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Continuous monitoring of noise levels in the Gulf of Catania (Ionian Sea). Study of correlation with ship traffic

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ABSTRACT

Acoustic noise levels were measured in the Gulf of Catania (Ionian Sea) from July 2012 to May 2013 by a low frequency (< 1000 Hz) hydrophone, installed on board the NEMO-SN1 multidisciplinary observatory. NEMO-SN1 is a cabled node of EMSO-ERIC, which was deployed at a water depth of 2100 m, 25 km off Catania. The study area is characterized by the proximity of mid-size harbors and shipping lanes. Measured noise levels were correlated with the passage of ships tracked with a dedicated AIS antenna. Noise power was measured in the frequency range between 10 Hz and 1000 Hz. Experimental data were compared with the results of a fast numerical model based on AIS data to evaluate the contribution of shipping noise in six consecutive 1/3 octave frequency bands, including the 1/3 octave frequency bands centered at 63 Hz and 125 Hz, indicated by the Marine Strategy Framework Directive (2008/56/EC).

1. Introduction

Anthropogenic underwater noise has increased substantially over the previous decades and a significant component of noise in marine environment is due to ship traffic. From the 1960s, when the first measures of noise levels were reported (Wenz, 1962), until the 1990s, underwater noise has almost doubled every ten years due to increases in shipping traffic (Andrew et al., 2002; McDonald et al., 2006; Merchant et al., 2012). While some recent studies describe slowly decreasing low-frequency ocean noise levels at different oceanic locations during the early 2000s (Andrew et al., 2011; Miksis-Olds and Nichols, 2016), the typical and long term trends for ship noise are still unknown in many regions of the world.

Exposure to noise can produce a wide range of deleterious effects on marine mammals (Weilgart, 2007), fishes and invertebrates (Buscaino et al., 2010; Celi et al., 2014; Slabbekoorn et al., 2010), from behavioral modifications to physiological and auditory effects.

The European Marine Strategy Framework Directive (MSFD) 2008/56/EC of 17th June, 2008 (European Parliament and Council, 2008) and the Decision 2010/477/EU (European Commission, 2010) intro-

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duced human-induced marine acoustic noise as an important indicator in defining the "Good Environmental Status" of a marine ecosystem. In particular, the Descriptor 11 of the MSFD requires that "the introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment". Concerning continuous low frequency sounds, the Indicator 11.2 requires year-round measurements of the temporal distribution of noise levels, within the 1/3 octave bands centered at 63 Hz and at 125 Hz. In June 2012, the cabled deep-sea multidisciplinary observatory NEMO-SN1 (NEutrino Mediterranean Observatory – Submarine Network 1) was deployed in the Gulf of Catania (Ionian Sea) (Favali et al., 2013). The acoustic sensors installed on board this observatory gave us the opportunity to monitor environmental and anthropogenic noise sources. High levels of anthropogenic noise from ship traffic were expected in the area due to the proximity of important touristic, commercial and military harbors and shipping lanes.

The main purpose of this study is to report the first long-term measurements of low frequency noise (10 Hz–1000 Hz), recorded during approximately 10 months of continuous acoustic monitoring, in the Ionian Sea. The present work also demonstrates the correlation between background noise measurements and ship traffic. This was achieved through the development of a fast numerical code that calculates the noise induced by ships passing in the area. The code uses information acquired by a ground based AIS proprietary antenna (Automatic Identification System). A comparison between simulated and measured acoustic noise levels was performed.

2. Materials and methods

2.1. The NEMO-SN1 observatory

The NEMO-SN1 seafloor cabled multidisciplinary observatory (Favali et al., 2013) is an operative node of EMSO-ERIC (European Multidisciplinary Seafloor and water-column Observatory - European Research Infrastructure Consortium) (Best et al., 2014, 2016; Favali et al., 2011). The observatory was jointly operated by INGV (Istituto Nazionale di Geofisica e Vulcanologia) and INFN (Istituto Nazionale di Fisica Nucleare) within the activities of EMSO and of the SMO (Submarine Multidisciplinary Observatory) project (SMO, 2016).

