Sperm whale presence observed using passive acoustic monitoring from gliders of opportunity

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Running page head**: PAM gliders observing Mediterranean sperm whale presence**

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Abstract

Habitat use of the endangered Mediterranean sperm whale subpopulation remains poorly understood, especially in winter. The sustained presence of oceanographic autonomous underwater vehicles in the area presents an opportunity to improve observation effort, enabling collection of valuable sperm whale distribution data, which may be crucial to their conservation. Passive acoustic monitoring loggers were deployed on vertically-profiling oceanographic gliders surveying the north-western Mediterranean Sea during winter 2012-

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2013 and June 2014. Sperm whale echolocation *usual click* trains, characteristic of foraging activity, were detected and classified in the recordings, providing information about presence of sperm whale along the glider tracks. Widespread presence of sperm whales in the north-western Mediterranean Sea was confirmed. Winter observations suggest different foraging strategies between the Ligurian Sea, where mobile and scattered individuals forage at all times of day, and the Gulf of Lion, where larger aggregations target intense oceanographic features in the open ocean such as fronts and mixing events, with reduced acoustic presence at dawn. This study demonstrates the ability to successfully observe sperm whale behaviour from passive acoustic monitoring gliders. We identify possible mission design improvements that would lead to benefit from passive acoustic monitoring glider surveys to significantly improve sperm whale population monitoring and habitat use.

Keywords

Passive acoustic monitoring, PAM, Glider, Autonomous Underwater Vehicle, Habitat use, Mediterranean Sea, Sperm whale, *Physeter macrocephalus*

1. Introduction

Sperm whales (*Physeter macrocephalus*) are widespread across the Mediterranean Sea (Gannier et al. 2002, Drouot et al. 2004c, Frantzis et al. 2011, Notarbartolo-Di-Sciara 2014, Carpinelli et al. 2014, Lewis et al. 2018) and constitute an isolated subpopulation, genetically distinct from the Atlantic population (Drouot et al. 2004a, Engelhaupt et al. 2009). The Mediterranean sperm whale subpopulation contains fewer than 2500 mature individuals (Notarbartolo-Di-Sciara 2014) and is considered as 'Endangered' by the International Union for Conservation of Nature (IUCN) (Notarbartolo di Sciara et al. 2012). Anthropogenic pressures on this subpopulation include bycatch in fishing gear (Notarbartolo di Sciara 1990, Notarbartolo di Sciara et al. 2004), ship strike (Carrillo & Ritter 2010, Frantzis et al. 2019), ingestion of marine debris (de Stephanis et al. 2013) and disturbance by anthropogenic noise (Frantzis et al. 2003, Weir 2008) and whale watching activities (Gordon et al. 1992, Notarbartolo-di-Sciara et al. 2008). Sperm whale distribution in the Mediterranean Sea is non-uniform (Gannier et al. 2002, Boisseau et al. 2010) and influenced by oceanographic (e.g. fronts, upwellings, primary production) and topographic features (e.g. steep slopes, sea mounts) (Cañadas et al. 2002, Gannier et al. 2002, Gannier & Praca 2007, Praca & Gannier 2008, Praca et al. 2009, Pirotta et al. 2011, 2019, Frantzis et al. 2014, Virgili et al. 2019). Information on the ecology of the Mediterranean sperm whale subpopulation remains sparse and does not meet the needs of conservation managers and policy makers (Pace et al. 2014). Broader surveys are needed, increasing observation effort in non-summer months in particular (Mannocci et al. 2018) to better understand the seasonality in habitat use, and identifying key seasonal habitats to allow appropriate management of shipping and fishing activities (Rendell & Frantzis 2016).

Sperm whales are highly vocal, producing four distinct types of clicks both for echolocation and social interaction purposes. When socializing at the surface, they use short stereotyped sequences of clicks, called *codas*, to maintain cohesion in a group (Weilgart & Whitehead 1993) and mature male sperm whales produce *slow click*s of lower frequency and longer inter-click interval (Weilgart & Whitehead 1988). When foraging, they produce extremely powerful and highly directional *usual clicks* (Møhl et al. 2000, Wahlberg 2002, Zimmer et al. 2005) punctuated by lower intensity and shorter inter-click interval *creak click*s during prey capture (Madsen et al. 2002, Miller et al. 2004). Sperm whales spend a substantial amount of their time foraging. When in a foraging cycle, they produce *usual clicks* during 60% of the time (Watwood et al. 2006, André et al. 2017), starting at a depth of 100 to 200 m at the beginning of the dive, until the beginning of the ascent phase (Madsen et al. 2002, Watwood et al. 2006). *Usual clicks* are emitted in series of tens to hundreds (Wahlberg 2002), in a 10 Hz – 30 kHz frequency band with an inter-click interval varying from 0.5 to 2 seconds (Madsen et al. 2002, Møhl et al. 2003). *Usual clicks* provide a reliable indicator of sperm whale presence and foraging activity (Whitehead 2003, Stanistreet et al. 2018) and their specific features allow them to be identified and detected up to a distance of 4 to 20 km (Gannier et al. 2002, Barlow & Taylor 2005, André et al. 2017, Miller & Miller 2018).

Passive acoustic survey methods have significantly improved over recent decades and are now commonly used in cetacean observation (Pavan et al. 2008, Van Parijs et al. 2009, Samaran et al. 2010, Au et al. 2014, Caruso et al. 2015, André et al. 2017, Miller & Miller 2018). Unlike more traditional visual survey methods, passive acoustic techniques offer sustained observations during nighttime and adverse weather conditions (Barlow & Taylor 2005, Mellinger 2007, Van Parijs et al. 2009) and when the whales are sub surface. In the specific case of sperm whale detection, highly vocal and deep divers, combined visual and acoustic surveys found that acoustic techniques are much more efficient than visual techniques, as sperm whales were always first detected acoustically (Boisseau et al. 2010).

Ocean gliders are autonomous underwater vehicles, carrying various payloads to monitor the ocean. They provide high resolution (~2 h, ~2 km) hydrographic profiles (Testor et al. 2010, Rudnick 2016), performing long autonomous missions (several months to a year, and several thousand km) unaffected by extreme weather events. They are highly suitable for passive acoustic monitoring (hereafter PAM), quietly gliding unpropelled through the water column and collecting information on the acoustic properties of the water column. PAM sensors have been successfully deployed on ocean gliders for weather observation (Cazau et al. 2018, Cauchy et al. 2018) and for cetacean monitoring purposes (Moore et al. 2007, Baumgartner & Fratantoni 2008, Klinck et al. 2012, Baumgartner et al. 2013).

This paper presents a case study on the ability to use PAM glider observations as a tool to study sperm whale habitat use. We added PAM sensors to oceanographic gliders deployed in the north-western Mediterranean Sea during winter 2012 – 2013 in the framework of the DEWEX experiment (Testor et al. 2018) and summer 2014 within the REP14-MED experiment (Onken et al. 2018), recording a total of five months of acoustic data along 3200 km of glider tracks. We focused on the detection of sperm whale *usual clicks* to monitor their presence along the glider tracks. We identified 39 distinct encounter events with one or more sperm whales, along the slopes and in the open ocean, in the Ligurian Sea, the Sea of Sardinia, and the Gulf of Lion.

2. Materials and methods

2.1. Instrumentation and field operations

The platforms we used in this study are the Slocum glider, developed by Teledyne Webb Research, and the Seaglider, developed by the University of Washington and distributed by Kongsberg. They are autonomous underwater vehicles driven by buoyancy changes, controlled by pumping oil into and out of a swim bladder, inducing a vertical motion in the water column, from the surface down to 1000 m depth. Fixed wings convert the vertical velocity into forward velocity. Internal battery displacements enable pitch and roll management for direction changes. This novel way of propulsion, performing successive V-shape dives along a pre-defined trajectory, makes it a very quiet platform between the oil pumping phases that occur at the apogee and perigee of each dive (every ~2 h for 1000 m dives), able to cover ~20 km per day for up to 6 months. Along with the PAM sensor, the gliders were typically equipped with integrated temperature, salinity, pressure, oxygen, turbidity and chlorophyll fluorescence sensors.

The Slocum gliders were equipped with an externally mounted Acousonde B003A-HF data logger, developed by Greenridge Sciences Inc (Figure 1). The Acousonde is a self-contained underwater acoustic recorder comprising two hydrophones, sensors for attitude, orientation, depth and temperature, a digital recorder, and a field-replaceable battery (Burgess 2010). The core of the sensor consists of a high frequency hydrophone (capable of sampling up to 232 kHz), with a sensitivity of -204 dB re 1 V Pa^{-1}. A 6-pole linear-phase anti-aliasing filter is used, with -3 dB passband (12.5 kHz – 42 kHz) and -22 dB at 100 kHz (Figure S1a). Data are stored on a 128 GB flash memory, with a 16-bit sampling resolution. An external 3-D-cell tethered battery pack allows up to 200 hours of recording. The Acousonde operates autonomously and has its own battery, memory and programmed mission. Data processing is undertaken after the sensor is recovered. Initially developed to be attached to marine mammals (Cazau et al. 2017), it has also been used on ocean gliders (Nott 2015, Cauchy et al. 2018).

