quiet seas

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

D4.2. Recommendations on the applicability of acoustic propagation modelling approaches for continuous sound assessment in the Mediterranean Sea and Black Sea regions

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3	Service hydrographique et océanographique de la marine	Shom	France
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5	Hellenic Centre for Marine Research	HCMR	Greece
6	Inštitut za vode Republike Slovenije/Institute for water of the Republic of Slovenia	IZVRS	Slovenia
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Abstract

This document is the Deliverable "D4.2. Recommendations on the applicability of acoustic propagation modelling approaches for continuous sound assessment in the Mediterranean Sea and Black Sea regions (17th May 2022)" of the QUIETSEAS project funded by the DG Environment of the European Commission within the call "DG ENV/MSFD 2020 call". This call funds projects to support the implementation of the second cycle of the Marine Strategy Framework Directive (2008/56/EC) (hereinafter referred to as MSFD), in particular to implement the new GES Decision (Commission Decision (EU) 2017/848 of 17 May 2017) laying down criteria and methodological standards on Good Environmental Status (GES) of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU) and Programmes of Measures according Article 13 of the MSFD. QUIETSEAS aims to support the practical development of the second implementation cycle under the MSFD for D11 (underwater noise).

The objective of this document is to provide recommendations on the applicability of acoustic propagation modelling approaches for continuous sound assessment in the Mediterranean Sea and Black Sea regions. The Mediterranean and Black Seas are challenging environments as regards the application of the appropriate acoustic models, due to their topography, bathymetry, and their physical characteristics. These regions are separated into appropriate marine assessment areas to help the user with a potential decision-making system. The most suitable acoustic propagation models for each of these areas is studied, taking into account their specificities, to assess low-frequency continuous sound from ship traffic. This report aims to serve as a milestone for the development of the project, by providing a useful management tool for continuous sound assessment.

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List of Abbreviations

CTN	Centro Tecnológico Naval y del Mar
ACCOBAMS	Permanent Secretariat of the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area
POLIMI-DICA	Politecnico di Milano-Department of Civil and Environmental Engineering
Shom	Service hydrographique et océanographique de la marine
HCMR	Hellenic Centre for Marine Research
IZVRS	Inštitut za vode Republike Slovenije/Institute for water of the Republic of Slovenia
MHD	Maritime Hydrographic Directorate, Romania
FORTH/IACM	Foundation for Research and Technology-Hellas, Institute of Applied and Computational Mathematics
MSFD	Marine Strategy Framework Directive
GES	Good Environmental Status
MS	Member States
MED	Mediterranean Sea
BS	Black Sea
CA	Competent Authority
NR	National Representative
SO	Specific Objective
TB	Thematic Block
IMMA	Important Marine Mammal Area
MPA	Marine Protected Area
CCH	Cetacean Critical Habitat
EBSA	Ecologically and Biologically Significant Area
SPAMI	Specially Protected Areas of Mediterranean Importance
IUCN	International Union for Conservation of Nature
MMPATF	Marine Mammal Protected Areas Task Force
AIS	Automatic Identification System
VMS	Vessel Monitoring System
MRU	Marine Reporting Unit
SSP	Sound Speed Profile
URN	Underwater Radiated Noise
TL	Transmission Loss
SPL	Sound Pressure Level
KA	KRAKENC adiabatic underwater acoustic propagation code
KC	KRAKENC coupled underwater acoustic propagation code
RG	RAMGeo underwater acoustic propagation code
BH	BELLHOP underwater acoustic propagation code

1. Introduction

The QUIETSEAS Project is funded by DG Environment of the European Commission within the call "DG ENV/MSFD 2020". This call funds MSFD development, in particular, the preparation of the next 6-year cycle of implementation. The QUIETSEAS project aims to enhance cooperation among Member States (MS) in the Mediterranean Sea Region (MED) to implement the third Cycle of the Marine Directive and in particular to support Competent Authorities and strengthen cooperation and collaboration in the Mediterranean Sea and Black Sea regions.

This deliverable is the result of work done on Activity 4. Specificities for the practical implementation of the Assessment Framework for Continuous Noise (D11C2) at (sub)regional level (Mediterranean Sea and Black Sea Regions) and support the achievement of the following specific objectives of the project:

- Specific objective 1 (SO1): To identify relevant indicators for criterion D11C2 (Anthropogenic continuous low-frequency sound in water).
- Specific objective 2 (SO2): To promote the consolidation of relevant indicators for D11 and support the operationalisation of indicators on the state, pressure and impacts of underwater noise in close coordination with TG Noise.
- Specific objective 3 (SO3): To promote harmonisation of regional work on threshold values with TG Noise recommendations.

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

2. Considerations on acoustic propagation modelling in a risk-based assessment framework for continuous noise

2.1. The role of modelling in a TG Noise-compatible risk-based assessment framework for continuous noise

According to the TG Noise recommendations for an assessment framework for EU threshold values for continuous underwater sound (TG Noise, 2021), acoustic monitoring is defined as either modelling or measurement of underwater sound, or a combination of both. In the relevant Annex 5, some considerations (examples) for choosing modelling as the primary employed methodology are: areas where spatial coverage is needed (soundscape maps); high shipping density, where no measurements of reference condition are possible; models can be used when the modelling results are representative for the area; when other information sources for non-AIS vessels are available, e.g., from harbour logs or earth observation (satellites).

An advantage of modelling is that it can provide high resolution results for large marine areas. However, it is actually a complex procedure requiring expert knowledge for the integrated model setup, requires computing power and availability of reliable environmental and shipping data, and it should be validated with measurements to provide results of a quantitative and not qualitative nature. More specifically, as mentioned in Step 4 of the description of the individual parts of the methodology in TG Noise (2021), the assessment of the acoustic state with regard to underwater noise requires information related to the properties of the ship traffic as well as to the acoustic environment of the sea. Information on ship tracks and speed is obtained from the Automatic Identification System (AIS) and information on fishing vessels is obtained from the Vessel Monitoring System (VMS). Environmental data are divided into two categories: dynamic data, such as wind and wave as well as temperature and salinity distribution; and static data such as the nature of the seabed. Knowledge of seabed properties at regional scales is fragmentary, but it can be found from national and international public services (For environmental data sources, see Section 3.2). Also, if modelling is employed, models should reflect the capacity to adequately simulate the shipping activity or other relevant continuous sound sources, and the natural soundscape. As the quantities are dynamic and partially uncertain, validation of the model result is required through direct measurements to ensure its credibility in supporting decision making to identify threshold values.

2.2. Grid Cell considerations

The Grid Cell is the basic building block of a TG Noise-compatible risk-based assessment methodology. As mentioned in the definition of the Grid Cell in TG Noise (2021), the grid cell needs to be considered as an area unit (2D) that includes bathymetry and oceanographic conditions. The cumulative effect of underwater sounds from several different ships in the specified time frame is used to assess the status of a Cell. Its acoustic status is used to evaluate the environmental status of the habitat under study by aggregating the status of multiple Grid Cells.

This Grid Cell is not necessarily identical with the numerical grid cell used for modelling purposes. However, the aforementioned definition notes that, for modelling, the Grid Cell can be used to calculate sound propagation (3D) as well as the time frame which is considered in assessing its status (4D). In TG Noise (2021), Annex 4, it is clarified that the resolution of the grid must be sufficient to cover the spatial variability of the sound field, but also computationally efficient. A fine grid needs to be used for soundscape maps as a result of modelling and a coarser grid as a means to display the (intermediate) results for comparison with other information (e.g., the distribution of indicator species). Also, various input data are supplied on a grid (e.g., bathymetry), which may be different from the assessment area. There should be sufficient numbers of Grid Cells within an assessment area such that any summary statistics reported (e.g., proportion of area assessed to be in GES) are not substantially affected by the choice of Grid Cell size. As regards the depth for which the noise will be assessed, it is dependent on the sound properties over depth. In case of a layered water column (in temperature and/or salinity), multiple depths may be chosen. The depth can be chosen relative to the sea bottom, or the surface or the sound can be averaged over one or more depth intervals.

2.3. Aspects of acoustic propagation modelling in the modelling procedure

Modelling of continuous sound in a marine area is based on three types of models:

- Models for sound propagation
- Models for the source properties
- Models for the oceanographic conditions (wind, waves, etc.) for the Reference Condition; see basic entities of the framework and definitions in TG Noise (2021).

The role of an acoustic numerical model in the process of modelling continuous sound from ships can be shown illustratively in Fig. 1, while more information on the shipping-noise modelling procedure can be found in the next section. Sound propagation models are used to produce a soundscape map based on a numerical grid size that usually is smaller than the Grid Cell (see Section 2.2 above). The soundscape maps are used to assess both the temporal and spatial distribution of noise.

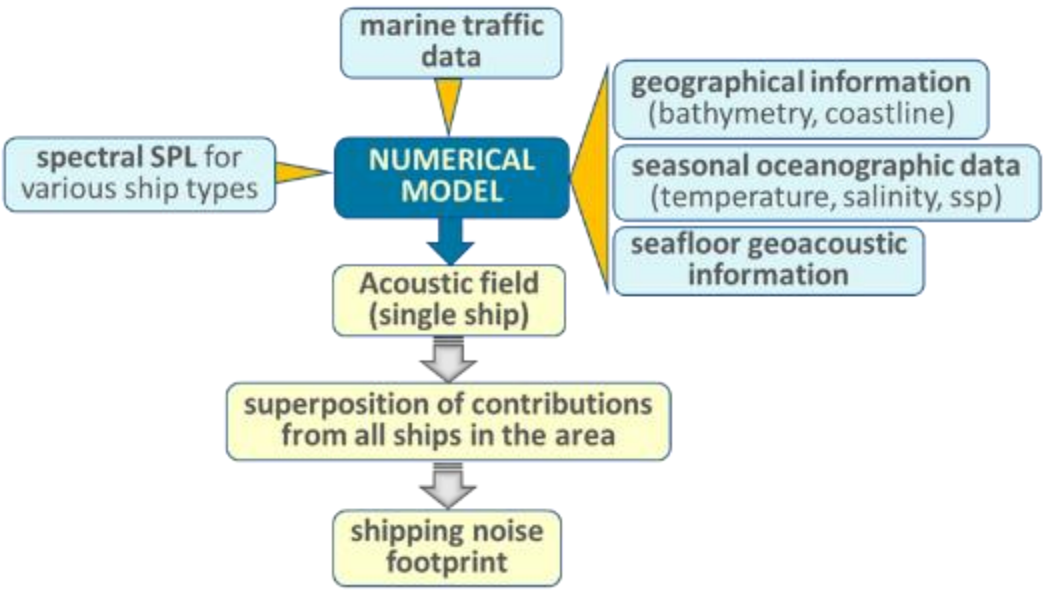

Figure 1. The process of numerical modelling for estimating the shipping noise footprint of a marine area (slightly modified from Prospathopoulos et al., 2019).

Several numerical models have been developed for sound propagation and the choice is dependent on the conditions of the assessment areas, such as bathymetry, sea bottom composition, and ice coverage. The input parameters for these models are primarily information on the sources and the source distribution, supplied by AIS. Furthermore, static and dynamic environmental conditions need to be known, for example bathymetry, sea bottom composition, stratification, weather and sea state. Apart from the distribution of sources, the source strength must also be estimated.

Spatial and temporal assessment of a marine area by soundscape maps at the low frequencies which are mainly of interest for shipping noise (1/3 octave bands with central frequencies at 63 and 125 Hz) may be quite time consuming for several cases and ocean environments. This is because the calculations which have to be performed by an appropriate numerical acoustic propagation model for a large number of ships appearing in a marine area may require considerable computational time even for a temporal snapshot. To overcome this problem, assumptions and approximations are applied both for specific cases of marine environments (e.g., shallow waters) and acoustic modelling approaches (e.g., avoiding fully 3D modelling and decoupling the solution of the acoustic field as regards the spatial coordinates). Nevertheless, sound propagation modelling can still be challenging in some cases; see Section 4.2.

Finally, acoustic modelling needs to be validated with field measurements. For sound propagation, the validation must be done for the oceanic conditions of the marine area under consideration and for the acoustic parameters that are used in the assessment (time series need not to be reconstructed). Measurements can be used both to refine input parameters for models and to validate model results.

3. Shipping-noise modelling procedure and acoustic propagation models

3.1. Importance of the acoustic propagation models in the shipping-noise modelling procedure

Selection of the appropriate propagation model is of significant importance for the estimation of the ship traffic noise field in the marine environment. The basic elements of shipping noise modelling are summarized in Figure 1, Section 2.3.

The scenario upon which the modeling is based, involves:

- The identification of the ships (type, speed, course) sailing in the environment under consideration, which is normally taken from an on-line real time system providing data of ships sailing in the seas and give tracking details (course, speed exact location, draught, etc.) based on the Automatic Integration System (AIS) which is available for commercial use.
- The association of a sound pressure level (SPL) spectrum for each ship, based on data from related databases,
- The application of a sound propagation model to assess the received level (RL) at a specific location in the area, and finally,
- The superposition of contributions from all ships in the area to obtain the traffic noise level at specific frequencies.

To get a clearer view of the importance of propagation modeling in noise prediction, the geometry of the noise estimation scenario (configuration of ships and environment modelling) will be briefly explained.

At some moment, the configuration of ships sailing under specific conditions could be represented by Figure 2.

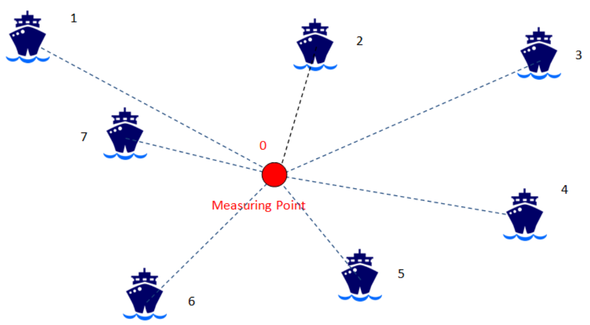

Figure 2. The configuration of ships around a "measuring" point

We assume that the point for which the estimation of the traffic noise is 0 (measuring point). The measuring point along with each ship considered in the area defines propagation slices (0-1, 0-2, etc.), each one of which is defined vertical to the ocean surface as in Figure 3. The definition of the vertical slice is dictated by the treatment of the propagation modeling in the environment as Nx2D due to the complexity of treatment of the acoustic propagation in 3D. The Nx2D approach is considered satisfactory, taking into account the assumptions involved in the ship noise modeling procedure. Then, the noise estimation procedure from each ship involves calculation of the acoustic field at the measuring point (receiver).

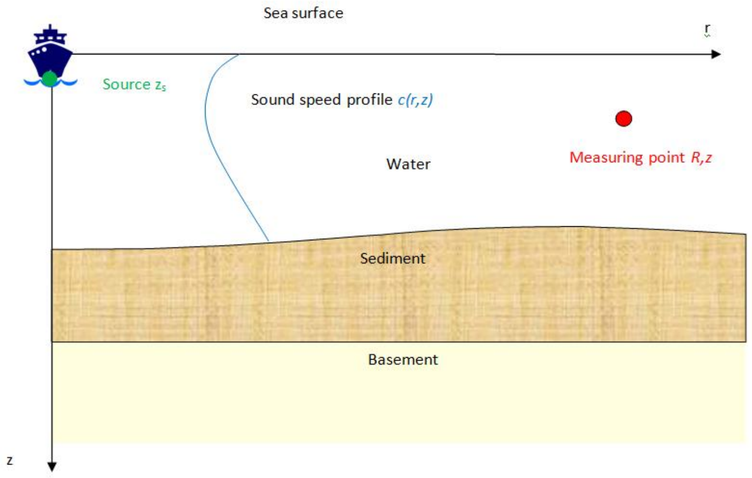

Figure 3. The vertical slice considered for the estimation of the ship noise contribution to the measuring point.

Each ship emits noise which can be attributed to the propeller cavitation, to the machinery or to the hydrodynamic flow. We know that the major source of noise is cavitation and that each ship has its own "acoustic signature" that has some invariant parts but in general changes according to the load of the ship, the speed, and other parameters. For modeling purposes, average signatures, taken from data bases according to the type of ship, are used for traffic noise modeling, neglecting in most cases the other operational parameters as, at least to our knowledge, there are no databases presenting systematic measurements of commercial ships signatures according to their essential operational parameters.

The acoustic signature from each ship is defined through a function $S(\omega)$ which expresses the acoustic pressure (ideally as a continuous function of frequency) that could be measured at 1m from the source which is considered as point source. The frequency here is expressed by means of the angular frequency ($\omega = 2\pi f$).

The sound propagates in the environment and the role of a propagation model is to define the mean squared acoustic pressure $P(\omega)$ at the measuring point. Standard propagation models provide the response of the acoustic channel to a point harmonic source of unit strength denoted, as $H(\omega)$. Therefore, taking into account filter theory and since the function $H(\omega)$ is system transfer function of the acoustic waveguide taken as the filter to the source excitation function $S(\omega)$, the actual pressure level is given by formula (1)

$$P(\omega) = H(\omega)S(\omega) \qquad (1)$$

To obtain the receiver level in dB re p_{ref}, where reference pressure in water is taken 1 μPa, the following expression holds:

$$RL = 10\log\frac{|P(\omega)|^2}{|P_{ref}|^2} = 20\log\frac{|H(\omega)S(\omega)|}{|P_{ref}|} = 20\log\frac{|H(\omega)|}{|P_{ref}|} + 20\log\frac{|S(\omega)|}{|P_{ref}|} \quad (2)$$

To get a comparable output from propagation models, the benchmark cases use the Transmission Loss quantity (*TL*) which expresses in dB the ratio between the predicted acoustic pressure with respect to the pressure that ideally would be measured at a distance of 1 m from the point source of unit strength $P_o(\omega)$. If the source excitation function is considered, $P_o(\omega) = S(\omega)$ and the following expression holds:

$$TL(\omega) = -20\log\frac{|P(\omega)|}{|S(\omega)|} = -\left(20\log\frac{|P(\omega)|}{|p_{ref}|} - 20\log\frac{|S(\omega)|}{|p_{ref}|}\right) = SL(\omega) - RL(\omega) \quad (3)$$

The Source Level (in dB re p_{ref}) is normally the quantity taken from the data bases and express the acoustic energy introduced to the system by the ship and $TL(\omega)$ is the output of the propagation model. Therefore, our subsequent analysis will be based on the comparison of the $TL(\omega)$ values obtained by the various models for the frequencies of interest.

The calculation of the system transfer function $H(\omega)$ or equivalently of the Transmission Loss $TL(\omega)$ is done by solving the acoustic propagation problem in the marine environment, which is defined by means of the linearized acoustic wave equation and, assuming harmonic waves, the Helmholtz equation.

Many numerical models (as the ones considered in this study) use a cylindrical coordinate system and solve the acoustic equation in an axially symmetric environment of the type presented in Figure 3. Also, they consider a point harmonic source located at some depth z_s at the beginning of the range axis. Using the appropriate form of the Laplacian operator for the cylindrical coordinate system

$$\nabla^2 = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \frac{\partial^2}{\partial^2 z}$$

and assuming axial symmetry, the linearized Helmholtz equation in a medium characterized by constant density is expressed as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p(r,z)}{\partial r}\right) + \frac{\partial^2 p(r,z)}{\partial^2 z} + k^2(r,z)\,p(r,z) = -\frac{\delta(r)\delta(z-z_s)}{2\pi r} \quad (4)$$

where $\mathbf{r} = (r,z)$ is the field location vector. The Helmholtz equation is supplemented by the appropriate boundary conditions at the water surface, the medium layers (including those of the bottom) and the behavior of the acoustic field at infinity to define a well-posed problem amenable to a unique solution.

Due to the complexity of the problem in general geometry and stratifications, several approaches have been applied to its treatment. Detailed analysis of the various approaches is found in Jensen et al. (2011).

3.2. Environmental input data

The transfer function calculated by the various models requires a geometric description of the environment (bathymetry, bottom structure) and a set of physico-chemical and geoacoustic parameters respectively characterizing the water column and the sea bottom. Among them, the bathymetry and the bottom structure can be considered as invariant, which means that data can be obtained from data bases describing the environment under consideration, while sound speed profile in the water column is changing following changes of the sea-water temperature and are season-dependent. It is known that the water temperature in the deep parts of the water column does not change much, but temperature at the shallower parts is seasonally dependent at a large scale, or even time dependent within a day at a very fine scale.

Publicly available data allow implementation of the assessment via modeling at least at a basic level. Bathymetry can be obtained from EMODnet[1]. Historical data of temperature and salinity data in the Mediterranean (and in other areas as well) can be found in Sea Data Net[2] and Copernicus base[3] and in various publications, while Argo profiles could be downloaded from the Coriolis data portal[4]. Real time data of sea-surface temperature and salinity can be found in dynamic databases monitoring the quality of the marine environment at specific areas but for the time being they cannot be considered as appropriate for estimating the sound speed profile in real time. Therefore, and for practical reasons, traffic noise prediction models should be based on pre-loaded data on the sound speed profile for the areas under consideration.

3.3. Acoustic propagation models

3.3.1. Codes and approaches considered

Our study will be concentrated on models that are supported by open codes that can be used without restrictions for the calculation of the acoustic field using in principle the problem defined by equation (4) and the appropriate boundary conditions.

An excellent source of these codes is the OALIB[5] (Ocean Acoustics Library). Interested researchers can find executable versions of several codes that have been developed for solving forward and inverse acoustic propagation problems in the marine environment. We have chosen to work with three basic models, KRAKENC, BELLHOP and RAMGeo, each one representing a different approach for solving the acoustic propagation problem in the marine environment.

KRAKENC and BELLHOP have been both developed by Michael Porter. KRAKENC is based on normal mode expansion of the acoustic pressure (Porter 1991, 2001), while BELLHOP is based on ray-theory (Porter 2011). RAMGeo was initially developed by Mike Collins and it is based on the Parabolic Approximation of the basic Helmholtz equation (Collins 1993b, 1993c).

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[1] https://www.emodnet-bathymetry.eu/
[2] https://www.seadatanet.org/
[3] https://www.copernicus.eu/en
[4] www.coriolis.eu.org/Data-Products/Data-Delivery
[5] https://oalib-acoustics.org

The models solve the acoustic equation for the acoustic pressure providing the pressure field over range and depth for a given frequency. The theory of acoustic propagation upon which the above three models are based can be found in the extensive relevant literature.

3.3.2. General comments on the applicability of the models used

Following a systematic analysis on the applicability of the abovementioned models in general environments, we can summarize their effectiveness in the following Table 1. Instead of mentioning specific codes, the underlying theory is presented in the Table for consistency with other publications (see e.g., Wang et al. 2014, Borsani et al. 2015). Red denotes "Not appropriate", yellow means "Limited applicability" and green indicates "Suitable Model".

Table 1. Applicability of the acoustic propagation models in the marine environment

Low Frequency		High Frequency	
Shallow Water	**Deep Water**	**Shallow Water**	**Deep Water**
Normal Mode	Normal Mode	Normal Mode	Normal Mode
Parabolic Approximation	Parabolic Approximation	Parabolic Approximation	Parabolic Approximation
Ray Theory	Ray Theory	Ray Theory	Ray Theory

Note that this table presents a general assessment based on specific benchmark exercises. In the current report, the applicability of the models will be based on the areas under consideration in the Mediterranean and Black Seas. As the focus is on noise due to low-frequency marine traffic, no systematic assessment of the performance of the models at high frequencies will be made.

Instead, the specific geometry of the water-sea bed interface will be shown to be an additional factor determining the applicability of the models.

3.3.3. Basic information on the use of the selected numerical codes

In this section additional information is provided on the specific codes chosen for evaluation. The Transmission Loss (TL) plots were plotted using the plotshd and plottlr functions found in the Acoustics Toolbox. The conversion of the pressure field to transmission loss is coded in those functions. For RAMGeo the appropriate AcTUP routines were used directly giving the TL for a specified depth and range. Specific choices and input data for the execution of the codes can be found in section 5.2.2.

KRAKENC

KRAKENC uses the expansion of the pressure field in terms of modes. The calculation of the modes in the waveguide is performed numerically. The half-space above the sea-surface is treated as vacuum, while the bottom half-space is considered elastic and the roughness of both boundaries is zero. The sound speed profile (SSP) is given in the form of depth and sound speed pairs, and the variation in depth of the SSP is considered linear. Additional sediment layers can also be included in the modeling of the environment.

The information about the environment and the necessary parameters to be used for the calculation, must be specified by the user in an input file (*.env). The SSP is specified in this file and the number of mesh points used for the water column for the numerical treatment of the problem is calculated automatically by KRAKENC.

KRAKENC also allows the user to specify the minimum and maximum phase speed to be included in the calculations, which directly relates to the range of modes (or the propagation angles) to be included in the pressure series expansion.

Range-dependent boundaries can be handled by discretizing the problem into $Nprof$ segments of small length, and then "matching" the segments together using continuity of pressure and normal velocity at the hypothetical vertical interfaces. Discretization is not a built-in functionality of KRAKENC, therefore the users will have to write their own script that compiles a large number of discrete environmental profiles into one input file or use the 'kraken_rd' function found in Matlab, written for the Acoustics Toolbox. The 'range_rd' script linearly interpolates bathymetry and SSP to create the segments.

KRAKENC stores the modes in a dedicated binary file (*.mod) as output. After the calculation of modes is successful, a second computation routine must be executed. FIELD uses the binary file containing the modes and a second input file (*.flp) that specifies the calculation of the pressure field. The field can be calculated using the Coupled Mode Theory or the Adiabatic Approximation.

All the remaining parameters are case-specific and directly relate to the dimensions of the waveguide. The number of segments used to linearize the range dependency must be specified again in the (*.flp) file.

Finally, FIELD produces as output a binary file containing the pressure field (*.shd).

RAMGeo

RAMGeo is the second generation of a computational model developed by Michael Collins using the parabolic equation. It takes one file as input (*.in) containing all the information about the waveguide dimensions and the parameters used in the calculation of the pressure field. The sound speed profile and geometry were input in more or less the same way as before. The user specifies the bathymetry of the environment providing range-depth pairs in meters, the SSP that applies, and the bottom properties. A feature of RAMGeo is that it can handle range dependence in all these features by specifying at which range span these properties apply.