The NEMO-SN1 seafloor observatory was installed in the Gulf of Catania (Lat 37.5477° N, Lon 15.3975° E), at a depth of 2100 m (EMSO-ERIC, 2015; Favali et al., 2013) (Fig. 1). The observatory was powered from shore and linked to the acquisition and control station, located in the Port of Catania, through a 28 km long electro-optical cable. Acquired data were sent in real time to the shore station for storage and analysis. The observatory was equipped with several geophysical, oceanographic and acoustic sensors (Favali et al., 2013).

2.2. Study area

The study area is characterized by steep slopes and high depths are reached at a very short distance from the shore. The deep-sea location of the platform and the proximity of the Port of Catania make the area a privileged observation point to monitor the acoustic noise produced by ship traffic. The characterization of background noise levels from fixed deep-sea recording sites has several advantages due to the low temporal variability in acoustic propagation features and in the sound velocity profile (Merchant et al., 2012). The location of the acoustic sensor and the inter-seasonal homogeneity of the sound velocity profile, in the deep sea, allow reliable estimates of the typical noise trends in the area. In the Western Ionian Sea the time variations of the sound velocity profile are significant only in the upper layers of the water column (depending on the depth of the seasonal thermocline). This avoids notable changes in the propagation of low frequency sounds from a source close to the surface, to a receiver, installed at high depth in an almost flat sea bottom.

2.3. Acoustic data acquisition and analysis

The acoustic noise was continuously (24/7) monitored, in the Gulf of Catania, for over 10 months, from 2nd July, 2012 to 10th May, 2013. The acoustic data used in this study were acquired by the SMID DT405D (V)1 seismic hydrophone. The hydrophone has an almost flat frequency response in the range from 50 mHz to 1000 Hz and an average sensitivity of 197 ± 1 dB re 1 V/μPa (Embriaco, 2012). Data were digitized offshore at a sampling rate of 2 kHz and they were sent to the shore station through the 28 km long electro-optical cable. A GPS signal was sent from the shore station to the observatory, to tag the digital acoustic data, providing time synchronization with millisecond accuracy. On shore, the acquired data were stored in 10-minute-long files for off-line processing. Further information about the data acquisition system, that was designed and operated under the SMO (Submarine Multidisciplinary Observatory) project (Simeone and Viola, 2011; SMO, 2016; Viola et al., 2013), is available from other studies (Embriaco, 2012; Giovanetti et al., 2016; Sciacca et al., 2015). The average values and percentile distribution of noise Power Spectral Density (PSD) were measured up to 1000 Hz. These values are useful indicators of the typical background noise trends in the area (Klinck et al., 2012; Merchant et al., 2015). The PSD of each file was computed using Welch's overlapped segment averaging estimator (2048 FFT points, Hamming window: 2048 samples, overlap 50%).

2.4. AIS data acquisition

The AIS is a vessel-tracking system that operates on VHF radio frequency bands. The transmission of VHF-AIS data is mandatory for all passenger ships, for cargo ships heavier than 500 tons and for every ship heavier than 300 tons and traveling in international waters, according to the International Convention for the Safety of Life at Sea (SOLAS) (IMO, 2004). The data transmitted carry all the information useful for the identification and location of the vessels. From this information, the position of the vessels, the MMSI (Maritime Mobile Service Identity), route, speed and heading can be derived. An AIS receiver is installed at the INFN-LNS laboratory, located in Catania, at approximately 160 m above sea level. The receiver allows the decoding of the input signal, decrypted through the standard NMEA 0183 Protocol (National Marine Electronics Association, www.nmea.org). Received data are then parsed and stored on a dedicated server for analysis. The receiver continuously provides information on ship traffic in a large area around the NEMO-SN1 location. The area of interest for this study lays between 36.8°–37.8° N and 15.0°–16.0° E. For this work AIS data were available almost continuously from 1st October, 2012 and 28th February, 2013 and allowed the determination of shipping noise impact on measured acoustic data (see Section 3.2).

Fig. 2 shows the cumulative minutes of ship traffic in the study area, calculated with a grid size of 100 m × 100 m, over the studied time interval. Vessels coordinates were recovered by the AIS receiver installed at the INFN-LNS. In this period the AIS receiver installed at the LNS collected 6,198,123 NMEA entries from 1937 vessels.

