Assessing Risk of Noise Pressure on Marine Life Using Bayes Estimator

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Abstract

The level of noise in the ocean has been increasing in the last decades, putting at risk a wide variety of marine species that rely on sound for their daily life. An important tool for assessing, and eventually mitigating, the potentially harmful effects of ocean noise on marine species is the so-called risk map. Noise risk maps result from the combination of noise pressure-level distribution and species density in the same time-space framework. A known drawback of the existing risk map methodologies is that they do not allow for direct comparison of the

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degree of risk between different periods of time, or locations, or between different species. The present study proposes a Bayesian inference-based technique, as an alternative for determining risk maps that return comparable and quantifiable absolute quantities. A simulation of a shallow water seismic survey along the southwest coast of Portugal is used to illustrate the proposed methodology. The test case considered two periods of the year (winter and summer), using as an example the common dolphin (*Delphinus delphis*) species. The results show that risk maps obtained with the proposed method favorably compare with those obtained with existing methods with, however, the advantage of being based on mean absolute values. These results encourage its use in future studies, targeting different species and/or different areas in order to give some hints for the production of indicators to support ocean protection policies.

Keywords

Ocean noise · Risk maps · Bayes estimation · Common dolphin

Introduction

Ocean noise produced by human activities has been continuously increasing in the past decades due to globalization that uses the ocean as the main route for shipping goods around the world (Redfern et al. 2017; Frisk 2012). This increase of ship traffic is accompanied by the corresponding increase of the global ocean noise level with direct implications in many marine organisms, in particular on cetaceans, as they depend on sound to forage, to interact in their community, to orientate, and to perceive the surrounding environment (Nowacek et al. 2007, 2016).

The potential impact of noise generated by human activities in the ocean drove scientists, governments, and policymakers to design policies, to set thresholds, and to monitor the good environmental status including ocean noise (DIRECTIVE 2008/56/EC 2008). Modeling is a possible way to assess the state of the soundscape that results in spatial- and temporal-level distribution of sound/noise, the so-called sound/noise maps (Soares et al. 2020; Neenan et al. 2016; Maglio et al. 2015; Nicolas et al. 2016). However, sound maps are of little use for policymakers and governments since they do not take into account sensitive species distribution. In fact, policymakers and governments are more interested in the estimation of the level of risk to which a specific species is exposed, as caused by a specific noise level, in a specific area and period of time.

Noise risk maps combine, for the same period of time and area, predicted noise maps with biological distributions. Consequently, noise risk maps may be used to implement and/or support some of the decisions at an institutional level regarding the protection of most exposed areas.

In this specific context, risk can be defined, as proposed by Verling et al. (2021), as the possibility of loss or injury inflicted by ocean noise in marine species described as

$$Risk = Likelihood \times Consequence \tag{1}$$

where “Likelihood” defines the points in space and time where a given sound pressure “overlaps” with the distribution/habitat of a particular species and the “Consequence” defines what exactly might happen in case of some likelihood. Assessing the “Consequence” is challenging and entails several particularities related to biological and physiological aspects of the species. For this chapter, it will be considered that Risk = Likelihood.

In line with this definition, several methods to produce risk maps have been proposed, combining noise prediction maps and species maps (Verling et al. 2021; Erbe et al. 2014; Merchant et al. 2018).

Even though species distribution and noise maps modeling are relatively well accepted and defined, the combination of the two is quite debatable. For example, Erbe et al. (2014*)* used an example with the Dall’s porpoise, where risk maps are obtained through multiplying species density maps by noise maps both provided in normalized scales and re-normalizing the final result. Merchant et al. (2018) follow the same methodology, with slight differences. Nevertheless, a major limitation of these methods is the fact that they preclude comparisons in time, in space, or between different species due to the normalization, so the resulting risk map becomes specific only for the considered area, time period, and species.

The present study proposes an alternative to produce risk maps based on the Bayes estimator which will make it possible to quantify risk areas while overcoming the drawbacks of current methodologies. It is believed that the alternative methodology presented in this chapter will help have a wider perception of the risk resulting from anthropogenic sources of noise and consequently promote the adoption of balanced regulations and legislation to protect marine species.

