A software tool for estimating shipping noise footprint with application to South Adriatic – Ionian Sea

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Summary
In the context of contributing to assess the anthropogenic continuous low-frequency sound in water, as required from the Marine Strategy Framework Directive, a software tool is developed for the estimation of the radiated noise of travelling ships, based on their specific parameters, mainly the propeller and the main engine system. Focusing on the octave bands centered at 63 Hz and 125 Hz, the KRAKEN coupled-mode model (Porter 2001, Jensen *et al.* 2011) is implemented for the calculation of sound propagation from point sources representing the travelling ships, which is considered appropriate for the low frequency part of the spectrum; see also Skarsoulis et al (2016). The developed model is used, in conjunction with geographical (bathymetry and coastline) information, oceanographic data (temperature, salinity, sound speed distribution), and geoacoustic parameters of the seafloor, to calculate the acoustic field in the geographical region of the Southern Adriatic – Ionian Sea, focusing on the area around the port of Otranto. The received acoustic fields from navigating ships are superimposed to define the shipping noise footprint in the studied area, at different seasons.

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1. Introduction

Sources of underwater sound in marine environment could be distinguished in two main categories, natural and anthropogenic. The first subset includes sources such as wind, rain, waves, lightning, subsea volcanic eruptions, earthquakes and vocalization of marine mammals and fishes, whereas the second mainly includes commercial shipping, offshore constructions, seismic surveys, fishery, research and military related activities. Recent studies provide evidence that the behaviour of marine mammals and marine fauna is affected by the low-frequency continuous ambient noise. The main anthropogenic source of the latter kind is the shipping traffic, which presents growing trends (Ross 1987 [1], Hildebrand 2009 [2]).

Commercial ships produce underwater noise with peak spectral power in the frequency band extending from 20Hz to 200Hz (McKenna *et al*, 2013 [3]), which is mainly generated from cavitation and singing of propellers, as well as other machinery (e.g. shafts, gears, engines). To assess the problem, methodologies and associated tools are necessary to quantify the noise level due to the growing shipping traffic.

Low-frequency continuous underwater noise has become a European concern, as reflected in the criterion D11C2 of the qualitative descriptor "Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment", the 11th descriptor used for determining the Good Environmental Status under the Marine Strategy Framework Directive (MSFD, 2008/56/EC). Recently, in the context of two EU-funded projects contributing to MSFD implementation, AQUO (www.aquo.eu) and SONIC (www.sonic-project.eu), software tools were developed to investigate and mitigate the effects of underwater noise generated by shipping traffic. In Skarsoulis *et al* [4], a prediction model for the shipping noise of the Eastern Mediterranean Sea is presented that combines real time ship data acquired by the Automatic Identification System (AIS, www.marinetraffic.com), ray theory codes, typical emission characteristics and environmental data. Also, in Soares *et al* [5], a shipping noise prediction tool is presented based on AIS data and KRAKEN acoustic propagation code [6,7], and is applied to Portuguese waters, off the Southwest Coast of Portugal, where heavy traffic shipping routes exist.

In the present work, a method for calculating the noise spectral level from shipping is implemented in a form of a Matlab® software tool. The latter is applied to the estimation of the radiated noise of travelling ships in the sub-region of the Mediterranean Sea, based on specific parameters of a ship, mainly the propeller and the main engine system. Focusing on the first octave bands centered at 63 Hz and 125 Hz, as suggested in the specifications and standardised methods for monitoring and assessment of the criterion D11C2 (2017/848/EU), the KRAKEN coupled-mode model [6,7] is used for the calculation of sound propagation from point sources representing the travelling ships, which is considered appropriate for the low frequency part of the spectrum; see also Skarsoulis *et al* [4]. The developed model is used, in conjunction with geographical (bathymetry and coastline) information, oceanographic data (temperature, salinity, sound speed distribution), and geoacoustic parameters of the seafloor, to calculate the acoustic field in the geographical region of the Southern Adriatic – Ionian Sea, focusing on the area around the port of Otranto. The received acoustic fields from navigating ships are superimposed to define the shipping noise footprint in the studied area, at different seasons. Preliminary results of the application of the software tool are presented for the noise prediction in the area of interest; see Fig.1.

