Master's Year 1 Internship Report - April 14 – June 19, 2025

Define the diving habits of Sperm Whales (*Physeter macrocephalus*) in the Mediterranean sea

Author :

Mélisande PAYET

Université de Toulon, Aix Marseille Univ, CNRS, LIS, DYNI, Marseille, France
Centre Int. d'IA en Acoustique Naturelle, Toulon, France, https://cian.univ-tln.fr

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Marine megafauna constitutes a large group of large-sized organisms. Cetaceans, pinnipeds, high trophic level fish, marine turtles, and seabirds can notably be mentioned (Pimiento et al., 2020). It plays a crucial role in maintaining the structure and function of marine ecosystems (Estes et al., 2016). These animals are ecologically significant as they regulate prey populations, being apex predators, and for some, "super-predators," meaning they are situated at the top of the trophic network (Malhi et al., 2015). Additionally, they act as nutrient vectors, ecosystem regulators, and bioindicators of ocean health (Heithaus et al., 2008). As apex predators, marine megafauna contributes to the balance of marine trophic networks (Ferretti et al., 2010). Beyond predation, marine megafauna also plays a role in the nutrient cycle, particularly through the vertical and horizontal transport of nutrients (Roman and McCarthy, 2010). For example, baleen whales transfer nutrients across different ocean depths and regions, thereby encouraging primary productivity (Roman et al., 2014). This effect, known as the "whale pump," promotes the growth of phytoplankton, which is at the base of the marine trophic network and plays a crucial role in carbon sequestration (Lavery et al., 2010). Being sensitive to environmental changes, marine megafauna acts as what could be called an effective "sentinel" for monitoring ocean health and the impacts of human activities (Sue.E, 2008).

Sperm whales (*Physeter macrocephalus*) are the largest species of odontocetes (C-R. McClain et al., 2015). Despite their size and status as predators, this species remains vulnerable, particularly in the Mediterranean (IUCN, 2017). Indeed, the sperm whale population in the Mediterranean is an isolated subpopulation, genetically distinct from the neighboring Atlantic population, which increases its fragility and vulnerability to anthropogenic threats (Notarbartolo di Sciara et al., 2016). The Mediterranean Sea is a high-density maritime traffic area: crossed by over 220,000 large ships each year, it is particularly exposed, especially in areas such as the Hellenic Trench, the Pelagos Sanctuary, and the Strait of Gibraltar, to an increased risk of collisions (OceanCare, 2022), which are key habitats and migratory routes for sperm whales. As a result, collisions significantly increase the risk of mortality, being the leading cause of unnatural death among sperm whales (A. Gannier and G. Marty, 2015; Bearzi et al., 2003). Studies have shown that more than 50% of stranded individuals bore collision marks, highlighting the severity of this threat (Frantzis et al., 2019). Ships do not only impact sperm whales physically but also acoustically through noise pollution: sperm whales use echolocation to hunt and navigate their environment (Pine et al., 2016). Unfortunately, boats disrupt their emitted signals, which are then disturbed and destabilized, causing them to lose all perception of their surroundings (Madsen et al., 2006). As such, the Mediterranean, being a highly trafficked area, is particularly vulnerable to the threats facing this species (Dolgov et al., 2017).

Furthermore, sperm whales exhibit remarkable diving behaviors, adapted to hunting prey located between 400 and 2500 meters deep (A. Gannier et al., 2012). During these dives, sperm whales emit regular click series at intervals of 0.5 to 2 seconds, interspersed with rapid "buzzes" as they approach prey, indicating an active hunting phase (Madsen et al., 2002). Consequently, these sound emissions are crucial for sperm whales to move and hunt in the dark depths of the ocean (Madsen et al., 2006). As sperm whales spend the majority of their time submerged, it is difficult to observe them visually at the surface. This is why researchers rely on passive acoustic methods to study their behavior and distribution. For example, the use of acoustic sensor networks, such as the NEMO-ONDE underwater observatory in the central Mediterranean, allows the tracking of sperm whale movements and activities by recording their echolocation clicks (Di Mauro et al., 2025). Acoustic studies have revealed that Mediterranean sperm whales adapt their diving behavior based on the vertical distribution of their prey (Watwood et al., 2006). They target vertically stratified prey layers, adjusting the depth and duration of their dives to maximize hunting efficiency (Watwood et al., 2006). This behavioral flexibility highlights their ability to effectively exploit available food resources in deep marine environments (L. Irvine et al., 2017). Another parameter studied is the IPI (Inter-Pulse Interval). The IPI corresponds to the rebound emitted in the sperm whale’s head at regular intervals, which helps estimate the size of its head, and subsequently, its overall size, age, and sex (Ferrari et al., 2024). The IPI can also serve as an indirect indicator, not only of size or sex, but also of the dive activity profile in sperm whales.

Thus, in response to the challenge of observing sperm whales, the WhaleWay missions come into play. These missions are part of the global research program "La Voix des Cachalots" led by the Longitude 181 association. It is a cross-disciplinary program (ethology, genetics, and acoustics) aimed at better understanding sperm whales in order to develop conservation protocols (V. Sarano and F. Sarano, 2022). The program first took place in Mauritius, with the goal of studying the evolution of the social structure of a clan and its implications for the Mauritian population, before expanding into the Mediterranean (Sarano et al., 2023; Girardet et al., 2022; Sarano et al., 2021). It specifically focuses on the dynamics of social structures in this species, as well as on tracking their deep-sea hunting behaviors through trajectory techniques (V. Sarano and F. Sarano, 2022). Five missions have taken place since 2022. These campaigns have focused on acoustic recordings, carried out in collaboration with the CIAN team from Université de Toulon (V. Sarano and F. Sarano, 2022).

The objectives of the study are multifaceted. First and foremost, the goal is to gain a comprehensive understanding of the social structures of sperm whales by combining individual acoustic monitoring with visual identification methods, supported by photo-identification. This technique involves taking photographs of the cetaceans, particularly their dorsal and caudal fins, to distinguish individuals and confirm their identity (Sarano et al., 2022), following a protocol already proven in research conducted around Mauritius (V. Sarano and F. Sarano, 2022). A key aspect of these missions is to determine the general positioning of sperm whales, their preferred areas of occupation or hunting, and their diving habits. The analysis of acoustic behavior in sperm whales helps identify several indicators of social cooperation: whether in dive synchronization, hunting coordination, communication, or juvenile protection, these collective behaviors reveal that sperm whales do not simply function as isolated individuals but adopt interdependence and solidarity strategies to optimize their survival (V. Sarano and F. Sarano, 2022). The nature of social affinities between certain individuals can then be identified, as well as the evaluation of their stability over time (V. Sarano and F. Sarano, 2022). The overarching aim of this program is to provide new detailed data on sperm whales in the Mediterranean to shed light on the dynamics of their populations (V. Sarano and F. Sarano, 2022).

All of these studies, which provide in-depth knowledge of sperm whales in the Mediterranean, may eventually enable the implementation of protection protocols for this critically endangered species (G. Notarbartolo-Di-Sciara, 2013). Conservation measures have already been proposed to mitigate these risks, particularly the rerouting of maritime traffic away from key sperm whale habitats. One study demonstrated that specific route modifications could reduce the overall collision risk by about 70%, with minimal impact on ship routes (Frantzis et al., 2019). Additionally, initiatives such as the REPCET system, which allows ships to report cetacean sightings in real-time, have been implemented in areas like the Pelagos Sanctuary to prevent collisions (Souffleurs d'Écume, 2016). However, these initial measures remain limited, and studies like the WhaleWay missions are crucial and represent a significant advancement in the preservation of this species, a key indicator of the proper functioning of an ecosystem (McDonald et al., 2017).

Thus, the goal of this internship is to assess the five WhaleWay missions based on the observation data collected in order to establish an initial overview of the diving behaviors of sperm whales.

