quiet seas

QUIETSEAS - Assisting (sub) regional cooperation for the practical implementation of the MSFD second cycle by providing methods and tools for D11 (underwater noise).

D8.1 Best practices of subregional cooperation to set mitigation measures to address underwater continuous noise pollution

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3	Service hydrographique et océanographique de la marine	Shom	France
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5	Hellenic Centre for Marine Research	HCMR	Greece
6	Inštitut za vode Republike Slovenije/Institute for water of the Republic of Slovenia	IZVRS	Slovenia
7	Specially Protected Areas Regional Activity Centre	SPA/RAC	Tunisia
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Abstract

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List of Abbreviations

CTN	Centro Tecnológico Naval y del Mar
ACCOBAMS	Permanent Secretariat of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area
DFMR	Department of Fisheries and Marine Research
IZVRS	Inštitut za vode Republike Slovenije/Institute for water of the Republic of Slovenia
HCMR	Hellenic Centre for Marine Research
UM	University of Malta -The Conservation Biology Research Group
POLIMI-DICA	Politecnico di Milano-Department of Civil and Environmental Engineering
SPA/RAC	Specially Protected Areas Regional Activity Centre
ICES	International Council for the Exploration of the Sea
Shom	Service hydrographique et océanographique de la marine
MHD	Maritime Hydrographic Directorate
MSFD	Marine Strategy Framework Directive
GES	Good Environmental Status
MS	Member States
MED	Mediterranean Sea
BS	Black Sea
CA	Competent Authority
NR	National representative
SO	Specific Objective
TB	Thematic Block

1. Introduction

The QUIETSEAS Project is funded by DG Environment of the European Commission within the call “DG ENV/MSFD 2020”. This call funds MSFD development, in particular, the support of the second cycle of implementation. The QUIETSEAS project aims to enhance cooperation among Member States (MS) in the Mediterranean Sea Region (MED) and Black Sea Region (BS) to implement the second Cycle of the Marine Directive and in particular to support Competent Authorities and strengthen cooperation and collaboration in the Mediterranean Sea and Black Sea regions.

This deliverable is the result of work done on Activity 8. Case study on effectiveness of coordinated mitigation measures:

- Specific objective 1 (SO1): To identify relevant indicators for criterion D11C2 (Anthropogenic continuous low-frequency sound in water).
- Specific objective 2 (SO2): To promote the consolidation of relevant indicators for D11 and support the operationalisation of indicators on the state, pressure and impacts of underwater noise in close coordination with TG Noise.
- Specific objective 3 (SO3): To promote harmonisation of regional work on threshold values with TG Noise recommendations.
- Specific objective 4 (SO4): To develop effective and efficient mechanisms for GES assessment and regional coordination by providing management tools for harmonization, reporting and assessment of D11.
- Specific objective 5 (SO5). To demonstrate the potential effectiveness of coordinated mitigation measures to reduce shipping noise.
- Specific objective 6 (SO6): To promote (sub)regional cooperation in order to ensure, i) coordination across the region/ subregions, ii) the involvement of Competent Authorities iii) long-term dissemination of the results.

The project is developed by a consortium made up of 10 entities coordinated by CTN and it has a duration of 24 months starting on 1st February 2021.

The object of this document is to quantify the effect of potential mitigation measures to reduce shipping noise through two different study cases i) multi-scenario of vessel speed reduction, which will be analysed to assess how the establishment of this measure at (sub)regional level would impact shipping noise, and in what measure this could lead to a reduction on shipping noise levels ii) the opportunistic activity-dependent scenario of traffic reduction created by the March 2020 COVID-19 lockdown.
Section 2 presents the general methodology employed to estimate shipping noise. In section 2, the terminology employed in the rest of the document is presented (subsections 2.1 and 2.3). The two case studies (methodology and results) are presented and extensively discussed in section 3. Section 4 compiles the recommendations and lesson-learned from the studies. Conclusions and perspectives are addressed in section 5. Two appendices present some additional figures (A.1.), and a review on mitigation measures (A.2.).

1.1. Context and driving questions

The assessment of the Programs of Measures (PoMs) presented by the European Commission (COM (2018) 562final), points that the quantification of how much of the pressure will be reduced and whether the measures themselves are sufficient to achieve Good Environmental

Status was not possible. This report explains that while acknowledging that this could not be done for some measures due to, for example, gaps in knowledge, the assessment would have been strengthened if Member States' efforts could be translated into a tangible assessment of the positive effects they will have on the marine environment.

According to this finding, QUIETSEAS Activity 8 was proposed in order to assess and quantify the effectiveness of potential coordinated measures to reduce shipping noise. Two case studies were identified to bring general answers regarding the efficiency of measures, accounting for regional specificities, and analysing the efficiency with regards to the spatial extent of the area concerned by the measure.

The first case scenario is the simulated mitigation measure of ship traffic speed reduction. Ship traffic speed reduction experiments have already been conducted in several parts of the world, with various results. However, these experiments were always limited to shallow-water areas, and were primarily designed either to reduce gas emissions, or to limit collisions with marine mammals, and the analysis of impact on shipping noise came as complementary objective (Morten *et al.*, 2022). The environment (bathymetry, bottom characteristics, sound speed profile) is expected to strongly impact the effect of such a measure, and the aim of this case scenario is to simulate speed limits in selected areas to evaluate how environment and traffic characteristics can influence the efficiency of a speed reduction measure. For practical reason, traffic speed reduction measures must be limited to- and focus on specific areas, that are of particular importance for marine ecosystems, and where an intense traffic generates particularly high noise levels. The question of the size of the considered area is also tackled as it is expected to influence on the effect of the measure.

The second case is a general ship traffic reduction. Reducing the amount of ship routing in an area suffers a lack of realism. Imposing a traffic reduction is difficult as it would impact the economy at several scales, and concerning various activities (people transportation, tourism and merchandise transportation being a few of them). In 2020, the **SARS-CoV-2** pandemic lead many countries to establish a lockdown which resulted in a global traffic reduction. The emergence of this realistic scenario of traffic reduction allowed to conduct an opportunistic analysis of its impact on shipping noise in the European waters, especially in Mediterranean and Black Sea.

General conclusions are drawn on the efficiency of the two measures, leading to practical recommendations for MS to design improved PoMs, that include guidance on whether specific modelling is required when considering a new couple {area, measure} or not. Finally, conclusions are formulated, including perspectives on new case scenarios that could be investigated.

1.2. Mitigation measures for the reduction of underwater noise from shipping

Typical sources of underwater ship noise are related to propeller cavitation, water flow and hull shape, ship machinery and ship operation (cf. Review of the underwater noise mitigation measures is attached in the Appendix A.2.).

1. **Mitigation measures used in design of the ship**
    - mitigation measures used in the propeller design
    - mitigation measures used in the hull design

2. **Mitigation measures used in design, selection and installation of on-board machinery**
   - mitigation measures used in selection of on-board machinery
   - mitigation measures used in selection of location, where machinery is installed in the ship hull
   - mitigation measures used to control vibrations and optimise of foundations

3. **Mitigation measures based on the use of additional technologies on existing ships**
   - design and installation of new state-of-the-art propellers
   - installation of wake conditioning devices
   - installation of air injection to propeller.

4. **Mitigation measures used during ship operation and maintenance**
   - cleaning of propeller
   - maintenance of the ship hull surface
   - re-direction of ships
   - selection of the proper speed

Measures to reduce propulsion power and propeller thrust loading are beneficial for energy efficiency, emission reduction and underwater radiated noise reduction. Measures to optimise hull design and execute regular maintenance, aimed at reducing hull resistance, are effective for reduced emissions and underwater noise. Design measures to reduce propeller cavitation are effective for underwater radiated noise reduction. In particular, the hull and propeller need to be designed together, as a unit, such that a uniform wake field is created to reduce propeller cavitation. To some extent these will also increase energy efficiency, and reduce emissions (De Jong *et al.*, 2020).

Speed limits ('slow steaming') have a potential to be effective to control shipping underwater noise as well as energy efficiency and emission reduction, but different ship types have different optimum speeds and not all ship types can slow down to the same extent (De Jong *et al.*, 2020). The benefits (i.e. decrease in fuel consumption, decrease in CO_2 emission and reduced underwater noise levels) potentially resulting from operation at lower speed need to be weighed against other factors, such as: increased voyage duration, possible increased total amount of acoustic energy released in the environment by extending the time spent in the speed reduction area, capital and crew cost, safety issues and the capability of the propulsion plant to sustain continuous operation at low speeds (AQUO and SONIC, 2015; Chion *et al.*, 2017).

2. Tools and methods

2.1. Terminology

In order to ease the understanding of the results, observations and conclusions exposed in this deliverable, the following section is dedicated to the definition of the physical metrics and statistical quantities that are used in the document. This document follows ISO 18405 for basic acoustical terminology.

2.1.1. Shipping noise

Physical quantities

The quantification of acoustic noise refers to sound/acoustic pressure levels. Acoustic pressure levels are expressed as the logarithm of the ratio of the mean square pressure to a reference square pressure, often set to $1\mu Pa^2$ underwater. In this document, this reference value is used for sound pressure level, which is expressed in dB relative to $1\ \mu Pa^2$. For the sake of clarity, this unit will be written "dB" in the document.

Spectrum level corresponds to sound pressure level over a unit frequency band and is expressed in dB re $1\mu Pa^2$ /Hz. Ships Source Level (SL) corresponds to the generated sound level at 1 m distance from the source, considered as a point source.

Meaningful frequencies

The results are expressed through the total acoustic pressure received within specific third octave frequency bands. A third octave frequency band centred on a given frequency fc is defined as the frequency band [f1 – f2], with $f1 = fc/2^{1/6}$ and $f2 = fc.2^{1/6}$.

Following MFSD, acoustic noise levels are provided for the two third octave bands centred on 63 and 125 Hz, that have been identified to be the most impacted by shipping noise.

Temporal scales

The TG Noise makes the distinction between the Temporal Observation Window (TOW), which represents the temporal resolution of the shipping noise estimation or measurement and the Temporal Assessment Window (TAW), which represents the temporal window over which the environmental status of the habitat is evaluated. In this work, following TG Noise terminology, the TOW ranges from 6 hours to 1 day, depending on the case study considered, and the TAW is in the order of the month, except when mentioned otherwise.

2.1.2. Statistics

Distributions

The acoustic levels considered are expected to vary according to certain dynamics, both spatial and temporal. To account for the statistical properties that characterise an acoustic quantity, the distributions of values taken by the considered quantity in a fixed context can be considered. A distribution is assumed to approximate, for any possible value, the likelihood that a sample of the considered quantity will be close to the value.

For example, we may consider the distribution of values that shipping noise takes at a selected location over time, when considering daily estimations (as TOW) over a month (as TAW). By normalising this distribution by the number of samples considered to build the distribution, one can access, for any chosen value of shipping noise, the likelihood that a random estimate of shipping noise will be within close range to the value (close relative to the resolution of the distribution).

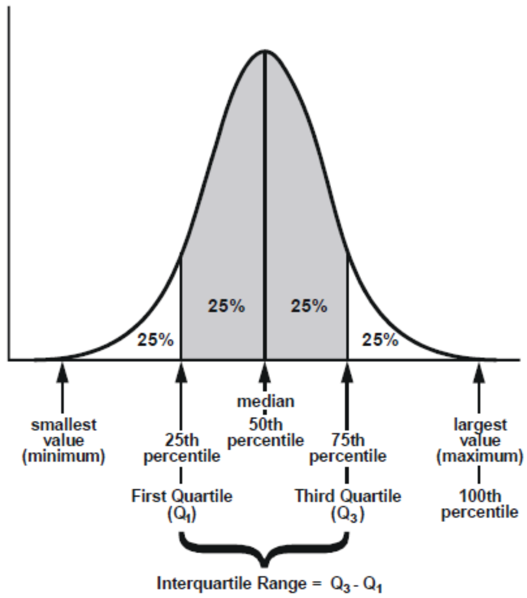

Figure 1. Example of a distribution, with quartile values Q1, Q2, Q3 marked in red.

Central tendencies and dynamic range

Many ways exist in order to simplify the information contained in a distribution. It is often summarised by extracting central tendencies and information on the dispersion, the spread of the values.

In this work, the median is used as an indicator of the central tendencies of distributions. The median of a distribution is a value that separates the half samples of highest values and the half samples of lowest values of the distribution. Half of the samples of the distribution takes values higher or equal to the median and half of the samples takes values lower or equal to it.

Similar to the median, other quantities permit to separate a distribution in consecutive portions of it. The three quartiles of a distribution noted Q1, Q2, Q3 are the values that separate the 25%, 50%, 75% samples of lowest values of the distribution from the 75, 50 and 25% samples of highest values respectively. The second quartile and the median are therefore equivalent.

Quartiles give information on the spread of values in the distribution. In this work, in order to quantify the spread of distributions, we use the interquartile range ΔQ, namely the difference between Q3 and Q1: $\Delta Q = |Q_3 - Q_1|$.

The Cumulative Distribution Function (CDF) of a distribution of a certain quantity at a reference value expresses the likelihood that a random estimate of the considered quantity would take a value below the reference value.

2.2. Quantification of shipping noise level

The general methodology is exposed here (see Fig. 2) and the following paragraphs provide more details on the methodology employed.

The methodology used to compute the ambient noise levels relies on Automatic Detection System (AIS) data and is described in Le Courtois *et al.* (2016) and Ollivier *et al.* (2019). AIS data are signals periodically transmitted by ships along their route, in order to prevent ships collisions. AIS data include navigation (position, heading, speed) and vessel (Marine Mobile Service Identity (MMSI), vessel type, length, flag, load) information, along with timing information.

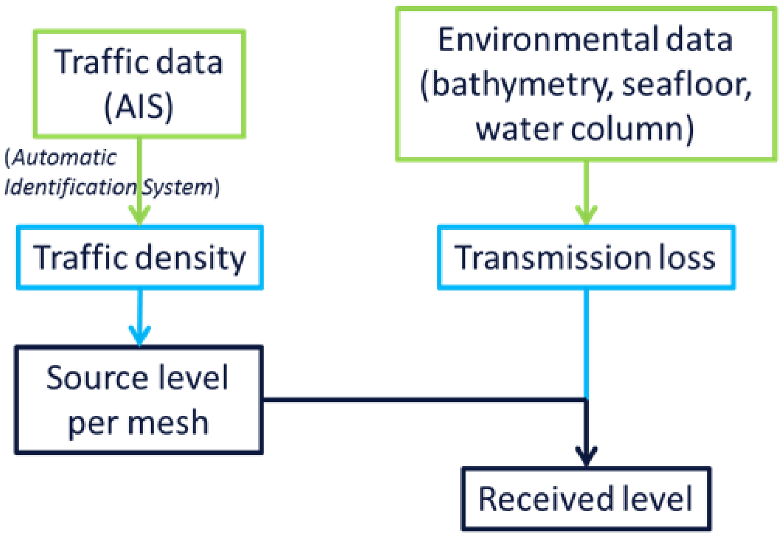

Figure 2. Methodology and data used in the estimation of shipping noise.

The collection of complete/exhaustive sets of AIS data on a region over a period of time permits to model the route of ships and to estimate the total traffic density over a time period, or the traffic density of specific categories of ships. Traffic density maps display the amount of time spent by different categories of vessels per unit area and over a given time period with unit [km-2].

The traffic density is converted into statistical Source Level (SL) maps by using the Randi 3.1 model to estimate the radiated noise of isolated ships (knowledge of the length and speed of ships are extracted from the AIS data emissions).

Transmission Losses (TL) are estimated for each couple {emission cell; receiver cell} and the Received Levels (RL) are computed following the SONAR equation.

2.2.1. Modelling shipping radiated noise

The processes that produce shipping radiated noise are complex, diverse, and are dependent upon the ship design. It is therefore difficult to formalize radiated noise models based on an exhaustive description of these physical processes. Instead, shipping radiated noise models were obtained empirically, identifying as most impacting parameters the vessels speed, the vessel length, the vessel tonnage, the number of blades, or the velocity of propeller blade tip and the displacement of the vessel, and formulating the relation between subsets of these parameters, the frequency of the radiated noise and the radiated noise level. Several studies attempt to estimate the sound radiated by ships by using measurements to identify noise sources in order to classify the levels according to ship categories (McKenna *et al.*, 2012, Simard *et al.*, 2016) or mitigation methods (Audoly *et al.*, 2017).

In this study, the Source Level (SL) is expressed as in Eq. 1, following the Randi3 model (Breedin *et al.*, 1996). According to this model, Fig. 3. presents the radiated noise spectra of a vessel of 50 m length for different speeds from 10 to 50 knots (kt), showing clearly how increasing vessel speed increases the radiated noise levels, according to Randi3.1 model.

Equation 1

$$SL\ (\boldsymbol{f},\boldsymbol{s},\boldsymbol{L}) = Sv(\boldsymbol{f}) + 60\ log_{10}(\frac{\boldsymbol{s}}{12}) + 20\ \ log_{10}\left(\frac{\boldsymbol{L}}{300}\right) + df.dl + 3.0$$

SL = source level in dB re 1µPa^2/Hz
s = speed in kt
L = ship length in m

$$Sv(f) = \begin{cases} -10\ log_{10}\left(10^{-1.06\ log_{10}\boldsymbol{f}\ -\ 14.34} + 10^{-3.32\ log_{10}\boldsymbol{f}\ -\ 21.425}\right) & if\ f < 500\ Hz \\ 173.2 - 18.0\ log_{10}\boldsymbol{f} & if\ f > 500\ Hz \end{cases}$$

$$df = \begin{cases} 8.1 & if\ f < 28.4 \\ 22.3 - 9.77 log_{10}\boldsymbol{f} & if\ 28.4 < \ f < 191.6 \\ 0.0 & if\ f > 191.6 \end{cases}$$

And

$$dl = \ 3643\ .\ \boldsymbol{L}^{1.15}$$

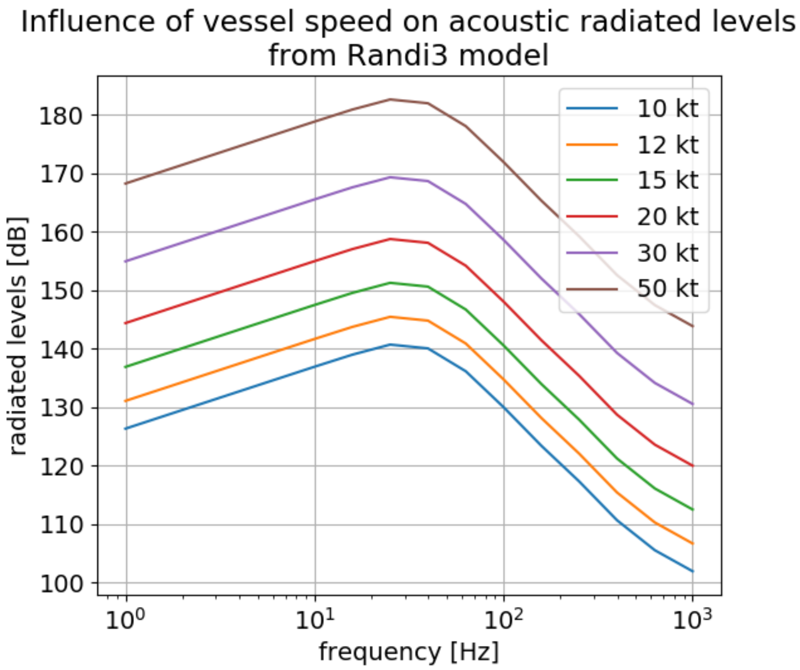

Figure 3. Influence of vessel speed on source levels according to Randi3 model, for a vessel of 50 m length.

In order to find the source level radiated from a position, vessels are sorted into 7 different categories, depending on their activity and their speed range and length. This categorization permits to gather ships sharing a same range of source levels. Categories 1 to 5 concern all types of commercial vessels, with increasing ranges of SL, category 6 gathers fishing vessels and category 7 gathers passenger vessels.
For each ship category, a traffic density map is computed. For a single ship, the SL is computed at 5 m depth following the RANDI 3.1 model (Breeding *et al.*, 1996). This source model relies on the vessel information of length and speed, extracted from the AIS database.

For each emitting mesh and each category of vessels considered, a Monte-Carlo scheme is performed to estimate the expectancy and standard deviation of SL of the category, from a subset of randomly sampled vessels. The expected SL of each category is then multiplied by the vessel's density of each category to account for the complete SL of the category within the given mesh. Finally, SL from all categories are summed up to obtain the mean source level at the centre of the mesh.

2.2.2. Computing received levels of shipping noise

The transmission losses are computed for each receiver. For frequencies higher than 300 Hz, the ray tracing code PRAMM is used. For frequencies below 300 Hz, parabolic equations solvers RAM (Range dependent Acoustic Modelling, Collins, 1995-1998) and RAMS (depending on the nature of the sea bottom) are used. Details on the environmental data exploited for the computation of transmission losses are given in the subsection 2.3. Data.

The received level RL_{ij} from the mesh j to the mesh i is then computed by subtracting the transmission loss TL_{ij} of the source level SL_j, according to the passive SONAR equation: $RL_{ij} = SL_j - TL_{ij}$. At the end, the total received level RL_i on the mesh i is the sum of the received levels from the all mesh j such as $RL_i = \sum_j RL_{ij}$. Only the sources located closer than 200 km from the receiver position are considered to improve computation times, hence removing the very small contributions from distant vessels. The received position is assumed to be at the centre of the cell at several depths.

2.3. Data

<u>AIS data</u>

AIS data are signals transmitted by vessels along their route. This data contains information on vessels features (Vessel type, activity, flag, load, size), position (location, time) and routing (speed, heading). The AIS emissions can be collected through two different receivers: land stations and satellites. For this work, AIS data were purchased from the company Exact Earth (now www.spire.com). The set gathers terrestrial and satellite AIS data that cover the Mediterranean Sea and the Black Sea for the two years 2019 and 2020. The size of the acquired data is about 1.8 Giga Octet (Go) per month for the Black Sea region and 10 Go per month for the Mediterranean Sea region.

<u>Environmental data</u>

The Mediterranean and the Black Sea basins present some levels of environmental complexity, impacting the acoustic propagation. This complexity is considered in the employed methodology that relies on fine resolution environmental data.

The bathymetry is marked by important contrasts (Fig. 3) with values reaching 5000 m depths. The bathymetry data used in this work is provided by GEBCO (https://www.gebco.net/data_and_products/gridded_bathymetry_data/) and has a resolution of 5 arc-minutes.

The seabed is mostly composed of mud, with some exceptions (see Fig. 4). The seabed nature used in this work has a resolution of 15 arc-minutes and is provided by the French Navy and Defence Services. Typically, a p-wave velocity of 1500 m/s of and attenuation in compression of 0.2 dB/λ are attributed to mud.

Finally, Sound Speed Profiles (SSP) are contrasted over the two basins (Fig. 5), and experience variations along the year. The sound speed dataset is composed of monthly SSP provided by the French Navy and Defence Services.