2. Components of the software tool

In order to build the software tool for the estimation of the noise footprint, a number of components are required, including an underwater sound propagation model for the calculation of the transmission losses, in conjunction with geographical information (bathymetry and coastline), seasonal oceanographic data (temperature, salinity

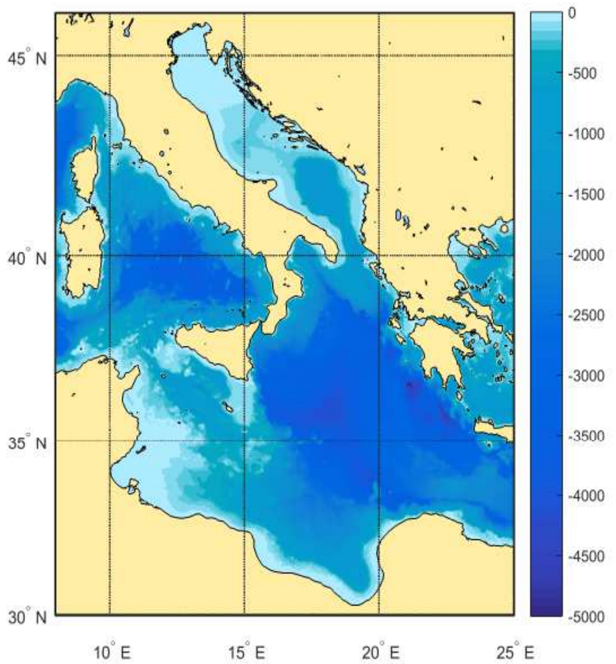

Figure 1. Geographical area of interest. The colormap indicates depth in meters

and sound speed distribution), and geoacoustic information of the seafloor.

For the calculation of the acoustic fields, a number options are available including ray theory, normal modes, parabolic equation models, wavenumber integration techniques, three dimensional models etc. Taking in account the extent of the calculations and the fact the final goal of the software tool is the ability to provide daily predictions in the low frequency band, where this work is focused on, the KRAKEN adiabatic/ coupled mode theory code has been selected as the propagation code in the present software.

Global bathymetric data are available from various sources (eg. ETOPO2, ETOPO1, GEBCO). The bathymetry of the South Adriatic – Ionian sea is acquired by the General Bathymetric Chart of Oceans [8]; GEBCO2014 Grid, version 20150318 (www.gebco.net). This is a 30 arc-second global greed of elevations generated by a combination of ship depth soundings with interpolation between sounding points guided by satellite-derived gravity data and other data sets. Moreover, for plotting the various geographical maps, the Shore line data for the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) is used [9].

For the calculation of the sound speed spatial distribution, data provided by World Ocean Atlas

2013 version 2 (WOA13 V2) are used, [10]. This database consists of a long-term set of climatologies (at annual, seasonal, and monthly periods) for temperature, salinity, oxygen, phosphate, silicate, and nitrate. Data are available with a vertical resolution consisted of 102 standard depth levels globally. Especially for temperature [11] and salinity [12], data are available with a spatial resolution of 1/4 of a degree.

In the context of the present software tool a database and tools were developed, for quick access and real time calculations of sound speed profiles and spatial distributions. As an example, in Fig. 2 the summer temperature distribution, at 100 depth, is presented, as obtained from the above database, and in Fig. 3 the corresponding plot of salinity. Using this data, the sound speed (SS) is estimated using the formula provided by Mackenzie (1981) [13], which is presented in Fig.4, for summer and at the depths of 0, 50 and 100 m.

3. Underwater sound modelling

In order to define the shipping noise footprint in the area of Southern Adriatic – Ionian Sea, a grid of geographical positions is considered with a resolution of 1/3 of a degree (905 points in the sea area), as shown in Fig. 5. For each grid position $\mathbf{x}_s = (x_s, y_s, z_s)$ a source is considered, and the acoustic pressure field $p(r, z \mid \mathbf{x}_{GP}; \omega, \theta)$ at all points $\mathbf{x} = (x, y, z)$ is calculated, at specific frequencies (centers of the first octave bands). The field, excited by each unit point harmonic source, is calculated as a solution of Helmholtz equation for stratified medium

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) + \rho(z)\frac{\partial}{\partial z}\left(\frac{1}{\rho(z)}\frac{\partial p}{\partial z}\right) + \frac{\omega^2}{c^2(z)}p = = -\frac{\delta(r)\delta(z - z_s)}{2\pi r} \quad . \qquad (1)$$

where $r^2 = (x - x_{GP})^2 + (y - y_{GP})^2$, and the azimuthal direction $\theta = \tan^{-1}\left((y - y_{GP})/(x - x_{GP})\right)$. The calculations are performed for a number of 24 azimuthal directions θ (covering 360 deg by 15deg spacing), for a given (central) frequency, $\omega = 2\pi f$, and extended to a total range of 500 km from the source.