MATERIALS AND METHODS

1. Study site

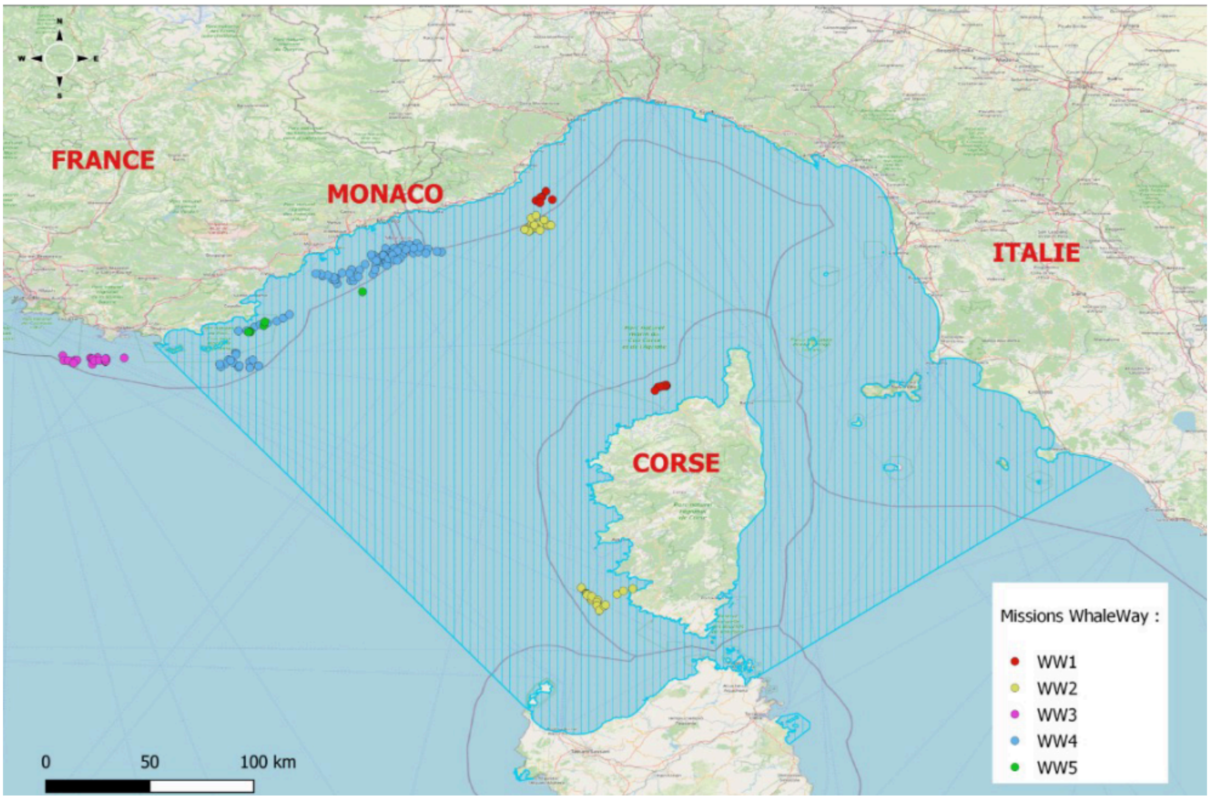


Figure 1. *A map representing the Pelagos Sanctuary (blue grid) with the three countries in agreement: France, Italy, and Monaco, as well as the location of the probes observed during the different WhaleWay missions in the Mediterranean (Author: PAYET Mélisande)*

The WhaleWay missions (except WW3) take place within the Pelagos Sanctuary (Figures 1 & 2), a sanctuary dedicated to the protection of marine mammals. The observation protocol is the same for each mission: 2 weeks of observations at sea, except for WW3, with a team of 10 people. This team consists of scientists: acousticians from Université de Toulon, the CIAN (Centre d'Intelligence Artificielle en Acoustique Naturelle) team, and the LIS (Laboratoire d'Informatique et Systèmes), as well as oceanographers from the Longitude 181 association. The crew members have access to a catamaran and, for certain missions, a zodiac.

Observations are made 24 hours a day. During the day, observers use binoculars to search for sperm whale blows in a 180° arc in front of the boat. To complement the visual effort, the boat is stopped for a 10-minute listening session every 30 minutes. This work is part of the acoustic search, which complements the visual search effort. The combination of the two thus strengthens the overall research on sperm whales because once the hunting is over, sperm whales can no longer be heard, as they stop emitting clicks, whereas when they are hunting, they cannot be observed with the naked eye. At night, since visual search is impossible, the acoustic search continues, relying on the regular hunting clicks of sperm whales, detected through various acoustic antennas (Baguera, Tétra, Aline), refined over the course of the missions. Additionally, the visual effort is complemented by photo-identification. A daily log is also kept by a crew member, compiling all information and observations, including time and GPS coordinates for each event observed. Furthermore, as soon as a sperm whale is sighted, observation forms, which collect various data, are filled out (Annexe 1).

Figure 2. *Summary table of the WhaleWay missions within the framework of the "La Voix des Cachalots" program*

Mission	Beginning	End	Duration	Location
WW1	06/06/2022	18/06/2022	12 days	North of Corsica
WW2	06/09/2022	21/09/2022	14 days	Week 1 : Imperia Week 2 : Southwest of Corsica
WW3	04/04/2023	06/04/2023	2 days	On the Toulon/La Seyne side
WW4	23/09/2023	07/10/2023	15 days	From Port-Cros to offshore Monaco
WW5	07/09/2024	21/09/2024	14 days	From the Île du Levant to offshore Monaco

2. Tracking method

Several approaches were used during the WhaleWay missions to study sperm whales in the Mediterranean. First, regarding the visual approach, various parameters were recorded on the observation forms when a sperm whale was sighted, such as GPS coordinates (longitude, latitude), the time, the action (i.e., the observed event, such as the probe), and other comments, such as the numbers of photos and videos taken, as well as the start and end times of sound recordings. Additionally, the photographer on board the zodiac took different photos to later create the Mediterranean Sperm Whale Identification Catalog. For WW1 and WW3, there was no zodiac, so everything was done from the catamaran. However, for WW2, WW4, and WW5, a zodiac was available. When a sperm whale entered the field of vision, team members would approach as close as possible (100 meters) and record the probe's position (GPS coordinates) on the observation forms, noting the blow when the sperm whale resurfaced to breathe and when it re-submerged (i.e., dived back into the depths). Thus, the time of the first probe was recorded, along with the blow and the second probe, with the corresponding GPS coordinates each time for all probes.

From an acoustic perspective, several antennas were deployed during the different missions to provide acoustic tracking in order to complement the identification of sperm whales. For example, the "Baguera" antenna, developed by the team of Professor Hervé Glotin (LIS Laboratory, CIAN Center of Université de Toulon, and SMIOT), features five hydrophones positioned vertically and laterally for better 3D discrimination of sound emissions. When the sperm whale is no longer observable because it hunts in the depths for about 50 minutes on average, the antennas help trace its path by listening to the echolocation clicks. The combination of acoustic and visual methods allows for optimal tracking of each individual, which can then be cataloged and identified. All methods (distant visual observations, photography, and acoustic recordings) are passive, non-intrusive techniques, meaning they do not interfere with the whale's natural rhythm and do not involve any direct contact with the animal.

3. Summary: data aggregation

Based on the observation sheets (Annexe 1) and the various data collected during the missions, the objective of this internship was to compile all of these data, and thus create tables grouping the GPS coordinates (latitude and longitude), the observation date, the time, the name of the individual if identified, the action (probe, blow, click stop, click resume); as well as the variables calculated during this internship: the duration of the probe, i.e., the time during which the sperm whale probes (dives) at a specific point until it is seen probing again at another point, the bathymetry, the IPI (Interval Inter Pulse), and the distance between two probes (Annexe 2).

Next, regarding the individual's name, the same observation sheets and mission logs are used to record when the desired individual was observed. When identified, the individual's name was noted. Researchers are familiar with the individuals since a catalog has been created. Unfortunately, the individual could not always be identified. When the individual was known, it was recorded in the table; otherwise, nothing was filled in or "N_ID" was noted for "not identified."

Regarding the "action" field, the following activities of the sperm whales were recorded: "dive," which refers to when the sperm whale is at the surface and then dives, and "blow," which refers to when the sperm whale surfaces and exhales air to breathe. These two actions are observed visually. The parameters "stop click" and "resume click" were recorded at night, which refer to when the sperm whale emits sounds while hunting, captured using the antennas with hydrophones. These actions are observed acoustically, and they help estimate the duration of the dive when it is impossible to observe visually.

To obtain the duration of the dive, the time of the first dive for the same individual is noted, followed by the time of the second dive. The time elapsed between the two dives is then calculated.

Regarding the IPIs, they were previously calculated by Pascale GIRAUDET, professor and researcher at the LIS.

Regarding the distance between two dives, a Python code was generated (Annexe 3) that takes into account the Haversine formula and the curvature of the Earth. The code calculates the orthodromic distance (the great-circle distance) by asking the user to input the latitude and longitude of the first dive, then the latitude and longitude of the second dive, and it calculates the distance between the two.

