sound bites

The data set that included the 2.5-s sound bites had also an issue with electronic noise, which resulted in frequent false positive detections that reduced the number of useful sound bites by approximately 50%. Only 46% of the stored sound bites contained sperm whale or delphinid signals. The analysis of the resampled sound bites from the 2010 data set showed that in 81 instances (79%) the sperm whale presence could still be identified in the shorter duration sound bites. However, the results clearly indicated that the reduced duration of the sound bites resulted in an underestimation of sperm whale detections. Because of the additional electronic noise issue, the available data could not be corrected for potential missed detections.

Modelling sperm whale acoustic occurrence pattern

The model that included the months of the year had the lowest AIC score and was selected over the model with the seasons. However, both models revealed a significant negative impact on sperm whale detectability in the 2.5-s sound bites. Additionally, both models indicated a significant negative relationship between the detectability of sperm whales and the detection of any delphinid acoustic signal. Overall, the model with month, SB, and DELPH as predictor variables had the lowest AIC, and was selected as the best model. The best model was used to predict the temporal variability of the probability of sperm whale detections conditional on the absence of delphinid acoustic signals in the sound bites and the use of 4.5-s long sound bites. The model predicted the lowest detection probability for August and January and the highest detection probability for September (Fig. 5). Higher probability was also predicted for March, April and June (Fig. 5). No data were available for the month of October for any of the sampling years.

Ambient sound levels

The ocean ambient sound level analysis provided a high-level picture of the variability in ambient sound levels in the Ionian Sea and the North Aegean Sea throughout the deployment duration. In addition, these data were used to assess the detection range of sperm whales at Pylos and Athos. The empirical probability density plots

Fig. 4: The number and proportions of recordings in a day (counting all sound bites) with each class of sperm whale counts ('1', '2', and '3+') in a weekly (top figure) and monthly (bottom figure) scale respectively for the entire duration of the sampling effort. Note that only the months that included sperm whale detections are shown. Since November 2008 until end of September 2009, the sound bites used were of half duration because of an operational error.

(Fig. 6) indicated that the median (50th percentile) spectrum levels at the 0.9 kHz (indicative of shipping activity) were about 64 and 59 dB (re 1 μPa^{2}Hz^{-1} throughout unless otherwise mentioned) at Pylos and Athos, respectively (grey dashed lines in Fig. 6). The SPD plots also showed that the mean ambient sound levels at the low frequency where sperm whales clicks are omnidirectional (3 kHz, grey solid arrows in Figure 6) were 55 dB at Pylos and 50 dB at Athos. It should be noted that the SPD levels for Pylos and Athos should not be directly compared because the data sets encompass different deployment durations.

Seasonal variability of daily sound levels was significant at both sites (Fig. 7). At Pylos, median (50th percentile) levels at 0.9 and 3 kHz were 4 dB and 5.5 dB higher in the winter compared to summer (0.9 kHz: 53 dB [1%], 76.5 dB [99%]; 3 kHz: 43.6 dB [1%], 69.2 dB [99%]). At Athos, median levels were about 7 dB (0.9 kHz) and 9 dB (3 kHz) higher during the winter months (0.9 kHz: 49.6 dB [1%], 69.4 dB [99%]; 3 kHz: 40.2 dB [1%], 62.8 dB [99%]). The median daily ambient sound levels at Pylos were 2-3 dB higher on average compared to Athos.

The observed seasonal patterns in sound levels at both frequencies (0.9 kHz and 3 kHz) were primarily related to non-biological sources. The CCF plots revealed a 68% and 85% correlation (zero lag) between the daily time series of the median wind speeds and the Pylos am-