The Seaglider was equipped with an integrated Seaglider PAM system (Figure 1). This acoustic data logger is made of an HTI-92-WB hydrophone, developed by High Tech Inc., with a sensitivity of -165 dB re 1 V Pa^{-1}, associated with a WISPR v1.1 digital signal processing board with Analog Devices BF537E Blackfin CPU and HM1 digital preamplifier developed by Embedded Ocean Systems. The frequency response of the preamplifier board is designed to be approximately equal to the inverse of typical deep-water ambient noise (Matsumoto et al. 2015) (Figure S1b). The sampling frequency is fixed at 125 kHz, and the data are stored on a 512 GB flash memory, with a 24-bit maximum sampling resolution.

The glider missions took place in the north-western Mediterranean basin. The PAM equipped Slocum gliders were deployed within the frameworks of Mediterranean Ocean Observing System for the Environment (MOOSE, http://www.moose-network.fr) and the Deep Water Experiment (DEWEX) (Testor et al. 2018). MOOSE offers year-long coverage of repeated sections to monitor oceanographic variability of the north-western Mediterranean basin over a continuum of spatial and temporal scales to assess the evolution of the oceanic circulation and the anthropogenic impacts. DEWEX was targeted at better understanding the dynamics of the vernal bloom that occurs in this region after deep convection events in winter. Slocum glider "Tintin" was deployed twice in the middle of the Pelagos Sanctuary, a Marine Protected Area created to protect marine mammals (Notarbartolo-di-Sciara et al. 2008). It followed a predefined transect crossing the Ligurian Sea, (Table 1, Figure 2). Slocum glider "Hannon" was deployed twice along a predefined transect covering the open ocean across the Gulf of Lion and the westernmost slopes of the basin (Table 1, Figure 2). Each of these transects includes a mooring site, DYFAMED/Azur (43.39 °N, 7.84 °E) and LION (42.06 °N, 4.64 °E) respectively, with permanent presence of a meteorological buoy and a mooring line equipped with oceanographic sensors at several depths. For consistency, these transects will be called Gulf of Lion (glider missions GoL1 and GoL2) and Ligurian Sea (glider missions LS1 and LS2), and the associated mooring sites Lion and Azur. Seaglider SG524 "Kong" was deployed within the REP14-MED experiment, aiming to demonstrate methods for the rapid characterisation of the marine environment using a fleet of gliders (Onken et al. 2018). It followed a repeated cross shelf zonal transect at latitude 39 ° 51' N, off the western coast of Sardinia in June 2014 (Table 1, Figure 2), hereafter called Sea of Sardinia (glider mission SoS).

2.2. Acoustic data sampling and processing procedure

The four MOOSE PAM glider missions (GoL1, GoL2, LS1 and LS2) were designed for Weather Observation Through Ambient Noise (WOTAN) purposes and to optimise the battery and memory usage (Cauchy et al. 2018). The Acousonde loggers were configured to record one minute every ten minutes, at a sampling frequency of 50 kHz. This setup saved battery, enabling a tenfold increase in the monitoring duration (compared to continuous recording) to match the duration of the glider mission, and produced 27 GB of data every month. The PAM equipped Seaglider of the SoS mission was configured to record continuously throughout the glider deployment, at a sampling frequency of 125 kHz, collecting 250 GB of data in 14 days.

The recordings made when the glider is sitting at the surface are contaminated by splash sounds coming from the interaction of the glider hull with the sea surface, and the sensor oscillating between air and water. Water turbulence around the sensor induces flow noise at low frequencies, related to the glider's speed (Erbe et al. 2015, Dos Santos et al. 2016), with no discernible effects at the sound level and frequency range of sperm whale click trains. In addition, self-noise generated by the glider comes from four identified behaviours: adjustment of the battery position for attitude (pitch and roll) management, rudder movements for heading adjustment (Slocum glider only), modification of the bladder volume for buoyancy management, and use of the altimeter. Using the metadata provided in the glider log files, we extracted the information about noise-generating behaviours of the glider and removed the contaminated samples from the recorded acoustic data. During the missions described here, the glider spent on average 13.1 % of the time at the surface (depth <5 m). When underwater (depth > 5 m), the glider was quiet 96.7 % of the time (Table 2). The amount of usable data, when the glider was in a quiet gliding phase, represents 84 % of the total deployment time. It is worth noting that the SoS dataset, collected using a Seaglider, presents a lower rate of quiet gliding time (74.8 %). The frequent battery movements performed during each dive for heading adjustment are the source of this increased self-noise generation. The frequency of such manoeuvres can be modified by the pilot, whether the focus is on accurate navigation or low noise emission or power consumption.

The recordings were processed manually to identify sperm whale *usual click* trains using a graphical user interface developed in Matlab (Figure 3). This tool provides two visual representations of the acoustic signal, spectrogram (40 ms Hann window, 4 ms overlap, 100 Hz frequency bands) and waveform, on which to detect sperm whale *usual click* trains. *Usual click* trains are wide-band, high-intensity with a regular ~ 0.5 s click interval, easily identified even in the presence of other cetacean clicks (e.g. dolphin) (Figure 3). The opportunity to listen to the audio was also given to the operator to dispel doubt when necessary. Each file was annotated with information of presence or absence of sperm whale clicks, and a flag added in case of identified anthropogenic noise (ship sonar, acoustic communication, acoustic trial). The whole dataset has been processed by the same operator. For evaluation purposes, a second operator processed a randomly selected subset of each dataset, representing 20 % of the glider dives, using the same tool. The classifications from the two operators agreed for 95 % of the files (Table S1).

The files recorded between two successive glider surfacing phases were then regrouped as a single glider dive, annotated as containing sperm whale clicks if a dive contained at least one file with identified presence of sperm whale clicks. Finally, we defined as an encounter an uninterrupted succession of glider dives with identified sperm whale presence. For each encounter, the duration (in hours) of the event was noted, the footprint of the encounter was estimated as the largest distance between two glider positions during the encounter (Figure 4), and a categorization as an aggregation or single individual was made. As it is not possible to get bearing information from a single hydrophone, it is difficult to differentiate sounds from several animals. We decided to limit our analysis to the identification of a single whale or an aggregation of multiple individuals. We defined as an aggregation the simultaneous detection of multiple individuals, acoustically identified as the overlap of two or more distinct sperm whale *usual click* trains.

The detection range of sperm whale echolocation clicks has been estimated to be 4 to 20 km, from moored hydrophones or towed hydrophones (Gannier et al. 2002, Barlow & Taylor 2005, Hildebrand et al. 2013, André et al. 2017, Miller & Miller 2018). In the case of glider surveys, there are no independent observation data available to estimate the detection range. The limitations in weight, size and power necessitate the use of a hydrophone of reduced sensitivity that affects the detection capacity of the system. We can therefore estimate our detection range to be no greater than the observed range from moored and towed instruments. This uncertainty does not affect our observation of the spatial and temporal distribution of sperm whale detections.

Underwater sound propagation is affected by variations in sound velocity, driven by temperature, salinity and pressure changes. Long-range propagation can occur in the deep sound channel, with sounds being refracted around the depth of minimum sound velocity without reflection loss on the seabed or the surface (Munk 1974). Measurements taken by the gliders provide contemporaneous knowledge of the local sound speed profile (0 – 1000 m), allowing estimation of its effects on sound propagation. We linearly extrapolated the sound speed profile to the full depth of the basin (2300 m) to model the refraction of acoustic rays. We modelled the propagation across depth layers of varying sound speed for acoustic rays emitted at multiple angles by sources at depths of 300 m and 1000 m (Jensen et al. 2011). The average sound speed profile observed during our winter surveys is characterised by a continuous positive gradient, refracting sounds towards the surface (Figure 5). Within the estimated detection range of sperm whale echolocation clicks (< 20 km), we expect no observable effect of the recording depth on the detection range of sperm whale clicks (Figure 5). The sound speed profile observed in June shows a strong negative gradient near the surface, a minimum around 100 m, then a continuous positive gradient to 1000 m, hence refracting up and down all sound emitted within 0 – 1000 m depth and possibly extending the detection range of sperm whale clicks (Figure 5).