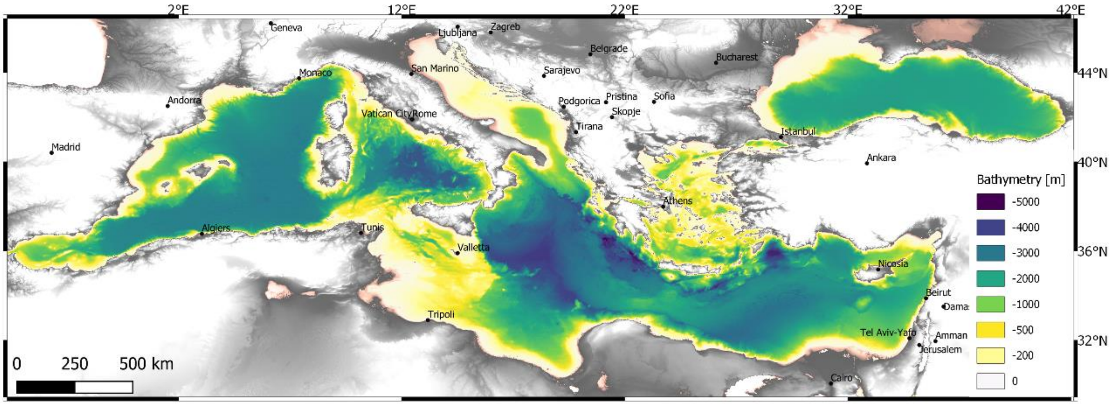

Figure 4. Map of the bathymetry over the Mediterranean Sea and Black Sea. Data from GEBCO

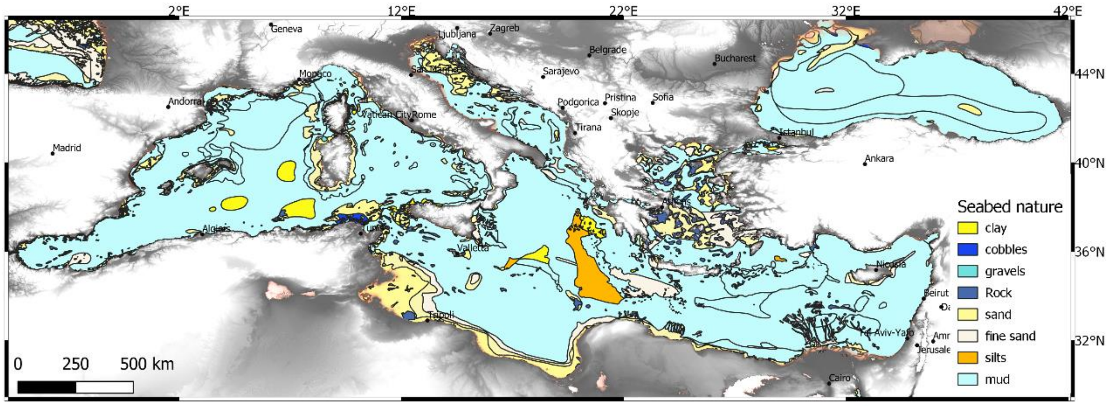

Figure 5. Map of the seabed nature in the Mediterranean Sea and Black Sea. Data from the French Navy and Defence Services.

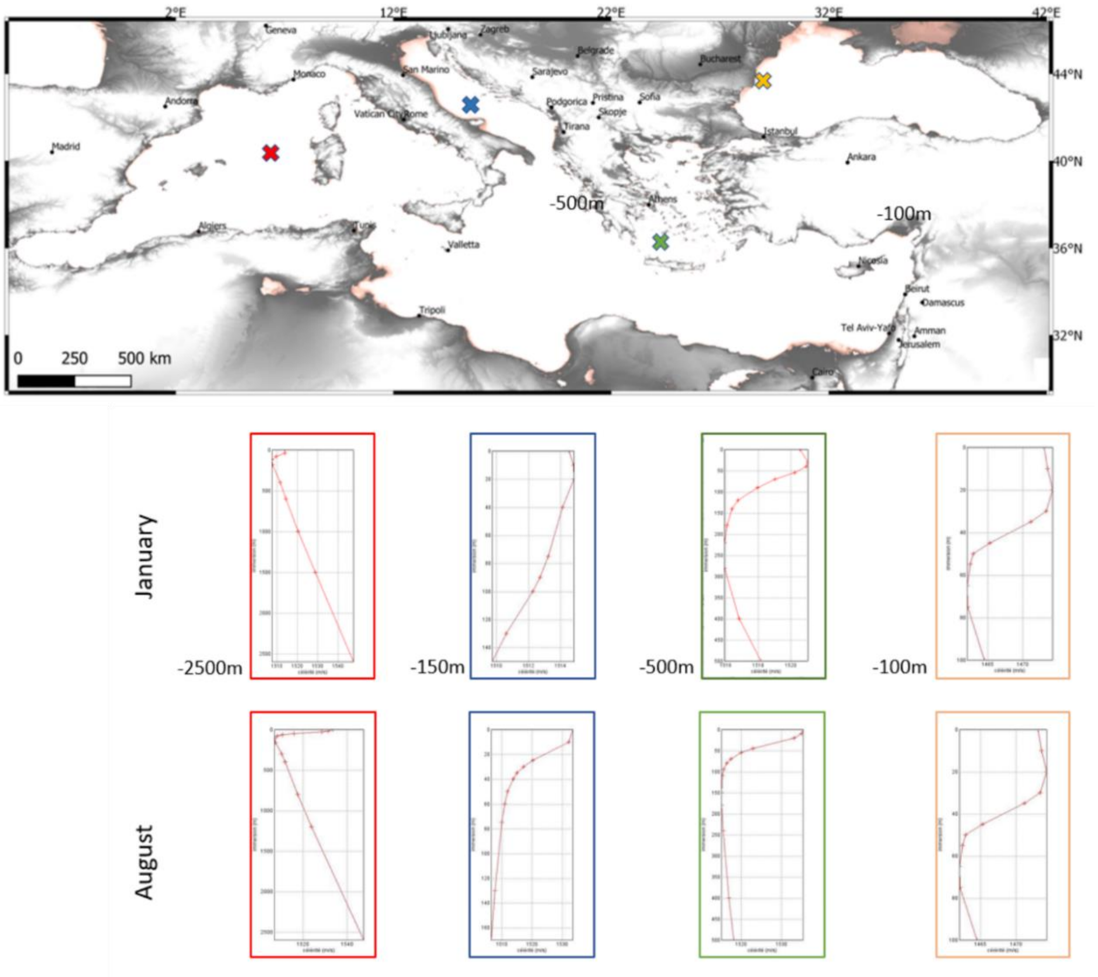

Figure 6. Sound speed profiles at four different locations (locations are marked by crosses on the map) for the months of January and August. Data from the French Navy and Defence Services.

2.4. Quantification of the effect of a specific measure

The analysis of the efficiency of a measure is performed by computing the difference Δ between the shipping noise estimated in the case when the measure applies, and the shipping noise computed for a reference state, as in Eq. 2.

Equation 2

$$\Delta = RL^{measure} - RL^{reference}$$

where $RL^{measure}$ is the received level when applying the measure and $RL^{reference}$ is the reference received level.

In this way, an efficient measure would lead to negative Δ values, while a counterproductive measure would lead to positive Δ values.

The noise levels are computed for several frequencies: 30, 50, 63, 80, 100, 125, 160, 250, 500 and 800 Hz, from which levels related to third octave bands centred on 63 Hz and 125 Hz are extracted by linearly interpolating the spectra and integrating the levels within the third octave frequency bands.

Computations are realised at several depths: 5, 30, 50, 90, 150, 300 and 1000 m. In the computation of Δ, the considered noise level at a specific location is the maximum noise level obtained over the different depths considered in the computation at this specific location, hence the maximum level over the sampled water column.

2.4.1. Accounting for temporal variability in the efficiency analysis

Shipping noise exhibits temporal variability according to the high temporal variability of the ship traffic density. Applying a mitigation measure can significantly change the dynamic of the traffic, potentially leading to a high variability in the efficiency Δ. For this reason, it is important to account for the temporal variability of the efficiency of the measure, in order to provide a complete understanding of the benefits a measure represents for reaching a good environmental status.

To this end, the effect of the measures is analysed over monthly scale (TAW) by computing Δ at the scale of the TOW (a few hours to one day). The choice of a TAW of one month is justified by the known dynamic of sound speed profiles, and their temporal sampling. It seems that a monthly estimation of the transmission losses is a good compromise (Sigray *et al.*, 2022). The choice of the TOW is driven by few considerations. Short TOW (few hours) leads to a large number of estimates of the shipping noise over the period of assessment. Short terms contrasts can be captured, such as variations of the shipping noise between day and night. Longer TOW (One or few days) will provide more homogeneous estimations, that are perhaps more representative statistically of the monthly levels. It permits to reduce greatly the computation time, which is necessary when computing received levels at the basin scale.

Statistics characterising the efficiency Δ over the month can then be computed: the first, second and third quartiles (Δ_{Q1}, Δ_{Q2}, Δ_{Q3}). The second quartile, or median, will provide the central tendencies of the efficiency Δ, and the interquartile range (|Q3 – Q1|) will inform on the stability of the efficiency (stable Δ value would lead to small interquartile range).

If a measure is efficient 100 % of the time, then all of the samples of the Δ distribution are expected to be negative: $\max(\Delta) < 0$). A measure acting on the shipping traffic should necessarily redistribute the sources of noise. For this reason, even in the case of an efficient measure, it could be expected that a small percentage of the time, the redistribution of sources related to the measure would act counter-productively and provide positive Δ values. Looking at the third quartile of the distribution permits in particular to identify areas displaying more than 25% of the time a counterproductive effect (i.e. $\Delta_{Q3} > 0$).

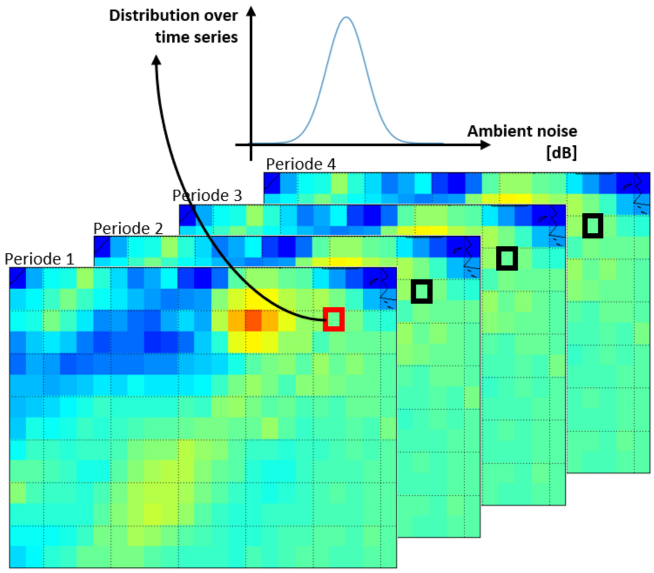

Figure 7. Extracting the temporal dynamic of shipping noise from high temporal resolutions maps (TOW of few hours to one day).

Finally, estimating the cumulative distribution function at Δ = 0 (zero efficiency) allows to apprehend the percentage of time that the measure is effective over the TAW. For example, when estimating the CDF of the efficiency Δ, at the specific value $\Delta_{ref} = 0$, a CDF below 50 % would mean that the measure is efficient less than 50 % of the time.

Three indicators were chosen for the analysis of the temporal variability of the measure:

1/ the first, second and third quartiles of the distribution, respectively called (ΔQ1, ΔQ2 and, ΔQ3,), of the efficiency values Δ estimated over the TOW over the month are indicators of the central tendency and spreading of the distribution;

2/ the interquartile range |Q3-Q1|is a way to quantify the spread of the distribution, hence how much the effect of the measure is stable or not over the considered month;

3/ The estimation of the cumulative distribution function of Δ for the specific value $\Delta_{ref} = 0$ provides an idea of the percentage of time over the month that the measure is efficient (i.e. the measure is not counterproductive).

3. Two case studies

3.1. Impact of a local speed limitation

3.1.1. Framework and motivations

The radiated noise level strongly depends on the speed of the ship, as presented is section 2.2. For this reason, one of the mitigation measures for the decrease of shipping noise level that is widely considered is traffic speed reduction measure. In this context, Voluntary Speed Reduction (VSR) experiments were performed in different areas of the world. Note that decreasing vessels speed presents additional benefits (decrease of greenhouse gas emissions and decrease of chemical pollutants, reduction of the collision risks) therefore, some of the experiments were realized in order to address other purposes than shipping noise reduction.

Among these programs, the ECHO program was implemented in the Salish Sea in 2017 for two months, and an opportunistic analysis of its repercussions on shipping noise was conducted through the installation of hydrophones and estimate from acoustic measurements the impact of the VSR experiment on shipping noise. The concerned area was the combination of the Haro Strait and the Boundary Pass, a shallow water zone (250 to 350 m depth) of particular interest for southern resident killer whales (Chion *et al.*, 2018, Pine *et al.*, 2018, Joy *et al.*, 2019). Another VSR experiment that led to estimations of the impact on shipping noise through sound recording was realized between 2014 and 2017, in the Santa Barbara channel (ZoBell *et al.*, 2021), a channel with bathymetry ranging between 200 and 800 m depth approximately leading to the major San Francisco Harbours.

For commercial vessels, a decrease in navigation speed may lead to a loss of profit or in a change in journey strategy. The question of the compliance of the measure was examined and a general analysis is provided by Morten *et al.* (2022). The analysis showed that speed reduction measures meet low cooperation levels when being voluntary, and that incentive measures, such as financial compensation and positive press, were necessary in order to increase the compliance to the proposed measures and the participation rate to the program. Other measures are sometimes envisioned, such as establishing areas to be avoided (Vanderlaan *et al.*, 2009). If reducing the speed of a single vessel should in theory reduce its level of emitted noise, the effect of reducing the vessels speed in a general case (any environment, any context of traffic), or even the applicability of the measure can be difficult to evaluate.

There exists a strong temporal variability of the shipping traffic, in relation to economical or seasonal factors, that can be uneven spatially, or locally increased. This variability increases the complexity in analysing the efficiency of VSR programs (Jensen *et al.*, 2015, Moore *et al.*, 2018, Redfern *et al.*, 2020). Considering noise pollution, the efficiency of the measure is not straight forward, and might depend strongly on environmental parameters, geomorphology, bathymetry, and on the nature of the shipping traffic in the targeted zone. Decreasing the navigation speed causes a densification of the shipping traffic in the zone, as vessels take an increased time to cross it. Finally, the engines of high-speed vessels might not be suited for low speed navigation, and an extra-noise might be produced by such vessels when navigating below the speed limitations suggested by VSR programs (Appendix A2). Hence, the overall result of a speed limitation is not only a decrease in the intensity of acoustic sources, but also a spatial and temporal redistribution of the noise sources in the area. These combined effects are difficult to anticipate.

3.1.2. **Parameters of the experiment**

Shipping noise maps were computed with a spatial resolution of 5 minutes arc.

3.1.2.1. Application area

<u>North West Mediterranean Sea, Slope and Canyon System Important Marine Mammals Area (IMMA)</u>

The boundaries of this area, except for the southern one, are represented by the limit of the continental shelf (200-m isobath) in the North-western Mediterranean Sea. Therefore, this IMMA includes all the slope (200 to 2 000 m depth) and abyssal plane (2 000 - 2 500 m) areas found in this part of the Mediterranean and the extension is 145 297 km². The southern limit connects the North-western Sardinia to the northern half of the Balearic Sea. Although the southern boundary appears as an arbitrary line, its position may be explained as it roughly delimitates the known distribution of fin whales in the north-western Mediterranean region.

Considering oceanographic features, the area is characterised by the presence of the Ligure-Provençal current, a cyclonic surface current originating from streams coming from the Tyrrhenian Sea and Algerian Sea up north to the Gulf of Genoa where they join and turn south-west, cross the offshore Gulf of Lion and continues towards the Spanish coasts. Moreover, deep water circulation is generated here by the strong mistral winds blowing in the Gulf of Lion. The Mistral lowers indeed the temperature of surface water that tends to go down in the water column while being pushed offshore by the wind itself. This area has also an intermediate circulation (200-500 m) that is part of an overall Mediterranean circulation regime of intermediate-depth waters. Finally, local currents exist due to the steep slopes that force cold deep water to come up to the surface, especially in areas with underwater canyons.

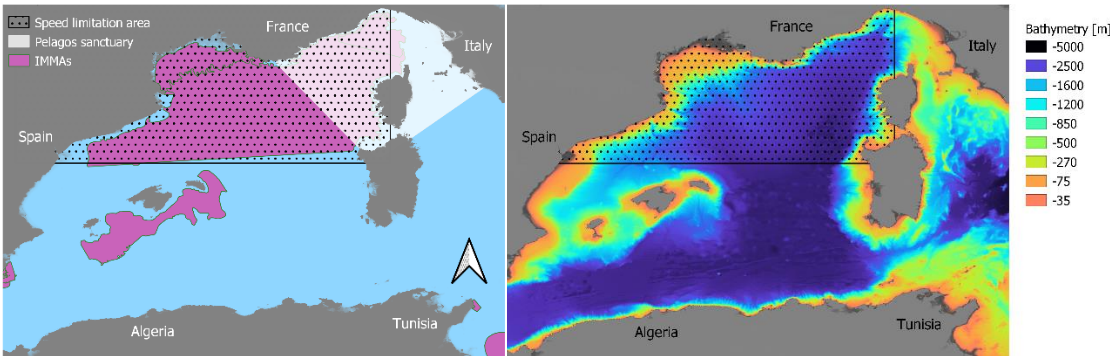

Figure 8. Regulated area, area of importance for marine mammals and bathymetry in the Wester Mediterranean Sea.

Such upwellings, together with the circulation regimes described above, induce a high rate of recirculation of nutrients from highly productive zones (e.g. the Gulf of Lion) to the rest of the area.

These characteristics make it possible for the area to support a great biological richness, including a large diversity of cetaceans. 8 species of cetaceans are indeed considered resident here: fin whale, sperm whale, Cuvier's beaked whale, pilot whale, Risso's dolphin, striped dolphin, short-beaked common dolphin and bottlenose dolphin.

Western Black Sea Natura2000 areas

The Romanian MPA network encompasses 7,457 km2 of the shelf, distributed among ten MPAs. For the purpose of the study, two Natura 2000 zones are identified, located along the southern Romanian shore (together represent 1.8% about 107.3 km2 of the surface of all Romanian protected areas). The MPAs support a rich biodiversity and have been recognized as biodiversity hotspots and important nursery grounds for several protected fish species through Habitat Directives and have been also listed in the Annex II of the Directive 92/43/EEC (Zaharia *et al.*, 2014).

- Capul Tuzla Marine Area (ROSCI0273) with a surface area of 4946.9ha, which is a habitat for the following species, referred to in Article 4 of Directive 2009/147/EC and listed in Annex II of Directive 92/43/EEC: the marine mammals *Tursiops truncatus*, and *Phocoena phocoena relicta*, and the fish *Alosa immaculata*, and *Alosa tanaica* (for more information, see natura2000.eea.europa.eu).
- Vama Veche (ROSCI0269) with a surface area of 12311 ha, which is also a habitat for the aforementioned species (for more information, see natura2000.eea.europa.eu). which use the area as a place of passage feeding and breeding for many marine species (Begun *et al.*, 2012; Paiu M., 2013); CENOBS Report D2.2.1, 2019.

The Romanian fishing area represents a high importance in the feeding and breeding of the main fish species, although the catches in this area do not exceed 2-3% of the total catch taken in the Black Sea basin (Radu G and Anton E., 2014; Tiganov *et al.*, 2018).

These protected areas, of interest for harbour porpoises and bottlenose dolphins, are shallow-water areas (less than 80 m of water depth), very close to the shore. In order to evaluate the effect of speed reduction measures on such specific areas, a zone including the two Natura2000 areas was selected and a speed reduction was simulated.

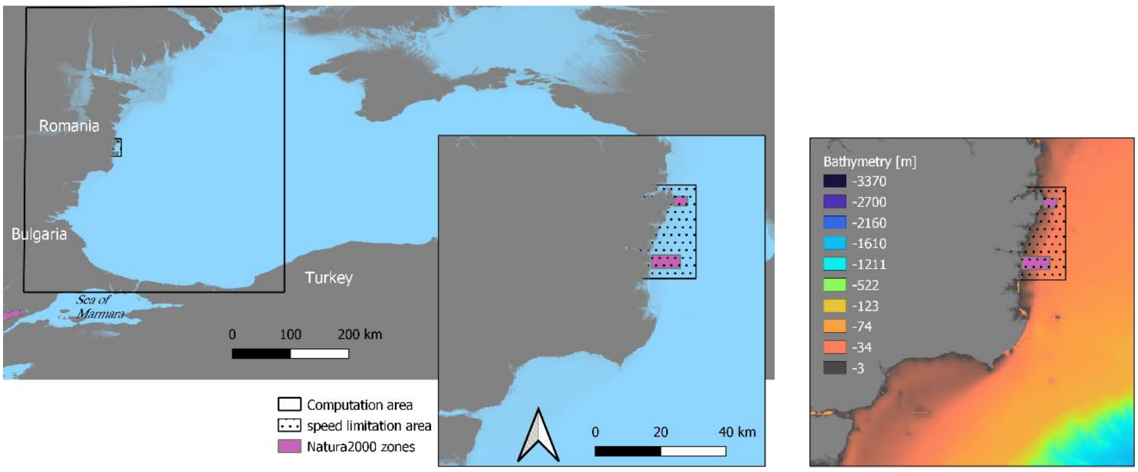

Figure 9. Regulated Natura 2000 area and bathymetry in the Western Black Sea's Natura 2000 area.

3.1.2.2. Temporal context

The experiment was performed for the month of August, the busiest month regarding shipping traffic (Campana *et al.*, 2017, Esteve-Perez *et al.*, 2019, Khodjet *et al.*, 2020), when pleasure boats and passenger vessels add up to the usual commercial shipping traffic.

As the shipping traffic is not expected to be evenly distributed over the day, assuming that the impact of the measure could as well be contrasted over a day, a TOW of 6h was chosen. As reducing the navigation speed tends to redistribute the sources in time, the usual alternation of levels between day and night is expected to be smoothed, and therefore, such high temporal resolution is interesting to capture the dynamic in the effect of the measure. A first set of experimentations were conducted first with a TAW of one week, and subsequently with a TAW of one 29 days.

3.1.2.3. Speed limitation

In the conducted experiment, the speed reduction simulated was a speed limitation. A maximum authorized speed was chosen. Unmodified AIS data inside the study zone were gathered and for each boat inside of the speed reduction zone, if exceeding the speed limitation, the AIS data was modified to simulate a navigation at the maximum authorised speed, into a new synthetic AIS dataset.

