UNIVERSITE SORBONNE UNIVERSITE
Paris, France

Thèse de Master
Année 2018-2019
Master Sciences de la Mer

Passive acoustic monitoring of the interactions between killer whales and demersal longlines in the Exclusive Economic Zone of Crozet Islands

Kinga KORYCKA
Réalisé sous la responsabilité de Flore Samaran
Laboratoire des Sciences et Techniques de l'information de la Communication et de la Connaissance (Lab-STICC), ENSTA Bretagne

Technopole Brest-Iroise
CS 83818
29238 Brest Cedex 3
France

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Table of Contents

Acknowledgements

Many people have contributed to the creation of this work. I am very grateful for each one of them.

At first I would like to thank my professors from Sorbonne Université, but also from Université des Antilles and Uniwersytet Adama Mickiewicza, because all of them played an invaluable role in preparing me for the effort of completing my Master's thesis.

I would like to thank my tutor at ENSTA Bretagne, Flore Samaran, for her trust, for the many substantive advices and for the great atmosphere.

Thank you, Gaëtan Richard, for the unbelievable passion, great patience and perfect scientific intuition.

I am very grateful to Julie Beesau for the hours she spent on labelling to provide me with priceless data for my work.

Thank you Fabio Cassiano for creating the software, without which it would not be possible to do this research.

I am very grateful for the whole SISO team for accepting me into your creative group.

I would like to also thank Muséum National d'Histoire Naturelle in Paris for providing valuable data that was indispensable to make our discovery.

Kinga Korycka

List of figures and tables

List of symbols and abbreviations

Symbol	Description	Pertinent value	SI Unity
m	meter		1000 mm
km	kilometer		1 km = 1000 m
day	d		1 d = 24 h = 86 400 s
h	hour		1 h = 60 min = 3600 s
min	minute		1 min = 60 s
s	second		$\Delta\nu_{Cs}$
ms	milisecond		0,001 or 10^{-3} or $^{1}/_{1000}$
Hz	hertz		s^{-1}
kHz	kilohertz		1 kHz = 1000 Hz
°	degree		1°= (π/180) rad

I Introduction

1.1 Problematic of depredation on demersal longline fisheries

Depredation is the most widespread and documented usage conflict between humans and wildlife in the world (Sillero-Zubiri & Laurenson 2001). It is defined as a behaviour of certain animal species, especially large predators, of feeding on a resource that is either produced (e.g. waste), elevated (e.g. livestock) or caught (e.g. fishing) by humans (Tixier 2012). Mostly documented in the terrestrial environment, depredation is also increasing significantly in the marine environment (Roche et al. 2007, Read 2008). The major factor responsible for the onset of large-scale depredation in the marine environment is the disruption of abundance, distribution and accessibility of some prey for predators, caused by growing exploitation of marine resources over the last six decades. The intensification of fishing industry has increased the chances of interactions between marine predators and fishing operations, leading to an increment of depredation events (Read 2005, Gilman, Brothers et al. 2007, de Bruyn, Tosh et al. 2013).

Most of the large-scale fisheries aggregate target catch within a more concentrated area than found in nature (Rose & Kulka 1999). These aggregations provide marine predators with an opportunity to forage successfully without high levels of energy expenditure from travelling and hunting (Trites et al. 1997). The ease of access to industrial resources can quickly trigger changes in the diet of a predator submitted to significant survival pressures associated with resource depletion (Mishra 1997, Mishra et al., 2003, Butler 2000). However, some studies are in agreement that when its natural prey are in abundance, a predator will primarily use this quarry in relation to an artificial resource such as fish catches (Tixier 2012). The possibility of injury from fishing gear (Hamer, Childerhouse et al. 2012, FAO 2018) which may lead even to death of the animal (Gosliner, 1999, Hamer et al., 2008, 2011) is an example of another negative impact of depredation on a predator.

For fisheries, depredation may generate heavy financial losses from reduced profit per unit of effort (Dalla Rosa and Secchi 2007, Roche, Guinet et al. 2007, Tixier, Gasco et al. 2010, Richard 2017). Dealing with wild animal species can be extremely expensive. Killer whale depredation is of global significance with some fisheries reporting over 8000 USD losses per day due to animals removing fish from the fishing gear (Hamer, Childerhouse et al. 2012). Longline fishing companies tend to compensate their financial losses due to depredation by increasing the fishing effort to complete their quotas, what may cause an overexploitation of natural resources (Trites et al. 1997, Richard 2017). In addition to the direct costs associated with depredation, indirect costs may arise from human-made efforts and strategies of prevention and protection.

Current mitigation strategies to prevent depredation focus on the survival of the depredating marine mammals and the reduction in economic losses to fisheries. These strategies have attempted to include methods that either restrict an animal from the fishing area (Wild, Thode et al. 2017), protect the target species from the predator (Hamer, Childerhouse et al. 2015) or influence management and operational decisions to include strategies of avoidance from depredation (Tixier, Garcia et al. 2015, Richard 2019a).

1.2 Situation at the Exclusive Economic Zone of Crozet Islands

This study focuses on killer whale (*Orcinus orca*) depredation on Patagonian toothfish (*Dissostichus eleginoides*) demersal longline fisheries in the French Exclusive Economic Zone (hereafter EEZ) of Crozet Islands. This fishery holds one of the largest Patagonian toothfish quota in the Southern Ocean (Guinet et al. 2015, COLTO 2016) and experiences the highest depredation levels of all other toothfish fisheries (Roche et al. 2007, Tixier et al. 2010a, Gasco et al. 2015, Janc et al. 2018). The interactions with killer whales have serious economic implications to the fisheries, as well as for sustainable management of fish stocks, raising the necessity to find mitigation solutions (Richard 2019a). The longline fishery of Crozet Islands has been fully controlled and monitored since the early 2000s, with fishery observers monitoring 100% of the fishing operations (Richard 2019a). This case of depredation issue has been studied since 2007 by the research project named OrcaDepred.

So far, the developed strategies of mitigation have shown limited effectiveness in suppressing or substantially reducing depredation, primarily because the extent and methods of depredation by killer whales along with their ability to interact with vessels is still poorly known (Richard 2019b). This lack of knowledge is mainly explained by the difficulty of collecting data on killer whale behaviour outside of visual observational periods during fishing operations. Visual monitoring studies are limited only to one stage of fishing operations (retrieval of the equipment), and they depend on multiple variables considering the experience and effort from observers, management decisions and external factors such as weather and light conditions (Richard 2019a). Therefore, depredation on demersal longlines by killer whales have always been described as occurring during the hauling phases. Towers et al. (2018) proved that killer whales are capable of performing deep dives (measured record around 1100 m of depth), what implies their ability to access some demersal longlines, which in the zone of Crozet Islands are deployed between 500 and 2500 m. Such behaviour had been described recently by Richard et al. (2019b). These two evidences demonstrate that is it possible for killer whales to depredate at the seafloor, it is not known however if this phenomenon is widespread or only occasional. Underestimated depredation rates may result in unaccounted fish mortality in fish-stock assessments, therefore it is of urgent need to answer this question. To do so, it is essential to find out what is happening below the sea surface. A method that proves useful even when visual observations are no more enough to provide new data, is the acoustics. Passive acoustic monitoring is an efficient approach, particularly in studying animals producing sounds, such as killer whales. For that reason, in our study we used this alternative method to monitor depredation by attaching an acoustic recording device directly to commercial fishing gear.

1.3 Passive acoustic monitoring

Acoustic approach, whenever brought up in the context of marine mammal depredation, is mostly associated with acoustic deterrents and repulsive devices, the use of was first mentioned over 40 years ago (Fish & Vania 1971, Shaughnessy et al. 1981, Jefferson & Curry 1996). There is little to no published research on the use of acoustics to observe or measure depredation behaviour up until 21st century (McPherson et al. 2004, Hernandez-Milian et al. 2008). The reasons for this are most probably of technological nature, as sufficiently small and autonomous recording devices were developed only over the past two decades (Thode et al. 2015). In this investigation, we aimed at applying passive acoustic monitoring (PAM) in the purpose to better understand killer whale occurrence and behaviour of depredation on demersal longlines. The working relationship between fishers and OrcaDepred project researchers resulted in the design of easy and quick in use attachment systems that made the deployment of recorders practical during commercial fishing operations (Richard 2019b).

The way killer whales use sound also encouraged the extensive use of PAM by OrcaDepred. This species lives in familial pods and usually hunt in groups. Most of the time they are acoustically active underwater, making sounds not only to forage but also to communicate with other pod members. Therefore, PAM of killer whales can provide an estimate of their occurrences in the area and their associate activities, even at the time their visual observation is difficult or impossible. So far, the use of acoustics has been successful for Northern Hemisphere killer whale-fishery interaction studies (Thode et al. 2007, 2015).

1.4 Objectives of the study

This study aims to apply the passive acoustic monitoring approach to better understand the feeding behaviour of killer whale population from the EEZ of Crozet and to determine spatial and temporal movements of killer whales around longline fishing gear. To achieve this goal, we compare the visual observations of killer whales from the fishing vessel during hauling of a longline, with the underwater sound recordings at one point, and check whether killer whales are acoustically active also aside from the fishing operation of hauling of a longline. This investigation is intended to bring a new insight to the fishing companies and scientists working on the development of new solutions to depredation.

II Materials and Methods

2.1 Data collection

Field study was conducted prior to this internship and was thus not part of the author's work.

The study focuses on the fishing activity within the EEZ of Crozet Islands. The acoustic data was collected at the Crozet Islands EEZ, located in the Southwest of the Indian Ocean on the Antarctic Plate (46°25'S, 51°59'E). The data was collected from a legal longliner fishing vessel in February 2018. The process of data collection was therefore adapted to the fishing routine.

In commercial longlining, the line is released from the stern of a fishing vessel adapted for this purpose. In Patagonian toothfish longlining, the mainline is oriented horizontally and rigged to sink to the bottom. The longline rig consists of six major elements: two floating buoys, two downlines, two anchors, a mainline, branch lines and the hooks. The floating buoys serve for the retrieval of a longline from water (Fig. 1). Below each buoy a downline ensures the connection with the mainline. Connected to this mainline at 1,2 m intervals are the branch lines, each terminating in an automatically baited hook. The mainline is maintained at the sea bottom by two anchors located at the junction between the mainline and the downlines. The mainlines can vary from 1 to 40 km of length, averaging 8 km. They are set on the seafloor at depths ranging from 500 to 2 500 m, depending on the bathymetry. Fishing in waters shallower than 500 m is prohibited to avoid the capture of juvenile toothfish (Collins et al. 2010a, Gasco 2011).

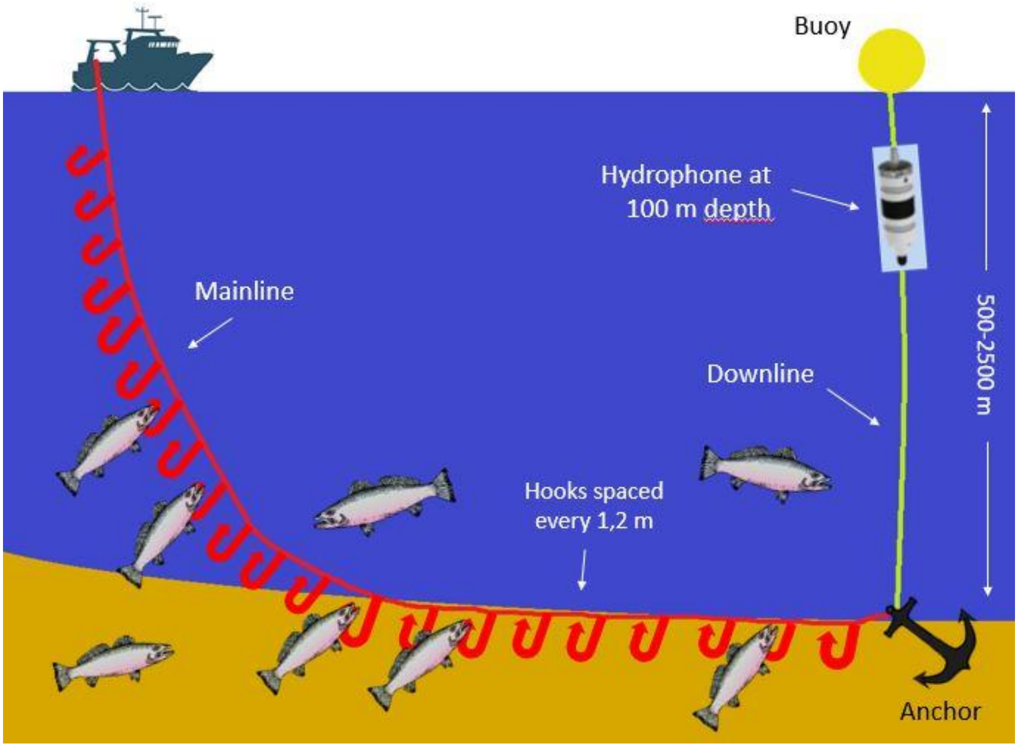

Fig. 1. **Scheme of a demersal longline during the operation of hauling.**

The fishing routine consists of a continuation of settings, soakings and haulings of the longlines. The *setting* is the totality of actions leading to the positioning of the mainline at the sea bottom. It is the shortest out of the three main fishing operations, lasting for 20 minutes on average. *Soaking* is the time during which the line is left alone in the sea while the vessel carries on other operations in different areas of the fishing zone. It is the longest part of the routine, and its duration averages 30 hours. *Hauling* is the totality of actions leading to the retrieval of the line aboard the vessel. It lasts usually about 90 minutes.

