Marine Pollution Bulletin 211 (2025) 117415

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

# Common dolphin's shipping noise risk assessment on the Portuguese coast

Giulia Spadoni [a,*], Ricardo Duarte [a], Cristiano Soares [b], Marc Fernandez [c], Sérgio M. Jesus [a]

[a] *LARSys, Universidade do Algarve, Estr. da Penha, Faro 8005-139, Portugal*
[b] *Marsensing Lda., Campus de Gambelas, Faro 8005-139, Portugal*
[c] *Marine and Environmental Sciences Centre/ARNET - Aquatic Research Network, ARDITI, Edif. Madeira Tecnopolo, Caminho da Penteada piso 2, Funchal 9020-105, Portugal*

ARTICLE INFO

*MSC:*
0000
1111

*Keywords:*
Underwater noise
Shipping noise
Habitat suitability
Risk maps
Common dolphin

ABSTRACT

Ocean noise generated by human activities at sea has been increasing over the decades, affecting marine ecosystems. Ship traffic flow between the Mediterranean or South Atlantic and northern Europe makes the coast of Portugal one of the most intense shipping highways on a global scale. Among the cetaceans of the coast of Portugal, the common dolphin (*Delphinus delphis*) was selected as a target species. Based on 15 years of observations, the common dolphins' habitat suitability was estimated, together with the shipping noise maps for the year 2019, to produce seasonal risk maps for the same year. A large number of areas with a high noise risk index (≥0.85) were found in Portugal's southern and southwestern coasts, especially during the summer and fall seasons. Comparably, the 0.50 risk index exceeds 7 % and 3.5 % of the total area in summer and fall, respectively. These percentages decrease to 1 % in spring and winter.

## 1. Introduction

Ocean noise is a global concern for its impact on marine life worldwide (National Research Council, 2003; Board et al., 2011; McKenna et al., 2013; Hildebrand, 2009). Underwater noise was considered an important stress factor for the Good Environmental Status (GES) of the ocean under the Marine Strategy Framework Directive (MSFD) (der Graaf et al., 2012). Noise generated by ships is the most pervasive and ubiquitous component of ocean noise (National Research Council, 2003; Soares et al., 2020; Redfern et al., 2017; Harris et al., 2016). The increase in global trading, with the inevitable increase of ship traffic, in turn led to an increase of underwater noise levels over the years (≈ 3 dB per decade) (Rolland et al., 2012; Frisk, 2012; Merchant et al., 2016).

Fig. 1 shows the global ship density over an entire year, according to Marine Traffic. Europe has a high or very high ship density, including Portugal, which is affected along its entire coast due to the north-south bound traffic to/from the Strait of Gibraltar, south America and Africa, and the north of Europe.

One of the most evident consequences of the increase in underwater noise levels is the harmful effect that it may have on marine species due to their dependency on sound (Hawkins and Popper, 2014; R. Duarte et al., 2021; C.M. Duarte et al., 2021; Finneran, 2016; Richardson et al., 1995; El-Dairi et al., 2024; Moretti and Affatati, 2023). The Portuguese coast offers exceptional conditions for marine life and biodiversity, favoring the presence of many different marine ecosystems (Martinho et al., 2015; Correia et al., 2015; Castro, 2010; Brito et al., 2009) which, due to the regions' upwelling, promotes the presence of prey for many cetaceans such as whales and dolphins, recurrently sighted in several periods of the year (Putland et al., 2017; Nowacek et al., 2007).

This paper evaluates the exposure to ship traffic noise of the common dolphin (*Delphinus delphis*), which is used in this study as representative of the small/medium-sized marine mammals due to its abundance on the North-East (NE) Atlantic (Brito and Sousa, 2011) in general and along the Portuguese coast in particular.

The analysis proceeds through the production of risk maps based on the combination/overlap of noise maps and habitat suitability (HS) maps, giving a visual output of the most endangered areas.

This paper follows a classical structure being divided into materials and methods, results/discussion, and conclusions. The materials and methods, Section 2, is broken down in three sub-sections addressing the description of the shipping noise model, the description of the HS model, and the methodology used to produce the risk maps. The results and discussion Section 3 follows a similar structure as Section 2, addressing the results obtained for shipping noise, for HS and finally for risk. The final section summarizes some conclusions and attempts to motivate future work.

* Corresponding author.
*E-mail address:* gspadoni@ualg.pt (G. Spadoni).

https://doi.org/10.1016/j.marpolbul.2024.117415
Received 12 April 2024; Received in revised form 3 December 2024; Accepted 3 December 2024
Available online 16 December 2024

## 2. Materials and methods

This section describes the methodology used to estimate the shipping noise maps, the HS maps, and the approach to calculate the resulting risk maps considering the common dolphin species for the complete Portuguese coast. Noise maps and HS maps were generated for the four seasons of the year: winter (December, January, and February), spring (March, April, and May), summer (June, July, and August), and fall (September, October, and November).

Fig. 2 shows the bathymetry (a) and the cumulative ship traffic based on the AIS along the Atlantic margin of the Iberian Peninsula (b). The rectangle indicates the selected target area considered in this study. The Portuguese coast is characterized by a continental shelf varying from approximately 8 km in the country's southwest cape (Sagres) to 70 km in the region to the north of Lisboa (40° north). Several long and deep submarine canyons can also be seen in Fig. 2(a). Note that most of the target area (approximately 60%) is for acoustic modeling purposes considered as shallow water (less than 200 m water depth). Fig. 2(b) shows the ship traffic cumulative density that can be divided into three components: large vessels using the offshore Traffic Separation System (TSS), large vessels reaching major ports (as for example, Porto, Aveiro, Lisboa and Sines), and coastal traffic due to small or medium-sized fishing and recreational boats (as for example in the south of Portugal, near Setúbal, or between Aveiro and Porto). Notice that the target area is placed at the border of the TSS.

### 2.1. Shipping noise modeling

Shipping noise maps were generated for the year 2019, based on the Automatic Identification System (AIS) extracted from ExactEarth database with a spatial resolution of 1 km by 1 km and a temporal resolution of 10 min. Considering that, at some frequencies, sound propagates for very long distances, the contributions of the vessels in the full area shown in Fig. 2 were considered for the modeling of the noise distribution in the black rectangle.

Shipping noise maps were generated following the methodology outlined in the diagram of Fig. 3.

Ship source level (SL) was assigned using the JOMOPANS-ECHO source model, which considers vessel type, speed and length drawn from AIS (Macgillivray and de Jong, 2021).

Acoustic transmission loss (TL) was calculated based on KRAKEN normal mode propagation model (Kuperman et al., 1991; Porter and Reiss, 1984) fed with the bathymetry (downloaded from GEBCO database (Weatherall et al., 2015)) and sound speed profiles (SSP) characterising the water column properties of the area, were determined through the MacKenzie nine-term equation (Mackenzie, 1981) through the salinity and temperature profiles (obtained from Copernicus Marine System database). The influence of bottom properties in the sound propagation in deep water is residual. Therefore, historical bottom properties obtained through extensive studies for the continental platform near Setúbal were used in the whole target area (Jesus et al., 2002). These properties consider a generic bottom composed of a sandy sediment layer over a rocky sub-bottom as described in detail in Table 1.

Once the TL was estimated for each source/vessel position (obtained from AIS) to every point in the spatial grid and for the considered number of frequencies $f$, the sound pressure level (SPL) was calculated according to the equation in Fig. 3 as the range-azimuth discs of each individual source converted to latitude-longitude-depth coordinates (vector $\mathbf{r}$) and then summed over all $Q$ sources, weighted by the estimated source level SL. This process is iterated for each time $t$ at 10 min interval.

The frequency band of [31–1008] Hz was covered through 1/3 octave bands (base 10). The KRAKEN model was run for the 1/3 octave bands center frequencies and for the receiver depths comprised between 10 and 50 m, which represent the usual diving and foraging depths of the common dolphin (Evans, 1994). The resulting noise field is a 5-dimensional hypercube, that was reduced as follows: SPL was first averaged in-depth (between 10 and 50 m) and then summed over the frequency band. Further reduction was obtained through time averaging in specific seasonal periods resulting in the latitude-longitude maps as shown in Section 3.