2.5. Modelling acoustic noise from AIS data

A fast custom MATLAB code was developed to calculate the acoustic noise induced by ship traffic in the Gulf of Catania (between 36.8° N to 37.8° N and 15.0° E to 16.0° E) from the data collected by the AIS receiver. The shipping source spectral density was calculated according to the Research Ambient Noise Directionality model RANDI 3.1 (Breeding et al., 1994) where ship source levels are estimated using a modified version of the empirical Ross formula (Ross, 1987). A simple geometric spreading model was used to take into account spherical spreading to the maximum water depth along the transect from the ship location and cylindrical spreading for the remainder of the transect (Erbe et al., 2012). These simplifications were implemented to run fast

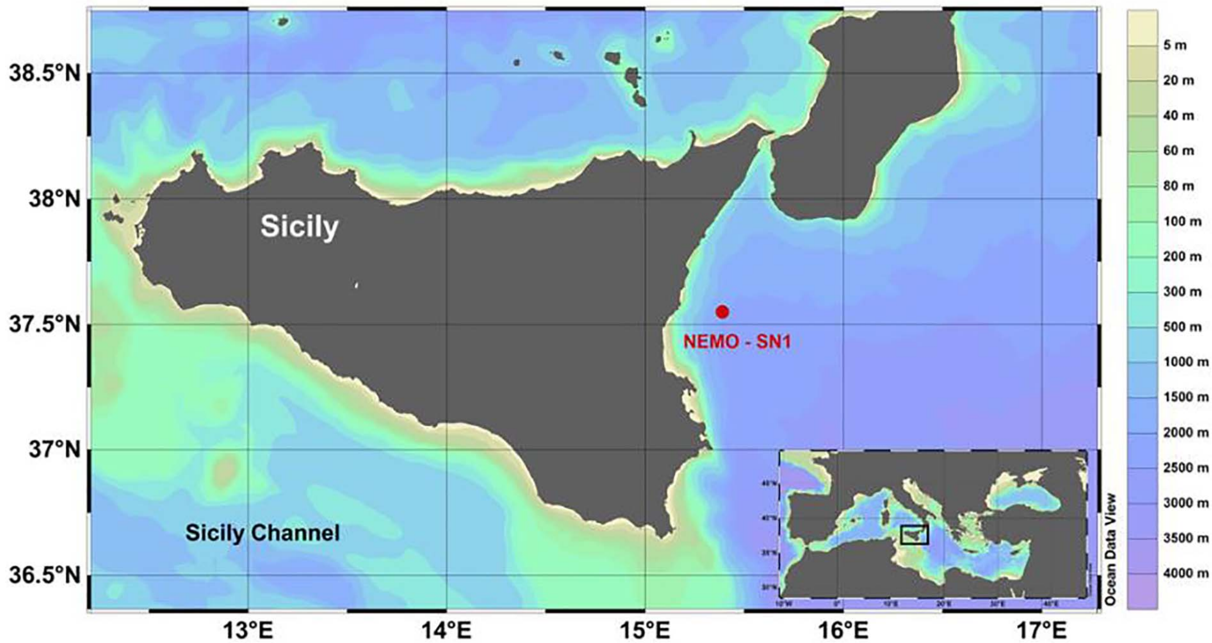

Fig. 1. Bathymetric map of the region showing the geographic location (Schlitzer, 2013) of the NEMO-SN1 deep-sea multidisciplinary cabled observatory (Lat 37.5477° N, Lon 15.3975° E, depth 2100 m), operative node of EMSO-ERIC.

numerical computations with limited computing resources and few input parameters. More sophisticated propagation models based on ray tracing or normal modes require an accurate knowledge of the acoustic characteristics of the medium in the whole study area as a function of the time (Etter, 2012). Taking advantage of the NEMO-SN1 location (see Section 2.2), the used geometrical spreading model allowed the modelling of the sound propagation in the area, in a first approximation, neglecting information on sound speed profile. In the model, the frequency-dependent attenuation induced by chemical absorption was also computed. The model also takes into account the surface-dipole