2.3. Estimation of the mixed layer depth

Mixed layer depth is a metric commonly used in physical oceanography studies to quantify vertical homogeneity of the water column. Estimation of the mixed layer depth was made from measurements of potential temperature collected by the gliders, detecting strong temperature gradients along each vertical profile. We used a double criterion, looking for gradients greater than $\Delta T_1 = 0.1$ °C with the reference temperature at 10 m in the upper 300 m of the water column, and gradients greater than $\Delta T_2 = 0.01$ °C with the reference temperature at 300 m when the mixed layer depth exceeds 300 m, to account for smaller temperature gradients in the deeper layers. This method was described in a previous study using some of the same glider data sets, focusing on deep convection events in the Gulf of Lion during 2007 – 2013 (Houpert et al., 2016).

2.4. Definition of detection ratios

Observation effort was not evenly distributed with regards to location, time of day or depth, due to specificities of the mission design and glider behaviour. The GoL and LS glider surveys were specifically designed with an increased sampling effort at the oceanographic mooring Azur and Lion locations for calibration purposes. When surveying waters shallower than 1000 m, gliders need to interrupt their dives before reaching their usual dive depth (1000 m), which results in a number of recorded samples decreasing with depth.

To analyse the spatial distribution of sperm whale detections with regards to distance travelled along a glider track, we defined a detection ratio corrected for uneven geographic sampling, as the ratio between the number of dives with sperm whale detected and the total number of dives in each 5-kilometre distance bin. To analyse distribution of sperm whale acoustic presence with regards the time of day, we defined the detection ratio as the ratio between the number of files with detected sperm whale acoustic presence and the total number of samples recorded in glider quiet gliding phases in each 1-hour bin. To analyse the distribution of sperm whale click detection with regards to measurement depth, we defined the detection ratio as the ratio between the number of files with detected sperm whale acoustic presence and the total number of files recorded in glider quiet gliding phases in each 100 m depth bin. We considered only the samples collected during a sperm whale encounter.

2.5. Statistical analysis

We used generalised additive models (GAM) to assess the statistical significance of our observations. We used R version 3.6.1 (R Core Team 2019) and the package geepack (Halekoh et al. 2006), to fit binomial GAMs, with logit link function and working independence model (Pirotta et al. 2011). For the analysis of the distribution sperm whale presence at the scale of a glider dive, we considered each encounter as an independent block. For the analysis of sperm whale presence at the scale of an acoustic file (1 minute), we considered each glider dive as an independent block. Statistical significance of each variable was assessed using a Wald's test.

2.6. Glider mission SoS

Glider mission SoS was part of the wider REP-14MED experiment (Onken et al. 2018). Acoustic trials were conducted during the REP14-MED experiment, overlapping with the glider mission and in the same geographical area. Acoustic sources, emitting repeated multitonal continuous wave pulses and linear frequency modulation pulses in the 300 – 4000 Hz frequency range, were towed from 12 to 20 June 2014 by NATO Research Vessel Alliance (Jiang 2016). These can be detected on the glider acoustic recordings. Our observations do not provide enough information to study the behavioural response of sperm whale to the acoustic trials. Such a study would require measurement of the sound level received by an individual whale, and the ability to track the individual before, during and after exposure, usually obtained by tagging the whale with a PAM sensor (Curé et al. 2016). However, sperm whale behaviour is likely to be affected by such a nearby contemporaneous acoustic trial. We considered our sperm whale observation as corrupted from 12 June 2014 onward.

PAM glider mission SoS is reduced to three days before the start of the acoustic trial and is our only dataset in summer season and in the Sea of Sardinia. We therefore kept it separated from other glider missions in our analysis.

3. Results

3.1. Opportunistic observations

The addition of PAM sensors to five opportunistic oceanographic glider campaigns in the north-western Mediterranean Sea allowed us to successfully detect sperm whale acoustic presence. Over the whole dataset, we identified 39 sperm whale encounters, five of which were aggregations of two or more individuals. These detections were made during 129 glider dives out of 1599, resulting in 1011 audio recordings containing sperm whale clicks (Figure 6; Table 3, Table 4). These data confirm the widespread presence of sperm whales in the area (Gannier et al. 2002, Drouot et al. 2004c, Frantzis et al. 2011, Notarbartolo-Di-Sciara 2014, Carpinelli et al. 2014). Sperm whales were encountered during 9.4 % and 11.6 % of glider dives during missions GoL1 and GoL2 in the Gulf of Lion, 3.9 % and 7.7 % of glider dives during missions

LS1 and LS2 in the Ligurian Sea, and 16.1 % of glider dives during missions SoS in the Sea of Sardinia (Table 3).

Duration and footprint of the encounters were highly variable (Table 4), depending on the mobility and speed of both the whales and the glider. At an average whale transit speed of 3 km h^{-1} (Drouot et al. 2004b), a sperm whale would cross the acoustic detection range (10 – 40 km diameter) in 3 – 13 h, which was the case of most of our encounters with single individuals (4.2 h average). In the case of stationary whales, a glider at a typical horizontal speed of 0.8 km h^{-1} would cross the detection range in 12 – 50 h. Encounters with aggregations tended to last longer (25.4 h on average) than encounters with single individuals, suggesting that sperm whale aggregations were less mobile or spread out over a wider area. Our definition of aggregation includes the simultaneous presence of several isolated animals in the same area, within the detection range of the PAM glider. This configuration would necessarily explain encounters of longer duration and larger footprint. In the specific case of encounter #3 of glider mission GoL1 (Table 4), the glider kept its position for 60 h, performing 'virtual mooring' dives, and was able to detect an aggregation of sperm whales for 11 h with a glider footprint of only 1 km (Table 4). The encounter #1 of glider mission SoS had a footprint of 53 km (Table 4), larger than our estimated detection range, which suggests that the aggregation was either scattered over a wide area or was moving along with the glider. We cannot eliminate the possibility that the whales were curious about the glider and followed it.

3.2. Repeated glider transects

Our gliders repeatedly followed cross-shelf transects, providing information about sperm whale presence relative to the slope, defined as the closest -2000 m isobath. In the Gulf of Lion, glider missions GoL1 and GoL2 followed two cross-shelf transect lines, between the middle of the Gulf of Lion, and alternatively the northern and western slopes. Our observations show two modes of increased sperm whale presence, around ~30 km and ~100 km away from the slopes (Figure 6, Figure 7, Figure 8). In the Ligurian Sea, glider missions LS1 and LS2 followed a cross-shelf transect line between two slopes, France to the north and the island of Corsica to the south. Our observations suggest an increased sperm whale presence within ~25 km from the northern slope. Sperm whales were also found in the open ocean and along the southern slope (Figure 6, Figure 7, Figure 8). Glider mission SoS followed a cross-shelf transect between the western coast of Sardinia and the open ocean. Our observations are reduced to one long-encounter with a large sperm whale aggregation, spread from the slope to the open ocean (Figure 6, Figure 7, Figure 8). Predictions of the distribution of sperm whale presence with respect to distance to the slope and associated p values for each of the three geographical areas studied are provided in the appendix (Figure S2).

3.3. Temporal patterns

Uninterrupted monitoring over weeks to months permits fine-scale observation of sperm whale acoustic activity. We studied the distribution of sperm whale presence with time of day, for each 1-minute file recorded by the gliders. In the Ligurian Sea, sperm whale clicks were detected at all times of day during both glider missions LS1 (Jan – Feb 2013) and LS2 (Apr 2013). In the Sea of Sardinia, sperm whale clicks were detected at all times of day during the glider mission (Jun 2014). In the Gulf of Lion, sperm whale acoustic activity showed a clear circadian pattern, with decreased detection ratio at dawn, for both glider missions GoL1 (Dec 2012) and GoL2 (Jan – Feb 2013) (Figure 9). Predictions of the distribution of sperm whale presence with respect to time of day and associated p values for each of the three geographical areas studied are provided in the appendix (Figure S3).

3.4. Large scale monitoring

Gliders are often deployed as a coordinated fleet, offering contemporaneous observations in multiple geographic areas. In the winter 2013 season, such monitoring was possible during the overlap between glider missions GoL2 and LS1 in Jan – Feb 2013 (Table 1). Aggregations of two or more individuals were encountered four times in the Gulf of Lion (Dec 2012 – Feb 2013) and only lone individuals were detected in the Ligurian Sea (Jan, Feb and April 2013) (Figure 6, Table 4). It is worth noting than no sperm whales were detected during the three weeks sampled in January 2013.

3.5. Collocated oceanographic measurements

Temperature profiles collected from the gliders allow to estimate the mixed layer depth for each glider dive, used as an index to describe homogenisation of the water column. Observation during glider missions GoL2, LS1 and LS2 suggest an apparent increased sperm whale presence with deeper mixed layers (Figure 10). Glider missions GoL1 and SoS only sampled stratified water masses (i.e shallow mixed layer). Predictions of the distribution of sperm whale presence with respect to mixed layer depth obtain from the GAM and associated p values for each of the three geographical areas studied are provided in the appendix (Figure S4).