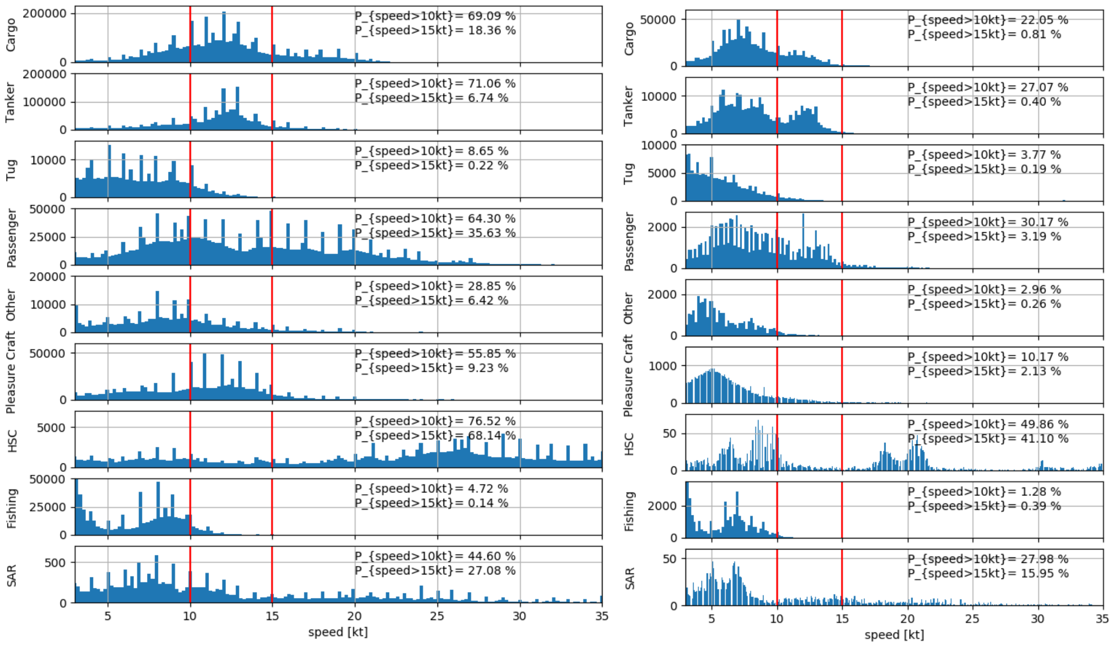

Figure 10. Distribution of vessel speeds for the most present categories of vessels in the month of August 2019 in the Mediterranean Sea (left) and Black Sea (right).

In the first set of experiments, the chosen speed limit was 10 kt. In the second set of experiments, two speed limitations were considered, 10kt and 15 kt.

Fig. 10 presents the distributions of navigation speed for the most present types of vessels in the Mediterranean Sea and in the Black Sea in the whole month of August.

In the Mediterranean Sea (Fig. 10 left), many types of ships exhibit central speed tendency between 10 and 15 kt (cargos, tankers, Passenger vessels and pleasure craft). The only types of vessels exceeding 15 kt are cargos, passenger vessels, High Speed Crafts (HSC) and Search and Rescue (SAR) vessels. Only HSC exhibit central tendencies above 15 kt.

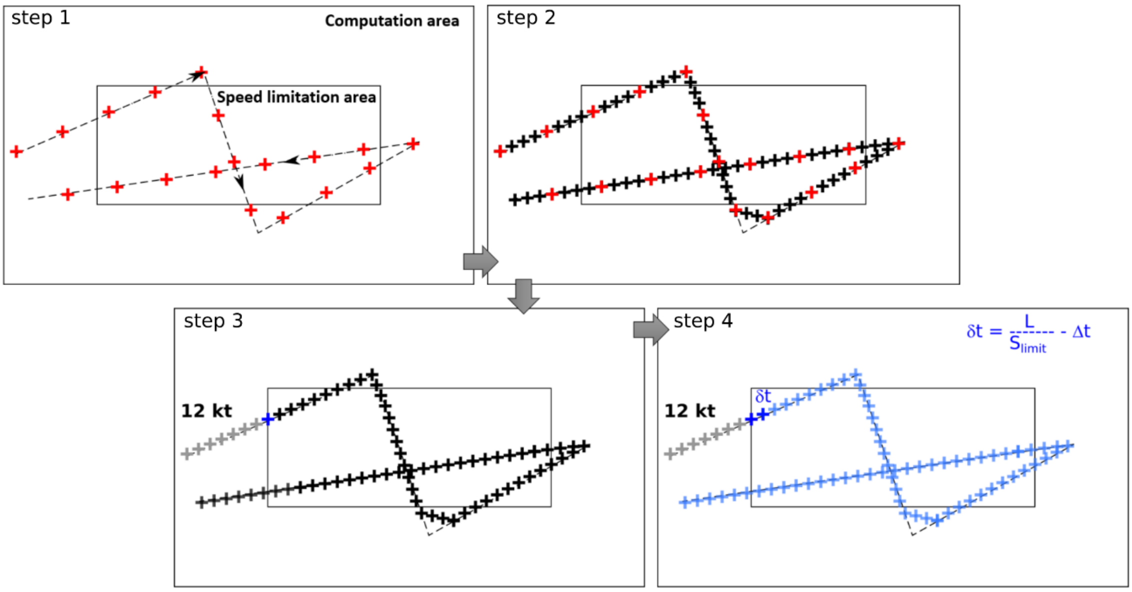

Figure 11. The four successive steps in simulating a delay related to a limited speed inside the Speed limitation area.1. Retracing the route of a specific vessel through AIS data; 2. Resampling of the AIS data along the route; 3. Identification of the vessel entrance in the speed limitation area (SLA); 4. For each section of the path inside the SLA, estimation of the vessel speed: if speed exceeds the speed limit, application of a delay to all following AIS emissions, in order to mimic the vessel speed being equal to the limitation speed.

In the Black Sea (Fig. 10 right), vessels seem to navigate at much lower speed. Except for HSC, all types of vessels present central tendencies below 10 kt and do not exceed 15 kt. Only cargos, tankers, passenger vessels and HSC occasionally exceed 10 kt.

3.1.3. Methodology

The VSR experiments were realised by modifying the AIS data set, and simulating in the data set a speed limitation inside a selected Speed Limitation Area (SLA). Here are the four steps that permit the creation of a modified AIS dataset:

- Retracing the route of a specific vessel through AIS data
- Resampling of the AIS data along the route
- Identification of the vessel entrance in the SLA
- For each section of the path inside the SLA, estimation of the vessel speed: if speed exceeds the speed limit, application of a delay to all following AIS emissions, in order to mimic the vessel speed being equal to the limitation speed.

In order to limit potential transient effects at the onset of the measure, in the simulated dataset, the measure was initiated 3 days prior to the experimentation period.

3.1.4. Results

The results are presented through the difference Δ (Eq. 2) between levels obtained with the speed reduction scenario and the reference level (with no speed limit), that aims at quantifying the efficiency of the speed reduction measure. This quantity takes negative values when the measure causes a decrease in shipping noise, and positive values when the measure causes an increase in shipping noise. This quantity is presented in the following sections for the third octave band centred on 63 Hz, considering for any location as received level the maximum received level over all sampled depths in the water column. The distribution of Δ values is analysed by looking at the quartiles.

3.1.4.1. First set of experimentation

The first set of experiments was conducted over a period of 1 week, on the two selected zones. In order to limit potential transient effects at the onset of the measure, in the simulated dataset, the measure was initiated 3 days prior to the experimentation period. The computation was realized with a TOW of 6h and a TAW of one week.

A speed limit of 10 kt was selected, impacting approximately 69 % of cargo vessels, 71 % of tankers, 64 % of passenger vessels, 56 % of pleasure craft, 77 % of HSC, 45 % of SAR vessels in the Western Mediterranean zone and 22 % of cargo vessels, 27 % of tankers, 30 % of passenger vessels, 50 % of HSC and 28 % SAR in the western Black Sea zone.

The area considered for the computation of shipping noise maps and for the simulation of a speed limitation measure is presented in Fig.8 (Western Mediterranean Zone) and Fig. 9 (Western Black Sea Zone).

<u>Western Mediterranean zone</u>

Fig. 12 presents the shipping noise computed for the two third octave bands centred on 63 and 125 Hz for the month of August 2019, considering the unmodified vessels speed. The computations are made assuming that all sources are point source located at 5 m depth. A few patterns can be noted from these maps.

On the third octave band centred on 63 Hz, levels in the zone are around 100 dB for the highest levels (Ligurian Sea, which is a complex zone, covered by multiple shipping paths) and 60 dB for the quietest zones (Gulf of Lion, a shallow water area (<50 m)). In the noisiest zones, levels are lower on the third octave band centred on 125 Hz than on the one centred on 63 Hz.

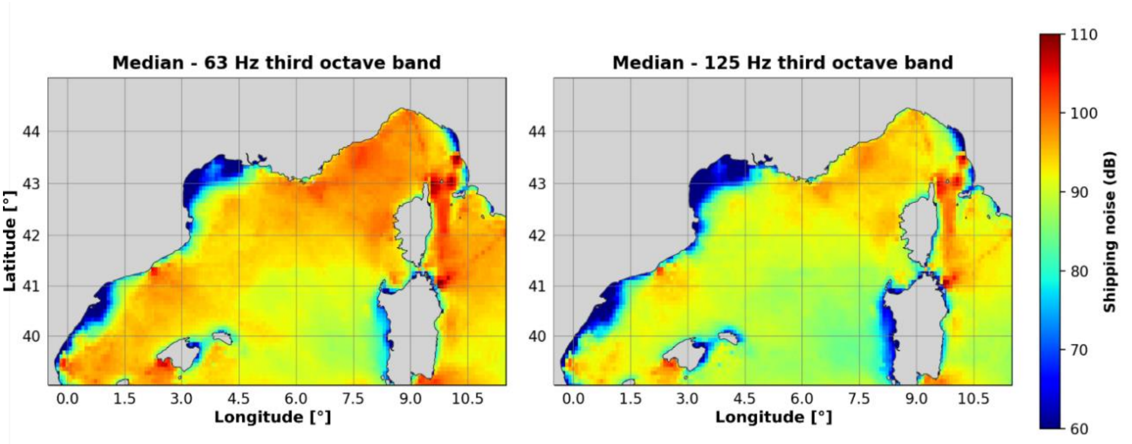

Figure 12. Monthly median of the shipping noise on the third octave bands centred on 63 and 125 Hz in August 2019 in the Western Mediterranean zone – maximum over the water column (resolution 5minutes arc).

Fig. 13 presents the first, second and third quartiles of the distribution of shipping noise difference Δ estimated for the third octave band centred on 63 Hz.

The median of the temporal distribution of Δ values is inhomogeneous and seems to depend on the presence of dense shipping traffic (harbours, traffic bottleneck) and on the bathymetry. Area of particular efficiency (low Δ value) appear as spots that are difficult to link solely to traffic patterns, nor to environmental characteristics, where Δ_{Q2} reaches -8 dB.

The third quartile of a distribution is the delimitation between the lowest 75% of the samples and the remaining highest 25%. The third quartile of the distribution of Δ values (Δ_{Q3}) indicates the low boundary of the 25 % highest Δ values.

In the Δ_{Q3} map, areas appearing in red colour ($\Delta_{Q3} > 0$) are affected at least 25% of the time by an increase of shipping noise in relation to the speed reduction measure. Results show that some areas are affected at least 25% of the time by an increase of shipping noise: some major shipping routes (Porto Torres – Barcelona lane; Civitavecchia – Barcelona Lane; Marseille Barcelona lane), Porto Torres, Gulf of Lion, Marseille port which probably endure some sort of traffic jam: vessels are slow down but stay longer time in the area, that become crowded.

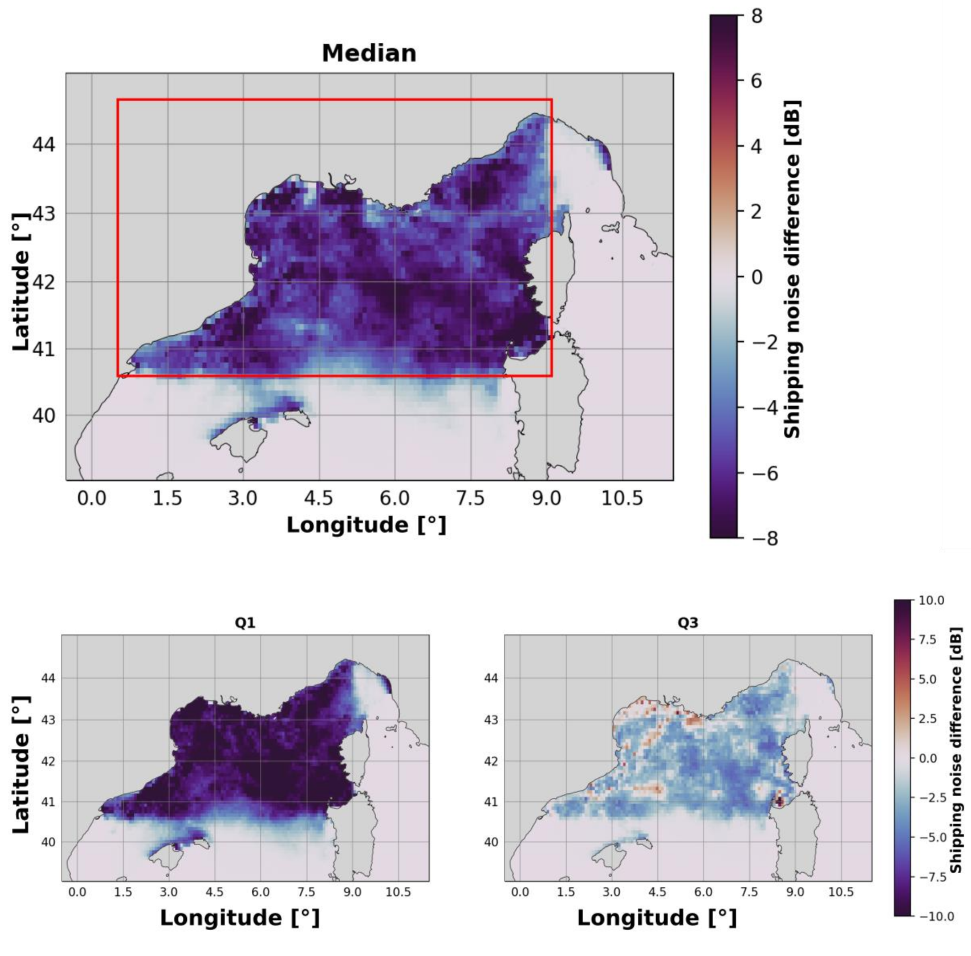

Figure 13. Median, first and third quartiles of the distribution of the shipping noise difference Δ in the first experiment in the French IMMA zone.

<u>Black sea Natura2000 zone</u>

Fig. 14 presents the shipping noise computed for the two third octave bands around 63 and 125 Hz for the month of August 2019 in the Western Black Sea zone, considering the unmodified vessels speed. The computations are made assuming that all sources are point source located at 5 m depth.

A few traffic lanes appear clearly, as well as a patchy hotspot of acoustic noise highlighting the access to the Port of Constanța. Because the bathymetry is characterised by a very progressive and smooth increase of water depths away from the shore, coastal areas are characterised by very low levels of acoustic noise. In this area, the propagation is expected to be very limited away from the sources. For that reason, the traffic lanes appear very clearly.

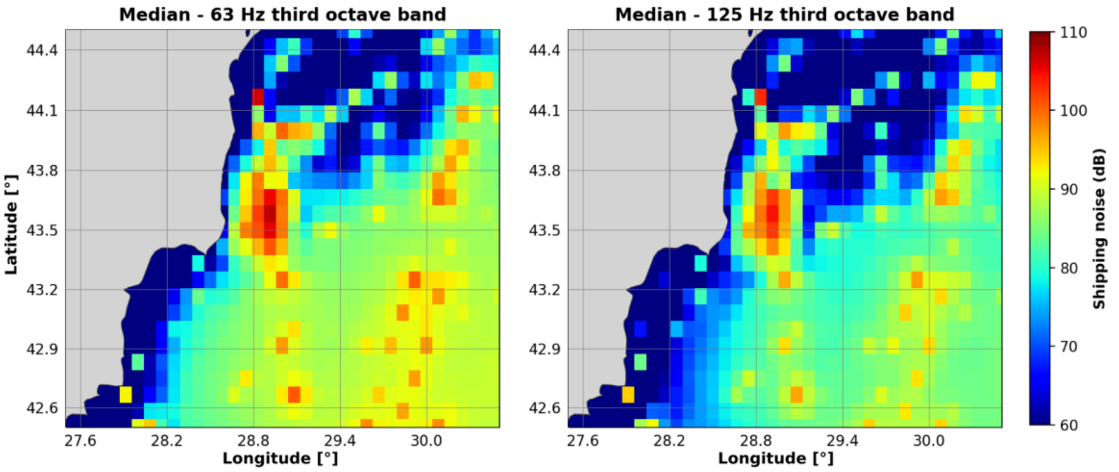

Figure 14. Monthly median of the shipping noise at 63 and 125 Hz in August 2019 in the Western Black Sea zone – maximum over the water column (resolution 5 minutes arc).

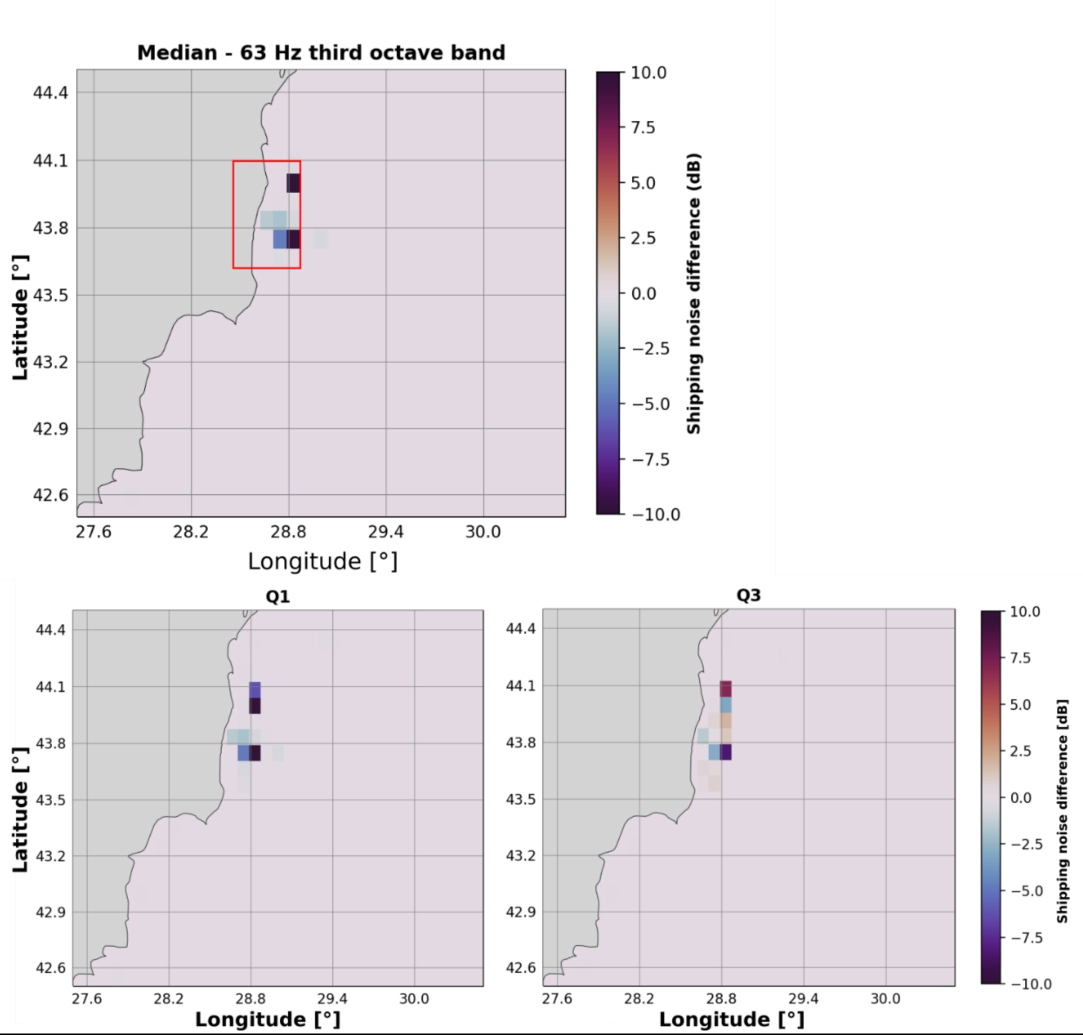

Figure 15. Median, first and third quartiles of the distribution of the shipping noise difference Δ in the first experiment in the Western Black Sea zone, hosting two Natura2000 areas.

Fig. 15 exposes the quartiles of the Δ distribution in the Black Sea zone. The maps show a great inhomogeneity in the effect of the speed reduction experiment. Only a few cells (3 to 5) seem to be significantly impacted by the speed reduction.

In this region, the speed limitation area is a very shallow water area, with limited traffic. In fact, very few vessels cross it. Moreover, in that region, it seems that vessels already adopt low navigation speed (Fig. 10). For this reason, the measure probably impacted the noise sources very locally and punctually.

The speed reduction area does not include the entire hot spot of noise. A question was how much the speed reduction would be masked by the surrounding noise. A decrease of shipping noise can still be observed very close to the hot spot, suggesting that the attenuation is strong enough such that a speed decrease inside the area can still be locally efficient, even in the proximity of a hotspot of shipping noise.

3.1.4.2. Second set of experimentation

The second set of experiments was only conducted on Western Mediterranean zone as the impact on the Western Black Sea zone was neglectable. In order to get more robust and reliable statistics, and to limit as much as possible the impact of the transition at the onset of the measure, the TAW was increased to 29 days, keeping a delay of 3 days at the onset of the speed limitation measure, prior to starting the analysis, to limit transient effects. The TOW was kept to 6h. Two speed limits were tested: 10 kt and 15 kt.

The median, first and third quartiles of the Δ distribution are presented in the case of a speed limit at 10 and 15 kt in Fig. 16.

In the case of a speed limit at 10 kt, the median shows a negative central tendency for the Δ value (from zero to -6 dB depending on the location), showing that the measure has generally produced a decrease of shipping noise (as in the first set of experiments).