Finally, to obtain the bathymetry, the GEBCO (General Bathymetric Chart of the Oceans) site was used: Gridded Bathymetry Data Download. On this site, information about the bathymetric grid with a resolution of 30 arc-seconds can be found. The most recent version of the grid available was selected. The region of interest (Northeastern Mediterranean, French, Italian, and Corsican coasts) was selected and downloaded in GeoTIFF format. A Python script was then generated. It reads the file in .csv format with the columns "latitude" and "longitude", extracts the bathymetry from the downloaded GeoTIFF GEBCO file, and saves a new file in .csv format with an additional "depth" column, which was added to the previous data for WW1, WW2, WW3, WW4, and WW5.

4. Data analysis

Statistical analyses were conducted using Python version 3.7.6 and R version 4.4.2. The study site map was generated using QGIS version 3.22. The normality of the data was tested with the Shapiro-Wilk test. For the correlation analyses between variables, the Spearman test was used because the data were not normally distributed, with a significance threshold of 0.05.

RESULTS

The WhaleWay missions totaled 57 days at sea, spread over three distinct seasons (April, June, and September). During these campaigns, 32 individuals were identified. A record number of dives was observed for the individual “Farouche” during WW4, who made 24 dives, followed by “Patte d’ours” with 13 dives. Approximately sixty hours of acoustic recordings were made using the “Baguera” antenna, including 48 hours continuously on two individuals, “Méric” and “Vespucci”. All of these data represent several terabytes of recordings, which are currently under analysis at the LIS/CIAN laboratory at Université de Toulon.

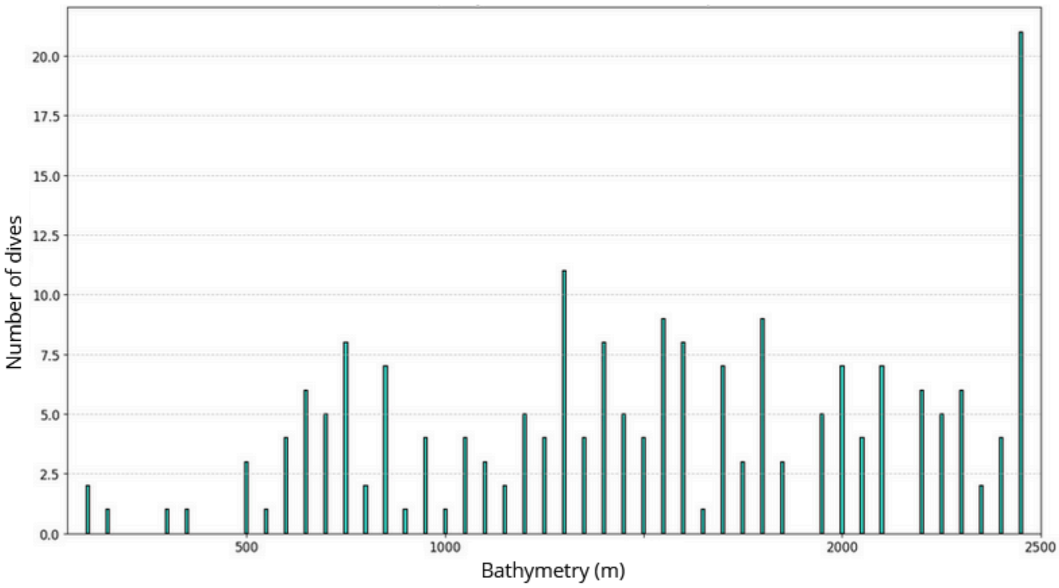


Figure 3. *Total number of dives of observed sperm whales in relation to bathymetry*

Figure 3 shows the total number of dives of observed sperm whales at different depths. The shallowest depth observed was 78 meters (WW2), while the deepest was 2469 meters (WW4). In this graph, the number of dives seems to vary depending on the depth. Indeed, the distribution is heterogeneous, with no specific bathymetry associated with a set number of dives. This suggests that the individuals move across various seafloors. In general, between 5 and 10 dives are observed between 600 and 2200 meters. However, it can be noted that there seems to be a record dive close to 2500 m, with about 20 dives. In contrast, fewer than 5 dives appear to be observed in shallow areas (< 500 m).

After statistical analysis using both the Shapiro-Wilk test and the Spearman test, the data for the number of dives and bathymetry give p-values of 2.2×10^{-16} and 0.0001973, respectively. The null hypothesis (H_0) is therefore rejected with a threshold of 0.05. Subsequently, the Spearman test gives a very weak negative rho of -0.05972278, meaning that there is no link between the number of dives and bathymetry. The p-value confirms this: 0.4118, which is above the significance threshold (0.05), indicating that there is no significant correlation between the number of dives and bathymetry.

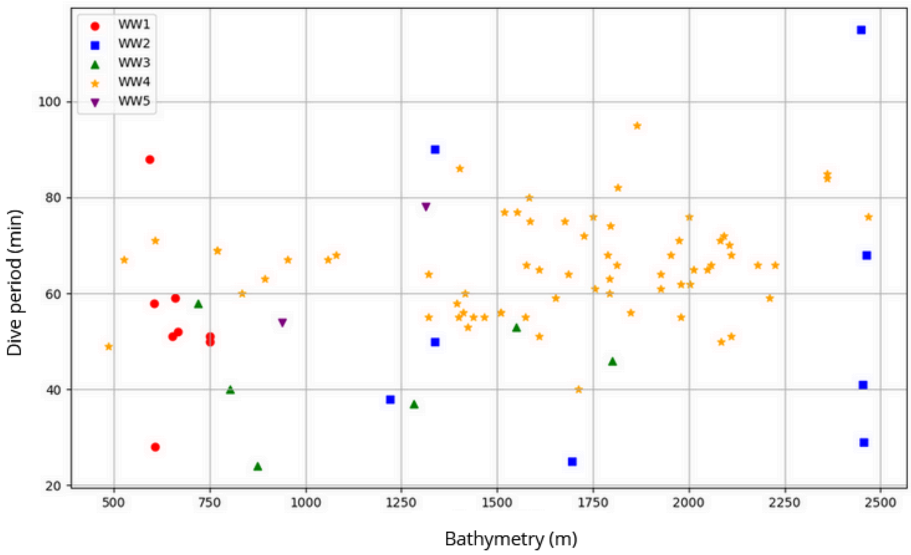


Figure 4. *Dive period as a function of bathymetry by mission*

Figure 4 shows the different dive periods observed as a function of bathymetry during the WhaleWay missions. The shortest dive duration observed was 28 minutes, and the longest was 115 minutes, with an average of 61 minutes. For the first mission of the campaign, WW1, we can observe that the individuals were in shallow waters, but the dive duration remains heterogeneous (ranging from about 30 minutes to 90 minutes). The WW4 mission has the highest number of observations, which are very heterogeneous. WW5 cannot be exploited due to a lack of data (only two observations). Therefore, from a visual analysis of this graph, it appears that the dive duration is around 60 to 80 minutes across different depths. This would suggest that regardless of bathymetry, the dive duration is not significantly influenced. There is a bias here: the lack of data prevents us from truly predicting whether the sperm whales tend to prefer deeper waters or not.

After statistical analysis using the Shapiro-Wilk test and the Spearman test, the data for dive duration and bathymetry resulted in p-values of 0.04505 and 0.002951 respectively. Therefore, the null hypothesis H_0 is rejected with a threshold of 0.05. Subsequently, the Spearman test gives a positive rho of 0.2602421, meaning that dive duration and bathymetry weakly increase together. Indeed, as depth increases, dive duration increases. The p-value confirms this trend: 0.01176, which is below the significance threshold (0.05), indicating a significant correlation between bathymetry and dive duration. As depth increases, the dive duration tends to increase as well, although this relationship remains relatively weak.