3.6. Observation from varying depth

The vertical profiling of the glider allows for observation of sperm whale acoustic presence from varying depths. Distribution of sperm whale detection ratio with regards to measurement depth was highly variable between the different deployments and showed no clear signal over the whole dataset (Figure 11a). However, the SoS glider mission showed a detection ratio increasing with depth. This dataset was dominated by one long duration encounter with a large aggregation (encounter #1: 53 hours), which was also analysed separately (Figure 11b).

4. Discussion

4.1. Sperm whale observation from opportunistic glider surveys

We deployed our PAM sensors on gliders of opportunity, whose missions were designed to collect oceanographic observations. We successfully detected sperm whale presence along the surveyed tracks. The PAM glider missions considered in this study offer a trial framework for PAM gliders as a tool for sperm whale observations and a preview of the monitoring capabilities of purposefully designed PAM glider surveys. Oceanographic gliders have been routinely deployed in the north-western Mediterranean Sea since 2005, with a specific focus on the winter season. In a near future, a similar coverage with PAM equipped glider surveys can be adapted for sperm whale population monitoring, providing long-term basin-wide observations. Repeated observation of sperm whale distribution along predefined glider transect lines can provide useful information about their habitat use (Verfuss et al. 2019). Intensive PAM glider observation during winter season can fill observational gaps such as the winter period or adverse weather conditions (Mannocci et al. 2018). Deployment of PAM gliders as a coordinated fleet can provide contemporaneous observations in multiple geographic areas to study geographical patterns.

4.2. Collocated oceanographic measurements

Oceanographic features (e.g. fronts, stratification, mixing, primary production) are a key parameter of sperm whale habitat models (Gannier & Praca 2007, Praca & Gannier 2008, Praca et al. 2009, Pirotta et al. 2011). PAM glider surveys provide collection of oceanographic profiles collocated with sperm whale detection. Deep convection events, such as the one starting in February 2013 in the middle of the Gulf of Lion (Testor et al. 2018), are associated with small scale convective plumes (<1 km diameter) characterized by significant vertical velocities (up to 18 cm s^{-1}) (Margirier et al. 2017). The surface signature of such events, cooling of surface waters, and the observed upwelling and downwelling (Margirier et al. 2017) are consistent with habitat use models made using sea surface temperature data (Praca et al. 2009, Pirotta et al. 2011).

Our observations in the Gulf of Lion covered only one winter season. We are therefore unable to conclude on the effect of the intensity of the mixing event on sperm whale distribution, nor on inter-annual variability. Our glider missions were primarily designed to monitor deep convection events, and therefore introduce a sampling bias towards an increased observation effort in deep mixed layer waters. Significance of the statistical model would benefit from correcting this bias and covering a wider variety of water column homogenisation.

4.3. Spatial distribution

The spatial distribution pattern we observed in the winter 2013 season, from contemporaneous glider missions in the Gulf of Lion and the Ligurian Sea, suggests a geographical segregation between the Ligurian Sea, where distant single individuals only were detected, and the Gulf of Lion where sperm whale aggregations were found. Sporadic encounters of single individuals in every area surveyed highlight sperm whale mobility in this part of the Mediterranean basin. Longer term observations are needed to better describe their complex distribution and migration pattern, such as their relative low presence in the Ligurian Sea in January, and the necessary regrouping between males and females for mating.

Cross shelf repeated observations in the Ligurian Sea suggest possible increased sperm whale concentration along the northern slope, not confirmed by the statistical model. This area is a well-known favourable sperm whale habitat, both for its topographic (steep slopes and canyons) and hydrographic (permanent front, upwellings) features (Gannier & Praca 2007, Laran & Drouot-Dulau 2007).

In the Gulf of Lion, the observed patches of increased sperm whale presence are not confirmed by the statistical model. The glider observations are designed to monitor an oceanographic hotspot (~ 2500 km^2) of intense deep mixing events occurring in winter, that are likely to favour prey availability and therefore favourable sperm whale habitats. Prey availability plays a key role in sperm whale distribution, as they adapt their distribution and group size to the size of prey patches (Relini et al. 2000, Jaquet & Gendron 2002, Drouot et al. 2004c, Soria et al. 2009).

4.4. Circadian pattern

Distribution of sperm whale click detection ratio with regards to time of day showed a significant circadian pattern (p-value = 6.9×10^{-7}) in the Gulf of Lion (Figure 9). Such a clear circadian pattern may suggest an adaptation of sperm whale foraging strategy to local prey behaviour (Stanistreet et al. 2018). Tag surveys have found evidence of diurnal variations of sperm whale foraging depth, linked to jumbo squid (*Dosidicus gigas*) migrating deeper during daytime in the Gulf of California (Davis et al. 2007), and warty squid (*Onykia ingens*) migrating from mid water during daytime to the bottom during nighttime in the Kaikōura submarine canyon (New Zealand) (Guerra et al. 2017). During long-term time series from passive acoustic moorings in the north-western Mediterranean Sea, various diurnal patterns have been observed. A daytime peak in sperm whale acoustic presence was reported in the north of the Gulf of Lion in all twelve months of 2012 (André et al. 2017). A seasonal shift from a constant foraging effort over day and night in summer to a nighttime peak in winter was observed in the Ligurian Sea (Giorli et al. 2016), supporting the idea that sperm whale foraging strategy is very flexible and adapts locally to environmental characteristics and prey behaviour (Stanistreet et al. 2018).

Limited time coverage of the PAM glider missions available in each geographical does not allow to conclude on the seasonality of the observed patterns, However, the contemporaneous glider missions GoL2 and LS1 (Table 1) suggest a geographical pattern in the winter season. Further observation of circadian patterns would provide valuable information on local variations of sperm whale diet and its seasonal and interannual variability.

4.5. Seasonal to inter-annual variations

No sperm whales were encountered in the Ligurian Sea during the three weeks sampled in January (Table 1, Figure 7). This does not allow to conclude on the absence of sperm whales but adds to similar observation previously reported for this month in the same region (Laran & Drouot-Dulau 2007). It is worth noting that the sperm whale detection range from passive acoustic can be affected by local phenomena increasing the background noise (e.g. ship traffic, storms). The glider surveys GoL1, GoL2, LS1 and LS2 have been previously used in a wind speed measurement study (Cauchy et al., 2018). There was no remarkable storm in January 2013 that could explain the absence of sperm whale detection.

The time coverage of the PAM glider surveys available for this study, one month in the Sea of Sardinia, three months in the Gulf of Lion and four months in the Ligurian Sea, do not exceed the intra-seasonal scale. Long-term monitoring via successive PAM glider surveys is needed to determine how the observations we made in this study vary with the seasons and through the years.

4.6. Depth distribution

We found no clear dependence of the sperm whale click detection ratio on the depth of the recording made by the glider. This result is consistent with the highly variable foraging depth of sperm whales, their constant click production throughout the dive, and the limited influence of the sound velocity profile on the detection range of sperm whale echolocation clicks. However, in the case of the SoS mission, focusing on the long duration encounter with a large aggregation (encounter #1: 53 hours), we observed an increased detection ratio with depth of the measurement (Figure 11b). This could be due to increased prey availability at depth, which would influence the foraging pattern of observed sperm whale aggregations. Specific analysis of such a large aggregation encounter, with measurement of the number of clicks detected with regards to depth, may provide more information about the foraging depth, and therefore diet, of an aggregation of whales at a certain time. The data available for this study does not allow to conclude whether this observed behaviour would be specific to this particular time and location, or representative of the general sperm whale behaviour in summer or in this region.

4.7. Sampling strategy

The PAM glider sampling strategy was not optimised for a sperm whale population monitoring activity. The speed and trajectory of our glider missions differ from the usual marine mammal survey design, introducing sampling bias that could not be corrected to estimate the sperm whale population or model its habitat. The spatial-temporal coverage of our observations was sparse, making impossible in general to conclude on whether observed patterns were geographical or seasonal and leading to large uncertainties in the statistical models. Observations from glider mission SoS must be taken with a particular care, as it was the only glider mission in its area and in a summer month (Table 1). It was also partially corrupted by contemporaneous acoustic trial activities occurring in the area and reduced to three encounters with sperm whales, twice with single individuals and once with a large aggregation (Table 4).

4.8. Acoustic detection

In this study, we limited our acoustic processing effort to visual detection of sperm whale *usual click* trains, and to a simple classification between the presence of a single individual and the simultaneous detection of several individuals. We were only interested in presence/absence of sperm whales during 1-minute samples, to demonstrate the opportunity to use PAM gliders to collect valuable data on sperm whales.

Use of onboard data processing systems is now possible on marine autonomous platforms, allowing for real time transmission of the observations. Development of an adapted automatic detection/classification system on PAM glider data would also allow to further investigate each acoustic file, to extract the number of detected clicks, number, gender and size of individuals (Caruso et al. 2015), to look for social interactions via detection of *coda* sequences.