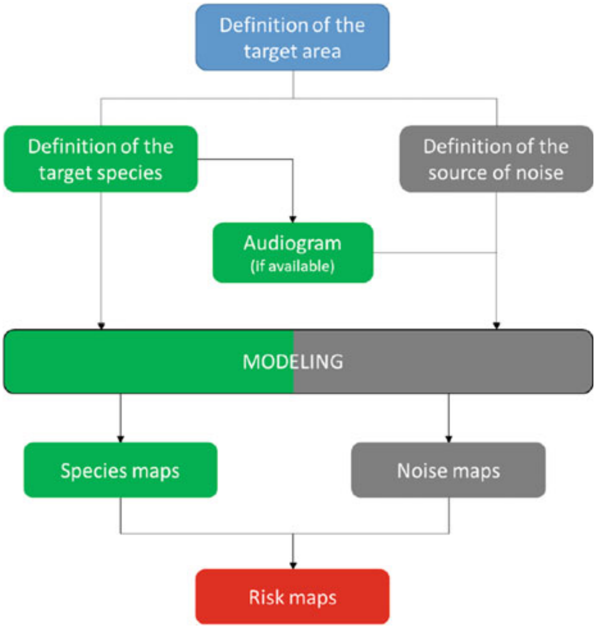
To illustrate the proposed methodology, a typical test case scenario of a light seismic survey off Setúbal on the southwest coast of Portugal was selected. This test case scenario was focused on two periods of the year, January and June, as representatives of winter and summer seasons. The selected geographic area is known to have a rich biodiversity and to host different species of cetaceans as, for example, the common dolphin that may be consequently affected by such impacting surveys.

This chapter is organized as follows: section “Materials and Methods” describes the materials and methods defining the target area, the target species, the noise source, the modeling inputs (noise and habitat suitability (HS) maps), and the Bayes estimator proposed method. Section “Results and Discussion” presents the results obtained with the proposed method and discusses its comparison with currently established methods. Finally, section “Conclusions” draws conclusions pointing out the main advantages and drawbacks of the proposed method and anticipates future work.

Materials and Methods

Producing risk maps passes through several well-described stages until obtaining the risk map itself. These steps are summarized in the diagram of Fig. 1. Usually, the process starts by defining the target area and then separating it in two parallel

Fig. 1 Generic noise risk map methodology flowchart



branches: the branch on the left (in green) leading to the habitat suitability (HS) map and the branch on the right (in gray) leading to the noise map. The only link between the two branches is the audiogram that is applied to the perceived noise field and depends on the selected species. Modeling is obviously different for the two branches. On the "biological branch," modelling the temporal and spatial distribution of the species may follow two approaches: through ecological niche models or through species density models depending on the available data (Fernandez et al. 2021). On the "noise branch," modeling the temporal and spatial distribution of noise is usually performed through the combination of several datasets such as bathymetry, sound speed profiles (SSP), Automatic Identification System (AIS) data, and bottom properties that are fed into acoustic propagation models for sound pressure-level (SPL) estimation (Soares et al. 2020; Neenan et al. 2016; Maglio et al. 2015; Nicolas et al. 2016). The last step consists on the combination of the HS map and noise maps to produce the risk map that will be, of course, conditioned on the specific area, the target species, and the source of noise.

To illustrate the proposed methodology, a hypothetical light seismic survey scenario taking place in the southwest coast of Portugal was designed. Shallow water (also called light) seismic surveys aim at superficial bottom sediment structure identification and are typically used in the initial area assessment for wind farms, bridges, breakwaters, wave energy generators, or cabling infrastructure development. This technique involves lower noise levels than classical deep water oil and gas seismic surveys and covers shallower areas when the required bottom penetration is on the order of only a few tens of meters which consequently involve higher-resolution and relatively lower-energy sources.