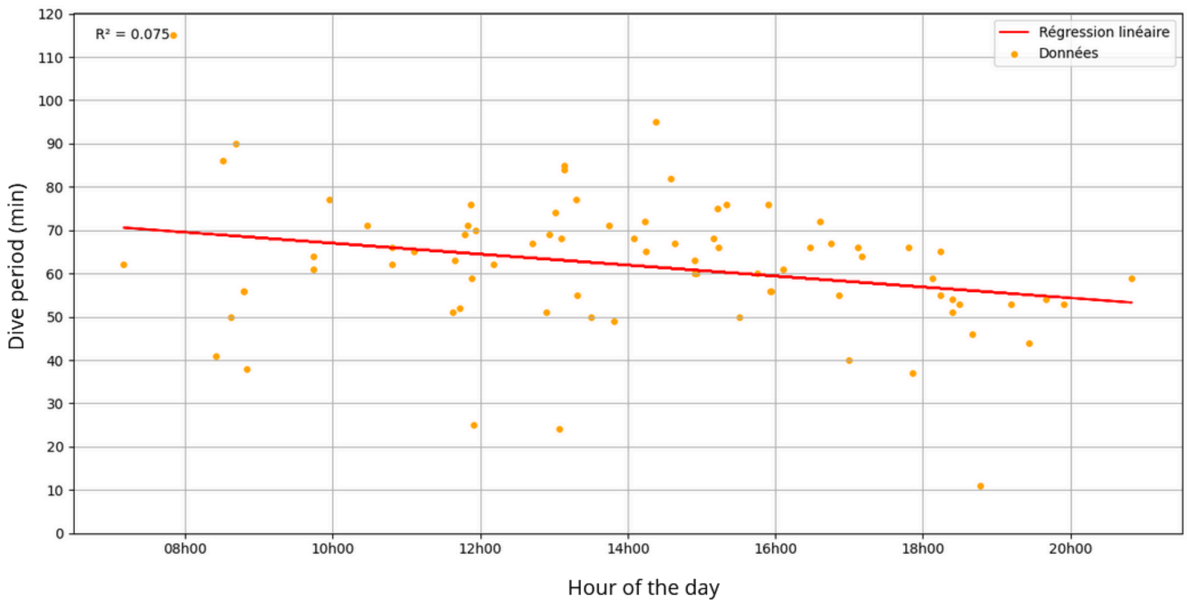


Figure 5. *Dive period depending on the time of day*

Figure 5 presents the dive period for the observed individuals depending on the time of day. Graphically, it appears that more individuals were observed during the afternoon, between 12:00 PM and 6:00 PM. During these hours, the dive durations seem to be the longest (over 60 minutes), in contrast to the morning, where there are fewer data points and the dive durations are much shorter (around 40 minutes). Visually, this suggests that sperm whales spend more time underwater in the afternoon.

After statistical analysis using both the Shapiro-Wilk test and the Spearman test, the p-values for the time of day and dive duration are 0.01262 and 0.007456, respectively. Therefore, the null hypothesis (H_0) is rejected with a significance threshold of 0.05. Next, the Spearman test yields a negative rho of -0.1305461, indicating no relationship between the dive duration and the time of day. The p-value confirms this: 0.1865, which is higher than the significance threshold (0.05), meaning that we reject the null hypothesis (H_0). There is no significant correlation between the time of day and the dive period.

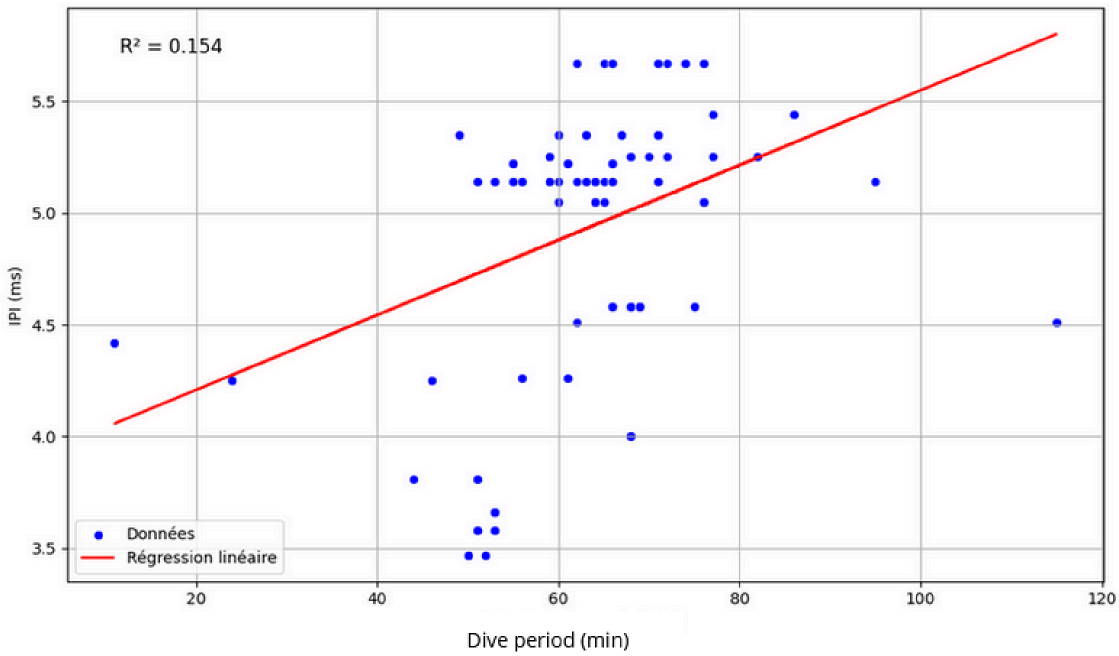


Figure 6. *IPI depending on dive period*

Figure 6 shows the inter-pulse interval (IPI) as a function of dive period. Graphically, we can observe that the IPI tends to increase with the duration of the dive. It is notable that most IPI values range between 5 and 5.5 ms for dive durations between 60 and 80 minutes. Therefore, this suggests that as the IPI increases, the duration of the dive tends to increase as well.

After statistical analysis using the Shapiro-Wilk test and the Spearman test, the data for the IPI and the dive duration give p-values of 1.274×10^{-6} and 6.236×10^{-5}, respectively. Thus, the null hypothesis (H_0) is rejected with a significance threshold of 0.05. Following this, the Spearman test gives a positive rho of 0.4783609, indicating that the IPI and the dive duration moderately increase together. Individuals with a higher IPI tend to have longer dives. The p-value confirms this trend: 4.856×10^{-5}, which is lower than the significance threshold (0.05), so we cannot reject the null hypothesis. There is a significant correlation between the dive duration and the IPI.

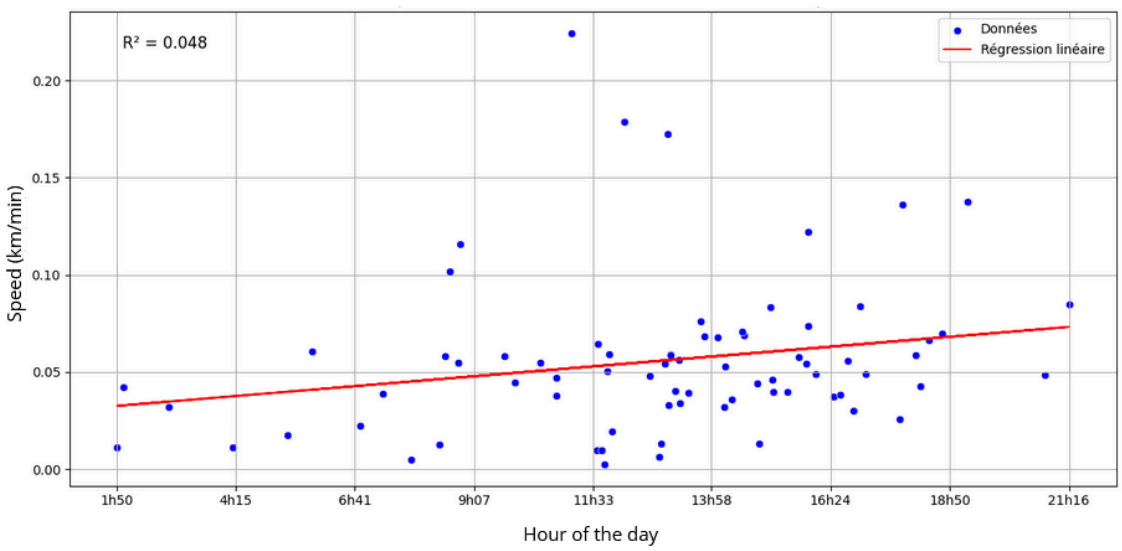


Figure 7. *Movement profile of sperm whales depending on the time of day*

Figure 7 presents the movement profile of sperm whales depending on the time of day. This profile was obtained from the distance between two dives (a calculated parameter) and the dive duration (a known parameter). It seems that most speeds range from 2.4 to 4.8 km/h. Visually, we can observe that speed increases throughout the day, especially after noon.

