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Mapping shipping noise in the Pelagos Sanctuary (French part) through acoustic modelling to assess potential impacts on marine mammals

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Résumé. **Cartographier le bruit engendré par le trafic maritime dans la partie française du Sanctuaire Pelagos par le biais d'un modèle acoustique pour évaluer les impacts potentiels sur les mammifères marins.** Le bruit sous-marin d'origine anthropique est reconnu comme une source de stress pour les cétacés. Cependant un manque de connaissances fondamentales entrave les efforts réalisés pour évaluer et gérer les impacts acoustiques à l'échelle du Sanctuaire Pelagos. Le présent travail vise à caractériser le bruit généré par le trafic maritime dans la partie française du Sanctuaire, puis à évaluer les impacts potentiels sur les populations de cétacés. Pour ce faire nous avons employé des techniques de modélisation de propagation sonore afin de produire des cartographies de bruit. Le modèle de propagation sonore fournit des estimations des niveaux de bruit dans l'ensemble de l'aire d'étude avec une résolution de 0,5 km. Les données d'entrée incluent des variables environnementales (température de l'eau, salinité, bathymétrie et nature du fond), une gamme de fréquences, ainsi que les positions des sources sonores dans l'aire d'étude (provenant du système de traçage des routes des navires nommé AIS, *Automatic Identification System*). Le flux temps-réel de données AIS alimente le système cartographique temps-réel qui a été développé (www.oceannoisemap.com), tandis que les données historiques ont été utilisées pour évaluer la distribution du bruit lors de l'été 2012 (période test). Dans l'ensemble de l'aire d'étude, les estimations des niveaux de bruit moyens varient entre 80 et 126 dB re 1µPa (rms). Les zones maritimes situées entre le continent et le nord-ouest de la Corse, ainsi qu'au nord-est de la Corse sont caractérisées par des niveaux de bruit moyens plus élevés que le reste de l'aire d'étude. Dans ces zones, les niveaux estimés excédaient 100 dB 95 % du temps, 110 dB 50 % du temps, et 120 dB 5 % du temps. Les niveaux instantanés atteignaient plus de 140 dB re 1µPa (rms). Sur la base des seuils connus d'apparition d'effets négatifs, ces résultats montrent que les niveaux de bruit estimés étaient suffisants pour engendrer un dérangement comportemental des cétacés. L'information obtenue lors de ce projet représente une première évaluation pour une grande surface des niveaux de bruit dans le Sanctuaire Pelagos et peut être utilisée dans le cadre de sa politique de gestion.

Mots-clés : bruit sous-marin, impact acoustique, cétacés, modélisation acoustique, Sanctuaire Pelagos.

Abstract. Anthropogenic underwater noise is widely recognised as a stressor for cetaceans, but current knowledge gaps hinder the efforts to assess and manage acoustic impacts in the Pelagos Sanctuary. The present project aimed at characterising noise from shipping through sound propagation modelling and mapping, and at assessing the potential impacts on cetaceans. The model provides estimates of noise levels throughout the study area with a resolution of 0.5 km. Input data are environmental variables (temperature, salinity, bathymetry and seabed type), a range of frequencies (models of noise spectra emitted by different categories of ships), and the positions of noise sources within the study area (coming from the ship tracking system named AIS for Automatic Identification System). The real-time flow of AIS data is used to feed the real-time noise mapping system that has been set up (www.oceannoisemap.com), while archival data were used to assess noise distribution during summer 2012 (taken as a test period). In the whole study area, average estimated noise levels varied between 80 and 126 dB re 1μPa (rms). Noisier zones were found in the area between continental France and north-western Corsica, as well as in north-eastern Corsican waters. In such areas, estimated levels exceeded 100 dB 95 % of time, 110 dB 50 % of time, and 120 dB 5 % of time. Maximum instantaneous levels reached more than 140 dB re 1μPa (rms). Based on known thresholds for the onset of negative effects, our results show that noise levels were sufficient to cause behavioural disturbance to cetaceans. The information gathered represents the first large-scale assessment of noise levels in the Pelagos Sanctuary and can be used as a basis for management purposes.

Keywords: underwater noise, acoustic impact, cetaceans, acoustic modelling, Pelagos Sanctuary.

Introduction

Marine mammals depend heavily on sounds for communication, navigation and prey detection. Their “acoustic habitat” is nowadays altered by anthropogenic noise having both direct and indirect effects on individuals and populations ((NRC (National Research Council), 2000, 2003; Simmonds *et al.*, 2004). Noise can indeed directly affect individuals by entailing behavioural or physiological changes, and may also cause secondary effects, for instance by disturbing their food sources. Sources of marine noise pollution include ship traffic, oil and gas exploration and exploitation, industrial and military sonar use, the use of experimental acoustic sources, undersea explosions, and offshore and inshore industrial construction works. In particular, ship traffic can be seen as a worldwide network of moving noise sources with variable characteristics (Scrimger and Heitmeyer, 1991). Noise from shipping is primarily produced by cavitation with most of energy in the low frequencies, i.e. less than 1 kHz (Wenz, 1962; Leaper and Renilson, 2012). As low frequency sound can travel over long distances (Tasker *et al.*, 2010; Van der Graaf *et al.*, 2012; Dekeling *et al.*, 2013), shipping noise contributes to raise background noise levels. At a global scale, shipping is the dominant source of underwater ambient noise at frequencies below 300 Hz (Wenz, 1962; Ross, 1976; Andrew *et al.*, 2002, 2011; Hildebrand, 2009), and for the Mediterranean case, even for frequencies up to 500 Hz (Pulvirenti *et al.*, 2014). The effects of ship radiated noise are mainly associated to behavioural changes rather than physiological damages, although conclusive results are not yet available (Southall, 2005; Pavan, 2008). The Pelagos Sanctuary, in the NW Mediterranean Sea, could be a pilot area to experiment new rules aiming to balance human activities and nature conservation; however, although the Parties to the Pelagos Agreement recognised the acoustic pollution as an important issue that need to be addressed (e.g. COP4_Resolution 4.1 Pelagos, 2009), concrete actions are hardly being implemented. This is partially due to knowledge gaps on baselines noise levels and to existing uncertainties about the effects of noise on marine mammals. In order to gather fundamental knowledge on the noise field created by ship traffic, the use of noise propagation models presents the advantage of allowing large scale assessments in a cost-effective way. Further, models can be used as a tool to simulate the noise field according to different scenarios, thus allowing the assessment of the effectiveness of quieting technologies and other mitigation measures (e.g. vessel route and speed management). Hence, our project aims at implementing a noise modelling tool in the area of the Pelagos Agreement in order to provide baseline knowledge to assess the potential impact of shipping noise on cetaceans, and lay the foundation for establishing long-term noise monitoring programmes.