A very important variable, both in terms of accuracy and computational time, is the range step used, dr. The computational (execution) time for RAMGeo depends on dr (the larger dr gives less execution time), so a good compromise should be searched for by modelers using RAMGeo for shipping noise modeling.

RAMGeo requires two different parameters to define the maximum computational depth. *zmplt* defines the maximum plotting boundary and *zmax* provides the maximum depth used in the computations. *zmax* is associated with the placement of an artificial absorbing bottom at that depth, to eliminate artificial boundary reflections, for the reliable inclusion of the bottom influence on the propagation field. Further analysis of the underlying theory falls beyond the scope of this report and can be found in (Collins, 1993a).

The original outputs of the RAMGeo model are a couple of files containing the transmission loss: **tl.line** in every range defined in the input file, and **tl.grid** as a decimated range-depth grid.

AcTUP contains routines that translate tl.grid to an (*.shd) file in order to be compatible with the Acoustics Toolbox pressure file format and we have exclusively used this. In principle, someone could alter the Fortran code to compute and output only the files needed to decrease execution time. Furthermore, one could also explore an implementation of RAM code in Python, PyRam, which supports multi-threading and can be found in OALIB.

BELLHOP

BELLHOP is a ray tracing program that can produce a variety of useful outputs including the pressure field as a (*.shd) file using Gaussian Beam Tracing. Being an integral part of the Acoustics Toolbox, BELLHOP shares similarities in inputs and outputs formats with KRAKEN.

BELLHOP requires only one basic input file (*.env) that describes the environment. Its structure is similar to the KRAKEN input file. We used the same parameters with KRAKEN where possible, such as SSP interpolation, automatic calculation of Nmesh points, boundary roughness, etc. The same (*.bty) file was used for bathymetry input.

As before, there are some parameters that are case independent and some that are related to the dimensions of the waveguide, which must be specified on each run.

The number of beams used for ray tracing is set to "0" which BELLHOP translates to automatically calculate the best number for the given problem; the same is true for the ray step. To model the point source as omnidirectional, the rays must be launched in an angular spread of $-90°$ to $+90°$. The box inside which the beam calculation takes place should be slightly bigger $(\sim 1\%)$ than the waveguide boundaries.

The relationship between the number of receivers and computational time is linear.

4. Marine areas in Mediterranean and Black Seas according to their physical characteristics. Classification and acoustic propagation modelling challenges

4.1. General physical characteristics

A general overview of the MED region's physical geography reveals an irregular, deeply indented coastline, especially in the north. Specifically, narrow and steep continental shelves exist off the coasts of southern and northern Turkey, Crete, Maritime Alps, Africa, Sardinia, Corsica and western Italian coast, Iberian Peninsula, and the Balearic Islands (Mediterranean Quality Status Report, 2017). Wide (more than 50 km) continental shelves are encountered off the estuaries of the Ebro and Rhone rivers. The most extensive continental margins are the Adriatic Sea and the Tunisian-Libyan margin. A submarine ridge between the island of Sicily and the African coast divides the MED into western and eastern parts. The deepest point 5267 m -the Calypso Deep- is located in the Hellenic Trench.

MED in generally characterized as a deep sea; however, it exhibits some special bathymetric features. Only 14% is under 100 m depth, while 69% exceeds 500 m, 58% exceeds 1000 m and 40% exceeds 2000 m. The 0.7% exceeds 4000 m. As regards the implementation of MSFD, MED is separated into the following subregions: Western Mediterranean Sea, Ionian and Central Mediterranean Sea, Adriatic Sea and Aegean-Levantine Sea (see e.g., Jensen & Panagiotidis, 2017). Among the above subregions, only the Adriatic exhibits the low percentage of 19% exceeding 500 m, while the corresponding percentages for the other subregions are about 78%, 68% and 73% for Western Mediterranean Sea, Ionian and Central Mediterranean Sea and Aegean-Levantine Sea, respectively. The Aegean-Levantine, although it is considered a single subregion, could be separated into two subregions based on the stark difference in bathymetric features. More specifically, the percentage of marine areas exceeding 500 m depth for the Aegean is about 36%, whereas it is about 85% in Levantine marine areas. Furthermore, Aegean shallow water areas (less than 100 m) cover about 23%, and only 11% exceed 1000 m. In contrast, in Levantine, shallow waters cover only about 8%, while about 76% exceed 1000 m depth.

The MED is also characterized by high salinities, temperatures, and densities. The salinity is uniformly high throughout the basin. The MED surface layer presents a longitudinal salinity gradient ranging from 36.2 psu near Gibraltar to 38.6 psu in the Levantine basin. The annual average MED sea surface temperatures (SST) are calculated to be 19.7±1.3◦C. The much warmer water occurred especially to the east of the Levantine sub-basin. The much colder area (<17.1◦C) occurred especially in the Gulf of Lion and in the north of the northern Adriatic sub-basin (Shaltout & Omstedt, 2014). Furthermore, the horizontal spatial distribution of annual mean sound speed at a 50 m depth displays a northwest to southeast gradient, with values between 1506 and 1508 m/s located in the Gulf of Lion, a minimum of 1505 m/s in the northern Adriatic Sea, and a maximum of up to 1527 m/s off the easternmost MED coast (Salon et al., 2003).

The MED is a crucial biodiversity spot, as its highly diverse marine ecosystem hosts around 4-18% of the world's marine biodiversity (Coll et al. 2010, Bianchi & Morri, 2000), although it has low nutrient levels. Additionally, MED provides vital areas for the reproduction of various pelagic species, such as sea turtles and Atlantic bluefin tuna.

The BS on the other hand, is an enclosed sea, which according to the MSFD is considered a single subregion, not divided into smaller subregions. A very large shallow continental shelf within the north-western BS (about 25 % of the total area of the sea) is a unique physical characteristic of the subregion. Regarding depth, 32% is under 100 m, with a transitional range of 6% between 100-500 m. Moreover, about 62% exceeds 500 m and 56% exceeds 1000 m depth. The maximum depth of 2212 m is located in the south-central sector of the sea.

The main characteristic of BS is that nearly 87% of the Sea is entirely anoxic (without oxygen) and contains high levels of hydrogen sulphide. In particular, oxygen is dissolved only in the upper water levels. Below a depth of about 70 to 100 m at the centre and 100 to 150 m near the edge, there is no oxygen; in those reaches the sea is contaminated by hydrogen sulfide, which results in a saturated, gloomy “dead” zone frequented only by bacteria adapted to those conditions (Maftei, 2015).

The basin interior has higher salinity than the periphery. The salinity of the surface waters is between 17 and 18 parts per thousand, whereas an increase of up to 21 parts per thousand occurs at depths of 50 to 150 m (Miladinova et al., 2016). The sea’s deepest parts, below 400 m, are distinguished by highly stable temperatures between 8.5 and 9 °C and salinities of 28 to 30 parts per thousand. The average sound speed of the BS basin is equal to 1487.0 m/s. The average sound speed in the 0–300 m layer is about 1469.8 m/s and in the 400–2000 m layer, 1490.2 m/s. Processes of winter convection lead to a steady increasing of sound speed with depth, providing positive refraction and favourable conditions of sound propagation. Seasonally, the predominant sound propagation conditions can be described as follows: winter – positive refraction; summer – negative refraction and SOFAR (Sound Fixing and Ranging Channel) propagation (Mihailov, 2020). The number of species in the BS is around one third of that in the MED. Yet, the abundance, total biomass, and productivity of the BS are much higher than in the MED.

4.2. Classification and modelling challenges

- Areas with depths of over 500 meters can be described as deep-water areas and can be found all over the MED. Here, the focus is on the large, deep-water areas. From a quick view of the EMODnet bathymetry database, in two of the four MED subregions (Western MED, Ionian and Central MED Sea), most of the marine water areas are deeper than 2000-2500 m (see also 4.1).

  The *Western MED* and especially the Tyrrhenian basin as a part of it, include areas with deep water, with a maximum depth of 3785 m and an average depth of 2000 m. The Western MED marine water areas, between the Balearic Islands and Sardinia, vary between 2500 and 3500 m, with a section where the depth is more than 2500 m between the North African coast and France.
  Ionian and Central MED Sea, east of Sicily (between Sicily and the Ionian Islands), contains deep marine waters with more than 3000 m depth and reaching 4000 m in the central MED. Also, the Hellenic Trench in the Ionian Sea includes depths of more than 3000 m, with the deepest point of the MED reaching more than 5000 m, as described in 4.1.

The *Aegean-Levantine region* also contains some deep-water areas (the Aegean Sea cannot be characterised as a deep-water area, however (see below)). In the Aegean Sea, there are a few areas with deep waters, e.g., close to Karpathos Island, with depths of 2000-2500 m, although it is not an extended deep area. The Levantine region is a unique area that includes deep-water areas south of Crete (depths are between 3000-4300 m southeast of Crete), being part of the Hellenic Arc. Another area with deep waters is the area southeastern of Rhodes Island. The depth reaches approximately 4400 m.

In the *Black Sea*, deep waters close to 2000 m are present in the center of the region. Arguably, the main body of the Black Sea is in deep waters (with two exceptions—in the northeast and Azov Sea).

- Extreme slopes, meaning areas where great depths are reached within a few kilometres of the coast, exist all over the MED region. These abrupt slopes are scattered over the MED, with an average angle of over 25° in areas such as the northwest coast of Africa, close to Toulon, east of Sicily (close to Syracuse), Pylos in the Hellenic Trench, west of Karpathos Island, and the whole Hellenic Arc. In the BS, the continental slope is steep everywhere, descending with an average angle between 5° and 8° (but the gradient can reach 20–30° in some sections (Barale & Gade, 2008)).
- Extremely complex bathymetric features can be found in areas where shallow waters, deep waters, and abrupt bathymetric features exist in parallel. In the MED, unique areas are the archipelago of the Aegean Sea (Fig. 4) and the Sicilian Channel (Fig. 5).

The Aegean Sea Archipelago is a special case due to the presence of hundreds of islands of the Cyclades, Northern Sporades, Dodecanese, etc. Aegean morphology includes many basins, ridges, submarine mountains, etc., from north to south. Representative parts of shallow waters are, e.g., the Thermaic Gulf in the north with 100 meters depth, Thracian Sea with also 100 m depth, Cyclades Plateau, and the area between Samos and Kos Island with similar depths. The southern part of the Aegean Basin is a rather geometric arcuate deep basin, separating the Cyclades Islands to the north from Crete to the south (Papanikolaou et al., 2002).

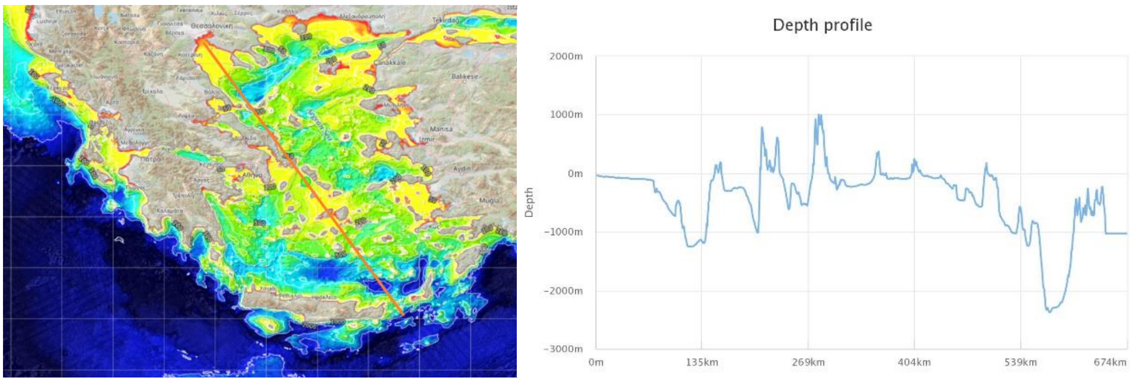


Figure 4. Transect in the Aegean Sea (with orange colour, left); depth profile of the depicted transect (right). The exceedance of 0-meter level indicates land, in particular islands. (From EMODnet Bathymetry Portal).

Additionally, in the North Aegean, between the Thermaic Gulf and Thracian Sea there are deep waters reaching 1000 meters. Extreme slopes and depths can also be found, e.g., in the South Aegean, with deep waters over 2500 meters and extreme slopes, e.g., in the Carpathian and Cretan Sea (east of Crete).

The Sicilian Channel, on the other hand, is characterised by wide continental shelves, deep and shallow channels as well as wide abyssal plains. The Channel comprises two sill systems separated by an internal deep basin. A narrow shelf separates these large sill systems in the central part, where the shape of the slope is extremely irregular, incised by many canyons, trenches and steep slopes (UNEP-MAP, 2015).

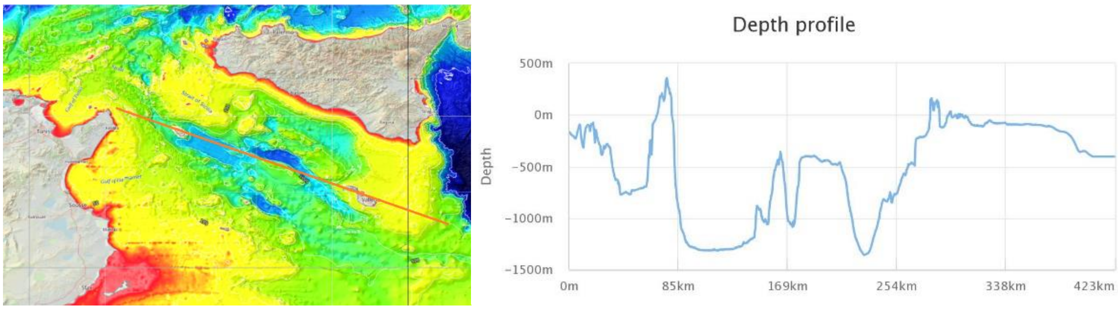


Figure 5. Transect in Sicilian Channel (orange-coloured, left); depth profile of the depicted transect (right). The exceedance of 0- meters level indicates land, in particular islands. (From EMODnet Bathymetry Portal).

- Areas below 100 meters are described as shallow waters. Extended areas with shallow waters can be found in Gulf of Lion, Northern Aegean Sea, Adriatic Sea (especially Northern), waters between Tunisia and Libyan coasts and waters close to Alexandria in Egypt. In BS, the western part of the region, especially in the northwest and Sea of Azov contain shallow waters, up to 60 meters.

5. Acoustic propagation modelling tests at selected marine areas in Mediterranean and Black Seas

5.1. Selection of the test marine areas

5.1.1. Selection criteria

The test marine areas are selected based on two criteria, both of which should be met:

A. The test areas should be representative of the different bathymetric features encountered in the four subregions of the MED and the BS region.
B. The test areas should constitute important habitats of cetacean or other representative species.

As regards criterion (A), the selection of potential areas follows the rationale of Section 4.2. As regards the criterion (B), the potential areas should be part of at least one of the following marine biodiversity protection schemes. Commonly, the following criteria overlap.

B1. EBSAs (Ecologically and Biologically Significant Areas, CBD)
EBSAs are special areas in the ocean that support the healthy functioning of oceans and the many services that they provide. The scientific criteria for identifying EBSAs have been set by the Convention on Biological Diversity (CBD). The EBSAs for the MED and BS can be identified in the interactive map in https://www.cbd.int/ebsa, while detailed relevant information can be found in https://www.cbd.int/ebsa/ebsas by selecting the appropriate EBSA region.

B2. Important Marine Mammal Areas (IMMAs)
IMMAs can be defined as discrete portions of habitat, important for one or more marine mammal species, that have the potential to be delineated and managed for conservation, where "important" (in the context of the IMMA classification) refers to any environmental condition, biological property, or value of a place, which supports marine mammals, and maintains or improves their conservation status. The criteria for identifying IMMAs have been set by the IUCN Marine Mammal Protected Areas Task Force (MMPATF). The IMMAs for the MED and BS and detailed relevant information can be identified in the interactive map in https://www.marinemammalhabitat.org/imma-eatlas.

B3. CCH (Cetacean Critical Habitats, ACCOBAMS)
CCH were defined as places or areas regularly used by a cetacean group, population or species to perform tasks essential for survival and equilibrium maintenance (UNEP-MAP RAC/SPA, 2011, Hoyt, 2005). ACCOBAMS is working on the identification of new relevant CCH in the ACCOBAMS area, to propose appropriate threats management or spatial management measures. The identification is based on the overlapping of areas of interest for Marine Mammals (IMMAs, see B2 above) and mapping of anthropogenic threats. Maps of CCHs for the MED and BS, also including nationally designated MPAs (see B4 below) and specific Natura 2000 sites (see B5 below), can be found in https://accobams.org/conservations-action/protected-areas.

B4. SPAMIs (Specially Protected Areas of Mediterranean Importance)
The Protocol for Specially Protected Areas and Biological Diversity in the Mediterranean (SPA/BD Protocol of Barcelona Convention) established the List of Specially Protected Areas of Mediterranean Importance (SPAMI List). The SPAMI List may include sites which: are of

importance for conserving the components of biological diversity in the MED; contain ecosystems specific to the MED area or the habitats of endangered species; and/or are of special interest at the scientific, aesthetic, cultural or educational levels. The List with relevant information can be found in http://www.rac-spa.org/spami

B5. Marine Protected Areas (MPAs) and Natura 2000 sites
MPAs involve the protective management of marine areas according to pre-defined management objectives. MPAs can be conserved for a number of reasons including economic resources, biodiversity conservation, and species protection. Natura 2000 is a network of core breeding and resting sites for rare and threatened species, and some rare natural habitat types. The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species and habitats (see, e.g., Natura 2000 network viewer), listed under both the Birds Directive and the Habitats Directive, both on land and at sea. Relevant information can be found in https://www.eea.europa.eu[6] and https://www.protectedplanet.net/en.

It was also taken into account that two test marine areas have been selected in the framework of the Activities 6 and 8 of the QUIETSEAS Project: i) the area covering the Northwest MED, Slope and Canyon System IMMA (including almost all the Western Ligurian Sea and Genoa Canyon IMMA) and the Shelf of the Gulf of Lion IMMA; ii) the Kaliakra to Danube Delta IMMA. These areas will be examined first with regards to the fulfilment of criteria A and B.

5.1.2. The selected test areas

According to the selection criteria described in 5.1.1, the test areas that are chosen are the following:

I. Northwest MED, Slope and Canyon System IMMA and the Shelf of the Gulf of Lion IMMA (Subregion: Western MED).
II. The Hellenic Trench (Subregion: Ionian Sea and Central MED)
III. Aegean Sea (Subregion: Aegean-Levantine Sea)
IV. The northern Adriatic (Subregion: Adriatic Sea)
V. The Kaliakra to Danube Delta IMMA (Subregion: BS)

The above test areas fulfill the selection criteria and at the same time are representative areas of all the subregions of the MED and BS according to MSFD.

I. The area covering the Northwest MED, Slope and Canyon System IMMA and the Shelf of the Gulf of Lion IMMA (abrupt slopes).

This area includes about half of the “Pelagos Sanctuary for Mediterranean Marine Mammals” (western part), which is a SPAMI, and about half of the “Cetacean migration corridor of the Mediterranean”, which is also a SPAMI (northern part). The IMMA Shelf of the Gulf of Lion completes the selected area; see Fig. 6. The area is also meets the EBSA criteria (North-western Mediterranean Benthic and Pelagic Ecosystems). The importance lies in the fact that abrupt

[6] https://www.eea.europa.eu/themes/water/europes-seas-and-coasts/assessments/marine-protected-areas

slopes and deep and rich waters in the shelf result in high seasonal concentrations of plankton, playing a key role as a refuge and reproductive habitat for a variety of species. The eastern part (Genoa Canyons) hosts marine mammal species and the "Cetacean migration corridor of the Mediterranean". The west contains habitat for cetacean species (pilot whale, sperm whale, Cuvier's beaked whale, bottlenose dolphin and striped dolphin, among others). Various Natura 2000 and MPAs are established here. Lastly, almost half of a CCH northwest of Sardinia is included in this selected area.

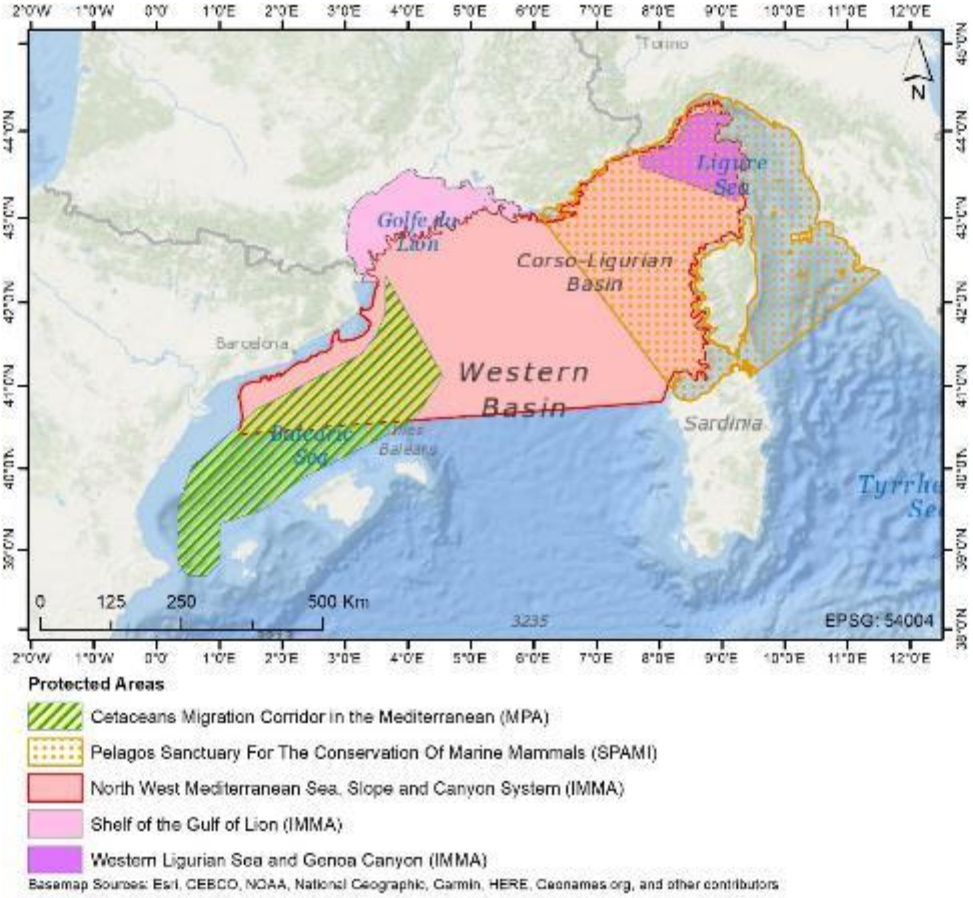


Figure 6. Selected Area of Northwest MED, Slope and Canyon System IMMA and the Shelf of the Gulf of Lion IMMA. The different protection schemes are illustrated with different colouring and pattern.

II. The Hellenic Trench (deep water)

Hellenic Trench is a long bathymetric feature that consists of a series of linear trenches and small troughs, in which the depth increases steeply; see Fig. 7. The 1000 m contour is typically within 3–10km of the closest island or mainland coast. The area as an IMMA and an EBSA as it is an important feeding ground for sperm whales in the eastern MED and even appears to be their core habitat for calving and nursing (Frantzis et al., 2014; Lewis et al., 2018). Additionally, it also features a sub-area which is the largest among five high-density areas of MED occurrence for Vulnerable Cuvier's beaked whales (Ziphius cavirostris). Hence, the Hellenic Trench includes several CCH, Natura 2000 and MPAs.

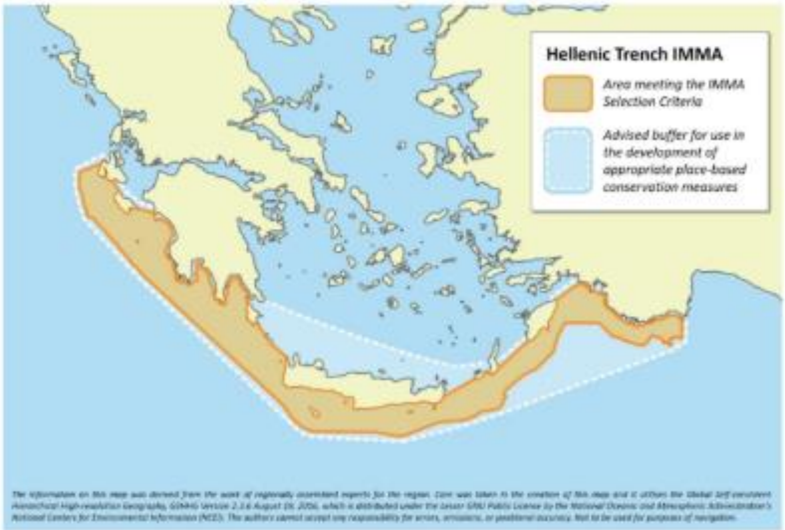


Figure 7. Selected Area of Hellenic Trench as it is illustrated according to IMMA criterion.

III. The Aegean Sea (Archipelago)-very irregular topography

Figure 8. Selected Area of Aegean Sea Archipelago, following the EBSA criterion.

The Aegean has an intricate configuration, with an extensive archipelago of hundreds of small islands. The Central and North Aegean are considered EBSA areas (see Fig. 8), and the Central Aegean, North Sporades and Northern Coast and Island of Thracian Sea are also IMMAs. The Northern Sporades includes the National Marine Park of Alonissos and is an MPA, which was established specifically to protect a colony of Endangered Mediterranean monk seals (*Monachus monachus*). The Northern Aegean includes some of the most important fishing grounds of the Aegean. Natura 2000 sites and MPAs have been identified in the area, and the Northern Sporades and Northern Aegean Sea include CCH, as well as waters surrounding Dodecanese's area.