Acoustic data was collected using one autonomous hydrophone Soundtrap ST300 HF (Ocean Instruments, New Zealand). The hydrophone was fixed on the downline deployed at 100 meters below the sea surface (Fig. 1). Recordings started with the beginning of the setting of the longline and finished either at the beginning or at the end of hauling, according to which downline was hauled first. The hydrophone was set up to record continuously with sampling frequency set at 144 kHz.

All the operational activities of the fishing vessel, as well as all the visual observations of killer whales during hauling were collected into *PECHEKER* database, stored and managed by the

French National Museum of Natural History (MNHN). It is a relational database for analysis and management of fisheries and related biological data from the scientific survey of the French Southern and Antarctic Lands (Martin & Pruvost 2007).

2.2 Labelling of the recordings

2.2.1 Categories of sounds

Killer whales are known to produce several types of sounds, which belong to three typical categories: clicks, pulsed sounds (here referred to as *calls*) and whistles.

Killer whale clicks (Fig. 2), typically produced in series, are brief pulses of sound generally employed as echolocation signals in odontocetes (Ford 1989). Echolocation is the use of a signal's echoes from an emitting animal to estimate the direction and the range of an object (Griffin 1958, Zimmer 2011). Echolocation is therefore a useful tool for foraging on fish. In this study, echolocation sounds are of highest interest because their occurrence can be used as a proxy of foraging activity of animals. Killer whale click durations range from 0,1 to 25 ms, and they can be repeated at rates from a few to over 300 clicks per second (Ford 1989). Clicks frequency content can be relatively narrow to broad, with most of the energy in the spectra concentrated between 20 and 60 kHz (Au et al. 2004). Fish generally have low-frequency hearing abilities, approximately up to 10 kHz (Fay & Popper 1975), so they are unlikely to hear the echolocation clicks of killer whales (Ford 1989).

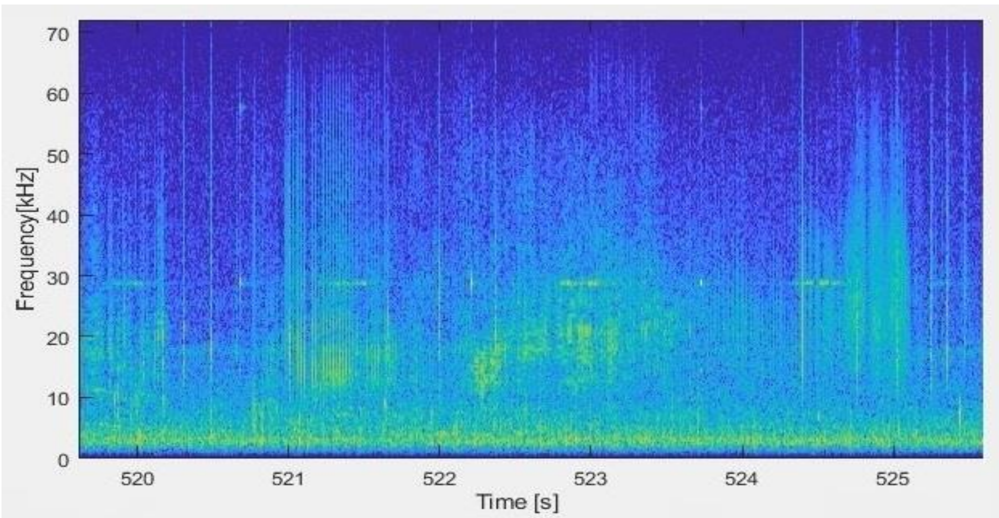

Fig. 2. **Killer whale activity of echolocation on a spectrogram.** Lighter than background vertical lines are multiple, quickly repeated clicks.

Calls (Fig. 3A) are the most abundant and characteristic class of vocalizations produced by killer whales. They are complex sounds with many harmonics. Calls have distinct tonal properties because of high pulse-repetition rates (Schevill & Watkins 1966). The pulses making up these calls can have either wide or restricted bandwidths and repetition rates extending to 4000 pulses per second or more. Primary energy of calls is usually concentrated between 1 and 6 kHz, with high-frequency components occasionally extending up to 30 kHz. Signal durations may range from less than 50 ms up to 10 s, with the majority between 0,5 and 1,5 s long (Ford 1987).

Whistles (Fig. 3B) are characterized by a non-pulsed or continuous waveform, which appears on a sound spectrogram as a single narrow-band tone with little or no harmonic or side-band structure (Ford & Fisher 1983). Whistles have an average bandwidth of 4,5 kHz, an average dominant frequency of 8,3 kHz, and an average duration of 1,8 s (Thomsen et al. 2001).

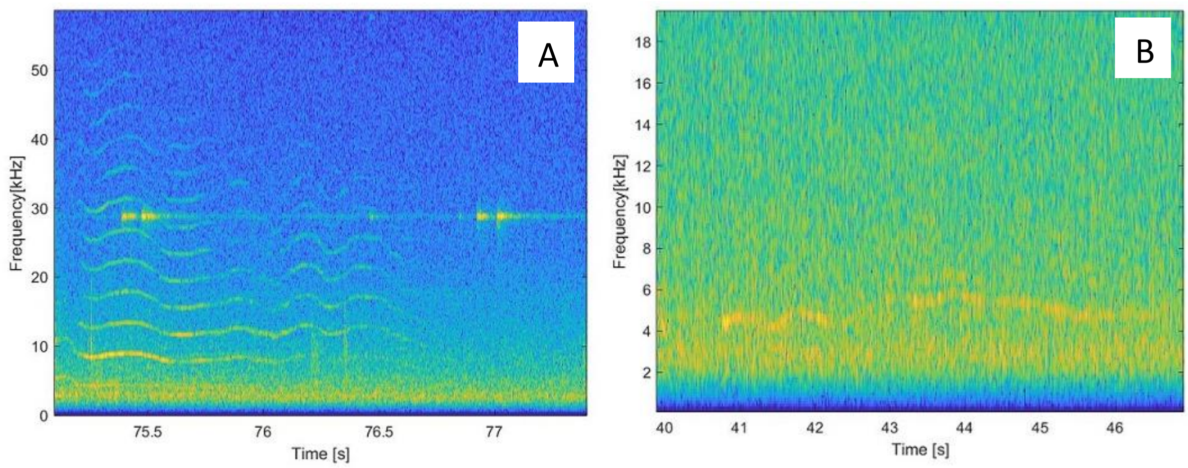

Fig. 3. **Killer whale activity of vocalizations on spectrograms.** A: a call with its multiple harmonics; B: a whistle.

In marine mammals, calls and whistles are primarily used in the communication between individuals and recognition of pods (Ford 1989, 1991, Thomsen et al. 2002, Riesch et al. 2006, 2012). In aquatic environment, sound is particularly important for interacting individuals because visual signals attenuate quickly and individuals frequently cannot see one another (Weiß 2011). These types of signals may therefore be reliable to determine socializing behaviour (Ford 1989, 1991, Deecke et al. 2000, Miller & Bain 2000, Filatova et al. 2013). Call rates may also be high during the activity of foraging (Ford & Fisher 1983), therefore one can conclude about the activity of socializing only in the lack of occurrence of echolocation signals.

Echolocation clicks are higher in frequency and lower in intensity than vocalizations, therefore, echolocation clicks attenuate faster than vocalization signals in the ambient noise.

In addition to the role of vocal signals, the difference between echolocation and vocalization sounds in cetaceans is of an anatomical nature. In echolocation, clicks are produced by a complex echolocation system similar to a sonar - phonic lips. A complex system of air sacs and specialized soft tissues vibrate as air moves through the nasal passages. The sound created in the air sacs is channelled through the fats of the melon, a lipid-filled sac in the forehead, used to focus the sound (Berta et al. 2005). Calls and whistles may be produced by both, phonic lips and larynx. As the vocal repertoire of killer whale population from ZEE of Crozet is not known, the differentiation between calls and whistles is difficult and not accurate. In this study therefore, calls and whistles were put together into one category of vocalizations. Reducing the number of sound categories allows to simplify and thus accelerate the process of labelling (see below: 2.2.3).

2.2.2 Manual spectrogram sorting

The first step of the data analysis was to find the fragment of recordings where acoustic events of interest (vocalizations and clicks emitted by killer whales) occurred, in order to avoid the necessity of listening to long fragments of recordings with no sounds. Each recording was treated in order to obtain a series of 10 seconds of spectrograms. Spectrograms were set up with different filters to zoom at the frequency range with the highest probability of encountering killer whale sounds (below 20 kHz). The low frequency band with the acoustic signature of the ship was also removed (a broadband noise from 100 to 2000 Hz, Richard 2018). Each spectrogram was checked to determine the presence of killer whale sounds and the corresponding fragments of recordings were manually labelled.

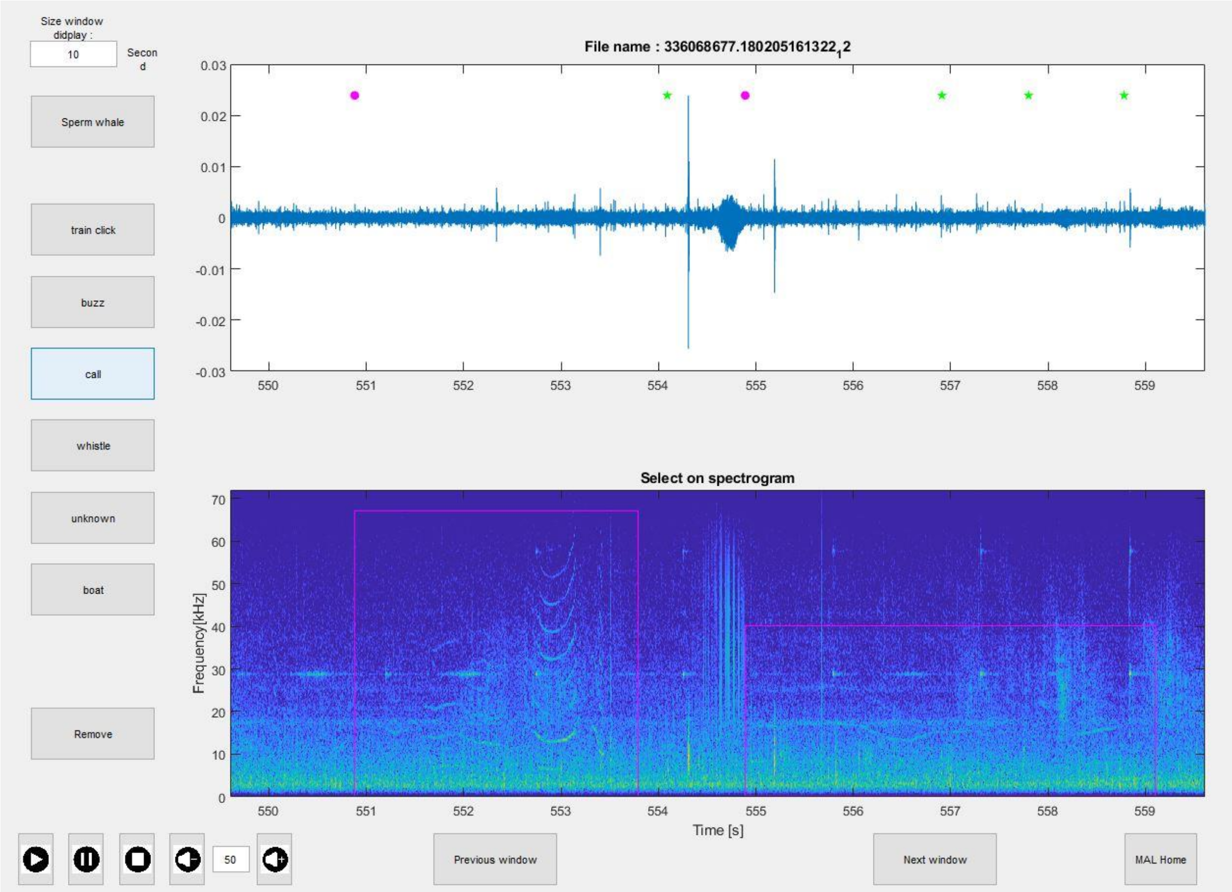

Fig. 4. **Interface of the labelling software Manual Acoustic Labelling.** Lower window displays a spectrogram, and the upper window shows a corresponding waveform. Pink frames and pink dots signify a labelled vocalization sound; green dots are the labels of echolocation signals.