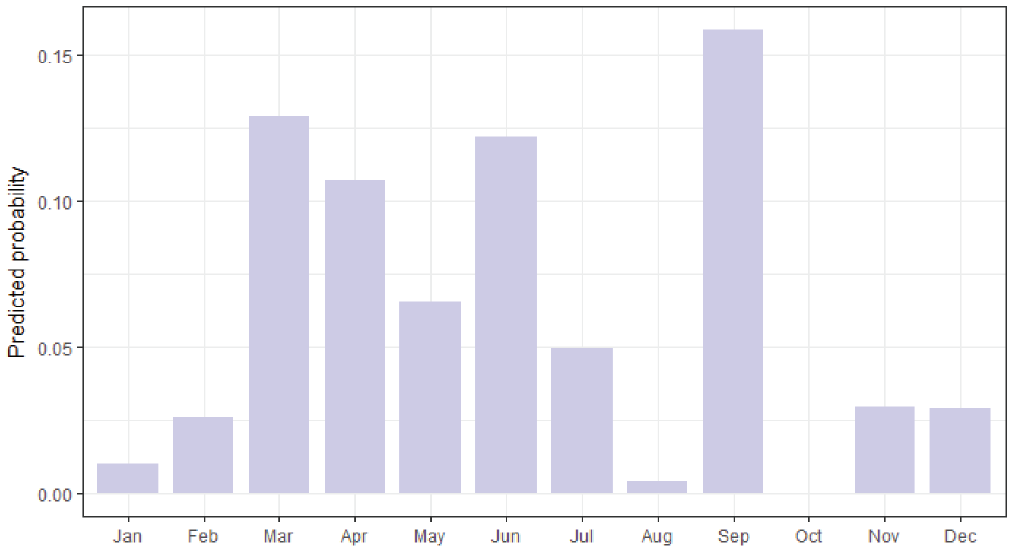

Fig. 5: The variability per month of the predicted probability to detect sperm whale clicks in a single sound bite at Pylos Station. These values represent the GLM model predicted results where we accounted for the effect of month, and conditioned for the absence of detections of delphinid sounds and the use of full 4.5-s sound bites.

bient sound levels at 0.9 kHz and 3 kHz, respectively. For Athos, the wind speeds measured at Limnos meteorological station showed a 57% and 75% correlation with the ambient sound levels at 0.9 kHz and 3 kHz (zero lag), respectively. CCF plots using wind speeds measured at the Athos buoy showed 88% and 93% correlation with the ambient sound levels at 0.9 kHz and 3 kHz (zero lag), respectively. Additionally, there was a high correlation between the wind speed values measured by the Limnos anemometer and the Athos buoy (86%, zero lag) indicating that the Limnos data is representative of the wind conditions at Athos.

Detection range

BELLHOP models were used to estimate the detection range of sperm whale usual clicks (low-frequency omnidirectional part). Results indicated seasonal detection radii of 13-22 km from the PAL deployed at Pylos, and 15-22 km from the PAL deployed at Athos (Table 1). Results indicate changes in the maximum detection ranges between seasons and for different depths of the simulated vocalizing whale (Table 1). At Pylos, the farthest detection ranges were modeled for summer (22 km) while no variability was observed between winter, spring and fall (13 km and 15 km for the 900 m and 300 m dives, respectively). The lowest median ocean ambient sound levels at 3 kHz were also measured in summer at Pylos (55 dB). At Athos, smaller detection ranges were observed for winter (15 km) and farther ranges for spring (22 km). These results corresponded to the seasonal highest and lowest median ambient sound levels measured at 3 kHz (54 dB and 44 dB). No data was available from Athos to assess the variability of ambient sound and detection ranges during summer and fall. A comparison between the two sites showed that similar ambient sound levels resulted the same detection ranges (Table 1). Overall, the maximum variability in detection range between the 300 m and the 900 m dives was observed in summer (9 km of difference); very low variability in detection ranges was observed in winter, spring and fall (2 km of difference; Table 1).

Discussion

Sperm whale presence

Autonomous passive acoustic recorders were deployed at two locations in the eastern Mediterranean Sea for which only limited data on marine mammal occur-

Table 1. The variability of sperm whale click propagation range at Pylos and Athos Stations for different seasons. We used a simulation of usual clicks (with 155 dB re 1 μPa^2/Hz source level at 3 kHz) emitted at 300 m and 900 m depth for Pylos, and 300 m for Athos. In Athos, complete ambient sound data were available only for the winter and spring seasons.

	Propagation range [km] (Ocean ambient sound levels [dB re 1μPa^2/Hz])		
	ATHOS	**PYLOS**	
Whale depth	*300 m*	*300 m*	*900 m*
Winter	15 (66.2)	15 (67)	13 (67)
Spring	22 (61.5)	15 (64.4)	13 (64.4)
Summer	-	22 (61.4)	13 (61.4)
Fall	-	15 (63.5)	13 (63.5)