IV. Northern Adriatic (shallow water)

The northern Adriatic is a shallow basin with the bottom sloping gently to the south and reaching a maximum of about 100 m, with an average depth of 35 m; see Fig. 9. The area hosts a strong diversity of benthic and pelagic habitats, bottlenose dolphin, loggerhead turtle, blue shark, and anchovies. It is one of the most productive areas in the MED. For all the above reasons, it is fulfilling the EBSA criteria as well as those for an IMMA. Additionally, several Natura 2000 and MPAs are established in Northern Adriatic. Waters along east coast of the Cres-Lošinj archipelago are a CCH.

Figure 9. Selected Area of Northern Adriatic, as it is illustrated according to IMMA criterion.

V. The Kaliakra to Danube Delta IMMA (shallow water)

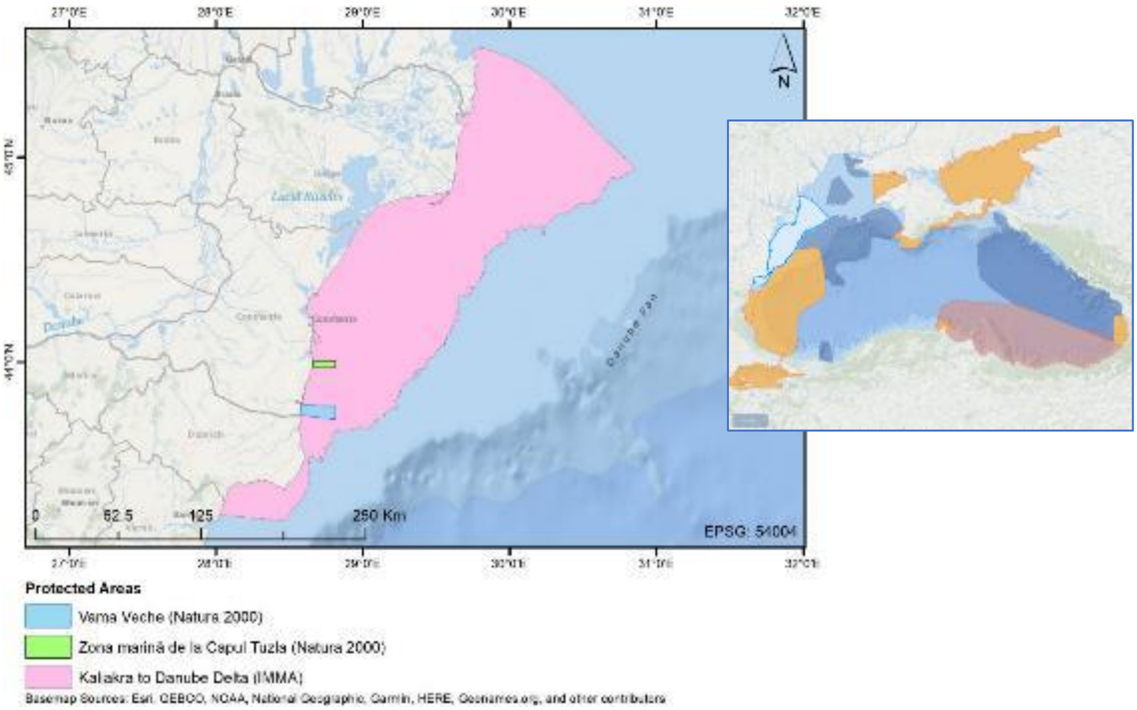


Figure 10. Selected Area of Kaliakra to Danube Delta IMMA with the two Natura 2000 of Vama Veche and Capul Tuzla.

This area is described by shallow waters, in which some of the rarest ecosystem types, such as natural hypersaline lakes, occur; see Fig. 10. The area, categorised as IMMA, contains habitats of various species of marine mammals, fish and invertebrates, while it is important for the survival and recovery for all three BS species of odontocetes. There are several Natura 2000 and MPAs, with the Capuz Tuzla Marine Area and the Vama Veche in Romanian waters, being very important ones. Additionally, the area is part of EBSAs.

5.2. Input data sets for the selected areas

5.2.1. Environmental data

The principles for collecting environmental data sets are mentioned in Section 3.2. For the purposes of the analysis presented here, the sound speed profiles for summer and winter will be taken from references Salon et al (2003) and Mikhailov (2020). Extreme cases will be considered (warm water in summer – cold water in winter) expecting that these cases will be enough to assess the functionality of the propagation models at the areas of interest. The bathymetric structure of the seabed was extracted from the EMODnet bathymetry[7] by selecting the appropriate areas and downloading the files in the GEOtiff format. A custom script was implemented in Python using GDAL (Geospatial Data Abstraction Library) for raster and vector geospatial data formats.

5.2.2. Parameters of the numerical codes

KRAKENC

- Range for the phase speeds: 0 to 5000 m/s as a standard for every case**.** All the propagating modes plus a sampling of the evanescent modes are considered, which was necessary to get a better representation of the near field and also for estimating the interaction between modes with greater accuracy (case of KARAKENC coupled).
- We initially adopted a standard rule for this discretization for each case: $Nprof = R_{\max}/2$, $R_{\max}$: maximum range of propagation (in m). For several cases this number had to be modified because KRAKENC was not able to reliably couple each segment when using a second medium and large segmentation. Modelers of shipping noise prediction codes should find a general rule for providing this number if KRAKENC is to be used.
- Range-dependent bathymetry was provided in a specific file (*.bty) as 99 range-depth pairs.
- Seabed description: Semi-infinite half space above which a sediment layer of small thickness was added with geoacoustic parameters equal to those of the half-space. The inclusion of this “artificial layer” was necessary for numerical reasons.
- Number of normal modes: maximum allowed by the code.
- Source depth: 10 m (in every case).
- Receiver grid used for all codes: 1 m in depth (from the surface to the deepest point of the waveguide, denoted as $D_{\max}$); 100 m in range (effectively creating rectangular grids of $(R_{\max}/100)\times(D_{\max}+1)$ mesh points). The +1 point is to account for a receiver placed right at the surface.

[7] https://www.emodnet-bathymetry.eu/

RAMGEO

- RAMGeo was executed using the AcTUP v2.2, developed by Amos Maggi & Alec Duncan, in the Matlab environment. This compiled version of RAM imposed a limit of 100 on the points used to approximate the bathymetry in each slice. This is the main reason for the use of 99 points to represent bathymetry in every code. AcTUP GUI (Graphical User Interface) was not used, but advantage was taken of a feature that allows the user to directly edit the input file before the execution of the code.
- Padé terms in the pressure expansion: 9 (for every case). A number of 5 should work 99% of the times, but the user can use up to 10, which is the limit imposed by the program.
- Reference speed: 1500 m/s.
- Stability constraints are left to default value of 1 and the maximum range for constraints at 0 m.
- Decimation factors (both for range and depth) for the pressure field output: 1 (no decimation).
- $\mathrm{dr} = 10\mathrm{m}$ (Standard for all cases due to dependence of the self-starter on dr and frequency and apparently interference with the pressure in the nearfield).
- Attenuation: 10 dB/λ (all bottoms); a standard rule for the depth of the artificial absorbing bottom was not used.

BELLHOP

- Receiver depths: 10 m intervals for deep seas (more than 1000 m depth); 1 m intervals for shallower seas.
- Range intervals: 100 m (as in KRAKEN).
- Receiver grid: $\left(\frac{R_{\max}}{100}\right)\left(\frac{D_{\max}}{10}+1\right)$ for deep water; $\left(\frac{R_{\max}}{100}\right)\left(D_{\max}+1\right)$ for shallow water

5.3. Modeling tests – Comparison between acoustic propagation codes

This section shows a comprehensive comparison of the model results for each test marine area as defined in Section 5.1.2. For each area, specific sites have been selected: three for Area I, one for Area II, and two for Areas III, IV and V.

The two basic frequencies of interest for the MSFD (63 and 125 Hz) have been considered. In two sites the additional frequency of 1000 Hz was also considered. For each site one or two transects representing characteristic environmental conditions have been tested. The sound source has been set at 10 m depth in all cases studied to represent a typical depth of the sound source of ship noise. For all the sites, typical simplified sound speed profiles for summer and winter have been used (see section 5.2.1). Also, for comparison reasons, a sandy seabed of longitudinal sound speed of 1650 m/s, density of 1850 kg/m^3 and attenuation of 0.5 dB/wavelength are used for all cases studied. Preliminary studies performed by changing the geoacoustic parameters of the seabed showed a rather consistent difference between models so it was decided for this study that a single type of seabed structure would be most desirable (see also Skarsoulis et al. 2017).

The conclusions derived are based on a systematic study of the acoustic field as calculated by the different models as a function of range and depth. Selected images representing Transmission Loss (TL) versus range and depth as well as versus range only, for specific depths are shown to support the conclusions derived. In all cases the selection of input parameters is reported and the execution time of the codes is mentioned. The time is based on runs on a computer equipped with an Intel i7-10750H Processor @ 2.6GHz.

General comments on the results of each test case are summarized, while conclusions and recommendations coming out from all the tests and model comparisons are presented in Section 6.2, taking into account specific considerations on MRUs and habitats in a risk-based assessment framework for continuous noise (section 6.1).

For the sake of compactness and size of the Deliverable, the exact description of the SSPs used, the results regarding the frequency of 1000 Hz and the results regarding TL.vs.range (which actually are very supportive to producing conclusive results for the performance of the models) have been omitted and can be found in the extended report (Taroudakis and Sapkas, 2022), prepared from FORTH, subcontractor of HCMR, for QUIETSEAS project.

5.3.1. Area I

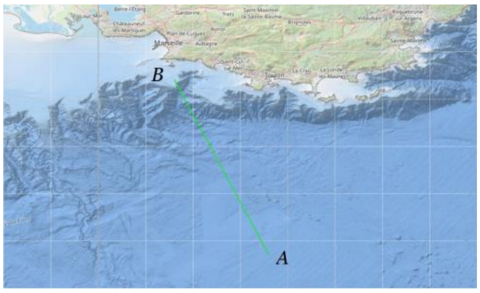
Three test sites were selected from Area I: 'Marseille', 'Barcelona' and 'Genova'. The sites with the specific transects, the bathymetric profiles and the SSPs for each site from Area I are shown in Figure 11, while relevant environmental features and input parameters of the numerical codes are described in Table 2.

Table 2. Environmental features and input parameters of the numerical codes for the test sites of the Area I.

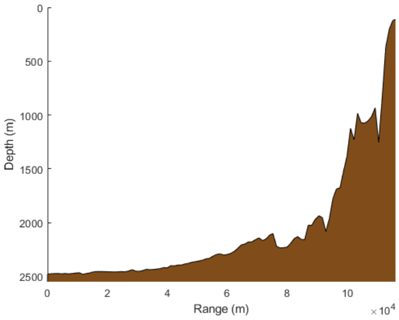
	'Marseille'	*'Barcelona'*	*'Genova'*
Environmental features	Propagation from deep sea to shore. Typical upslope environment. No abrupt bathymetric changes up to approximately 100 km from the source. The bathymetry changes abruptly afterwards; maximum range: approximately 118 km.	Propagation from deep sea to shallow water. Relatively simple environment, with a prominent shallow water part appearing abruptly during the last 25-30 km. This feature could be challenging for the reverse propagation (see test case 5.3.5.3).	Propagation from deep sea to shallow water. Upslope bathymetry which presents a depression of approximately 400 m depth close to the coast. This depression seen from another perspective signalizes a wide mount extending from a distance of 20 to 60 km from the shore.
Parameters of numerical codes			
KRAKENC	No. of segments in range: 58; no intermediate medium was used	No. of segments in range: 80; a second, intermediate, medium was used.	No. of segments in range: 41; a second, intermediate, medium was used.
BELLHOP	No. of receivers: 1161x251	No. of receivers: 1870x231	No. of receivers: 804x199

RAMGeo	Artificial, absorbing bottom placed at 2900 m depth.	Artificial, absorbing bottom placed at 3800 m depth.	Artificial, absorbing bottom placed at 3400 m depth.

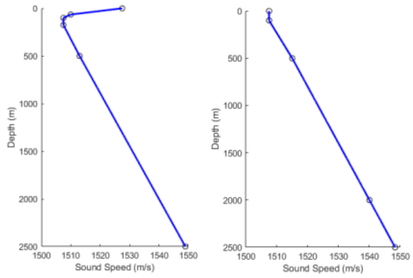
Marseille **Transect**



Marseille **Bathymetry**

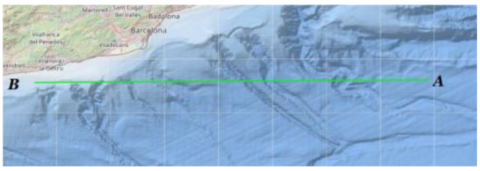


Marseille **SSP (summer / winter)**

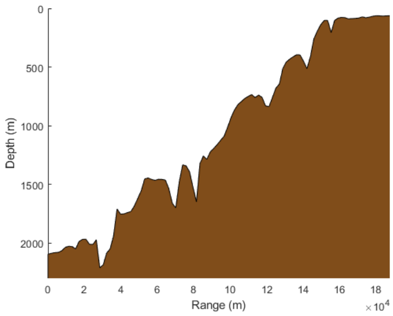


Transect length ~ 118 km

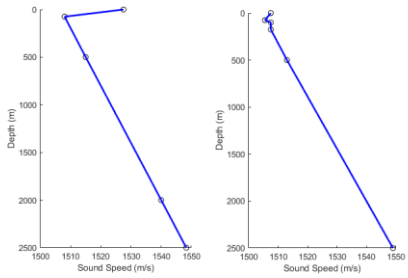
Barcelona **Transect**



Barcelona **Bathymetry**

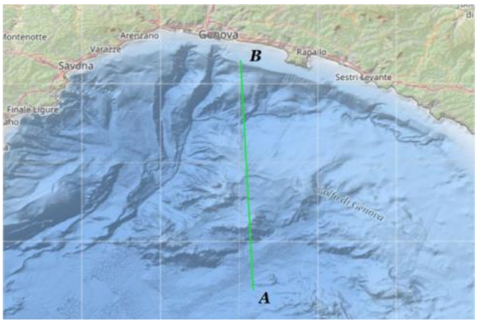


Barcelona **SSP (summer / winter)**

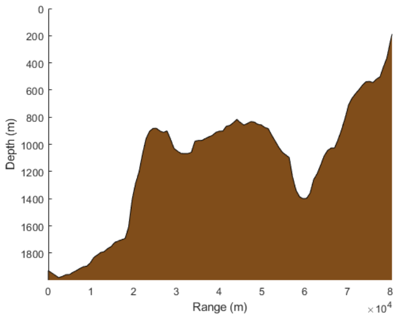


Transect length ~ 185 km

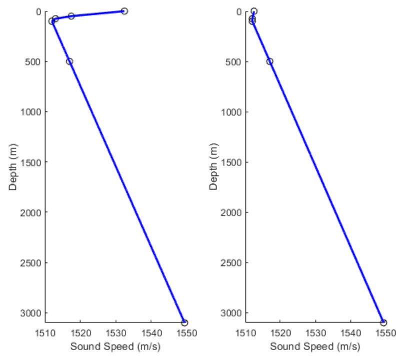
Genova **Transect**



Genova **Bathymetry**



Genova **SSP (summer / winter)**



Transect length ~ 80 km

Figure 11. Sites with transects, bathymetric profiles and SSPs for Area I. Left: Sites and propagation transects; middle: bathymetric profile; right: SSPs for summer (left) and winter (right).

5.3.1.1. *Marseille*

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 12.

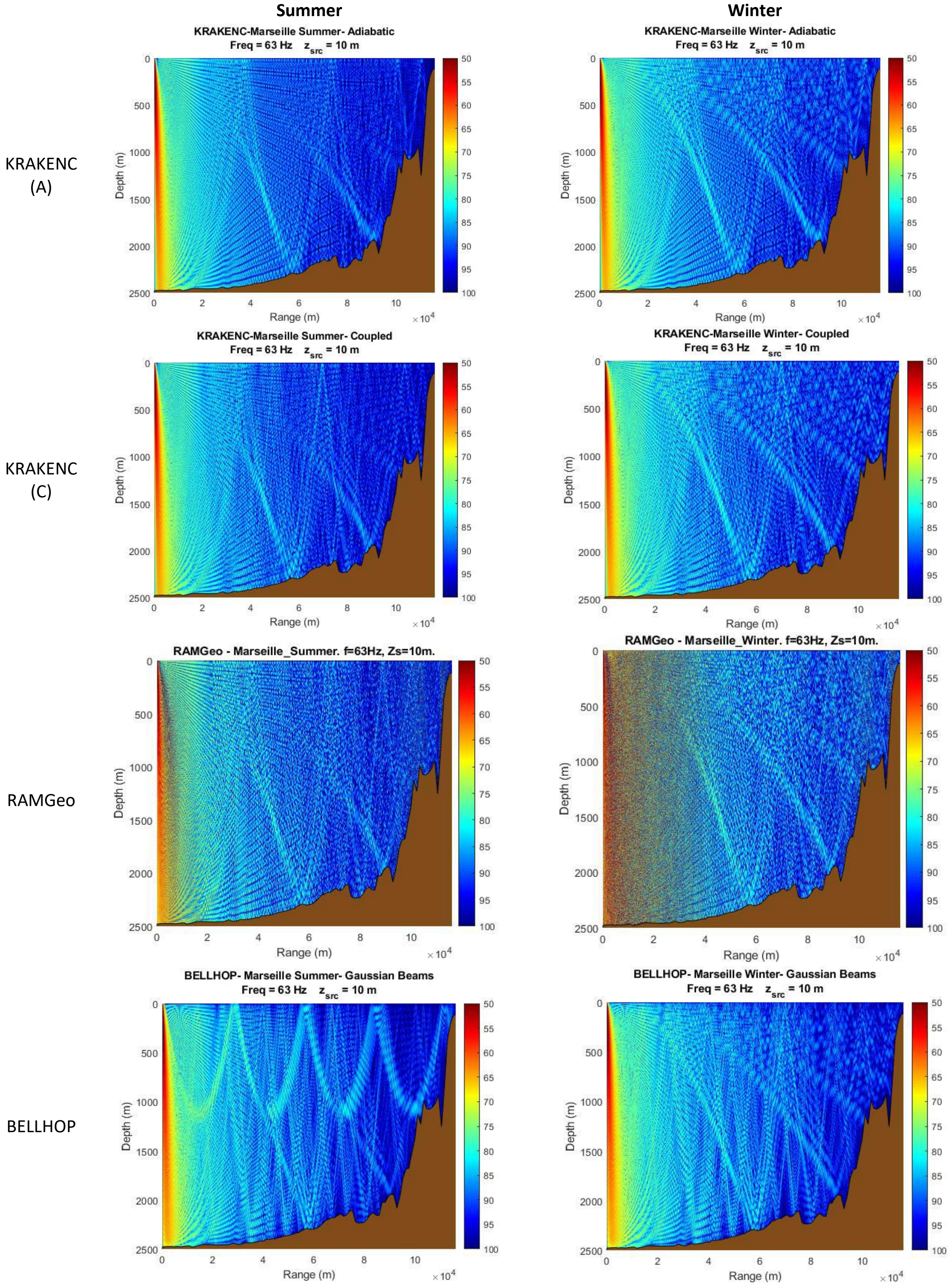


Figure 12. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Marseille test site (Area I) at 63 Hz.

The results from the simulations for the **frequency of 125 Hz** are shown in Figure 13.

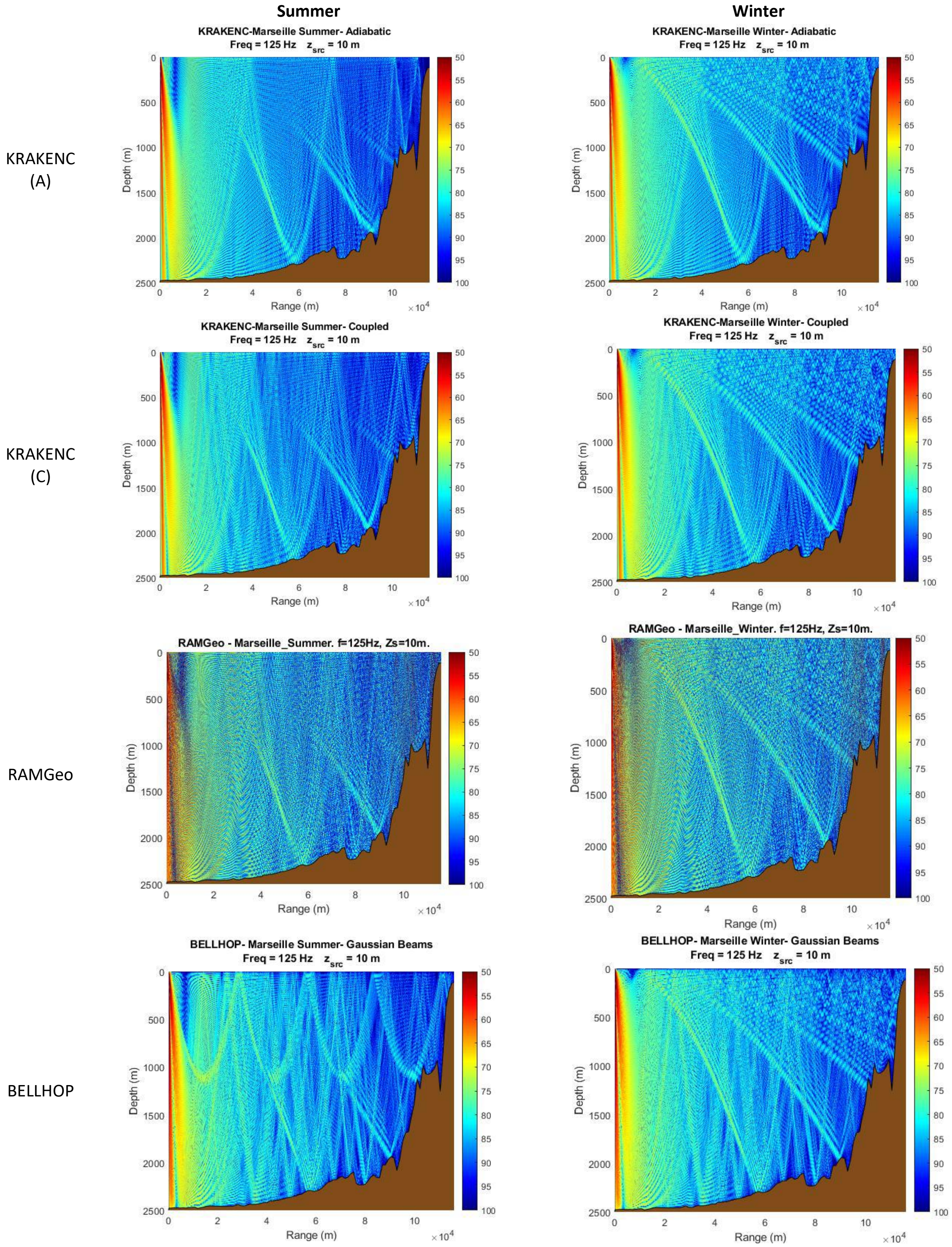


Figure 13. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Marseille test site (Area I) at 125 Hz.

In addition, simulations were performed with incoherent addition of the modal and rays contributions the acoustic field for this scenario (at 63 Hz) using the KRAKENC and BELLHOP codes (Fig. 14). The reason for performing this study is to have an indication of the differences in the calculation of the acoustic field when the phase of the complex acoustic field represented by a mode or a Gaussian beam is neglected. We know in theory that incoherent treatment gives an indication of the average energy structure of the field, which, however, can prove to be a good solution in the calculation of the contribution of each ship to the noise field in the area of interest, given the fact that the acoustic signature of the ship used in the shipping noise modeling does not contain information on the actual phase of the component of the source spectrum in each frequency. Incoherent addition of modes or rays smooths the differences of the acoustic field observed at different ranges or depths but eventually these differences may be smaller than the uncertainties inherent in the procedure to assign a specific source level for a specific ship in a frequency of interest. As the purpose of this study was to evaluate the accuracy of the various models in predicting the acoustic field at specific areas due to a given source, and given the fact that there is no difference in the performance of the models in incoherent vs. coherent mode, we performed this study only for one site of Area I for the frequency of 63 Hz and for the summer and winter SSP.