2.2.3 Manual acoustic labelling

When a fragment of recording with killer whale sounds was found on the 10 s spectrogram, an additional verification of the preceding three to five minutes of the recording was carried on by listening, using headphones (Bose, QuietComfort 25 Acoustic Noise Cancelling). At this step, if a sound of killer whale was heard, the manual labelling was processed using *M.A.L.* (Manual Acoustic Labelling), an application developed in MATLAB environment (Fabio Cassiano, ENSTA Bretagne, 2018). The interface of *M.A.L.* (Fig. 4) displays the spectrogram and waveform over a chosen time-window (10 s for sufficient resolution) and can play the corresponding fragment of the recording. In order to remove the disturbing ship and ambient noise, the minimum frequency filter of 2500 Hz was applied to the recordings within the software. The choice of such a frequency of the filter is explained by the best trade-off between the reduction of fishing vessel noise and the preservation of sounds produced by killer whales.

When a sound produced by killer whale had been found on the spectrogram, a frame-box was drawn around the sound and a label was given (echolocation or vocalization). When the annotator sketches a frame, *M.A.L.* automatically preserves its time coordinates, by which means the time of occurrence and duration of each frame-box were registered in a csv file. Simultaneously, jpeg images for vocalization frame-boxes were automatically saved within the application. A training set of records had been created to prepare the annotators before starting the study.

2.3 Annotation variability analysis

The time assigned for the manual acoustic labelling of 400 hours of data was two months, and the process of annotating was shown time-consuming. Two annotators (Kinga Korycka, the author and Julie Beesau, research assistant at ENSTA Bretagne) were therefore needed to treat the acoustic data. The data was divided into two sets, each of whom was labelled by a different annotator. In order to evaluate how the manual labelling is dependent on the annotator sensitivity and learning progress (Leroy et al. 2018), a study of annotation variability has been conducted. Starting from the premise that the annotators improve their sound recognition skills with time, it was decided that two to three random files (of 10 minutes of duration each) should be labelled by both annotators per week of annotation. It allowed to acquire 19 common files at the end of the manual labelling work, which is a sufficient amount to obtain significant results of comparison.

All common files labelled by the two annotators were compared to each other for the number of killer whale sounds detected, summed on the time scales of a duration of 5 and 60 seconds. The choice of such time scales shows how different degree of precision affects the estimation of killer whale sounds manually detected in the context of the entire 10-minutes recording. Each of these recordings was divided into fragments of a given duration (5 or 60 seconds) through the software R (R Development Core Team, 2015). The rate of agreement between the two annotators was then calculated by two different approaches. In the first approach, the agreement between the two annotators was checked for the presence and absence of sounds in the given time-window. In the second approach, the accordance was determined for the annotation of sounds of specific type - echolocation and vocalizations. The results of this comparison were subsequently treated in order to obtain boxplots for each time scale.

2.4 Acoustic detection of killer whales during fishing activities

In order to assess the occurrence of killer whales found by the passive acoustic monitoring during the fishing activity, the information regarding the longlines given in the PECHEKER dataset was exploited. The following PECHEKER records attributed to each deployment were used: date, time, latitude and longitude of the beginning and of the end of the longline's setting and hauling; visual observation of the presence or absence of killer whales during hauling.

2.4.1 Detection range

The detection range of killer whales' sounds by the hydrophone was approximated from the comparison of the distances between the static hydrophone and two types of events: (1) the occurrence of both visual and acoustic observations of killer whales at the same time and (2) the occurrence of visual observations of killer whales only. The effort for visual observations was carried on from the fishing vessel only during hauling of the lines. Therefore, the geographical position of those observations is known, as is the position of the static hydrophone. The sound detection range has a major importance in the evaluation of killer whales' spatial and temporal movements around longlines. The sound, while propagating, is submitted to the transmission loss. We hypothesized that the further away from the hydrophone the individuals were observed, the less chance there was of detecting the sounds produced by them. When both visual and acoustic detection occurred at the same time, while the fishing vessel was within the sound detection range, we assumed that the individuals heard on the recording, and the ones observed from the fishing vessel were the same animals. By comparing the distances at which both types of detection occur (visual and acoustical) with the distances at which killer whales appeared only visually, it was possible to find when the killer whales were too far from the hydrophone to be detected acoustically, providing by this means the range of sound detection.

The distribution of distances between the hydrophone and the fishing vessel at the time of simultaneous visual and acoustical detection was plotted and overlapped with the distribution of distances between the hydrophone and the vessel at the time only visual presence of killer whales was detected. The distances at which the two lines cross gave the most probable limits of killer whales' sounds detection by hydrophone. A mean was calculated for these distances (n=11), and the result was applied as the detection range of killer whales' sounds by the hydrophone for all of the deployments.

2.4.2 Rates of observations during different fishing operations

The occurrence of killer whale sounds within the deployments obtained by manual labelling was plotted on a time axis together with the duration of different fishing activities (setting and hauling) and the occurrence of visual observations of killer whales acquired from the PECHEKER database. Another set of graphs was plotted for the distances separating the beginning and end of each fishing operation from the static hydrophone (also PECHEKER), with an additional line showing the detection limits of the hydrophone (as described above).

By comparing these two types of graphs, it was possible to estimate the rates of acoustical detection of killer whales per fishing activity. The estimation was carried on in reference to segments of three types: (1) setting of the longline, (2) hauling of the longline and (3) intervals between these two fishing operations. Only the operations carried on after the setting of the hydrophone and before its hauling were taken into account. The total number of segments in one deployment was considered as equal to 100% of its duration.

As the visual observations of killer whales depredating on the longlines take place only during hauling, therefore acoustic tools are not indispensable to monitor killer whales' behaviour of depredation during this type of fishing operation. Our interest focused thus on the killer whale activities at the time they could not be seen from the fishing vessel during hauling. Because the visual observations (presence or absence of killer whales) during data collection were noted at the time scale of an entire operation of hauling, the precise time of whales' presence at the sea surface is unknown. Therefore, the analysis of killer whale behaviour in the context of fishing activities was adapted to the same time scale as visual observations, that is per segment.

The following information was verified for each segment of the deployment: (1) whether the fishing vessel was inside or outside the detection range of killer whales' sounds by the hydrophone, (2) what fishing operations was the vessel performing, (3) whether killer whales were visually observed around the fishing vessel (during hauling), (4) whether killer whale sounds (and what type) were recorded by the hydrophone. Taking into account all the options associated with killer whale detection and fishing operations in the zone, there were several possibilities of the interpretation in the context of depredation, as presented in the table below (Tab. 1).

	Fishing operations	**Killer whale detection**	**Interpretation**
1	The fishing vessel was **inside detection range** of killer whales' sounds, **hauling** a longline.	Acoustic and visual	The killer whales detected by the hydrophone were probably the same as the ones observed visually and they might have been depredating on the line during hauling.
		Only visual	The killer whales might have been depredating on the hauled line, but remained silent.
		Only acoustic	The killer whales were active nearby the longline equipped with the hydrophone, but not interacting with the fishing vessel.
2	The fishing vessel was **outside detection range** of killer whales' sounds, **hauling** a longline.	Acoustic and visual	The killer whales observed visually could not be the same as the ones recorded by the hydrophone. Visually detected whales might have been depredating on the hauled line, and acoustically detected whales were active nearby the hydrophone.

		Only visual	The killer whales detected visually might have been depredating on the hauled line, and no killer whale was present nearby the hydrophone.
		Only acoustic	The killer whales detected acoustically were active nearby the longline equipped with the hydrophone, and no killer whale was interacting with the fishing vessel.
3	The vessel was **not hauling** a longline.	Only acoustic	The killer whales were active nearby the longline equipped with the hydrophone, and no killer whale was interacting with the fishing vessel.

Tab. 1. **Possible interpretations of killer whale detection in the context of fishing operations.**

The analysis of different cases, combined with the acoustic cues of killer whale behaviours, allowed to presume whether an activity of depredation on the longlines could occur. Indeed, in passive acoustic monitoring, the factor determining to the full extent whether killer whales were depredating or not, was the presence of echolocation sounds in the given fragment of the recording, as those sounds are assigned to the activity of foraging.

III Results

3.1 Data collection

During the period of field study, the hydrophone was moored on 11 deployments, what resulted in 400 hours of recordings. The acoustic presence of killer whales was detected in six deployments, and visual observations occurred in eight deployments. The overall results showed that each deployment was highly variable and it was not possible to generalize the interpretation of killer whale behaviour in the context of fishing activities for the totality of the campaign. However, we observed some interesting trends of killer whale activity around longlines equipped with the hydrophone. Indeed, we found all types of cases, with fishing vessel inside and outside of the detection range, with both acoustical and visual detection of killer whales at the same time and with only acoustical or only visual observations. There were some deployments with numerous killer whale sounds and other ones with no detection at all. Some of the qualitative results of our analysis are presented here below (Figs. 5 and 6), other may be found in the Appendix. In the next step, we quantified the acquired data in order to obtain a more complete picture of the situation at EEZ of Crozet Islands.

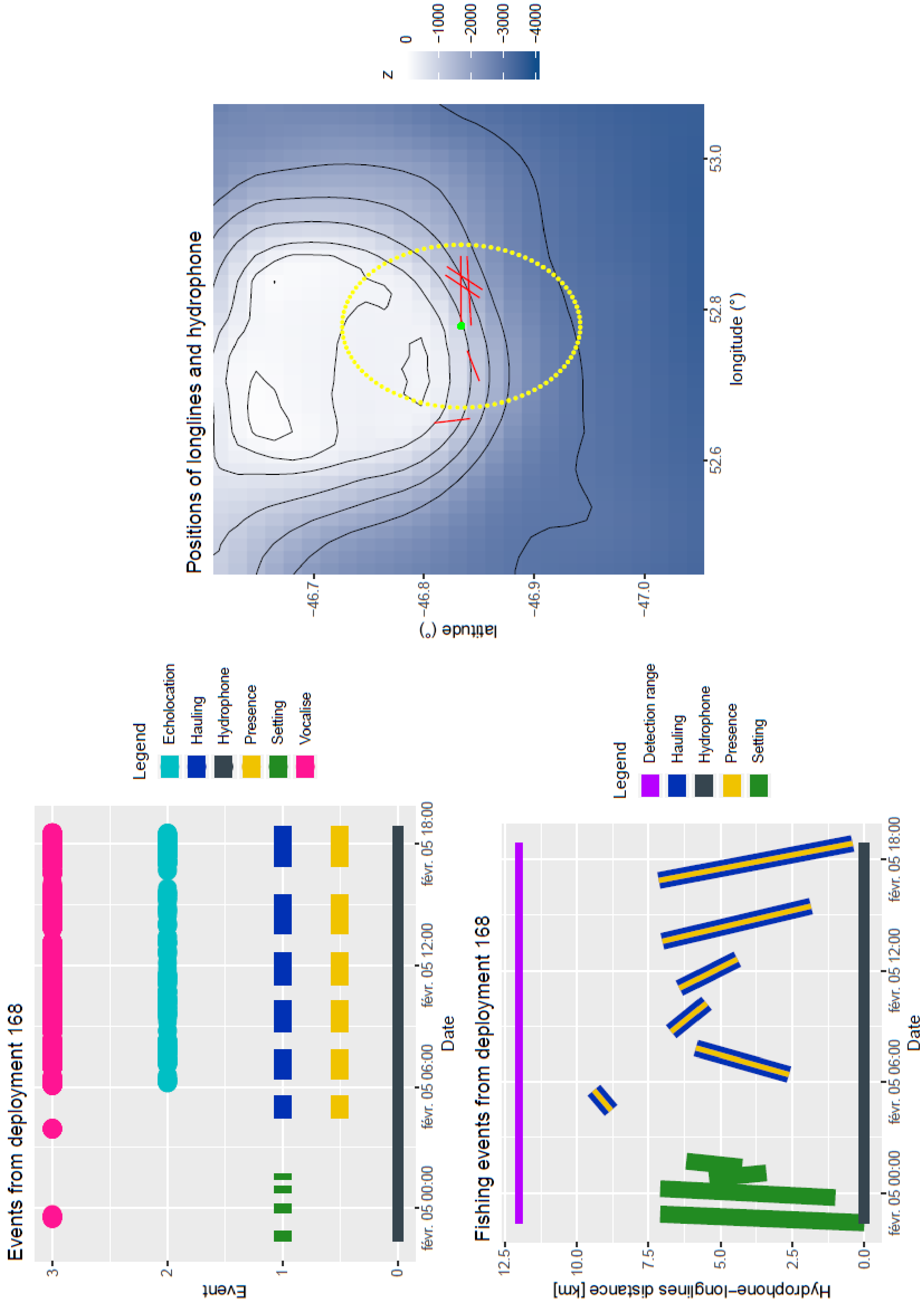

Fig. 5. **Killer whale activities and fishing operations during deployment 168.** The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).