The choice of this area was based on the fact that the Portuguese southwest coast is well known for its rich biodiversity and because a few years ago the Portuguese Government had provided concessions for oil and gas exploration in that area (Offshore Magazzine 2007; Almeida and Khalip 2018; Tavares Pires et al. 2019; Castro-Santos et al. 2020; Silva et al. 2018; Salvação and Soares 2017).

Thus, the Portuguese coast is an important spot for marine biodiversity, hosting a large number of fish species, invertebrates, sea turtles, and a variety of cetaceans that visit this coast throughout the year. Species of whales and dolphins are frequently sighted in the central part of the country, in the waters near the region of Setúbal (Correia et al. 2015; Castro 2010). Among them, the common dolphin (*Delphinus delphis*) is notably abundant, and it may, therefore, be at risk due to the plans for extensive offshore seismic surveying.

Target Area

The area of interest was limited to −9.3° and −8.5° longitude west and 38.2° and 38.6° latitude north, with a spatial resolution of 1 × 1 km, as shown in Fig. 2. The bathymetry shows a slowly varying water depth over the continental platform extending up to approximately 45 km from the coastline, where it reaches the border of the continental shelf at approximately 250 m and then rapidly increases to deeper waters to the west. An interesting feature of this region is the Setúbal canyon, an

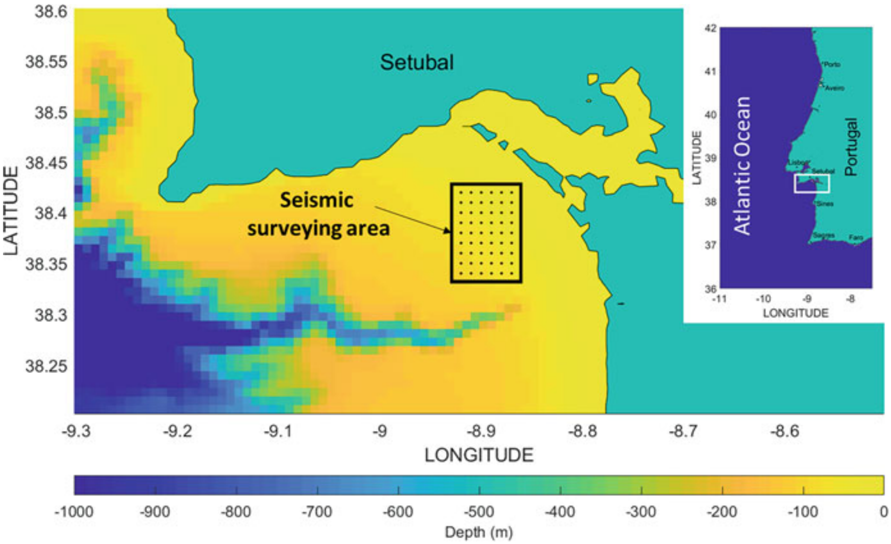


Fig. 2 Bathymetry of the test case geographical region and the seismic surveying area (black-dotted rectangle)

east-west oriented steep-sided valley at approximately 38.3° latitude north, that entails the platform with depths reaching 1000 m. For simulation purpose, the seismic survey event was centered on a relatively small rectangular area of 50 km^2 delimited by the following coordinates, longitude $-8.92°$ and $-8.87°$ and latitude 38.34° and 38.42°, shown as a black-dotted rectangle in Fig. 2. The water depth of the surveying area varies from 30 to 150 m depth which is appropriate for the installation of offshore wind farms (Oliveira et al. 2021).

Target Species

The selected species for this study (common dolphin) is one of the most abundant species in this region, being in fact one of the species with the highest number of records in dedicated databases. According to the Sociedade Portuguesa para o Estudo das Aves (SPEA), there are more than 3000 records of sightings for this species in 2019. The other reason that drove the selection of this species was the fact that common dolphins may be included in both the small cetacean group and high-frequency cetaceans group which allow future extrapolation regarding the effect of noise in different cetacean groups and gives more relevance for the study (Southall et al. 2019).