### 2.2. Habitat suitability modeling

Habitat suitability (HS) maps were developed for the common dolphin species using the occurrence records of three independent companies: a) Sociedade Portuguesa para o Estudo das Aves (SPEA), b) SeaEO Tours, and c) MarIlimitado.

The dataset provided by SPEA was obtained from linear transect surveys carried out with the European Seabirds At Sea (ESAS) method

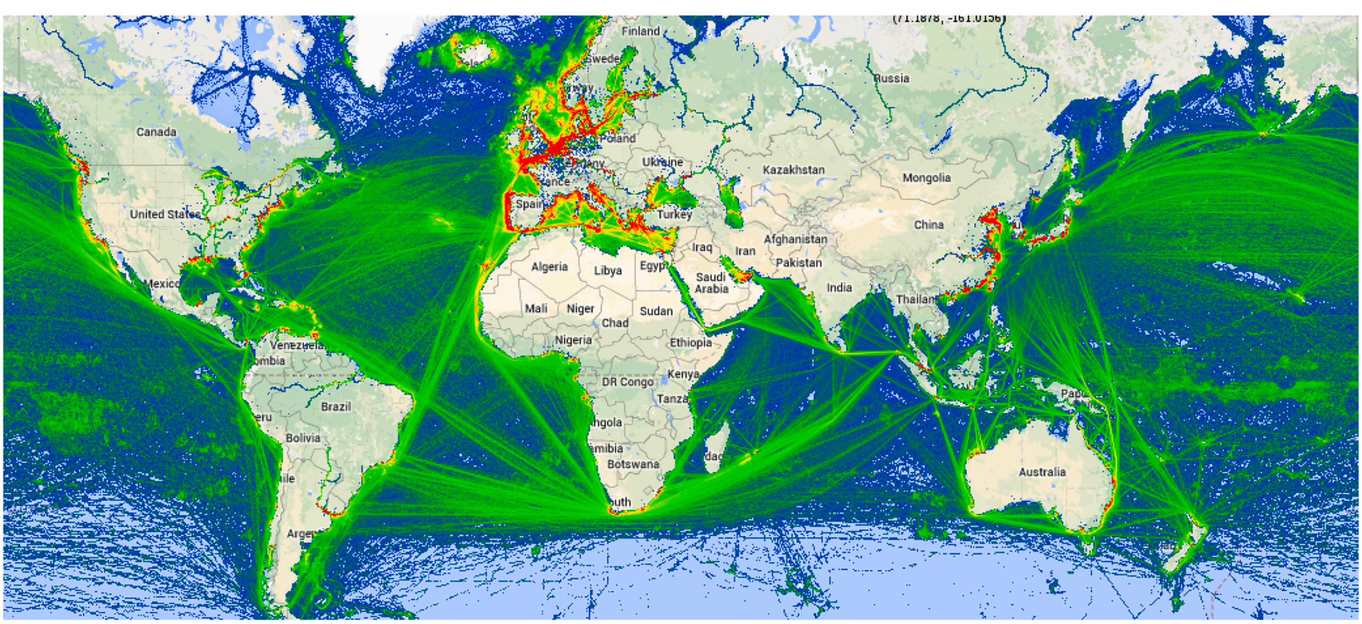


**Fig. 1.** Global ship traffic density over an entire year obtained from Marine Traffic, with the following color coding: blue (zero), green (low), yellow (intermediate) and red (high) ship density. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

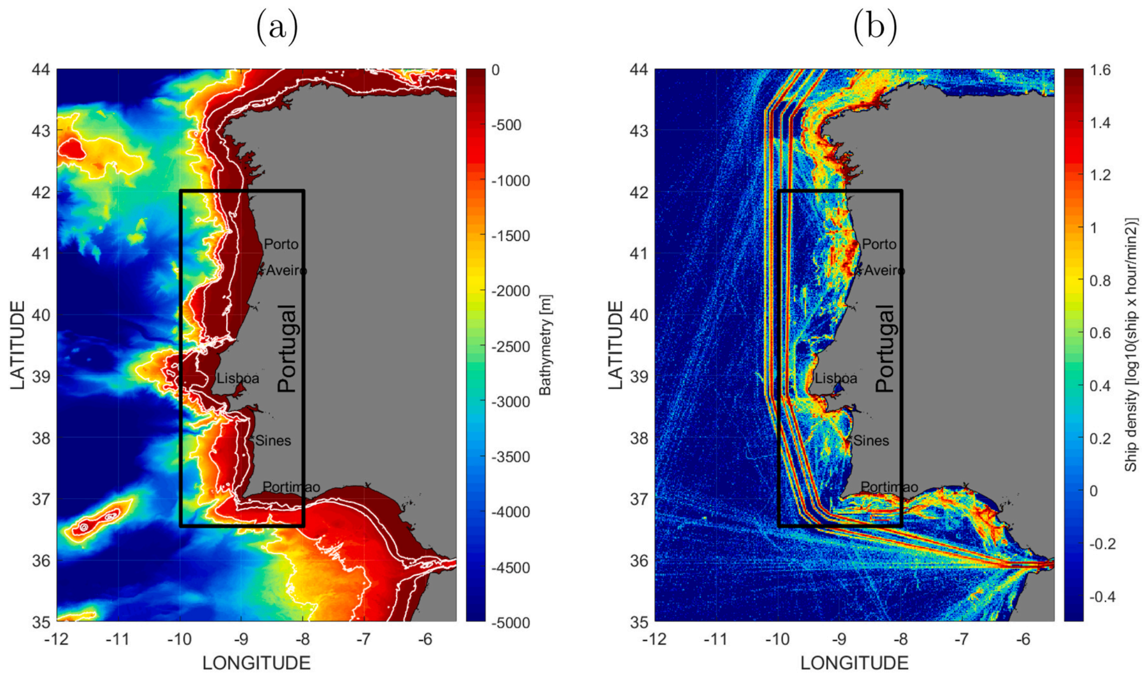


**Fig. 2.** Bathymetry (a) and cumulative ship traffic distribution based on the AIS of 2019 (b) along the Iberian Peninsula. The rectangle indicates the target area considered for this study [longitude −10; −8] and [latitude 36.5; 42].

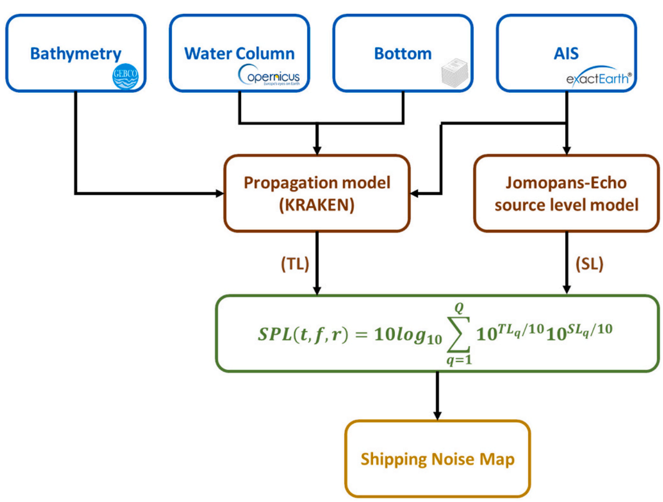


**Fig. 3.** Shipping noise estimation diagram: environmental data and AIS inputs (top), sound propagation and source level computer models (middle) combining formula for SPL estimation and shipping noise map output (bottom).