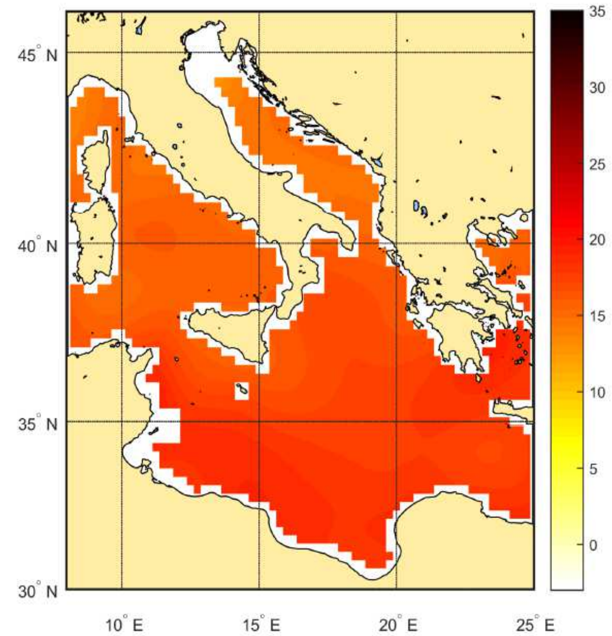

Figure 2. Summer temperature (in deg C) distribution at 100m depth.

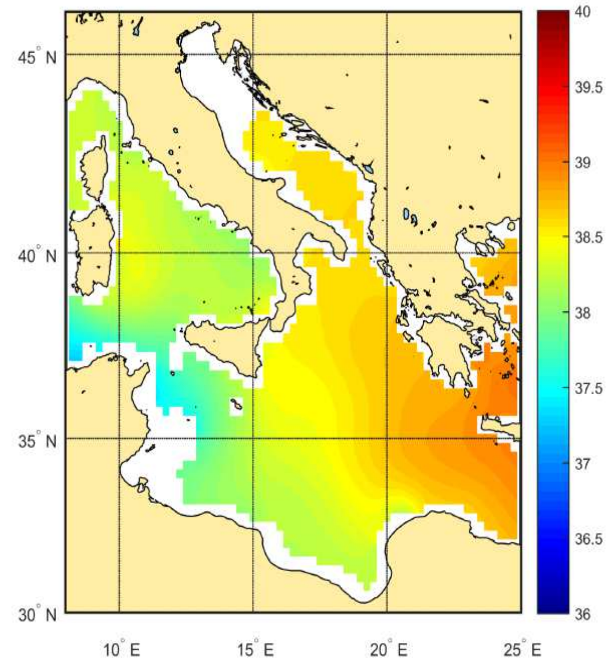

Figure 3. Summer salinity (in ppt) distribution at 100 m depth.

KRAKEN model is used for the numerical solution of the 2D equation (1) in cylindrical coordinates, for each azimuhal direction, with given bathymetry, sound speed distribution and density variation, and bottom geoacoustic characteristics from the data bases.