Noise Source

A commonly used apparatus for light seismic surveys is the “sparker.” These seismic sources are specially designed for shallow water usage that require less energy and higher bottom resolution. Sparkers operate by sudden discharge (spark) of a high-voltage electrical current between submerged arrays of electrodes. Modern sparker systems use several electrodes, which produce a seismic energy pulse typically between 300 and 20,000 Joules (Trabant 1995). A Geo-Source 200 sparker with two arrays of 100 electrode tips each was modeled as an example. (Developed and commercialized by GEO Marine Survey Systems, the Netherlands.) This system may reach a peak source level of 223 dB at 1 m depth, suitable for water depths from 2 to 500 m.

For the simulation purpose, the sparker source was placed at 1 m depth with a 5 s firing interval considering a ship moving at 5 knot in a traditional lawn mower pattern, which gives rise to a regular set of emission positions along the area (Fig. 2). A total duration of 1 month was considered with a time resolution of 10 min for the estimated SPL field.

Modeling

As shown in the flowchart of Fig. 1, risk maps require two inputs: species maps and noise maps. Considering that the focus of the present work is to present an alternative methodology for producing risk maps, the modeling aspects will be omitted, and the interested reader is referred to Spadoni et al. (2022) for details.

Species Maps: Common Dolphin Habitat Suitability Maps

Habitat suitability (HS) maps for the *Delphinus delphis* (i.e., common dolphin) population were developed by Spadoni et al. (2022) for the months of January and June as representatives of winter and summer seasons (Fig. 3).

HS maps present a higher quality of the habitat in coastal areas, until the bathymetric line of 200 m, especially during the month of June. This observation was expected due to the better feeding conditions in summer than in winter which creates a more suitable habitat for the species. Note that Cabo Espichel and Comporta represent high-quality areas for the common dolphin species in both cases.

Noise Maps: Seismic Survey

Sound pressure level (SPL) is a representative metric for the noise produced by a seismic source. The propagation of noise resulting from seismic surveys is shown in Fig. 4 (see (Spadoni et al. 2022)). An important influence of the environmental characteristics of the area can be noticed, as, for example, that of the bathymetry,

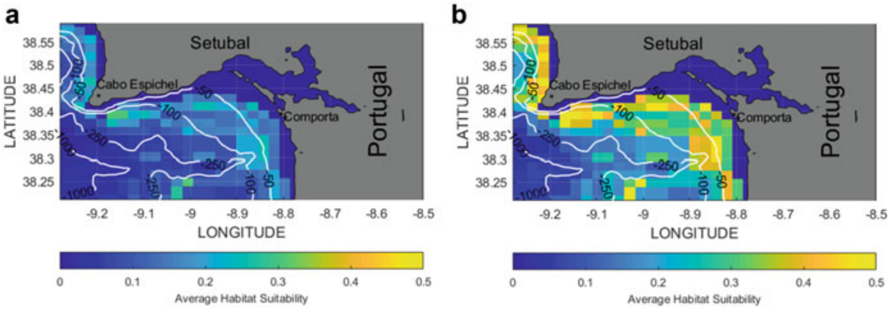


Fig. 3 Common dolphin habitat suitability for the months of January (**a**) and June (**b**). HS maps were extracted from Spadoni et al. (2022)

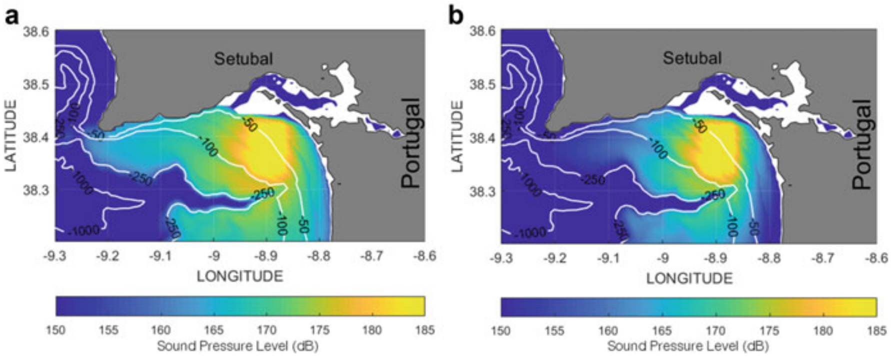


Fig. 4 Sound pressure-level distribution for the months of January (**a**) and June (**b**). SPL maps were extracted from Spadoni et al. (2022)