Materials and Methods

The present study has been carried out over an area of about 45 000 km^2 corresponding approximately to the extent of the French exclusive economic zone (EEZ) lying within the borders of the Pelagos Sanctuary. A shipping noise prediction tool has been set, based on the Automatic Identification System (AIS) for gathering data about ships navigating in the Sanctuary. Such data are used to analyse the propagation of ship radiated noise through acoustic modelling, and to compute received noise levels across the study area. This tool can be used for different purposes. In the present project, it was used for setting up a real-time monitoring system and for analysing historical data.

AIS Data: collection and processing

The AIS is currently a major anti-collision system, and it is mandatory for every ship with tonnage above 300 tons to continuously broadcast AIS messages. These messages identify uniquely each user, and contain several parameters about the navigation, like the position, speed, and heading; and about the ship, like the ship type and status (navigating or mooring). AIS data can be used in order to enable realistic shipping noise mapping, as it provides parameters required as input for an acoustic modelling system. For the present project, AIS data come from www.aishub.net, an internet platform for AIS data sharing and vessel tracking. Our system uses a computer code (described later in the text) which samples AIS data on a regular basis, analyses the propagation of sound from noise sources (i.e. ships), and generates instantaneous pictures of noise levels over the latitude/longitude plane with a defined time step. A 10 minute sampling period was selected as to provide a reasonable balance ensuring both the computational load required for calculating instantaneous noise levels over the surface, and a sufficient sampling rate for generating a representative time-series for *a posteriori* statistical processing. Therefore AIS messages are stored in a database, extracted, sorted over time, and finally organised in 10 minutes intervals. For each 10 minutes interval only one position for each ship is selected for processing.

The real-time monitoring system uses a real-time AIS data stream continuously feeding the noise mapping system. Therefore, noise maps are produced every 10 minutes and uploaded on the server, becoming available for displaying on the website www.oceannoisemap.com, which has been developed as a result of the project. Moreover, archival data were used to carry out statistical assessments of noise conditions during a test period. As no previous knowledge was available concerning noise at large spatial and temporal scales in the Sanctuary, the test period was arbitrarily identified in summer 2012. Consequently, shipping noise has been modelled for a period of 3 months: July, August, and September 2012. Archival data collected during this period were readily available via the AIS platform aforementioned. Plots with ship count for each 10 minutes interval are presented in Fig. 1. A great variability can be noticed (from 0 to about 100 ships present in the area in each 10 minutes interval). Very low values are mostly explained by difficulties in receiving AIS messages from ships navigating far away from land, due to fluctuations in radio propagation, and to lesser extent due to sudden shut down of AIS receivers at locations with poor coverage. In order to mitigate the impact of such fluctuations in the noise modelling, AIS data yielding extremely low ship count were excluded. Following a trial and error method, we found acceptable to use percentile 20 of the instantaneous ship count distribution as a threshold for exclusion of unreliable data. Therefore, only data files containing more than percentile 20, computed separately for each month, were considered. Hence, 10369 out of 12960 10-minutes intervals were used for acoustic analysis. In Fig. 1, grey circles indicate periods not considered for acoustic modelling.