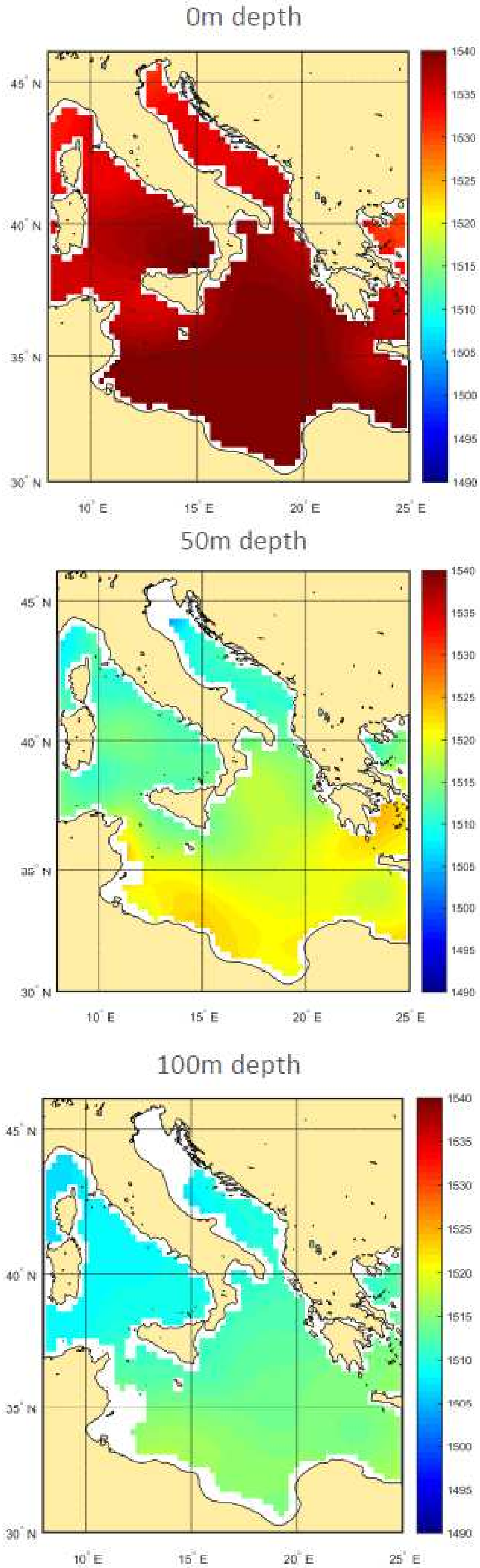

Figure 4. Sound speed distribution (in m/s) in the examined geographical area during summer at depths: (a) 0 m, (b) 50 m, (c) 100 m.

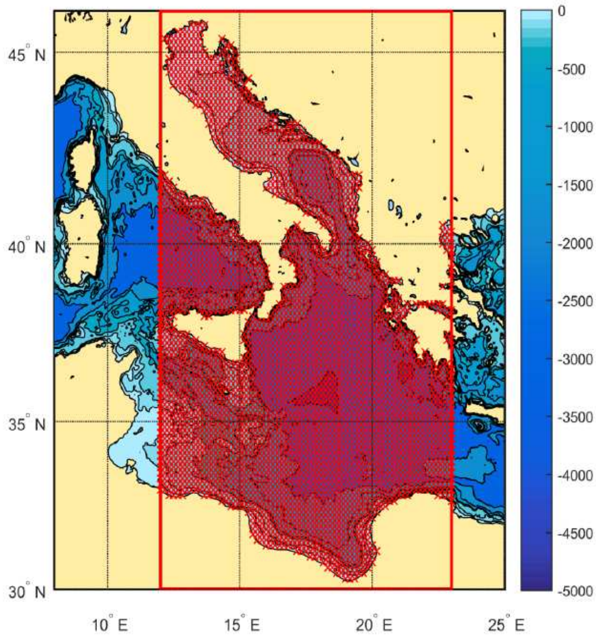

Figure 5. Geographical area of interest, bathymetry and global (1/3 deg) grid of the acoustic sources (indicated by using dots).

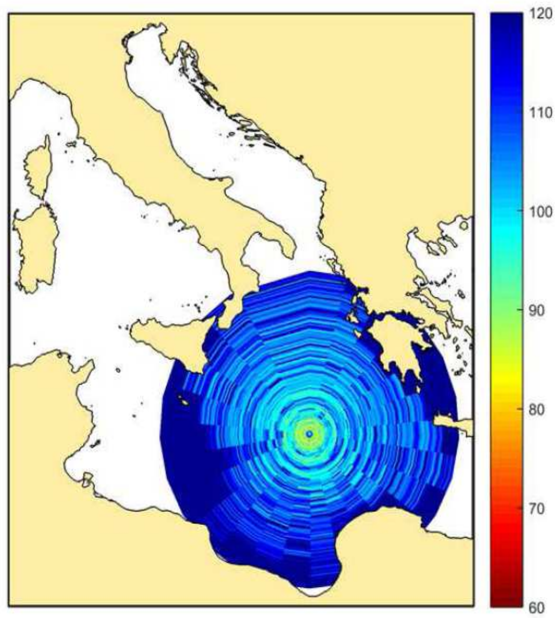

Figure 6. Transmission losses (in dB) of a unit source at the depth of 100 m.

Calculations are performed for source frequencies of 63Hz and 125Hz, and source depth of 10m (indicative depth of large ship propellers). Along each azimuthal direction θ, a vertical section of the bathymetry and the corresponding sound speed profiles are extracted with a discretization step of 10km. For modelling the medium, two bottom layers (sediments) are considered, an upper layer with sound speed of 1600 m/s, density of

1.6gr/cm^3 and attenuation of 0.8 dB/wavelength and a rocky one with a sound speed of 1800m/s, density of 2.0gr/cm^3 and attenuation of 0.6 dB/wavelength; see [6,7] for typical values. Attenuation of sound in water is evaluated by the following formula, Jensen *et al* (Eq. 1.47) [7],

$$\alpha \simeq 3.3\cdot 10^{-3} + \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f^2} + \\ + 3.0\cdot 10^{-4} f^2 (dB/km) \quad . \tag{2}$$

Results are spatially organized in various depths (10:10:40, 60:20:100, 200:100:500, 750, 1000m) in a database. The user of the software tool may extract the results spatially for a specific grid point position and depth. In Fig. 6, a typical distribution of the calculated transmission losses for the depth of 100m is presented. Results concerning each depth, azimuthal direction, and grid (source) point are stored in a database.