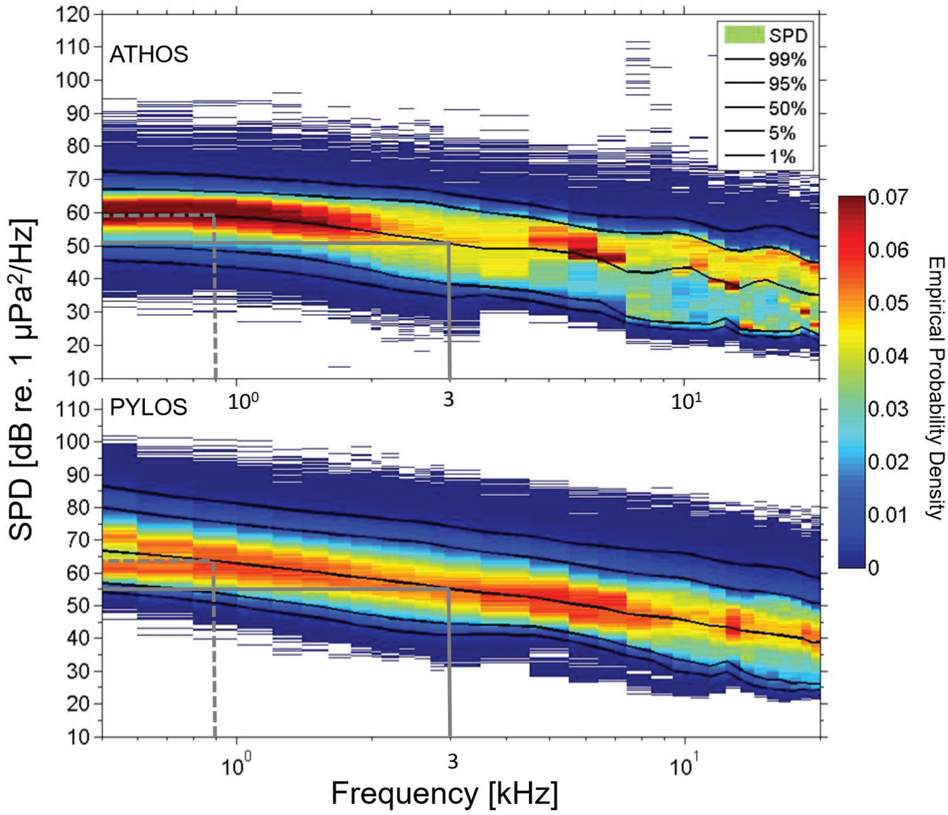

Fig. 6: Spectral probability density (SPD) plots for the stations of Athos (top) and Pylos (bottom) calculated by the almost continuous records of individual spectral data. The colors indicate the likelihood of a given spectral level in a specific frequency band. The 1%, 5%, 50%, 95%, 99% percentiles are shown in this order with black contour lines from the bottom upwards. The solid grey arrows connect the median (50^{th} percentile) sound level to the frequency where sperm whale vocalizations are omnidirectional (~3 kHz). The dashed grey lines connect the median sound level to the frequency at 0.9 kHz, below which ambient sound levels are indicative of shipping activity

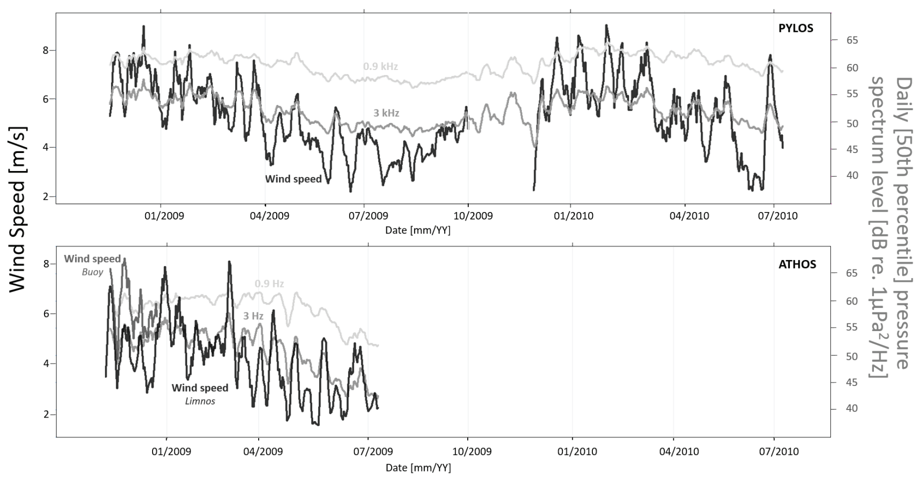

Fig. 7: Seasonal patterns of the daily median (50^{th} percentile) 0.9 and 3 KHz spectrum levels and the wind speed in Pylos and Athos. All lines are smoothed with a 7-day moving average.