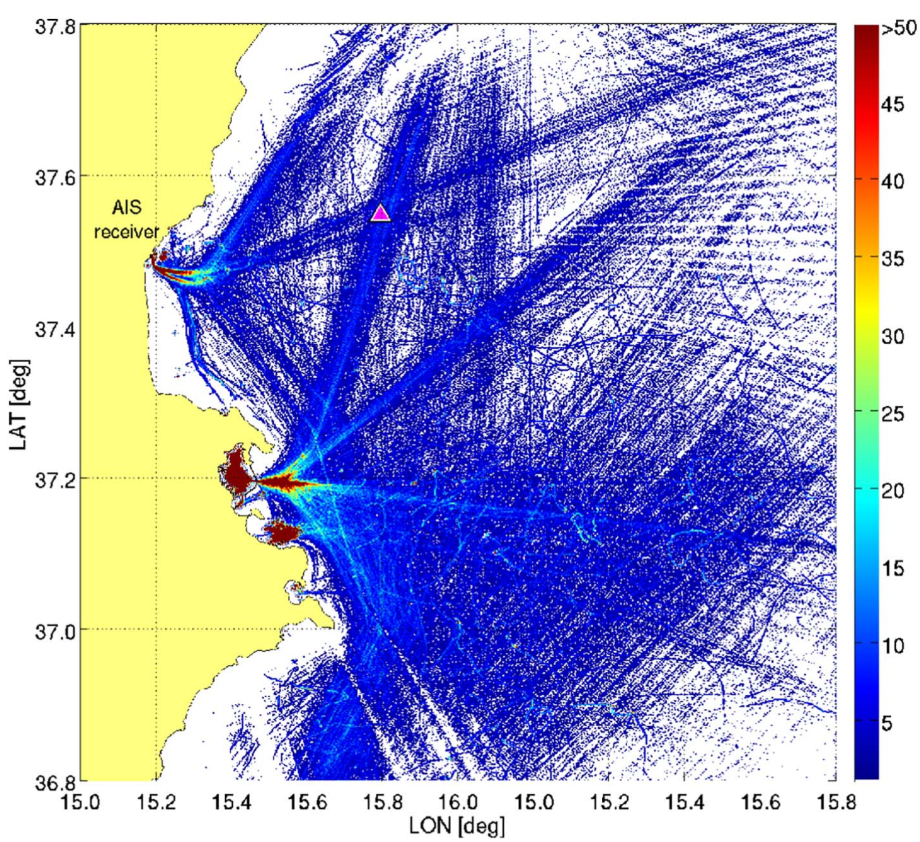

Fig. 2. Ship traffic density in the study area, obtained by proprietary AIS data from 1st October, 2012 to 28th February, 2013. Color map refers to the cumulative minutes of ship presence in a 100 m × 100 m grid. The pink triangle indicates the location of the NEMO-SN1 observatory (Lat 37.5477° N, Lon 15.3975° E, depth 2100 m). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

interference on radiated sound power (Brekhovskikh, 2003). The depth of the propeller was evaluated according to Erbe et al. (2012). It was considered 0.5 m for vessels having a length smaller than 10 m, 1.25 m for vessel length between 10 m and 25 m, 3 m for length between 25 m and 50 m and 6 m when the length exceeds 50 m (Erbe et al., 2012). The acoustic noise induced by ship traffic at the NEMO-SN1 location was then evaluated within six 1/3 octave frequency bands centered at 50 Hz, 63 Hz, 80 Hz, 100 Hz, 125 Hz and 160 Hz, including the 1/3 octave bands centered at 63 Hz and at 125 Hz, indicated by the EU MSFD (Dekeling et al., 2014; European Commission, 2010; European Parliament and Council, 2008). The model was applied on the AIS data acquired between 1st October, 2012 and 28th February, 2013. Results of the model were eventually correlated with the experimental measurements of acoustic noise measured by the SMID DT405D(V)1 hydrophone.

3. Results

3.1. Background noise measurements

Underwater noise was monitored continuously for over 10 months, at a depth of 2100 m. The average values of the PSD were computed every 10 min, corresponding to the duration of each recording. For the entire dataset collected by the SMID DT405D(V)1 hydrophone, the spectrogram up to 1000 Hz was performed with a time resolution of 10 min. The spectrogram, shown in Fig. 3, was obtained by laying side by side the mean PSDs calculated in each 10-min long file. This figure reveals a high temporal variability of the noise levels (PSD) throughout the analyzed period. This variability can be attributed to the passage of vessels in the study area during the analyzed period, as described in Section 3.2. Within the same dataset fin whale vocalizations (20 Hz), airgun pulses (> 300 Hz) and seismic activity (> 50 Hz) were also found (Sciacca et al., 2016). However, these signals are not clearly discernible from the 10-min average spectrogram due to the presence of continuous ship noise in the recordings. The tones at approximately 250 Hz, 280 Hz and 350 Hz are due to the intrinsic electrical noise of the data acquisition system.

