SAFE WAVE

STREAMLINING THE ASSESSMENT OF ENVIRONMENTAL EFFECTS OF WAVE ENERGY

DELIVERABLE 2.3
Acoustic monitoring

This Project is co-funded by the European Climate, Infrastructure and Environment Executive Agency (CINEA)

WP 2
Deliverable 2.3 Acoustic Monitoring

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SAFE WAVE project synopsis

The European Atlantic Ocean offers a high potential for marine renewable energy (MRE), which is targeted to be at least 32% of the EU's gross final consumption by 2030 (European Commission, 2020). The European Commission is supporting the development of the ocean energy sector through an array of activities and policies: the Green Deal, the Energy Union, the Strategic Energy Technology Plan (SET-Plan) and the Sustainable Blue Economy Strategy. As part of the Green Deal, the Commission adopted the EU Offshore Renewable Energy Strategy (European Commission, 2020) which estimates to have an installed capacity of at least 60 GW of offshore wind and at least 1 GW of ocean energy by 2030, reaching 300 GW and 40 GW of installed capacity, respectively, moving the EU towards climate neutrality by 2050.

Another important policy initiative is the REPowerEU plan (European Commission, 2022) which the European Commission launched in response to Russia's invasion of Ukraine. REPowerEU plan aims to reduce the European dependence amongst Member States on Russian energy sources, substituting fossil fuels by accelerating Europe's clean energy transition to a more resilient energy system and a true Energy Union. In this context, higher renewable energy targets and additional investment, as well as introducing mechanisms to shorten and simplify the consenting processes (i.e., 'go-to' areas or suitable areas designated by a Member State for renewable energy production) will enable the EU to fully meet the REPowerEU objectives.

The nascent status of the Marine Renewable Energy (MRE) sector and Wave Energy (WE) in particular, yields many unknowns about its potential environmental pressures and impacts, some of them still far from being completely understood. Wave Energy Converters' (WECs) operation in the marine environment is still perceived by regulators and stakeholders as a risky activity, particularly for some groups of species and habitats.

The complexity of MRE licensing processes is also indicated as one of the main barriers to the sector development. The lack of clarity of procedures (arising from the lack of specific laws for this type of projects), the varied number of authorities to be consulted and the early stage of Marine Spatial Planning (MSP) implementation are examples of the issues identified to delay projects' permitting.

Finally, there is also a need to provide more information on the sector not only to regulators, developers and other stakeholders but also to the general public. Information should be provided focusing on the ocean energy sector technical aspects, effects on the marine environment, role on local and regional socio-economic aspects and effects in a global scale as a sector producing clean energy and thus having a role in contributing to decarbonise human activities. Only with an informed society would be possible to carry out fruitful public debates on MRE implementation at the local level.

These non-technological barriers that could hinder the future development of WE in EU, are being addressed by the WESE project funded by European Maritime and Fisheries Fund (EMFF) in 2018. The present project builds on the results of the WESE project and aims to move forward through the following specific objectives:

1. Development of an **Environmental Research Demonstration Strategy** based on the collection, processing, modelling, analysis and sharing of environmental data collected in WE sites from different European countries where WECs are currently operating (Mutriku power plant and BIMEP in Spain, Aguçadoura in Portugal and SEMREV in France); the SafeWAVE project aims to enhance the understanding of the negative, positive and negligible effects of WE projects. The SafeWAVE project will continue previous work, carried out under the WESE project, to increase the knowledge on priority research areas, enlarging the analysis to other types of sites, technologies and countries. This will increase information robustness to better inform decision-makers and managers on real environmental risks, broad the engagement with relevant stakeholders, related sectors and the public at large and reduce environmental uncertainties in consenting of WE deployments across Europe.

2. Development of a **Consenting and Planning Strategy** through providing guidance to ocean energy developers and to public authorities tasked with consenting and licensing of WE projects in France and Ireland; this strategy will build on country-specific licensing guidance and on the application of the MSP decision support tools (i.e. WEC-ERA[1] by Galparsoro et al., 2021[2] and VAPEM[3] tools) developed for Spain and Portugal in the framework of the WESE project; the results will complete guidance to ocean energy developers and public authorities for most of the EU countries in the Atlantic Arch.
3. Development of a **Public Education and Engagement Strategy** to work collaboratively with coastal communities in France, Ireland, Portugal and Spain, to co-develop and demonstrate a framework for education and public engagement (EPE) of MRE enhancing ocean literacy and improving the quality of public debates.

[1] https://aztidata.es/wec-era/;
[2] Galparsoro, I., M. Korta, I. Subirana, Á. Borja, I. Menchaca, O. Solaun, I. Muxika, G. Iglesias, J. Bald, 2021. A new framework and tool for ecological risk assessment of wave energy converters projects. Renewable and Sustainable Energy Reviews, 151: 111539
[3] https://aztidata.es/vapem/

Glossary

dB – Decibel.

EMFF - European Maritime and Fisheries Fund.

EU – Europe Union.

WP – Work Package.

TX.Y – Task X.Y.

f - Frequency [Hz].

IQR – Interquartile range.

RPM – Revolutions per minute.

SPL – Sound Pressure Level.

H – Significant wave height.

WEC – Wave Energy Converter.

Ω – Average RPM across all turbines of the Mutriku power plant.

Q1 – Quartile 25.

Q2 – Quartile 50 (median).

Q3 – Quartile 75.