rence patterns exist (Mannocci *et al.*, 2018). Data analysis was challenging because of the duration and, at times, quality of the acoustic recordings. Nevertheless, the results provided valuable information on temporal occurrence patterns of cetaceans in the Greek Seas between November 2008 and July 2010. The results revealed that sperm whales were present during all seasons at Pylos, including the winter months. In most cases, more than one individual was detected in the recorded sound bites.

For the Hellenic Trench, the model results suggested a higher probability for sperm whale detections during late spring to early fall and a lower probability for the winter months. Throughout the winter months, a high number of delphinid detections was registered. The PAL's mode of operation likely contributed to lower sperm whale detections during this period. The model indicated the highest probability for a sperm whale detection to occur for the month of September. This was also the month with the lowest number of delphinid detections. In addition, September contained a high percentage of detections with sperm whale groups of three or more individuals (Fig. 4), which may have increased the detection probability for sperm whales during this period. For these reasons, the reported sperm whale patterns are biased by the presence of delphinids and possibly by seasonal changes in sperm whale group sizes. Overall, the number of sperm whale detections reported for Pylos likely significantly underestimated the actual number of days that sperm whales were present at this location.

The absence of sperm whale detection from Athos was also largely unsurprising. Only a few sperm whale sightings and strandings have previously been reported for other parts of the Aegean plateau (Frantzis *et al.*, 2003). More recent PAM studies in the area failed to detect sperm whales (Ryan *et al.*, 2014). A plausible explanation for the absence of sperm whales at Athos is the shallow water depth (400 m). Sperm whales show clear preference for deeper habitats with steep bathymetric gradients (shelf breaks, seamounts, and canyons; Pirotta *et al.*, 2011; Frantzis *et al.*, 2014). The most frequent acoustic detections at Athos were associated with the presence of Risso's dolphin (*Grampus griseus*), which tends to inhabit the upper part of the continental slope habitat (Praca & Gannier, 2008).

Sperm whale detection range and ambient sound levels

A comparison of the two sites showed that the detection ranges of sperm whale usual clicks were the same between Athos and Pylos. Thus, the lack of sperm whale detections at Athos could not be attributed to unfavorable sound propagation conditions. At both sites, the largest variability in propagation distances (15-22 km) occurred between seasons and was driven by differences in ambient sound levels. Additionally, results from Pylos indicated that clicks emitted at 300 m during all seasons propagated farther than clicks produced at 900 m. Overall, during summer, depth of the vocalizing animal had the largest impact on detection distance (difference of 9 km; Table 1). During winter, spring and fall, the depth of the vocalizing animals had a minor impact on detection range (difference = 2 km). These differences are a result of the seasonal variability in the sound speed. The seasonal variability in ambient sound levels measured at Pylos and the corresponding variability in detection ranges likely contributed to biased sperm whale occurrence patterns (e.g. increased detection range during the summer would allow for a higher number of sperm whales to be detected). Overall, the detection range predictions agree with previous results from the Mediterranean Sea (André *et al*., 2011).

At both sites, the seasonal variability of ambient sound levels at 3 kHz was strongly correlated with wind speeds. This relationship was weaker at frequencies below 1 kHz, indicating that other sound sources, such as shipping, contributed to the sound levels at these frequencies. In fact, during the summer, ambient sound levels at the shipping-relevant frequency (0.9 kHz) were up to 10 dB higher at Pylos compared to Athos. This was not surprising since shipping activities of large vessels are lower at Athos. Additionally, shipping activity in the Greek Seas typically intensifies during the summer months. Pylos, in particular, is located in the vicinity of a major shipping lane and marine animals in the Hellenic Trench are exposed to higher ambient sound levels.