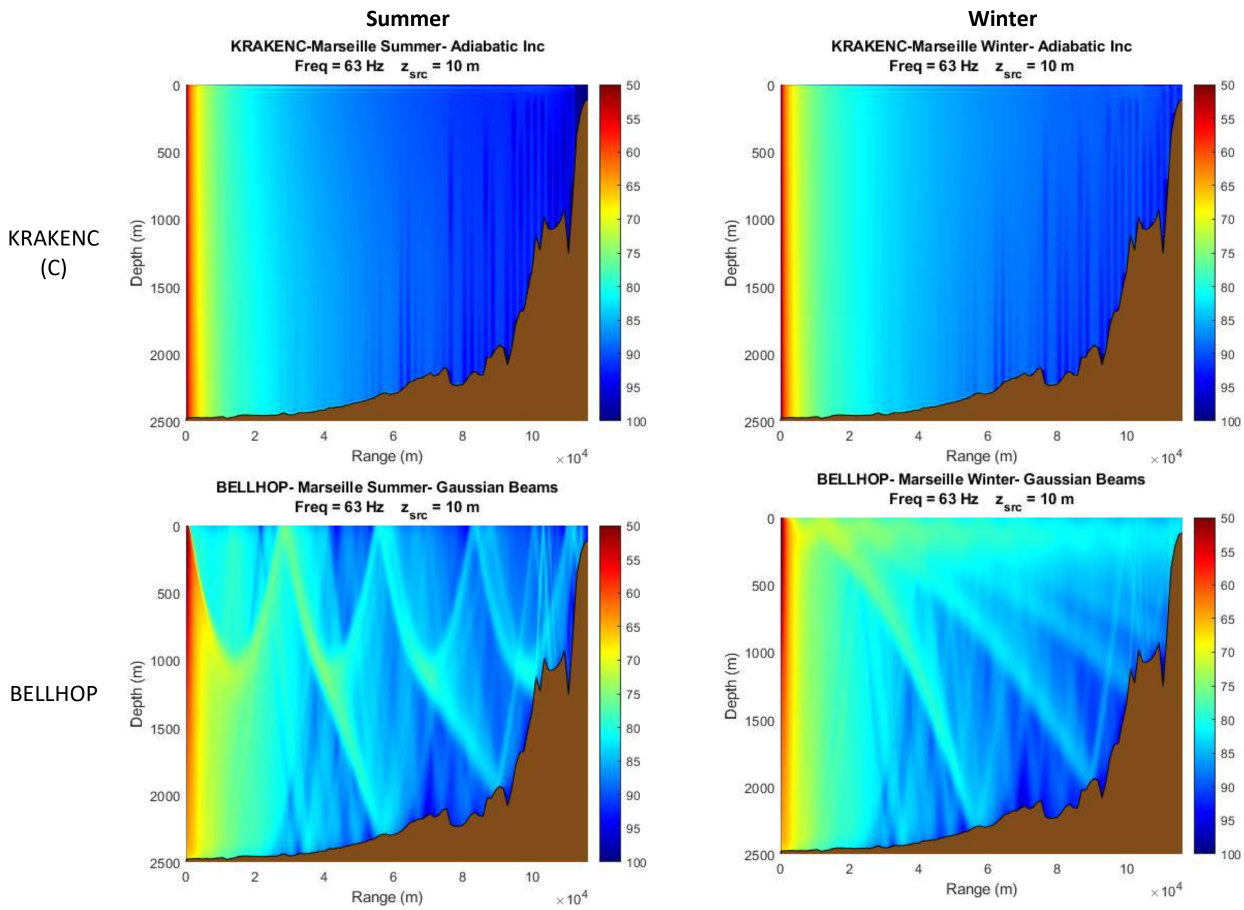


Figure 14. Acoustic propagation models (incoherent mode) outputs for summer (left column) and winter (right column) profiles and two models (KRAKENC Adiabatic and BELLHOP) for the Marseille test site (Area I) at 63 Hz.

Summary

The execution (run) times of the codes for the summer and winter profiles at 63 Hz, 125 Hz and 1000 Hz appear in Table 3.

Based on this table, the BELLHOP seems to be the fastest code to be applied in sites similar to the Marseille environment, as it provides reliable output at less than half the time required by KRAKENC at the frequency of 63 Hz and one quarter of time required at 125 Hz. The corresponding differences between BELLHOP and RAMGeo are not that significant as they are very close to each other for the summer SSP, while BELLHOP is twice as fast at 63 Hz and 125 Hz.

It should be noted that the KRAKENC calculation of the propagation modes is de-linked to the calculation of the acoustic field. It is noticeable that there is no difference between calculations of the acoustic field with KRAKENC adiabatic with respect to KRAKENC coupled which means that the code is developed with enough efficiency to allow for the calculation of the coupling terms at negligible time. Note that the time required by RAMGeo is reduced to only 3 sec, if the range step chosen is taken to be 100 m instead of 10 m.

Table 3. Execution (run) times of the examined codes for the Marseille test site at 63 Hz, 125 Hz and 1000 Hz.

	Summer			Winter		
	63 Hz	125 Hz	1000 Hz	63 Hz	125 Hz	1000 Hz
Model	Execution time is seconds (s)			Execution time is seconds (s)		
Incoherent KRAKENC Adiabatic	14	41	~2096	14	42	~2098
KRAKENC Adiabatic	10	33	~2055	10	34	~2035
KRAKENC Coupled	9	32	~2036	9	33	~2048
RAMGeo	6	12	12	15	15	9
Coherent BELLHOP	7	8	15	7	8	14
Incoherent BELLHOP	4	5	12	4	5	12

In summary, KRAKENC adiabatic and KRAKENC coupled provide results very close to each other and they can be used with high confidence for predicting the acoustic field in areas similar to the Marseille site. BELLHOP is a second choice. For the receiver depths under consideration (100 and 500 m), the differences of the predicted TLs with respect to those of the KRAKENC are not significant. Taking into account the fact that BELLHOP is faster than KRAKENC it can be considered as a good compromise. RAMGeo, seems to be less consistent with respect to KRAKENC in predicting TL for all ranges.

The case of 1000 Hz indicates the suitability of BELLHOP at high frequencies. KRAKENC adiabatic provides results that are very close to BELLHOP but using much more time. Thus, BELLHOP is the best option if relatively high frequencies are considered. KRAKENC coupled, at least for the parameters chosen, definitely fails to predict reliable results and it wouldn't be a suggestion for this frequency range. Similar results are derived for RAMGeo.

With respect to the case of coherent vs. incoherent addition of modes, by comparing KRAKENC adiabatic and BELLHOP, we observed differences that could be attributed to the way that the two codes treat the incoherent addition of modes (KRAKENC) and ray-beams (BELLHOP). Our opinion is that if incoherent addition is required, KRAKENC adiabatic is the best code, although there is no considerable gain in execution time when the incoherent addition is adopted.

5.3.1.2. *Barcelona*

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 15.

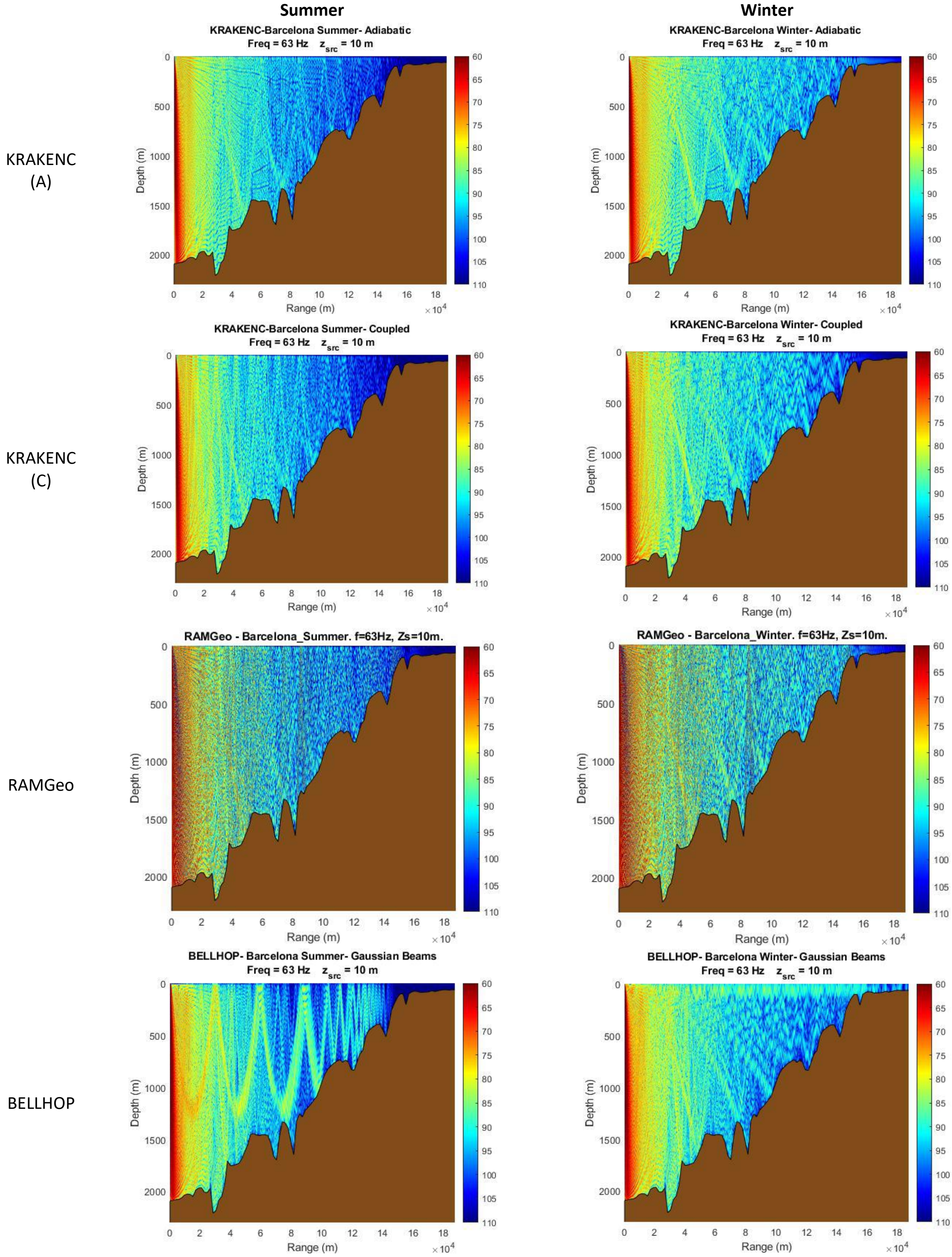


Figure 15. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Barcelona test site (Area I) at 63 Hz.

Summary

The execution (run) times of the codes for the frequency of 63 Hz (summer and winter SSPs) are shown in the Table 4.

Table 4. Execution (run) times of the examined codes for the Barcelona test site at 63 Hz.

Frequency 63 Hz	Summer	Winter
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	18	17
KRAKENC Coupled	18	17
RAMGeo	24	25
Coherent BELLHOP	7	8

Based on the above, the BELLHOP seems to be the fastest model to be applied in sites similar to the Barcelona environment, as it provides reliable output at less than half the time required by KRAKENC and one third the time required by RAMGeo. KRAKENC and RAMGeo need comparable time to predict the acoustic field at all ranges and depths required.

Apart from that, the Barcelona site presented no significant difference in the performance of the models with respect to Marseille site. Again, the KRAKENC (adiabatic or coupled) seem to provide the most accurate results at reasonable time. In this site, a second choice would once more be the BELLHOP code, mainly due to its fast execution.

It should, however, be noted once more that the execution time depends on the operational parameters and for all the sites the choice of the optimum parameter set, that is the parameter set for which numerical results converge, would reduce or increase the execution time.

5.3.1.3. *Genova*

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 16.

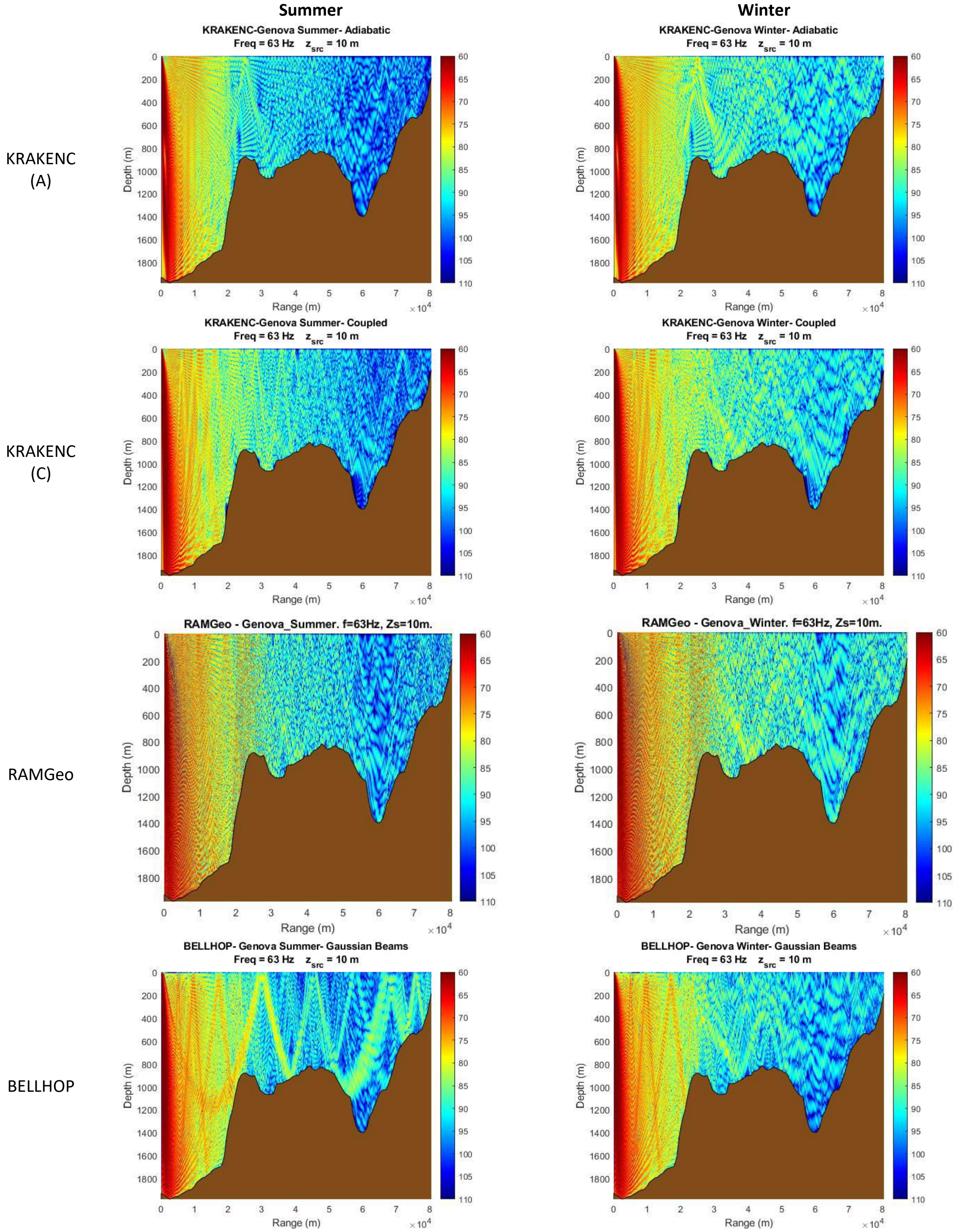


Figure 16. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Genova test site (Area I) at 63 Hz.

Summary

The execution (run) times of the codes for the frequency of 63 Hz (summer and winter SSPs) are shown in the Table 5.

This area, although apparently complicated with respect to the bathymetry, presented coherent results among the models for summer and winter sound speed profiles. As we are mainly interested in shallow receivers, all models can be used for the estimation of the TL in an area and SSP with the characteristics of the Genova environment.

Table 5. Execution (run) times of the examined codes for the Genova test site at 63 Hz.

Frequency 63 Hz	Summer	Winter
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	12	12
KRAKENC Coupled	12	12
RAMGeo	11	11
Coherent BELLHOP	2	2

Based on the above, the BELLHOP seems to be the most efficient model to be applied in sites like the Genova environment, as it provides reliable output at a speed almost 5 times faster than that of KRAKENC and RAMGeo. KRAKENC and RAMGeo need comparable times to predict the acoustic field at all ranges and depths required. The only difference is that KRAKENC calculation of the propagation modes is de-linked to the calculation of the acoustic field. Propagation modes are calculated in both cases at 11 seconds, while calculation of the acoustic field requires only 1 sec. It is noticeable that there is no difference between calculations of the acoustic field with KRAKENC adiabatic with respect to KRAKENC coupled which means that the code is developed with enough efficiency to allow for the calculation of the coupling terms at negligible time.

5.3.2. Area II

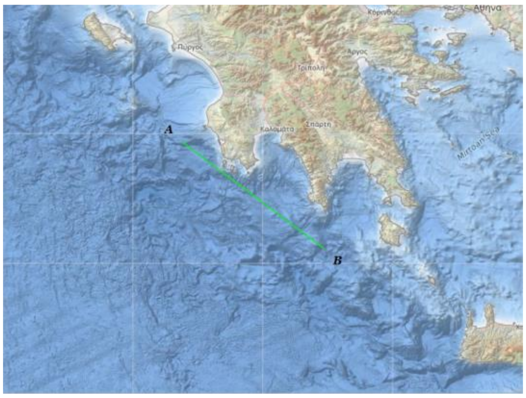
One test site was selected from Area II: the Hellenic Trench.

The sites with the specific transect, the bathymetric profile and the SSPs for this site of Area II is shown in Figure 17, while relevant environmental features and input parameters of the numerical codes are described in Table 6.

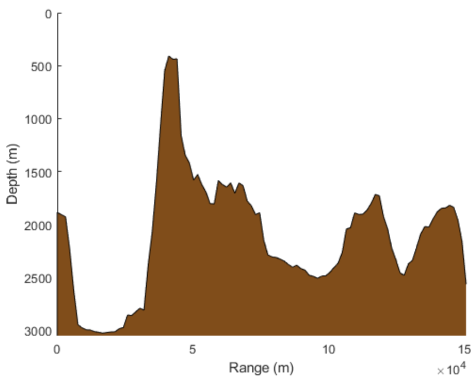
Table 6. Environmental features and input parameters of the numerical codes for the test sites of the Area I.

	'Hellenic Trench'
Environmental features	Propagation from NW to SE. Complicated environment involving very deep areas and seabeds along a path of 150 km. The highest seabed reaches a depth of approximately 480 m while the maximum depth is almost 3000 m.
Parameters of numerical codes	
KRAKENC	No. of segments in range: 101; a second intermediate medium was used
BELLHOP	No. of receivers: 1508x304
RAMGeo	Artificial, absorbing bottom placed at 3800 m depth

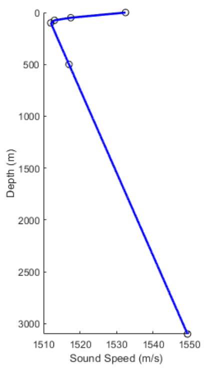
Hellenic Trench **Transect**



Hellenic Trench **Bathymetry**



Hellenic Trench **SSP (summer)**



Hellenic Trench **SSP (winter)**

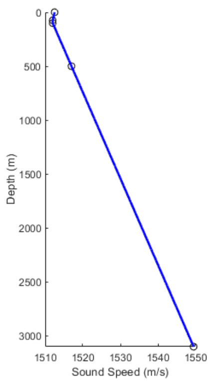


Figure 17. The Hellenic Trench site with the transect, bathymetric profile and SSPs for Area II. First row: The site and propagation transect (left) and the bathymetric profile (right); second row: SSPs for summer (left) and winter (right).

5.3.2.1. ***Hellenic Trench***

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 18.

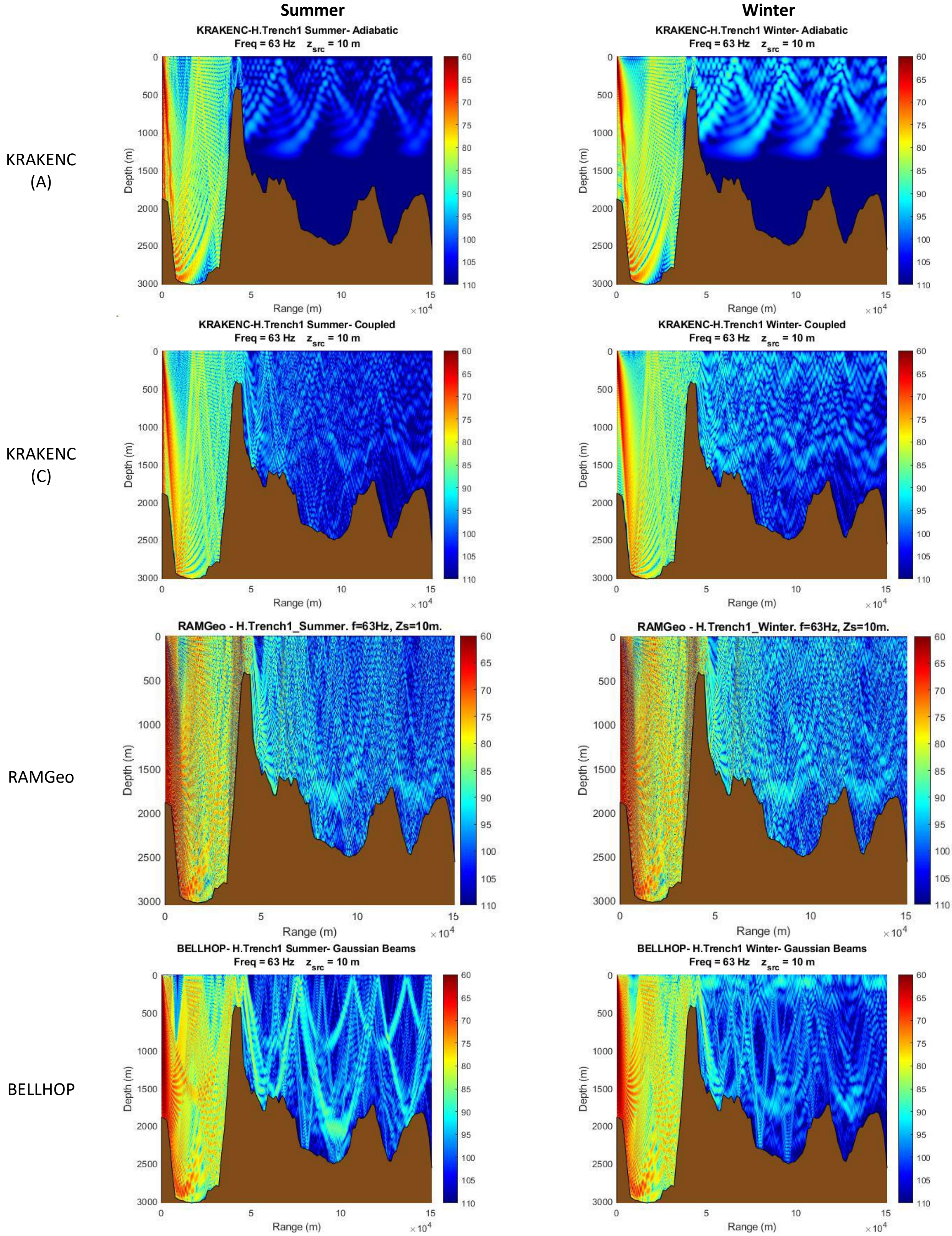


Figure 18. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Hellenic Trench test site (Area II) at 63 Hz.

The results from the simulations for the **frequency of 125 Hz** are shown in Figure 19.

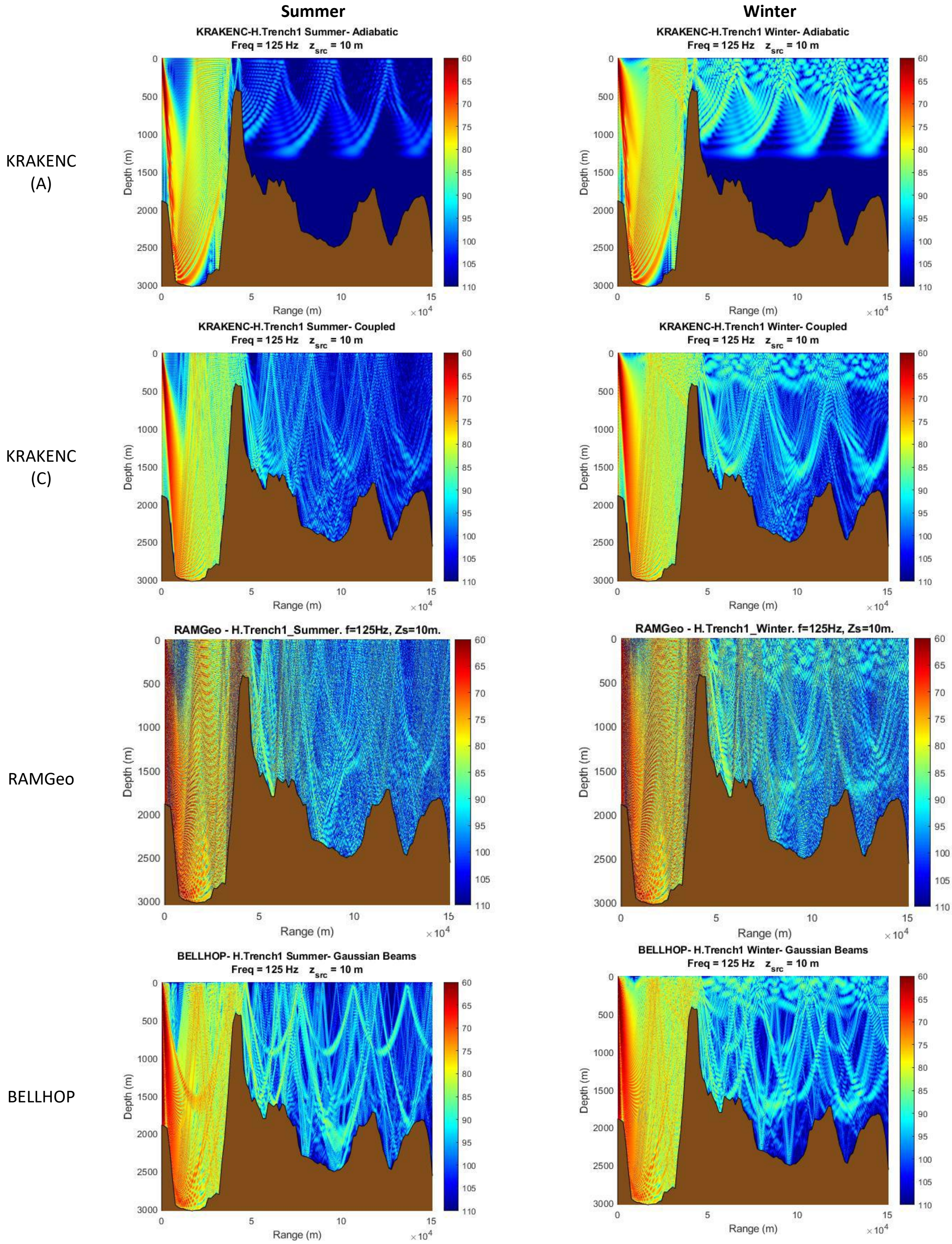


Figure 19. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Hellenic Trench test site (Area II) at 125 Hz.

Summary

The execution (run) times of the codes for the frequencies of 63 Hz and 125 Hz (summer and winter SSPs) are presented in Table 7.