when sound travels to the platform border and of the water column temperature variation, registering higher levels in January than in June. Significant sound pressure levels may be attained in large swaths of the considered area. A larger spread is particularly clear in January. The survey area registered SPL levels in excess of 185 dB re 1μPa, for both months. In both cases, it is observed that noise levels may reach exceptionally high values which according to Spadoni et al. (2022) may have an impact on the temporary and permanent threshold shifts of species' hearing perception, in a range of about 40 km around the surveying zone.

Risk Assessment Using the Bayes Estimator

The proposed approach to produce risk maps and estimate risk areas is based on Bayesian inference considering that biological and anthropogenic variables are somehow correlated, if the same location and time period are considered.

To facilitate the explanation throughout this section, one may consider the common dolphin HS as a random variable A and anthropogenic noise denoted by random variable B with an empirical probability density functions (pdf) $p(a)$ and $p(b)$, respectively. Then, if variable A is represented by a prior distribution of the HS ($p(a)$), then the conditional density of $b|a$ (spelled as b when a) will be given by the distribution of noise. It follows that the posterior distribution of variable A, after noise observation, denoted as the random event $a|b$, will be given by the classical Bayes theorem (2):

$$p(a|b) = \frac{p(b|a)p(a)}{p(b)}, \tag{2}$$

where the denominator is the normalizing factor $p(b) = \int p(b|\ a)p(a)da$. This normalizing factor fulfils the crucial role of a proper probability density normalization.

Estimation theory indicates that an estimator that minimizes the Bayesian mean square error is given by the conditional mean of the posterior distribution (after observation) or the mathematical expectation $E[A|B]$ written as:

$$\widehat{\mathrm{A}} = E[A|B] = \int ap(a|b)da. \tag{3}$$

Although in many cases the species distribution/habitat suitability is represented by an index which may be assimilated to a probability, in practice, sample sizes may be insufficient (or not available at all) which may prevent us from obtaining a truthful prior pdf estimate $p(a)$ making the usage of (2) and thus of estimator (3) impossible. This limitation may be overcome if one assumes that variables A and B follow Gaussian distributions which, in fact, are quite acceptable in many applications involving real data (Fisher 2021). If the prior and the observation densities are both Gaussian, then the posterior is also Gaussian, which simply states the fact that the product of two Gaussian functions is also a Gaussian function. So, under the Gaussian assumption (and only under that assumption) if $A : \mathcal{N}(m_A, \sigma_A^2)$ and $B \mid A : \mathcal{N}\left(m_{B|A}, \sigma_{B|A}^2\right)$, the posterior density $p(a|b)$ of a random variable $A|B$ is still $\mathcal{N}\left(m_{A|B}, \sigma_{A|B}^2\right)$ in which mean and variance are given by:

$$m_{A|B} = \frac{m_A \sigma_{B|A}^2 + m_{B|A} \sigma_A^2}{\sigma_A^2 + \sigma_{B|A}^2}, \tag{4}$$

and

$$\sigma_{A|B}^2 = \sqrt{\frac{\sigma_A^2 \sigma_{B|A}^2}{\sigma_A^2 + \sigma_{B|A}^2}}, \tag{5}$$

respectively. Therefore, if the prior densities on the right-hand side of (2) are approximately Gaussian and their means and variances are known or can be estimated, the maximum a posterior Bayes estimator (3) can be calculated using expression (4). The variance of the resulting distribution is given by (5), which is not the variance of the estimator but is a measure of performance since it represents the Bayesian mean square error, i.e., the smaller the better.