It is worth noting that using two or more acoustic sensors would enable to collect bearing information, critical in counting, identifying and tracking individuals, analysing inter pulse interval variations (Caruso et al. 2015, Kusel et al. 2017).

5. Conclusion

This study demonstrates that the addition of PAM sensors to existing oceanographic glider missions, with mission design adjustments, offers a possible opportunity for sustained monitoring of the Mediterranean sperm whale subpopulation over the winter months for which there is clear lack of crucial data for conservation. Our ability to observe the population distribution in different geographic areas of the north-western Mediterranean Sea, across the slopes and the open ocean, highlighted the complexity of sperm whale's behaviour, foraging strategy and habitat use.

We detected isolated animals in the three areas monitored both on the slopes and in the open ocean. We observed areas in the open ocean, in the Gulf of Lion, where sperm whales were less distant and were detected at the same time from the PAM glider. The collocated collection of oceanographic measurements allowed us to identify vertically mixed waters as possible hotspots for sperm whale habitat. Continuous day and night monitoring over several months allowed identification of a circadian pattern in sperm whale acoustic presence in the Gulf of Lion, possibly linked to a specific diet or prey availability pattern.

The use of PAM sensors can expand the observation range of existing oceanographic infrastructure. Such sustained multi-disciplinary observations would allow better description of the oceanographic parameters of sperm whale preferred habitat. The opportunity for sustained long-term monitoring of cetacean population would improve behaviour description, identification of key habitat and potentially harmful interaction with anthropic activities.

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Zimmer WMX, Tyack PL, Johnson MP, Madsen PT (2005) Three-dimensional beam pattern of regular sperm whale clicks confirms bent-horn hypothesis. J Acoust Soc Am 117:1473–1485.

Tables

Table 1: Time coverage of the glider missions in the Gulf of Lion (blue), Ligurian Sea (green) and Sea of Sardinia (orange).

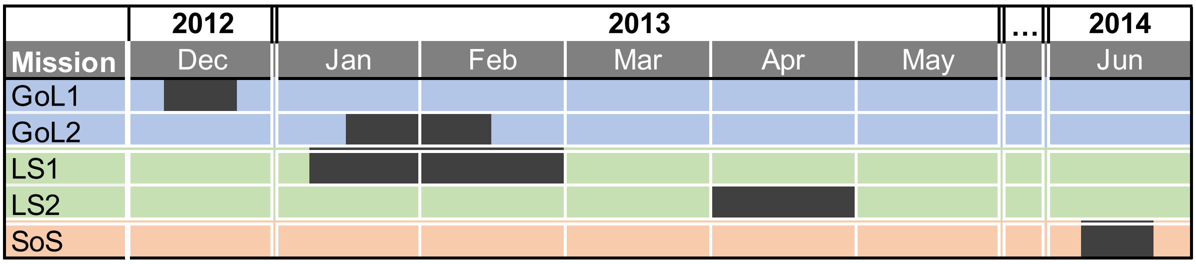

Table 2: Deployment area, platform and PAM sensor used, duration, time spent underwater and free from self-noise for glider missions GoL1, GoL2, LS1, LS2 and SoS.

Glider mission	**GoL1**	**GoL2**	**LS1**	**LS2**	**SoS**
Deployment area	Gulf of Lion		Ligurian Sea		Sea of Sardinia
Platform	Slocum				Seaglider
Sensor	Acousonde				Integrated
Days deployed	15.9	29.8	51.0	33.9	13.9
Days underwater (>5 m)	13.8	25.9	45.2	28.7	11.9
Days quiet	13.5	25.5	44.1	27.8	10.4
Days quiet (%)	84.9	85.6	86.5	82.0	74.8

Table 3: Number of files and dives available for analysis and with identified sperm whale click detected, for glider missions GoL1, GoL2, LS1, LS2 and SoS.

	GoL1	**GoL2**	**LS1**	**LS2**	**SoS**
Number of available files	1970	4350	6088	4114	5130
Files with click detection	55	214	54	102	586
Files with click detection (%)	2.8	4.9	0.9	2.5	11.4
Number of dives	139	276	560	456	168
Dives with click detection	13	32	22	35	27
Dives with click detection (%)	9.4	11.6	3.9	7.7	16.1

Table 4: Duration and footprint of each sperm whale encounter for glider missions GoL1, GoL2, LS1, LS2 and SoS. Encounters with aggregations of sperm whales are in **bold** font. "Encounter id" is the identification number of each encounter within a glider mission.

Encounter id		1	2	3	4	5	6	7	8	9	10	11	12
GoL1	Duration (h)	**5**	2	**11**	1	1	1	3					
	Footprint (km)	***5***	*2*	***1***	*1*	*1*	*1*	*1*					
GoL2	Duration (h)	1	**17**	1	7	7	**41**	1	4				
	Footprint (km)	*1*	***13***	*1*	*2*	*5*	***11***	*1*	*2*				
LS1	Duration (h)	1	5	10	1	3	8	6	11	1			
	Footprint (km)	*1*	*6*	*9*	*1*	*5*	*13*	*1*	*11*	*1*			
LS2	Duration (h)	4	4	5	5	6	1	1	8	9	4	3	1
	Footprint (km)	*6*	*5*	*5*	*5*	*4*	*1*	*1*	*5*	*9*	*6*	*2*	*1*
SoS	Duration (h)	**53**	6	8									
	Footprint (km)	***39***	*6*	*8*									

Figures

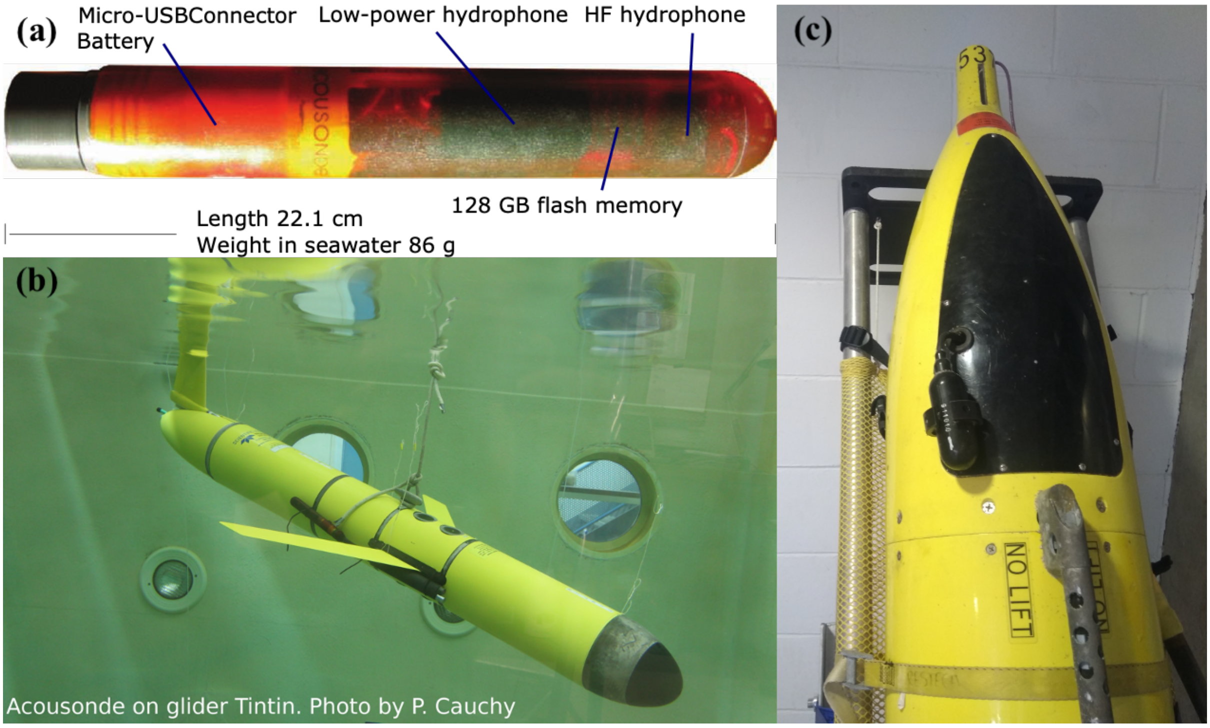

Figure 1: (a) Internal layout of the Acousonde™ and (b) experimental setup, externally attached on a Slocum glider in the ballasting tank. (c) Seaglider integrated PAM unit. Only the sensor can be seen outside the hull, the electronics is integrated in the glider's pressure housing.