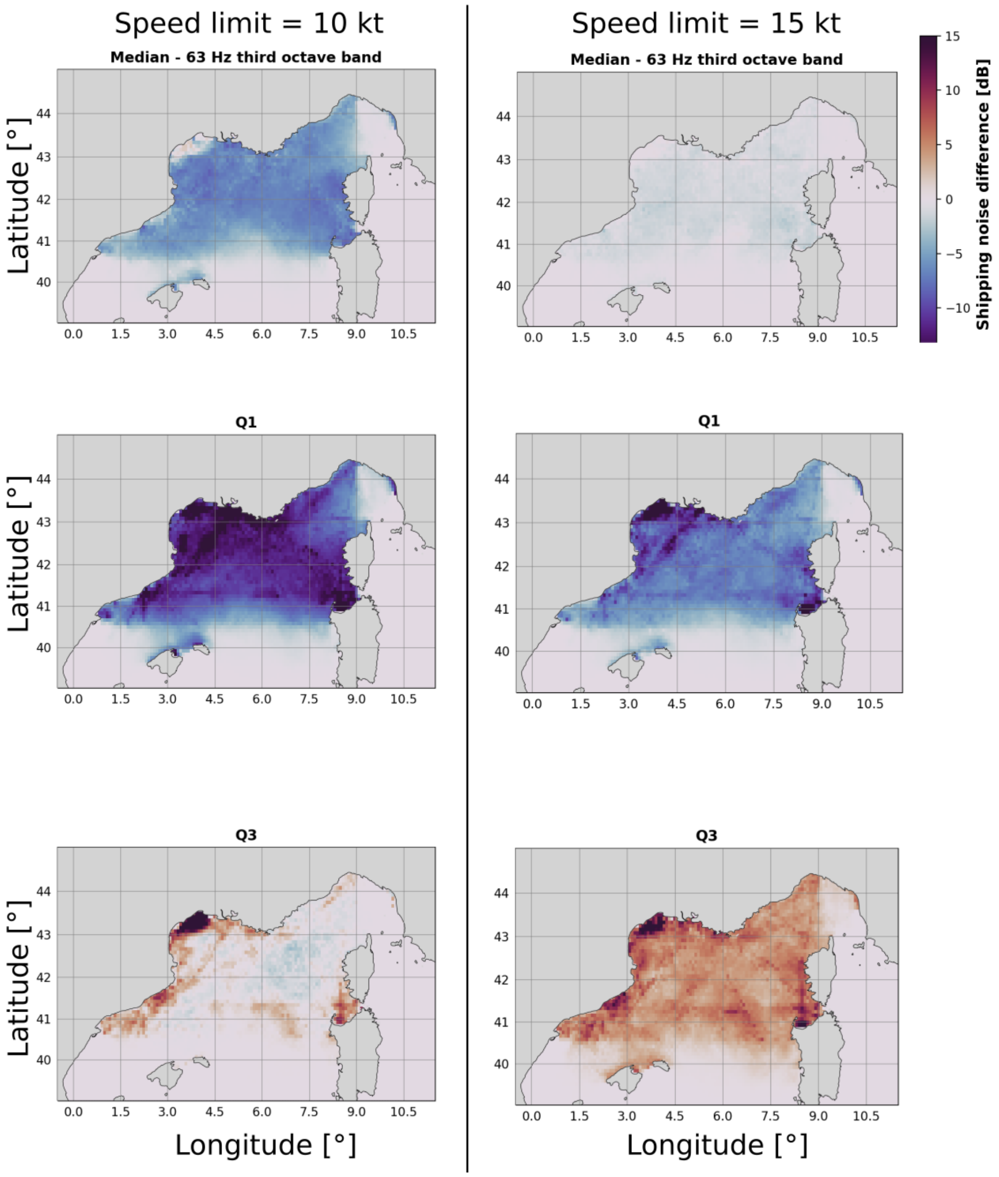

Figure 16. Median, Q1 and Q3 for the 63 Hz. Measure efficiency estimated in the 63 octave frequency band, maximum in the water column: median (top), first (middle) and third (bottom) quartiles of the distribution of shipping noise difference Δ over the experiment period for limitation speeds of 10 kt (left column) and 15 kt (right column).

Zones with particularly low Δ_{Q1} appear, as well as zones with particularly high Δ_{Q3}, that are in good agreement with the first set of experiments (some major traffic lanes, as well as crowded harbours and bottleneck areas). Where these zones overlap, the effects of the measure are very variable in time, and the efficiency lack stability.

Results show that in the 15 kt speed reduction case, the central tendency (median) is very close to $\Delta = 0$, suggesting a zero efficiency, and Δ_{Q1} and Δ_{Q3} are of nearly opposite signs, highlighting areas of increased variability in the efficiency (Δ_{Q1} particularly low and Δ_{Q3} particularly high). This very low efficiency could be anticipated from the fact that very few vessels exceed 15 kt (Fig. 10), the measure impacts therefore a very limited number of vessels.

In order to capture the dynamic in the efficiency of the measure, the second indicator consisted in calculating the percentage of time that the measure was efficient (D<0). This indicator was computed over the entire area, in the case with a speed limit at 10 kt. We attributed a low efficiency to percentages lower than 50 %, a medium efficiency to percentages between 50 and 75 % and a high efficiency to percentages higher than 75 %, gathering this result in Fig. 17.

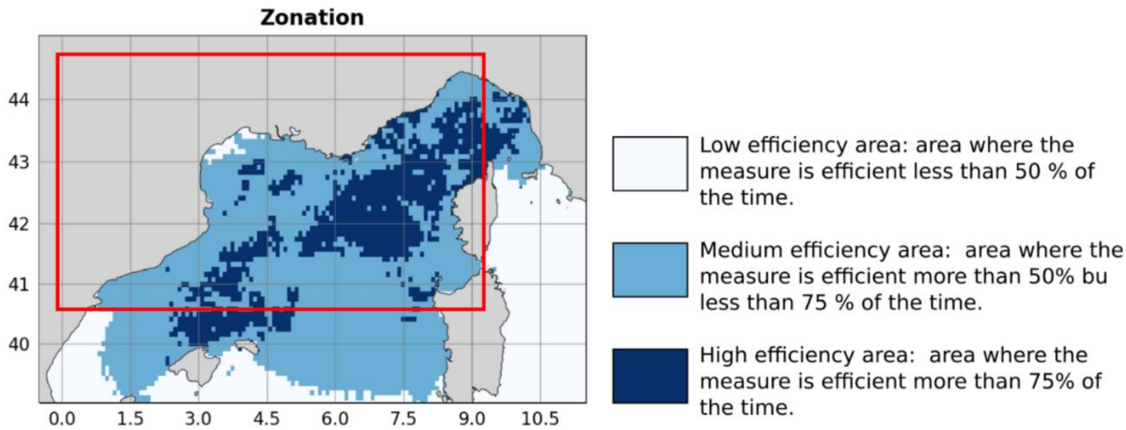

Figure 17. Distribution of zones where the measure presents a low (measure efficient less than 50% of the time), medium (measure efficient more than 50% but less than 75% of the time) and high efficiency (measure efficient more than 75% of the time) efficiency.

From this indicator, it is observed that

- Except for the Gulf of Lion, which is a very shallow water area, the entire speed reduction zone experiences at least a medium efficiency: at least 50% of the time, the speed reduction measure at 10 kt results in a decrease of shipping noise.
- Some zones present a high efficiency. It seems to concern mostly deep-water area (>2000m). No clear relation is derivable between shipping traffic characteristics and possibility of high efficiency of the measure.
- Deep water areas (1000 m and more) outside of the speed reduction zone, along its boundaries, present as well a medium to high efficiency. This effect is related to the propagation of sounds that can occur along large distances in deep water environments.

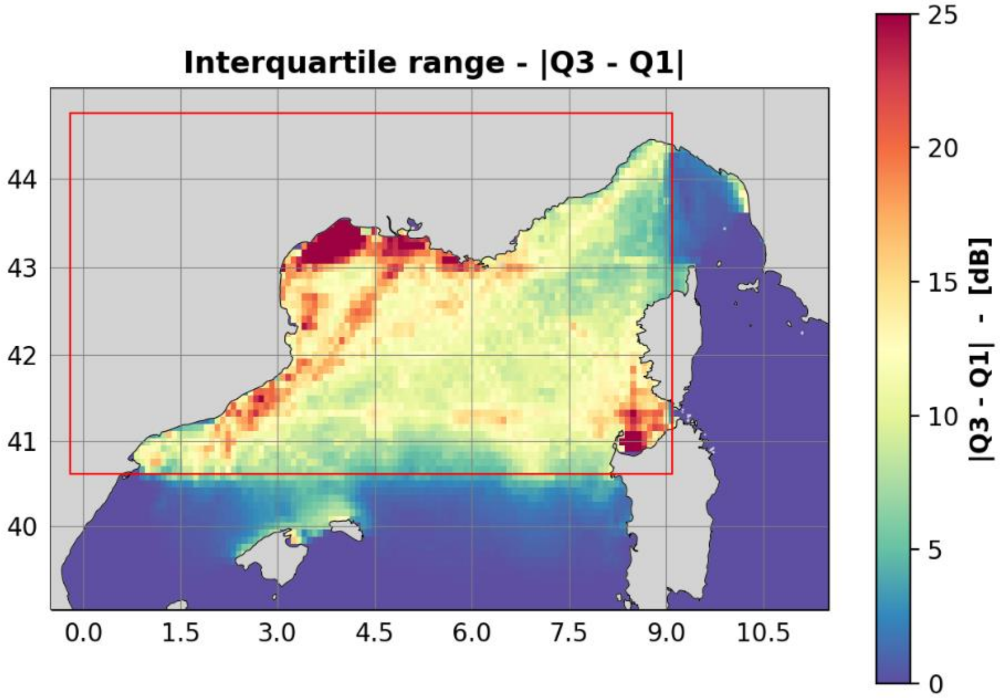

Figure 18. Map of the interquartile range |Q3-Q1| as indicator of the temporal variability of the measure efficiency.

The third indicator aims to assess how stable the effects of the measure are stable in time. This is explored through the spread of the distribution of Δ. This spread can be expressed with several manners (standard deviations, interquartile range) and is an indicator of the variability that can be found in the measure efficiency. Here, the interquartile range $|\Delta_{Q3}-\Delta_{Q1}|$ is chosen to quantify the spread, as it is robust to extreme values, and is expressed in dB. In Fig. 18, the interquartile range is represented for the third octave frequency band 63 Hz. Most of the area appears with an interquartile range between 5 and 10 dB. Few zones are characterised by higher interquartile range, reaching 25 dB: major shipping routes, Portos Torres area and Gulf of Lion.

Fig. 19 compiles the two indicators (efficiency of the measure and spread of the effect in time), presenting zones of low, medium and high efficiency in the two case-scenario: 1/ stable effect of the measure, i.e. the interquartile range is below 12 dB and 2/ unstable effects of the measure, i.e. the interquartile range is above 12 dB.

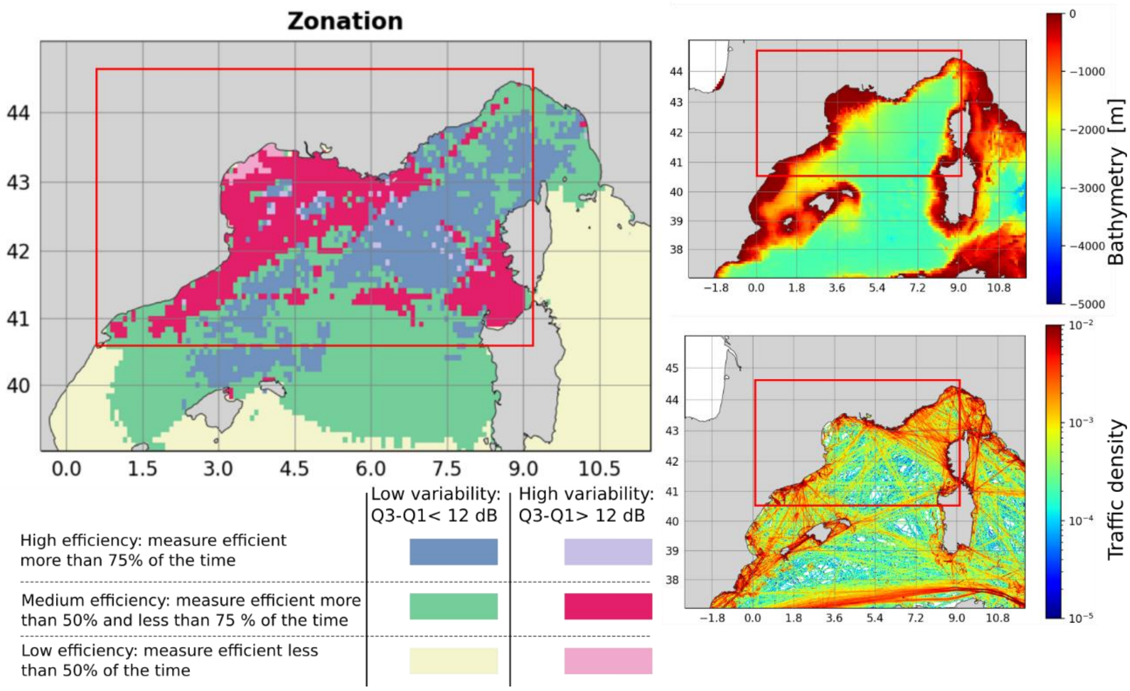

Figure 19. Distribution of zones of high variability and low variability of the measure, in relation to the local median efficiency (left) in relation to the bathymetry (top right) and the traffic (bottom right) in the Western Mediterranean Sea. The zone of traffic reduction is delineated in red.

From this map, it appears that a good stability is difficult to reach in shallow water environments. In deep water environments, unstable effects can be observed in areas where the traffic is 1-dimensional (along a lane) and is not homogeneously distributed. For example, a modification of the traffic along the Porto Torres – Barcelona lane will lead to an unstable modification of the shipping noise in the surrounding zone. On the contrary, in the Ligurian Sea, where many lanes cross and cover the area, the sources are evenly distributed at the sea surface and the effect of speed reduction is quite stable.

If a medium efficiency is observed outside of the speed limitation zone, along its boundaries, it can be noted that this efficiency seems to be stable in time.

3.1.5. Outcomes of the study

Environment		Effect of the measure	
Traffic characteristics	**Bathymetry**	**Efficiency of the measure**	**Stability of the effects**
Dense homogeneous traffic	Shallow water	Low	Low stability
	Deep water	High	High stability
Dense traffic along an isolated shipping route	Shallow water	Low	Low stability
	Deep water	Medium	Low stability
No dense traffic	Shallow water	Low	Low stability
	Deep water	Medium – high	High stability
Intense traffic in proximity to a hot spot of noise	Shallow water	High	High stability

No dense traffic in proximity to a hot spot of noise	Shallow water	Very low	High stability

Table 1. Gathered results of the speed reduction experiments.

3.1.6. Discussion

The next paragraphs tackle the limits of the study, related to the methodology, the data, and the chosen context to conduct the study.

A first limit concerns the noise model employed. It is very difficult to model accurately the source level of a ship. Each physical phenomenon contributing to the shipping noise cannot be singularly described, and empirical models are preferred when conducting large-scale studies with multiple complex sources, such as this present study. Randi3.1 empirical model, used in the methodology, is accurate in the very specific context used to determine it. Several characteristics, not accounted for in the Randi3.1 model, might still impact the source levels, such as vessel weight, engine type and age, hull characteristics (See Appendix A.2) Moreover, a drastic traffic speed limitation would lead vessels usually navigating at a speed around 30 kt to navigate at less than half their usual speed. For this reason, extra noise sources might add up, related to an « extra-solicitation » of the engine, working under none-nominal operating speed (see Appendix A.2). This assumed extra noise-component is very likely to occur but cannot be accounted for without an extensive study to explore whether it is neglectable or not, and if not, to model it.

It is known that seasonality has a great impact both on the traffic as industrial, dishing and passenger transport activity vary along the year, and on the acoustic propagation, through changes in temperature profiles. Although the seasonal variations of the environment were considered in the model, the impact of seasonality on the measure was not analysed as the experiments were only conducted in the month of August.

The cost of slowing down vessels drastically may limit such measures to small areas. In order to provide some orders of magnitude, for a navigation between Barcelona and Porto Torres (approximatively 316 nm), navigating at 30, 20, 15 and 10 kt would respectively take about 10:30, 15:45, 21 and more than 31:30.

Finally, the levels obtained in the reference cases and in the simulated cases of a speed reduction zone could be translated into an estimation of indicators of the Good Environmental Status (GES) related to acoustic noise, and difference of noise levels could be translated into differences in GES indicators.

3.2. Impact of a traffic decrease in the specific case of the 2020 Sarscov-2 Pandemics

3.2.1. Framework and motivations

The increase year after year of the marine traffic worldwide has been, for the past half century, a lasting phenomenon, to which it seems difficult to run counter. Tournadre *et al.* (2014) analysed that the worldwide marine traffic has increased by more than 300 % between 1992 and 2012, and an increase of 3.4 % per year is suggested by the UNCTAD for the period 2019 - 2024 (United Nations Conference on Trade and Development (UNCTAD-ref)).

In this context, the COVID-19 pandemic marked an interlude, as many countries went into lockdown, leading to a forced pause of the economy as well as a drastic reduction of movement of people, all of which led to a decrease in marine traffic.

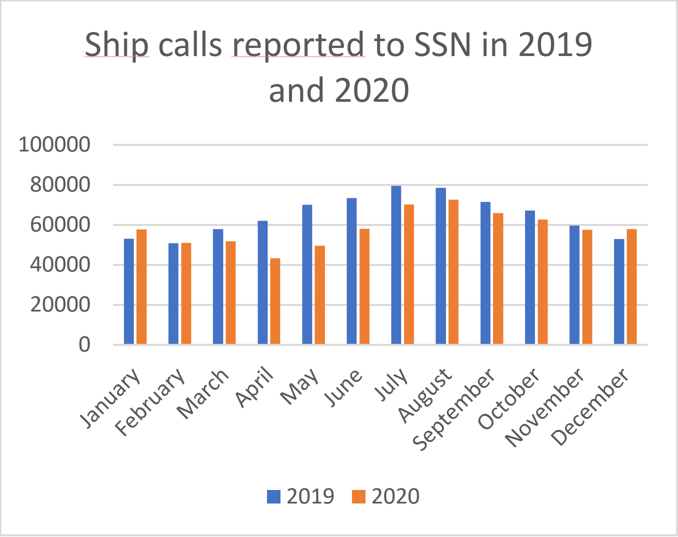

Figure 20. Ship calls reported to SSN in 2019 and 2020 in the EU member states - from: EMSA report: COVID-19 – impact on shipping, June 2021.

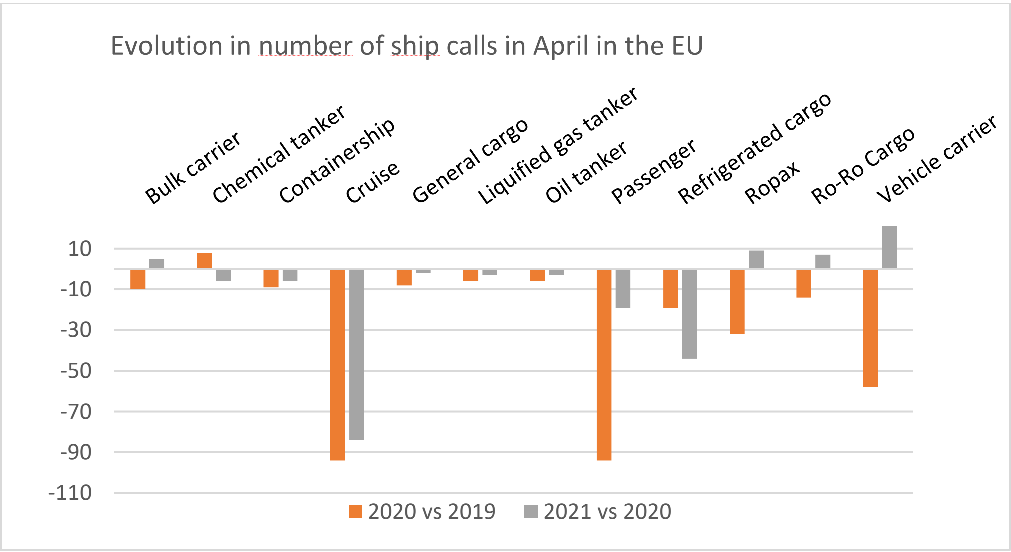

Figure 21. Evolution of number of ships calls between in 2020 in relation to 2019 and in 2021 in relation to 2020 for several categories of ships, in the month of April.

The impact of lockdowns on marine traffic was analysed in few publications. The EMSA issued two reports analysing the impact of COVID-19 pandemic on the maritime sector (EMSA 2021) and on shipping (EMSA 2022) in the EU waters, presenting notably the evolution of ship calls between 2019 and 2020 month by month, for different categories of ships (Fig. 20 and 21).

March *et al.* (2021) noted a decrease in traffic in 70.2 % of the exclusive economic zones, with a peak in global traffic decrease in April, and identified that passenger vessels were most impacted, and for a longer time. Millefiori *et al.* (2021) pushed the analysis one step further and analysed in detail and specifically for a few regions the impact of the lockdown measures on shipping industry, by characterising the vessels mobility. Millefiori *et al.* (2021) noticed a general reduction of the activity from March to June 2020.

Many studies analysed the impact of COVID-19 pandemic and lockdown on ambient noise, both in marine and in aerial environments.

<u>Majors dates in the first COVID-19 lockdown</u>

Many Mediterranean and European countries went into lockdown during the month of March 2020, at different dates. Italy was the first European country to declare a lockdown (8-10th of March), Spain declared the lockdown on the 15th of March, France on the 17th. The transition towards an effective reduction of the traffic started in the mid-March, and the effective reduction of traffic seems to be effective from March to May (Fig. 20), with a progressive return to the usual state of traffic in June and July. Millefiori *et al.* (2021) indeed noticed that the recovery of the traffic mostly occurred in June.

3.2.2. Parameters of the study

In order to analyse the impact of COVID-19 lockdowns on shipping noise, shipping noise maps were realized month by month for the year 2019 and 2020. The TAW was set to a month, and the TOW was set to a day.

This analysis was conducted over the two basins (Mediterranean Sea and Black Sea at once). Only the coastal waters along the Libyan shore was masked in the results, due to a lack of confidence on the AIS data gathered from that area. Shipping noise maps were computed at a resolution of 10 arc-minutes.

Δ was computed, considering as reference state the year 2019 and as perturbed state ($RL^{measure}$) the year 2020, such that $\Delta = RL^{2020} - RL^{2019}$. Once again, this quantity is evaluated by accounting for the local maximum value over the sampled depths.

3.2.2.1. Environmental properties

3.2.2.2. Characteristics of the traffic in the area

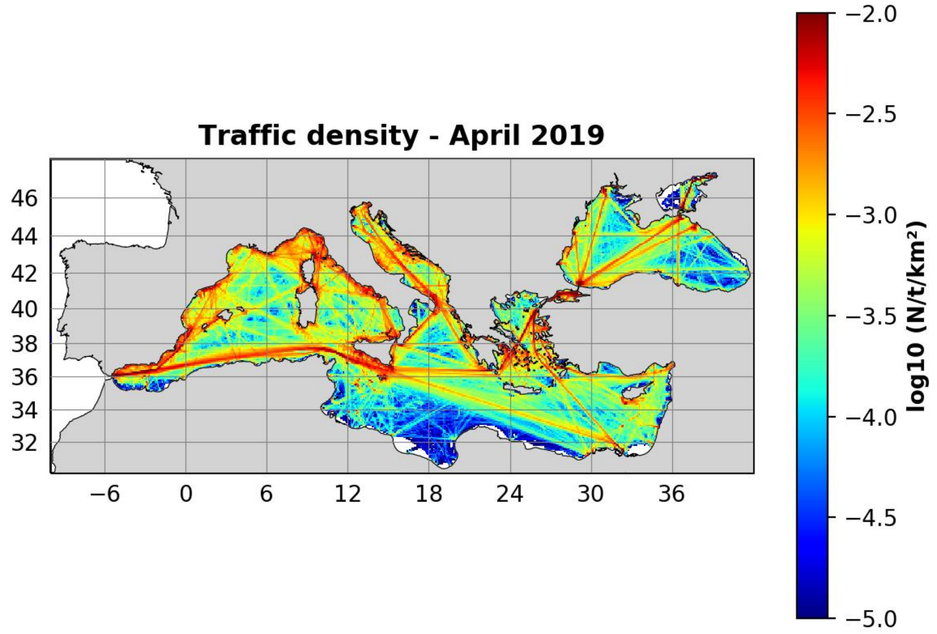

Figure 22. Traffic density map in the Mediterranean and Black Seas for the month of April 2019.