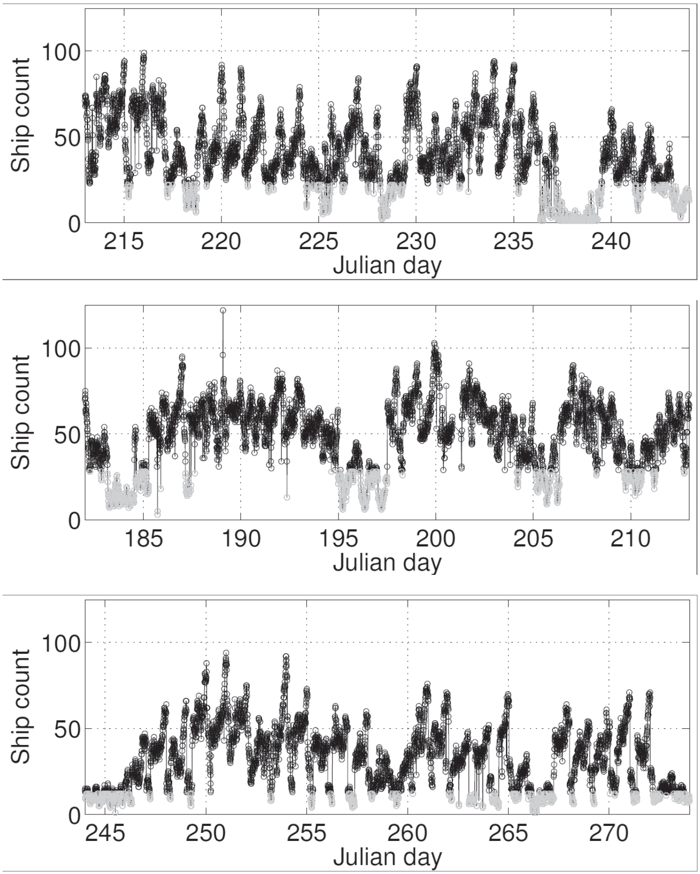


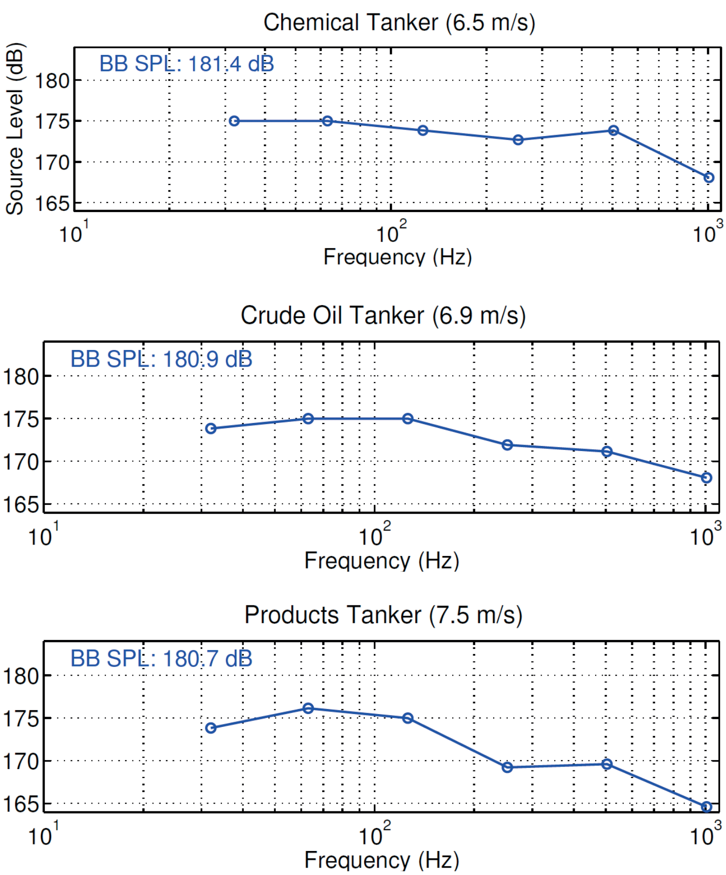
Figure 1. Monthly ship count from AIS data: July (upper panel); August (middle); September (bottom). Grey circles represent periods not considered for the purpose of acoustic modelling as they correspond to very low ship count, mostly explicable by fluctuations in AIS system efficiency and considered as not representative of a plausible situation.

Source geometry

The acoustic sources are represented by the ships found in the AIS data. For each time step, multiple ships exist in the area, and therefore a multiple number of acoustic sources must be considered for each instant. In the model, each source is located at geographical coordinates found in the AIS data, and a depth is assigned to each source. The depth of the source varies according to ship type and speed, propeller position, and charge. Following Scrimger and Heitmeyer (1991), source depth was set for all ships to 7 m, which is a common propeller depth for commercial ships.

Source spectra

In the present study, we used source levels in octave bands with frequencies centred at 32, 63, 126, 252, 504, and 1 008 Hz. The emission spectra used to characterise ships were taken from McKenna *et al.,* (2012) as shown in Fig. 2. Seven spectra are used, corresponding to a ship type related to a speed: chemical tanker (6.5 m/s), crude oil tanker (6.9 m/s), products tanker (7.5 m/s), open hatch (7.0 m/s), bulk carrier (7.2 m/s), vehicle carrier (8.5 m/s), and container ship (10.8 m/s). For each ship, a spectrum is selected by the following algorithm: first, spectra eligible in terms of ship type are inspected; then, the ship speed closest to the actual ship speed is used to decide on the spectrum. In this study sources are considered omnidirectional.



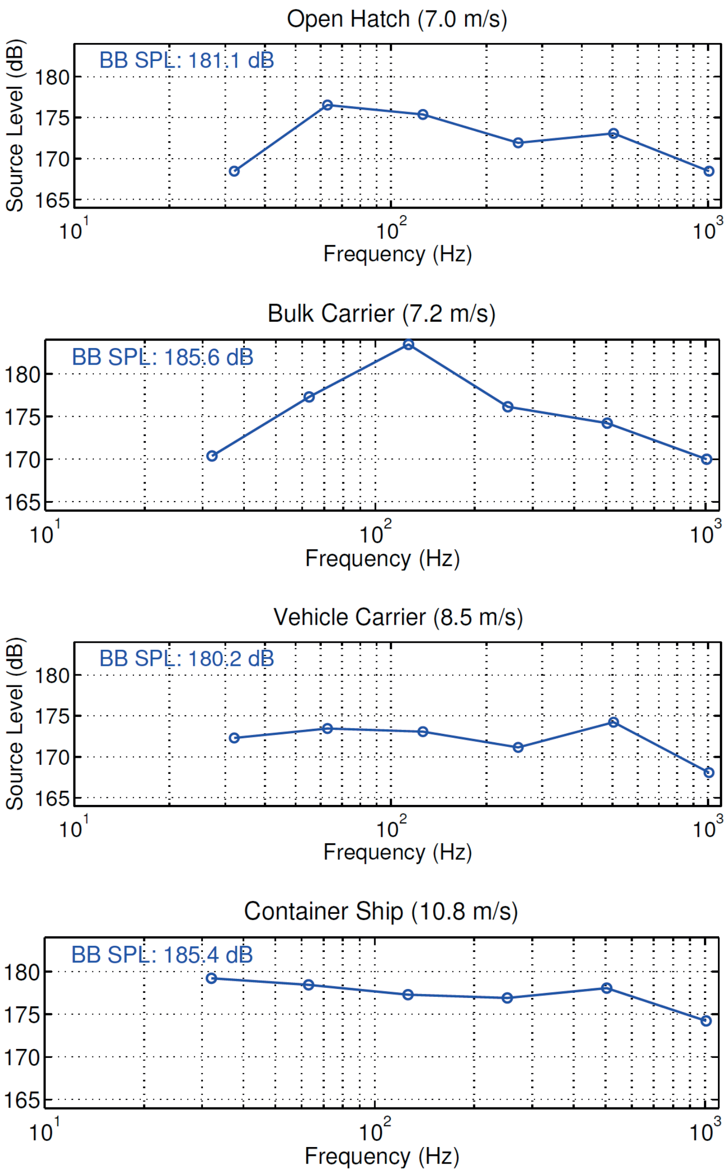


Figure 2. Source emission spectra used in the acoustic model according to ship type (McKenna *et al.*, 2012). BB SPL = Broadband Sound Pressure Level expressed in dB re 1 Pa ("re 1 µPa" means that the reference pressure was 1 µPa).