Based on this table, the BELLHOP seems to be the most efficient model to be applied in sites similar to the Hellenic Trench 1 environment, as it provides reliable output at 22-26% of the time required by KRAKENC and approximately one third the time required by RAMGeo for 63 Hz and just 7 % of the time required by KRAKENC and again one third the time required by RAMGeo for 125 Hz.

Table 7. Execution (run) times of the examined codes for the Hellenic Trench test site at 63 and 125 Hz.

Summer	63 Hz	125 Hz
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	41	162
KRAKENC Coupled	41	162
RAMGeo	25	26
Coherent BELLHOP	9	11

Winter	63 Hz	125 Hz
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	32	156
KRAKENC Coupled	40	155
RAMGeo	26	25
Coherent BELLHOP	9	11

It is interesting to note, though, that given the fact that the calculation of the modes by KRAKENC is the most time-consuming part of the code, the advantage of the BELLHOP may be not as important when the modes are defined for the whole area and then the field is calculated.

For this reason, BELLHOP and KRAKENC coupled can be used with equal confidence in a site with the characteristics of the Hellenic Trench. RAMGeo would be the third choice. KRAKEN C adiabatic is considered reliable only for shallow-water receivers.

5.3.3. Area III

Two test sites were selected from Area III: 'Aegean Sea I' and 'Aegean Sea II'. The sites with the specific transects, the bathymetric profiles and the SSPs for each site from Area III are shown in Figure20, while relevant environmental features and input parameters of the numerical codes are described in Table 8.

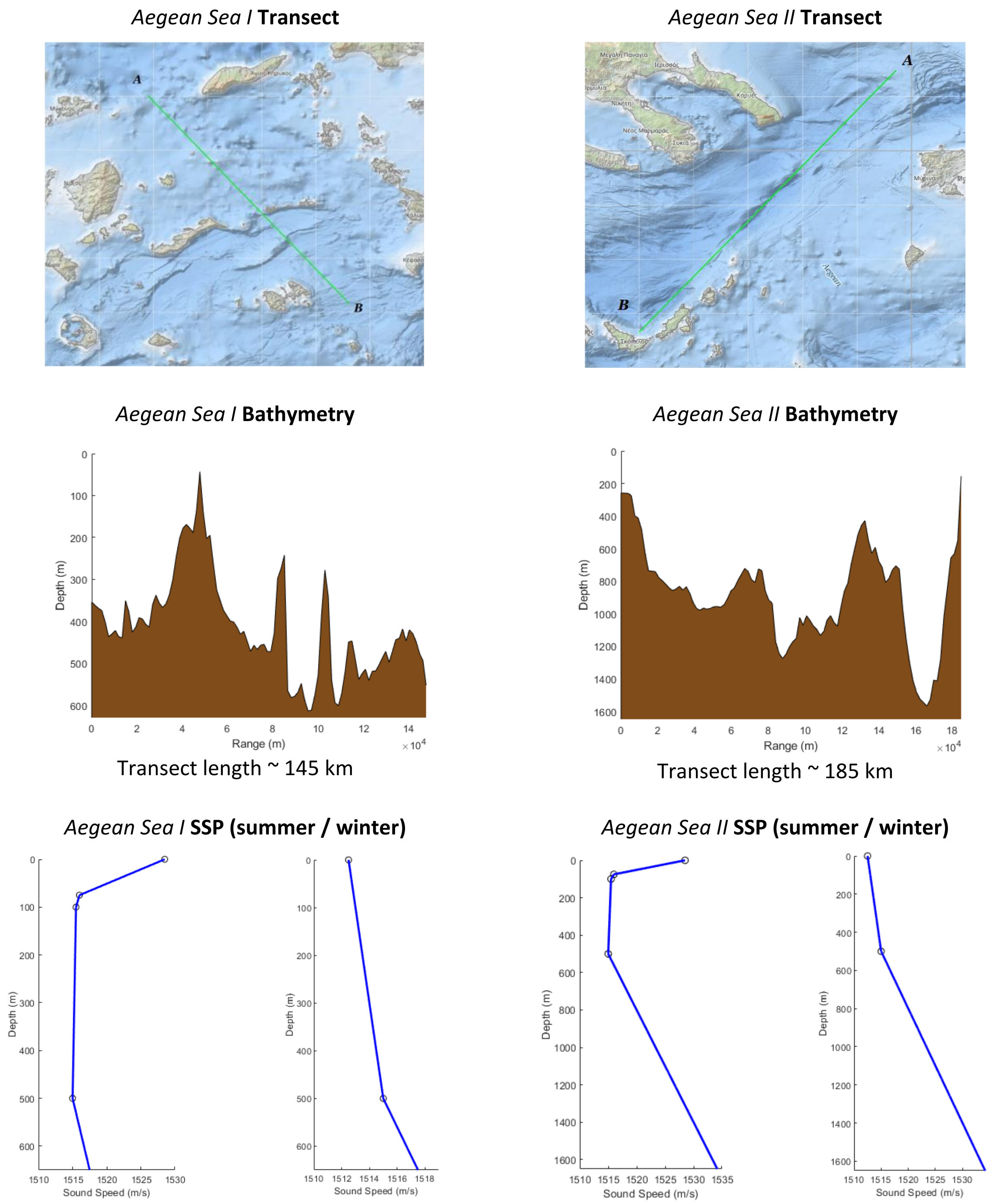


Figure 20. Sites with transects, bathymetric profiles and SSPs for Area III. Propagation transects, the bathymetric profiles and SSPs for Aegean Sea I (left column) and Aegean Sea II (right column).

Table 8. Environmental features and input parameters of the numerical codes for the test sites of the Area III.

	'Aegean Sea I'	*'Aegean Sea II'*
Environmental features	Site in Cyclades Isl. complex. Propagation from NW to SE. It would be ideally treated as 3-D environment due to the presence of numerous islands. For the sake of avoiding complexity, a 2-D transect between the Amorgos Isl. and Kinaros Isl. is considered in this study. Irregular bathymetry involving three significant mounts, the first one of which reaching 50 m depth. Two significant depressions between seabeds. Bathymetric type resembles Hellenic Trench site.	Site south of the Athos peninsula. Propagation from NE to SW. It would be ideally treated as 3-D environment; see also Aegean Sea I site. Irregular bathymetry involving two significant mounts and corresponding depressions.
Parameters of numerical codes		
KRAKENC	No. of segments in range: 75; a second intermediate medium was used	No. of segments in range: 90; a second, intermediate, medium was used.
BELLHOP	No. of receivers: 1471x621	No. of receivers: 1849x161
RAMGeo	Artificial, absorbing bottom placed at 1800 m depth.	Artificial, absorbing bottom placed at 2800 m depth.

The Aegean Sea I environment is very difficult for the acoustic propagation codes. Extensive results and detailed comments can be found in the report of Taroudakis and Sapkas (2022). It is worth mentioning that in that report, three sub-sections in the examined transect were distinguished to analyse the performance of the propagation codes. The first section was defined from the source to the peak of the first mount which occurs at a distance of 48 km from the source. The second section was defined from the peak of the first mount to the peak of the second mount at a distance of 85 km from the source. The third section was defined between the peak of the second mount and the location of the receiver. Furthermore, the Aegean Sea I site was chosen as one of the two sites (the other is the 'Marseille' site) for testing the performance of the codes at the frequency of 1000 Hz.

5.3.3.1. *Aegean Sea I*

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 21.

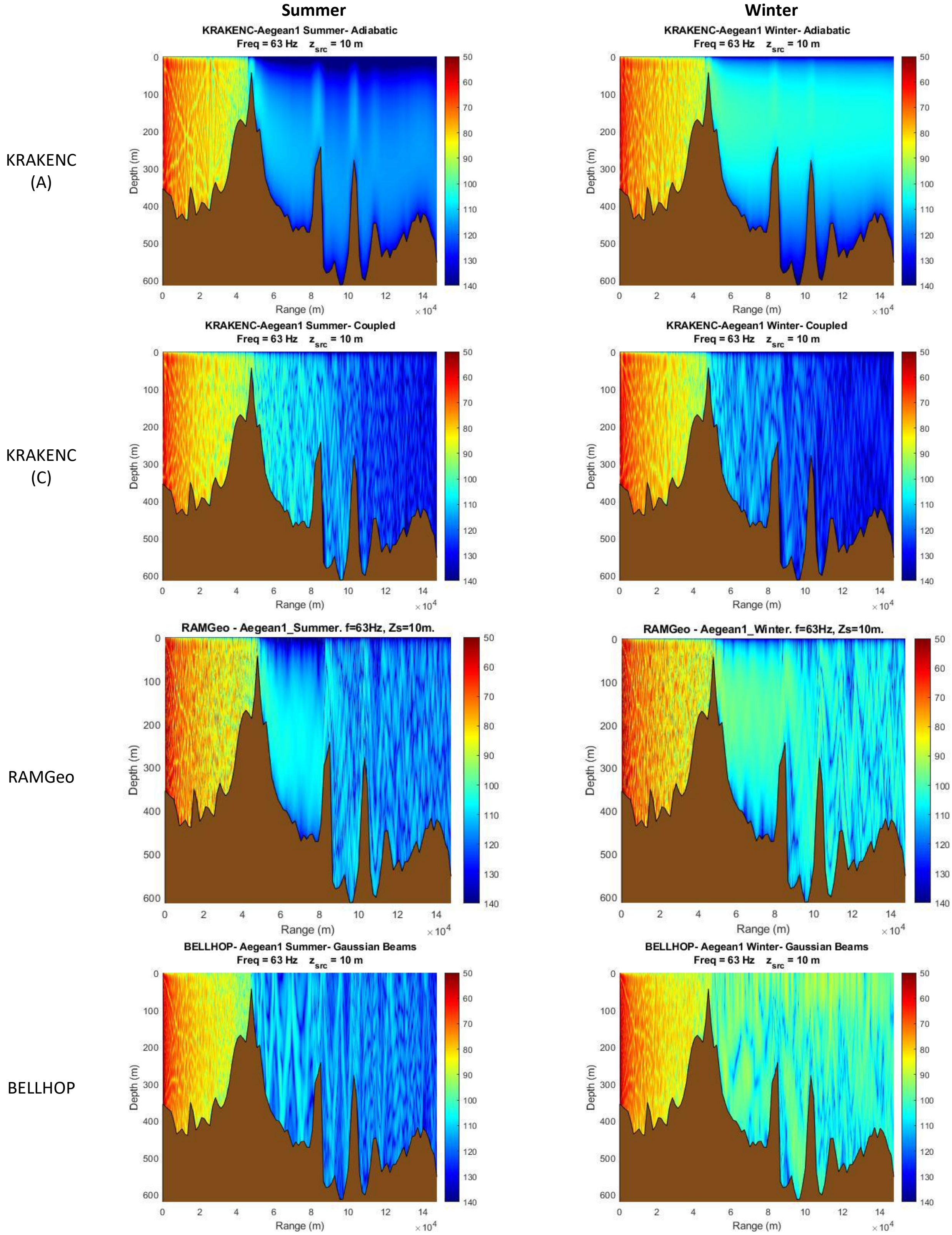


Figure 21. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Aegean Sea I test site (Area III) at 63 Hz.

The results from the simulations for the **frequency of 125 Hz** are shown in Figure 22.

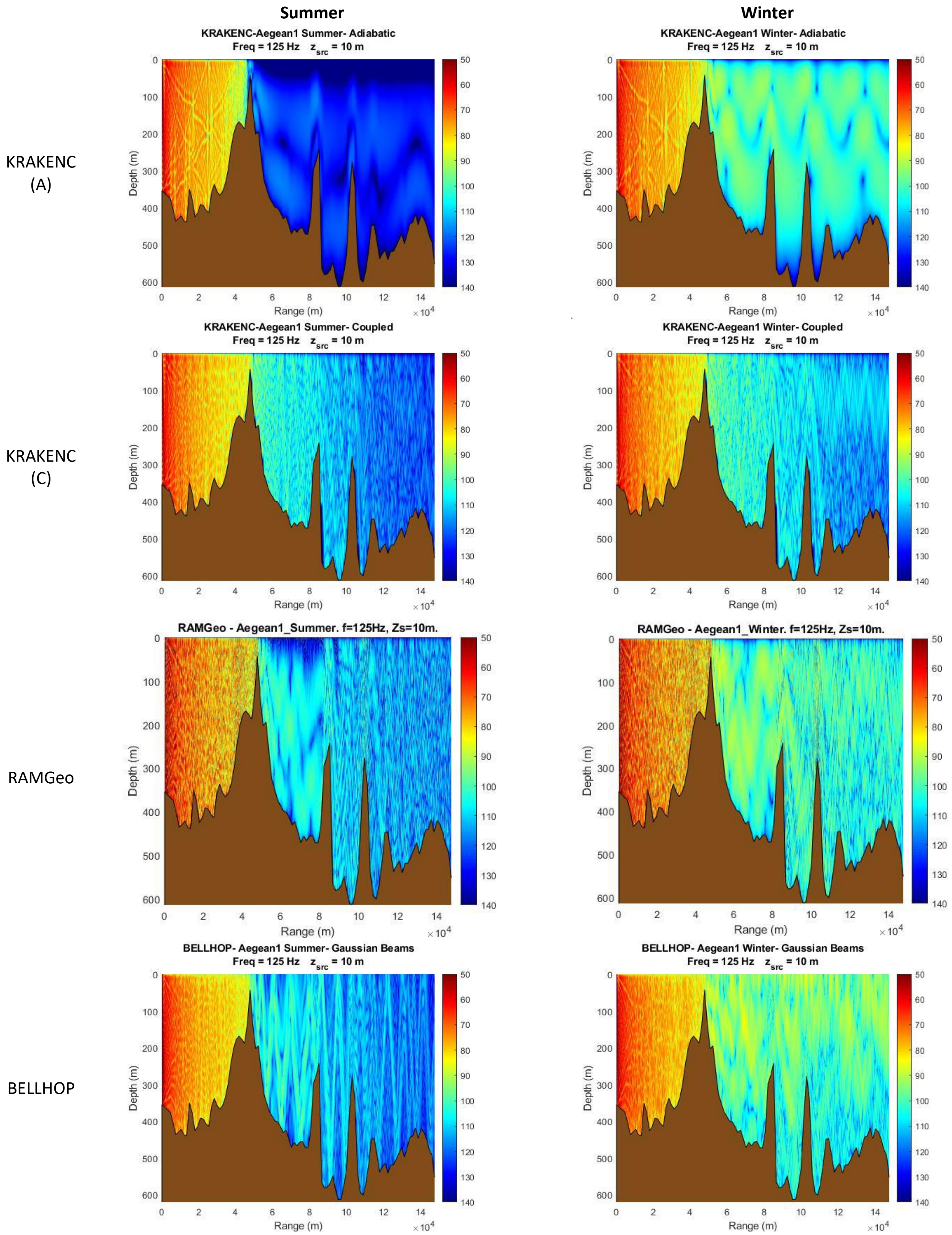


Figure 22. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Aegean Sea I test site (Area III) at 125 Hz.

Summary

This site is considered as a very complicated one, requiring further analysis. More transects should be considered to compare results and conclusions derived and possibly more receiver depths should be considered given the complexity of the acoustic field in this area. Nevertheless, some conclusions to be derived for this area could be considered as critical for the application of sound field prediction models for shipping noise prediction.

The execution (run) times of the codes for 63 Hz, 125 Hz and 1000 Hz are presented in Table 9.

Table 9. Execution (run) times of the examined codes for the Aegean Sea I test site.

	Summer			Winter	
	63 Hz	125 Hz	1000 Hz	63 Hz	125 Hz
Model	Execution time is seconds (s)			Execution time is seconds (s)	
KRAKENC Adiabatic	5	12.5	896	4.5	11
KRAKENC Coupled	5	12.5	896	4.5	11
RAMGeo	9	9	10	9	9
Coherent BELLHOP	16	17.5	27.6	22	26

A general conclusion that can be derived for this area is that KRAKENC adiabatic cannot be used for predicting the acoustic field at the deep parts of the environment, even for the low frequencies. It cannot be used for the prediction of the acoustic field in shallow or deep water at 1000 Hz, when the propagation is considered beyond the peak of a shallow mount. However, it can be used for an approximate prediction of the acoustic field in shallow water at the low frequencies, when absolute accuracy is not required.

KRAKENC coupled, although in principle the most reliable model with respect to the underlying theory, it faces several problems of applicability probably due to reasons associated with the numerical treatment of the modal expansion of the acoustic field. Further study is required to assess the possibility of improving the reliability of the results by appropriate tuning of the operational parameters. At the 1000 Hz frequency, it is very slow in calculating the modes and its accuracy is questionable. BELLHOP results seem to be the most consistent model for summer and winter cases and for the various frequencies of interest. From this point of view and despite the fact that the low frequency results must be interpreted with caution, it could be a good choice for an environment with the characteristics of Aegean I.

All the models provide comparable results in the first section which is described as shallow water with irregular bathymetry facing an abrupt elevation of the sea-floor. The fact that the models behave differently after the seabed elevation is because the environment is strongly range-dependent. For reasons attributed to their numerical treatment, the models cannot show the same performance. It is also interesting to note that KRAKENC seems to be the fastest code for application in this area for 65 Hz, while RAMGeo is the fastest in 125 Hz.

A general comment for this site is that due to its complexity, no general conclusions can be derived. For instance, for shallow receivers only, a good compromise between reliability, requirements for traffic noise modelling, and speed would be KRAKENC adiabatic if the frequency of interest is 125 Hz. This not the case for the frequency of 63 Hz.

Obviously, this environment requires further study for defining the most appropriate code to be used in connection with the set of optimal operational parameters.

5.3.3.2. *Aegean Sea II*

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 23.

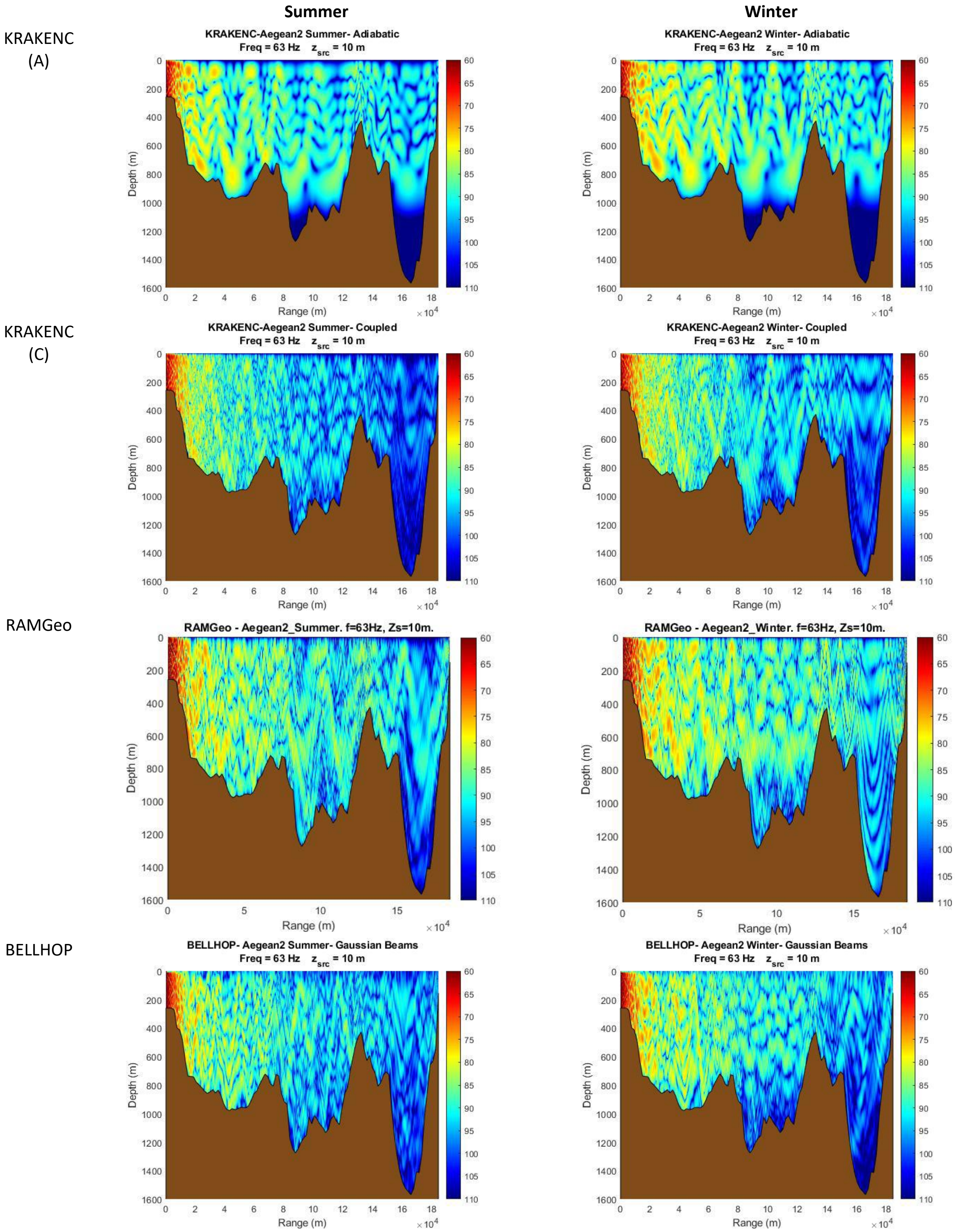


Figure 23. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Aegean Sea II test site (Area III) at 63 Hz.

The results from the simulations for the **frequency of 125 Hz** are shown in Figure 24.

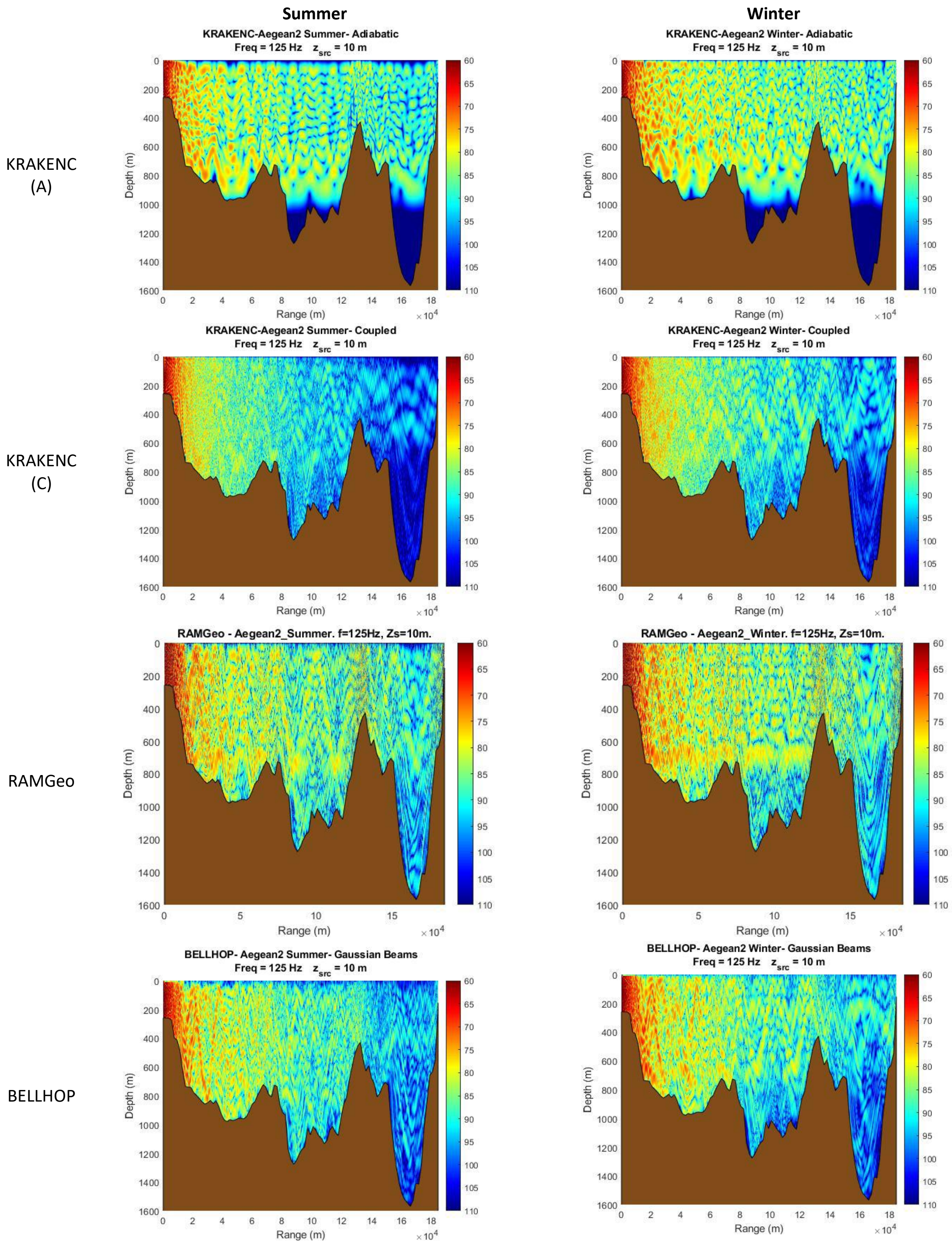


Figure 23. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Aegean Sea II test site (Area III) at 125 Hz.

Summary

The execution (run) times of the codes for the frequencies of 63 Hz and 125 Hz (summer and winter SSPs) are presented in Table 10.

Table 10. Execution (run) times of the examined codes for the Aegean Sea II test site at 63 Hz and 125 Hz.