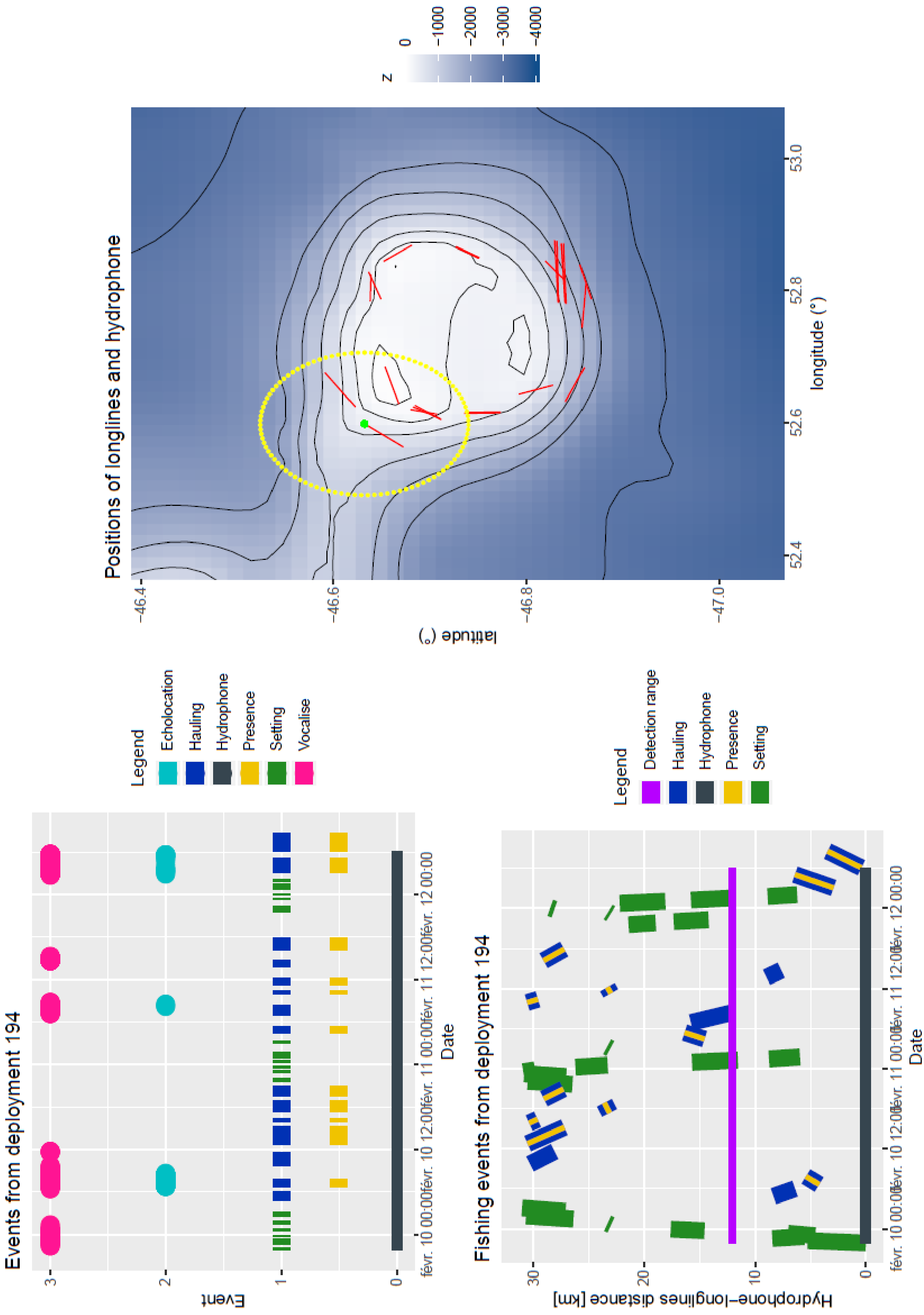

Fig. 6. **Killer whale activities and fishing operations during deployment 194.** The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).

3.2 Annotation variability

In total, 19 random files were labelled by both annotators to test their variability of annotation (Fig. 7).

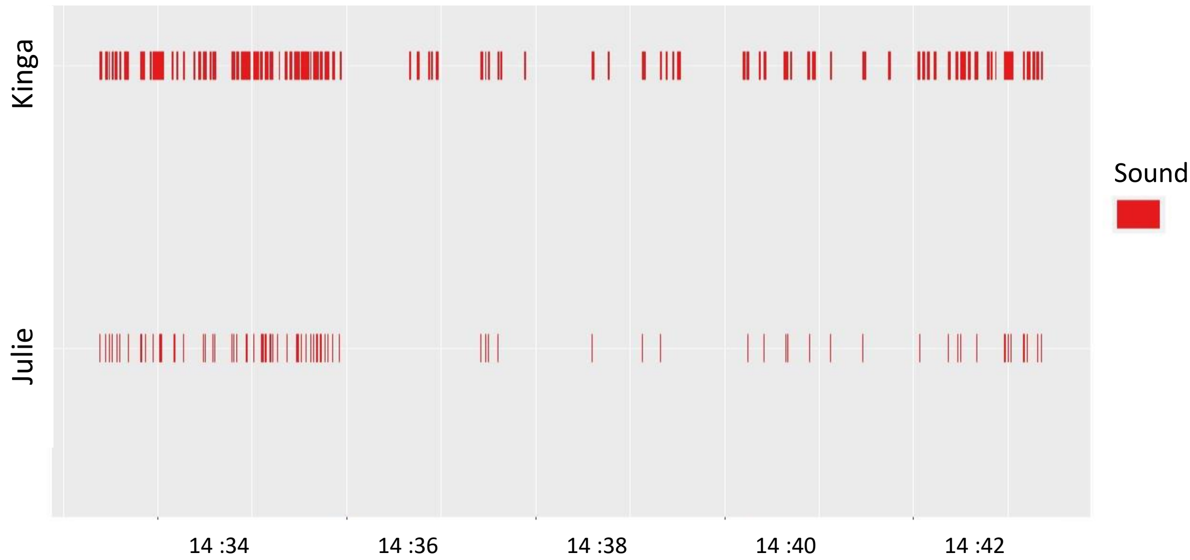

Fig. 7. **An example of annotation variability between the two annotators** (y axis) at a scale of 10 minutes (x axis). Although one person annotated more sounds than the other, there is a visible agreement on the presence of sounds on a 60 second scale.

The agreement between the two annotators increased along with time scale extension from 5 to 60 seconds (Fig. 8). At the time scale of 5 seconds, the annotators tended to agree more for the presence or absence of killer whale sounds in a given time frame (Fig. 8, Total [5s]), than for the category of labelled sounds (Fig. 8, Sounds [5s]). At a scale of 60 seconds however this difference disappeared (Fig. 8, Total [60s] and Sounds [60s]). Two minimum outliers (Fig. 8, Sounds [5s] and Sounds [60s]) correspond to one file, where no agreement for the sound category was found between the annotators. Taking into account that in this file all the sounds labelled by both annotators lasted for only 1.7% of the duration of the file, this disagreement can be neglected.

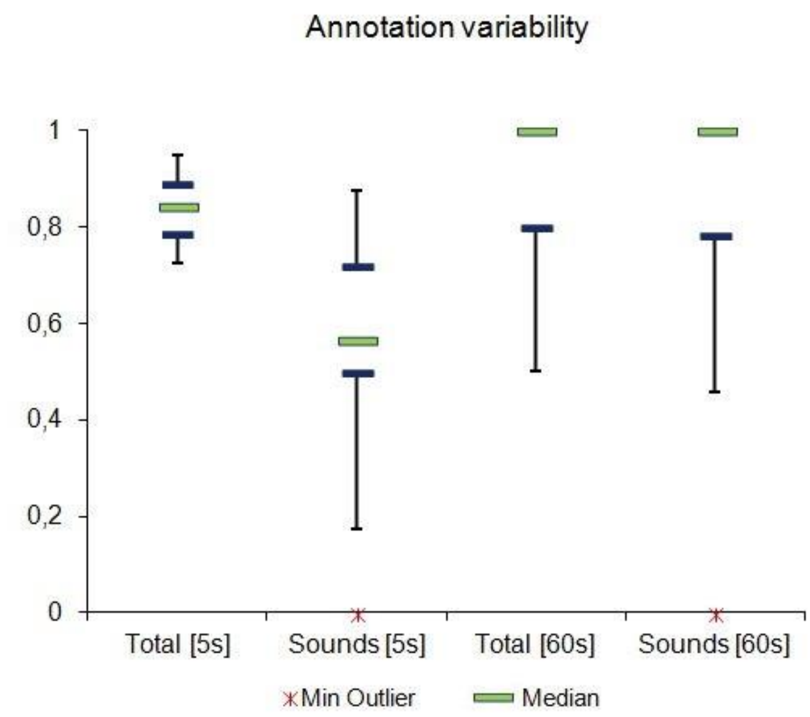

Fig. 8. **Boxplot of annotation variability between two annotators.** Summary results are shown for two categories of sounds (echolocation, vocalizations) for the time scales of 5 and 60 seconds. *Total* corresponds to the agreement for the presence of sounds; *Sounds* correspond to the agreement for the category of labelled sounds.

The agreement between the two annotators is very high at the time scale of 60 seconds for both presence (0.88 ± 0.16) and category of sounds (0.85 ± 0.26); for most of files the rate of agreement is contained between 0.8 and 1, and it never descends below 0.5. The time scale of 60 seconds is very precise for the application in analysis of killer whale activities over the deployments, in comparison to the large scale of fishing activities of one deployment (minimum 15 hours up to several days of duration in this study). These results revealed that the annotations of the two annotators are very comparable, allowing us to use the recordings labelled by both of them as a unitary whole.

3.3 Acoustic detection of killer whales during fishing activities

3.3.1 Detection range

The comparison of distances between the hydrophone and the fishing vessel at the time of concurrent visual and acoustical detection and the distances between the hydrophone and the vessel at the time when killer whales were spotted only visually, was presented on figure 9 (Fig. 9).

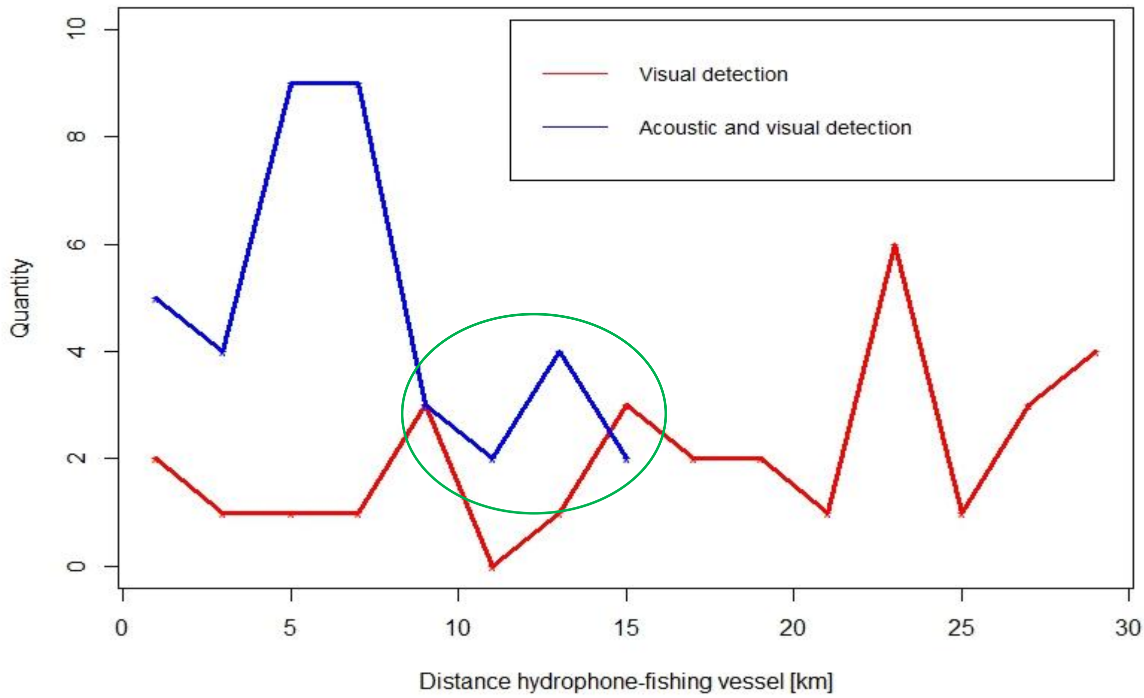

Fig. 9. **Sound detection range by the hydrophone.** Distances between the hydrophone and the fishing vessel at the time of simultaneous visual and acoustical detection (blue line) were plotted and overlapped with distances between the hydrophone and the vessel at the time only visual presence of killer whales was detected (red line). The green ellipse points out the values which were used for the calculation of the detection range.