3.2.3. **Results**

The results are presented through a monthly comparison. The Δ value is estimated at the scale of the TOW, and the monthly distribution is presented through maps of the three quartiles: Q1, Q2 (the median) and Q3. These three quartiles separate the distribution into 4 parts of the same size (number of samples). The median is an indicator of the central tendency of the distribution. As a reminder, negative median of Δ values - which appear in blue on the maps - indicate a medium decrease of shipping noise in 2020 relative to 2019, while positive median Δ values – in red – indicated a medium increase of shipping noise in 2020 relative to 2019.

In order to apply the same vocabulary as in the previous case study, in this section, we call “measure” the decrease of traffic related to the COVID-19 pandemics, even though this modification of the traffic is not directly related to any measure controlling the traffic. Hence, we characterise by “effective” the so-called measure if it led to a decrease of the shipping noise level.

Finally, gathering the temporal distributions obtained in all estimated cells, the distribution of the percentage of time that the measure is efficient over the entire area (Mediterranean and Black Seas) is presented. In this distribution, each cell corresponds to one sample of the distribution, and the value related to this sample is the cumulative distribution function of Δ estimated at Δ = 0. For a single cell, this value expresses the proportion of time that the COVID-19 produced a decrease of shipping noise. The distribution over the area expresses therefore the spatial dynamic of the percentage of time that the COVID-19 locally produced a decrease of shipping noise.

- If such a distribution is centred around 50 % (i.e. median close to 50%), it means that a half of the surface area considered experienced more than 50 % of the time a decrease of shipping noise, while the other half of the surface area experienced less than 50 % of a decrease of shipping noise.
- If such a distribution is centred around values lower than 50%, it means that less than 50% of the surface area experienced more than 50% of the time a decrease of shipping noise in relation to COVID-19 lockdowns.
- If such a distribution is centred around values higher than 50%, it means that more than 50% of the surface area experienced more than 50% of the time an increase of shipping noise in relation to COVID-19 lockdowns.

<u>Difference of shipping noise for the month of March</u>

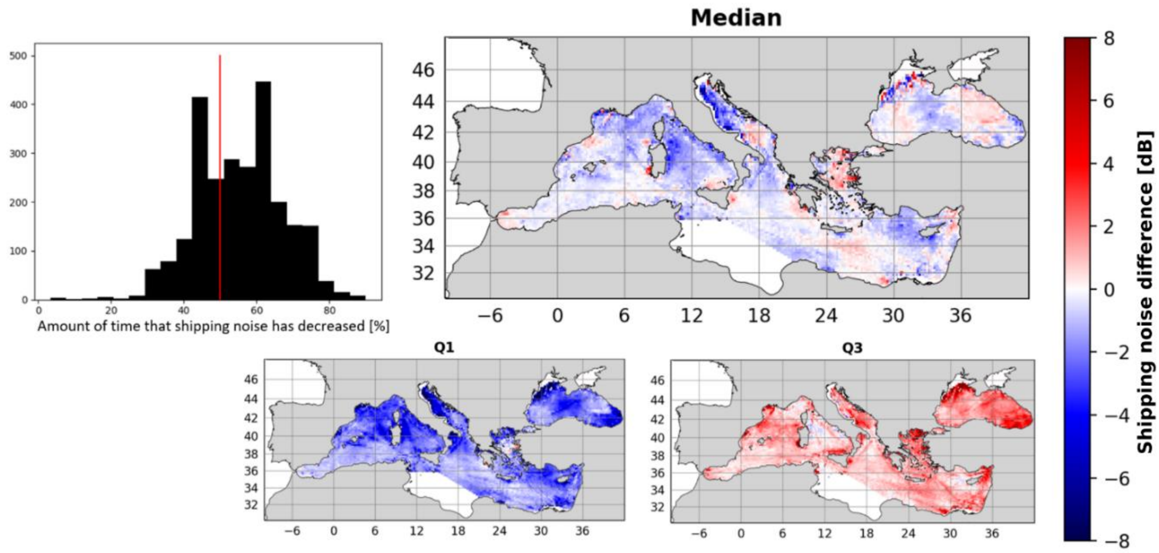

Figure 23. Difference for the month of March between 2019 and 2020: distribution of the percentage of time when the shipping noise has decreased in relation to the pandemics (A < 0) over the entire area (top left) and maps of the median, first and third quartiles of the temporal distribution of shipping noise difference over the month of March.

<u>Difference of shipping noise for the month of April</u>

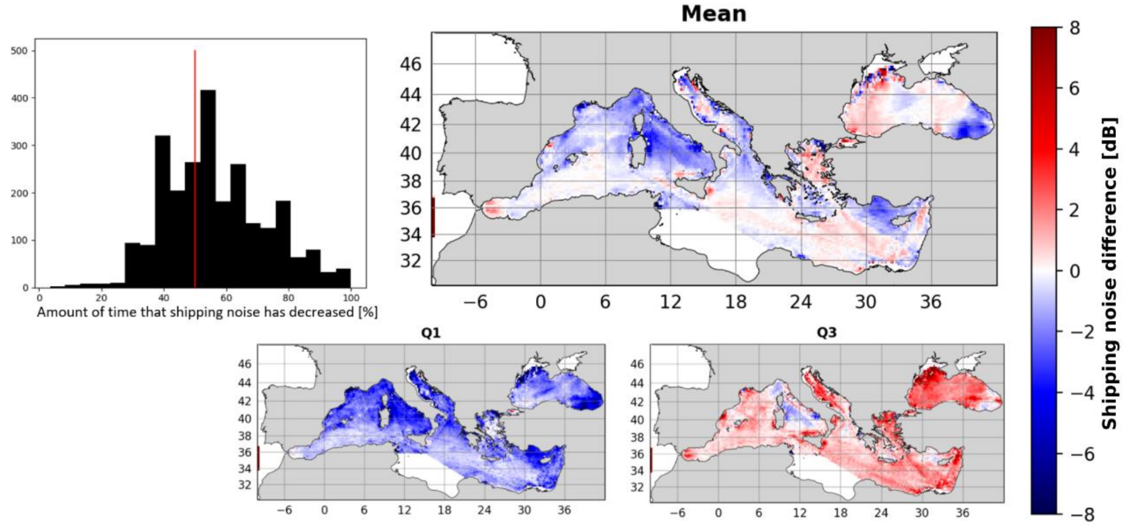

Figure 24. Difference for the month of April between 2019 and 2020: distribution of the percentage of time when the shipping noise has decreased in relation to the pandemics (A < 0) over the entire area (top left) and maps of the median, first and third quartiles of the temporal distribution of shipping noise difference over the month of April.

Difference of shipping noise for the month of May

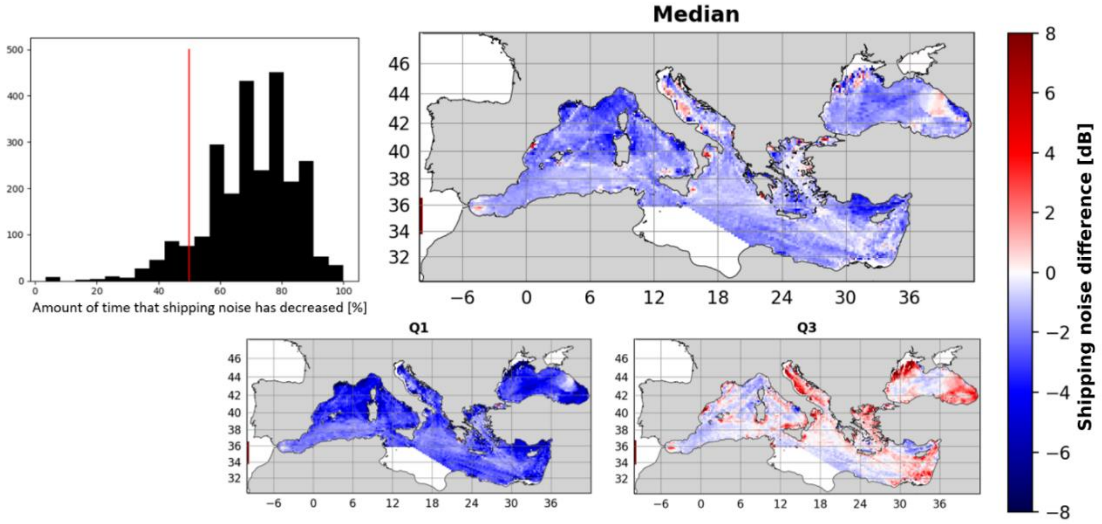

Figure 25. Difference for the month of May between 2019 and 2020: distribution of the percentage of time when the shipping noise has decreased in relation to the pandemics (A < 0) over the entire area (top left) and maps of the median, first and third quartiles of the temporal distribution of shipping noise difference over the month of May.

- From March to May, the median Δ shift progressively towards negative values.
- In March, the distribution of percentage of time that the measure is “effective” is centred around 50 % meaning that a half of the surface area considered experienced more than 50 % of a decrease of shipping noise, while the other half of the surface area experienced less than 50 % of a decrease of shipping noise.
- From March to May, the distribution of percentage of time that the measure is “effective” is progressively shifted towards values higher than 50%, suggesting that more and more surface area experience more than 50 % of the time decreased noise level in 2020 relative to 2019.

- These observations show that the effect of lockdowns on shipping noise took time to settle in the entire basin.
- All subregion did not experience the same evolution of Δ.
- Some areas present positive median Δ in May (Gibraltar strait, North-East Italian shore, Eastern Black Sea) suggesting that the central tendency in these subregions was an increase of shipping noise during COVID-19 lockdown relative to 2019.

Time-series on specific chosen points

The observations drawn from Fig. 23, 24 and 25 suggested that the effect of COVID-19 lockdown was very contrasted over the two basins, and a focus on specific zones (see Fig. 27) brings to light on how the temporal evolution of shipping noise occurred in 2020 relative to 2019. These time-series, and the related time-series of the "instantaneous" difference of level Δ (expressed in percentage of variation relative to the 2019 reference levels) are analysed based on a relative traffic density computed over an area surrounding the observation point, for each vessel category independently and for all categories gathered, for the month of April and May. The provided traffic density in these figures is relative as it is not normalized by the surface area of the computation zone.

A set of 23 spots were selected (Fig. 27), as being either particular cases of traffic, such as traffic constriction zones, major shipping routes, hotspots of traffic, hotspots of shipping noise, or representative of an entire zone regarding the observed effect of the pandemic. Fig. 28 to 32 present these results on a few numbers of spots. More results are used for the analysis, and related figures can be found in the Appendix A.1.

Point n°	Bathymetry	Received levels	Mono- or multiple paths
1	Deep water	Medium	Multiple
3	Deep water	Medium	Mono
8	Deep water	Low to Medium	Multiple
9	Shallow w.	High	Multiple Mono
10	Deep w.	High	Mono
11	Deep water	Low	Multiple
12	Shallow w.	Low to Medium	Mono
13	Deep water	High	Mono
14	Deep water	High	Mono
15	Shallow w.	Very High	Mono
16	Deep water	High	Mono
17	Shallow w.	Very high	Mono
18	Deep water	Low	Mono
19	Medium	High	Mono
20	Shallow w.	High to Very high	Multiple
21	Deep water	Low	Multiple
22	Deep water	Low	Multiple
23	Deep water	High	Mono

Table 2. Environmental characteristics of the spots selected for the analysis of shipping noise time-series. Deep water refers to a bathymetry larger than 200 m depths and shallow water to a bathymetry smaller than 200m. Received levels are extracted from the modelled levels, "Very high" refers to levels higher than 100 dB, "High" refers to levels higher than 90 dB, "Medium" to levels higher than 85 dB and "Low" to levels lower than 85 dB. Mono path refers to

a major shipping route with a single direction while multiple paths refers to multiple shipping routes along several directions, potentially taken by several categories of ships.

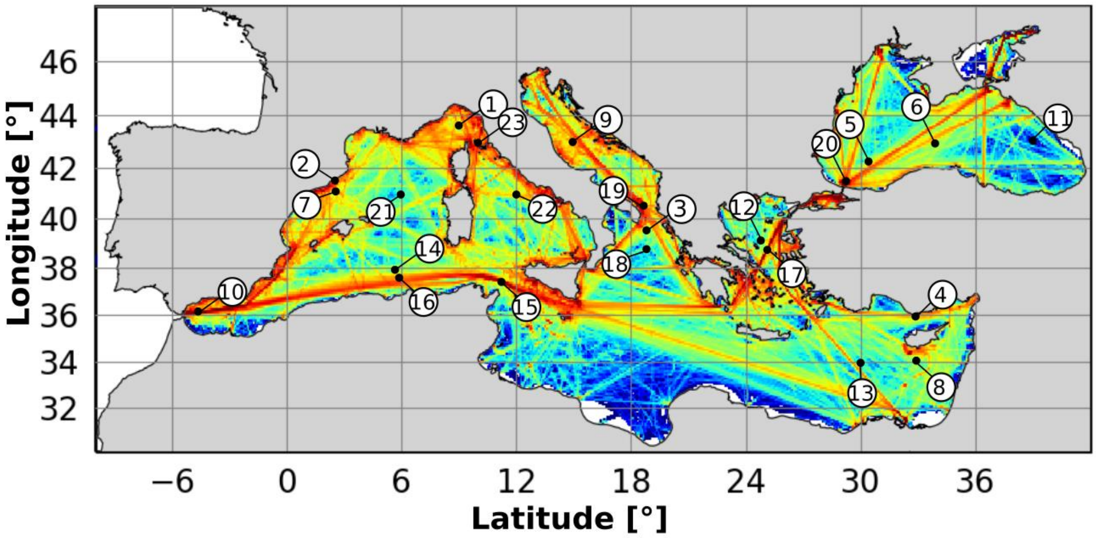

Figure 26. Map of the spots selected to analyze the shipping noise time-series in 2019 and 2020.

In order to ease the analyses of the time-series, from each zone of interest, the local traffic density over the surrounding area was extracted. Each of the selected points is representative of a particular case regarding the type of environment and the type of traffic, this information is presented in table 2, where the bathymetry (deep water: (>200 m), and shallow water: (< 200 m)), the levels of noise received ("Very high" refers to levels higher than 100 dB, "High" refers to levels higher than 90 dB, "Medium" to levels higher than 85 dB and "Low" to levels lower than 85 dB), the source intensity and the 1-dimensional (mono-path; unique shipping route) or 2-dimensional (multiple-paths, similar to what can be observed in the Ligurian Sea (1)) distribution of the sources in the area are indicated.

<u>Zones of multiple-paths traffic: Ligurian Sea (1), Balearic Sea (2) and Tyrrhenian Sea (22)</u>

The Ligurian Sea appears to be one of the zones that was continuously impacted from the onset of the lockdown until the end of May, and where a strong decrease of both commercial and passenger vessels resulted in a strong decrease of the shipping noise (more than 3% of mean decrease; Fig. 27). The Ligurian Sea is an area of intense traffic, that is not crossed by a single important navigation route, but rather by multiple routes (Fig. 19 – bottom right and Fig. 20) taken by different categories of vessels.

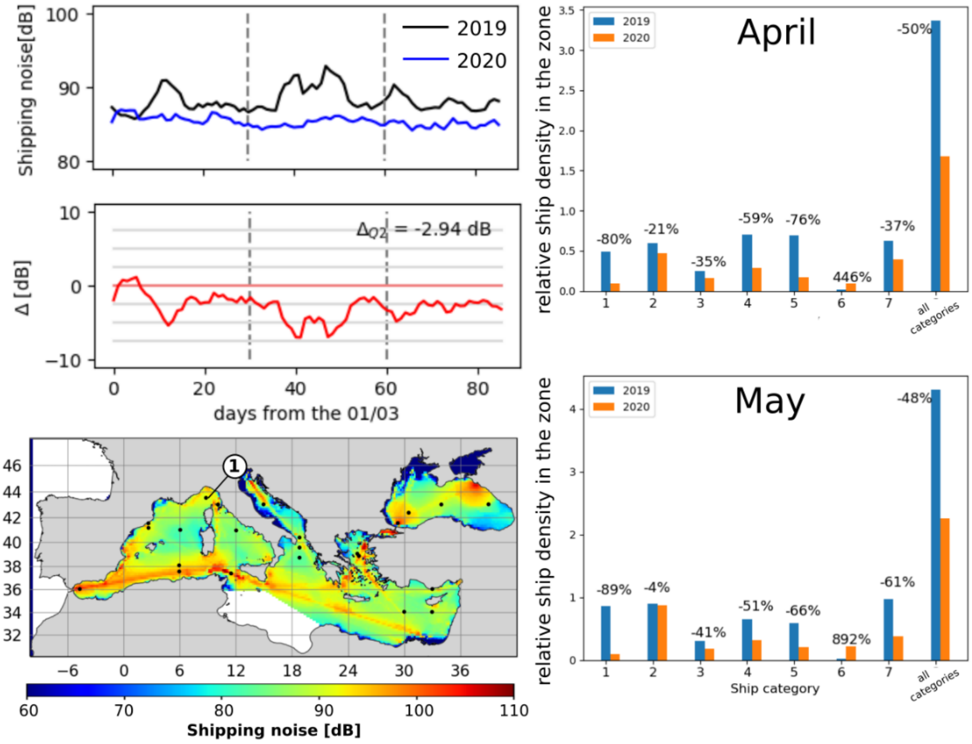

Figure 27. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left, the indicative mean is computed over the months of April and May only) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the Ligurian Sea (area surrounding the point 1 in the bottom left map). Time-series are smoothed over time windows of 5 days.

Two other zones are presented (point 21 and 22, Fig. A1.1 and A1.2), with similar characteristics: even distribution of sources, and multiple paths with multiple directions taken by all different categories of vessels, but with shipping noise levels 5 to 10 dB lower than in the Ligurian Sea. In these two areas, a strong decrease of the traffic density can be observed right at the onset of the lockdowns in Europe (around 25 and 50 % decrease respectively in 2020 regarding 2019). As a result, a mean decrease of the shipping noise of 1.37% and 2.38% respectively are observed for the 3 months (March to May) of 2020 regarding the same three months of 2019.

<u>Along major shipping routes: entrance of Adriatic Sea (9) and route from Gibraltar to the Eastern Mediterranean Sea (14, 15, 16)</u>

Points 14, 15 and 16 are located on -or close to the shipping route from the Strait of Gibraltar to the Eastern Mediterranean Sea (Fig. 26 and appendix A1.3 A1.4 respectively). They are all characterised by a high traffic density, mostly composed of commercial vessels. Passenger vessels are under-represented in these areas. Points 14 and 16 are in deep water environment, and point 15 is in shallow water environment. This is however not expected to impact on the results as point 15 is located in the zone of highest traffic density, the sources are very close and the propagation is not expected to play a large role in the received levels.

In this context, it appears that the categories 4 and 5 mostly influence the shipping noise. In all three points, the shipping noise difference Δ between 2020 in the month of April is close to zero, and takes negative values in the month of May, around -2%. Since the observation points are located very close to the sources (i.e. on the shipping route), the impact of propagation is therefore highly reduced, and this monthly contrast should not be related to environmental seasonality. Comparing the traffic presence for all categories between the two months, it appears that amongst the important categories at these locations are the commercial categories 2 to 5, and the ones marked by a strong decrease from April to May are categories 4 and 5.

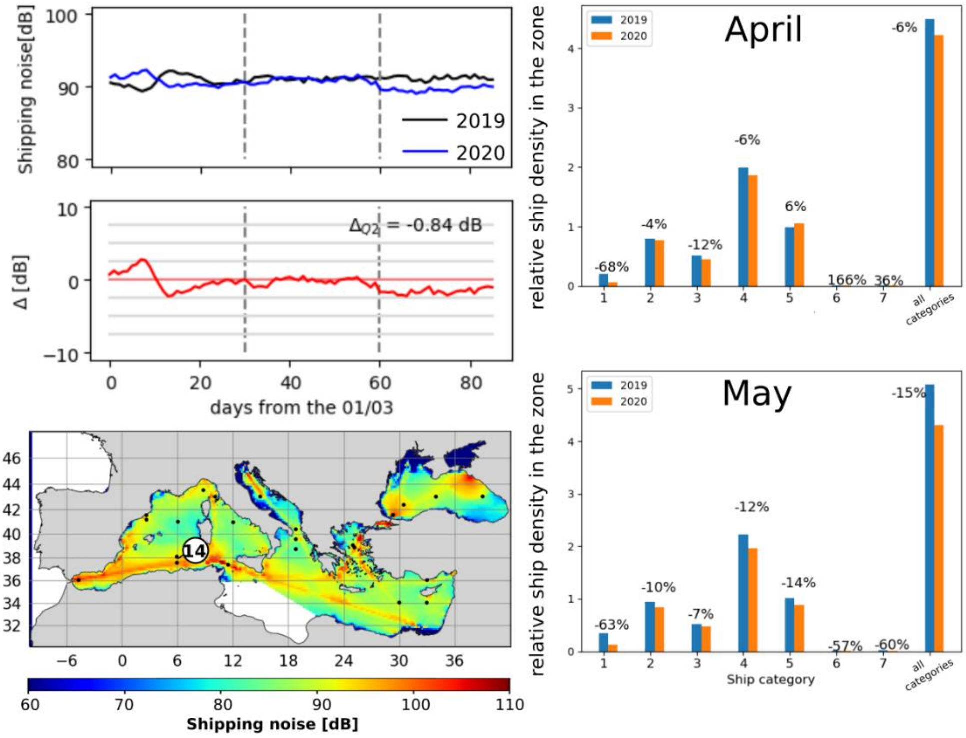

Figure 28. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left, the indicative mean is computed over the months of April and May only) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the major traffic lane between the Gibraltar Strait and the Eastern Mediterranean Sea (area surrounding the point 14 in the bottom left map). Time-series are smoothed over time windows of 5 days.

This could be anticipated as categories 1 to 5 are sorted depending on the length and speed of the vessels, i.e. on the assumed source levels of ships, and categories 4 and 5 are assumed to be the noisiest. Hence, suppressing few vessels in these categories should have a high impact on shipping noise, compared to suppressing the same proportions of vessels from the 3 other categories.

Another case of important traffic lane that is analysed in this part is the Strait of Otranto leading in and out of the Adriatic Sea through the points 19, 18 and 3 (Fig. 29 and A1.5 A1.6). In these areas, the traffic at each point is quite steady with a 16 and 21% decrease of total traffic density from 2019 to 2020 in April and May respectively. As a result, the shipping noise is decreased in 2020 relative to 2019 by 1 to 1.9%.

As Millefiori et al. (2021) suggests that the recovery of the traffic that mostly occurred in June, in most areas within the two basins, no increase of shipping noise is observed in May. The entrance of the Adriatic Sea is an exception to this observation, and all 3 points display in consequence a clear increase of shipping noise level at the end of May 2020.

It can be noted that the contrasts of shipping noise between 2019 and 2020 observed on the 3 points and mentioned in the previous paragraphs are quite similar, whether the point is located on the sources, with strong levels (point 19 and to a lesser extent 3) or away from it, with low noise levels (point 18).