**Table 1**
Assumed seabed parameters.

| Model parameter (units) | Value |
|---|---|
| Sediment speed (m/s) | 1650 |
| Sediment density (g/cm$^3$) | 1.9 |
| Sediment attenuation (dB/$\lambda$) | 0.8 |
| Sediment thickness (m) | 10 |
| Sub-bottom speed (m/s) | 1800 |
| Sub-bottom density (g/cm$^3$) | 2.8 |
| Sub-bottom attenuation (dB/$\lambda$) | 0.2 |

(Adapted from Jesus et al. (2002); Soares et al. (2015).)

along the whole coast of Portugal to a maximum distance of 75 km from the coastline. This dataset spans the period from 2005 to 2020, with records equally distributed throughout the year. The datasets provided by the other companies were much more limited in space and time. For SeaEO Tours the observations cover a complete two-year period between 2019 and 2020 and for Mar Ilimitado, the data set covered the period between April and October over the years of 2005–2020.

This methodology is fully detailed in Fernandez et al. (Fernandez et al., 2021) in which the combination of the target species' observation records and the target area's environmental characteristics was used to perform an Ecological Niche Model (ENM) through a maximum entropy algorithm called MAXENT (Philips et al., 2018). Terrain variables of water depth and seabed slope from NOAA ETOPO 1 Global Relief Model were used together with oceanographic variables of sea surface temperature (SST) from Copernicus database and chlorophyll-a also from Copernicus database. A minimal temporal resolution of 8 days throughout the period from June 2005 until June 2020 was used. Then, the HS data in this period was averaged to obtain the HS maps for each season. A spatial resolution of 2 km by 2 km was considered. The variance inflation factor (VIF) was implemented to avoid collinearity among environmental predictor variables (using *usdm* R package (Naimi, 2015)). A targeted selection approach was used to correct for biases and provide better distributional estimates.

Different background selections were made according to the different nature of each dataset. It was used the Minimum Sampled Area for whale watching data as implemented in Fernandez et al. (Fernandez et al., 2021). Background data for the surveys were extracted following the same principle, but in this case adding a buffer on the surveyed area each 8-day period. An identical seasonal division that was used for noise modeling was adopted for the production of HS maps.

### 2.3. Risk map calculation

Generating risk maps requires combining shipping noise and species density maps. Firstly, since the spatial resolutions were not the same, both maps were re-adjusted to the lower spatial resolution of 2 km by 2 km. Risk maps were then created considering a similar approach to that of Erbe et al. (Erbe et al., 2014), which normalizes from 0 to 1 both the species density maps and the noise maps. The only difference between Erbe's et al. (Erbe et al., 2014) and the present study is the fact that HS maps were used instead of species density maps. The maximum value over the whole year was considered for HS and shipping noise normalization. In the next step, shipping noise and HS normalized maps were overlapped by a point-to-point multiplication of the normalized noise and habitat maps, over the whole space. The resulting risk scores were also normalized between 0 and 1, considering, again, the year's maximum value. The normalization by year's maximum allows for comparing risk between seasons.

In order to take advantage of the 15-year-long series of common dolphin observations, HS maps plus or minus one standard deviation ($\pm\sigma_{HS}$) were calculated, and the procedure above was repeated to obtain the respective risk maps, still using the shipping noise distribution map of 2019. This strategy allows for the observed HS variability of 15 years to be used as an indicator of possible upper and lower risk bounds if such variability was observed with the shipping noise of 2019.

## 3. Results and discussion

This section presents the results of, first, the shipping noise map produced for each season of the year 2019; second, the HS map for the common dolphin species; and third, the resulting risk map for the entire Portuguese coast. Finally, the overall meaning of our findings and potential future studies are discussed.

### 3.1. Shipping noise maps

Mean broadband shipping noise is shown in Fig. 4, where higher noise levels can be seen in the winter season (a), followed in decreasing order, by fall (d), spring (b), and summer (c).

As expected, the higher noise levels are registered in the vicinity of the TSS, as well as in the vicinity of important ports such as Porto, Aveiro, and Sines, and in occasional coastal spots, especially in the south of Portugal. Most of the TSS crosses deep water where sound propagates easily in a typical periodic pattern of shadow and convergence zones, that may be broken when encountering the steep slope of the continental platform towards the Portuguese coast. The net result is an abrupt noise level decrease when entering the continental shelf, which is clearly noticed in almost the whole area. The exception is the zone slightly to the north of Lisboa, where the TSS actually crosses over the continental platform, giving rise to a ducted propagation at relatively high levels towards the coast (winter case of Fig. 4(a)).

In winter (plot (a)), the noise level near ports is remarkably intense, followed by fall (d), spring (b) and summer (c), in decreasing order. Additionally, comparing noise levels between ports one can remark that Porto and Aveiro show the most intense noise levels followed by Sines and Setúbal/Lisboa. This may indicate that Porto and Aveiro have higher traffic than Sines, but also that the bathymetric slope is sharper in Sines than off the ports in the north of Portugal. In the south of Portugal, higher noise levels were obtained during the summer, and it may be speculated that fishing and tourism are the main contributors. This results from a simple correlation with two main activities taking place in that region, precisely in that period of the year. One may argue that many touristic recreational boats may not have an AIS transponder and, therefore, would not be included in this distribution, which reinforces that these noise maps represent optimistic lower levels, at least for some areas and periods of the year.

### 3.2. Habitat suitability maps

HS results are shown in Fig. 5 for winter (plot(a)), spring (b), summer (c) and fall (d). These results show a significant variability between seasons, with the highest HS values in summer, followed by fall, spring and winter. The high scores obtained in winter and summer were somehow expected, as well as those of spring and fall. This might be explained by the water temperature and chlorophyll content in the water. Common dolphins are generally found in cold and highly productive upwelling-modified waters (Au and Perryman, 1989; Roden and Mullin, 2000; Santos et al., 2001; Jefferson et al., 2009). The spring–summer seasonal upwelling variability off the Portuguese west coast greatly influences the recruitment dynamic of sardines and horse mackerel (Santos et al., 2001), which are the main prey of the diet for common dolphin in this area (Marçalo et al., 2018). Therefore, the

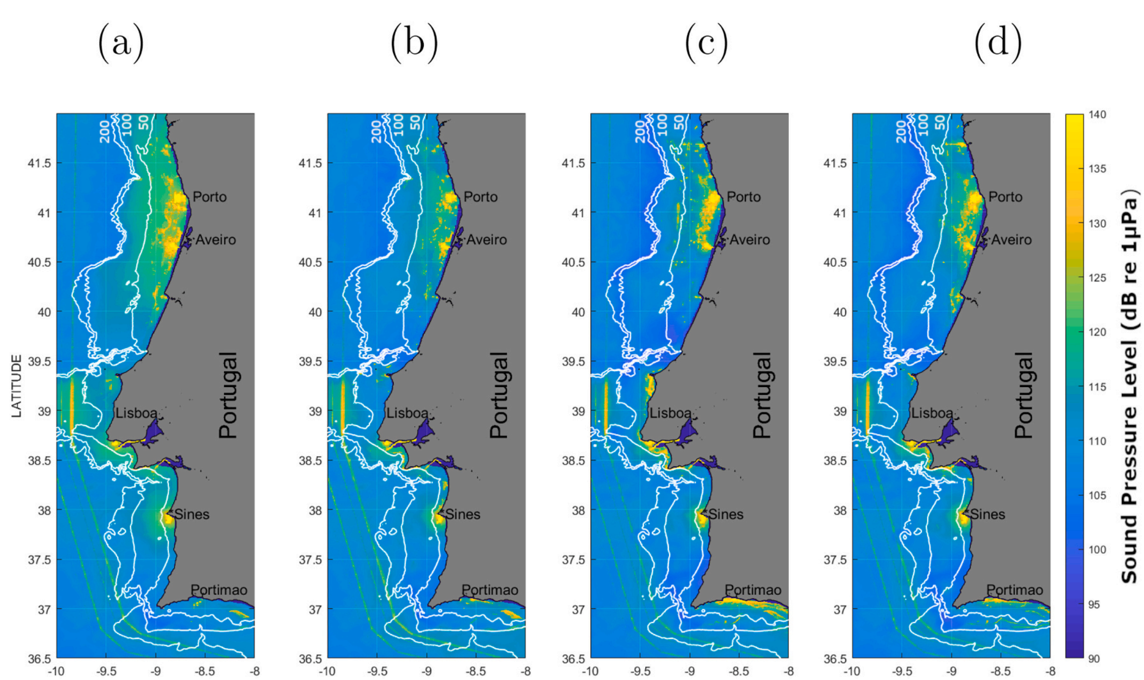


Fig. 4. Mean broadband shipping noise predictions considering 1/3-octave band levels (base 10) during the four seasons of the year 2019: winter (a), spring (b), summer (c) and fall (d).