Starting from the premise that killer whales recorded by the hydrophone were the same as the individuals seen simultaneously on the sea surface, and that individuals only detected visually were missed on recordings because of being out of detection range, it was possible to find the distance from the sound's source at which the hydrophone was not able to detect any more sound. The distances with only visual observations (red line on the histogram) reach much higher values than the distances with both types of observation (blue line). Indeed, for distances above 15 km, visual observations of killer whales are only more frequent, suggesting that at these distances killer whales observed from the fishing vessel could not be recorded by the hydrophone if they emitted sounds. Additionally, we observed a higher number of acoustic recordings paired with visual observation from the fishing vessel at distances from the hydrophone below 9 km (Fig. 9). This suggests that at such a close range killer whales observed and heard were the same animals. From these observations we could assume that the detection range of killer whale sounds vary from 9 to 15 km. For the rest of the analysis we decided to use the mean detection range of 12 km (n=11). Thus, when fishing vessel was hauling at a distance closer than 12 km, we considered that killer whales heard on the hydrophone were depredating on the longline being hauled. On the contrary, for a vessel hauling longline further than 12 km from the hydrophone, we assumed that killer whales detected acoustically were not interacting with the hauled longline.

3.3.2 Rates of observations during different fishing operations

In the six deployments where acoustic presence of killer whales was detected (Tab. 2), it varied widely, from 18% to 85% of segments of the deployment's duration (Tab. 2, % Acoustic presence). Among the segments with acoustical detection, from 14% to 43% overlapped temporarily with the operation of hauling, and from 57% to 86% (Tab. 2, % Acoustic presence aside from hauling) of segments were not associated with this activity. Echolocation sounds were detected on five deployments, within a large range of segments, from 10% to 62% (Tab. 2, Echolocation). Among the segments with echolocation, from 13% to 67% were related to hauling, and from 33% to 88% (Tab. 2, % Echolocation aside from hauling) were not.

DEP.	% Segs. with acoustic presence	% Acoustic presence aside from hauling	% Segs. with echolocation	% Echolocation aside from hauling
161	28	60	17	33
168	63	58	53	50
175	80	67	60	56
190	85	82	62	88
194	30	86	10	71
220	18	57	0	0

Tab. 2. **Percentages of segments with acoustic detection of killer whales per deployment (DEP).** Column 1: % of segments with acoustic presence; column 2: % of acoustic presence not related to haulings of longlines; column 3: % of segments with echolocation sounds; column 4: % of echolocation sounds not related to haulings of longlines.

Killer whales were detected shortly after the beginning of the fishing campaign, during the first hauling of the first deployment (Appendix), and they stayed in the fishing zone for 12 days. Initially they were spotted visually, and later they were detected by the hydrophone.

By comparing different types of activities of both killer whales and of the fishing vessel, we distinguished several trends. In three deployments (Tab. 2, DEP. 168, 175 and 190) we observed that killer whales were acoustically present and echolocating for more than 50% of segments. In two cases the fishing vessel was mostly present within the acoustic range of detection (DEP. 168, 175), whereas in the third one the fishing vessel drew away from the range of detection by the hydrophone for a significant amount of time (DEP. 190).

In other three deployments (DEP. 161, 194, 220) killer whales were acoustically active only for 30% of segments or less, however a considerable part of their activity occurred aside from hauling. In those deployments, killer whales were echolocating during very small amount of segments (0% to 17%), even though in deployment 194 the rate of echolocation aside from hauling was high (71%). In deployment 220, where 0% of echolocation occurred, the fishing vessel was outside of the acoustic detection range for most of the time, moving away for over 140 km from the hydrophone. In deployment 161, the fishing vessel stayed either within or at the limit of the detection range, and in deployment 194 it drew away for a significant amount of time.

Generally, all acoustic presence of killer whales mainly occurred during segments aside from hauling (>55% of segments). For the echolocation, high proportion (>50%) of segments aside from hauling was found in four out of six deployments (168, 175, 190, 194). Acoustic detection of killer whales aside from hauling suggests the foraging activity of killer whales around the hydrophone and no interaction with the vessel.

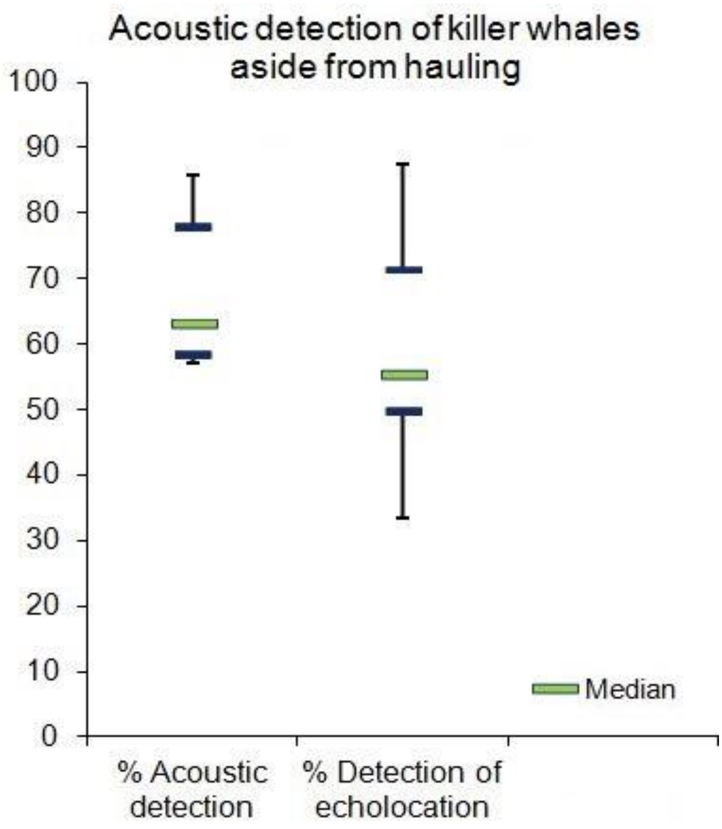

Fig. 10. **Boxplot of acoustic detection of killer whales aside from the fishing activity of hauling.** <u>% Acoustic detection</u>: the percentage of segments with acoustic detection that were not associated with the activity of hauling (n=6). <u>% Detection of echolocation</u>: the percentage of segments with detection of only echolocation sounds that were not associated with the activity of hauling (n=5).

Our results indicate that within the six deployments where acoustic detection of killer whales occurred, the whales were often acoustically active while not interacting with the fishing vessel hauling a longline (Fig. 10). The rate of acoustic detection aside from the activity of hauling was generally higher for all the sounds than just for echolocation, what is explained by the faster attenuation of echolocation sounds than of vocalizations. Acoustic detection with no visual observations occurred on 35 ± 21% of segments on average (Tab. 2), what indicates that acoustic methods of monitoring in the case of killer whale depredation bring additional information to visual survey.

IV Discussion

This study revealed for the first time an important proportion of acoustic detection of killer whales with echolocation (as in the case of deployments 168, 175, 190 - see Tab. 2) occurring aside from the fishing operations of hauling. Therefore, we assumed that individuals were actively and repeatedly foraging within the fishing zone and especially while they could not interact with the fishing vessel. Although different cases varied widely, our results provide the confirmation of earlier assumptions about killer whale foraging behaviour within a depredation context (Richard 2019a). The recorded individuals were actively and repeatedly foraging within the fishing zone and at the times they could not interact with the fishing vessel.

The fast arrival of killer whales during the first deployment (DEP. 161) implies that most probably they were already present in the zone before the beginning of the campaign. A possible explanation for killer whales' preference for this location (a seamount located Southeast of the East Island), is that this zone includes a hotspot of Patagonian toothfish. Indeed, it has been recently confirmed that Patagonian toothfish belong to the natural diet of Crozet killer whales (Tixier et al. 2019), and that some individuals performed natural foraging behaviour on this location (seamount, see Richard et al. 2019b).

Several restraints may be suspected to have played a role in the course of acoustic detection of killer whales and/or the interpretation of the results. To start with, both annotators participating in the process of manual acoustic labelling, were doing it for the first time. Taking into account that the skills of sound recognition improve with time, it would be possible to obtain slightly different results if the persons performing the labelling had more experience. However, by selecting files over time of the labelling process for the test of annotators' variability, we were able to limit the negative impact of this factor and obtain reliable results (Leroy et al. 2018). The frequency filter exerted on the recordings to remove the acoustic signature of the fishing vessel, could have masked some of the killer whale vocalizations below 2500 Hz. Still, sounds produced at such low frequencies can reveal high frequency harmonics, making them detectable. Besides, we detected numerous sounds above this frequency range, and moreover, the time scale of deployments is sufficiently large not to be affected by small omissions. Therefore, this constraint does not influence the detection of killer whales. The sound detection range is not of a constant value but can vary according to several conditions, such as: the bathymetry (e.g. presence of a solid obstacle between the source and the detector), weather conditions, intensity of sound at its source, noise caused by fishing vessels, presence of sounds produced by other species of cetaceans. In addition, the direction in which the sound is emitted may play a role in the capacities of the hydrophone to detect it. For these reasons we applied a mean of distances for the approximation of the sound detection range. The lack of visual confirmation of the presence of killer whales detected by the hydrophone during hauling of a longline within the sound detection range (like at some point in deployment 194) does not give a certainty that the animals are depredating on a soaked line. For the visual observations to occur there are also conditions that need to be fulfilled, such as time in a day with enough sunlight and suitable weather conditions.

The core of this study was the analysis of killer whale behaviour in the context of the operations performed by fishing vessel. To estimate when and where different activities of killer whales occur, we calculated the percentages of different types of segments in each deployment. This approach provides a general view of what is happening during the deployments, but is not as precise as would be with the use of exact time and duration of the actions of both killer whales and the fishing vessel. An accurate quantification of the events is feasible, through the calculation of detection-positive minutes (a widespread technique in PAM). However, it requires more time, therefore it was not possible to accomplish this goal within the duration of this internship.

Revealed in this study high percentage of echolocation of killer whales aside from hauling, suggests a possibility of killer whales foraging around longlines soaked at the seafloor. Echolocation signals known as a proxy of foraging, were also used before as depredation cues on a whole variety of species (e.g. Thode et al. 2015). According to all these elements we can presume that killer whales in the proximity of longlines were foraging or depredating. As far as the conclusions may go, it is not possible to confirm with a certainty which one of these two activities the killer whales were performing. However, the hypothesis of foraging seems less likely, considering the additional effort and energy expense the killer whales would have to undertake without a guarantee of success, while an easy catch is awaiting attached to the hook.

So far, no techniques are able to provide full evidence in this matter, because doing so would require installation of cameras at great depths, along with lighting that would affect the behaviour of both, killer whales and fish. Further investigation is advised with the use of greater amounts of data collected over a longer period of time. A useful approach could be carried on with the use of a mobile hydrophone stereo system for real-time acoustic localization of killer whales, to obtain more accurate data on spatial movements of killer whales around longline fishing gear. The slowness of the process of manual acoustic labelling implies the need to develop automatic tools for the detection of killer whale sounds.

This study has major implications for the way depredation is estimated and incorporated into fish stock assessment as well for the conservation of depredating odontocete populations. Our results demonstrate that visual observations from fishing vessels are not enough to correctly quantify depredation rates. The rates of depredation are estimated from the difference between catch per unit effort on longlines in absence of cetaceans and longlines in presence of cetaceans (e.g. Hucke-Gaete et al. 2004, Purves et al. 2004, Roche et al. 2007, Gasco et al. 2015). Seafloor depredation cannot be quantified because of lack of observation, what causes the depredation rates to be underestimated.

To conclude, there is a high probability that killer whale depredation on a longline soaking at the seafloor could be a common behaviour. This evidence brings a new insight to the fishing companies and scientists working on the development of new solutions to depredation. Indeed, previous efforts to minimize toothed whale depredation on demersal longline fisheries have primarily relied on the assumption that the predator would remove fish from hooks only during hauling of longlines (Gilman et al. 2006, Werner et al. 2015). However, if killer whales depredate fish on the seafloor, as suggested by the present study, efforts to develop new mitigation techniques should be orientated toward the development of a system that would protect the fish and/or deter the whales throughout the entire period of a deployment.