Summer	63 Hz	125 Hz
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	12	44
KRAKENC Coupled	14	44
RAMGeo	17	17
Coherent BELLHOP	11	12

Winter	63 Hz	125 Hz
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	12.5	49.5
KRAKENC Coupled	12.5	49.5
RAMGeo	18	18
Coherent BELLHOP	11	12

The site is considered as complicated with respect to the bathymetry. It is simpler than that of the Aegean Sea I case, and the codes are able to predict similar acoustic fields. For shallow receiver depths all codes can be used with relative confidence and the results obtained by summing the contribution from different sources which at some moments are placed at different ranges (ships) are expected to be similar. With respect to the time required to run the codes, there is not much difference, with KRAKENC showing similar execution time compared to BELLHOP. Given the fact that the modelling of the shipping noise can be made with the propagation modes pre-calculated, KRAKENC (adiabatic or coupled) may be the first choice for this environment and for shallow receivers.

5.3.4. Area IV

Two test sites were selected from Area IV: ‘Adriatic Sea I - Ancona’ or simply ‘Ancona’ and ‘Adriatic Sea II- Venice’ or simply ‘Venice’. The sites with the specific transects, the bathymetric profiles, and the SSPs for each site from Area IV are shown in Figure 25, while relevant environmental features and input parameters of the numerical codes are described in Table 11.

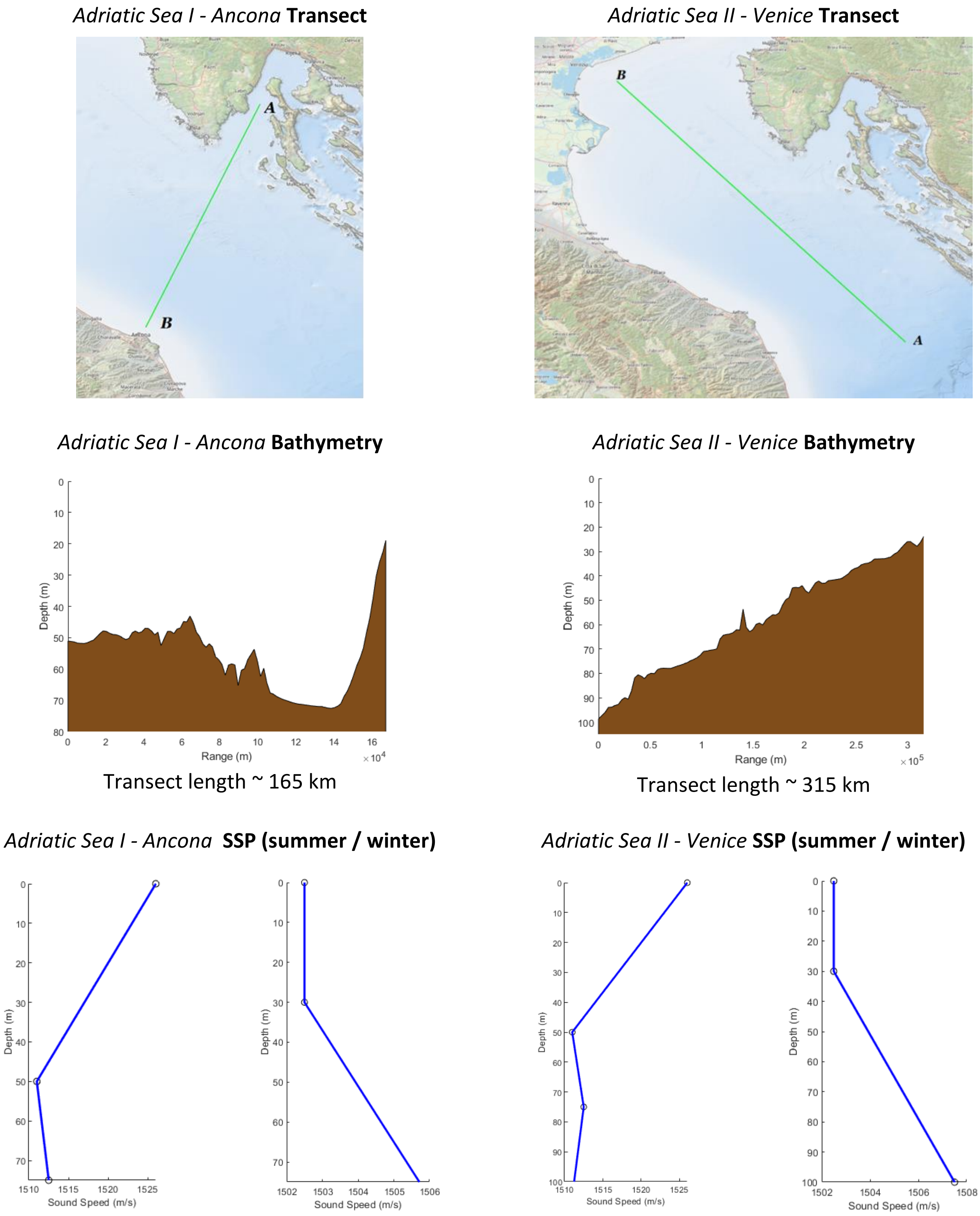


Figure 24. Sites with transects, bathymetric profiles and SSPs for Area IV. Propagation transects, the bathymetric profiles and SSPs for ‘Ancona’ (left column) and ‘Venice’ (right column) test sites.

Table 11. Environmental features and input parameters of the numerical codes for the test sites of the Area IV.

	'Adriatic Sea I - Ancona'	*'Adriatic Sea II - Venice'*
Environmental features	Propagation from NE to SW. The environment is characterised as shallow water with smooth changes in the bathymetry, with the exception of the sub-area close to the Croatian shore for which upslope propagation is observed.	Propagation from SE to NW. The environment is characterised as an up-slope shallow-water one. It is considered very simple.
Parameters of numerical codes		
KRAKENC	No. of segments in range: 75; a second intermediate medium was used	No. of segments in range: 99; a second, intermediate, medium was used.
BELLHOP	No. of receivers: 1471x621	No. of receivers: 306x101
RAMGeo	Artificial, absorbing bottom placed at 1800 m depth.	Artificial, absorbing bottom placed at 190 m depth.

5.3.4.1. *Adriatic Sea I – Ancona*

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 26.

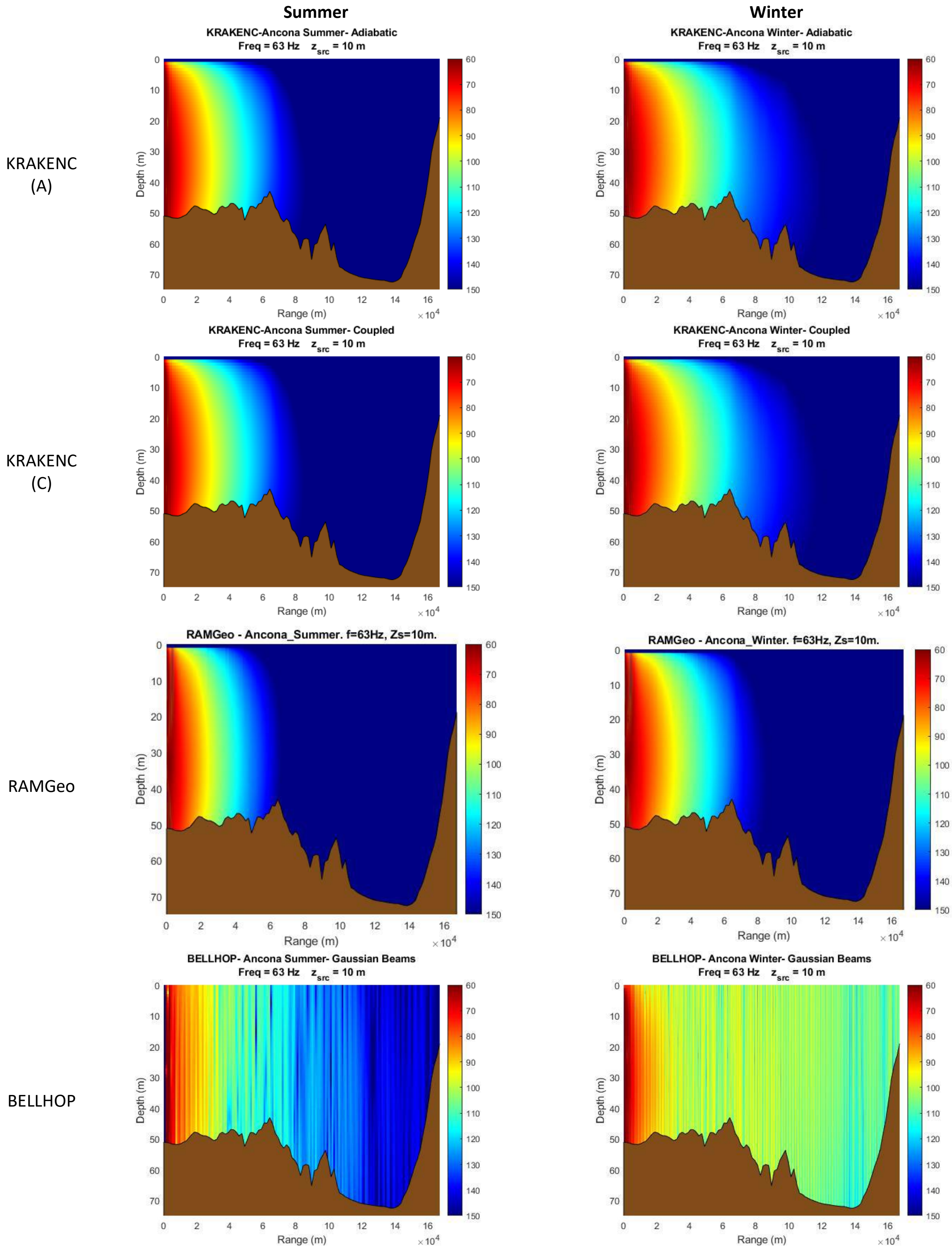


Figure 25. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Ancona test site (Area IV) at 63 Hz.

The results from the simulations for the **frequency of 125 Hz** are shown in Figure 27.

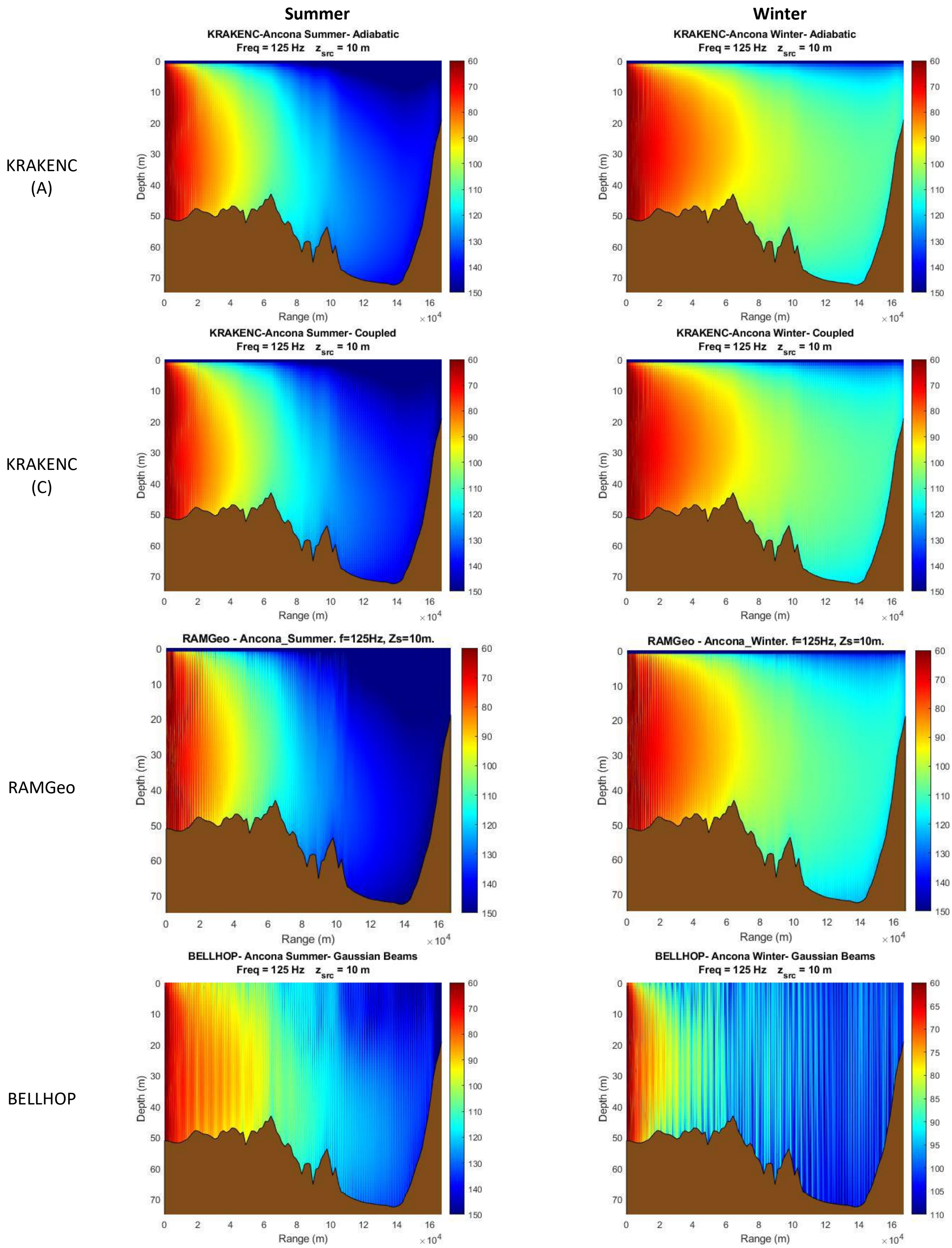


Figure 26. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Ancona test site (Area IV) at 125 Hz.

Summary

The execution (run) times of the codes for the frequencies of 63 Hz and 125 Hz (summer and winter SSPs) are presented in Table 12.

Table 12. Execution (run) times of the examined codes for the Adriatic Sea I – Ancona test site at 63 Hz and 125 Hz.

Summer	63 Hz	125 Hz
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	2	2
KRAKENC Coupled	2	2
RAMGeo	3	1
Coherent BELLHOP	112	114

Winter	63 Hz	125 Hz
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	2	2
KRAKENC Coupled	2	2
RAMGeo	2	2
Coherent BELLHOP	109	108

This site is described as shallow water for the full length of the propagation path. For the low frequencies which are of interest for this study, it is well known that the wave theory is ideal for treating acoustic propagation problems. This was confirmed by means of the results obtained for the summer and winter SSP for both 63 and 125 Hz. It is also interesting that the running time for both codes was less than 2 sec, almost equal to that of the RAMGeo, which provided identical results for the case of 125 Hz, but showed an overestimation of the losses at long ranges in 63 Hz. BELLHOP was proven not reliable for this environment and frequencies, and in addition the running time was very high (108-114 sec).

Based on these results, the best choice for this area is KRAKENC (coupled or adiabatic).

5.3.4.2. *Adriatic Sea II – Venice*

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 28.

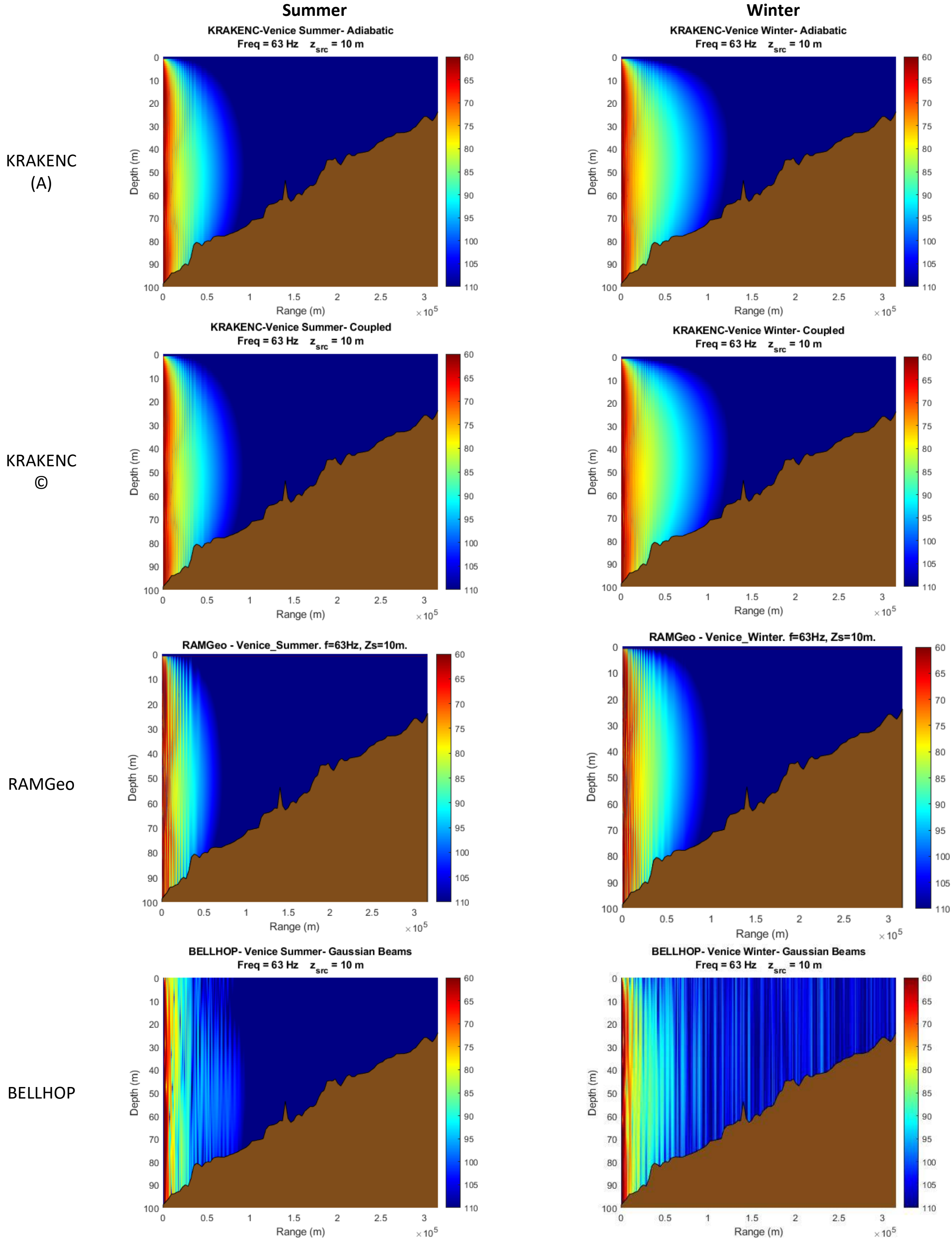


Figure 27. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the Venice test site (Area IV) at 63 Hz.

Summary

The execution (run) times of the codes for the frequency of 63 Hz (summer and winter SSPs) are presented in Table 13.

Table 13. Execution (run) times of the examined codes for the Adriatic Sea I – Venice test site at 63 Hz.

Frequency 63 Hz	Summer	Winter
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	2	2
KRAKENC Coupled	2	2
RAMGeo	3	2
Coherent BELLHOP	12	20

This site is described as shallow water for the full length of the propagation path. For the low frequencies which are of interest for this study, it is well known that the wave theory is ideal for treating acoustic propagation problems. This was confirmed by means of the results obtained for the summer and winter SSP for both 63 Hz. The same conclusions are derived for the 125 Hz (not shown here). It is also interesting that the running time for both codes was less than 2 sec, almost equal to that of the RAMGeo, which provided results very close although not identical to those of KRAKENC for the case of 125 Hz. Also, it showed an overestimation of the losses at long ranges in 63 Hz. BELLHOP was proven not reliable for this environment and frequencies.

The general comment of the Adriatic Sea is that wave-theory models (KRAKENC adiabatic or KRAKENC coupled) are the most appropriate and reliable to be used for predicting Transmission Loss in this area, as they are able to provide consistent results for all frequencies and propagation paths in shallow water.

5.3.5. Area V

Two test sites were selected from Area V: ‘Black Sea I – Constanza I’ or simply ‘Constanza I’ and ‘Black Sea II – Constanza II’ or simply ‘Constanza II’. The sites with the specific transects, the bathymetric profiles and the SSPs for each site from Area V are shown in Figure 29, while relevant environmental features and input parameters of the numerical codes are described in Table 14.

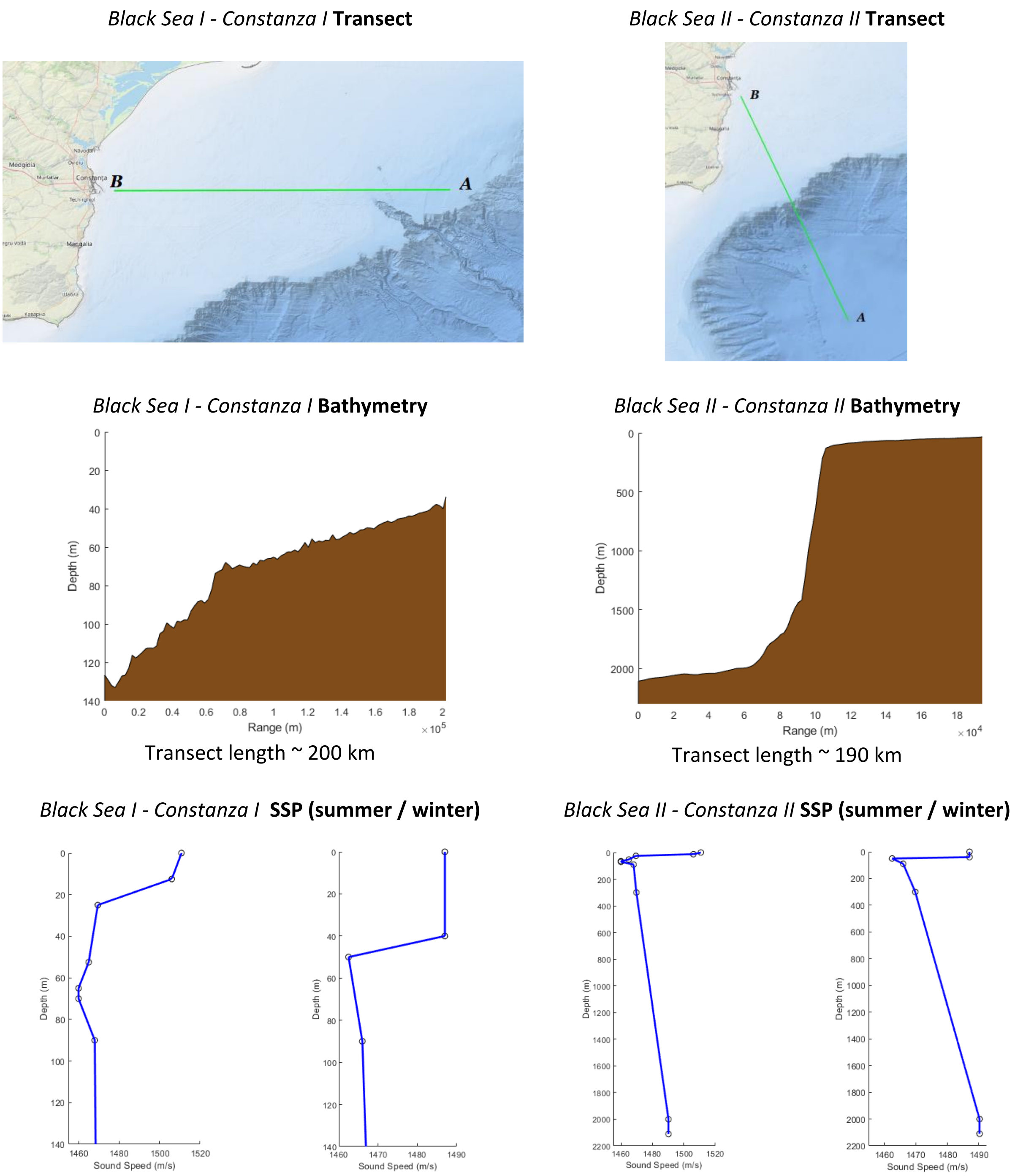


Figure 28. Sites with transects, bathymetric profiles and SSPs for Area V. Propagation transects, the bathymetric profiles and SSPs for ‘Constanza I’ (left column) and ‘Constanza II (right column) test sites.

Table 14. Environmental features and input parameters of the numerical codes for the test sites of the Area V.

	'Black Sea I - Constanza I'	*'Black Sea II - Constanza II'*	*'Black Sea II - Constanza II RP'*
Environmental features	Propagation from E to W. It concerns an area in the Black Sea towards the Romanian shore close to Constanza. The environment is characterized as shallow water with up-slope propagation with the shallowest depth approximately 38 m. In this respect, it is reminiscent of the environment of the Venice test site.	Propagation from SE to NW. It concerns an area in the central Black Sea towards the Romanian shore close to Constanza. The difference of this site with respect to 'Black Sea I – Constanza I' is that it involves a deep water part. Water depth at the deepest part of the slice is on the order of 2100 m. Up-slope propagation is considered with abrupt change of the bathymetry.	Environment same with 'Constanza II', but reverse propagation (RP) is examined. Propagation from NW to SE up to a range of 120 km. Source placed closer to the continental shelf than the exact reversion of 'Constanza II' case by 75 km. This case is examined for monitoring shipping noise at deep areas while ships are sailing close to the shore. It is expected that conclusions derived from this case can be generalized to reverse propagation in other cases.
Parameters of numerical codes			
KRAKENC	No. of segments in range: 97; a second intermediate medium was used	No. of segments in range: 94; a second, intermediate, medium was used.	No. of segments in range: 60; a second, intermediate, medium was used.
BELLHOP	No. of receivers: 1945x212	No. of receivers: 1945x212	No. of receivers: 1145x2018
RAMGeo	Artificial, absorbing bottom placed at 450 m depth.	Artificial, absorbing bottom placed at 2800 m depth.	Artificial, absorbing bottom placed at 2900 m depth.

5.3.5.1. *Black Sea I - Constanza I*

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 30.