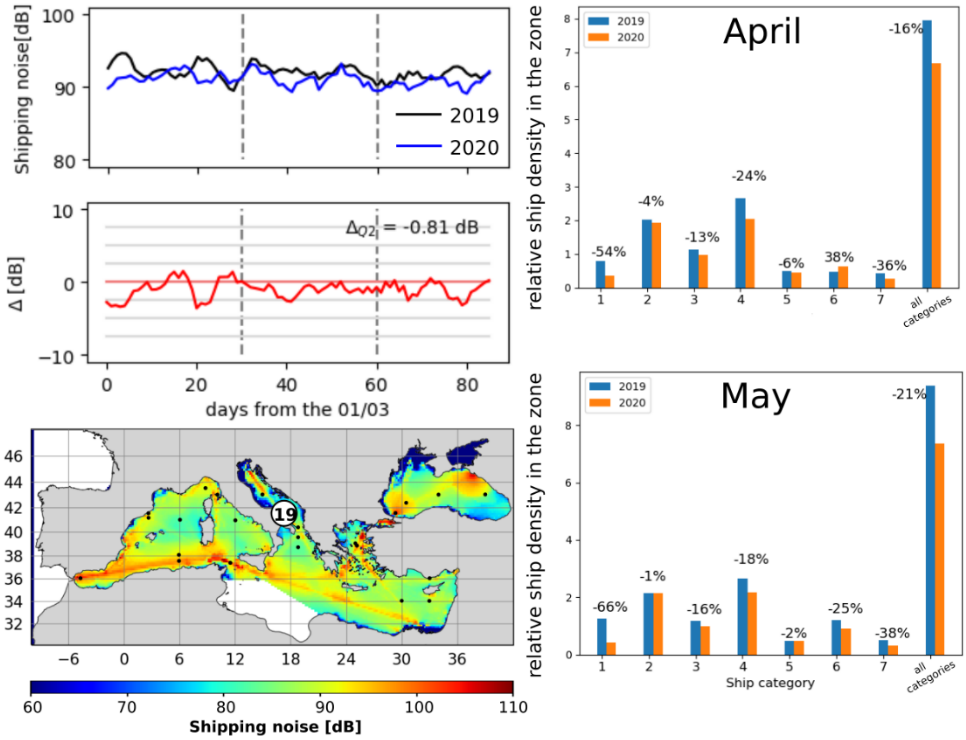

Figure 29. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left, the indicative mean is computed over the months of April and May only) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 at the Otranto Strait (area surrounding the point 19 in the bottom left map). Time-series are smoothed over time windows of 5 days.

<u>Constriction zones: Gibraltar Strait, Aegean Sea, Bosporus Strait</u>

The zones of constriction of the traffic seem very particular. Indeed, the traffic in these areas took the longest time to be reduced after the beginning of the lockdown, or, did not decrease at all (Fig. 30 and Fig. A1.7 and A1.8). This is probably due to a traffic jam effect.

The Gibraltar strait (point 10) experienced indeed an increase both for April and May of the number of vessels, leading to an increase of shipping noise in the 3 months of 2020 related to 2019. The Aegean Sea seems to have experienced the same context of traffic. In the Bosporus strait on the contrary, the analysis displays a very clear decrease in shipping noise in the second part of May, explained by a decrease in the presence of commercial vessels of category 1 to 4, and despite an increase of passenger vessels in 2020 in relation to 2019.

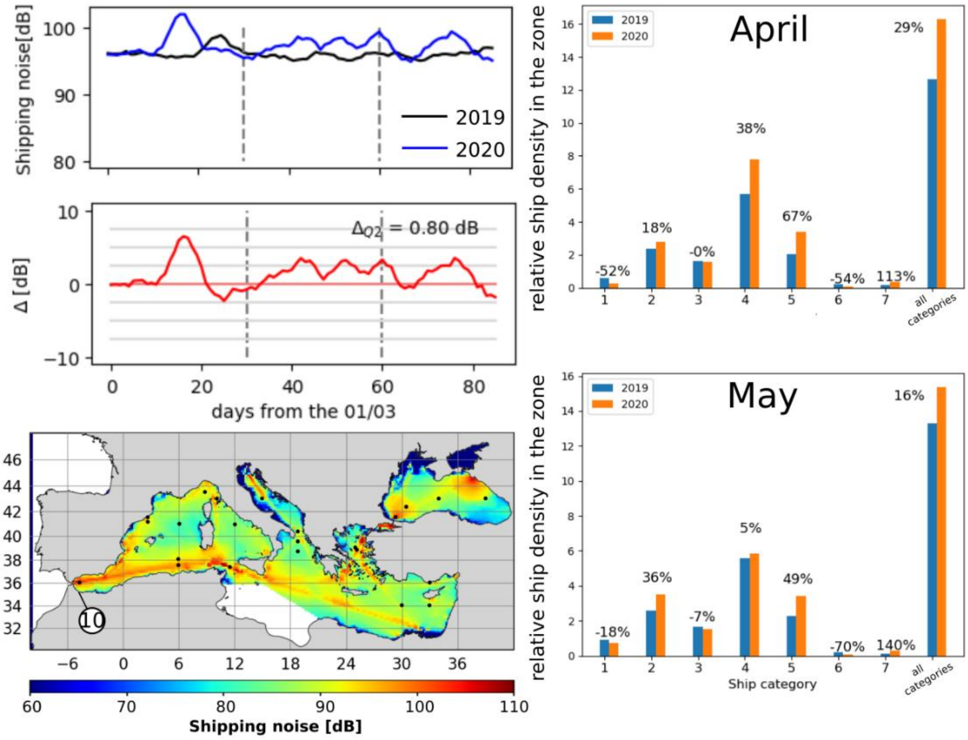

Figure 30. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left, the indicative mean is computed over the months of April and May only) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 at the Gibraltar Strait (area surrounding the point 10 in the bottom left map). Time-series are smoothed over time windows of 5 days.

Zones marked by a notable increase of shipping noise

A few areas are marked by an increase of shipping noise. Spots 11 and 13 are representative of such area (Fig. 31 and appendix A1.9 respectively) and to a lesser extent, point 9 (Appendix Fig. A1.10).

Point 11 (Fig. 31) presents a clear increase of the traffic density in 2020 regarding 2019, that mostly concerns the categories 1 to 3, the most present categories in the area. In this location, the increase of 73 % (April) and 49% (May) of the total traffic leads to a very limited increase of shipping noise: 0.7%. This again put at light that small and slow vessels have a very limited contribution to shipping noise, and categories 4 and 5 (long and/or fast commercial vessels) play a major role in the settling of shipping noise.

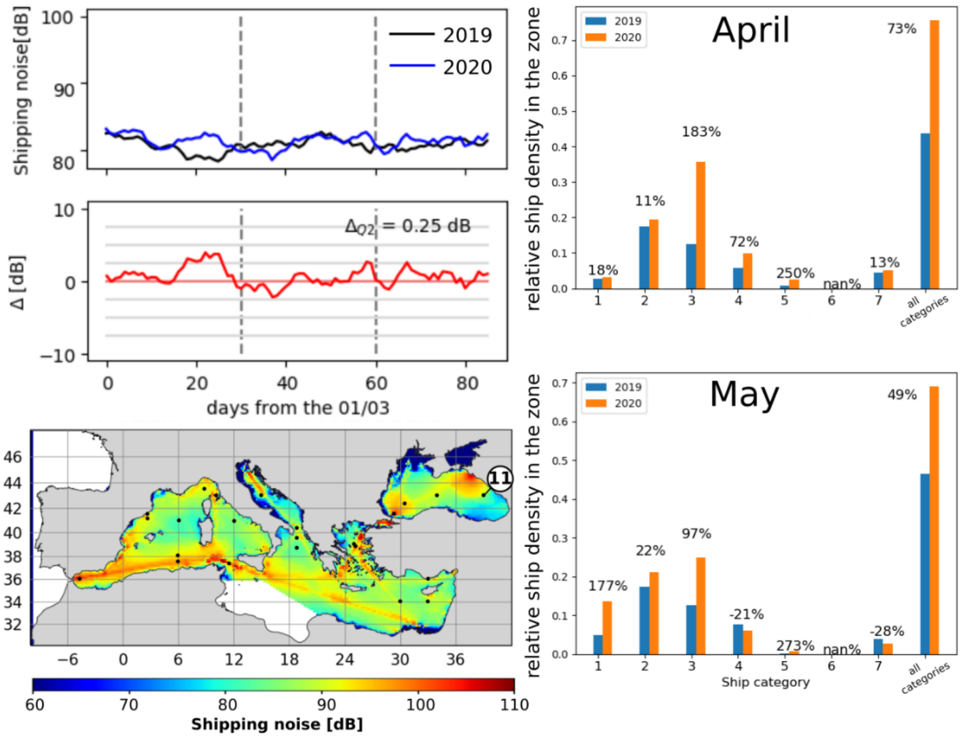

Figure 31. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left, the indicative mean is computed over the months of April and May only) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the Eastern Black Sea (area surrounding the point 11 in the bottom left map). Time-series are smoothed over time windows of 5 days.

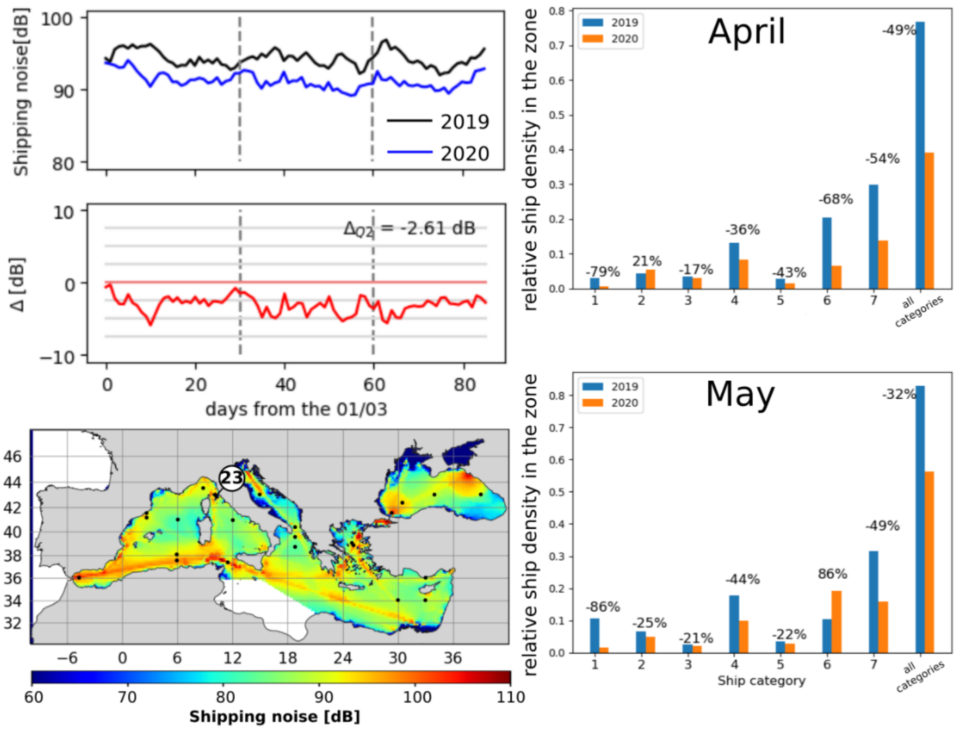

Figure 32. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left, the indicative mean is computed over the months of April and May only) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the Eastern Ligurian Sea (area surrounding the point 23 in the bottom left map). Time-series are smoothed over time windows of 5 days.

<u>Zones of navigation of passenger vessels</u>

The sector the most directly impacted by COVID-19 lockdown is the people transportation sector, since the displacement of people completely stopped during the lockdown. As a consequence, zones where the ship traffic is mostly composed of passenger vessels were impacted a lot by the lockdown. Point 23 (Fig. 32) illustrates this effect in the Eastern Ligurian Sea, where an important part of the traffic concerns the passenger transportation between northern Italy, Corsica and Sardinia, causing high levels of shipping noise (around 94 dB according to Fig. 32). During the COVID-19 pandemic and lockdown, in April and May 2020, the traffic density of passenger vessels in that zone was decreased by half. As a result, a mean decrease of more than 3% of the shipping noise is observed during the three months. For a noise level of 100 dB, a decrease of 3% of the level corresponds to a decrease of 3 dB, which is quite interesting as it means a decrease by half of the pressure field.

3.2.4. **Outcomes of the study**

Environment			**Effects of COVID-19 lockdown**	
Traffic properties	Dominant categories	Shipping noise levels	On traffic density	On shipping noise
Bottleneck area	All categories	High	Increase at the onset of the lockdown Decrease eventually at the end of May (?)	Increase and eventually decrease at the end of May in the Bosporus Strait – Steady increase for the Gibraltar Strait
Mono-path area	Cat. 1 to 3	Low	Increased by 50 to 70 % (point 11)	Limited increase (0.7 %)
		Medium	Decreased by 40 to 50 % (point 8)	Limited decrease (less than 0.5 %)
	Cat. 4 and 5	High	Decrease by 15 % (point 14 -may)	Decrease of 2 %
	Passenger transportation	High	Important & fast decrease	Drastic decrease of the shipping noise observed (3%)
Multiple paths area	All categories	High and low	Fast decrease at the onset of the measure for most categories	Fast decrease – 1 to 3% decrease observed

Table 3. Gathered results of the analysis of COVID-19 lockdown traffic reduction scenario.

3.2.5. Discussion

The general effect of COVID-19 lockdown turns out to be complex. As a general decrease of the traffic and of the ship-calls is observed for the European waters, locally on specific zones, the precise effect is much more convoluted and multiple over the two basins. Different categories of vessels did not experience the same effect, and there are no general rules as to relate specific zones of traffic to the impact of the lockdown on their crossing by the different categories of vessels. In the case of a real traffic reduction measure, the environment (bathymetry, properties of the sea bottom, sound speed profiles) would probably play an important role. However, it is not possible to grasp this aspect in the present study, given the fact that the effect of COVID-19 lockdown on the traffic was too variable spatially.

In addition to that, the choice of a temporal observation window of one day permits to see that the fluctuations of shipping noise from one day to the next can be quite strong, and that each zone experienced its very own evolution of both traffic density and shipping noise from March to the end of May. This makes it difficult to draw a complete analysis of the effect on shipping noise.

Few elements must be pinpointed in order to evaluate the limits of the analysis.

The first one concerns the long-term increase of traffic worldwide. Because of this year-to-year increase, the shipping noise levels expected in 2020 in case of no lockdown would exceed the levels inferred from 2019. Hence, taking as reference levels the levels computed for the year 2019 does not make complete sense, and a correction could be accounted for, in order to estimate the theoretical levels of 2020 in case of no lockdown. It is however difficult to deduce this correction, it would require indeed to be able to model the year-to-year increase with great precision. In the absence of this model, the levels of 2019 were selected as reference levels.

The study is based on AIS datasets. The possibility that the dataset might not be complete, in certain regions, or at certain moments, exists to a certain level, and would alter the observation drawn in this second case-study. In particular, it was suggested that part of the increase of fishery traffic observed from 2019 to 2020 was related to an increased use of AIS transponders (www.emodnet-humanactivities.eu/blog/?p=1258 - Estimating the impact of COVID-19 on fishing).

It is difficult to draw general conclusions from the COVID-19 case. Indeed, some of the observed features seem rather related to the brutal and uncontrolled onset of a traffic reduction scenario, than to the traffic reduction itself. For example, the traffic jams or excessive traffic in the zones of traffic constriction close to straits are entirely due to the brutal change caused by the lockdown.

Nevertheless, some general observations concerning the relation between impacted categories and effect on the shipping noise are drawn and compiled in table 3.

3.3. Comparing the two measures

Despite the presented differences between the two studies, a comparison of the two measures is proposed in this section. This comparison should be considered as the occasion to emphasize on the key characteristics of the two measures, rather than as a conclusion on the absolute effectiveness of the two measures.

In the speed reduction case study, the sources were redistributed spatially and temporally, while their amplitude were importantly reduced. In the traffic reduction case study, only the number of sources was decreased, and sources were slightly redistributed spatially.

In the speed reduction experiment, that the selected source model accounts for speed as one of the major parameters. As a consequence, a drastic speed limit concerning a large number of vessels (10 kt speed limit) provides an important medium decrease of the received levels in the whole area. The speed limitation at 15 kt concerns a lower number of vessels, and therefore, the shipping noise medium decrease is smaller. The importance of the environment came as major element (bathymetry and traffic characteristics) and the temporal variability of the effect was studied as it came as important matter (zones with high variability of the efficiency were observed due to the complex redistribution of the sources). Because of that, the efficiency of the measure was determined considering the percentage of time that the shipping noise was decreased by the measure, instead of quantifying the effective shipping noise reduction.

The measure of traffic reduction was much more difficult to analyse as it includes a very erratic component related to the brutal and chaotic onset of COVID-19 lockdown. The variation of traffic density is highly dependent upon the location and the vessels category considered. Important decrease of shipping noise was mostly related to a decrease of traffic from passenger vessels, and from large and fast vessels from categories 4 and 5. Bottleneck areas experienced at first, and until the second half of May at least an increase of vessel density, and the shipping noise levels were consequently increased.

3.3.1. Different contexts

The two measures in this study are related to two different contexts.

The months concerned are not the same (March to May for the traffic reduction case and August for the speed reduction case). This has impacts both on the nature of the traffic, and on the propagation characteristics. A first point that should be raised is probably that while designing and estimating the effect of a measure, it may be important to estimate the effects at different moments in the year as the seasonality might influence significantly the effect.

Another difference that is worth mentioning is the spatial extent of the area impacted by the measure. In the traffic reduction case study, the entire Mediterranean and Black Sea basin is considered, with variable results depending on the location considered. Decreasing even slightly the shipping noise levels over such a large area might have as impact to provide a slightly improved environment for many different species. On the contrary, the speed reduction measures that were modelled were applied to much smaller areas. Such a measure is always considered inside a restricted area. The efficiency of such a measure can be quite high, if the measure is drastic (10kt in the case of the Western Mediterranean zone provided a very good efficiency in deep water environments). It would then improve greatly the environment for the few species and individuals hosted in this area. Hence it seems that there is a balance to identify between the exclusivity of the individuals to target in the measure, its efficiency, and its impact on human activities.

3.3.2. Different sources of uncertainties

Considering the employed methodology, the expected major sources of uncertainties are not the same for the two case-study.

In the speed reduction case study, the modelling of shipping noise source is the major source of uncertainty on the results of the study. Indeed, as commented in section 3.1.5., the models used might be incomplete when considering vessels navigating under none-nominal conditions of speed (much lower speed than it was conceived for).

In the COVID-19 case study, the major source of uncertainty is the completeness of the dataset. The lack of a part of the AIS emissions related to a variable use of AIS that can be expected from one year to another, and the evolutions of receiver constellation and stations would potentially bias and disrupt the observations realized in that case study.

Moreover, no calibration of the model could be applied for the Mediterranean and Black Sea basins. Therefore, an accurate quantification of an effect in terms of shipping noise level contrasts cannot be proposed.

4. Recommendations on designing mitigation measures for the reduction of shipping noise

This work helped identify the essential parameters that control the efficiency of two mitigation measures for shipping noise reduction.

Speed reduction measures

- Are effective in deep water environments.
- Are not so effective in shallow water environments.
- Have stable effects where the traffic occurs along multiple paths with variable directions.
- May produce short terms increase of shipping noise in some areas.
- Should be designed in areas where a significant number of vessels navigate at particularly high speed.

Traffic reduction measures

- Are particularly effective when targeting large and / or fast commercial vessels or passenger vessels.
- Should have effects that depends upon the environment properties, although this could not be tested in this work.
- Can be applied to large areas.

Although it is rather difficult to extrapolate recommendations concerning the design of any mitigation measure, in a general manner, few parameters appear to impact a lot on the efficiency of the measures.

The choice of an application zone for a specific measure should depend on the location of shipping routes, the environment and the existence of potential distant powerful noise sources that may be important contributors to the acoustic noise. Economic considerations are probably the first barrier limiting the dimension of the chosen zone. A robust base to guide the choice of the zone is the Potential Usable Habitat (PUHa, Azzellino *et al.*, 2012) for the species occupying the concerned area. The PUHa permits to map the areas presenting more or less importance of for specific species, helping determine to what extent improving the sound scape locally would improve the well-being of the species considered in the zone.

The type of environment should be identified: the bathymetry (shallow- or deep-water environment?), the nature of the sea bottom, and the distribution of sources, in order to grasp the importance of the acoustic attenuation.

Additionally, information on the sources are important. Evaluating the categories of vessels that contribute to shipping noise in the area is important.

- Density of vessels (lots of sources or few sources in the area?)
- Emission levels of the source?

- Distribution over a single major route or many medium intensity routes?

The design of any mitigation measure could be determined through a modelling work such as the ones presented in this document. A few elements need to be considered when doing so.

1/ The temporal observation and assessment windows should be chosen carefully, according to the temporal dynamic expected in relation to the application of the measure and to the seasonality of environmental parameters.

2/ It is important to account for the contribution of sources outside the area of application of the measure, particularly in deep water area. Since sound propagates through large distances in deep water environments, the presence of a major source close to the boundary and outside of the designed area could potentially limit locally the efficiency of the measure.

3/ It is known that seasonality has a great impact both on the traffic as industrial, dishing and passenger transport activity vary along the year, and on the acoustic propagation, through changes in temperature profiles. It is important to analyse the variation of the effect along the year.

5. Conclusions and perspectives

This work presents the analysis of two mitigation measures for the reduction of shipping noise.

The first measure is a speed reduction measure. Reducing vessels navigation speed is assumed to reduce the source levels radiated from the ships. Experiments of speed limitations were simulated on two zones, shedding a light on the importance of bathymetry and traffic distribution on the effect of the measure.

It appeared that speed reduction produces a redistribution of sources in space and time that results locally on a high temporal variability of the effect of the measure. This led us to consider not only the amount of shipping noise decrease/ difference but also to look at statistical parameters of the shipping noise difference, expressing for example the percentage of time that the measure results in a reduction of shipping noise, and quantifying over the area of speed limitation how variable the effect can be.

The second measure is a traffic reduction measure, that aims at reducing the amount of noise sources in a specific area. To address this measure, the real case scenario of traffic reduction that occurred during COVID-19 lockdown was considered, as a clear reduction of the traffic was observed consequently. The study was conducted on the Mediterranean and Black Sea basins.

It actually appeared that the traffic reduction that occurred during the COVID-19 pandemic was very dependent on 1/the location considered, particularly in relation to the type of traffic usually occurring in different places; 2/ the categories of vessels navigating in the location considered and 3/ time of the year. The chaotic onset of the COVID-19 lockdown reverberated on the marine activities, and instead of a simple decrease of the traffic, some areas experienced a clear increase of the traffic for several weeks. The analysis was therefore quite complicated, and did focus on the contrasts of traffic density observed at a local scale (10’ arc x 10’ arc) and on the categories of vessels concerned by these contrasts.