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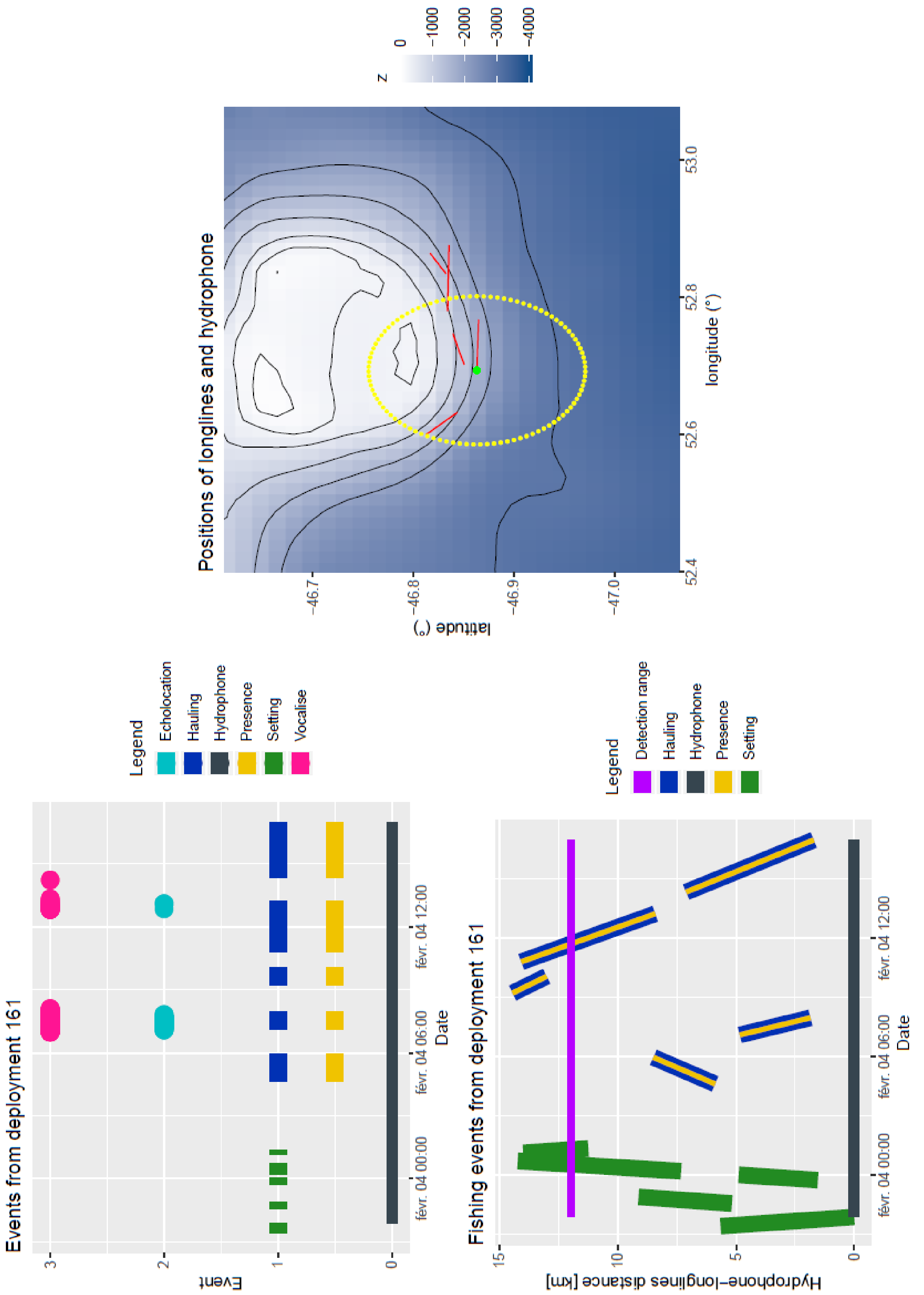
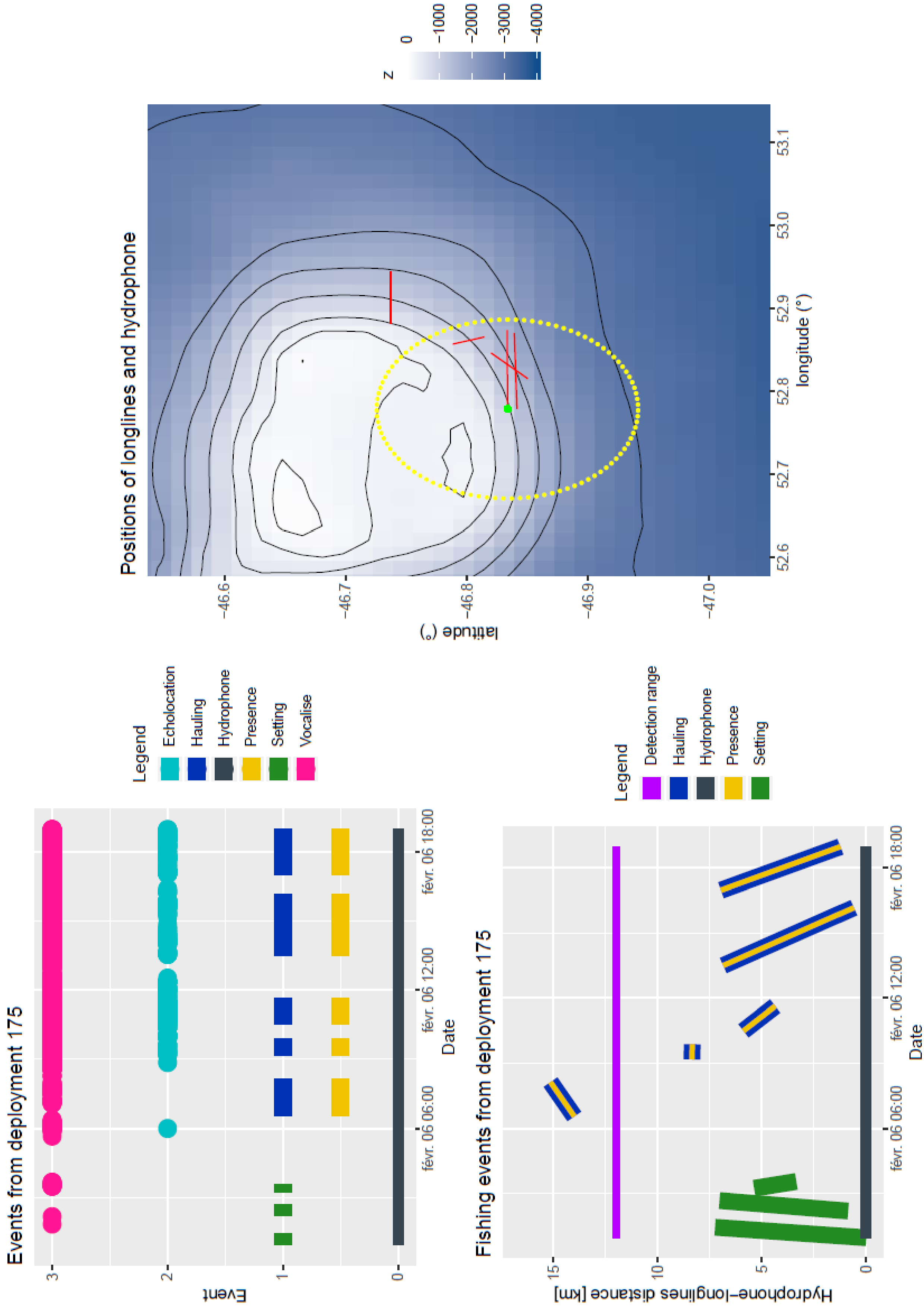
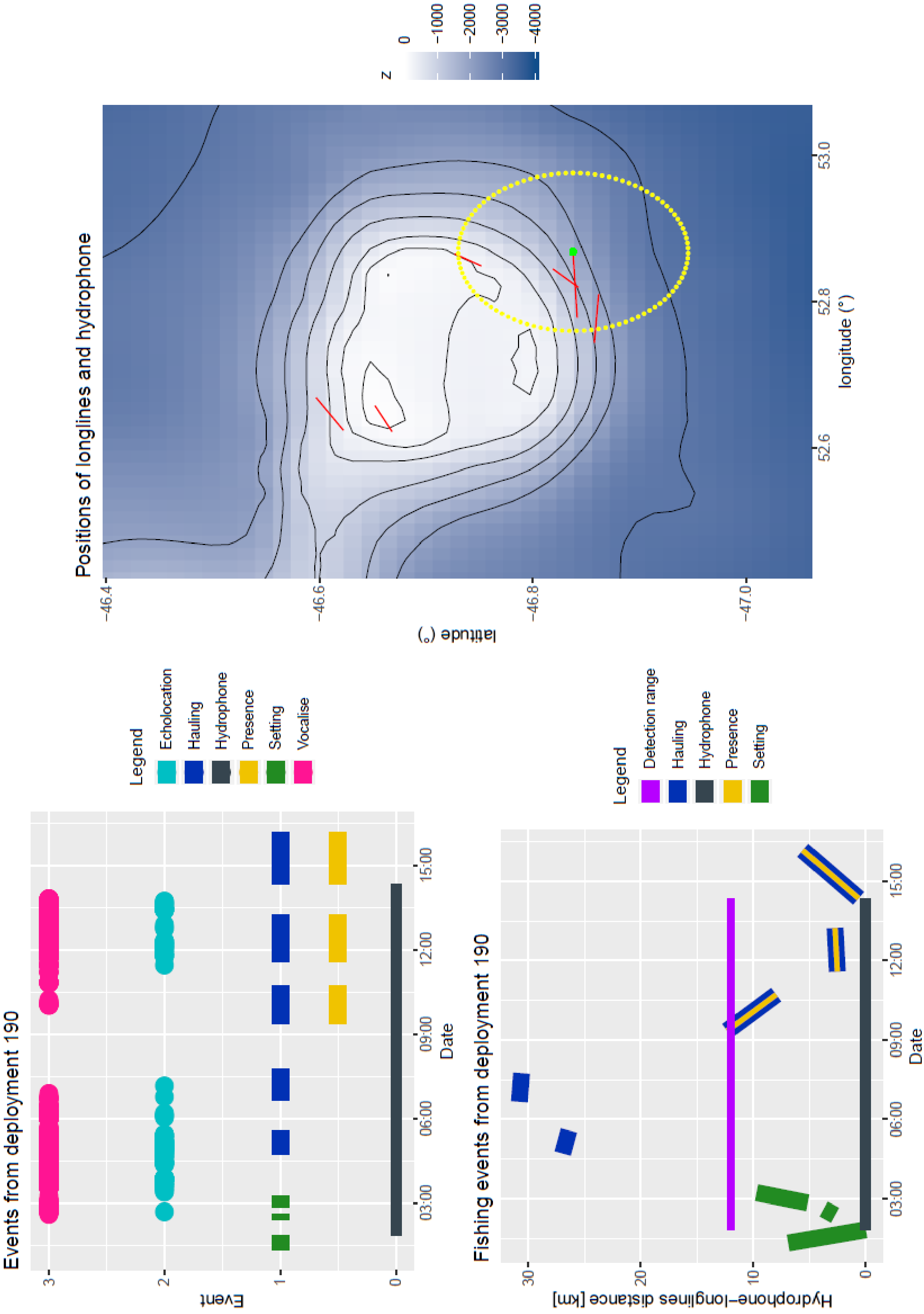
Appendix