For a specific ship traffic scenario, the pressure field $\hat{p}_{k-ship}\left(r,z\,|\,\mathbf{x}_{k-ship};\omega,\theta\right)$ of a unit source positioned at an arbitrary ship location is calculated using the above database and an interpolation scheme. The latter scheme is implemented using a triangulation of the grid points; see Fig. 7. For each ship position $\mathbf{x}_{k-ship}$ the enclosing triangle, with corners the grid points GP_i, $i=1,2,3$, is found and the corresponding barycentric coordinates *u,v,w=1-u-v* are calculated,

$$u = \frac{area(S,GP_2,GP_3)}{area(GP_1,GP_2,GP_3)}, \quad v = \frac{area(S,GP_3,GP_1)}{area(GP_1,GP_2,GP_3)} . \tag{3}$$

In order to calculate the pressure at a target point (*r,z*), the corresponding contribution of the unit sources at the triangle corners GP_i are evaluated using the stored data. The final pressure field of a unit source at the location of a ship is evaluated as a weighted sum of the fields at the three corners:

$$\hat{p}_{k-ship}\left(r,z\,|\,\mathbf{x}_{k-ship};\omega,\theta\right) = u\cdot p\left(r,z\,|\,\mathbf{x}_{GP_1};\omega,\theta\right) + \\ + v\cdot p\left(r,z\,|\,\mathbf{x}_{GP_2};\omega,\theta\right) + \\ + w\cdot p\left(r,z\,|\,\mathbf{x}_{GP_3};\omega,\theta\right). \tag{4}$$

For each *k*-ship the Sound Pressure Level (SPL), in $dB\ re\ 1\mu Pa^2\ @1m$, is calculated by,

$$SPL_k = N_k + 10\log_{10}\delta f = 10\log_{10}\left(p^2 @1m / 1\mu Pa^2\right), \tag{5}$$

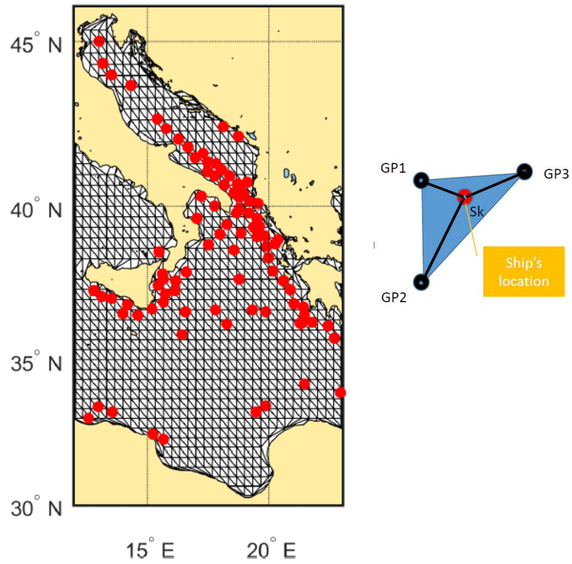

Figure 7. Triangulation of the geographical area (left) and interpolation scheme for an arbitrary position of a point source (right).

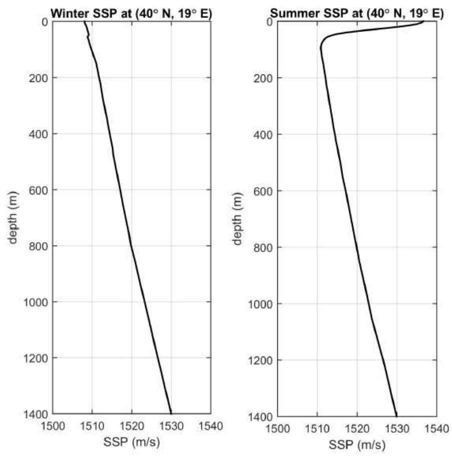

Figure 8. Typical sound speed profiles for the studied area during winter (left) and summer (right).