In Fig. 4 we report the empirical probability density (EPD) of the average PSD values for the whole dataset, measured with a resolution of 1 dB re 1 μPa^2/Hz. The values of median, 95th and 5th percentiles are also shown. Up to about 70 Hz, the median of the average PSD often exceeds 100 dB re 1 μPa^2/Hz.

In Table 1, the mean value, minimum, 5th percentile, median, 95th percentile and maximum of the average SPLs, calculated for each recording in the standard 1/3 octave bands, are reported.

3.2. Correlation between recorded acoustic data and shipping noise

The AIS-based model described in Section 2.4 was applied to estimate the ship noise at the NEMO-SN1 location over the period between 1st October, 2012 and 28th February, 2013. The SPL values, simulated in the 1/3 octave bands centered at 50 Hz, 63 Hz, 80 Hz, 100 Hz, 125 Hz, 160 Hz, were compared with the experimental values measured in the acoustic recordings with the same time resolution (10 min). In the comparison we considered only recordings having at least one AIS entry in the corresponding time period. These represent 77.13% of the total recordings in the analyzed period. In Fig. 5 we show, for each analyzed 1/3 octave band, the probability density of the simulated SPLs as a function of the measured SPLs. Binning is 1 dB re 1 μPa for both axes. We excluded from the comparison recordings for which SPL values are lower than the 5th percentile or greater than the 95th percentile of measured SPL distribution. This choice excludes measured SPL bins having a number of entries too low to be statistically significant. The red line corresponds to a perfect agreement between modelled and measured SPL. The band enclosed in the two dotted lines delimits the plot region where the deviation between modelled and measured SPLs is less than 6 dB. The distribution of the simulated SPLs exhibits a negatively skewed distribution. This asymmetry can be attributed to the presence in the study area of vessels operating without AIS device, such as small boats, to the noise coming from distant sources (e.g. ships outside the AIS antenna detection range) or to other natural or anthropogenic noise sources. For instance, the analysis of NEMO-SN1 recording has revealed during the investigated time interval airgun signals, emitted at several hundred kilometers far from the station (Sciacca et al., 2016), that were not included in the simulation. In Table 2 we summarize for the six 1/3 octave bands the percentage of entries for which the difference between the simulated SPL values and the measured SPL values, both expressed in dB re 1 μPa, are respec-