Environmental parameters

Environmental parameters considered here are bathymetry, water temperature, salinity and seafloor type. Bathymetric data were readily available from an online free database (http://maps.ngdc.noaa.gov/viewers/wcs-client/). Further, given the preliminary character of this pilot study, some assumptions were used for approximating the rest of environmental variables. Water temperature and salinity give the sound speed profile, which is a function of the water depth. The sound speed profile has been obtained based on a single CTD measurement taken in July, 2003 at latitude 42°30.02’ N and longitude 009°53.77’ E, which lies at the eastern border of the area considered in the present study (Jesus *et al.*, 2003). Such speed profile is assumed to be a typical summer profile applicable to our study period. Fig. 3 shows bathymetry and sound speed profile used in this study.

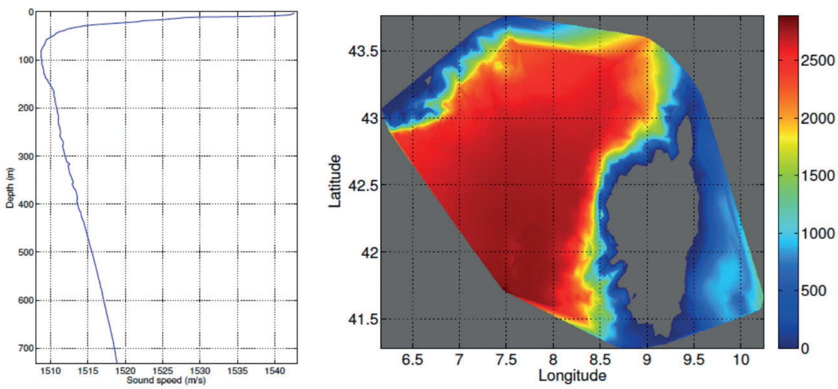


Figure 3. Water column sound speed profile (left picture) and bathymetry (right picture) used for acoustic modelling.

Then, the seabed is assumed to consist of a sandy sediment layer over a rocky infinite sub-bottom. This type of seabed composition is mainly found in eastern Corsican waters. Parameters used for the model are summarised in the following table (Tabl. I).

Table I. Parameters of seabed used for acoustic modelling.

Model parameter (unit)	**Value**
Sediment speed (m/s)	1650
Sediment density (g/cm^3)	1.9
Sediment attenuation (dB/λ)	0.8
Sediment thickness (m)	4
Sub-bottom speed (m/s)	1800
Sub-bottom density (g/cm^3)	2.0
Sub-bottom attenuation (dB/λ)	0.6

Propagation modelling

The KRAKEN model, a normal-modes acoustic propagation computer code, was used for generating acoustic fields (Kuperman *et al.*, 1991). The KRAKEN model provides accurate approximation for computations of transmission loss at low frequencies, and is computationally highly efficient. To calculate the acoustic transmission loss (TL) between each ship location and a given set of receiver positions, the KRAKEN model is fed with source and receiver geometry, a discrete set of source frequencies, and environmental parameters. The received acoustic field is calculated by combining the TL with a given source spectrum. Receiver depth was selected at the same depth of the minimum sound speed in water column, which is 80 meters (Fig. 3), as at this depth sound energy tends to concentrate and noise levels are likely to be the highest throughout the water column. This choice is justified by the aim of our study, which is allowing a preliminary assessment of the potential impact of shipping noise on cetaceans. Hence, if we founded that at this depth noise levels cause no impact (i.e. they are not sufficient to elicit any response of any cetacean species), then it is likely that shipping noise does not represent a real threat in the Sanctuary. Therefore, for each source and for each discrete frequency a TL disc is calculated with the following characteristics: 100 km radius, 80 m depth, 0.5 km range resolution (201 ranges), and 6 degrees bearing resolution (61 bearings). The acoustic field generated at a given frequency is given by the following formula:

$$Y(f_k, \underline{\theta}_S, \underline{\theta}_R) = H(f_k, \underline{\theta}_S, \underline{\theta}_R) S(f_k)$$

Where $\mathbf{Y}(\mathbf{f}_k, \underline{\boldsymbol{\theta}}_S, \underline{\boldsymbol{\theta}}_R)$ is the field received at position $\underline{\theta}_\mathbf{R}$ due to a source at position $\underline{\theta}_\mathbf{S}$, $\mathbf{H}(\mathbf{f}_k, \underline{\boldsymbol{\theta}}_S, \boldsymbol{\theta}_R)$ is the acoustic response between source and position $\underline{\theta}_\mathbf{R}$, and $\mathbf{S}(\mathbf{f}_k)$ is the source level for frequency $\mathbf{f}_k$. Model outputs are Sound Pressure Levels (SPL) expressed in dB re 1µPa rms (root mean square).

Results

Real-time noise mapping system

www.oceannoisemap.com is currently online (Fig. 4). Concentric circles centred in ship positions show sound wave propagation patterns influenced by convergence zones. In other words, sound waves move upward and downward along the water column (vertical axis) while propagating far from the source on the horizontal axis.

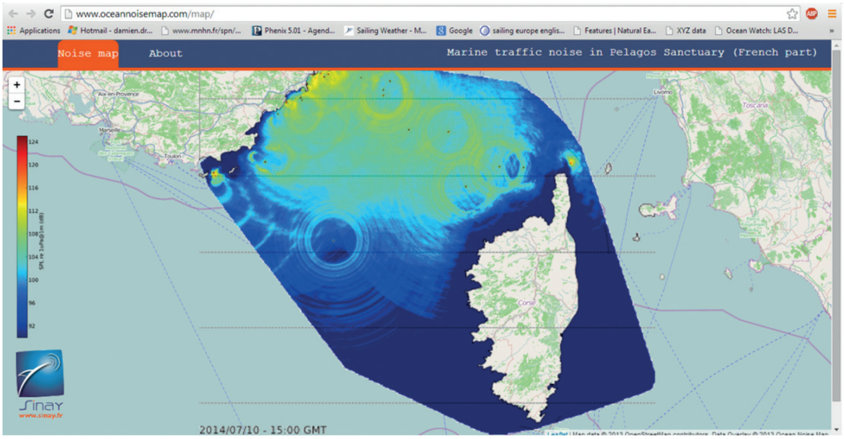


Figure 4. Real-time noise mapping system www.oceannoisemap.com. This example shows noise conditions at 80 meters of October 10th 2014, at 15:00 GMT (Greenwich Meridian Time), generated by 22 ships simultaneously navigating in the area. Dark red points represent noise levels exactly downward the position of ships. Concentric circles are zones of higher noise far from the source due to the sinusoidal propagation of sound waves.