Results and Discussion

This section presents first the resulting risk maps obtained using the Bayes estimator, and second, it compares these results with those obtained using a classical method to estimate risk (Erbe et al. 2014). This comparison will be used to validate the results obtained and the assumptions made, for the proposed alternative noise risk map estimation method.

Bayes Estimator Results

Figure 5 shows the risk distribution maps using the proposed Bayes-based mean estimator for the months of January (a) and June (c) and their variances (b) and (d), respectively. According to the mean estimator which, in fact, represents the simulated risk resulting from the exposure of the common dolphin population to a seismic survey, a higher sensitivity was observed in coastal areas, until the bathymetric line of approximately 200 m, specially near Comporta and Cabo Espichel. The higher- and lower-risk spatial distribution areas are similar in both months, albeit in June the risk levels are, overall, considerably higher than in January. The estimated risk levels show that a seismic survey in June is potentially more risky, for this species, than in January due to the higher species HS and also by the fact that the propagation is more

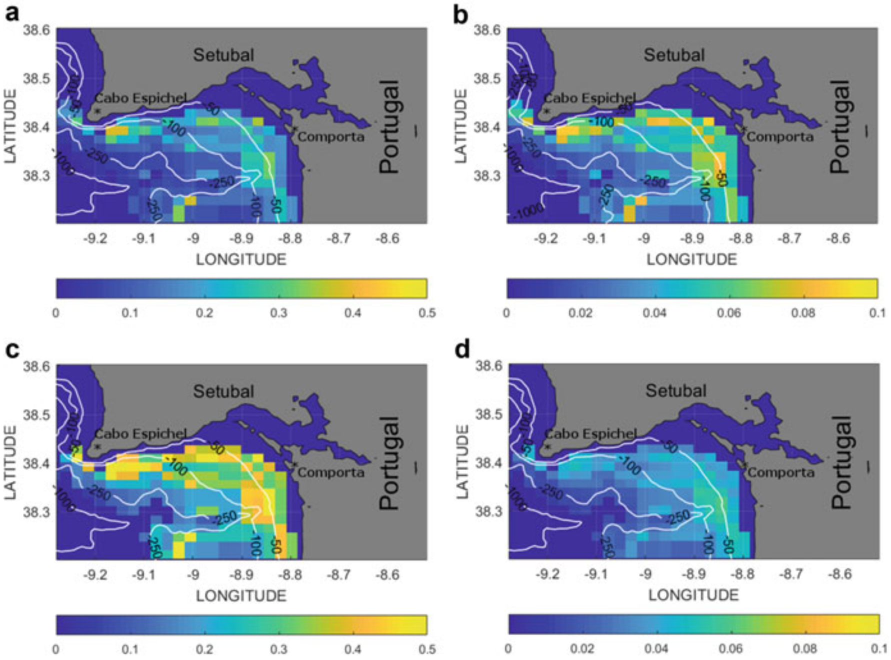


Fig. 5 Risk maps estimated with the Bayes-based mean estimator for January (**a**) and June (**c**) and their respective variance (**b**) and (**d**), respectively (according to (4) for mean and (5) for variance)

condensed in the areas where the population's HS is higher. These results were expected since, first, the seismic survey was assigned to a coastal area which in fact is the most visited area for this particular species and, second, because the habitat suitability is higher during June than in January, as it was shown in Fig. 3.

A sub-product of the proposed method is that it gives additional information on the variance, providing an indication of the quality of the estimate, since it represents the Bayesian mean square error (Bmse). Smaller variance means a better estimate and a label of higher confidence. In our simulated example, it points out for a better estimate in June than in January, as shown in Fig. 5b, d, respectively.