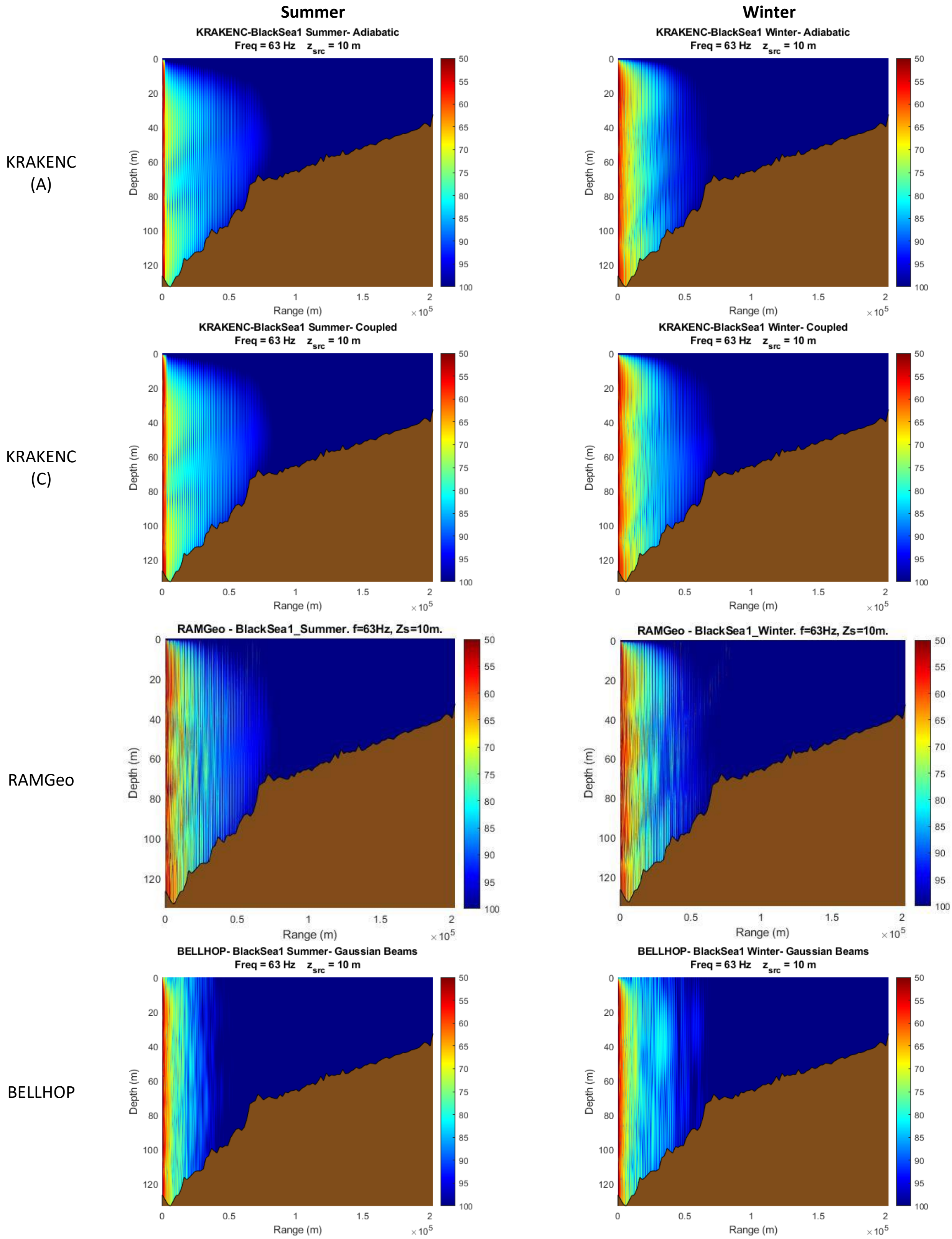


Figure 30. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the 'Constanza I' test site (Area V) at 63 Hz.

The results from the simulations for the **frequency of 125 Hz** are shown in Figure 31.

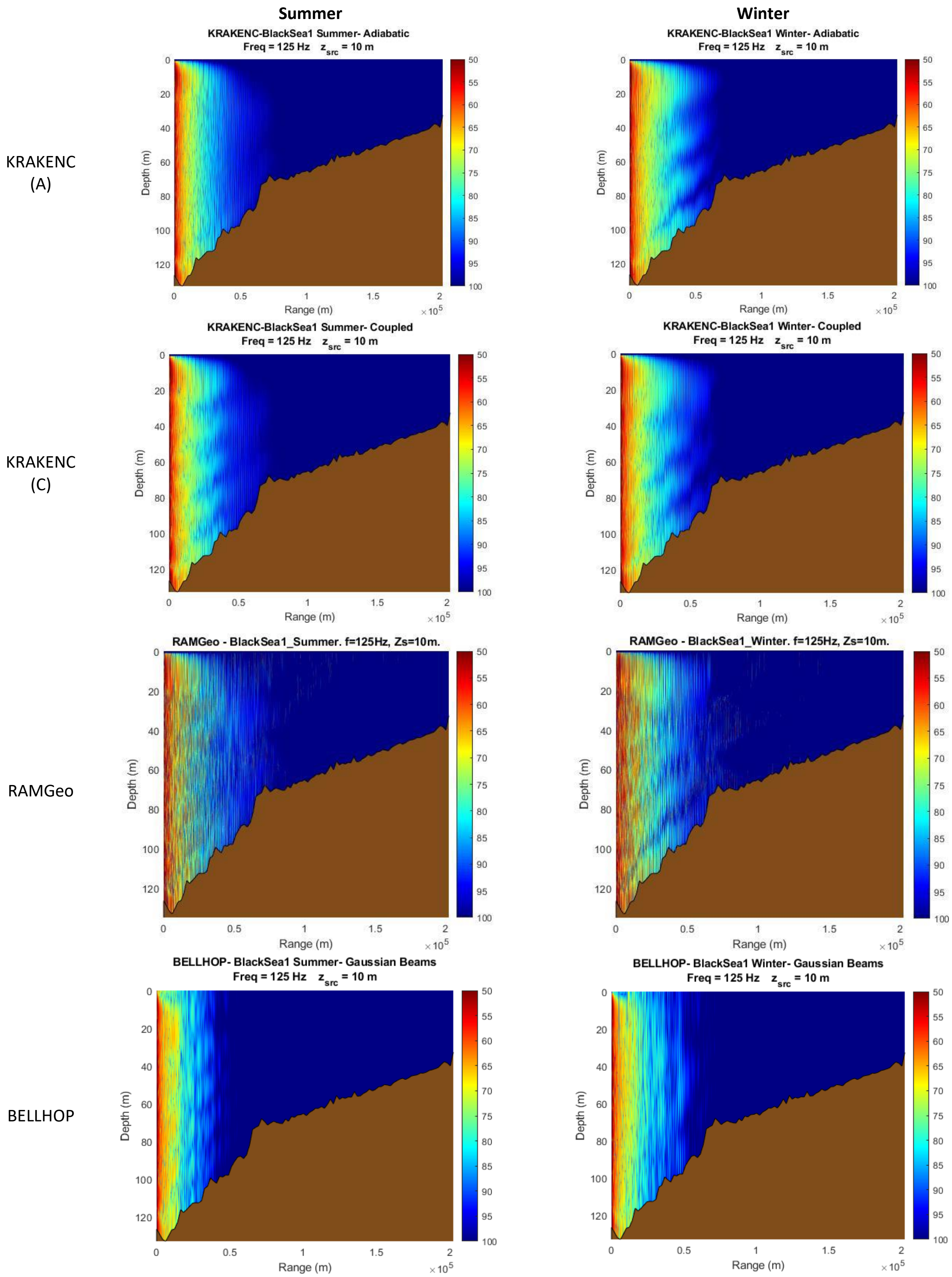


Figure 9. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the 'Constanza I' test site (Area V) at 125 Hz.

Summary

The execution (run) times of the codes for the frequencies of 63 Hz and 125 Hz (summer and winter SSPs) are presented in Table 15.

Table 15. Execution (run) times of the codes for the 'Black Sea I – Constanza I' test site at 63 Hz and 125 Hz.

Summer	63 Hz	125 Hz
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	2	2
KRAKENC Coupled	2	2
RAMGeo	3	3
Coherent BELLHOP	7	11

Winter	63 Hz	125 Hz
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	2	2
KRAKENC Coupled	2	2
RAMGeo	3	3
Coherent BELLHOP	60	58

This site is described as shallow water up-slope for the full length of the propagation path. For the low frequencies which are of interest for this study, we confirmed once more the reliability and speed of the KRAKENC codes (adiabatic and coupled) as they were able to predict the acoustic field at less than 1 sec, for both 63 and 125 Hz frequencies. RAMGeo provided identical results for the case of 125 Hz, but showed an overestimation of the losses at long ranges in 63 Hz exactly as observed in the Adriatic Sea. In addition, it proved to be a little slower than the KRAKENC codes and the execution time for both frequencies was of the order of 3 sec. BELLHOP was proven not reliable for this environment and frequencies, and in addition the running time was very high.

5.3.5.2. *Black Sea II – Constanza II*

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 32.

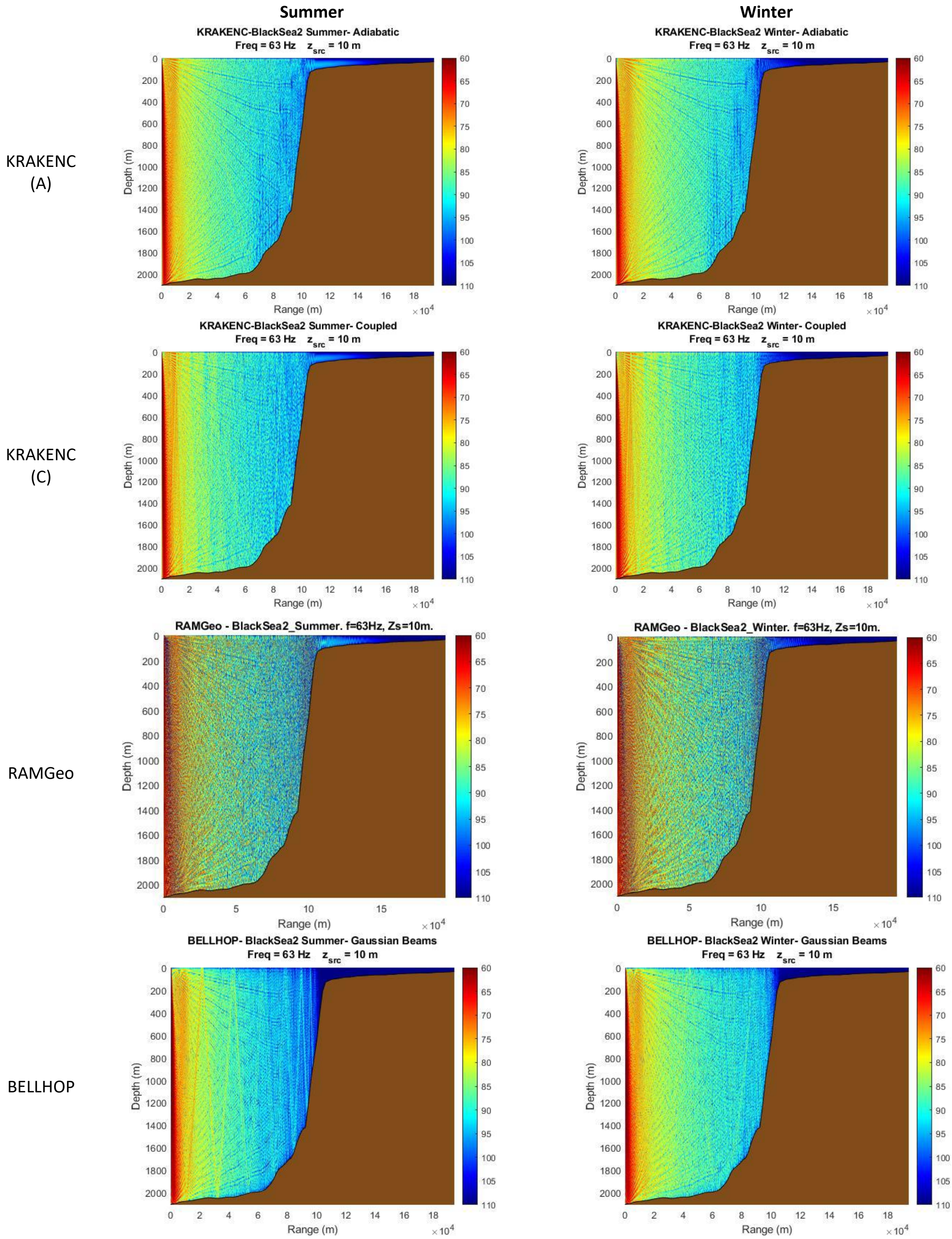


Figure 10. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the 'Constanza II' test site (Area V) at 63 Hz.

Summary

The execution (run) times of the codes for the frequency of 63 Hz (summer and winter SSPs) are presented in Table 16.

Table 16. Execution (run) times of the codes for the 'Black Sea II – Constanza II' test site at 63 Hz.

Frequency 63 Hz	Summer	Winter
Model	Execution time is seconds (s)	
KRAKENC Adiabatic	7	7
KRAKENC Coupled	7	7
RAMGeo	16	16
Coherent BELLHOP	7	9

This site is described as an environment of abrupt transition from deep water to shallow water. For the low frequencies which are of interest for this study, we confirmed once more the reliability and speed of the KRAKENC codes (adiabatic and coupled). RAMGeo provided very similar results in both deep water and shallow water areas. BELLHOP was proven not reliable for the transition and shallow part of the environment. The observations were consistent for both summer and winter SSP.

Based on the above, the choice of KRAKENC (adiabatic or coupled) for estimating the TL in such an environment is suggested.

5.3.5.3. *Black Sea II – Constanza II RP*

The results from the simulations for the **frequency of 63 Hz** are shown in Figure 33.

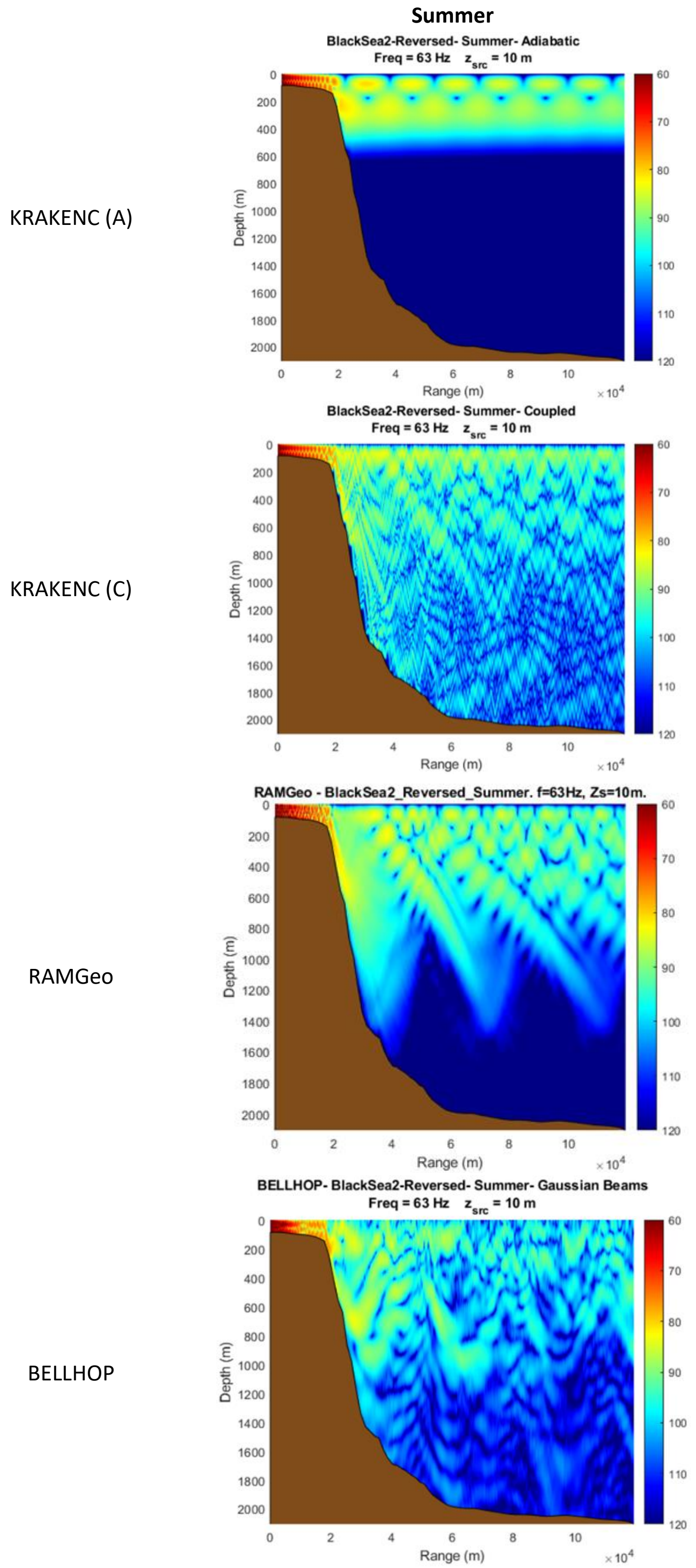


Figure 11. Acoustic propagation models outputs for summer (left column) and winter (right column) profiles and the four considered models (rows) for the 'Constanza II RP' test site (Area V) at 63 Hz.

Summary

The execution (run) times of the codes for the frequency of 63 Hz (summer SSP) are presented in Table 17.

Table 17. Execution (run) times of the codes for the 'Black Sea II – Constanza II RP' test site at 63 Hz.

Frequency 63 Hz	Summer
Model	Execution time is seconds (s)
KRAKENC Adiabatic	14
KRAKENC Coupled	15
RAMGeo	11
Coherent BELLHOP	50

This case is characterized by downslope propagation with an abrupt change from shallow to deep water. This is perhaps an extreme case, requiring more elaborate study concerning the operational parameters of the various codes to get reliable predictions of the acoustic field. As part of the propagation is in very shallow water, BELLHOP cannot considered as reliable due to the additional factor of low frequencies; furthermore, its execution time is considerably higher. On the other hand, the abrupt transition from shallow to deep water does not allow the derivation of definite remarks with respect to the suitability of the other two codes for the prediction of the acoustic field in deep and shallow water areas. In the absence of ground-truthing, and based on the underlying theory upon which the codes are based, KRAKENC coupled seems to be the best choice for this area, with RAMGeo being the second choice.

It is very important to note that the case of 'Black Sea II – Constanza II RP' in Area V can be met at many sites in the MED and BS, where -going offshore- abrupt slopes and deep water follow a shallow or relatively shallow water bathymetry; see e.g., the 'Barcelona' site in Area I. Other characteristic examples in Area I are the NE Balearic Isl., almost the whole French coast offshore, west of Sardinia Isl. and offshore Tunis, but similar sites can be found in Central MED (an extended area southeast of Sicily Isl.), in south-eastern MED (offshore Egypt and Israel), and even in the Aegean Sea (Area IV).

6. Use of acoustic propagation approaches/models in appropriate assessment areas of the Mediterranean and the Black Sea

6.1. Considerations of MRUs and habitats in a risk-based assessment framework for continuous noise

Given that the acoustic propagation modelling approaches in this report are examined with a view to applying them to a shipping noise model supporting a risk-based assessment framework for continuous noise, specific points of the recently-adopted relevant TG Noise (2021), related to the issue of assigning acoustic propagation models to appropriate marine areas of the MED and BS, will be considered in this section.

According to the Annex 2 of TG Noise (2021), Grid Cell is the area where the acoustic condition is evaluated to conclude if the Grid Cell is non-significantly or significantly affected. Habitat is the area where the acoustic status is determined and characterised as tolerable or not tolerable by aggregating the condition of multiple Grid Cells. MRU is the area where the environmental status is assessed to conclude if the MRU is at GES or not at GES.

According to Annex 1 of SWD (2020)62, the term Habitat may refer either to the environment used and occupied by a single species (the nature and scale of the habitat can vary markedly according to the particular needs of the species across all stages of its life history) or to a multi-species concept, where the habitat comprises particular biotic and abiotic characteristics. In contrast to the habitat of a single species, this use of the term habitat refers to something that is more uniform in its character, leading to the definition and classification of habitat types and the ability to produce maps of habitats.

On the other hand, according to SWD (2020)62, Section 5.4, MRUs are termed as the specific areas of each region or subregion to which each assessment applies. A judgment is made on whether GES has been achieved and the extent to which GES has been achieved is reported. According to the same document, it is recommended that the appropriate scale of GES assessment for D11C2 is: regions, subregions and a suitable (and preferable low) number of subdivisions (of regions or subregions), the latter being potentially delineated using national borders of marine waters. This recommendation is in line with the Commission Decision (EU) 2017/848 under "Methodological standards" for D11, while guidance for MRUs is expected to be updated.

It should be stressed here that the scope of TG Noise (2021) is the evaluation of the condition of the Grid Cells and the determination of the status in a Habitat, while details on the link between Habitats and MRUs has been left to be resolved in TG Noise DL4 (options for threshold values for continuous noise). Nevertheless, TG Noise (2021) recommends that:

a. Habitats and indicator species can be firstly considered at MS level
b. When habitats expand to more than one MS, then the subregional/regional level is recommended.

At this point it should be additionally noted that

c. Even when a habitat is of a small spatial extent, the effect of continuous noise on its marine life (hence the determination of its acoustic status) should appropriately account for sufficiently distant contributions. Thus, acoustic propagation and shipping noise modelling should be considered at sufficiently larger areas than that of a spatially limited habitat.

Taking (a), (b) and (c) into account, QUIETSEAS D4.1 concludes that, at least for the important indicator-species category of wide-ranging cetaceans, the choice of the subregion as a MRU seems to be the minimum scale to carry out meaningful assessments for low-frequency long-propagating continuous noise generated from shipping, and that the multi-species habitat might be considered of similar scale with the subregion assessment scale (see QUIETSEAS D4.1, section 4.1-Biodiversity and section 4.4-Linking habitats with MRUs). An exception could be the subregion of Aegean-Levantine, where the elongated embayment of Aegean archipelago exhibits essentially different physical features from the Levantine Sea, so -as suggested in section 4.1- Aegean and Levantine Seas could be handled as two distinct subdivisions regarding D11C2 determination of status of their habitats and GES assessment. Actually, the specificities of the Aegean archipelago are clearly revealed in the relevant test cases presented in Section 5.3.

6.2. Conclusions and Recommendations

To make meaningful conclusions and recommendations based on the study presented in Section 5.3, it is important to summaries the basic features/constraints that dictated the research conducted.

a) Four open codes representing three different propagation models were used.
b) No attempt was made to change anything in the source code associated with each model.
c) Although some preliminary evaluation of the performance of the models was performed for the areas of interest and the operational parameters were chosen so that a generally good behavior of the models was assured for all cases (areas, seasons, and frequencies) considered, no attempt was made to fine-tune the operational parameters for each test case to ensure that the results are the best in each case.
d) Due to the complexity of the environment with respect to the bathymetry in each area, one or two typical vertical slices were chosen as the environment of the test cases. This choice cannot be considered adequate to assess in detail the performance of the models in areas exhibiting different bathymetry.
e) A range-independent sound speed profile was considered for each case studied, different for summer and winter.
f) The seabed in all cases was considered fluid and semi-infinite in extent with specific geoacoustic parameters and a standard attenuation of 0.5 dB/wavelength.
g) The results presented here are referred to as transmission loss (TL) values which are consistent with the goal of the study associated with ship traffic noise modeling.
h) Long propagation paths have been considered.
i) No ground-truthing was available, which means that the results obtained cannot be compared with measured acoustic field data.

In view of the above, the analysis presented here cannot been considered as an absolute tool for assessing the suitability of the available acoustic propagation models to be used in the development of shipping noise prediction models or for a complete analysis of the acoustic propagation characteristics in the areas of interest. On the other hand, given the fact that the test cases studied are characterized by different bathymetries, the conclusions can be used for assessing the general suitability of the models in areas exhibiting typical bathymetry sections.

Based on the above, the areas considered can be classified as following:

- Upslope propagation (Deep or Shallow)
- Downslope propagation (Deep or Shallow)
- Irregular bathymetry (Deep or Shallow)

Combinations of these features were met in all the cases studied, and variations from one feature to another were observed within each section considered.

It was observed that the behavior of the models does not change between summer and winter at least to a degree that would dictate the use of a different model among these seasons. Of course, the acoustic field predicted in summer is different than that predicted for winter conditions, but there is a consistency between the behavior of the codes for winter and summer sound speed profiles. For this reason, the assessment is based on the propagation frequency only. Note that for practical reasons it is not considered feasible to change the underlying model in a shipping noise prediction tool according to the frequency, unless the modeling allows the use of more than one codes for the prediction of the noise levels.

In Table 18 the observations made for the various areas as regards the applicability of the four codes considered are summarized. Red stands for "Not appropriate", yellow for "Limited applicability or applicable with caution" and green for "Suitable Model". When a code is considered suitable, the letters A, B, C indicate priority, with A characterizing the most suitable one. Note that the execution time for each code has been considered for defining the priority. However, this is not an absolute criterion as the codes behave differently for the calculation of the acoustic field. The KRAKENC codes can calculate the modal field for a whole region and then be used for the calculation of the field. Depending on the programming algorithm this might prove an important benefit with respect to the other models. The codes are indicated as following: **KA** KRAKENC adiabatic, **KC** KRAKENC coupled, **RG** RAMGeo, **BH** BELLHOP.