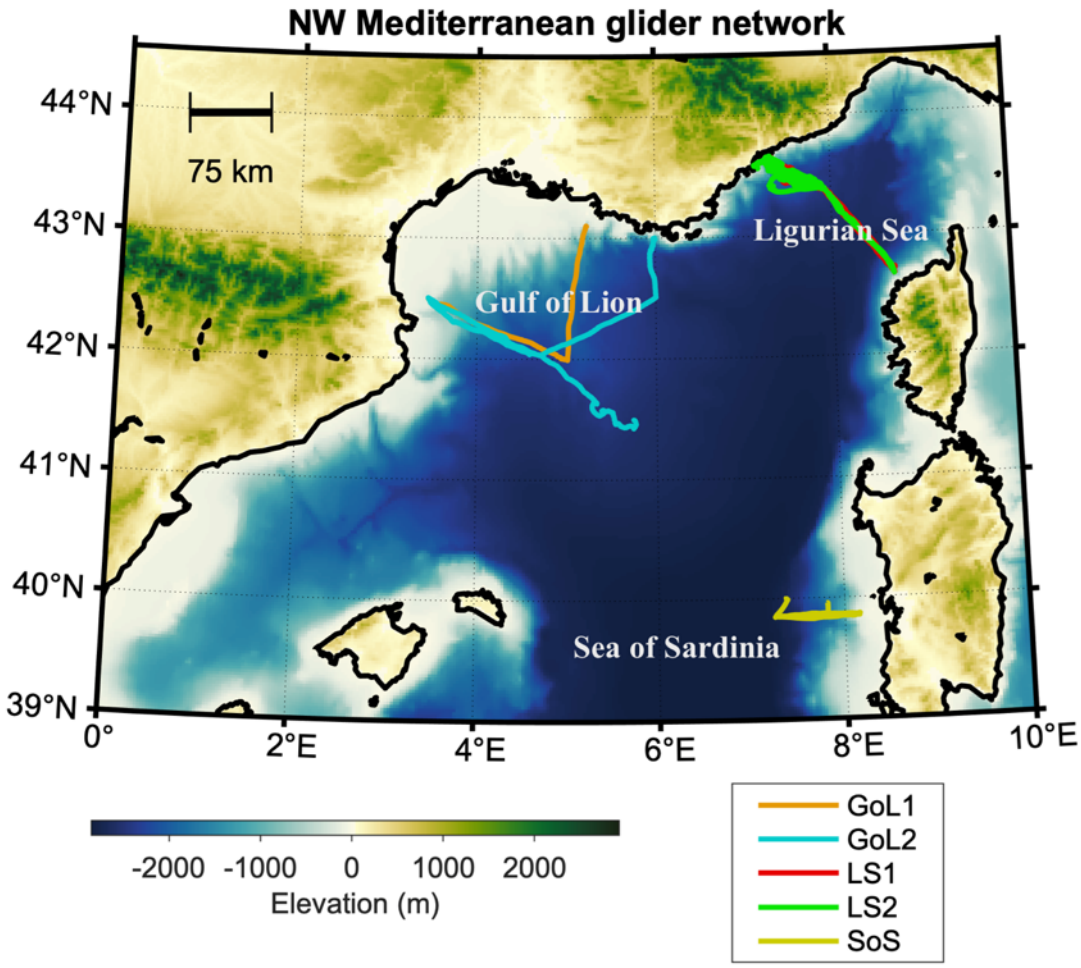

Figure 2: Map of the glider tracks. Glider missions GoL1 and GoL2 follow a predefined transect across the Gulf of Lion; Glider missions LS1 and LS2 follow a predefined transect across the Ligurian Sea; Glider mission SoS is in the Sea of Sardinia, off the Sardinian coast.

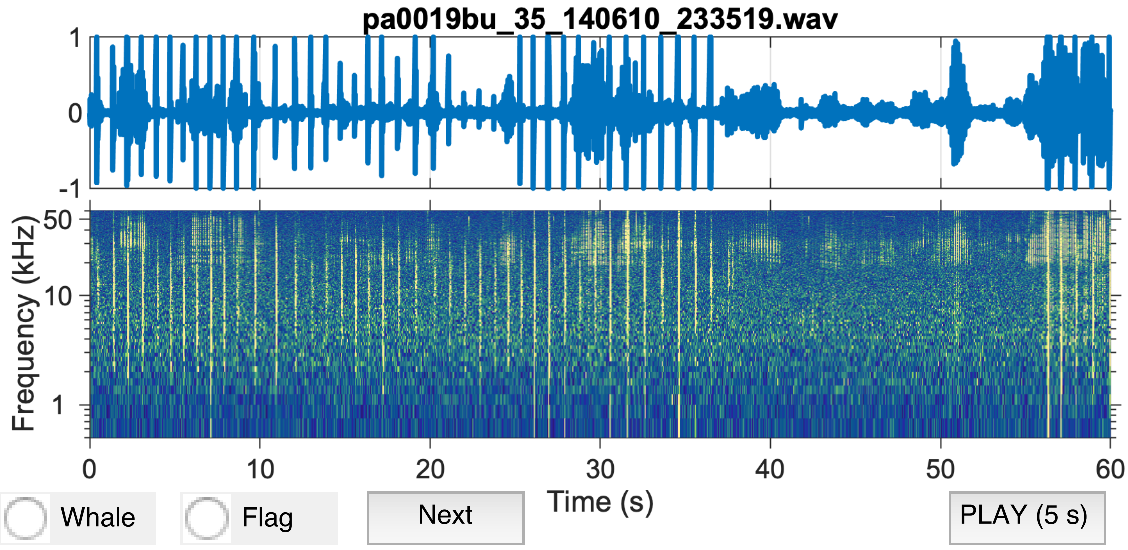

Figure 3: Graphical user interface used for visual annotation of the acoustic files. Top panel shows the acoustic signal recorded as a waveform, the bottom panel as a spectrogram (40 ms Hann window, 4 ms overlap, 100 Hz frequency bands). The operator is given the opportunity to zoom in on both panels, select and play a 5 s audio sample if needed. On this example, the wide-band high-intensity sperm whale clicks trains, at ~ 0.5 s click interval, are easily identified even in the presence of dolphin sounds (narrower frequency band, higher frequency and click rate, higher time variability).

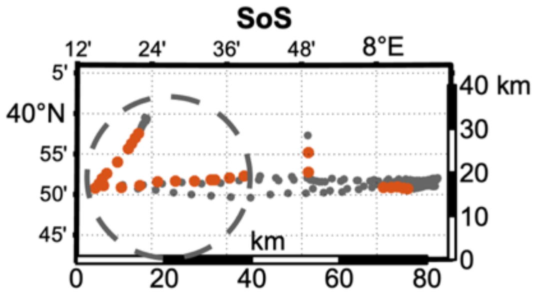

Figure 4: Schematic of footprint estimation, using as an example the first encounter with sperm whales during glider mission SoS. Glider dive locations are represented by orange dots when a sperm whale was detected, dark otherwise. The estimated footprint of the encounter is the diameter of the dashed circle, 39 km.

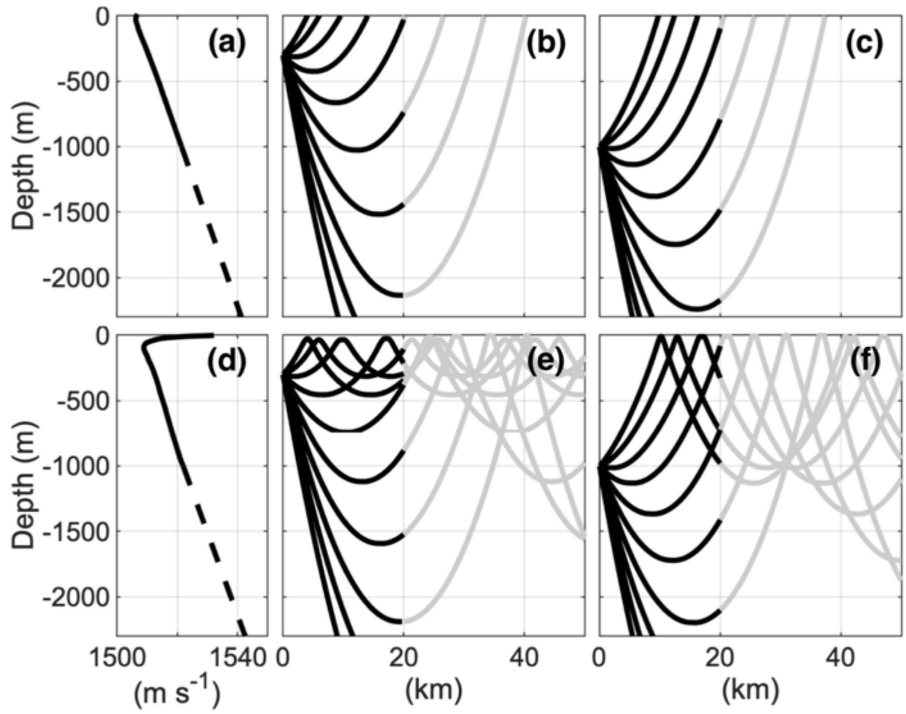

Figure 5: Average sound velocity profiles calculated from glider temperature and salinity profiles in winter (a) and summer (d), and associated effects on the refraction of sounds emitted at 300 m (b, e) and 1000 m (c, f). Only the direct paths are shown (no reflection). The linear extrapolation of the sound velocity profile at depth greater than 1000 m is shown as a dashed line. The acoustic rays are in black within the empirical sperm whale detection range (< 20 km) and grey outside (>20 km).