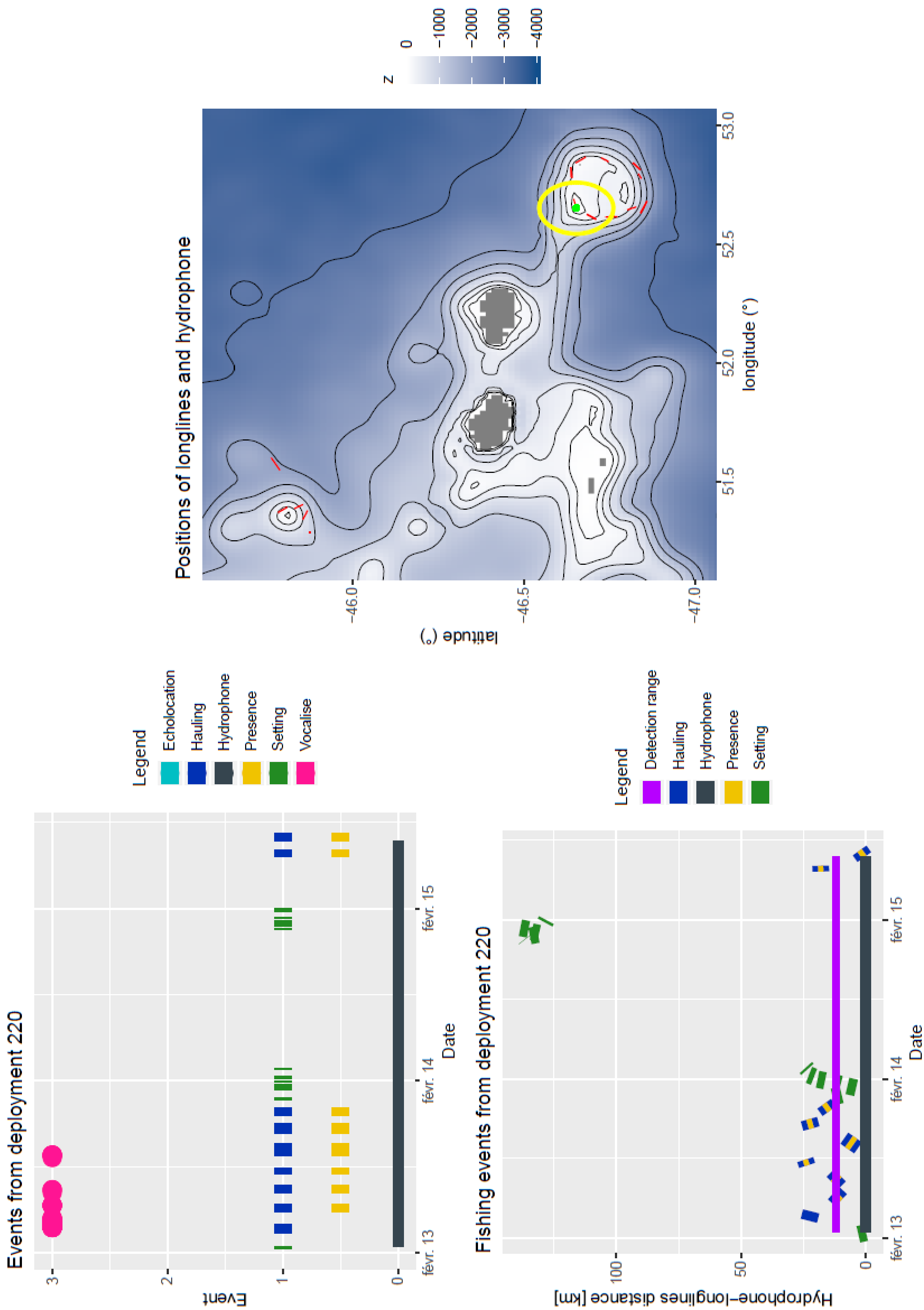
Killer whale activities and fishing operations during deployment 161. The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).



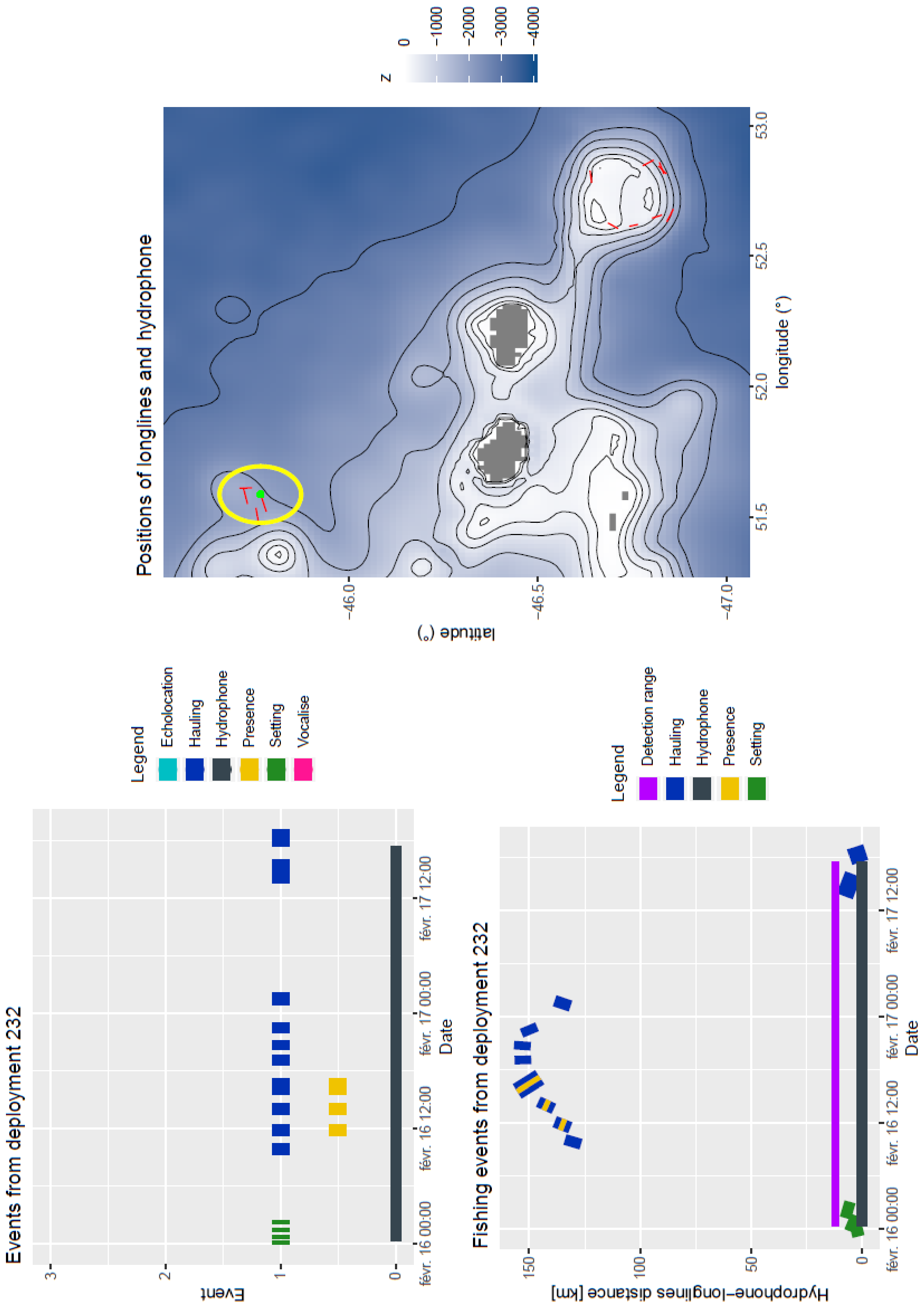
Killer whale activities and fishing operations during deployment 175. The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).



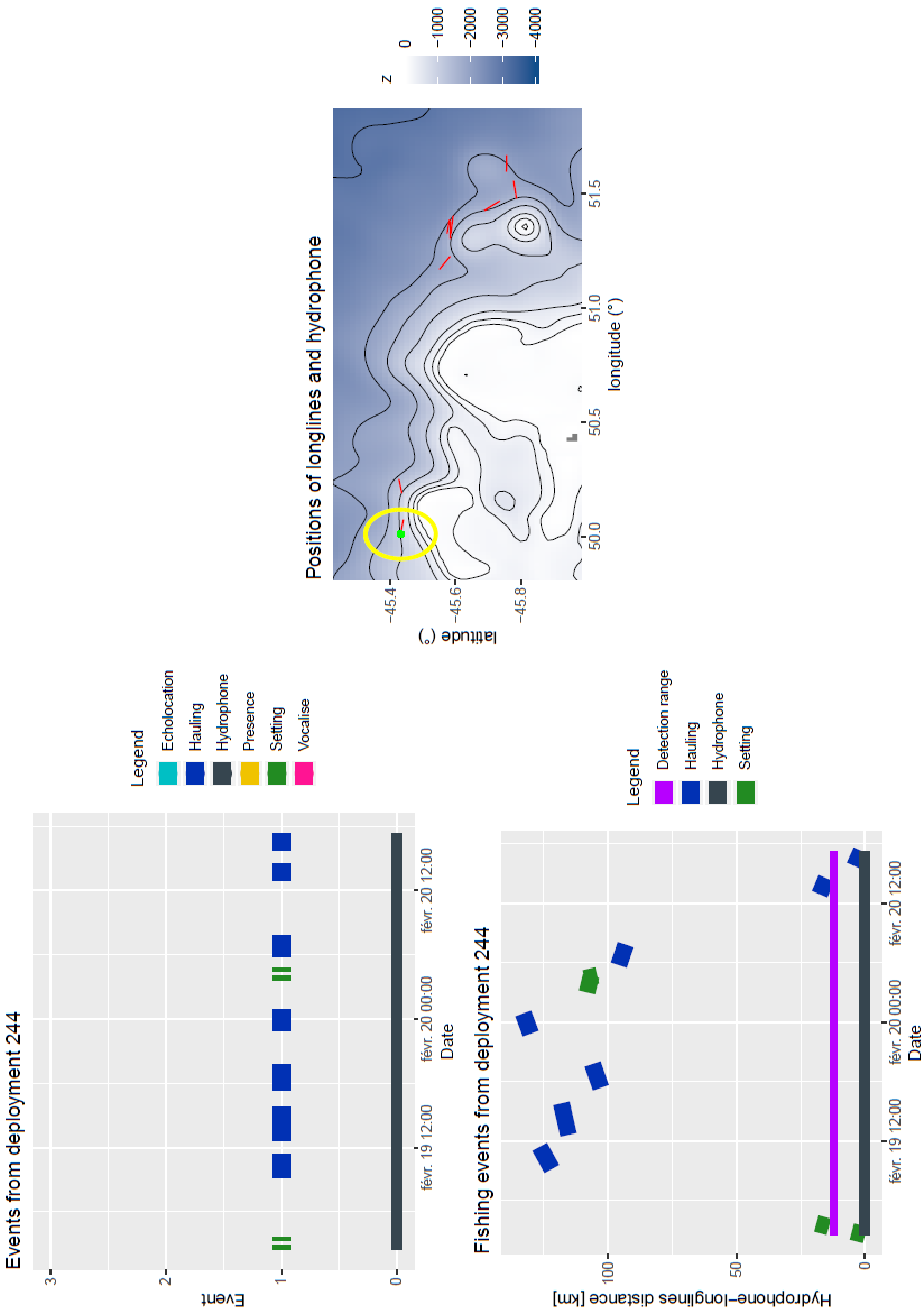
Killer whale activities and fishing operations during deployment 190. The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).



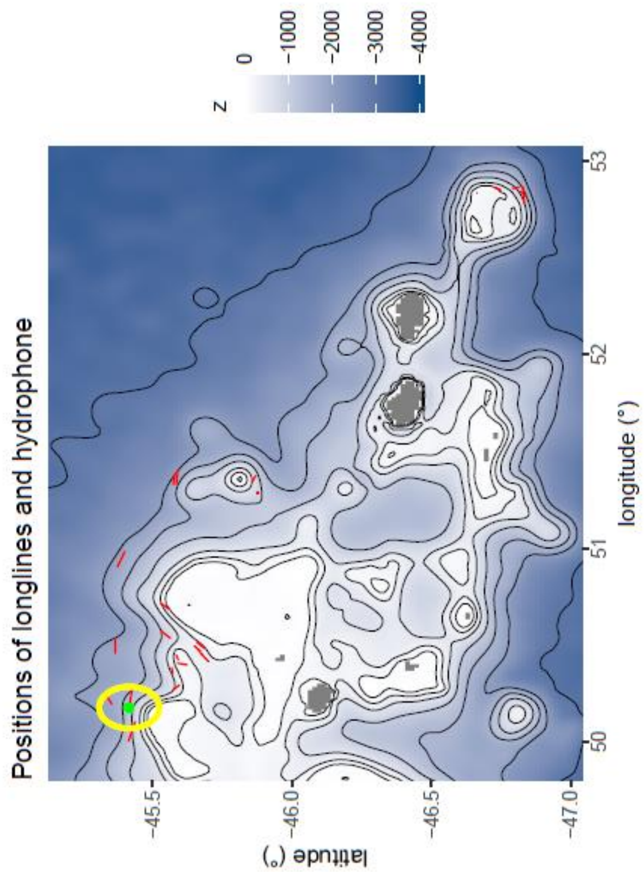
Killer whale activities and fishing operations during deployment 220. The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).