This type of studies based on shipping noise modelling is efficient in order to test specific designs of measures, when it comes to identify where a certain measure is particularly efficient, and where it is not. It appeared clearly that speed reduction is in particular efficient in deep water environment, and seems more stable where the traffic multifold. Other measures could be studied in order to identify measures presenting a complementary context of high efficiency. For example, studying the efficiency of setting areas of traffic avoidance should provide interesting results. Such a measure would consist in displacing all the sources inside an area on a single traffic lane at the border of that area. In deep water environment, where the sound propagates long distances with limited attenuation, such a measure might be ineffective. However, it might be quite effective in shallow water environment, as the produced noise may be contained around the traffic lane at the border of the area, making it a shallow-water complementary measure to speed reduction.

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APPENDIX A1: Analysis of time-series related to COVID-19 lockdown traffic reduction – additional figures

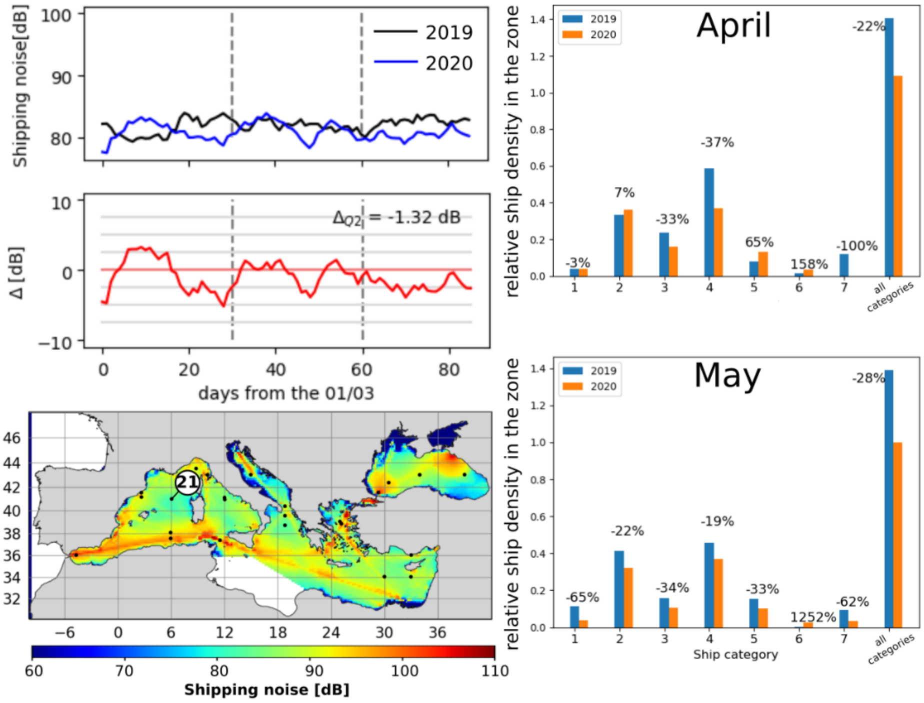

Figure 33. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the Balearic Sea (area surrounding the point 21 in the bottom left map). Time-series are smoothed over time windows of 5 days.

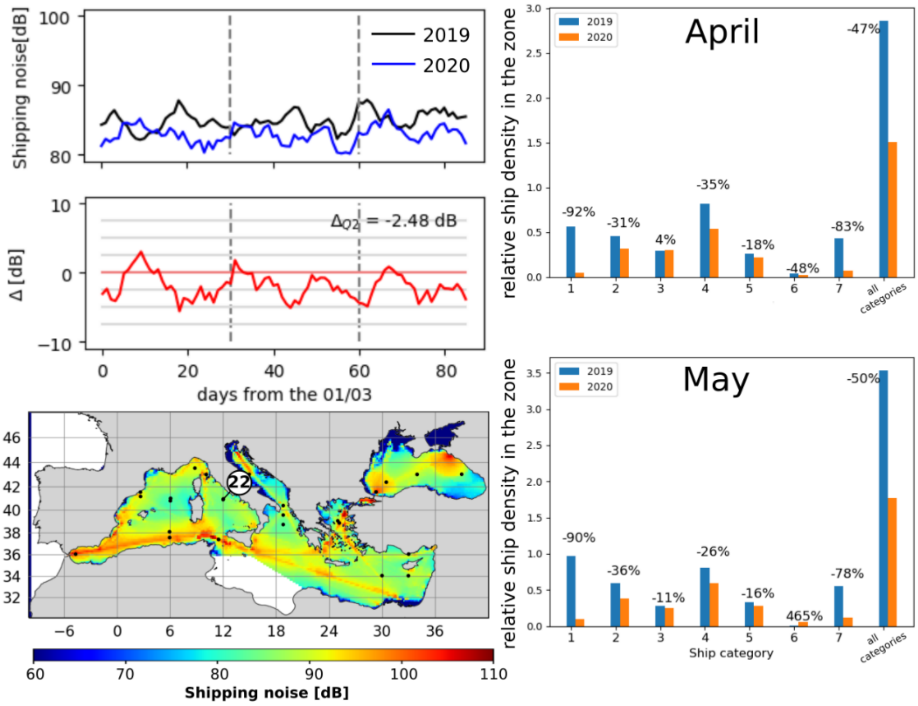

Figure 34. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the Tyrrhenian Sea (area surrounding the point 22 in the bottom left map). Time-series are smoothed over time windows of 5 days.

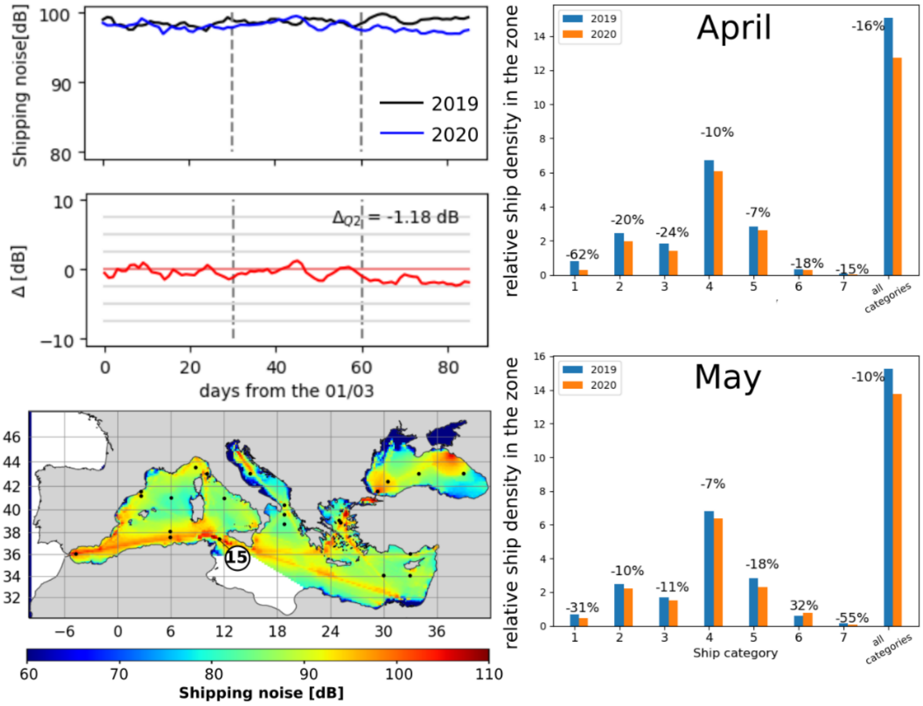

Figure 35. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 at Cap Bon major traffic lane (area surrounding the point 15 in the bottom left map). Time-series are smoothed over time windows of 5 days.

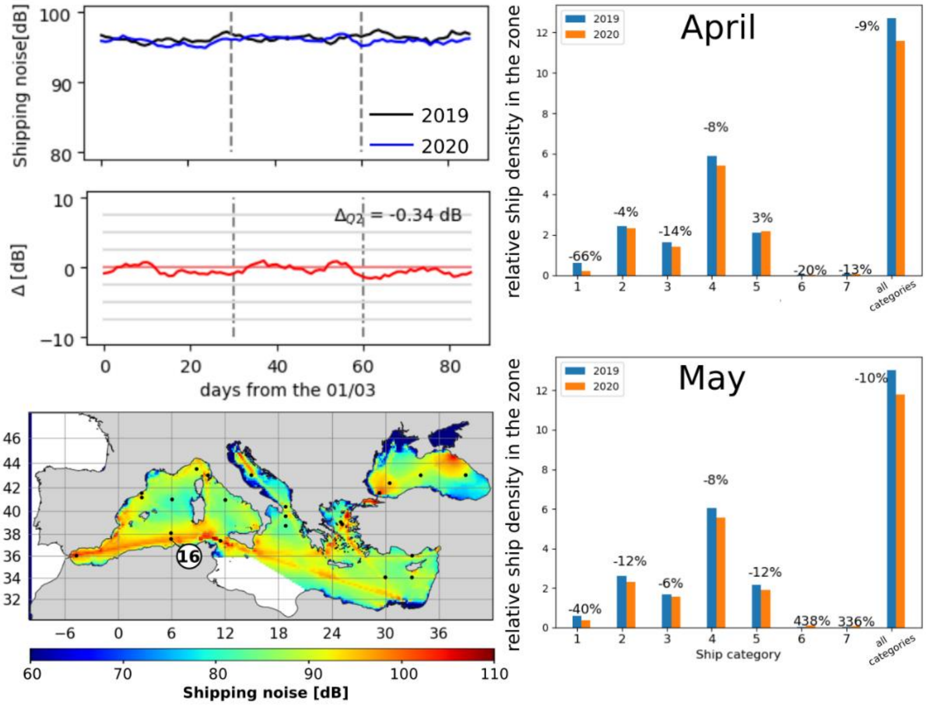

Figure 36. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 at the major traffic lane from Gibraltar Strait to the Eastern Mediterranean Sea (area surrounding the point 16 in the bottom left map). Time-series are smoothed over time windows of 5 days.

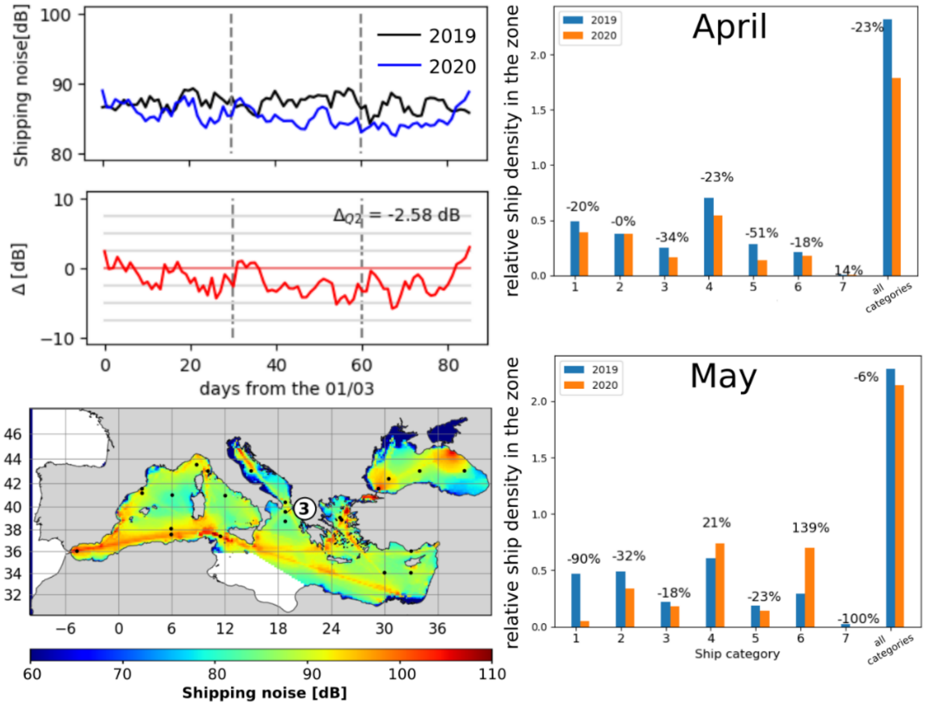

Figure 37. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the Ionian Sea (area surrounding the point 3 in the bottom left map). Time-series are smoothed over time windows of 5 days.

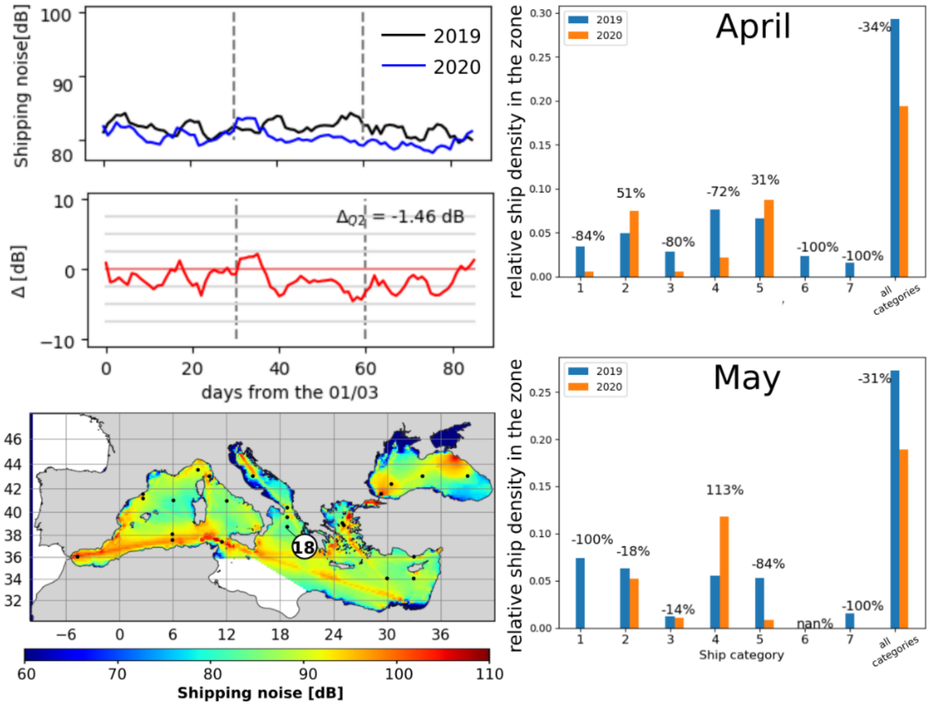

Figure 38. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the Ionian Sea (area surrounding the point 18 in the bottom left map). Time-series are smoothed over time windows of 5 days.

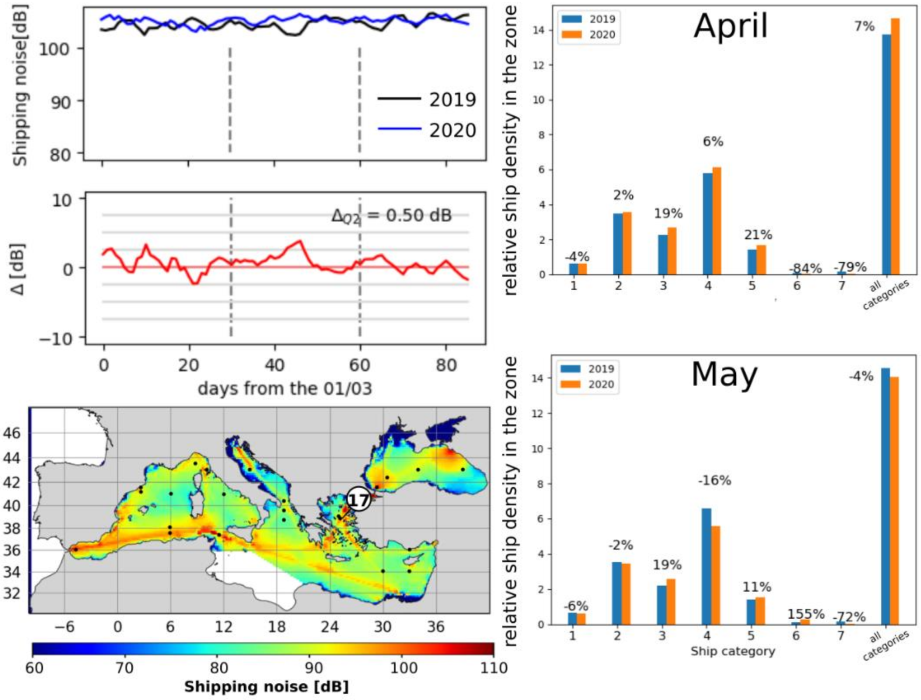

Figure 39. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the Aegean Sea (area surrounding the point 17 in the bottom left map). Time-series are smoothed over time windows of 5 days.

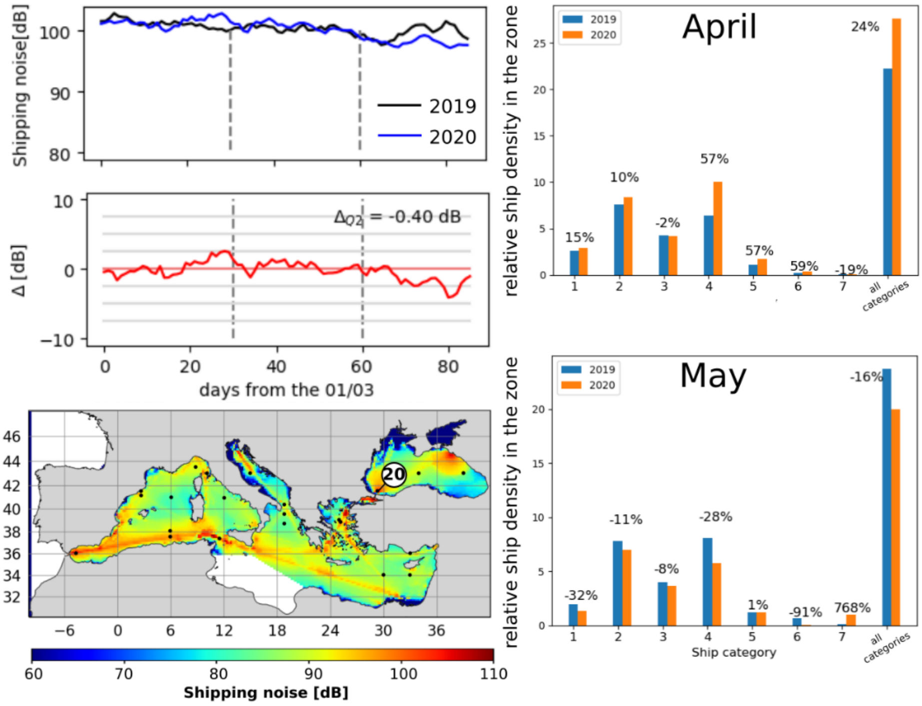

Figure 40. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 at the Bosporus Strait (area surrounding the point 20 in the bottom left map). Time-series are smoothed over time windows of 5 days.

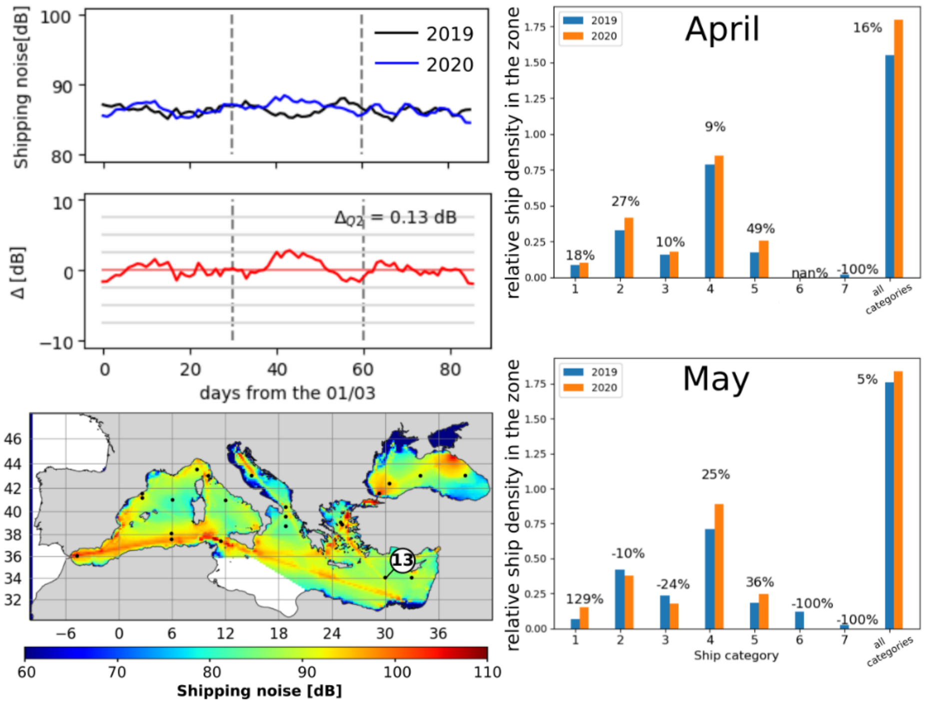

Figure 41. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the Levantine Sea (area surrounding the point 13 in the bottom left map). Time-series are smoothed over time windows of 5 days.

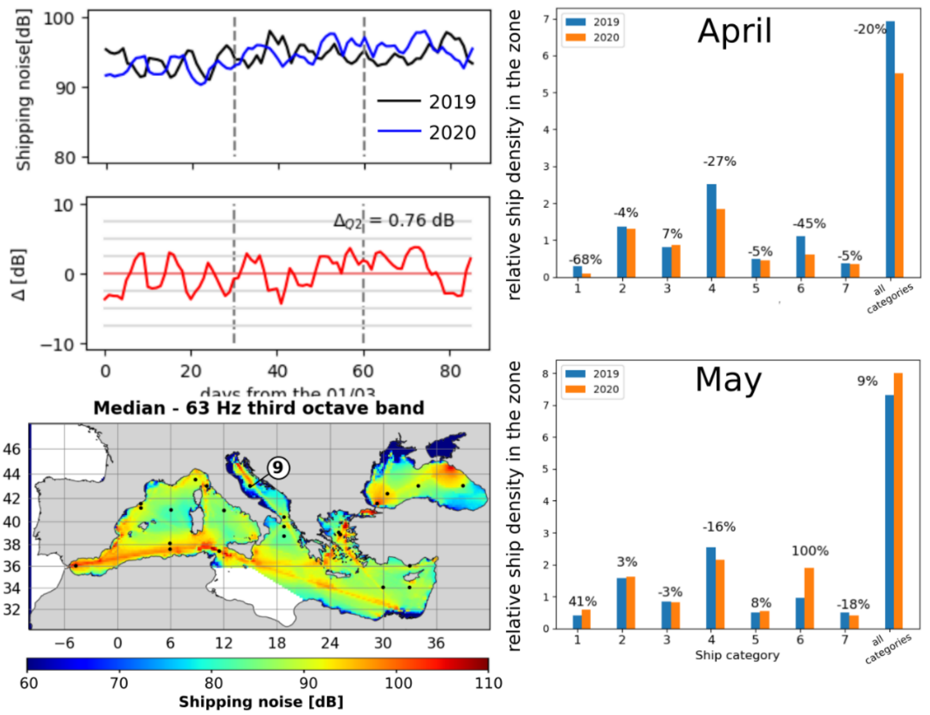

Figure 42. Relation between time-series of shipping noise in 2019 (black) and 2020 (blue) (top left), time-series of shipping noise difference Δ (middle left) and relative ship density for the 7 categories of ships as described in section 2.2.1 in April (top right) and May (bottom right) in 2019 and 2020 in the Adriatic Sea (area surrounding the point 9 in the bottom left map). Time-series are smoothed over time windows of 5 days.