After statistical analysis using the Shapiro-Wilk test and the Spearman test, the data for the movement speed and the time of day yielded p-values of 7.234×10^{-8} and 0.049, respectively. Therefore, the null hypothesis (H_0) is rejected with a significance threshold of 0.05. Next, the Spearman test gives a positive rho of 0.2949159, indicating a weak positive correlation between movement speed and time. In fact, the speed increases throughout the day. The p-value confirms this trend: 0.01021, which is below the significance threshold of 0.05, meaning we cannot reject the null hypothesis (H_0). There is a weak but significant correlation between movement speed and the time of day.

Other parameters were also analyzed (Annexes 4 & 5).

Regarding the IPI as a function of bathymetry (Annexe 4), an R^2 of 0.144 was obtained. The statistical tests show a p-value of 8.903×10^{-8} and 0.0001186 for the Shapiro-Wilk test, indicating that the data do not follow a normal distribution. For the Spearman test, the data show a positive rho of 0.2312359, which means that the IPI and bathymetry increase weakly together. Individuals with a high IPI are found at greater depths. The p-value confirms this: 0.01039, which is lower than the significance threshold of 0.05, so we cannot reject the null hypothesis (H_0). There is a weak but significant correlation between bathymetry and the IPI.

Regarding the dive period as a function of the distance between two dives (Annexe 5), an R^2 of 0.011 was obtained. Statistical tests show a p-value of 0.03394 and 4.819×10^{-15} for the Shapiro-Wilk test, indicating that the data do not follow a normal distribution. For the Spearman test, the data show a positive rho of 0.201026, which could suggest that the duration of the dive and the distance between two dives increase weakly together. However, the p-value obtained is greater than 0.05, meaning we reject the null hypothesis (H_0), and there is no significant correlation between the distance between two dives and the duration of the dive.

DISCUSSION

The distribution of dives during the WhaleWay mission campaigns (WW1 to WW5) highlights an increased frequency in certain bathymetric ranges, with a marked peak around 2,400 meters, suggesting a preference for these areas, although statistical tests could not confirm this in Figure 3. Indeed, sperm whales are capable of regularly reaching depths greater than 2,000 meters to primarily hunt cephalopods (Watwood et al., 2006). The concentration of dives in areas between 1,000 and 2,500 meters is therefore consistent with knowledge about their foraging ecology. These depths often correspond to regions of deep Deep Scattering Layers (DSL), which are rich in prey, particularly in the Mediterranean's deep trenches and canyons (e.g., the Gulf of Lion or Nice canyons), known to attract high trophic-level species due to the concentration of prey they generate (Druon et al., 2012). These bathymetric structures promote aggregation, which in turn attracts sperm whales. It is interesting to note that dives are rarer in shallow areas (< 500 meters), which may be partly due to the scarcity of targeted prey in continental shelf waters. However, it is worth mentioning that in the Mediterranean, deep waters are relatively close to the coast, especially along the Liguro-Provençal basin's edge, contributing to the presence of sperm whales near the shore (Figure 1). Thus, these results seem to indicate a preference for higher bathymetries, but caution is warranted. These findings are based on field observations, which are influenced by the areas surveyed. Therefore, one should not exclude the presence of sperm whales in unsurveyed zones.

The relationship between the dive duration and bathymetry was studied across the five WhaleWay missions (WW1 to WW5). According to Teloni et al. (2008), feeding dives last on average 45 minutes, followed by short surface recovery periods, typically less than 10 minutes. Similarly, Drouot et al. (2004) observed in the north-western Mediterranean that sperm whale dives also lasted about 45 minutes, reaching depths of 500 to 800 meters. This study also notes that the size of individuals influences the duration and depth of dives. Likewise, Gannier et al. (2012) reported dive depths of up to 2500 meters, with an average of around 1348 meters, for similar durations (approximately 44 minutes). In the case of the WhaleWay missions, it appears that most of the dive durations are longer (sometimes over 1.5 hours) and that most individuals frequent relatively deep waters (around 2000 meters), unlike Drouot et al. (2004), where most dives were found to be in the 800-meter range. However, the low determination coefficients (R^2) suggest that other unmeasured factors (such as prey availability or environmental conditions, for example) would likely influence diving behavior. While the WhaleWay missions still include a limited amount of data, they are a crucial factor in understanding sperm whale ecology.

The variation in the sperm whales' dive durations observed throughout the day was highlighted. The literature indicates a behavioral adaptation related to the vertical migrations of prey: Chambault et al. (2021) showed that, although dives are often deeper during the day, their duration does not vary significantly between day and night (with an average duration of about 35 minutes), suggesting that the duration is more constrained by physiological limits (oxygen capacity, pressure tolerance) than by the depth distribution of prey. Other research conducted in underwater canyons, such as the study by Guerra et al. (2017), revealed that sperm whales adjust the depth of their dives according to the vertical distribution of prey, but maintain a relatively constant dive duration. These results align with the observations in Figure 3, where dive durations show little variation based on the time of day.

The IPI (Inter-Pulse Interval) as a function of the dive duration, that is, the time the sperm whale spends underwater, has been demonstrated. The results suggest that the dive duration is higher with a larger IPI. This seems consistent because a larger IPI indicates a bigger head size in the sperm whale, thus having a larger body size (Ferrari et al., 2024), which in turn results in greater lung capacity. It has been shown that individuals with a higher IPI (likely males) perform longer dives, consistent with an enhanced ability to reach greater depths to access deep prey (Madsen et al., 2002; Watwood et al., 2006). These results support the hypothesis that IPI can be an indirect indicator not only of size or sex but also of the dive activity profile in sperm whales.

The movement profile of sperm whales in relation to the time of day has also been highlighted. Several studies show that the speed of sperm whale movement significantly varies depending on the time of day, reflecting behavioral adaptations linked to the circadian cycle. Notably, Shabangu and Andrew (2020) observed in South Africa that sperm whales increase their speed at night, reaching values higher than those observed during the day. This nocturnal variation is associated with faster transit movements between feeding areas, linked to the vertical migration of prey (squids) that move toward the surface at night. During the day, sperm whales tend to reduce their speed, favoring prolonged diving and feeding phases in specific areas. These results are consistent with Watwood et al. (2006), who used satellite tags and acoustic recordings to indicate that nocturnal speeds can exceed 1.5 km/min, compared to less than 1 km/min during the day. This variation in speed suggests an optimized energy strategy, allowing sperm whales to adapt their behavior based on resource availability.

The analysis of the relationship between dive duration and the distance traveled between two dives reveals that the distance between dives is likely not a determining factor for dive duration. This idea is consistent with the observations of Drouot et al. (2004), who reported an average distance of about 1.3 nautical miles (approximately 2.4 km) traveled between two dive cycles, without demonstrating a direct relationship with the duration of the dives. This suggests that sperm whales do not necessarily follow straight-line trajectories underwater, and that this could potentially depend on the sex or age of the individual.

The relationship between the IPI (Inter-Pulse Interval) and bathymetry is consistent with the work of Madsen et al. (2002), which indicates that the IPI reflects the size of the spermaceti (head). Other studies, such as Wahlberg (2002) and Teloni et al. (2008), suggest that the IPI may also adapt to the acoustic conditions of the environment at depth. Therefore, individuals with a larger IPI tend to favor deeper waters. Additionally, the work of Ferrari et al. (2024) highlights that a higher IPI (> 5 ms) corresponds to males, who are larger in size and thus have a higher lung capacity for deep hunting. Consequently, it is surprising to find a correlation between IPI and bathymetry, as well as IPI and dive duration, but not between bathymetry and dive duration.

CONCLUSION

The analysis of data collected during the five WhaleWay missions (WW1 to WW5) allowed for an initial characterization of the dive behaviors of sperm whales (*Physeter macrocephalus*) in the Mediterranean, within the context of significant anthropogenic pressure. The studies confirm a preference for deep bathymetric zones (such as underwater canyons), especially beyond 1,000 meters, which is consistent with the vertical distribution of prey that varies between day and night, although the results do not significantly prove this here. A correlation between the inter-pulse interval (IPI) and dive duration suggests that larger individuals perform longer dives, potentially linked to a higher lung capacity. However, the absence of significant correlations between most measured parameters (speed, bathymetry, time) indicates a high degree of individual and contextual variability. This variability, combined with the still-limited sampling, prevents making general conclusions regarding sperm whale diving habits, their areas of interest, or their presence at the surface during the day.