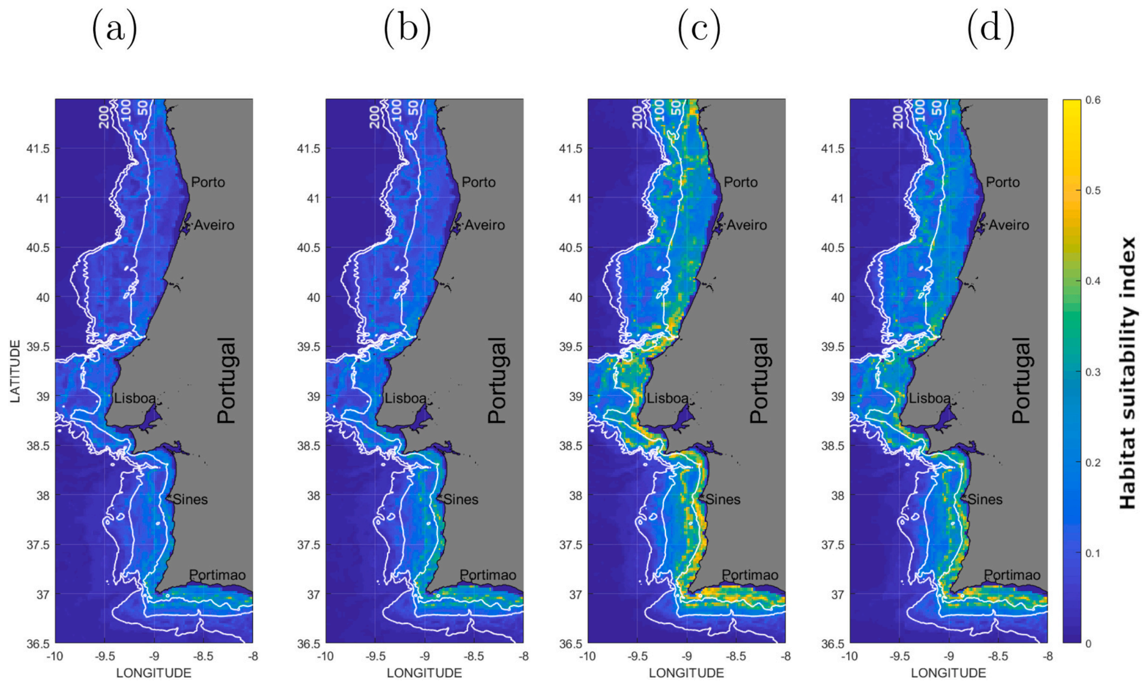


**Fig. 5.** Common Dolphin's average HS distribution index along seasons: winter (a), spring (b), summer (c) and fall (d).

typical summer upwelling season (June–September), which positively affects the recruitment of small pelagic species, is influencing the habitat suitability of common dolphins presented here, with higher values during summer and fall.

Fig. 5 shows higher HS values near the coast till the bathymetric line of 200 m, following the limits of the continental platform for all seasons. Also, in this case, this could be explained by the small pelagic fish, which are the primary nourishment for dolphins, that are especially abundant in shallower waters (Yen et al., 2004; Moura et al., 2012; Jefferson et al., 2009), and consequently favoring the habitat near the coast. This is especially true during the summer season, which is also reflected in Fig. 5.

### 3.3. Risk maps

This section presents risk maps for the target area, considering the common dolphin's average HS distribution of the previous fifteen years and the shipping noise produced over the four seasons of 2019. Fig. 6 shows the risk index for winter (plot (a)), spring (b), summer (c) and fall (d).

Risk maps show an important seasonal and spatial variability in which summer presents the higher risk index spread for wider areas,

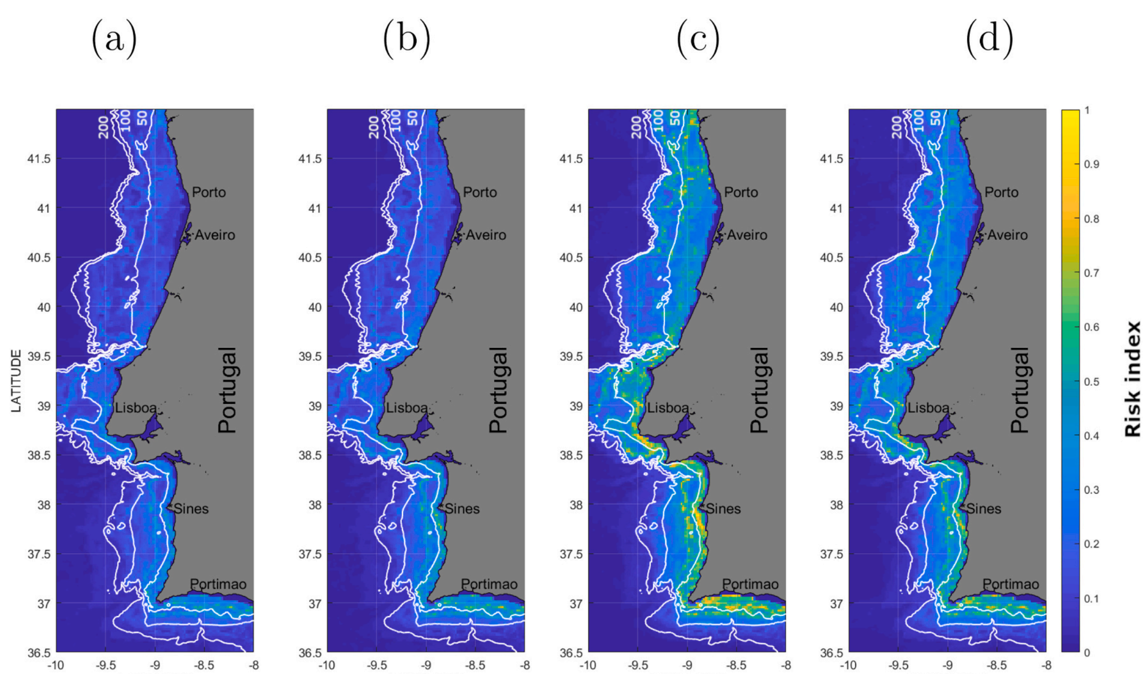


**Fig. 6.** Risk index for the Portuguese coast for each season: winter (a), spring (b), summer (c) and fall (d).

followed by fall, spring and winter. These results are interesting since, even if the highest noise levels occur during the winter season (see Fig. 4), because the HS index is low during that period (see Fig. 5), the risk index is reduced. The opposite occurs in the summer season, with shipping noise levels being lower than in the rest of the year but, in this case, the HS is very high in coastal areas, resulting in a higher risk index. The fact is that the target area shows an almost homogeneous noise distribution (apart from a few localized spots), which results from the shallow bathymetry near the coast and the shipping routes being offshore. This makes risk maps mostly modulated by HS variability, which is itself biased towards the shallow areas with high productivity along the continental shelf, thus the preferred areas for the common dolphin. So, in general, higher risk levels are concentrated in shallow water, extending till the continental platform limits (≈ the bathymetric line of 200 m).

Contrary to what could be expected, risk maps do not suggest a major influence of the TSS. Analyzing Fig. 4, one can see high noise levels in the region of the TSS, which occur in deep water. Knowing that the common dolphin habitat is mainly situated in water depths lower than 200 m, there is a lack of spatial coincidence and, consequently, the area of the TSS presents a low-risk index. The exception is the region off Lisboa, where the TSS is crossing a shallow water area, with higher noise levels closer to the regions where common dolphin may be present, resulting in higher risk.