The sperm whale population and their habitat in the Greek Seas are in need of targeted conservation efforts. No management actions for the protection of the species have been implemented by the Greek government. This study confirms the high importance of the Hellenic Trench for this small population. The proposed oil and gas exploration activities in that region, including seismic surveys and potentially drilling, could impair vital sperm whale life functions related to foraging, breeding, and nursing. In addition, the busy shipping lanes increase the risks of ship strikes. Passive acoustic monitoring is an efficient tool to cost-effectively study vocal cetacean species and anthropogenic noise levels for extended periods. The large data gaps reported for the eastern Mediterranean Sea (Mannocci *et al.*, 2018) can effectively be bridged with increased use of passive acoustics. In addition, acoustics is species-agnostic and can be used to monitor a wide variety of marine animals (cetaceans, fish, and crustaceans) simultaneously. An important research goal should be the establishment of long-term acoustic stations in the Greek Seas to monitor for shifts in ambient sound levels and cetacean occurrence patterns. This work also demonstrates that the PAL in its current configuration lacks the ability to document most fine-scale temporal occurrence patterns of cetacean species. With limitations in battery and memory capacity, the PAL allows long-term recordings of odontocete signals (high frequency sounds that require large memory) that are collected under a subsampling strategy rather than a continuous sampling scheme. The PAL's daily quota of acoustic files makes the assessment of temporal patterns in sperm whale occurrence challenging when other vocal cetacean species occur frequently at the deployment site. However, the collected data provides valuable information on year-round sperm whale presence and variability of the ambient sound levels at both sites. For marine mammal research, it would likely be better to increase the number of sound bites that PAL can store, and to not rely on the onboard detection algorithm. Instead, the PAL could store sound bites at a pre-defined interval throughout the deployment.

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APPENDIX

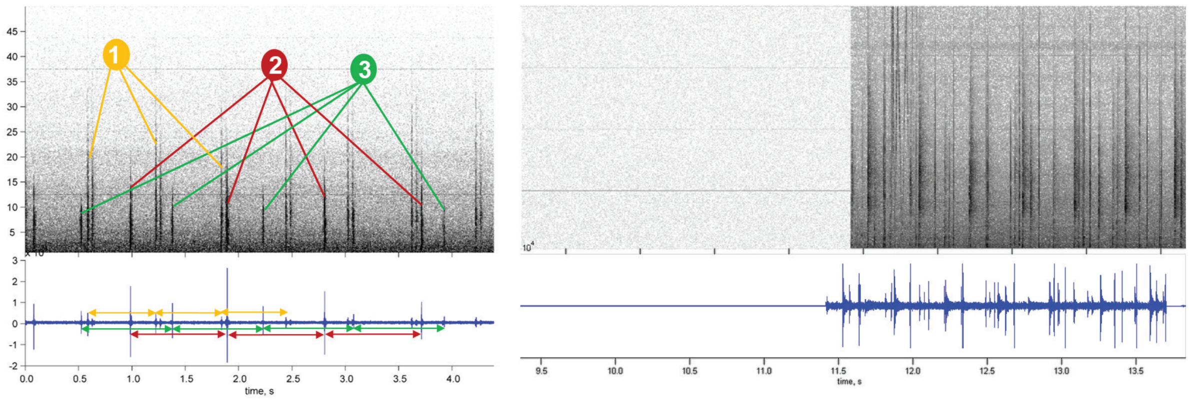

Fig. A1: Spectrograms (1024 Fast-Fourier Transform, Hamming window, 50% overlap) (top panels) and waveform (bottom panels) of sperm whale usual clicks from 3 individuals (the echo is shown for the first individual, on the left) and more than 3 animals (on the right) recorded by a Passive Aquatic Listener (PAL) (duration: 4.5 sec, sampled at 100 kHz) at Pylos Station. Individual click trains, distinguished by the waveforms, the consistent inter click intervals (ICIs), similar frequency range, and the gradual decay or increase in amplitude, are color-coded. Note that the recording on the right represents a half-duration sound bite.