These results nonetheless confirm the value of combining acoustic and visual approaches for the non-invasive monitoring of sperm whales, an endangered species in the Mediterranean. They also highlight the need to continue long-term observational campaigns to strengthen datasets and identify preferential zones or robust behavioral patterns. One interesting parameter to analyze is the number of "creaks" heard in the acoustic recordings. These are clicks at closely spaced intervals followed by "silence," which indicates that the sperm whale has approached its prey and is feeding. By using this parameter, it would be possible to estimate the feeding success depending on the area, as a higher number of creaks would suggest a higher abundance of prey. Consequently, estimating feeding success could provide insights into the spatial preferences of sperm whales in the Mediterranean. In the long term, these insights could support the implementation of targeted conservation measures, particularly in terms of regulating maritime traffic and reducing noise pollution in key habitats for the species.

REFERENCES

• Amano M, Aoki K, Kobayashi H, Minamikawa S, Sato K and Kubodera T. (2023) *Stereotypical diel movement and dive pattern of male sperm whales in a submarine canyon revealed by land-based and biologging surveys. Front. Mar. Sci.* 10:1150308.

• Chambault P, Fossette S, Heide-Jørgensen MP, Jouannet D, Vély M. (2021) *Predicting seasonal movements and distribution of the sperm whale using machine learning algorithms. Ecol Evol*,1432-1445.

• Di Mauro, L. S., Diego-Tortosa, D., Sciacca, V., Riccobene, G., & Viola, S. (2025) *Acoustic Tracking of Sperm Whales (Physeter macrocephalus) in the Central Mediterranean Sea Using the NEMO-ONDE Deep-Sea Observatory. Journal of Marine Science and Engineering,* 13(4), 682.

• Druon, J.-N., Laran, S., Pettex, E., & David, L. (2012) *Potential feeding habitat of fin whales in the western Mediterranean Sea: an environmental niche model. Marine Ecology Progress Series,* 464, 289–306.

• Drouot, V., Gannier, A., & Goold, J. C. (2004) *Diving and feeding behaviour of sperm whales (Physeter macrocephalus) in the northwestern Mediterranean Sea. Aquatic Mammals*, 30(3), 419–426.

• Estes, J.A. & Palmisano, J.F. (1974) *Sea otters: Their role in structuring nearshore communities. Science*, 185(4156), 1058–1060.

• Estes, J.A. et al. (2016) *Megafaunal impacts on structure and function of ocean ecosystems. Annual Review of Environment and Resources*, 41, 83–116.

• Ferrari, M., Trinh, M., Sarano, F. et al. (2024) *Age and interpulse interval relation from newborn to adult sperm whale (Physeter macrocephalus) off Mauritius. Sci Rep* 14, 18474.

• Ferretti, F. et al. (2010) *Patterns and ecosystem consequences of shark declines in the ocean. Ecology Letters,* 13(8), 1055–1071.

• Frantzis, A., Alexiadou, P., & Gkikopoulou, K. C. (2019) *Shipping routes through core habitat of endangered sperm whales along the Hellenic Trench, Greece: Can we reduce collision risks? PLOS ONE*, 14(2)

• Gannier, A., Dulau, V., & Petiau, E. (2012) *Foraging dives of sperm whales in the north- western Mediterranean Sea. Journal of the Marine Biological Association of the United Kingdom*, 92(8), 1835–1846.

• Gannier A, Marty G. (2015) *Sperm whales ability to avoid approaching vessels is affected by sound reception in stratified waters. Mar Pollut Bull*. 95(1):283-8.

• Girardet J, Sarano F, Richard G, Tixier P, Guinet C, Alexander A, Sarano V, Vitry H, Preud'homme A, Heuzey R, Garcia-Cegarra AM, Adam O, Madon B and Jung J-L (2022) *Long Distance Runners in the Marine Realm: New Insights Into Genetic Diversity, Kin Relationships and Social Fidelity of Indian Ocean Male Sperm Whales. Front. Mar. Sci*. 9:815684

• Giuseppe Notarbartolo-Di-Sciara (2013) *Sperm whales, Physeter macrocephalus, in the Mediterranean Sea: a summary of status, threats, and conservation recommendations. Aquatic Conservation : Marine and Freshwater Ecosystems*, Vol.24, Issue S1, Pages 4-10.

• Heithaus, M.R. et al. (2008) *Predicting ecological consequences of marine top predators. Ecology*, 89(11), 2894–2906.

• Irvine L, Palacios DM, Urbán J, Mate B. (2017) *Sperm whale dive behavior characteristics derived from intermediate-duration archival tag data. Ecol Evol.* 7(19):7822-7837.

• Lavery, T.J. et al. (2010) *Iron defecation by sperm whales stimulates carbon export in the Southern Ocean. Proceedings of the Royal Society B*, 277(1699), 3527–3531.

• Madsen, P. T., Wahlberg, M., & Møhl, B. (2002) *Male sperm whale (Physeter macrocephalus) acoustics in a high-latitude habitat: implications for echolocation and communication. Behavioral Ecology and Sociobiology*, 53(1), 31–41.

• McClain CR, Balk MA, Benfield MC, Branch TA, Chen C, Cosgrove J, Dove AD, Gaskins L, Helm RR, Hochberg FG, Lee FB, Marshall A, McMurray SE, Schanche C, Stone SN, Thaler AD. (2015) *Sizing ocean giants: patterns of intraspecific size variation in marine megafauna. PeerJ* 3:e715

• McDonald, E. M., Morano, J. L., DeAngelis, A. I., & Rice, A. N. (2017) *Building time budgets from bioacoustic signals to measure population-level changes in behavior: A case study with sperm whales in the Gulf of Mexico. Ecological Indicators*, 72, 360–364.

• OceanCare. (2022) *High-risk collision hotspots in the Mediterranean Sea.*

• Pimiento C, Leprieur F, Silvestro D, Lefcheck JS, Albouy C, Rasher DB, Davis M, Svenning JC, Griffin JN (2020) *Functional diversity of marine megafauna in the Anthropocene. Sci Adv*. ;6(16).

• Roman, J. & McCarthy, J.J. (2010) *The whale pump: marine mammals enhance primary productivity in a coastal basin. PLOS ONE*, 5(10), e13255.

• Roman, J. et al. (2014) *Whales as marine ecosystem engineers. Frontiers in Ecology and the Environment,* 12(7), 377–385.

• Sarano Véronique, Sarano François, Girardet Justine, Preud'homme Axel, Vitry Hugues, Heuzey René, Sarano Marion, Delfour Fabienne, Glotin Hervé, Adam Olivier, Madon Bénédicte & Jung Jean-Luc (2022) *Underwater photo-identification of sperm whales (Physeter macrocephalus) off Mauritius, Marine Biology Research.*

• Sarano, V. & Sarano F. (2022) *Rapport de Mission - Programme La Voix des Cachalots : Méditerranée 2022-2023*

• Sarano, F., Sarano, V., Tonietto, M-L., Yernaux, A., Jung, J-L., Arribart, M., Girardet, J., Preud'homme, A., Heuzey, R., Delfour, F., Glotin, H., Charrier, I., & Adam, O. (2023) *Nursing behavior in sperm whales (Physeter macrocephalus). Animal Behaviour and Cognition*, 10(2), 105-131.

• Sarano François, Girardet Justine, Sarano Véronique, Vitry Hugues, Preud'homme Axel, Heuzey René, Garcia-Cegarra Ana M., Madon Bénédicte, Delfour Fabienne, Glotin Hervé, Adam Olivier and Jung Jean-Luc (2021) *Kin relationships in cultural species of the marine realm: case study of a matrilineal social group of sperm whales off Mauritius island, Indian Ocean. R. Soc. Open Sci*. 8 :201794

• Shabangu, F. W., & Andrew, R. K. (2020) *Clicking throughout the year: Sperm whale clicks in relation to environmental conditions off the west coast of South Africa. Endangered Species Research*, 43, 475–494.

• Souffleurs d'Écume. (2016) *REPCET: Real-time Plotting of Cetaceans.*

• Sue E. Moore, (2008) *Marine Mammals as Ecosystem Sentinels, Journal of Mammalogy*, Volume 89, Issue 3, Pages 534–540

• Teloni, V., Mark, J. P., Patrick, M., & Madsen, P. T. (2008) *Shallow food for deep divers: Dynamic foraging behavior of male sperm whales in a high latitude habitat. Journal of Experimental Marine Biology and Ecology*, 354(1), 119–131.