In the example shown in Fig. 4, 22 ships are concentrated in the northern part of the study area while no ships appear around south-western and eastern Corsican water. Sound propagation patterns entail an insonification of the zone between northern Corsica and continental France, characterised by levels higher than 100 dB re 1µPa (rms) in this portion of the study area.

Shipping noise during summer 2012

Mean SPL broadband values due to ship traffic over the whole study period (3 months, i.e. 10369 10-minutes intervals) are presented in Fig. 5 with a grid of cell size equal to 0.125 degree in latitude and longitude. According to this figure, levels higher than 100 dB are found in most of the study area at a 80-m depth. Highest average level throughout the area (i.e. among all grid cells) is 126 dB. Along the French Riviera and in north-eastern Corsican waters we found noise values between 120 and 126 dB, while the area located between continental France and Corsica are between 110-120 dB. The south-eastern part of Corsica has the lowest average noise levels (< 100 dB).

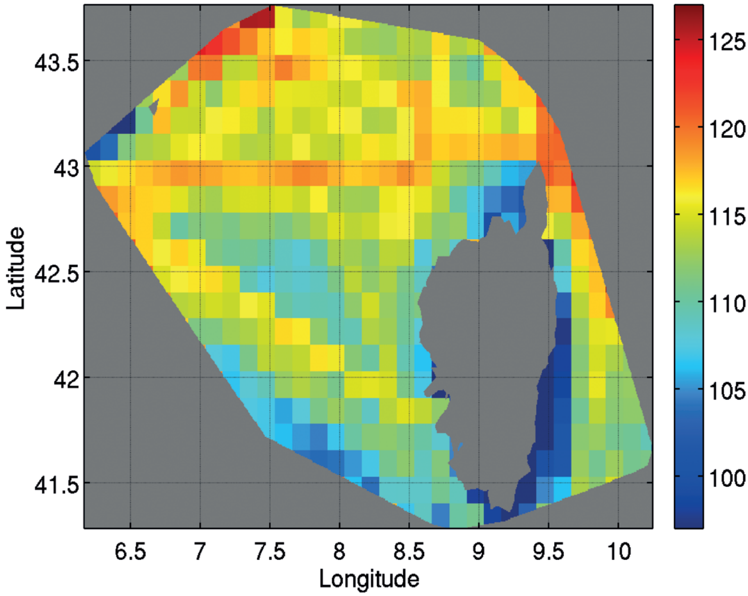
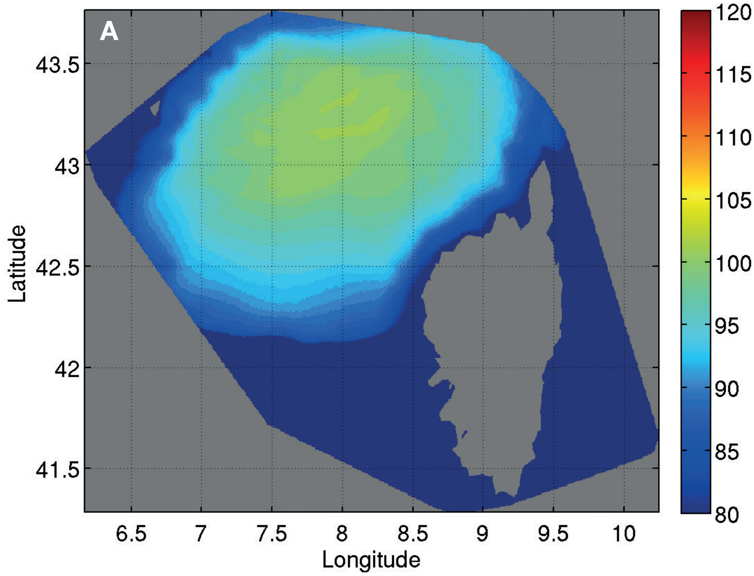


Figure 5. Mean SPL (Sound Pressure Level) at 80-m depth during the study period (3 months) over a grid with cell size equal to 0.125 degrees in latitude and longitude.