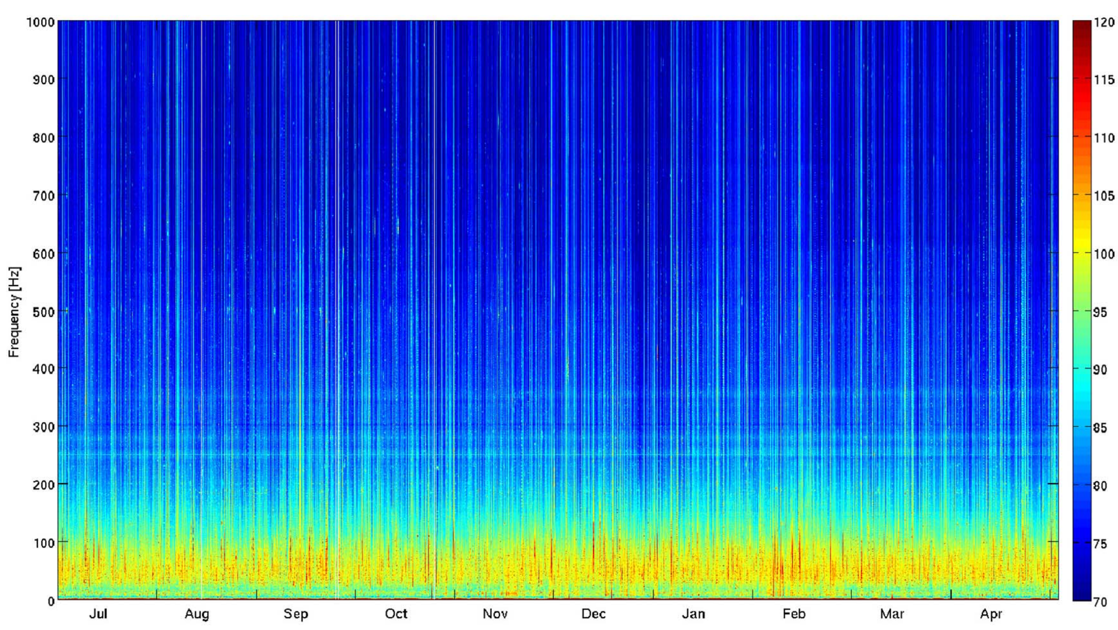

Fig. 3. Long term average spectrogram (in dB re 1 μPa^2/Hz), computed over the whole NEMO-SN1 dataset. The spectrogram is calculated by measuring the mean Power Spectral Density up to 1000 Hz for each file of 10 min (2048 FFT points, Hamming window: 2048 samples, 50% overlap). Vertical white lines refer to missing recordings.

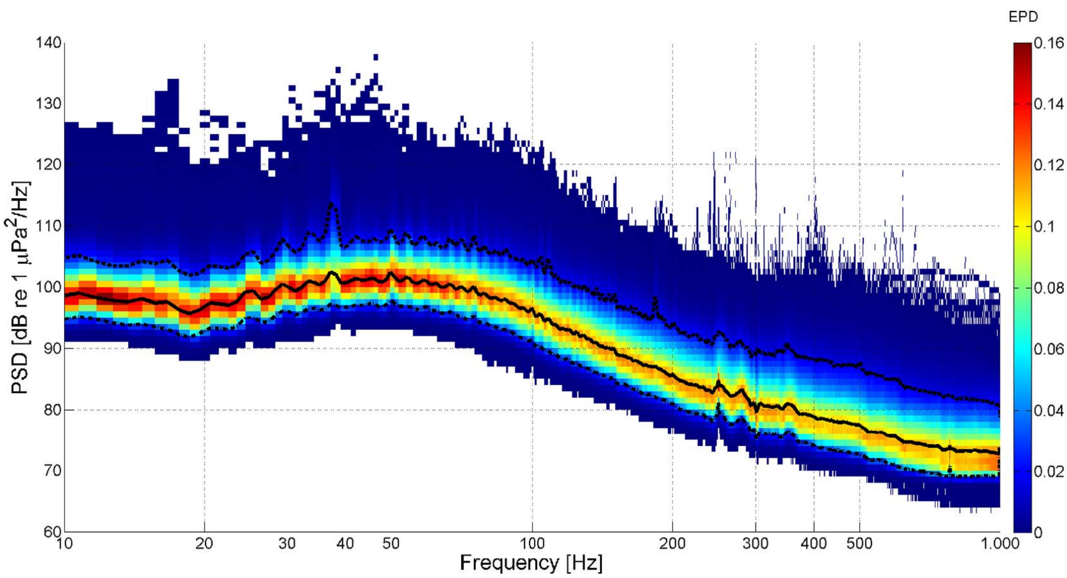

Fig. 4. Empirical probability density (EPD) of the mean values of the PSD within each 10 min long recording (binning: 1 dB re 1 μPa^2/Hz) between the 2nd July, 2012 and the 10th May, 2013. The PSD of each file was computed using Welch's overlapped segment averaging estimator (2048 FFT points, Hamming window: 2048 samples, overlap 50%). The whole NEMO-SN1 acoustic dataset comprises 46,040 recordings. The figure also includes the curves of the 50th (solid line), 5th (dash-dotted line) and 95th percentiles (dashed line) of the mean values of the PSD calculated on the whole acoustic dataset.

Table 1
Values of mean, minimum, 5th percentile, median, 95th percentile and maximum of the average SPLs, calculated for each 10-minute long recording in the standard 1/3 octave bands (expressed in dB re 1 μPa).