• UICN France (2017) *La Liste rouge des espèces menacées en France*

• Wahlberg, M. (2002) *The acoustic behaviour of diving sperm whales observed with a hydrophone array. Journal of Experimental Marine Biology and Ecology*, 281(1–2), 53–62.

• Watwood, S. L., Miller, P. J. O., Johnson, M., Madsen, P. T., & Tyack, P. L. (2006) *Deep diving foraging behaviour of sperm whales (Physeter macrocephalus). Journal of Animal Ecology*, 75(3), 814–825.

• Y. Malhi, C.E. Doughty, M. Galetti, F.A. Smith, J. Svenning, & J.W. Terborgh, (2016) *Megafauna and ecosystem function from the Pleistocene to the Anthropocene, Proc. Natl. Acad. Sci. U.S.A*. 113 (4) 838-846.

ACKNOWLEDGMENTS

Firstly, I would like to express my sincere gratitude to my internship supervisor, Justine GIRARDET, for providing invaluable advice and recommendations, and for supporting me throughout my internship. She dedicated time to address all my questions, and thanks to her, I have learned a great deal about sperm whales and data processing.

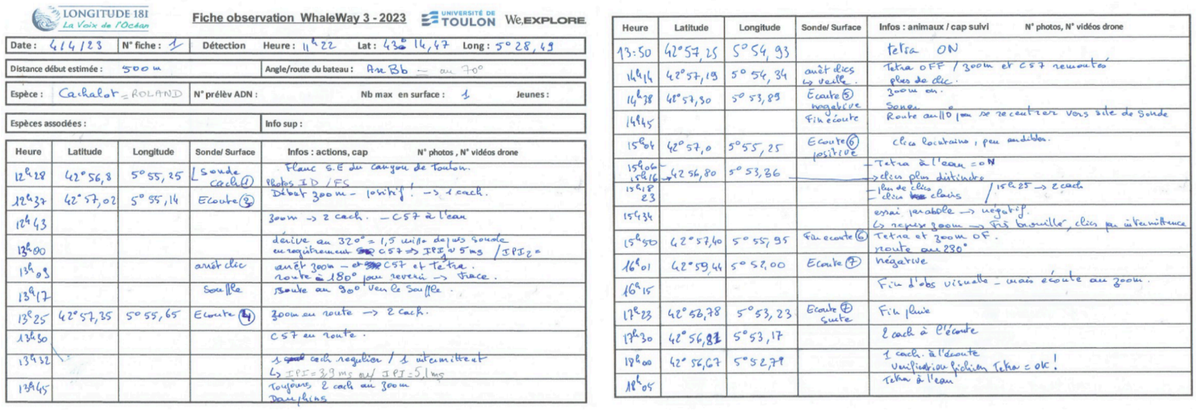
I also wish to thank my second supervisor, Prof. Hervé GLOTIN, who organized several conferences at the laboratory, with the participation of speakers such as Véronique and François SARANO, oceanographers and founders of the Longitude 181 association, Mr. Yves Tupinier, and Mr. Walter Zimmer. I would also like to thank him for giving me the opportunity to be a volunteer at the United Nations during the United Nations Ocean Conference in Nice (UNOC 3) from June 7th to 13th, 2025.

I would like to thank Prof. Pascale GIRAUDET for accepting me for this internship and for the topic at the LIS laboratory, and for sharing her knowledge about sperm whales, especially IPI.

I would also like to thank Mrs. Véronique SARANO for providing me with her advice and answers to my questions about the WhaleWay missions that she and her team had conducted.

ANNEXES

Annexe 1. Example of an observation sheet for the WW3 mission on April 4, 2023



Annexe 2. Excerpt from the filtered table grouping all the observed and calculated parameters from the five WhaleWay missions

Latitude	Longitude	Individu	action	heure	date	periode_sonde (min)	Profondeur (m)	IPI (ms)	distance_inter_sonde_km	Mission
42.798068333	8.996385000	Janus	sonde	11h38	11/06/22	51	-653.0	3,81	0,5	WW1
42.797095000	8.995146667	Trinacria	sonde	11h43	11/06/22	52	-667.0	3,47	0,511	WW1
42.796358333	8.994301667	Efkaristo	sonde	11h50	11/06/22		-667.0	3,58		WW1
42.802063333	8.993626667	Janus	sonde	12h29	11/06/22		-679.0	3,81	0,5	WW1
42.800080000	8.990385000	Trinacria	sonde	12h35	11/06/22		-687.0	3,47	0,511	WW1
42.796690000	8.978068333	Trinacria	sonde	13h30	11/06/22	50	-751.0	3,47	1,975	WW1
42.790813333	8.955228333		sonde	14h20	11/06/22		-832.0		1,975	WW1
42.788693333	8.946250000		sonde	16h03	11/06/22		-1024.0			WW1
42.792408333	8.959320000	Efkaristo	sonde	18h24	11/06/22	51	-750.0	3,58	3,392	WW1
42.769876667	8.931296667	Efkaristo	sonde	19h15	11/06/22		-853.0	3,58	3,392	WW1
		Efkaristo	sonde	19h55	11/06/22	53		3,58		WW1
			sonde	20h48	11/06/22					WW1
		Janus	sonde	19h26	12/06/22	44		3,81		WW1
		Janus	sonde	20h10	12/06/22			3,81		WW1
43.853900000	8.349323333		sonde	18h33	16/06/22		-813.0			WW1
43.900843333	8.313136667	WW1_NID₁	sonde	20h50	16/06/22	59	-660.0			WW1
			arret_clic	21h25	16/06/22					WW1
		WW1_NID₁	sonde	21h49	16/06/22					WW1
			arret_clic	22h23	16/06/22					WW1
43.847953333	8.257071667		arret_clic	5h49	17/06/22	58	-604.0		3,515	WW1
43.868315000	8.290601667		arret_clic	6h47	17/06/22	28	-608.0		0,626	WW1
43.866830000	8.283066667		arret_clic	7h15	17/06/22	88	-594.0		3,412	WW1
43.836280000	8.279031667		arret_clic	8h43	17/06/22	NA	-697.0	3,4		WW1
43.697652778	8.215556944		sonde	19h50	12/09/22		-2465.0			WW2
43.7172222	8.234166666666667	Meric	sonde	20h06	12/09/22		-2387.0	4,51		WW2
43.711536111	8.276151389		arret_clic	21h16	12/09/22	68	-2463.0		5,782	WW2
43.711536111	8.276151389		arret_clic	21h16	12/09/22		-2463.0			WW2
43.692383333	8.209283333		arret_clic	22h24	12/09/22		-2467.0			WW2
			arret_clic	00h09	13/09/22	57				WW2
			arret_clic	1h06	13/09/22	69				WW2
			arret_clic	2h15	13/09/22	61				WW2
			arret_clic	3h16	13/09/22	NA				WW2
			arret_clic	5h14	13/09/22	54				WW2
43.693472222	8.253134722		arret_clic	6h08	13/09/22	29	-2456.0			WW2
			arret_clic	6h37	13/09/22	NA				WW2
		Meric	sonde	7h10	13/09/22	62		4,51		WW2
		Vespucci	sonde	7h32	13/09/22			4,42		WW2
		Meric	sonde	8h12	13/09/22			4,51		WW2

Annexe 3. Python code to calculate the distance between two probes

```
from math import radians, sin, cos, sqrt, atan2
```

Import of necessary libraries

```
def haversine(lat1, lon1, lat2, lon2):
    R = 6371.0 # Rayon de la Terre en km
```

Creation of a definition to perform the calculation

```
    # Conversion in radians
    lat1, lon1, lat2, lon2 = map(radians, [lat1, lon1, lat2, lon2])

    # Differences
```

Subtraction of the latitude and longitude respectively of the position of probe 1 and 2

```
    dlat = lat2 - lat1
    dlon = lon2 - lon1

    # Haversine formula
    a = sin(dlat / 2)**2 + cos(lat1) * cos(lat2) * sin(dlon / 2)**2

    c = 2 * atan2(sqrt(a), sqrt(1 - a))
    distance = R * c
    return distance

if __name__ == "__main__":
  print("Entrez les coordonnées du premier point :")
```