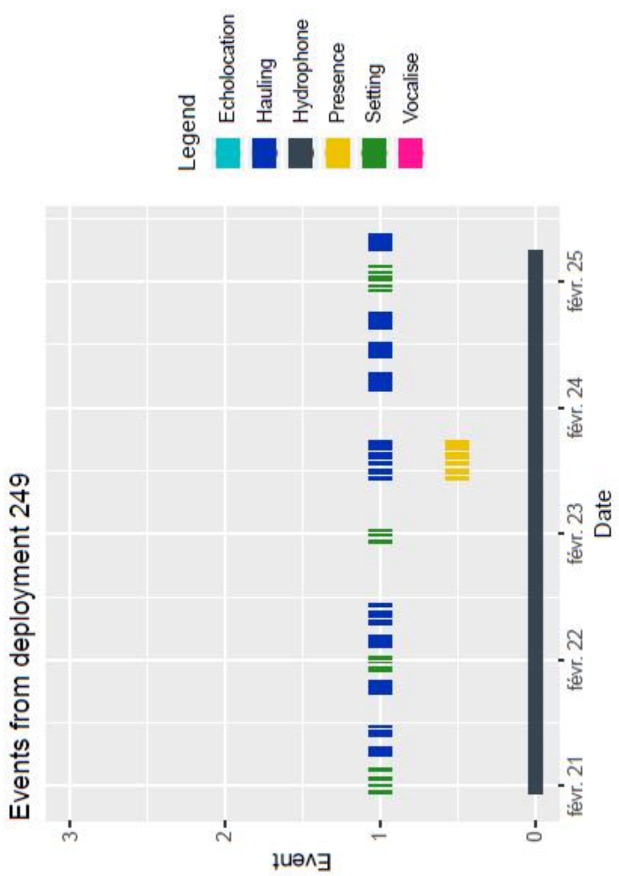


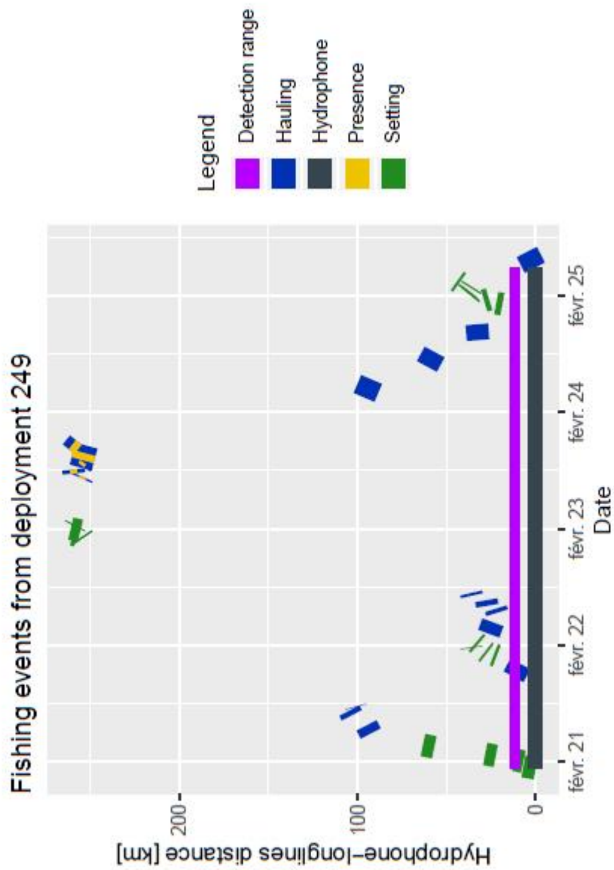
Killer whale activities and fishing operations during deployment 232. The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).



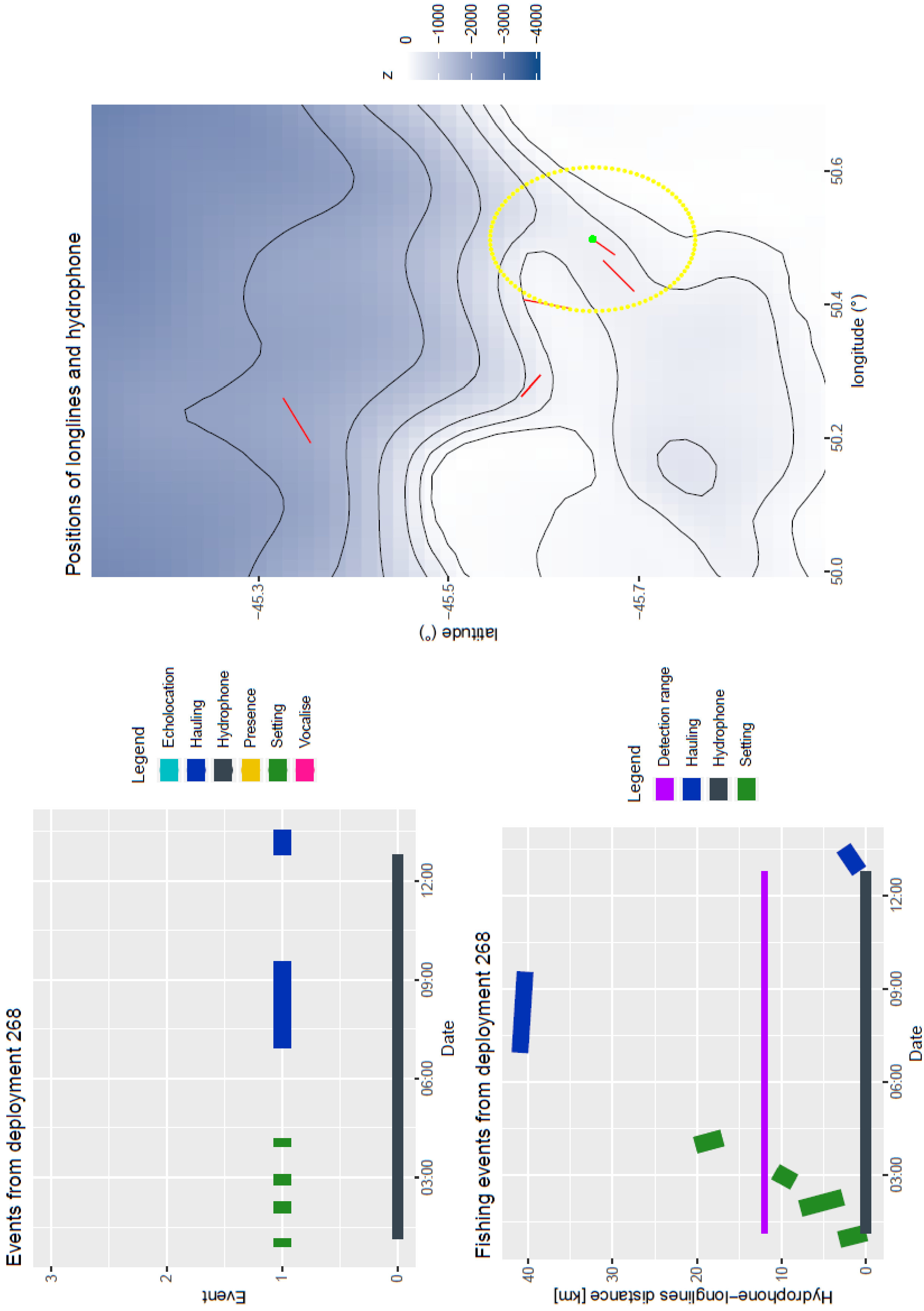
Killer whale activities and fishing operations during deployment 244. The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).



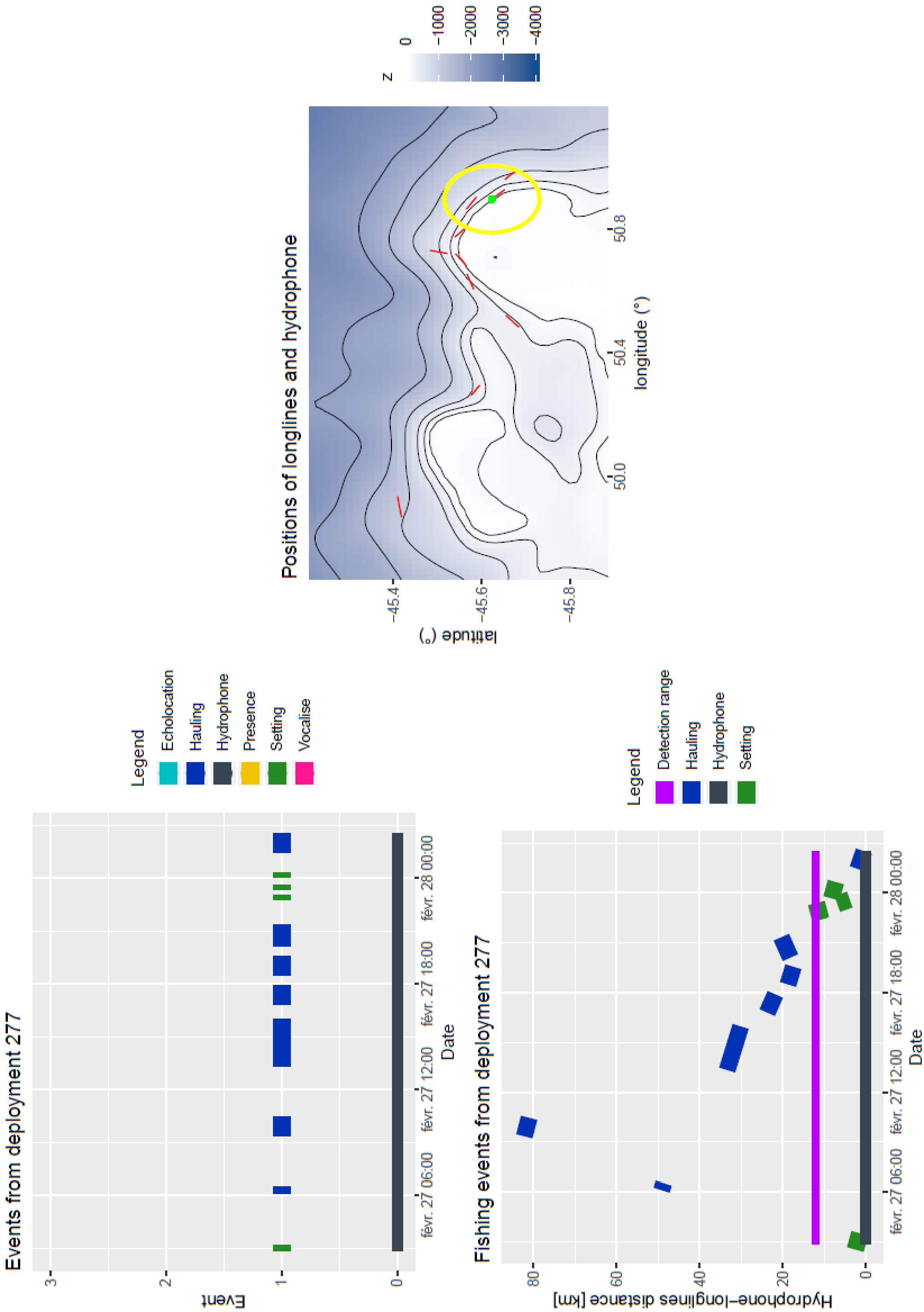




Killer whale activities and fishing operations during deployment 249. The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).



Killer whale activities and fishing operations during deployment 268. The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).



Killer whale activities and fishing operations during deployment 277. The bathymetrical map shows the positions of all the longlines within the deployment (red lines), the position of the hydrophone (green dot) and the approximate detection range (yellow circle).

Suivi des interactions orques-palangres par acoustique passive dans la Zone Economique Exclusive de Crozet

Résumé

Les odontocètes et d'autres espèces marines se nourrissant de poissons capturés lors de la pêche à palangre, constituent un problème croissant dans le monde entier. Ce comportement, appelé déprédation, a un impact important sur la rentabilité de la pêche, mais peut également jouer un rôle important dans la conservation de la faune. Causant des problèmes de bien-être animal et des préoccupations socio-économiques pour les pêcheries, le phénomène de déprédation soulève la nécessité cruciale de développer des solutions d'atténuation. L'estimation actuelle de l'ampleur de la déprédation est probablement inexacte, car la connaissance du problème dans le temps et dans l'espace est limitée. Dans la présente étude, nous avons étudié la déprédation par les orques (*Orcinus orca*), l'espèce considérée comme l'une des plus impliquées, sur les palangres démersales de la pêcherie française à la légine australe des îles Crozet (Océan Austral). Pour estimer le comportement des orques dans le contexte des opérations de pêche, nous avons utilisé l'approche du Suivi par l'Acoustique Passive. Nos résultats ont fourni une nouvelle preuve que les orques peuvent déprédater pendant tout le processus de la pêche, et pas seulement lorsqu'ils interagissent avec le navire de pêche. Cette découverte devrait être envisagée dans le futur développement des solutions pour ce problème.

Mots-clés : *orque, déprédation, foraging, pêche à la palangre démersale, suivi par l'acoustique passive*

Passive acoustic monitoring of the interactions between killer whales and demersal longlines in the Exclusive Economic Zone of Crozet Islands

Abstract

Odontocetes and other marine species feeding on captured fish in longline fisheries, is a growing issue worldwide. Such behaviour, known as depredation, have a great impact on the profitability of fisheries, but may also play an important role in the wildlife conservation. Causing animal welfare issues and socioeconomic concerns for the fishing companies, the phenomenon of depredation raises a critical need for mitigation solutions to be developed. The current estimation of the scale of depredation is likely inaccurate as there is limited knowledge of the issue in both space and time. In the present study, we investigated depredation by killer whales (*Orcinus orca*), the species considered as one of the most involved, on demersal longlines in the French Patagonian toothfish fishery of Crozet Islands (Southern Ocean). To estimate killer whale behaviour in the context of fishing operations, we used the approach by Passive Acoustic Monitoring. Our results provided a new evidence that killer whales might depredate during the whole fishing process, and not only while interacting with the fishing vessel. This find should be considered in future developments of mitigation solutions to the issue.

Key words: *killer whale, depredation, foraging, demersal longline fishery, passive acoustic monitoring*