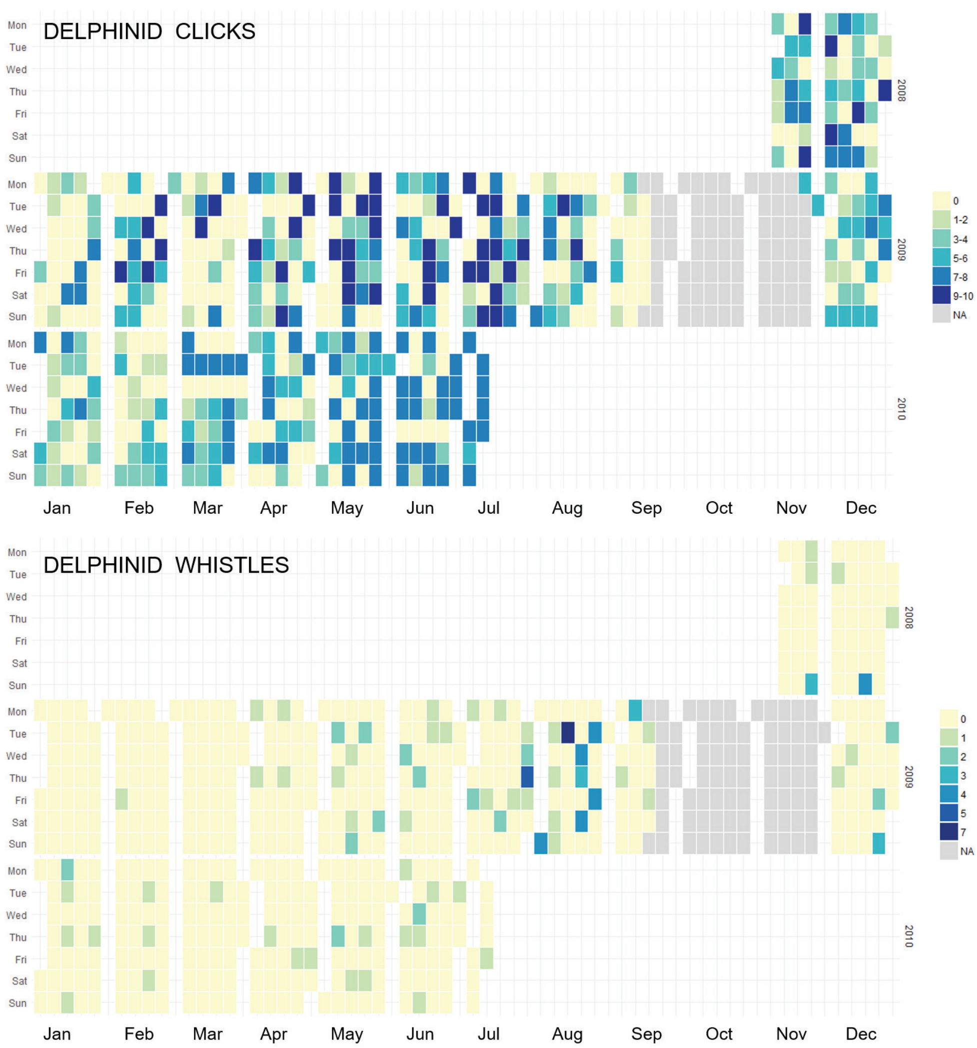

Fig. A2: Days with delphinid click detections (top panel) and delphinid whistle detection (bottom panel) at the recordings from Pylos Station over the sampling period, November 11 2008 until July 8 2010. A data gap, due to scheduled service interval of the oceanographic buoy, is shaded in grey.

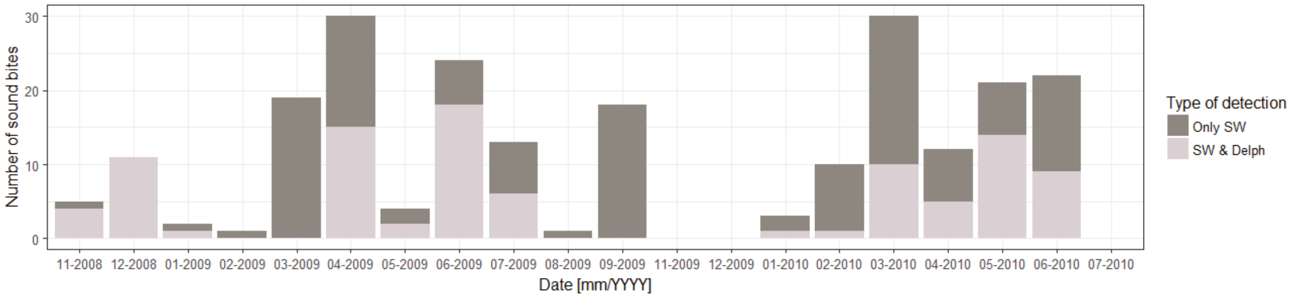

Fig. A3: The monthly variability of sound bite numbers that included sperm whale clicks at Pylos Station, grouped into two categories based on their coexistence with other odontocete acoustic signals. Each color represents a detection category: (a) only sperm whale clicks (dark grey), (b) sperm whale clicks and delphinid signals (light grey).