The user is asked to enter the GPS coordinates of the first probe's position

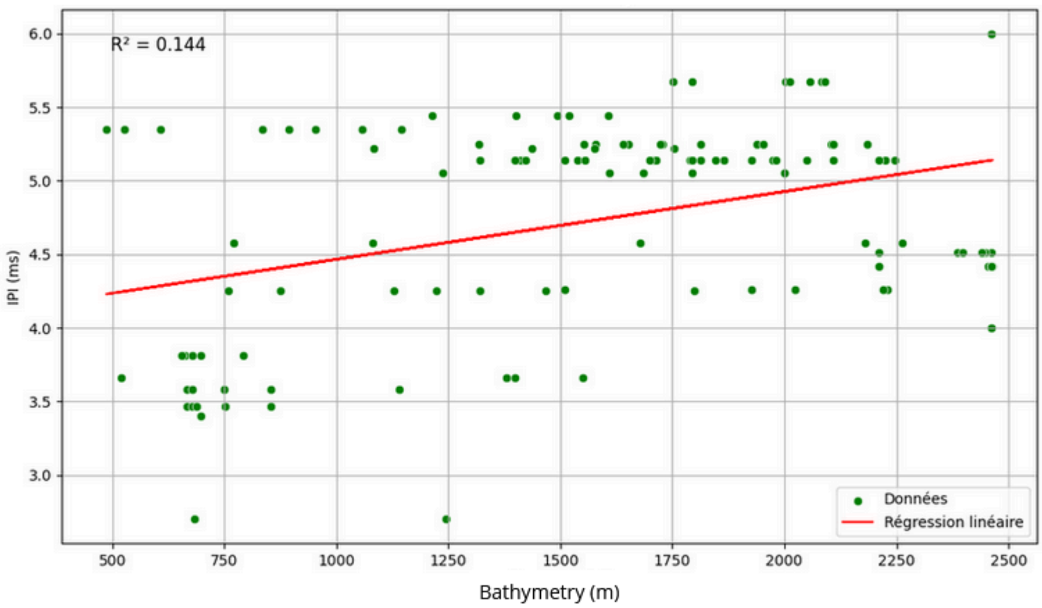
```
    lat1 = float(input("Latitude 1 : "))
    lon1 = float(input("Longitude 1 : "))

    print("\nEntrez les coordonnées du deuxième point :")
```

The user is asked to enter the GPS coordinates of the second probe's position

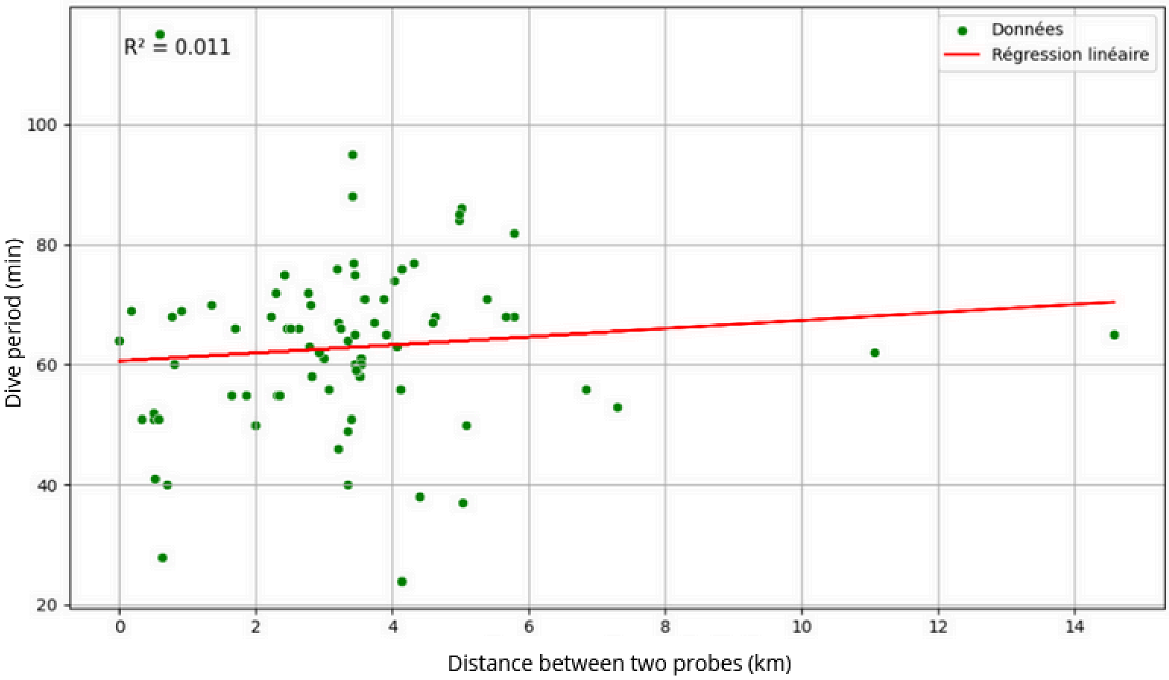
```
    lat2 = float(input("Latitude 2 : "))
    lon2 = float(input("Longitude 2 : "))

    dist = haversine(lat1, lon1, lat2, lon2)
```

Based on the Haversine calculation, the distance (as the crow flies) is obtained in km

```
    print(f"\nDistance à vol d'oiseau : {dist:.3f} km")
```



Annexe 4. IPI as a function of bathymetry



Annexe 5. Probe duration as a function of the distance between two probes

ABSTRACT

Sperm whales (Physeter macrocephalus) are the largest marine mammals of the odontocete order (toothed cetaceans). Their diet consists primarily of cephalopods, particularly squids. In the Mediterranean sea, they are frequently observed near submarine canyons, which are favorable zones for deep-sea hunting. However, this sea is also one of the most heavily trafficked maritime areas, especially by cargo ships and trawlers. This intense anthropogenic pressure has placed the species in a critical situation: it is currently classified as "Vulnerable" by the UICN. Sperm whales play a vital ecological role, particularly in maintaining trophic balance and preserving fishery resources. The Mediterranean population is especially noteworthy because it is genetically isolated from other populations, such as those in the Atlantic. Studying their diving behavior therefore allows for improved monitoring of this population—for instance, through the identification of areas of frequent presence or bathymetric preferences—with the aim of implementing conservation protocols to mitigate the impacts of maritime traffic and associated noise pollution. It is within this context that the WhaleWay missions were developed. The five campaigns conducted have made it possible to collect various variables such as GPS coordinates, bathymetry, dive duration, IPI etc. The results generally show no significant correlations between the different measured parameters. However, a trend indicating that IPI increases with dive duration can be observed. Therefore, the WhaleWay missions represent an initial approach to studying the sperm whale population in the Mediterranean, but the current dataset remains insufficient to draw firm conclusions. It is thus essential to continue and intensify sampling efforts and observation campaigns in order to contribute to the conservation of this species, which is under significant anthropogenic pressure.

ABSTRACT IN FRENCH

Les cachalots (Physeter macrocephalus) sont les plus grands mammifères marins de l'ordre des odontocètes (cétacés à dents). Leur alimentation repose principalement sur les céphalopodes et en particulier les calmars. En Méditerranée, ils sont fréquemment observés à proximité des canyons sous-marins, zones propices à la chasse en profondeur. Cependant, cette mer est également l'une des zones les plus densément parcourues par le trafic maritime, avec notamment les cargos et les chalutiers. Cette forte pression anthropique place l'espèce en situation critique : elle est aujourd'hui classée comme «Vulnérable» par l'UICN. Les cachalots jouent un rôle écologique essentiel, notamment dans le maintien des équilibres trophiques et la préservation des ressources halieutiques. La population de Méditerranée présente une particularité majeure : elle est génétiquement isolée des autres populations, notamment celles de l'Atlantique. Étudier les habitudes de plongée permet ainsi d'améliorer le suivi de cette population comme par exemple avec l'identification de zones de présence régulière ou de préférences bathymétriques ; dans le but de mettre en place des protocoles de préservation face au trafic maritime et la pollution sonore engendrée. C'est dans ce contexte que s'inscrivent les missions WhaleWay. Les cinq campagnes menées ont permis de récolter différentes variables : coordonnées GPS, bathymétrie, durée des sondes, IPI etc. Les résultats montrent globalement l'absence de corrélations significatives entre les différentes paramètres mesurés. Toutefois, une tendance à l'augmentation de l'IPI avec la durée des sondes peut être observée. Par conséquent, les missions WhaleWay constituent une première approche pour l'étude de la population de cachalots en Méditerranée, mais les données actuelles restent insuffisantes pour tirer des conclusions solides. Il est donc crucial de poursuivre et d'intensifier les efforts d'échantillonnage et les campagnes d'observation, afin de contribuer à la conservation de cette espèce menacée par la pression anthropique.