1/3 octave band	Mean	Min	5th perc.	Median	95th perc.	Max
12.5 Hz	103.55	95.73	99.35	103.17	108.76	128.58
16 Hz	104.40	95.43	99.69	104.19	109.94	127.04
20 Hz	104.35	96.24	100.02	104.05	109.57	125.51
25 Hz	107.06	99.28	102.92	106.82	111.98	128.05
31.5 Hz	109.93	101.32	105.51	109.46	115.80	131.54
40 Hz	112.22	102.98	107.43	111.72	118.96	138.46
50 Hz	112.85	104.61	108.49	112.44	118.66	138.58
63 Hz	112.89	104.66	108.37	112.44	118.92	133.91
80 Hz	112.29	103.38	107.46	111.82	118.59	135.42
100 Hz	110.58	101.10	105.36	110.11	117.29	134.77
125 Hz	107.83	98.23	102.54	107.33	114.79	128.58
160 Hz	105.34	95.53	100.23	104.76	112.44	125.18
200 Hz	103.28	93.77	98.02	102.60	110.70	122.63
250 Hz	101.80	92.65	96.72	101.19	109.10	124.56
315 Hz	100.43	91.07	95.24	99.69	108.15	119.17
400 Hz	98.83	89.10	93.35	98.01	107.24	122.55
500 Hz	98.81	89.40	93.18	98.02	107.10	119.73
630 Hz	97.50	86.94	92.05	96.85	105.44	122.83
800 Hz	96.92	85.29	91.72	96.31	104.47	124.02

tively less than 3 dB, 6 dB and 10 dB.

4. Discussion and conclusions

Cabled multidisciplinary observatories represent an essential tool for the long term monitoring of the deep-sea environment. Thanks to connections on optical fibers, large amounts of data can be transmitted from deep-sea instrumentation to shore to be analyzed in real time or stored for further off-line analysis. The analysis of the acoustic data acquired by NEMO-SN1, over about 10 months, shows that in the study area the median of the SPL values exceeds 100 dB re 1 μPa in the standard 1/3 octave bands up to 250 Hz. In particular the median values of the SPL in the 1/3 octave bands centered at 63 Hz and 125 Hz, considered in the descriptor 11.2 of the MSFD, reach respectively 112 dB re 1 μPa and 107 dB re 1 μPa. The NEMO-SN1 observatory is located in proximity to a commercial port and to shipping lanes. Hence, together with the measurement of acoustic data, ship traffic was also monitored in the area. In particular, ship movements were tracked in the Gulf of Catania by a proprietary AIS antenna. To estimate the acoustic noise induced by the ships passing through the monitored area, a simple numerical model was developed and applied, by using AIS data. Increases in acoustic noise levels were measured in coincidence with the presence of vessels in the study area over the 5 months, in which AIS data were almost continuously available. The difference between measured SPL values and SPL values expected by the simulation was calculated within six 1/3 octave bands, including the 1/3 octave bands centered at 63 Hz and 125 Hz, indicated by the MSFD for the monitoring of continuous noise levels. Results of the comparison between experimental and simulated values show that noise levels measured in the NEMO-SN1 recordings in the 1/3 octave bands centered at 50 Hz, 63 Hz, 80 Hz, 100 Hz, 125 Hz and 160 Hz are largely attributed to ship traffic.

Although in the simulation only ship traffic information acquired by the proprietary AIS antenna was used, the difference between measured and simulated SPL values was lower than 10 dB, 6 dB and 3 dB, respectively in about the 80%, the 60% and the 35% of the analyzed recordings. The monitoring of the acoustic noise produced by ship traffic is requested by the EU Directive on Marine Strategy in order to promote legislative acts for the achievement of Good Environmental Status (GES) of coastal zones, seas and their resources (Dekeling et al., 2014; European Commission, 2010; European Parliament and Council, 2008). Approaches similar to that used in this study (e.g. the correlation of the acoustic measurements with AIS data) will be also useful in the prediction of future scenarios of ship noise. This is essential in the planning of new routes for shipping traffic, such as those foreseen for the future European Motorways of the Sea (Neenan et al., 2016). Furthermore, the methodologies applied and the presented results provide critical information in the evaluation of the acoustic impact of ship traffic on aquatic life. As an example, this can be useful in elaborating the required mitigation measures for protected species living or transiting in the area, that could be endangered by high noise levels at low frequencies, such as the fin whale (Sciacca et al., 2016). By comparing modelled noise distribution and trends with animal density data, it will also be possible to identify noise hot-spots for the most sensitive species (Erbe et al., 2014).