In summary, the results suggest that risk maps are strongly influenced by the coastal character of the selected species and by the traffic/noise levels near the main ports. It may be speculated that for species prevailing in the deeper ocean, say beyond the 200 m water depth, the influence of shipping noise and the TSS would have been accentuated. Considering the risk along the Portuguese coast, the central and southern regions of Portugal show the highest risk levels, which may be due to the quality of the habitat of the common dolphin in those areas.

In order to have a quantified picture of the risk level along the seasons and the area covered by a specific risk level, Fig. 7 shows the percentage of the area assigned to a specific risk index for each season. This figure reveals, as expected, that summer has a higher risk index for a higher percentage of the area, followed by fall, spring, and winter with the lowest risk index. For example, it is observed that a risk index of 0.5 is exceeded for 7 % of the area in summer, 3.5 % in fall and less than 1 % in spring and winter.

Besides the risk index estimates for the year 2019, which were based on the HS means and shipping noise, it is important to define risk as a range and not just as a single value for a specific location in space. The risk index maps shown in Fig. 6 are drawn from one year of shipping noise and 15 years of HS data, through the usage of their respective

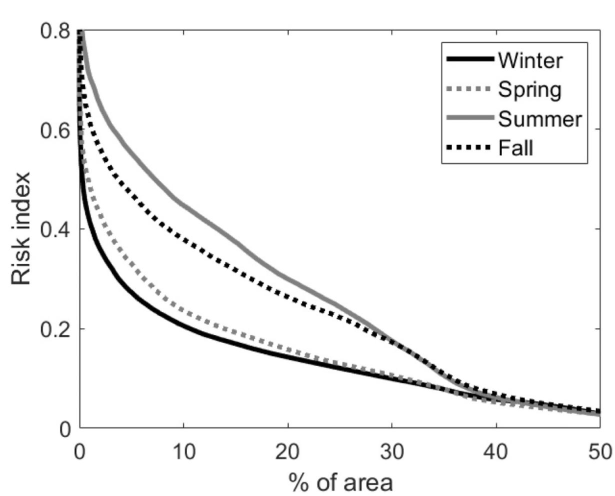


**Fig. 7.** Risk index per percentage of ocean area for all seasons.

means. In order to take advantage of the richness of the HS data set it was decided to produce risk maps for 2019 as if HS was one standard deviation off the mean, in order to define data-based upper and lower risk index bounds.

Fig. 8, shows the lower-bound risk index map at HS$-\sigma_{HS}$ for the target area along the four seasons of 2019. In this case, summer remains the season with higher risk levels, followed by fall, spring and winter. This lower-bound analysis still places the higher risk levels in the south and in the southwest coast.

On the other hand, Fig. 9 shows the upper-bound risk index limit at HS$+\sigma_{HS}$ for the considered seasons. Also in this case, summer presents the higher risk levels followed by fall, spring and winter. It should be noted that, beyond the risk areas observed in previous maps, a slightly higher risk area is observed in the north of Portugal, between the ports of Aveiro and Porto, especially in summer and fall. Fig. 10 shows the percentage of area that exceeds a specific risk level, taking into account the lower and upper-risk index bounds presented above. Comparing the results for the four seasons, summer shows a smaller interval between limits, followed by fall, winter and spring. This risk interval may help in the definition of risk ranges for specific seasons of the year or even for specific areas.

An additional remark relates to the slope of the curves that, for a small percentage of the area, the inclination is much higher for winter and spring than for summer and fall. This clearly indicates that high risk in winter and spring is concentrated in small areas, whereas it is more spread in summer and fall.

In the summer (Fig. 10(c)) it is possible to see that the average risk index curve is above the maximum of the season (HS$+\sigma_{HS}$), which is due to the fact that the $\sigma_{HS}$ in this season is higher.

Although the frequencies used by the common dolphin (which can range from 1 to 50 kHz (Griffiths, 2009)) are higher than those produced by shipping noise (in this case from 30 Hz to 1 kHz), several studies show impacts from high shipping noise levels on odontocetes (Pirotta et al., 2015; Halliday et al., 2019; Jensen et al., 2009), including species with historically high frequencies, like the harbour porpoise (*Phocoena phocoena*) (Wisniewska et al., 2018) and the beluga whale (*Delphinapterus leucas*) (Martin et al., 2023). Vessel noise was affecting the foraging behaviour in harbour porpoises and the swim speed in belugas. This can be explained by recent studies that have demonstrated that a vast range of vessels actually produce noise at higher frequencies than the typical values, used in this study, frequencies which are closer to those of the odontocetes (Wisniewska et al., 2018; Hermannsen et al., 2014; McKenna et al., 2013). Moreover, research studies such as (Fouda et al., 2018) observed impacts on the dolphins despite the range of frequencies being below the dolphin's call bandwidth. This has been explained as a consequence of a general increase in ambient noise which has shown impacts not only on dolphins but also on primates, birds, bats and other species (Barber et al., 2010). Furthermore, most of the studies about effects of shipping noise on cetaceans, have been focused on baleen whales because of their low-frequency bandwidth which overlaps with the frequencies emitted by vessels. On the contrary, little is known about the effects of shipping noise on odontocetes, including the common dolphin, which tend to use and produce sound at higher frequencies. Therefore, investigating specific effects of shipping noise on the common dolphin is a subject that, as mentioned above, requires further consideration and was not the main scope of this study, which was more focused on describing a proposed methodology from a to z to calculate risk maps. Before developing any regulation and mitigation it is essential to deepen the actual knowledge on the potential impacts of shipping noise on the common dolphin, taking into account its perspective (Popper et al., 2020) and understanding potential long-term effects of a chronic exposure.

## 4. Conclusions

Understanding the exposure of marine species to an increasing noise

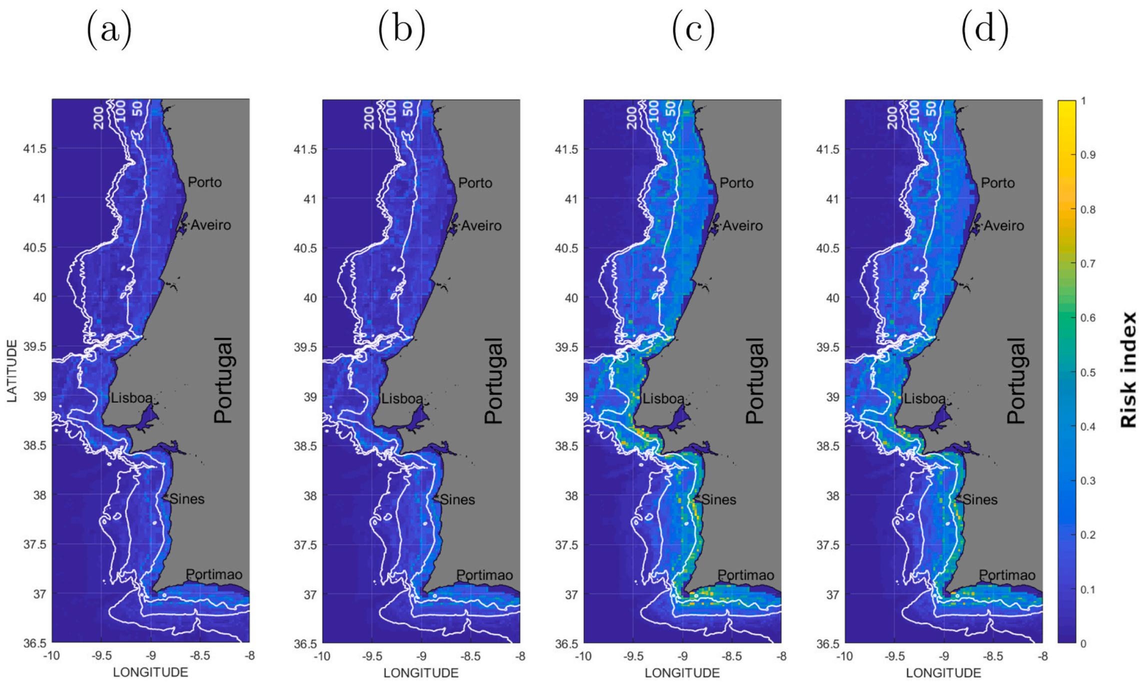


**Fig. 8.** Lower risk level index calculated using the HS-$\sigma_{HS}$ for the Portuguese coast by season: winter (a), spring (b), summer (c) and fall (d).