In general, we can conclude that:

- For shallow-water areas, the use of ray-tracing models implemented by codes such as BELLHOP is not recommended. Ray-tracing can be used as an alternative model when areas characterized as deep water, without strong interaction with very shallow water parts, are of interest or when incoherent calculations are requested. Furthermore, BELLHOP indicated the highest dependence of propagation paths with the sound speed profile gradient, and therefore should be used with caution. However, its efficiency in the complex cases of Aegean Sea (Area III) even for low frequencies is worth noting.
- A normal-mode model could be considered for predicting low-frequency shipping noise for the whole MED and BS, after appropriate tuning of its operational parameters. This model, which in our study was implemented by means of the KRAKENC – coupled code, is reliable and fast for most of the cases studied, which represent typical areas in the MED. This model can also be used with high confidence in shallow-water areas such as the Adriatic Sea and extended areas of the BS. Also, its successful use for the test case of Area V with reverse propagation is worth noting, since similar environments are often met in MED and BS.
- RAMGeo solutions are generally consistent with KRAKENC – Coupled, but exhibit 'noise' in the calculation of the field, which could be a limiting factor. In the case of shallow-water

seas, the usage of an absorbing bottom becomes a crucial factor in pressure field attenuation and extremely case-dependent. It can be considered as a fair solution for the prediction of the acoustic field in most cases, since it was not characterised as "not appropriate" in any of the low-frequency test cases.

Table 18. Evaluation summary of the performance of the codes used in this study

AREA 1 (Marseille)							
63 Hz				125 Hz			
KA (A)	KC (A)	RG	BH (B)	KA (A)	KC (A)	RG	BH (B)
1000 Hz							
KA	KC	RG	BH (A)				
AREA 2 (Barcelona)							
63 Hz							
KA (A)	KC (A)	RG	BH (B)				
AREA 3 (Genova)							
63 Hz				125 Hz			
KA (B)	KC (B)	RG(C)	BH (A)	KA (B)	KC (B)	RG(C)	BH (A)
AREA 4 (Hellenic Trench 1)							
63 Hz				125 Hz			
KA	KC (B)	RG(C)	BH (A)	KA	KC (B)	RG(C)	BH (A)
AREA 5 (Aegean 1)							
63 Hz				125 Hz			
KA	KC (C)	RG(B)	BH (A)	KA (A)	KC (D)	RG(C)	BH (B)
1000 Hz							
KA	KC	RG	BH (A)				
AREA 6 (Aegean 2)							
63 Hz				125 Hz			
KA (A)	KC (A)	RG(C)	BH (B)	KA (A)	KC (A)	RG(C)	BH (B)
AREA 7 (Ancona)							
63 Hz				125 Hz			
KA (A)	KC (A)	RG	BH	KA (A)	KC (A)	RG(B)	BH
AREA 8 (Venice)							
63 Hz							
KA (A)	KC (A)	RG	BH				
AREA 9 (Constanza 1)							
63 Hz				125 Hz			
KA (A)	KC (A)	RG	BH	KA (A)	KC (A)	RG(B)	BH
AREA 10 (Constanza 2)							
63 Hz				125 Hz			
KA (A)	KC (A)	RG(B)	BH	KA (A)	KC (A)	RG(B)	BH
AREA 10 (Constanza 2 reverse propagation)							
63 Hz							
KA	KC (A)	RG (B)	BH				

- Finally, it seems necessary that a more elaborate analysis of the acoustic propagation conditions in the MED and BS is required, if a ship traffic noise model adjusted to specific areas is to be developed. In this case, the operation parameters of the codes to be chosen can also be tuned to the corresponding areas of interest. A comprehensive study of a sufficient number of cases to be encountered in a considerable number of areas in the MED and BS, accompanied by a validation effort via selected measurements, could be a very good reason for a large-scale joint project to support the use of source shipping noise modelling in the challenging environments of MED and BS.

- Taking into account the considerations of Section 6.1 (especially the last paragraph) and the above general conclusions of this section, in an attempt to distinguish marine areas of the MED and BS as regards continuous noise assessment by means of shipping noise modelling, the following areas could potentially be considered:
    - Western Mediterranean Sea (subregion), appropriately extending the modelling area to take into account the shipping noise contributions from the SE border with Central Mediterranean Sea
    - Adriatic Sea (subregion), appropriately extending the modelling area to take into account the shipping noise contributions from the south border with Ionian Sea
    - Aegean Sea (subdivision of subregion), appropriately extending the modelling area to take into account the shipping noise contributions from the SW border with Ionian Sea and the SE border with Levantine Sea
    - Black Sea (region; excluding Azov Sea)
    - Azov Sea
    - Marmara Sea

The situation is more complicated as regards the Central Mediterranean and Ionian Sea (subregion) as well as Levantine Sea (subdivision of subregion). The first one is affected by the ship traffic from the western border with Western MED, from the northern border with Adriatic Sea, and heavily from the eastern wide border mainly with Levantine but also Aegean Sea. The second one is affected by the ship traffic from the northern border with Aegean Sea, but heavily from the western wide border with Central MED. This is the reason that the Eastern part of MED (including Central MED and Ionian Sea, Levantine and part or the entire Aegean Sea) can be found modelled as one system (see e.g., Skarsoulis et al., 2017).

6.3. Preliminary use of selected models in an on-line assessment tool

In the context of the Saturn project, CTN has developed an online application that allows the user to calculate the TL (or propagation losses) along selected transects in the Mediterranean Sea and in some areas of the Atlantic Ocean in order. This online tool has the capability of including underwater acoustic propagation models (or similar ones) used in the framework of the case studies of Section 5.3. In this section we illustrate the use of this high-level user-oriented tool which is referred to as URN tool.

The first required step is the positioning of the source and the receiver (that defines the transect along which the propagation is calculated), which can be performed either numerically (via specifying longitude, latitude and depth), or directly selecting the location in the map using the cursor (Figure).

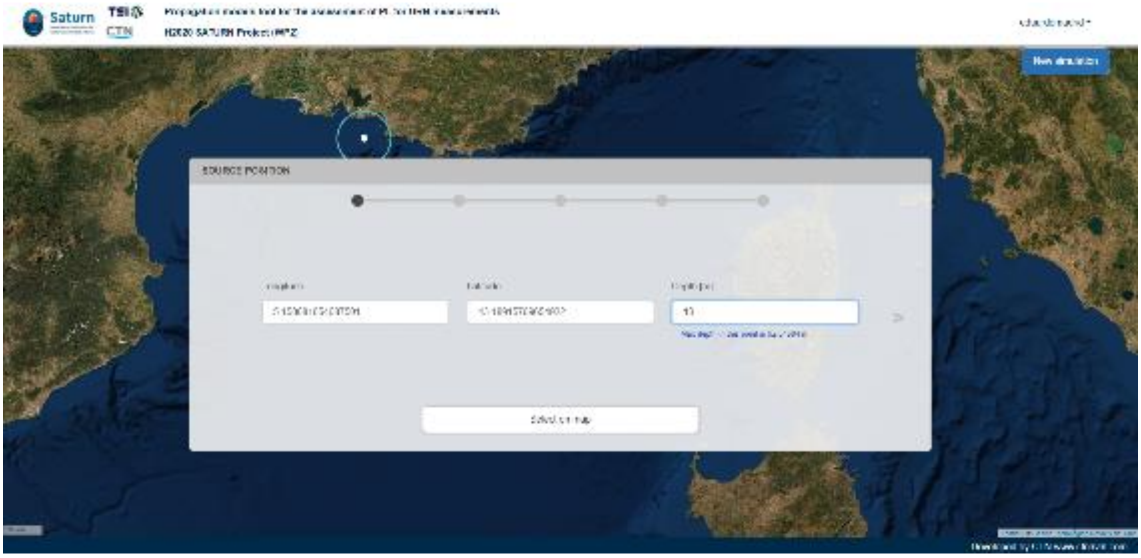


Figure 34. Source position specification in the URN tool.

Next, we specify the receiver position in the same way as the source (Figure). Once this has been done, the tool samples the sound speed profile, as well as the seabed acoustic properties along the considered transect, as it is a tool capable of handling range-dependent environments.

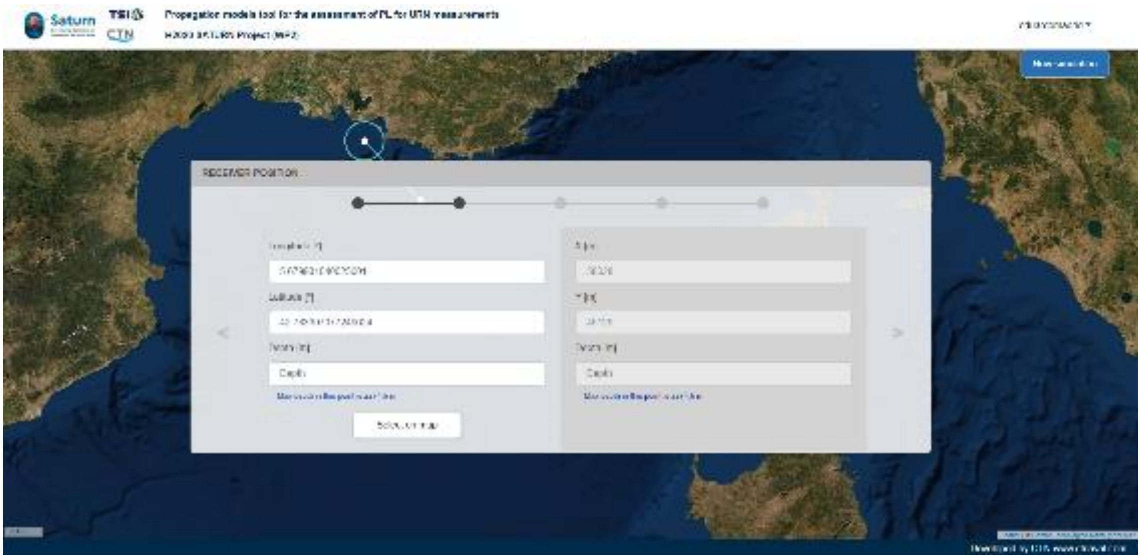


Figure 35. Receiver position specification in the URN tool.

The tool allows to select octaves, thirds of octave and decidecades as frequency bands, from a minimum frequency of 20 Hz up to 100 kHz (Figure).

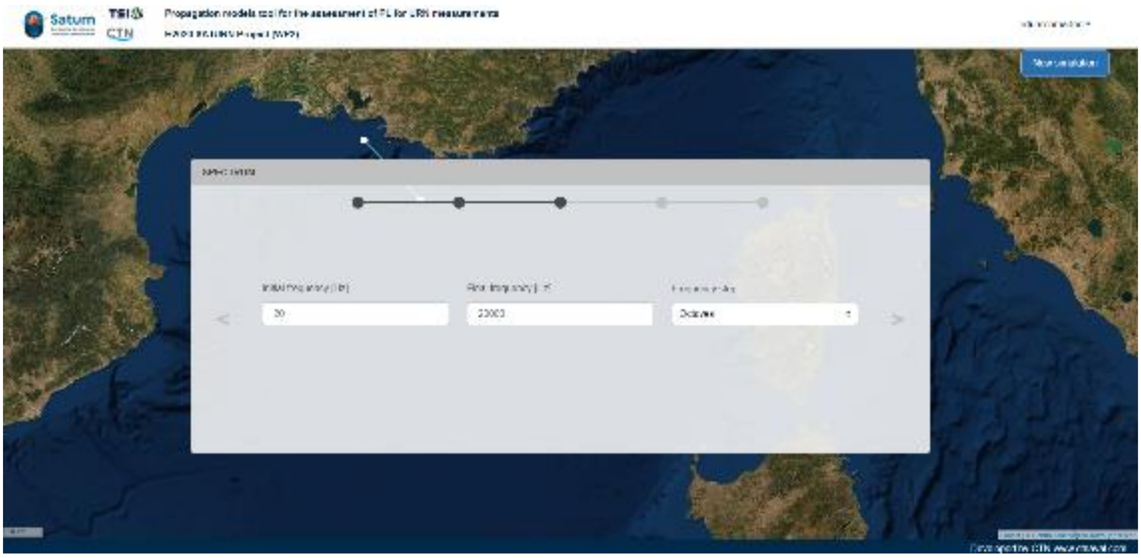


Figure 36. Frequency spectrum selection step of the URN tool.

A set of 9 models are supported, ranging from simple (i.e. analytic) to advanced and complex models, such as ray theory (BELLHOP), normal modes (KRAKEN), and parabolic equation (developed by CTN), as can be seen in Figure.

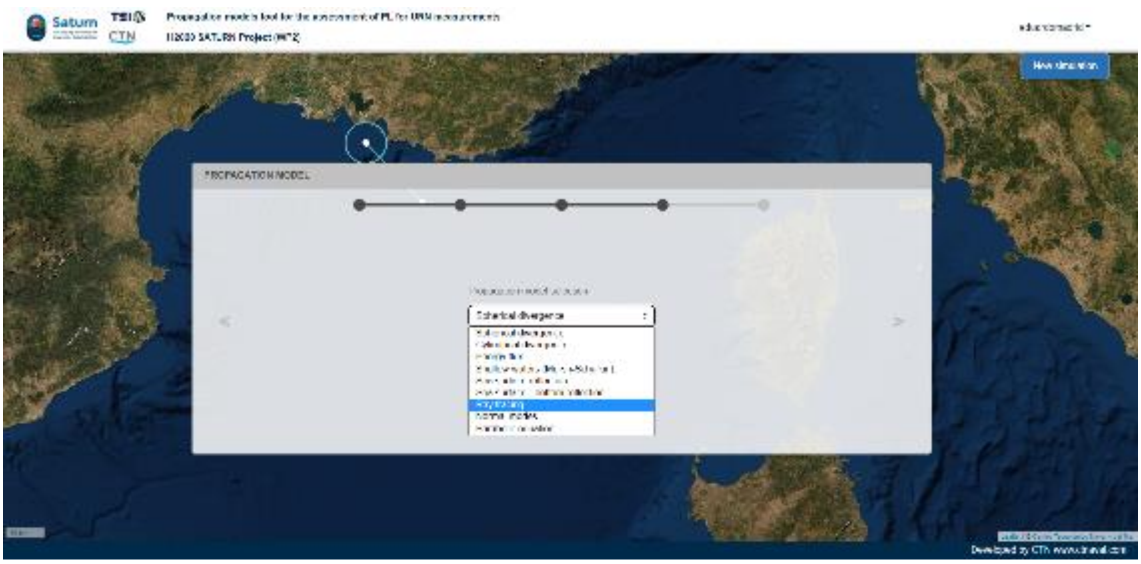


Figure 37. List of models eligible for propagation modelling in the URN tool.

Finally, as a last step, a summary window appears to check that all settings are in accordance with the user's preferences (Figure).

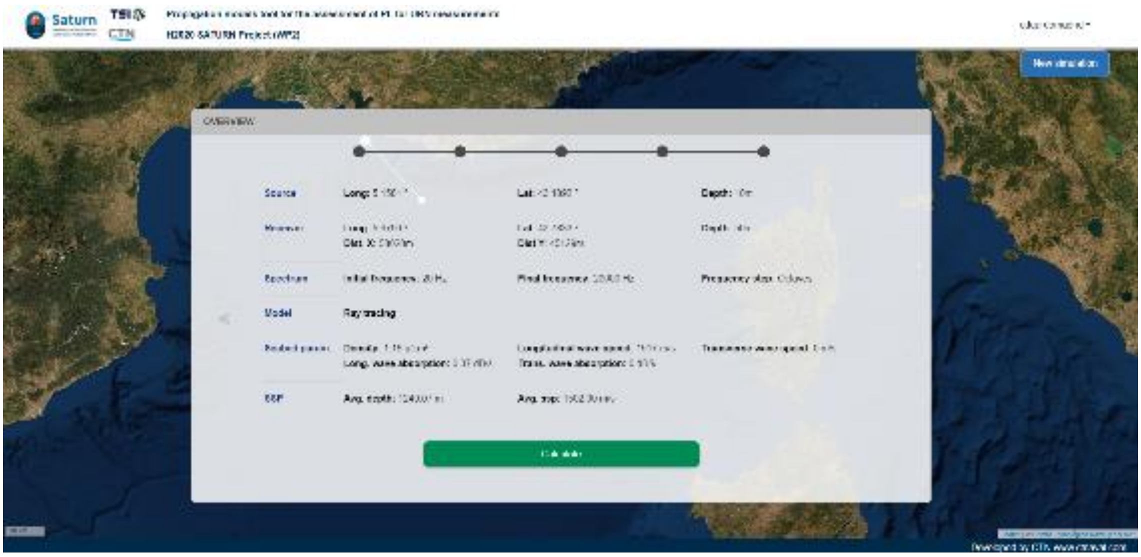


Figure 38. Last step before calculating propagation losses with the URN tool: the overview of simulation parameters input by the user.

6.3.1. Examples

The objective of this section is to present some examples obtained from the URN tool, thus evaluating the functionality of an online tool applying various underwater acoustic propagation models. The tool is currently designed for end users, not necessarily very familiar with the details of the different simulation techniques, and it automatically defines some parameters to optimize calculation times. So, an exhaustive comparison of its results with those obtained in Section **Error! Reference source not found.** is beyond the scope of this document. Nevertheless, a preliminary comparison shows that the default BELHOP model of the tool shows a greater absorption, which results in quite similar behavior to those of Section 5.3 for distances up to 20 km, but greater losses for greater distances. In addition, it is observed that the behavior of the KRAKEN models is very similar. Conclusively, the URN on-line tool allows for modification of both the front-end (parameterization of the models) and the back-end by introducing new propagation models.

Area I - Marseille - BELLHOP - Summer

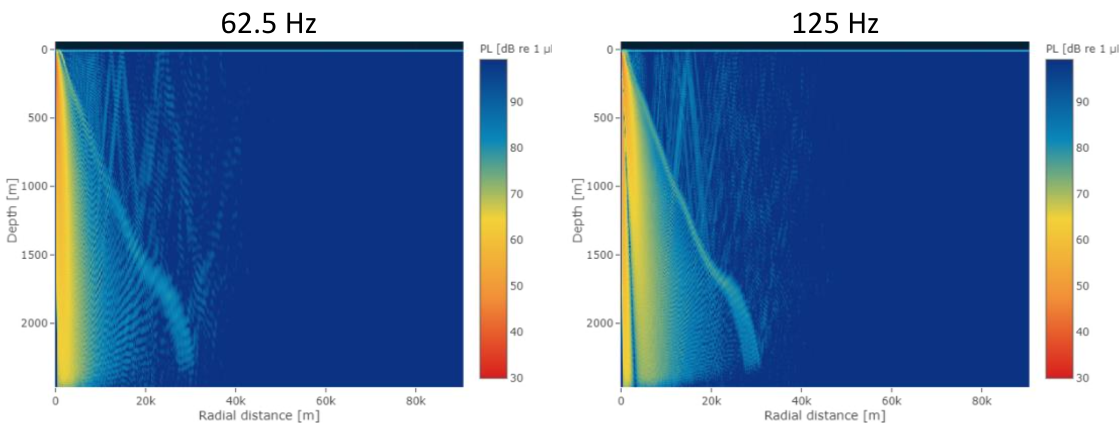


Figure 39. Propagation losses for the Marseille environment (Area I) from the URN tool using the BELLHOP model.

Area I - Barcelona - BELLHOP - Summer

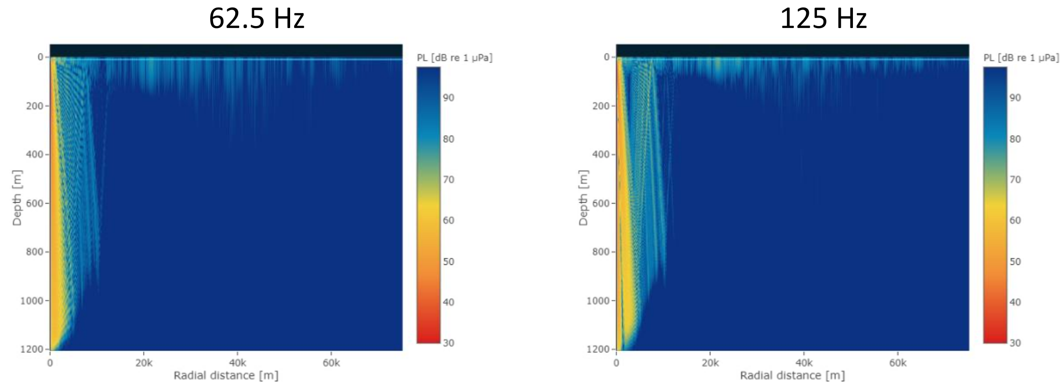


Figure 40. Propagation losses for the Barcelona environment (Area I) from the URN tool using the BELLHOP model.

Area II - Hellenic Trench - BELLHOP - Summer

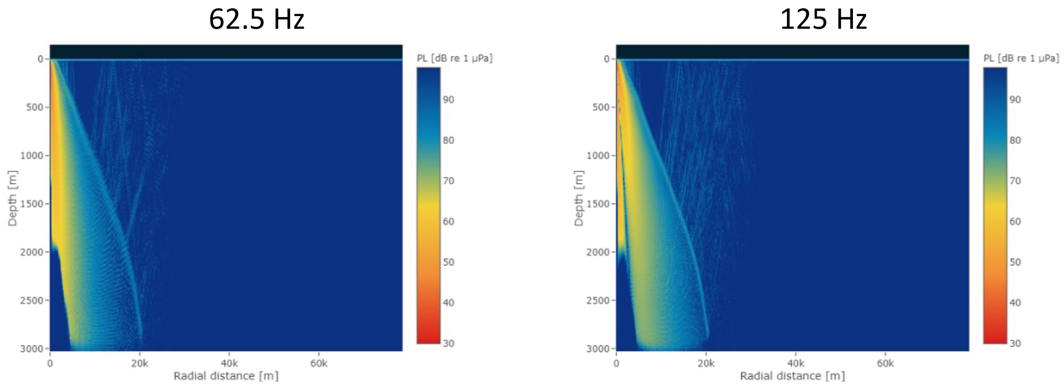


Figure 41. Propagation losses for the Hellenic Trench environment (Area II) from the URN tool using the BELLHOP model.

Area IV - Adriatic Sea I - Ancona - KRAKEN - Summer

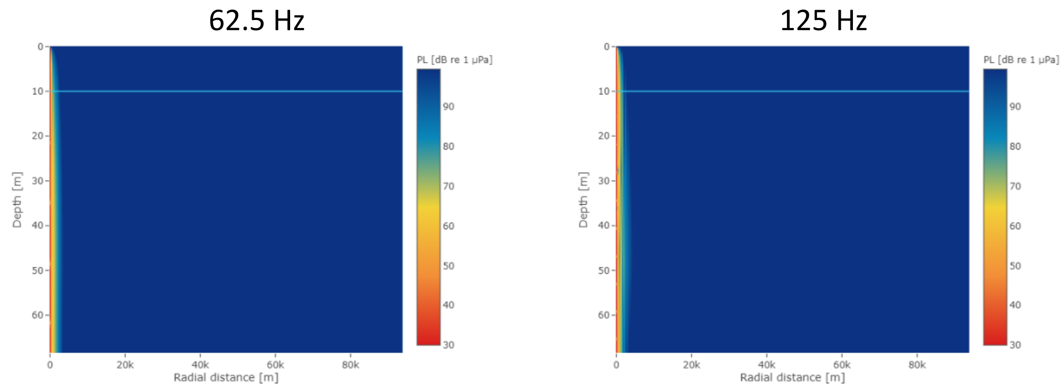


Figure 42. Propagation losses for the Adriatic Sea I – Ancona environment (Area IV) from the URN tool using the KRAKEN model.

Area IV - Adriatic Sea II - Venice - KRAKEN - Summer

62.5 Hz 125 Hz

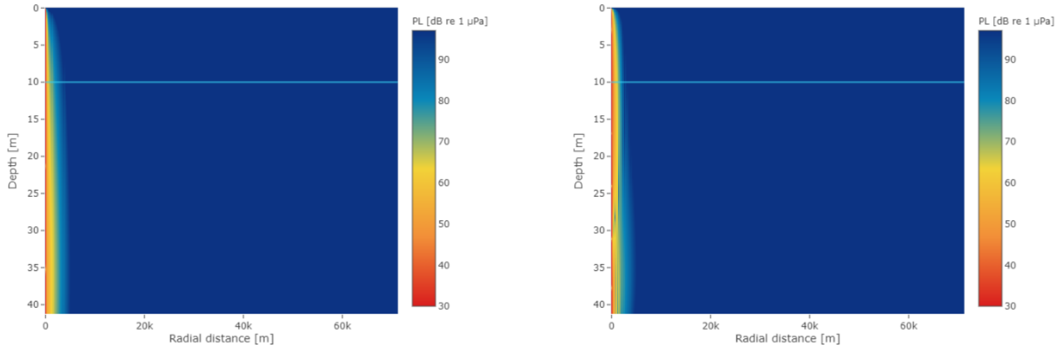


Figure 43. Propagation losses for the Adriatic Sea II – Venice environment (Area IV) from the URN tool using the KRAKEN model.

Area V - Black Sea I - Constanza I - KRAKEN - Summer

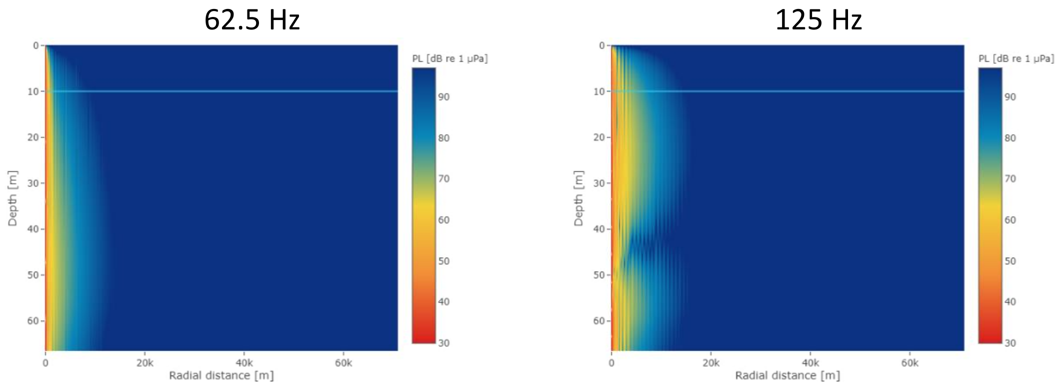


Figure 44. Propagation losses for the Black Sea I – Constanza I environment (Area V) from the URN tool using the KRAKEN model.

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