where δf is the octave bandwidth and N_k the corresponding spectral level. The intensity of each source at the ship's location is then obtained by

$$S_k = \sqrt{10^{\frac{N_k}{10}-12}\,\delta f}\ (Pa) \quad . \tag{6}$$

The total pressure field created by a specific ship traffic scenario is then calculating by the summation of the contribution of each source with the above intensity for each ship using the pressure fields of unit sources at the ship's location,

$$p(r,z,\theta\,|\,\omega) = \sqrt{\sum_k \left[\left(4\pi S_k\right)\hat{p}_{k-ship}\left(r,z\,|\,\mathbf{x}_{k-ship},\omega,\theta\right)\right]^2} \ . \tag{7}$$

Finally, the noise spectral level (NSL), measured in $dB\ re\ 1\mu Pa^2 / Hz\ \ @\ 1m$ is then calculated by

$$NSL = 10\log_{10}\left[p^2\left(r, z, \theta \,|\, \omega\right) / 1\mu Pa^2 / \delta f \right]. \qquad (8)$$

4. Numerical results

Preliminary results of the application of the software tool for the estimation of the shipping noise footprint in the area of the South Adriatic – Ionian Sea are presented in this section. A scenario of a total of 290 ships travelling in the examined area is considered, which are distributed using patterns derived from MarineTraffic Automatic Identification System - AIS data (www.marinetraffic.com). AIS is an automatic system for tracking the position of ships and it was developed by IMO with a main goal to be used as a tool to avoid collisions. Another very important use of AIS is to make available data for shipping traffic in near real time globally. This data includes vessel details (i.e. name, type, main particulars, etc.), location, speed and heading.

Using this data, the noise characteristics can be estimated. The values of spectral level, for the frequencies of the first two octaves, range from 130 to 159 $dB\ re\ 1\mu Pa^2 / Hz\ \ @1m$; see e.g. [12], varying significantly between different classes of ships. In the specific scenario, each ship corresponds to an acoustic source with a spectral acoustic level randomly distributed in the above range (all located at 10m depth).

In Fig. 8 typical sound speed profiles of the studied area are presented, as obtained from the database. For winter almost a linear profile is observed, while for summer a rapid decrease is observed up to a minimum around the depth of 100m followed by an almost linear increase in depth. In Fig. 9 the calculated spectral sound level is shown for the frequency of 62.5 Hz (the central frequency of the first octave) at the 40m depth for winter, and in Fig. 10 for summer, respectively.

During winter season the sound noise level is increased in comparison with summer, since corresponding sound speed profile guides the sound to greater depths resulting in lower noise levels at the sea surface layer where the acoustic sources are located.

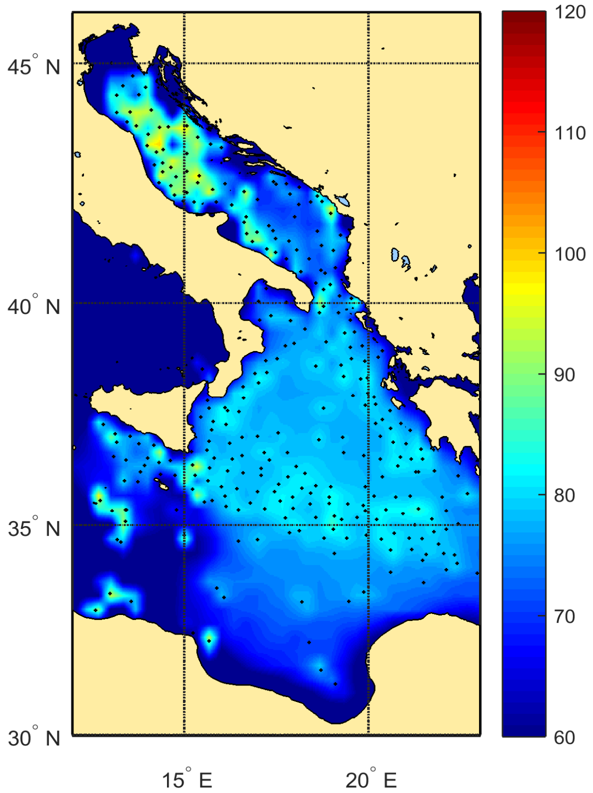

Figure 9. Estimated spectral noise level in dB re 1 μPa/Hz @ 1 m at a depth of 40 m – Winter.