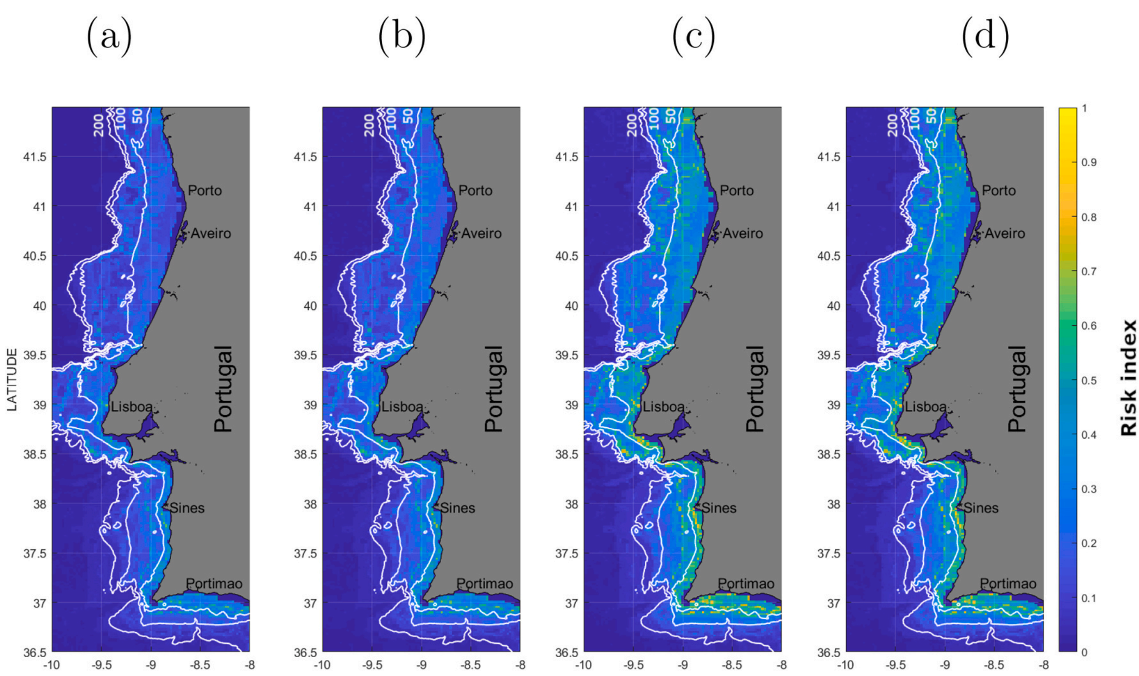


**Fig. 9.** High risk level index calculated using the HS+$\sigma_{HS}$ for the Portuguese coast by season: winter (a), spring (b), summer (c) and fall (d).

due to human activities is progressively becoming a subject of interest and a global challenge.

The main objective of this study is to propose a risk assessment methodology and use that methodology to assess the level of risk to which the common dolphin is exposed, considering the noise produced by shipping along the Portuguese coast. The year 2019 was used due to the availability of the AIS distribution for that year.

Portugal has one of the busiest coasts on a global scale, potentially leading to significant noise levels that may impact species and even entire ecosystems. The common dolphin is one of those species, taken in this study as a target species because of the availability of observation data along the Portuguese coast. Additionally, cetaceans need sound for vital activities, which makes them particularly sensitive to noise. Risk level evaluation is typically based on risk maps that take into account the stressors' level distribution on one hand and the target species density distribution on the other. The produced risk maps in this particular case revealed three important aspects: first, the differences between seasons, in which summer is that with higher risk levels; second, regional differences between the north, the center, and the south of Portugal, with the south and southwest coast those with higher risk

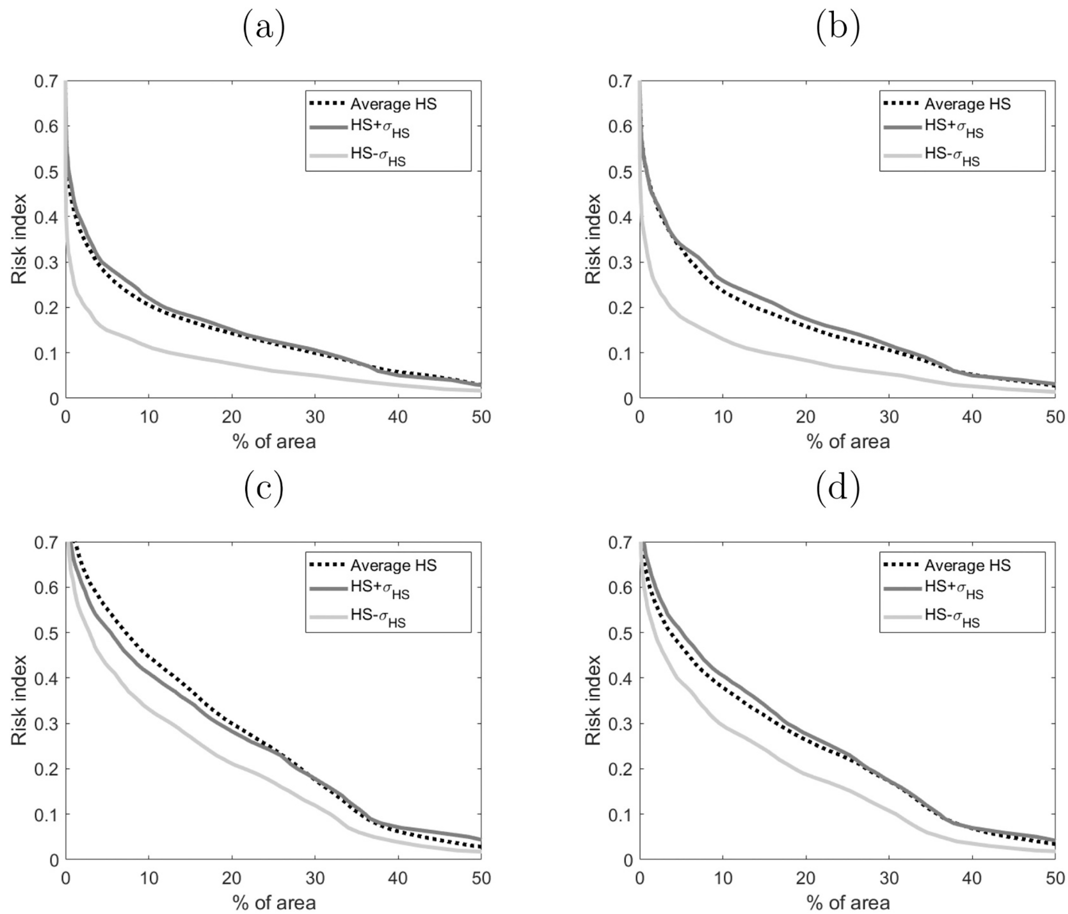


**Fig. 10.** Range of risk index, considering HS$\pm\sigma_{HS}$, per percentage of area for all seasons: winter (a), spring (b), summer (c) and fall (d).

levels and third, a relatively constant risk index in the approaches to large ports for all seasons. These three aspects are of major importance in a context of risk level assessment and risk management. Using the full span of data available for determining species distribution and projecting onto 2019 shipping noise distribution, risk index indicators as a function of area percentage were proposed. Calculating these values is a piece of valuable information for deriving potential protection and mitigation strategies. Nonetheless, we would like to highlight that the results from this study should be interpreted with caution before any management decision is undertaken, as we haven't gone as far as estimating the actual impacts of shipping noise on the common dolphin, the subject of potential future studies. The risk level mapping methodology and the associated indicators proposed in this work provides a first assessment of the area, highlighting potentially "acoustic hotspots" and high-risk periods where shipping noise overlaps with important habitats for the common dolphin. As an example, it was shown that the continental shelf area crossed by the TSS at the level of Lisboa is a potential generator of risk. However, for other reasons, the same applies to the south and southwest coasts during the summer period.