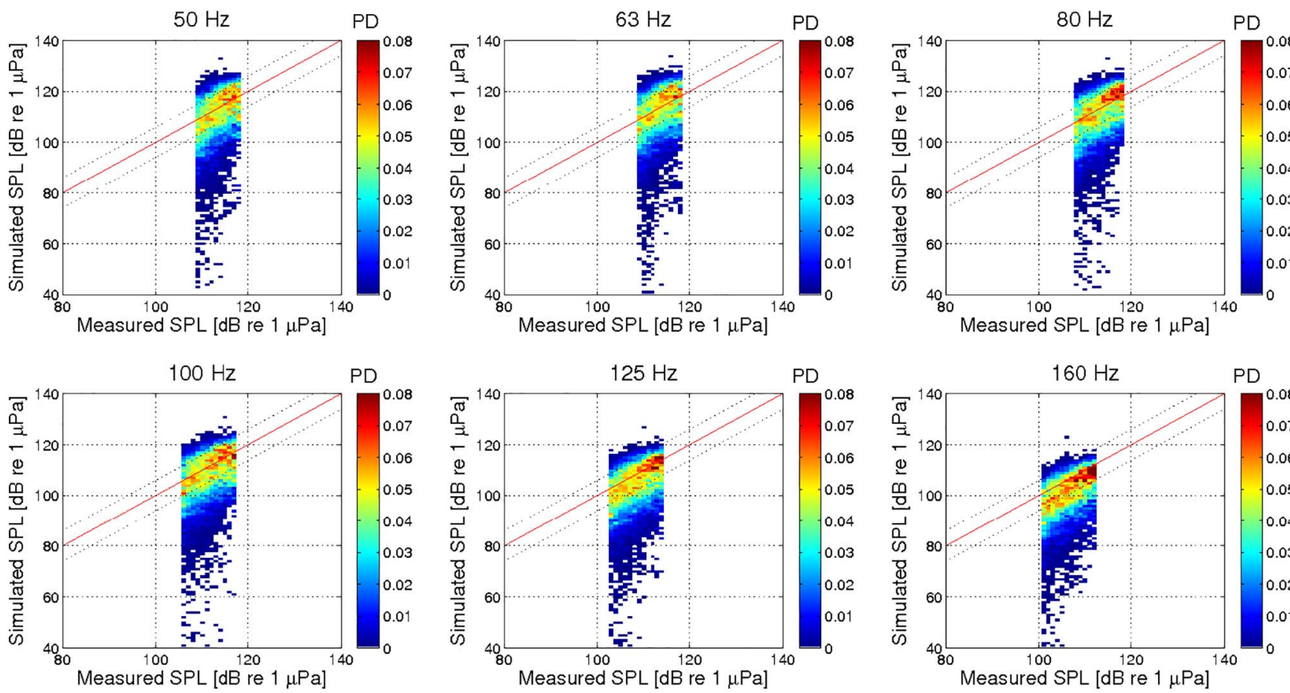

Fig. 5. Probability density (PD) of the simulated SPLs as a function of the measured SPLs for each analyzed 1/3 octave band. Binning is 1 dB re 1 μPa for both axes. We excluded from the scatterplots data for which SPLs are lower than the 5th percentile or greater than the 95th percentile of the measured SPL distribution. The red line corresponds to a perfect agreement between modelled and measured SPL. The band enclosed in the two dotted lines delimits the plot region where the deviation between modelled and measured SPLs is less than 6 dB.

Table 2
Percentage of entries for which the module of the difference between simulated SPL values and measured SPL values, both expressed in dB re 1 μPa (Δ SPL), within the 1/3 octave bands, centered at 50 Hz, 63 Hz, 80 Hz, 100 Hz, 125 Hz and 160 Hz are less than 3 dB, 6 dB and 10 dB.

1/3 octave bands	$|\Delta SPL| < 3$ dB	$|\Delta SPL| < 6$ dB	$|\Delta SPL| < 10$ dB
50 Hz	33.52%	60.23%	81.53%
63 Hz	33.73%	59.93%	82.30%
80 Hz	35.23%	60.63%	82.34%
100 Hz	34.50%	60.85%	81.34%
125 Hz	35.77%	59.71%	79.04%
160 Hz	32.98%	54.06%	74.14%

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