Comparison with a Classical Method

As stated in Erbe et al. (2014), normalizing the input maps (noise and species maps) makes it impossible for comparing the resulting risk maps. However, considering the same period of time, same location, and same species, it is possible to perform a spatial distribution comparison of the two methods which will allow to test the validity of the method proposed in this study (and assert of the assumptions made). To facilitate this comparison, it was decided to set both maps color bars between 0 and 1. Figure 6 shows the risk maps produced using the classical method (top) for

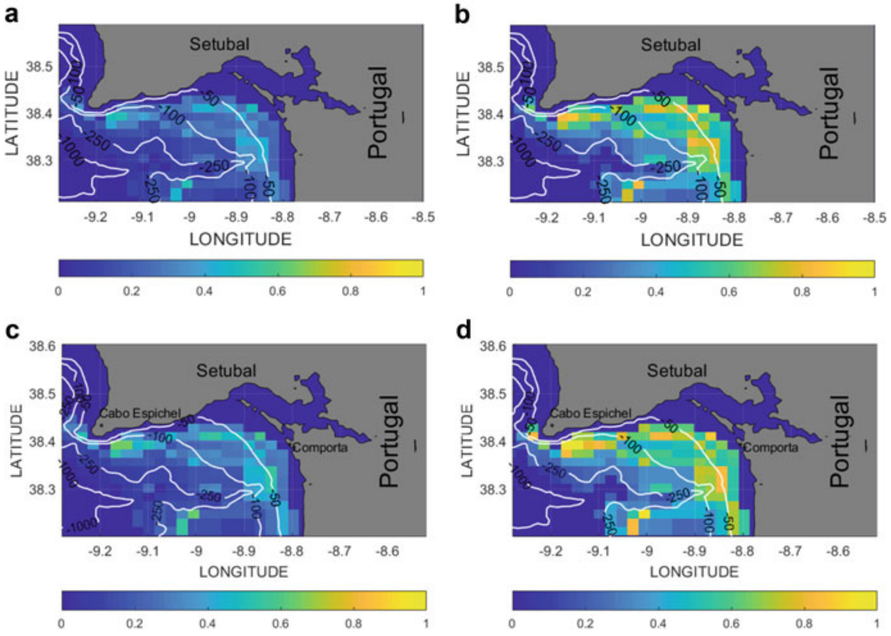


Fig. 6 Comparison between the classical method of Erbe et al. (2014) (top) and Bayes estimator method (bottom) for January (left) and June (right)

the months of January and June (right and left, respectively) and the risk maps produced with the Bayes estimator method for the same months (bottom). Noise risk maps estimated with the proposed method (Fig. 6c, d) look quite coherent with those obtained with the "classical method" (Fig. 6a, b). It can be observed that the spatial distribution of lows and highs follows the same pattern and the overall behavior between the 2 months is also similar. This sustains the validity of this alternative to produce risk maps.

Conclusions

It is of major importance to assess the impact of anthropogenic noise in the ocean-living organisms, in order to develop effective protection measures. A way to predict the most impacted areas is through the production of the so-called noise risk maps, which combine the biological and anthropogenic distributions with a single time-space map. The current limitation associated with the production of noise risk maps is the fact that the existing methods preclude comparisons between different locations, at different periods of time or between different species. This limitation, at some point, may prevent the development and the adoption of protection measures for specific areas.

The present work proposes an alternative method to produce/calculate noise risk maps which results in quantifiable maps that can be compared between them. To illustrate this methodology, a case study was designed modeling a seismic survey and its impact in the population of common dolphins in the southwest coast of Portugal. The test case results show that there is a higher seismic survey noise impact if the survey is to be carried in June than in January, specially near coastal areas. This suggests that there are periods of the year that are "better suited" for seismic surveying than others. Although this is only a simulated exercise, it shows that comparability not only in time but also in space and between species is determinant for a previous evaluation of environmental factors of the target area to support environmental management policies or to support political decisions. The contributions of the present work may be summarized as follows: (1) offers a sound theoretical framework to the ad hoc noise risk likelihood estimation used in the literature, allowing for a clear normalization of the result and its absolute comparability; (2) in case the statistic is insufficient for probability density estimation, the proposed method allows to still obtain a data coherent noise risk map estimate in case the statistics are Gaussian distributed, which is often the case whenever substantial real data is involved; and finally (3) the proposed Bayes-based methodology may be adapted to risk assessment maps, other than ocean noise.

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