As a final conclusion, it can be asserted that in general, the TSS is not the main contributor to the estimated risk level maps for the studied species along the coast of Portugal. The only exception is perhaps the already mentioned continental shelf region off Lisboa. Instead, the main contributors to ship noise risk are shown to be the approaches to the main ports, fishing and coastal recreational traffic.

## CRediT authorship contribution statement

**Giulia Spadoni:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ricardo Duarte:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Cristiano Soares:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Marc Fernandez:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Sérgio M. Jesus:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

The authors gratefully acknowledge funding of the JONAS project, under the INTERREG Atlantic Area program (contract EAPA 52/2018). This work would not have been possible without the collaboration of the Portuguese Society for the Study of Birds (SPEA) for giving access to their data set of cetaceans and seabirds along the Portuguese coast, as well as to the whale-watching companies Mar Ilimitado and SeaEo tours for providing cetaceans observation records for the region of Sagres and Setúbal, respectively.

## Data availability

The data that has been used is confidential.

## References


Au, D.W., Perryman, W.L., 1989. Dolphin habitats in the eastern tropical pacific. Collected Reprints 1, 14.

Barber, J.R., Crooks, K.R., Fristrup, K.M., 2010. The costs of chronic noise exposure for terrestrial organisms. Trends Ecol. Evol. 25, 180–189. https://doi.org/10.1016/j.tree.2009.08.002. URL: https://www.cell.com/trends/ecology-evolution/abstract/S0169-5347(09)00261-4 (Elsevier).

Board, E., Simmen, J.A., Bucker, C.P.H., Dyer, I., Jenson, F.B., Livingston, E.S., 2011. Ocean Ambient Noise.

Brito, C., Sousa, A., 2011. The environmental history of cetaceans in Portugal: ten centuries of whale and dolphin records. PLoS One 6, e23951.

Brito, C., Vieira, N., Sá, E., Carvalho, I., 2009. Cetaceans occurrence off the west central Portugal coast: a compilation of data from whaling, observations of opportunity and boat-based surveys. Journal of Marine Animals and Their Ecology 2, 10–13.

Castro, J.M.C.d., 2010. Characterization of Cetaceans in the south coast of Portugal between Lagos and Cape São Vicente. URL: https://repositorio.ul.pt/handle/10451/2422 (accepted: 2011-02-01T16:53:45Z).

Correia, A.M., Tepsich, P., Rosso, M., Caldeira, R., Sousa-Pinto, I., 2015. Cetacean occurrence and spatial distribution: habitat modelling for offshore waters in the Portuguese EEZ (NE Atlantic). J. Mar. Syst. 143, 73–85. https://doi.org/10.1016/j.jmarsys.2014.10.016. URL: https://www.sciencedirect.com/science/article/pii/S0924796314002541.

der Graaf, A.V., Ainslie, M., André, M., Brensing, K., Dalen, J., Dekeling, R., Robinson, S., Tasker, M., Thomsen, F., Werner, S., der Graaf, A.V., Ainslie, M., André, M., Brensing, K., Dalen, J., Dekeling, R., Robinson, S., Tasker, M., Thomsen, F., Werner, S., 2012. European Marine Strategy Framework Directive - Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater Noise and Other Forms of Energy.

Duarte, C.M., Chapuis, L., Collin, S.P., Costa, D.P., Devassy, R.P., Eguiluz, V.M., Erbe, C., Gordon, T.A., Halpern, B.S., Harding, H.R., Havlik, M.N., Meekan, M., Merchant, N.D., Miksis-Olds, J.L., Parsons, M., Predragovic, M., Radford, A.N., Radford, C.A., Simpson, S.D., Juanes, F., 2021a. The soundscape of the Anthropocene ocean. Science 371.

Duarte, R., Spadoni, G., Soares, C., Jesus, S.M., 2021b. Anthropogenic Noise Prediction for Light Seismic Surveys off the SW Coast of Portugal, pp. 1–6. https://doi.org/10.23919/OCEANS44145.2021.9705823.

El-Dairi, R., Outinen, O., Kankaanpää, H., 2024. Anthropogenic underwater noise: a review on physiological and molecular responses of marine biota. Mar. Pollut. Bull. 199, 115978. https://doi.org/10.1016/j.marpolbul.2023.115978. URL: https://www.sciencedirect.com/science/article/pii/S0025326X23014133.

Erbe, C., Williams, R., Sandilands, D., Ashe, E., 2014. Identifying modeled ship noise hotspots for marine mammals of Canada's Pacific region. PLoS One 9, 1–10. https://doi.org/10.1371/journal.pone.0089820.

Evans, W.E., 1994. Common dolphin, whitse-bellied porpoise delphinus delphis linnaeus. Handbook of Marine Mammal 5, 191–224.

Fernandez, M., Alves, F., Ferreira, R., Fischer, J.C., Thake, P., Nunes, N., Caldeira, R., Dinis, A., 2021. Modeling fine-scale Cetaceans' distributions in oceanic islands: Madeira Archipelago as a case study. Front. Mar. Sci. 8, 1–22. https://doi.org/10.3389/fmars.2021.688248.

Finneran, J.J., 2016. Auditory Weighting Functions and TTS/PTS Exposure Functions for Marine Mammals Exposed to Underwater Sound. Space and Naval Warfare Systems Center Pacific, San Diego United States, pp. 1–79. URL: http://www.dtic.mil/dtic/tr/fulltext/u2/1026445.pdf.

Fouda, L., Wingfield, J.E., Fandel, A.D., Garrod, A., Hodge, K.B., Rice, A.N., Bailey, H., 2018. Dolphins simplify their vocal calls in response to increased ambient noise. Biol. Lett. 14, 20180484. https://doi.org/10.1098/rsbl.2018.0484. URL: https://royalsocietypublishing.org/doi/full/10.1098/rsbl.2018.0484 (Royal Society).

Frisk, G.V., 2012. Noiseonomics: the relationship between ambient noise levels in the sea and global economic trends. Sci. Rep. 2, 2–5. https://doi.org/10.1038/srep00437.

Griffiths, E.T., 2009. Whistle Repertoire Analysis of the Short-beaked Common Dolphin, Delphinus delphis, From the Celtic Deep and the Eastern Tropical Pacific Ocean. Bangor University.

Halliday, W.D., Scharffenberg, K., MacPhee, S., Hilliard, R.C., Mouy, X., Whalen, D., Loseto, L.L., Insley, S.J., 2019. Beluga vocalizations decrease in response to vessel traffic in the Mackenzie River Estuary. Arctic 72, 337–346. URL: https://www.jstor.org/stable/26867457 (Arctic Institute of North America).

Harris, P., Philip, R., Robinson, S., Wang, L., 2016. Monitoring anthropogenic ocean sound from shipping using an acoustic sensor network and a compressive sensing approach 16, 415–435. https://doi.org/10.3390/s16030415, doi:https://doi.org/10.3390/s16030415.

Hawkins, A., Popper, A., 2014. Assessing the impacts of underwater sounds on fishes and other forms of marine life. Acoust Today 10, 30–41.

Hermannsen, L., Beedholm, K., Tougaard, J., Madsen, P.T., 2014. High frequency components of ship noise in shallow water with a discussion of implications for harbor porpoises (Phocoena phocoena). J. Acoust. Soc. Am. 136, 1640–1653. https://doi.org/10.1121/1.4893908.

Hildebrand, J.A., 2009. Anthropogenic and natural sources of ambient noise in the ocean, 395, 5–20. https://doi.org/10.3354/meps08353.

Jefferson, T.A., Fertl, D., Bolaños-Jiménez, J., Zerbini, A.N., 2009. Distribution of common dolphins (Delphinus spp.) in the western Atlantic Ocean: a critical re-examination. Mar. Biol. 156, 1109–1124. https://doi.org/10.1007/s00227-009-1152-y.