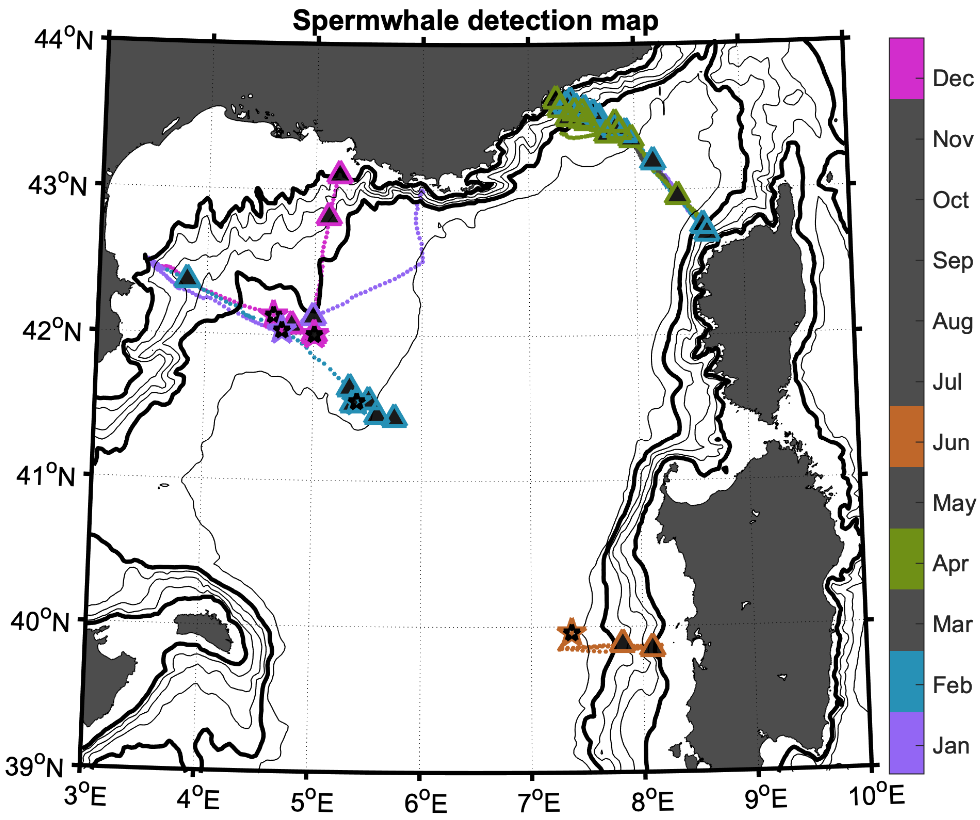

Figure 6: Sperm whale encounters detected along the tracks of the oceanographic gliders patrolling the north-western Mediterranean Sea. Triangles show single individual detections, stars show the identified sperm whale aggregations, time of year is colour coded. Bathymetry contours are shown from 500 m to 2500 m with 500 m interval. 200 m and 2000 m bathymetry contours are in bold.

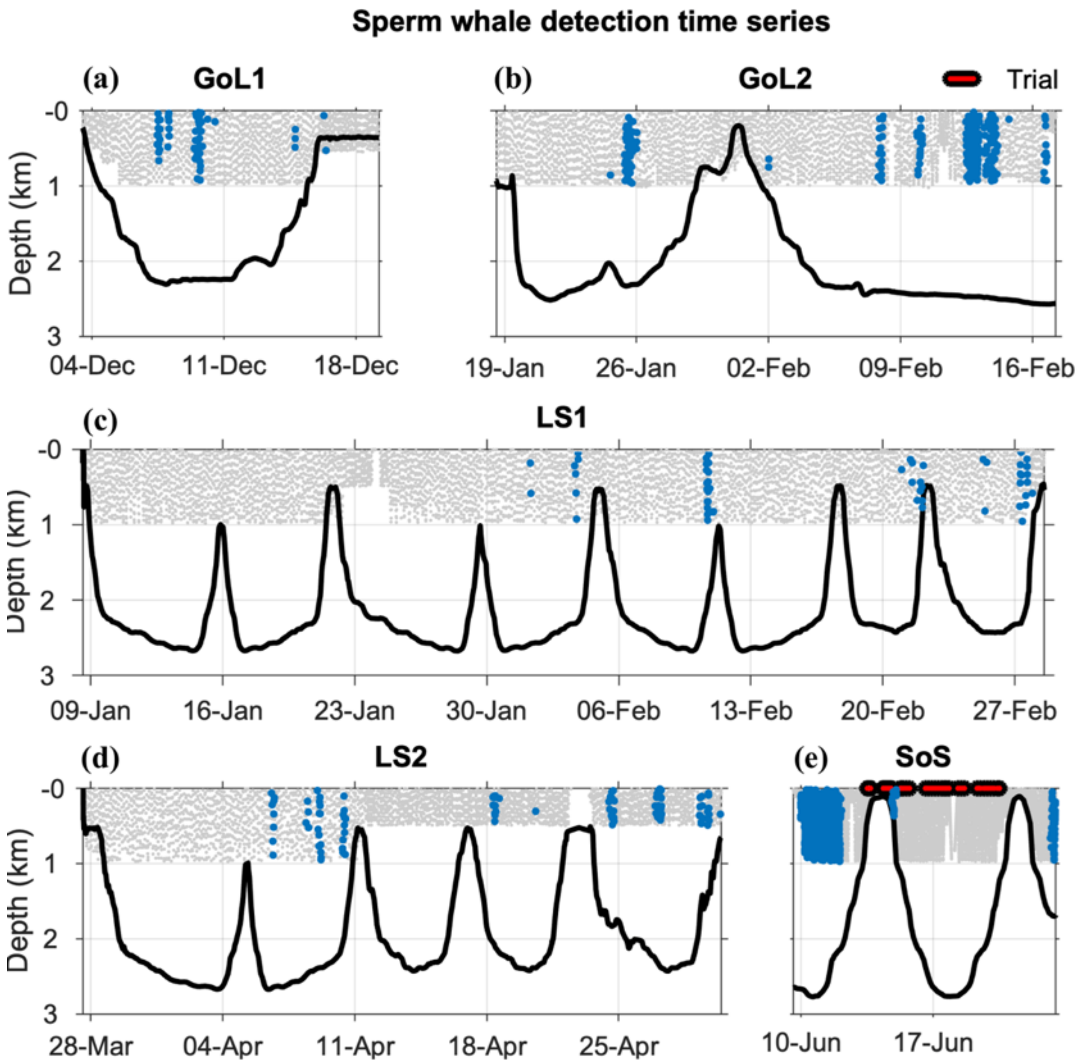

Figure 7: Time series of sperm whale click detections along each glider section, according to the depth of the detection and bathymetry. The time and depth of each recorded file is shown in grey when no whale is detected, in blue when a whale is detected. The bathymetry is shown, with the slope angle colour coded when the glider is on the slope. Detection of the REP14-MED acoustic trial activity is shown at the surface in red.

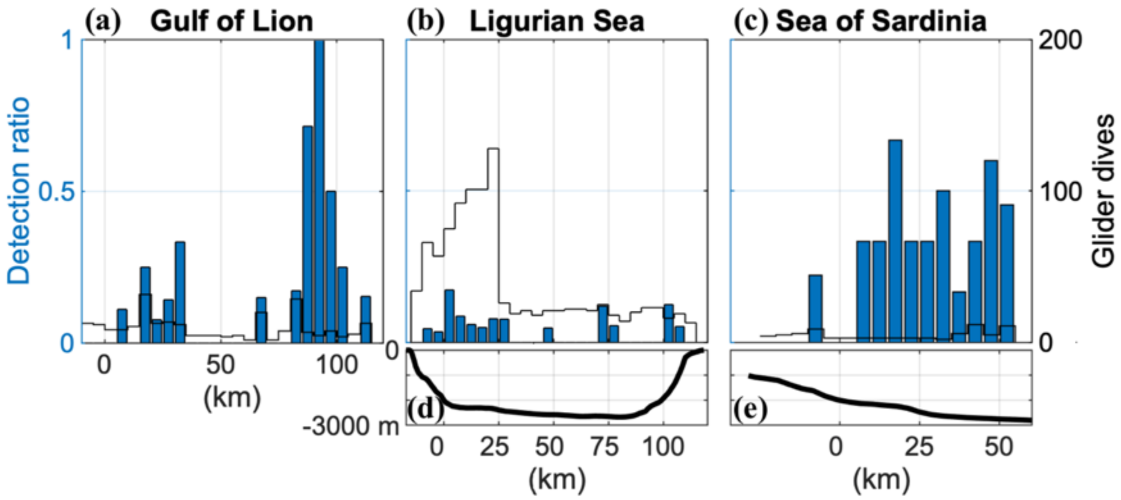

Figure 8: Number of glider dives with acoustic recording available for analysis (black line, black vertical axis) as a function of the distance to the slope in the Gulf of Lion (a), and along the repeated glider transect line in the Ligurian Sea (b) and the Sea of Sardinia (c). The bars (blue vertical axis) show the detection ratio (dives with sperm whale detection / total number of glider dives) in each 5-km distance bin. The bathymetry along the glider transect lines is shown for the Ligurian sea (d) and the Sea of Sardinia (e).