Fig. 6 (A, B, C) shows noise levels in percentile. Here we use the definition given by the international standard ISO 1996-1:2003(E), defining the percentiles in terms of exceedance levels. According to this definition, the percentile *N* is noise level exceeded for *N* % of the time of the study period. Therefore, levels expressed in percentile show, for each point of the study area, how much time a noise level is exceeded over the study period. Resolution of such pictures, i.e. the cell size of the grid, is 0.5 km. Figure 6 presents percentiles 95, 50 and 5, meaning noise levels which are exceeded 95 %, 50 % and 5 % of time, respectively. Fig. 6-A shows that in the zone between 42.5 and 43.5 degrees of latitude, and 7 and 9 degrees of longitude, 100 dB are exceeded 95 % of time. Such zone is displayed in light blue to green. Similarly, Fig. 6-B show that around Monaco waters, 110 dB are exceeded 50 % of time and that all the central area among Corsica and continental France has values exceeding 100 dB 50 % of time. Finally, Fig. 6-C shows that 120 dB are exceeded 5 % of time along the central and eastern French Riviera and in the NE of Corsica, while almost the whole area is found at levels higher than 100 dB 5 % of time.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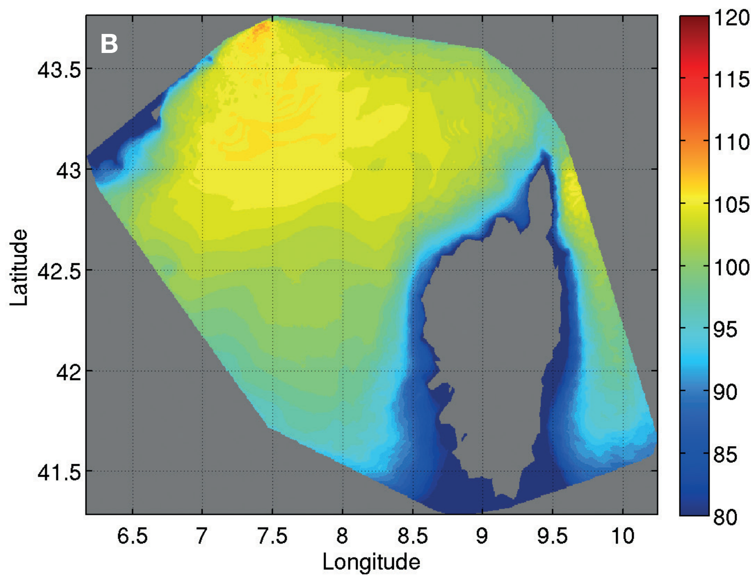
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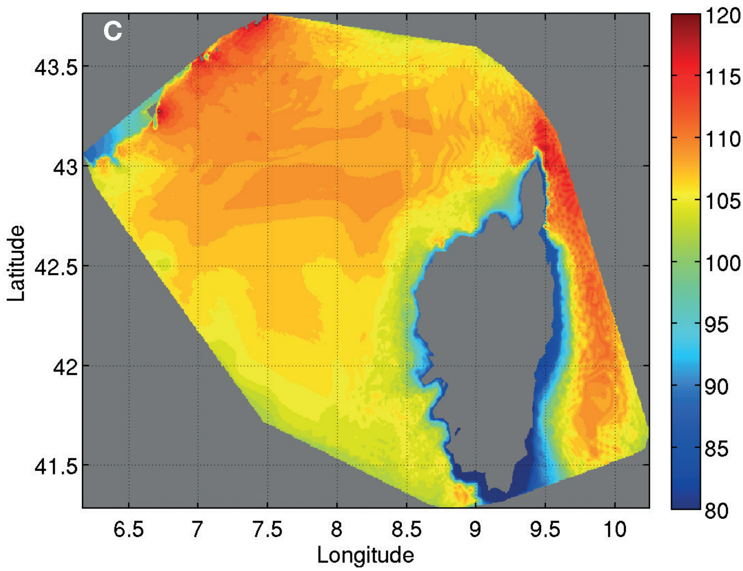

Figure 6. Levels in percentile (or Exceedance levels). Picture A shows levels exceeded 95 % of time, Picture B shows levels exceeded 50 % of time, and picture C shows levels exceeded 5 % of time.

Instantaneous levels (corresponding to each single "10 minute AIS picture") can be monitored over time in selected points. Fig. 7 shows an example taken at latitude 43°N and longitude 08°E (located approximately in the centre of the study area). In this point, maximum instantaneous levels reach more than 140 dB. The reason for these peaks is probably one or more ships passing near this point, as this lies on one of the major ship lanes linking northern Corsica with continental France. However, this has not been inspected closely and a deepest insight in our results is needed to confirm such deductions.

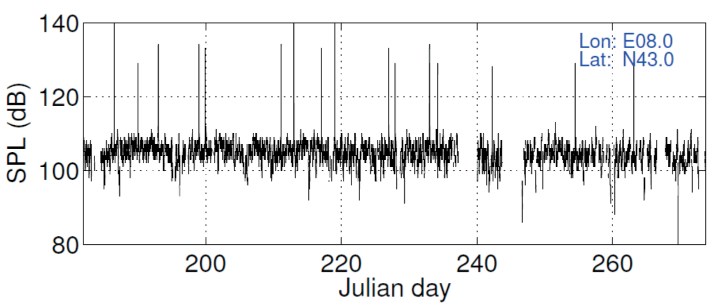

Figure 7. Instantaneous noise levels (SPL: Sound Pressure Levels) at 80 m depth over time at a selected position (latitude 43°N, longitude 08°E, approximately located in the centre of our study area).

Discussion

With regard to shipping noise during summer 2012, results show that in most of the study area mean SPL broadband levels calculated at 80 m depth are higher than 100 dB, whereas natural ambient noise is expected to be found between 60 and 80 dB (Wenz, 1962). All noise maps highlight the coastal zone among Monaco and Saint-Tropez (French Riviera) as an area characterised by constantly higher noise values than the rest of the study area. On the other hand, a greater variability is associated to Corsican waters. Looking at Fig. 6-A, all eastern Corsican waters appear as being less affected by shipping noise, while Fig. 6-B and Fig. 6-C highlight the NE part as being as noisy as the French Riviera. This variability could be associated with the heavier ferry traffic possibly occurring during the “high season” in the summer period. However, this deduction is speculative and needs to be confirmed by further investigations on ship traffic patterns over the study area. Also, the contribution of recreational craft to the whole noise picture should be assessed, especially in the coastal waters of the French Riviera, an area known to be heavily exploited by such navigation.

Globally, the Ligurian Sea is subjected to high anthropogenic pressure compared to other marine regions in the Mediterranean and elsewhere. For instance, a difference up to 40 dB exists among the Ligurian Sea and the Sea of Cortez (Mexico) in the low frequency bands up to 250 Hz (Pavan, 2010). However, scientific knowledge is not enough developed today as to assess with due precision the impacts on marine wildlife, particularly on cetacean populations, of such noise levels. In fact, very few studies focused on the effects of marine traffic noise on cetaceans. Behavioural effects (i.e. disruption of foraging behaviour) on one individual of Cuvier’s beaked whale (*Ziphius cavirostris*) were determined in response to the passage of a large ship causing the whale to receive 136 dB, as broadband SPL calculated in the 356 - 44800 Hz range (Aguilar de Soto *et al.*, 2006). Furthermore, a recent study in the Bahamas showed evidence that broadband ship noise (source level = 206 dB re 1 μPa rms) caused a significant change in Blainville beaked whale (*Mesoplodon densirostris*) behaviour up to at least 5.2 kilometres away from the vessel (Pirotta *et al.*, 2012). However, this study does not relate animal response to received levels and hence determining dose-response relationship is difficult.

To our knowledge, the most advanced progress in understanding shipping noise-cetacean interactions has been achieved via combined shipping noise models, based on comparable methodology to that used in our study, marine mammal audiograms, and population density models (Erbe *et al.*, 2012, 2014). Such studies outline a methodology for identifying ship noise hotspots for marine mammals of Canada's Pacific region. An approach based on such results is highly recommendable for the Pelagos Sanctuary, as well as for other national or international legal frameworks concerned with the impact of underwater noise on marine mammals in the Mediterranean region and elsewhere (ACCOBAMS, ASCOBANS, UNEP/MAP, etc.).