APPENDIX A2: REVIEW OF THE UNDERWATER NOISE MITIGATION MESURES FOR THE REDUCTION OF UNDERWATER NOISE FROM SHIPPING

A.1. Sources of shipping noise

Typical underwater noise level of large merchant ships range from 180 dB re 1µPa to 195 dB re 1µPa, which predominates in the ambient underwater noise of many oceans and seas (Gotz *et al.,* 2009; McKenna *et al*., 2013; Veirs *et al.,* 2016). In this regard, reducing ship noise is the best way to reduce underwater noise in the oceans (Leaper and Renilson, 2012). Furthermore, the reduction of ambient underwater noise is important for achieving a good status of the marine environment (GES) (Dekeling *et al*., 2014).

Underwater noise of ships is caused by propeller cavitation and vibrations of the hull. Typical sources of underwater ship noise are related to propeller cavitation, water flow and hull shape, ship machinery and ship operation (McKenna *et al.,* 2012; Arveson and Vendittis, 2000; Trevorrow and Vasiliev, 2008; Ross, 1976; IMO, MEPC 61/19, 2010; IMO, MEPC.1 / Circ.833, 2014; Abrahamsen, 2012; Leaper et al., 2014; Spence and Fischer, 2016; Lee, 2017).

1. Propeller noise

The main mechanism of propeller underwater noise is propeller induced cavitation. When a ship's propeller rotates through the water, it generates the pressure difference across its blades that propels the ship. Where the under-pressure drops below the local vapour pressure, the water vaporizes locally. This creates cavities ('bubbles' and 'bubble sheets'), which implode when they move out of the low-pressure area. These cavitation processes generate tonal noise at blade rate harmonics (due to the rotation of the propeller blades in the inhomogeneous wake flow) as well as broadband noise (due to the sharp implosions of the cavities) (De Jong *et al*., 2020).

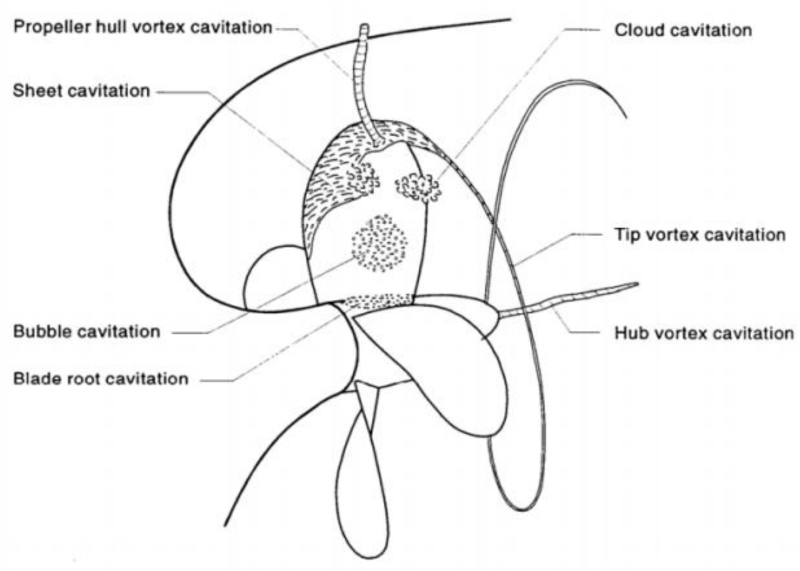

Figure 43. Cavitation types that occur on ship propellers (ITTC, 2002)

Various cavitation types can occur, i.e.: propeller hull vortex cavitation, sheet cavitation, cloud cavitation, tip vortex cavitation, hub vortex cavitation, bubble cavitation and blade root cavitation (Figure 1).

2. *Machinery noise*

The second relevant group of ship radiated noise sources consists of the onboard machinery for propulsion (e.g. engines and gear boxes) and auxiliary tasks (e.g. power generators, pumps and air-conditioning equipment). All machinery items transmit vibrations to their foundation structure, as well as radiate airborne noise in the machinery spaces. This noise travel though ship structure and air to the hull, where it is radiated into the water as radiated noise (De Jong *etal.*, 2021; Ross, 1976; De Jong, 2002; Spence & Fischer, 2016).

A.2. Underwater noise mitigation measures according to IMO, ACCOBAMS and HELCOM guidelines

IMO Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life (IMO, MEPC.1/Circ.833, 2014) provide general advice about reduction of underwater noise to designers, shipbuilders and ship operators. The Guidelines focus on primary sources of underwater noise, which are associated with propellers, hull form, onboard machinery and operational aspects. Guidelines consider common technologies and measures that may be relevant for most sectors of the commercial shipping industry.

ACCOBAMS Guidance on underwater noise mitigation measures (ACCOBAMS-MOP7/2019) adapted mitigation measures for minimizing underwater noise from commercial ships from the IMO Guidelines (IMO, MEPC.1/Circ.833, 2014). Furthermore, ACCOBAMS proposed some structural solutions and technologies for reduction of propeller cavitation.

HELCOM Underwater noise mitigation measures for shipping (HELCOM, 2016) summarised measures from the IMO Guidelines (IMO, MEPC.1/Circ.833, 2014).

1. *Mitigation measures for reduction of continuous underwater noise during design of the ship (propeller and hull design)*

Reduction of underwater noise could be considered during the design of new ships. Existing ships may also be upgraded, if this is reasonable and feasible.

Flow noise around the hull has a negligible influence on radiated noise, whereas the hull form has influence on the inflow of water to the propeller. For effective reduction of underwater noise, hull and propeller design should be adapted to each other. These design issues should be considered holistically as part of the overall consideration of ship safety and energy efficiency (IMO, MEPC.1/Circ.833, 2014).

1.1. Mitigation measures during the propeller design

Cavitation is the dominant radiated noise source, which could be reduced through proper design, such as optimizing propeller load, ensuring as uniform water flow as possible into propellers (which can be influenced by hull design), and careful selection of the propeller characteristics such as: diameter, blade number, pitch, skew and sections (IMO, MEPC.1/Circ.833, 2014; Renilson *et al.*, 2012).

Brown (1976) developed the following equation to estimate the level of underwater noise generated by propeller cavitation, in which he used the main parameters to design the propeller and to estimate the size of the cavitation area:

$$Lp \propto 10Log\ BD4N4+10Log\ (AcAD)$$

where *B* is the number of propeller blades, *D* is the diameter of the propeller, *N* is the rotation speed, A_c is the cavitation surface, A_D is the surface area of the propeller disk (e.g. πD2/4). The equation holds when the cavitation surface is not equal to zero.

Propeller design affects underwater radiated noise through the following factors (De Jong *et al*., 2020):

- **Number of propellers**: distribution of the thrust over more than one propeller can reduce propeller loading and cavitation. Moreover, the wake flow into the propeller can be more uniform if the propellers are placed off the centre line of the vessel.

- **Fixed or Controllable pitch**: propeller blades can have fixed blade angles (fixed pitch) or adjustable blade angles (controllable pitch). Pitch control enables adjusting the thrust (and hence ship speed) independent of the rate of rotation (rpm). Consequently, reducing the speed of a ship equipped with controllable pitch propellers does not necessarily result in a radiated noise reduction. When the shaft speed can be controlled as well, the combination of shaft speed and propeller pitch can potentially be optimized with respect to cavitation performance and noise.

- **Number of blades, blade area and shape (pitch and skew)**: no general guidelines can be given for these design parameters, since they need to be optimized against multiple requirements. However, it is advised to include cavitation behaviour and noise control as essential boundary conditions for the design process.

- **Hub**: hub cavitation should be avoided using technical solutions, such as propeller boss cap fins.

- **Azimuth thrusters**: marine propellers can be placed before or after underwater pods that can be rotated to any horizontal angle (azimuth), increasing manoeuvrability and making a rudder unnecessary. A (diesel or diesel-electric) motor can either be inside the ship and connected to the outboard unit by gearing (L- or Z-drive), or the motor may be diesel or diesel-electric. Depending on the shaft arrangement, an electric motor is fitted in the pod itself. ('podded propulsion'). This drive type allows for a more uniform inflow into the propeller, leading to improved cavitation behaviour, at the cost of a more direct connection between the motor and the water, leading to higher machinery noise radiation.

- **Air injection**: can be used for either reducing propeller cavitation by air injection directly into the cavitating region, or attenuating noise radiation by generating an isolating bubble curtain around the propeller and its downstream flow.

ACCOBAMS proposed the following technologies for reduction of propeller cavitation (ACCOBAMS-MOP7/2019):

- **Schneekluth duct** – device installed on the hull of the ship in order to improve the flow on the upper part of the propeller and decrease cavitation;

- **Becker Mewis Duct** – a duct positioned in front of the propeller along with an integrated fin system;

- **Propeller boss cap fins** – improves the propeller performance characteristics via minimising the hub vortex and resultant rudder cavitation;

- **EnergoProFin (Wartsila)** – an energy saving propeller cap with fins that rotate together with the propeller;

- **ECO-Cap (Nakashima)** – propeller cap for propeller hub reduction.

If predicted peak fluctuating pressure at the hull above the propeller in design draft is below 3 kPa (1st harmonic of blade rate) and 2 kPa (2nd harmonic) for ships with a block coefficient below 0.65 and 5 kPa (1st harmonic) and 3 kPa (2nd harmonic) for ships with a block coefficient above 0.65, this could indicate a potentially lower noise propeller. Comparable values are likely to be 1 kPa higher in ballast condition (IMO, MEPC.1/Circ.833, 2014).

The speed of the ship is directly related to the effects of cavitation. If the speed of the vessel is lower than the speed at which cavitation begins, cavitation does not occur and there is no noise due to this source. This speed depends on the shape of the ship hull and the propeller (Spence and Fischer, 2016). Ships with a controllable pitch propeller could have some variability on shaft speed to reduce operation at pitch settings too far away from the optimum design pitch which may lead to unfavourable cavitation behaviour (some designs may be able to operate down to a shaft speed of two thirds of full) (IMO, MEPC.1/Circ.833, 2014).

The ship and its propeller could be tested in a cavitation test facility such as a cavitation tunnel for optimizing the propeller design with respect to cavitation induced pressure pulses and radiated noise. Optimal propeller with regard to underwater noise reduction cannot always be employed due to technical or geometrical constraints (e.g. icestrengthening of the propeller). It is also acknowledged that design principles for cavitation reduction (i.e. reduce pitch at the blade tips) can cause decrease of efficiency (IMO, MEPC.1/Circ.833, 2014).

2. *Mitigation measures during the hull design*

Uneven or non-homogeneous wake fields are known to increase cavitation (IMO, MEPC.1/Circ.833, 2014). Therefore, the ship hull form with its appendages should be designed such that the wake field is as homogeneous as possible. This will reduce cavitation as the propeller operates in the wake field generated by the ship hull (IMO, MEPC.1/Circ.833, 2014).

Hull design affects underwater radiated noise through the following factors (De Jong et al., 2020):

- **Resistance**: optimisation of the hull form and the application of anti-fouling and low-friction coatings, for reduced resistance will reduce the required propulsion power at the same speed, which will generally lead to reduced propulsion noise (less propeller cavitation). Reduced resistance is also beneficial for energy efficiency and reduces emission of greenhouse gases.

- **Wake field**: optimisation of the hull form with its appendages such that the wake field (in the propeller plane) is as homogeneous as possible, which will reduce propeller cavitation. Various technical solutions (fins, ducts) to improve the inflow into the propeller are proposed as propulsion improving devices (PIDs), since these are generally beneficial for energy efficiency as well.

- **Structure**: optimization of the hull structure (mass, stiffness and damping) can potentially reduce the underwater radiation of structure-borne and air-borne machinery noise. Only relevant when machinery noise exceeds propeller noise.

- **Hull treatments**: air emission systems can be installed to reduce resistance (air lubrication), which likely reduce machinery noise radiation as well (decoupling the vibrating hull from the surrounding water). Decoupling can also be achieved by application of a flexible hull coating (de Jong, 2002). Such decoupling techniques are used on naval vessels (submarines as well as surface ships) with stringent acoustic signature requirements.

- **Appendages and openings (sea chests)**: improper design of appendages and hull openings (e.g. for cooling water intake) can lead to local cavitation or flow induced noise (Ross, 1976; Blake, 2017).

Consideration can be given to the investigation of structural optimization to reduce the excitation response and the transmission of structure-borne noise to the hull (IMO, MEPC.1/Circ.833, 2014). In this regard, ACCOBAMS proposed some structural solutions, i.e. structural damping, increased hull thickness and the use of lightweight materials like Fibber Reinforced Plastic (ACCOBAMS-MOP7/2019).

2. *Mitigation measures for reduction of continuous underwater noise during design, selection and installation of on-board machinery*

It is important to select proper onboard machinery, to use appropriate vibration control measures, to select proper location of equipment in the hull, and to optimize of foundation structures that may contribute to reducing underwater radiated and onboard noise affecting passengers and crew (IMO, MEPC.1/Circ.833, 2014).

1. ***Mitigation measures during the selection of on-board machinery***

Reduction of underwater noise and noise on board the ship can be achieved by appropriate selection of ship machinery and equipment (IMO, MEPC.1 / Circ.833, 2014):

- The most common ship propulsion is a diesel engine. Four-stroke engines cause significantly less vibration and noise than two-stroke engines. Thus, four-stroke engines are more suitable from the point of view of reducing underwater noise.

- Diesel-electric propulsion has been identified as an effective option to reduce underwater noise. The use of high-quality electric motors may also help to reduce vibration being induced into the hull.

2. Mitigation measures during the selection of location, where machinery is installed in the ship hull

Ship designers, shipowners and shipbuilders should request that manufacturers supply information on the airborne sound levels and vibration produced by their machinery in order to allow prediction of underwater noise levels based on the numerical modelling. Based on these calculations, they can recommend appropriate methods and location of installation of onboard machinery and devices to help reduce underwater noise (IMO, MEPC.1/Circ.833, 2014; Spence in Fischer, 2016).

3. Mitigation measures to control vibrations and optimization of foundations

For effective noise reduction, consideration should be given to mounting diesel engines on resilient mounts, possibly with some form of elastic coupling between the engine and the gear box (IMO, MEPC.1/Circ.833, 2014; Spence and Fischer, 2016). The reduction in structural noise transmission generated by ship engines is achieved by lining the hull and deck with a viscoelastic material that dampens vibrations (Turner, 1969; Buiten, 1972; Nilson, 1978).

Consideration should be given for improved dynamic balancing for reciprocating machinery such as refrigeration plants, air compressors and pumps. Vibration isolation of other items and equipment such as hydraulics, electrical pumps, piping, large fans, vent and AC ducting may be beneficial for some applications, particularly as a mitigating measure where more direct techniques are not appropriate for the specific application under consideration (IMO, MEPC.1 / Circ.833, 2014).

3. Mitigation measures for reduction of continuous underwater noise based on the use of additional technologies on existing ships

The following technologies are known to contribute to noise reduction for existing ships (IMO, MEPC.1/Circ.833, 2014):

- design and installation of new state-of-the-art propellers;
- installation of wake conditioning devices;
- installation of air injection to propeller.

4. Mitigation measures for reduction of continuous underwater noise during ship operation and maintenance

Although the main components of underwater noise are generated from the ship design (i.e. hull form, propeller design and machinery configuration), operational modifications and maintenance measures should be considered as ways of reducing noise for both new and existing ships (IMO, MEPC.1/Circ.833, 2014).

1. Mitigation measure: cleaning of propeller

Marine fouling could be removed with proper propeller polishing, which reduces surface roughness and helps to reduce propeller cavitation (IMO, MEPC.1/Circ.833, 2014).

2. *Mitigation measure: maintenance of the ship hull surface*

Ship's energy (fuel) efficiency could be improved with the maintenance of a smooth underwater hull surface and smooth paintwork, which reduces ship's resistance and propeller load. This mitigation measure helps to reduce also underwater noise emanating from the ship. (IMO, MEPC.1/Circ.833, 2014).

3. *Operational mitigation measures – selection of the proper speed*

Reducing speed of the ship, which is equipped with fixed pitch propeller, could be a very effective operational measure for reducing underwater noise, especially when the speed becomes lower than the cavitation inception speed (IMO, MEPC.1/Circ.833, 2014). On a contrary, reducing speed of the ship, which is equipped with controllable pitch propeller, may not result in noise reduction. Therefore, consideration should be given to optimum combinations of shaft speed and propeller pitch in order to reduce the effects of cavitation and with this reduce the underwater noise.

There may be some overriding reasons for a particular speed to be maintained, such as safety, operation and energy efficiency. In this case, critical ship speeds should be avoided mainly due to the effects of cavitation and the consequent increased emission of continuous underwater noise (IMO, MEPC.1/Circ.833, 2014).

4. *Re-direction and operational measures for reduction of harmful effects on marine organisms*

Reducing the speed of ships or re-routing ships outside sensitive marine areas with well-known habitats or migratory pathways, especially during migration, will help to reduce the harmful effects of underwater noise on marine organisms (IMO, MEPC.1/Circ.833, 2014; Chion *et al.*, 2017; Halliday *et al.,* 2018).

3. Underwater noise mitigation using slow steaming scenario

Reductions of vessel radiated noise can be achieved by decreasing ship speed, thus underwater noise in sensitive areas could be reduced by setting speed limits. Results of first studies on the effect of introducing a speed limit on a shipping route were presented by AQUO and SONIC project (2015). In the speed reduction scenario **20 % of loudest vessels had to undergo a speed limitation to the maximum speed of 80 % of all observed vessels**, i.e. 15.9 kn. The achieved reduction was very small (<1 dB) and, due to the longer time needed for the transit through the area with lower ship speeds, even a slight increase of the received levels could be observed.

The benefits (i.e. decrease in fuel consumption, decrease in CO_2 emission and reduced underwater noise levels) potentially resulting from operation at lower speed need to be weighed against other factors, such as: increased voyage duration, possible increased total amount of acoustic energy released in the environment by extending the time spent in the speed reduction area, capital and crew cost, safety issues and the capability of the propulsion plant to sustain continuous operation at low speeds (AQUO and SONIC, 2015; Chion et al., 2017).

A modest 10 % speed reduction across the global fleet has been estimated to reduce overall greenhouse gas emissions by around 13 % (Faber *et al*., 2017). Leaper (2019) **concluded that such a 10 % speed reduction, could reduce the total sound energy from shipping by around 40 %**.

De Jong *et al.* (2021) proposed a scenario in which the **maximum speed of all vessels is limited at 75 % of their design speed**. This proposal was based on the following considerations:

- Slower steaming is a measure for reduction of air emissions as well as underwater radiated noise.

- The propulsion power at 75 % of the design speed is about 36 % of the design power – maximum continuous rating (MCR). Sailing at power rates lower than 36 % of MCR will not always be technically possible, because it could damage the engines.

- Considering the additional sailing time at a reduced speed, calculations suggested that the proposed speed limit could lead to a ~14 % reduction of emissions, for the selected ships and period.

- The JOMOPANS-ECHO ship source level model suggests that reducing the speed of a ship from 85 % to 75 % of design speed will result in a 3 dB reduction of its underwater radiated noise.

- Regulating maximum speed is easier to implement (and probably more effective for noise reduction) than regulating average speed per journey.

- Speed regulations can best be differentiated to ship type and size so that ships do not have to operate at technically challenging low loads and in order not to disturb the competition between ship types.

In the slow steaming scenario, the time loss due to slow steaming have been compensated by reducing waiting time of individual vessels in the port (De Jong *et al*., 2021).

De Jong *et al.* (2021) have carried out numerical simulations in the North Sea to study the potential benefit of slow steaming for the reduction of air emissions as well as underwater radiated noise. Because the main interest was in the effects of slow steaming for the merchant shipping fleet, recreational vessels and special and small vessels were excluded from the study.

Calculations for the proposed slow steaming scenario resulted in (Table 1):

- 10 % reduction of the emission of CO_2, NO_x, SO_x and PM_{10}
- 5 % reduction of the volatile organic compounds (VOC) emission and
- 3.5 % increase of the CO emission. The increase of CO-emissions is caused by less efficient combustion caused by low-load of engines.

Substance	CO_2	NO_X	SO_X	CO	PM_{10}	VOC
Reduction (%)	10	11	10	-3,5	10	5
Reduction (kilotons/year)	1800	38	1.6	-0.7	0.7	0.8

Table 4: Calculated yearly reduction of emissions for the proposed slow steaming at the North Sea (based on data of May 2019) (De Jong *et al*., 2021).

The calculations for the slow steaming scenario result in a reduction of the ship radiated underwater noise in the North Sea (De Jong *et al*., 2021):

- The slow steaming scenario leads to a reduction of the median background noise in space and time by **1.5 dB**.
- Reductions up to **4 dB** can be observed in local areas, around the main shipping lanes, during 10 % of the time of the month.

The slow steaming scenario is effective for reducing emissions as well as underwater radiated noise for the four largest vessel classes: container ships, tankers, bulkers and large passenger vessels (cruise vessels and ferries) (De Jong *et al*., 2021).

Chion *et al.* (2017) implemented underwater acoustic modelling of ship-whale movements and interactions in the St. Lawrence Estuary in Canada, using two scenarios: without and with protection measures (using speed reduction areas (SRA) and no-go areas). The results of multiple simulations showed: a statistically-significant **1.6 % decrease in the total amount of noise received** by belugas in their critical habitat following the implementation of the protection measures. Although slowing down ships reduced instantaneous radiated noise, it also increased the total amount of acoustic energy released in the environment by extending the time spent in the SRA. Accordingly, their simulations showed a **2.4 % increase in the cumulative noise from shipping received** by beluga in the SRA. Conversely, belugas located in the Upper Estuary, experienced a **5.4 % reduction in the cumulative received level of shipping noise**.

4. Summary

Measures to reduce propulsion power and propeller thrust loading are beneficial for energy efficiency, emission reduction and underwater radiated noise reduction. Measures to optimize hull design and execute regular maintenance, aimed at reducing hull resistance, are effective for reduced emissions and underwater noise. Design measures to reduce propeller cavitation are effective for underwater radiated noise reduction. In particular, the hull and propeller need to be designed together, as a unit, such that a uniform wake field is created to reduce propeller cavitation. To some extent these will also increase energy efficiency, and reduce emissions (De Jong *et al*., 2020).

Speed limits ('slow steaming') have a potential to be effective to control shipping underwater noise as well as energy efficiency and emission reduction, but different ship types have different optimum speeds and not all ship types can slow down to the same extent (De Jong *et al*., 2020).

The benefits (i.e. decrease in fuel consumption, decrease in CO_2 emission and reduced underwater noise levels) potentially resulting from operation at lower speed need to be weighed against other factors, such as: increased voyage duration, possible increased total amount of acoustic energy released in the environment by extending the time spent in the speed reduction area, capital and crew cost, safety issues and the capability of the propulsion plant to sustain continuous operation at low speeds (AQUO and SONIC, 2015; Chion *et al*., 2017).

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