Jensen, F.H., Bejder, L., Wahlberg, M., Soto, N.A., Johnson, M., Madsen, P.T., 2009. Vessel noise effects on delphinid communication. Mar. Ecol. Prog. Ser. 395, 161–175. https://doi.org/10.3354/meps08204. URL: https://www.int-res.com/abstracts/meps/v395/p161-175/.

Jesus, S.M., Soares, C., Onofre, J., Picco, P., 2002. Blind Ocean Acoustic Tomography: experimental results on the INTIFANTE'00 data set. In: Proc. of European Conference on Underwater Acoustics (ECUA'02), Gdansk, Poland, pp. 1–10.

Kuperman, W., Porter, M.B., Perkins, J.S., 1991. Rapid computation of acoustic field in three-dimensional ocean environments. J. Acoust. Soc. Am. 89, 125–133.

Macgillivray, A., de Jong, C., 2021. A reference spectrum model for estimating source levels of marine shipping based on automated identification system data. Journal of Marine Science and Engineering 9. https://doi.org/10.3390/jmse9040369.

Mackenzie, K., 1981. Nine-term equation for sound speed in the oceans. J. Acoust. Soc. Am. 70, 807–812.

Marçalo, A., Nicolau, L., Giménez, J., Ferreira, M., Santos, J., Araújo, H., Silva, A., Vingada, J., Pierce, G.J., 2018. Feeding ecology of the common dolphin (Delphinus delphis) in Western Iberian waters: has the decline in sardine (Sardina pilchardus) affected dolphin diet? Mar. Biol. 165, 44. https://doi.org/10.1007/s00227-018-3285-3.

Martin, M.J., Halliday, W.D., Storrie, L., Citta, J.J., Dawson, J., Hussey, N.E., Juanes, F., Loseto, L.L., MacPhee, S.A., Moore, L., Nicoll, A., O'Corry-Crowe, G., Insley, S.J., 2023. Exposure and behavioral responses of tagged beluga whales (Delphinapterus leucas) to ships in the Pacific Arctic. Marine Mammal Science 39, 387–421. https://doi.org/10.1111/mms.12978._eprint.

Martinho, F., Pereira, A., Brito, C., Gaspar, R., Carvalho, I., 2015. Structure and abundance of bottlenose dolphins (Tursiops truncatus) in coastal Setúbal Bay, Portugal. Mar. Biol. Res. 11, 144–156.

McKenna, M.F., Wiggins, S.M., Hildebrand, J.A., 2013. Relationship between container ship underwater noise levels and ship design, operational and oceanographic conditions 3, 1760. doi:https://doi.org/10.1038/srep01760. URL: http://www.nature.com/articles/srep01760.

Merchant, N.D., Brookes, K.L., Faulkner, R.C., Bicknell, A.W.J., Godley, B.J., Witt, M.J., 2016. Underwater noise levels in UK waters, 6, 36942. https://doi.org/10.1038/srep36942. URL. http://www.nature.com/articles/srep36942.

Moretti, P.F., Affatati, A., 2023. Understanding the impact of underwater noise to preserve marine ecosystems and manage anthropogenic activities. Sustainability 15, 10178.

Moura, A.E., Sillero, N., Rodrigues, A., 2012. Common dolphin (Delphinus delphis) habitat preferences using data from two platforms of opportunity. Acta Oecol. 38, 24–32. https://doi.org/10.1016/j.actao.2011.08.006. URL: https://www.sciencedirect.com/science/article/pii/S1146609X11001305.

Naimi, B., 2015. Usdm: Uncertainty Analysis for Species Distribution Models. R Package Version 1.

National Research Council, N.R.C, 2003. Ocean Noise and Marine Mammals.

Nowacek, D.P., Thorne, L.H., Johnston, D.W., Tyack, P.L., 2007. Responses of cetaceans to anthropogenic noise. Mammal Rev. 37, 81–115.

Philips, S.J., Dudik, M., Schapire, R.E., 2018. Maxent software for modeling species niches and distributions (version 3.4.1). URL: https://biodiversityinformatics.amnh.org/open_source/maxent/.

Pirotta, E., Merchant, N.D., Thompson, P.M., Barton, T.R., Lusseau, D., 2015. Quantifying the effect of boat disturbance on bottlenose dolphin foraging activity. Biol. Conserv. 181, 82–89. https://doi.org/10.1016/j.biocon.2014.11.003. URL: https://www.sciencedirect.com/science/article/pii/S0006320714004200.

Popper, A.N., Hawkins, A.D., Thomsen, F., 2020. Taking the animals' perspective regarding anthropogenic underwater sound. Trends Ecol. Evol. 35, 787–794. https://doi.org/10.1016/j.tree.2020.05.002. URL: https://www.cell.com/trends/ecology-evolution/abstract/S0169-5347(20)30132-4 (Elsevier).

Porter, M.B., Reiss, E.L., 1984. A numerical method for ocean acoustic normal modes. J. Acoust. Soc. Am. 76.

Putland, R.L., Constantine, R., Radford, C.A., 2017. Exploring spatial and temporal trends in the soundscape of an ecologically significant embayment. Sci. Rep. 7, 5713. https://doi.org/10.1038/s41598-017-06347-0.

Redfern, J.V., Hatch, L.T., Caldow, C., DeAngelis, M.L., Gedamke, J., Hastings, S., Henderson, L., McKenna, M.F., Moore, T.J., Porter, M.B., 2017. Assessing the risk of chronic shipping noise to baleen whales off Southern California, USA. Endanger. Species Res. 32, 153–167. https://doi.org/10.3354/esr00797.

Richardson . Jr, W.J., C.R.G., Malme, C.I., Thomson, D.H., 1995. Marine Mammals and Noise. Academic Press.

Roden, C.L., Mullin, K.D., 2000. Sightings of cetaceans in the northern caribbean sea and adjacent waters, winter 1995. Caribb. J. Sci. 36, 280–288.

Rolland, R.M., Parks, S.E., Hunt, K.E., Castellote, M., Corkeron, P.J., Nowacek, D.P., Wasser, S.K., Kraus, S.D., 2012. Evidence that ship noise increases stress in right whales. Proc. R. Soc. B Biol. Sci. 279, 2363–2368. https://doi.org/10.1098/rspb.2011.2429.

Santos, A.M.P., de Fátima Borges, M., Groom, S., 2001. Sardine and horse mackerel recruitment and upwelling off Portugal. ICES J. Mar. Sci. 58, 589–596.

Soares, C., Zabel, F., Jesus, S.M., 2015. A shipping noise prediction tool. In: MTS/IEEE OCEANS 2015 - Genova: Discovering Sustainable Ocean Energy for a New World, Genova, Italy, pp. 1–7. https://doi.org/10.1109/OCEANS-Genova.2015.7271539.

Soares, C., Duarte, R.J., Silva, M.A., Romagosa, M., Jesus, S.M., 2020. Shipping noise in the Azores: a threat to the Faial-Pico cetacean community? International Conference on Underwater Acoustics 40, 070012. https://doi.org/10.1121/2.0001313.

Weatherall, P., Marks, K., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J., Rovere, M., Chayes, D., Ferrini, V., Wigley, R., 2015. A new digital bathymetric model of the world's oceans. Earth and Space Science 2, 331–345.

Wisniewska, D.M., Johnson, M., Teilmann, J., Siebert, U., Galatius, A., Dietz, R., Madsen, P.T., 2018. High rates of vessel noise disrupt foraging in wild harbour porpoises (Phocoena phocoena). Proc. R. Soc. B Biol. Sci. 285, 20172314. https://doi.org/10.1098/rspb.2017.2314 (Royal Society).

Yen, P.P.W., Sydeman, W.J., Hyrenbach, K.D., 2004. Marine bird and cetacean associations with bathymetric habitats and shallow-water topographies: implications for trophic transfer and conservation. J. Mar. Syst. 50, 79–99. https://doi.org/10.1016/j.jmarsys.2003.09.015. URL: https://www.sciencedirect.com/science/article/pii/S0924796304001198.