Considering studies conducted on other noise sources, it is known that fin whales modify their behaviour in response to impulsive noise at very long ranges, reaching more than 100 km (Borsani *et al.*, 2008). Further, research efforts focused on beaked whales response to low and mid-frequency sonars suggest different threshold for the onset of behavioural effects: 140 dB re 1μPa rms (Tyack *et al.*, 2011; Finneran and Jenkins, 2012), 89-127 dB re 1μPa rms (Deruiter *et al.*, 2013).

Discussions about thresholds are very often a controversial issue and a lot of uncertainties still exist in this domain. This is why recent important political initiatives aimed at including underwater noise in marine environmental management did not come to definite recommendations yet. This is the case of the European Union, through the Marine Strategy Framework Directive (2008/56/EC) and the Barcelona Convention, through the implementation of the Ecosystems Approach (EcAp process, see Decision 20/4 and Decision 21/3 of the 17th and 18th Meeting of the Contracting Parties to the Barcelona Convention, respectively). However, it is noteworthy that the National Oceanic and Atmospheric Administration (NOAA) and the National Marine Fisheries Service (NMFS) of the United States use since 1995 a precautionary value for behavioural disturbance caused by continuous noise on cetaceans of 120 dB rms (NMFS, 1995; NOAA, 2006).

For the purpose of this study, it can be assumed that noise thresholds discussed in the previous paragraphs apply to our study case. Therefore, during summer 2012, in some areas of the French part of the Pelagos Sanctuary estimated noise levels were sufficient to cause behavioural effects to sensitive cetacean species (i.e. fin whales and Cuvier's beaked whales).

As a result, a question can be addressed: are such behavioural effects significant in ecological terms? Though a specific answer is not among the aims of the present study, some elements can be provided in order to further the discussion on this issue. A fundamental concept is that discussing about the ecological significance of anthropogenic pressures leads to discussing about populations rather than individuals. Recalling the results of Aguilar de Soto *et al.* (2006), short-term behavioural effects may occur for the populations of Cuvier's beaked whales due to ship noise. Given the intense development of marine traffic in the area, the main concern of shipping noise is then represented by the chronic exposure that is caused to animals. This means that repeated small short-term behavioural effects may become problematic on the long term (e.g. decreased foraging efficiency may lead to decreased mating success). In addition, masking biological signals, as those used by baleen whales, could also lead to population effects (for example by disrupting communication of baleen whales across very large areas and thus impacting on courtship and mating behaviours). However, current uncertainties on these issues prevent quantifying such impacts on marine mammal populations (and on populations of other marine wildlife).

The methodology used to carry out the present study made use of several approximations and assumptions for acoustic analyses. Therefore improvements are needed, along with new data on the impact of noise on marine mammals. Model outputs can be easily improved in the future by providing more accurate environmental data than those used here. Particularly, data needed for improving model outputs are sound speed profile data and seabed characteristics. Further significant improvements are achievable with ad-hoc field measures of individual ships and their emission geometry aimed at updating sound emission spectra used in this study and validating our results.

Conclusion

Two goals have been attained by this project. First, a demonstrator system for real-time noise monitoring has been built up in an important conservation area where noise due to anthropogenic sources has been recognised to be a threat for marine mammals. www.oceannoisemap.com represents an original system having the potential to become a helpful tool for implementing conservation, management and mitigation policies. In fact, several functions can be added to the current system, including noise estimates at different depths (for example, 10, 100 and 1000 m, while the current version calculates noise fields at the 80 m depth layer), as well as several simulation options. For example, it will be possible to simulate what happens whether we achieve reducing by a given value in decibel the noise of 1 % of the circulating ships (or 10 % or other portion of the circulating ships). More simulation options can address more scenarios, like varying ship speeds, modifying navigation lanes etc. Second, our study for the first time gives a wide-scale overview on ambient noise due to shipping in the Pelagos Sanctuary. During the study period, noise levels were estimated to be sufficient to mask low frequency communicative signals of fin whales and cause behavioural disruption to sensitive species like Cuvier's beaked whales, in the sub-superficial layer. Such results confirm the need to bring forward the efforts to better understand the impact of underwater anthropogenic noise on marine mammals, in order to assess whether such impacts are ecologically significant, and hence implement conservation measures where needed.

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References

AGUILAR DE SOTO N., JOHNSON M., MADSEN P.T., TYACK P.L., BOCCONCELLI A., BORSANI F.J., 2006. - Does intense ship noise disrupt foraging in deep-diving Cuvier'S Beaked Whales (*Ziphius cavirostris*)? *Mar. Mam. Sci.,* 22: 690-699.

ANDREW R.K., HOWE B.M., MERCER J.A., DZIECIUCH M.A., 2002. - Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. *Acoust. Res. Lett. Online,* 3: 65-70.

ANDREW R.K., HOWE B.M., MERCER J.A., 2011. - Long-time trends in ship traffic noise for four sites off the North American West Coast. *J. Acoust. Soc. Am.,* 129: 642-651.

BORSANI J.F., CLARK C.W., NANI B., SCARPINITI M., 2008. - Fin whales avoid loud rhythmic low- frequency sounds in the Ligurian Sea. *Bioacoustics,* 17: 151-193.

DEKELING R., TASKER M.L., VAN DER GRAAF A.J., AINSLIE M.A., ANDERSSON M.H., ANDRÉ M., BORSANI J.F., BRENSING K., CASTELLOTE M., CRONIN D., *et al.*, 2013. - *Monitoring guidance for underwater noise in European seas - Executive Summary*. 2nd Report of the Technical Subgroup on Underwater Noise (TSG Noise). European Marine Strategy Framework Directive: 1-13.

DERUITER S.L., SOUTHALL B.L., CALAMBOKIDIS J., ZIMMER W.M.X., SADYKOVA D., FALCONE E.A., FRIEDLAENDER A.S., JOSEPH J.E., MORETTI D., SCHORR G.S., *et al.,* 2013. - First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar. *Biology Letters,* 9: 20130223.