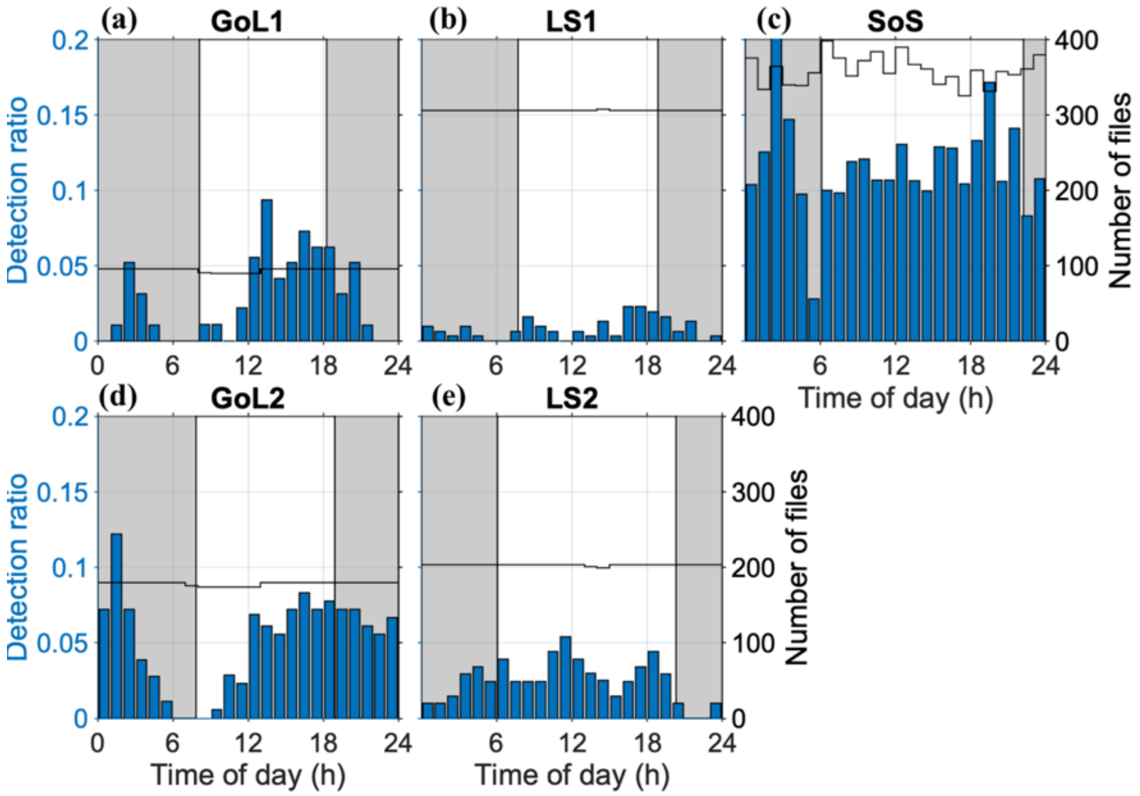

Figure 9: Number of acoustic files available for analysis (black line, right axis) per 1-hour bin. The bars (left axis) show the detection ratio (files with sperm whale detection / available files) in each 1-hour bin. Each panel represents one glider mission, arranged so that each column covers one deployment site: (a, d) Gulf of Lion, (b, e) Ligurian Sea, (c) Sea of Sardinia.

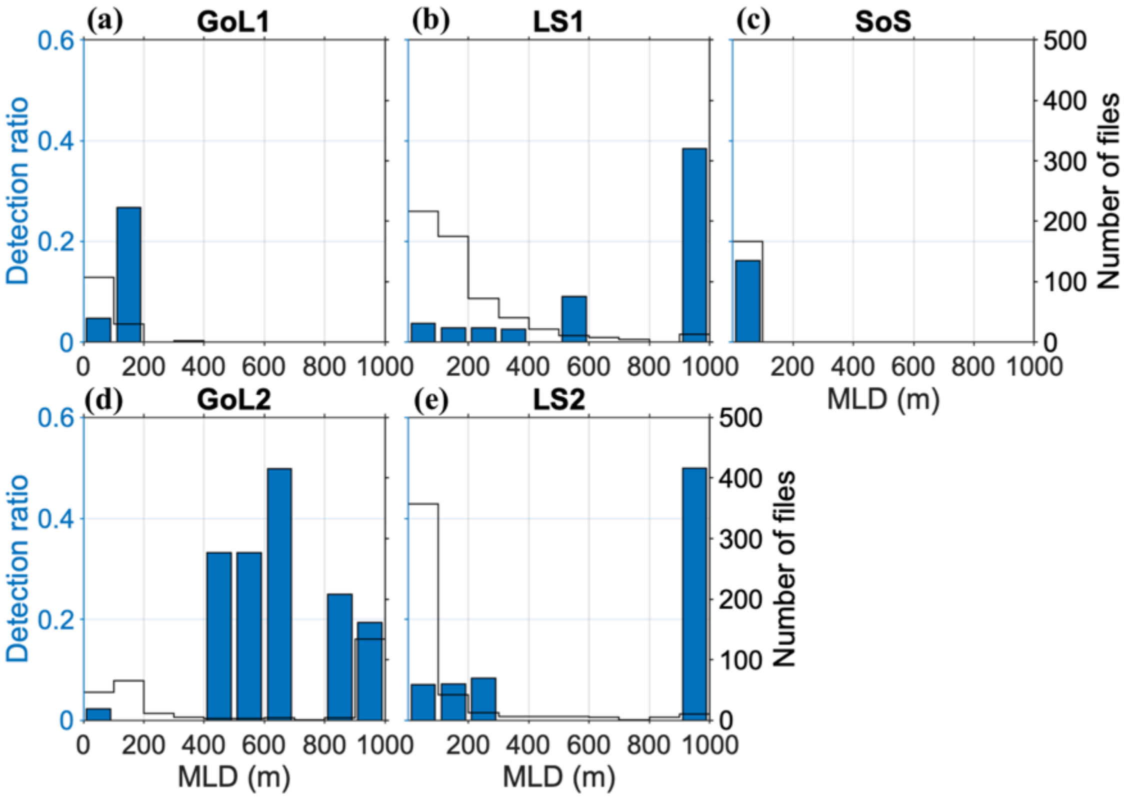

Figure 10: Number of glider dives with acoustic recording available for analysis (black line, right axis) per 100 m MLD bin. The bars (left axis) show the detection ratio (dives with sperm whale detection / total number of glider dives) in each 100 m MLD bin. Each panel represents one glider mission, arranged so that each column covers one deployment site: (a, d) Gulf of Lion, (b, e) Ligurian Sea, (c) Sea of Sardinia.

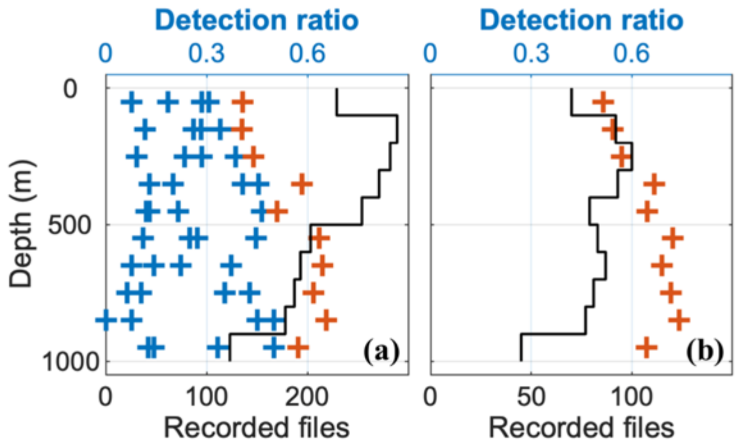

Figure 11: Number of acoustic files available for analysis (black line, lower axis) as a function of the depth of the glider. Panel (a) shows the detection ratio (files with sperm whale detection / available files) for the four winter (blue crosses) and summer (red crosses) glider deployment (upper axes). A specific focus on encounter #1 of glider mission SoS is shown in panel (b).