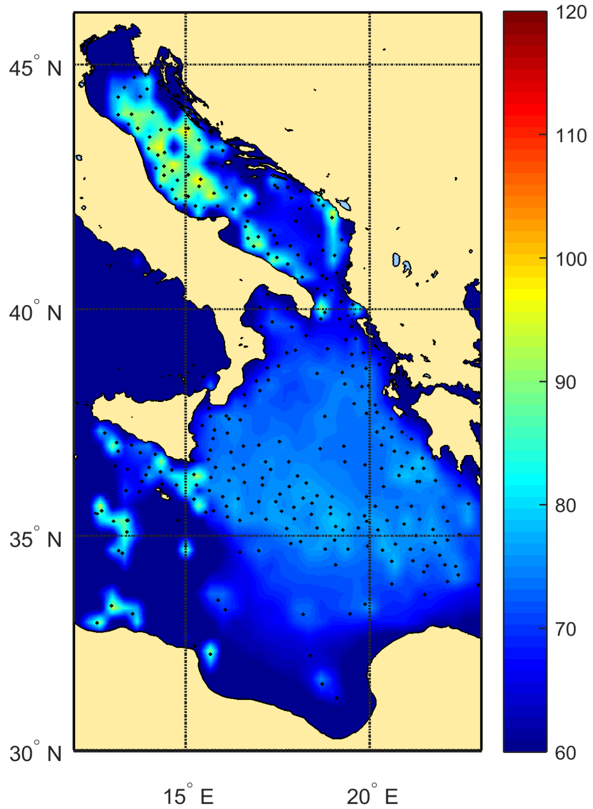

Figure 10. Estimated spectral noise level in dB re 1 μPa/Hz @ 1 m at a depth of 40 m – Summer.

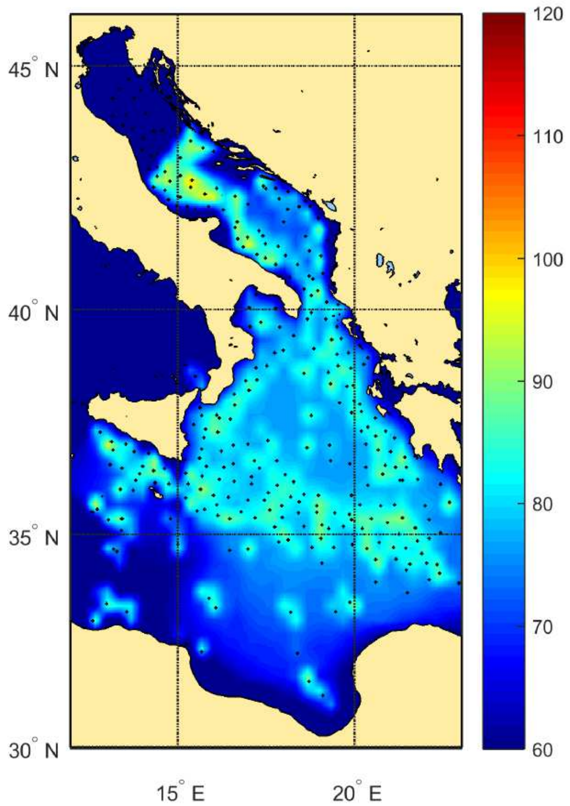

Figure 11. Estimated spectral noise level in dB re 1 μPa/Hz @ 1 m at a depth of 100 m – Winter.

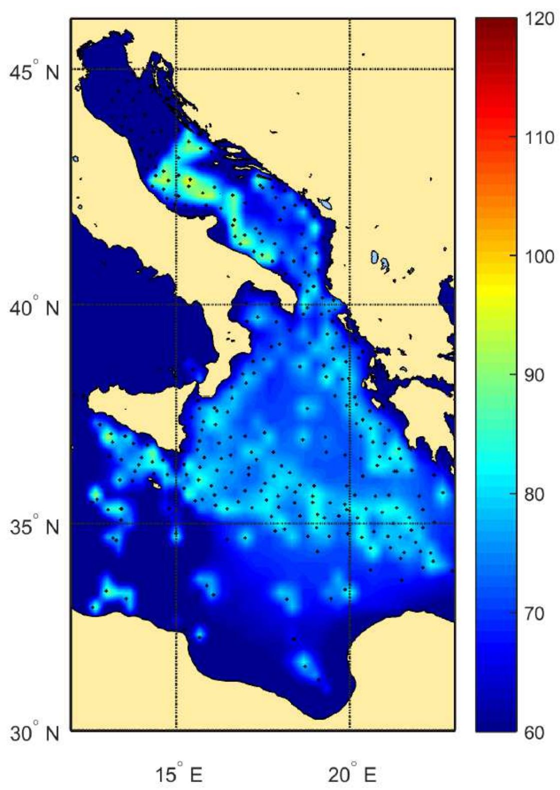

Figure 12. Estimated spectral noise level in dB re 1 μPa/Hz @ 1m at a depth of 100 m – Summer.