ERBE C., MACGILLIVRAY A., WILLIAMS R., 2012. - Mapping cumulative noise from shipping to inform marine spatial planning. *J. Acoust. Soc. Am.,* 132: EL423-428.

ERBE C., WILLIAMS R., SANDILANDS D., ASHE E., 2014. - Identifying modeled ship noise hotspots for marine mammals of Canada's Pacific region. *PloS one* 9: e89820.

FINNERAN J.J., JENKINS A.K., 2012. - *Criteria and thresholds for U.S. Navy acoustic and explosive effects analysis.* Technical report. Space and Naval Walfare Systems Center Pacific, San Diego: 1-60.

HILDEBRAND J.A., 2009. - Anthropogenic and natural sources of ambient noise in the ocean. *Mar. Ecol. Prog. Ser.,* 395: 5-20.

JESUS S.M., SILVA A., SOARES C., 2003. - *Acoustic oceanographic buoy test during the MREA'03 sea trial*. CINTAL, Universidade de Algarve, Faro: 1-38.

KUPERMAN W.A., PORTER M.B., PERKINS J.S., EVANS R.B., 1991. - Rapid computation of acoustic fields in three-dimensional ocean environments. *J. Acoust. Soc. Am.,* 81: 125-133.

LEAPER R.C., RENILSON M.R., 2012. - A review of practical methods for reducing underwater noise pollution from large commercial vessels. *Int. J. Marit. Eng.,* 154: A79-A88.

MADSEN P.T., WAHLBERG M., MØHL B., 2002. - Male sperm whale (*Physeter macrocephalus*) acoustics in a high-latitude habitat: implications for echolocation and communication. *Behav. Ecol. Sociobiol.,* 53: 31-41.

McKENNA M.F., ROSS D., WIGGINS S.M., HILDEBRAND J.A., 2012. - Underwater radiated noise from modern commercial ships. *J. Acoust. Soc. Am.,* 131: 92-103.

NMFS, 1995. - Small takes of marine mammals incidental to specified activities; offshore seismic activities in southern California. *Federal Register,* 60: 53752-53760.

NOAA. 2006. - Small takes of marine mammalsiIncidental to specified activities; rim of the Pacific (RIMPAC) Antisubmarine Warfare (ASW) exercise training events within the Hawaiian Islands operating area (OpArea). *Federal Register,* 71: 20986-21003.

NRC (National Research Council), 2000. - *Marine mammals and low-frequency sound*. National Academy Press: Washington, DC.

NRC (National Research Council), 2003. - *Ocean Noise and Marine Mammals*. National Academy Press: Washington, DC.

PAVAN G., 2008. - The shipping noise issue, a challenge for the survival and welfare of marine life? In *Maritime traffic effects on biodiversity in the Mediterranean Sea: Review of impacts, priority area and mitigation measures*, Abdulla A., Linden O. (éds). IUCN Centre for Mediterranean Cooperation: Malaga: 10-21.

PAVAN G., 2010. - *The shipping noise issue*. Final Report of the GIOHNA Project. Università degli studi di Pavia, Pavia: 1-45.

PELAGOS. 2009. - *Risoluzione 4.1 Impatto di origine antropica sui mammiferi marini*. IV Riunione dei Paesi Parte, Monaco, 19-21 Ottobre 2009. Accordo per la costituzione del Sanctuario per i mammiferi marine nel Mediterraneo, Monaco : 1-2.

PIROTTA E., MILOR R., QUICK N., MORETTI D., DI MARZIO N., TYACK P., BOYD I., HASTIE G., 2012. - Vessel noise affects beaked whale behavior: results of a dedicated acoustic response study. *PloS one,* 7: e42535.

PULVIRENTI S., INSERRA P., CARUSO F., GIOVANETTI G., GRASSO R., LAROSA G., PAVAN G., PELLEGRINO C., RICCOBENE G., SIMEONE F., *et al.,* 2014. - Analisi del rumore acustico sottomarino e correlazione con il traffico navale presente nell'area del Golfo di Catania. In *Associazione Italiana di Acustica, Convegno Nazionale,* 17-19 giugno 2014, Pisa, Associazione Italiana di Acustica: 1-7.

ROSS D., 1976. - *Mechanics of underwater noise*. Pergamon Press, New York.

SCRIMGER P., HEITMEYER R.M., 1991. - Acoustic source-level measurements for a variety of merchant ships. *J. Acoust. Soc. Am.,* 89: 691-699.

SIMMONDS M., DOLMAN S., WEILGART L. (édits.), 2004. - Oceans of noise : A WDCS Science report. WDCS publ., Chippenham: 1-169.

SIROVIC A., HILDEBRAND J.A., WIGGINS S.M., 2007. - Blue and fin whale call source levels and propagation range in the Southern Ocean. *J. Acoust. Soc. Am.,* 122: 1208-1215.

SOUTHALL B.L., 2005. - Shipping noise and marine mammals : a forum for science, management, and technology. In: *Final report of the National Oceanic and Atmospheric Administration (NOAA) Symposium,* U.S. NOAA Fisheries, Arlington, Virginia, May 18-19, 2004.

TASKER M.L., AMUNDIN M., ANDRÉ M., HAWKINS A., LANG W., MERCK T. *et al.*, 2010. - *Marine Strategy Framework Directive, Task Group 11 Report, Underwater noise and other forms of energy Underwater noise*. JRC and ICES publ.: 1-64.

TYACK P.L., ZIMMER W.M.X., MORETTI D., SOUTHALL B.L., CLARIDGE D., DURBAN J.W., CLARK C.W., D'AMICO A., DIMARZIO N., JARVIS S., *et al.,* 2011. - Beaked whales respond to simulated and actual navy sonar. *PloS one,* 6: e17009.

VAN DER GRAAF S., AINSLIE M.A., ANDRÉ M., BRENSING K., DALEN J., DEKELING R.P.A., ROBINSON S., TASKER M.L., THOMSEN F., WERNER S., 2012. - *European Marine Strategy Framework Directive Good Environmental Status (MSFD-GES): Report of the Technical Subgroup on Underwater noise and other forms of energy. Final Report*: 1-75.

WENZ G., 1962. - Acoustic ambient noise in the ocean : spectra and sources. *J. Acoust. Soc. Am,* 34: 1936-1956.