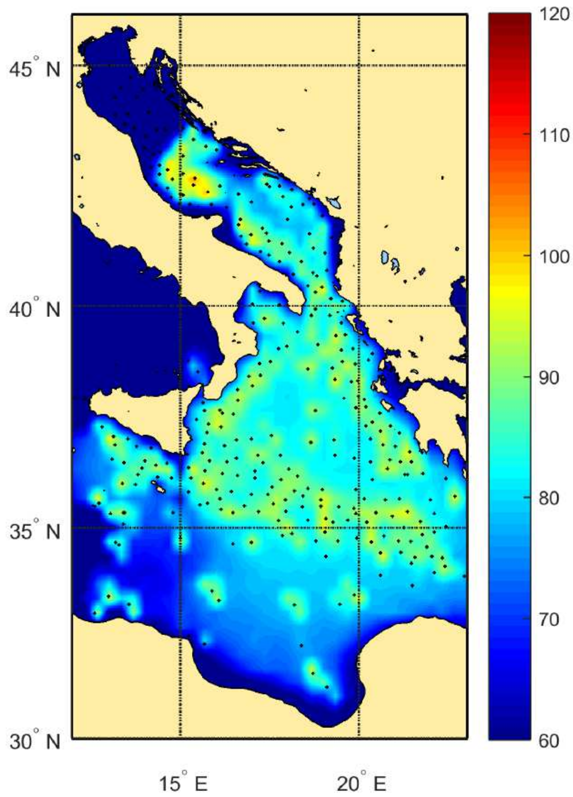

Figure 13. Estimated spectral noise level in dB re 1 μPa/Hz @ 1 m, for the frequency of 125 Hz (central frequency of the second octave) at a depth of 100 m – Winter.

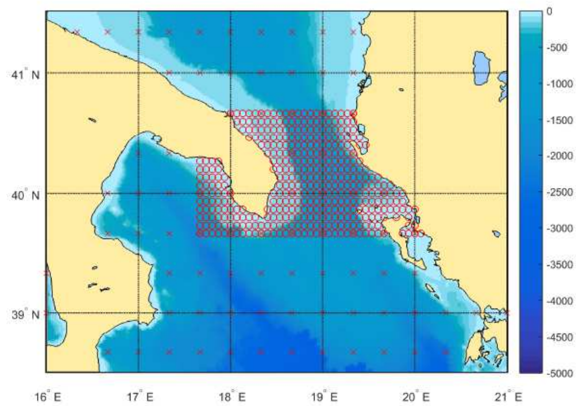

Figure 14. Local (refined 1/15 deg) grid around Otranto straights.

In Figs. 11 and 12 corresponding results for winter and summer are presented for a depth of 100 m, where the minimum of the summer sound speed profile is approximately located.

Finally, in Fig. 13 the corresponding results for winter and the depth of 100 m are presented for frequency 125 Hz (central frequency of the second octave band), showing an increased sound noise level in comparison with the corresponding results for the first octave presented in Fig. 11.

Future results will focus on the application of the developed software tool, in conjunction with realistic shipping traffic data from AIS, and its validation in comparison with measurements in an close to Otranto. For this purpose, a local refined grid around this region shown in Fig. 14 will be used, in conjunction with the global grid of Fig. 5.

5. Conclusions

A software tool is presented for the estimation of the radiated noise of travelling ships, based on specific parameters of the ship, mainly the propeller and the main engine system. Focusing on the octave bands centered at 62.5 Hz and 125 Hz, as indicated by the MSFD methodological standards and guidelines, the KRAKEN coupled-mode model is implemented for the calculation of sound propagation from point sources representing the travelling ships, which is considered appropriate for the low frequency part of the spectrum. The developed model is used, in conjunction with geographical (bathymetry and coastline) information, oceanographic data (temperature, salinity, sound speed distribution), and geoacoustic parameters of the seafloor, to calculate the acoustic field in the geographical region of the Southern Adriatic – Ionian Sea, focusing on the area around the port of Otranto. The received acoustic fields from navigating ships are superimposed to define the shipping noise footprint in the studied area, at different seasons. Comparison with measured data in the area of interest and validation will be the subject of a future work.

Acknowledgement

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