Executive summary

This deliverable contains the methodology and results from Task 2.3 of SafeWAVE project (Acoustic Monitoring), which essentially is about the acquisition of acoustic, sea state and operational data in four wave energy converter (WEC) prototype test sites. Monitoring campaigns were carried out during non-operation and operational regimes, in order to obtain underwater Sound Pressure Levels for a range of sea states and frequencies. The final goal is to characterize the acoustic signature of the WEC prototypes.

First, for **Aguçadoura** (Portugal) test site two pre-installation monitoring campaigns were carried out in January and May 2022. Median SPL values were found to be between 75 and 105 dB re 1 µPa (for the lowest end of the spectrum and the band centred around 200 Hz, respectively). The state of the sea is most reflected on the high frequencies 4 kHz and 10 kHz for the January and May campaign, respectively, as well as on the 100 Hz band for the latter. A first commissioning campaign was performed in September 2023, where some differences were (+10 dB re 1 µPa) found for the wave heights bin [2, 2.5). However, due to the short campaign duration (9 days), and this campaign happening during the commissioning of the device (meaning that it's not fully representative of the WEC real operational state, as its forced between states), no concluded results should be extracted.

Second, for the **BiMEP** test site (Spain), two monitoring campaigns were undertaken: pre/installation and post-installation (of the PENGUIN II WEC). For the first one, an increase of more than 15 dB re 1 µPa is found for high wave heights after the deployment of the mooring lines of the WEC, with increases of up to 20 dB re 1 µPa during the installation period. The higher differences in SPL between the background noise levels are found in the lower frequencies.

The results from the post-installation campaign data indicate that there exists some contribution from the device to the background noise levels, especially in the lower frequencies. These occur when comparing the On

and Off states SPL distributions with respect to those of the Uninstalled periods (in fact, the comparison between On-Off SPL show no significant differences). These differences can be up (in median value) to 28 dB re 1 µPa for the lowest frequencies (decreasing approximately linearly with frequency). In addition, during the decommissioning of the device, noise levels were the highest found in the campaign, with values over 120 dB re 1 µPa (centred around 300 Hz). It is worth noting that mooring lines were also detectable above background noise for rough sea states around the 3 and 4 kHz bands.

Third, for **Mutriku** (Spain), one monitoring acoustic campaign was undertaken during March-April 2022. No contribution to the background soundscape from the WEC was found from our analysis. This was inferred comparing day and night SPL distributions as well as carrying out a causality test that showed no link between operational status of the power plant and the SPL time series for any frequency.

Lastly, in the **SEM-REV** test site (France), one monitoring acoustic campaign was undertaken during July-August 2021. The analysis indicates no significant contribution of the WEC to the ambient noise (WAVEGEM by GEPS Techno), although it must be noted that the study was limited by the scarcity of operational data of the WEC device. Additionally, as in the BiMEP test site, mooring lines could be detected above background noise as a peak centred in 4 kHz that increases with wave height. Finally, the highest values in SPL are localized in a narrow band centred in 30 Hz, with values reaching almost 120 dB re 1 µPa. This narrow peak could be caused by the WEC, when forced by strong waves, but without more operating data or a baseline campaign this remains a hypothesis.

1. Introduction

This deliverable collects all information regarding the execution of the acoustic noise monitoring campaigns, the subsequent processing of the collected data, the analysis and synthesis of the obtained results.

It consists of three central sections classified in corresponding sections: acoustic monitoring campaigns (section 22), collected data (section 33) and processed data (section 44). In the first of these sections, the acoustic monitoring campaigns as eventually executed are described (the reader can refer to D2.1 for further details omitted here for brevity); while in the second and third sections the collected and processed data are analysed, respectively.

In more details, the collected data does not only consist of noise data, but also other auxiliary time series data, such as sea state conditions and operational regime of the WECs. These auxiliary datasets allow for a classification of noise levels according to the state of the sea and the WEC's operation. The processed data refers here to Sound Pressure Levels in a range of frequencies of interest, as is explained in section 4.1.

The objective of this task is to eventually know the contribution of the WECs to the background noise, which in this report was defined as the difference between the SPL values when the WECs are operating (or are simply installed) and those corresponding to the non-operation of the device (or when it is not yet installed or is already decommissioned).

Four different wave energy devices were studied in this project: CorPower WEC C4 (offshore, Aguçadoura test site), Wello's PENGUIN II (offshore, BiMEP test site), Mutriku power plant (onshore, Mutriku), and GEPS-TECHNO's WAVEGEM (offshore, SEM-REV test site). More information about these devices can be found in D2.1(Vinagre *et al.*, 2021).

2. Acoustic monitoring campaigns

In this section the acoustic monitoring campaigns are detailed. It must be noted that, although most plans elaborated in Task 2.1 of the project and correspondingly presented in D2.1 (Vinagre *et al.*, 2021) were followed, slight deviations always occur when deploying equipment in the sea. Most of the cases follow the same procedure: deploy (up to) three hydrophones close to the WEC and register 10 minutes each hour continuously for around one month.

It is worth mentioning that a specific retrieval date does not mean that the date of the last measurement taken matches such date. In any case, in the section 3, in which the actual collected data are shown, the number of acoustic files generated in the campaigns (and their date ranges) will be specified.

2.1 Aguçadoura (Portugal)

In the Aguçadoura test site there were two different pre-installation campaigns, as follows in the next subsections.

2.1.1 Pre-installation campaign 1 (January)

The first pre-installation monitoring campaign was carried out from 17-21 of January of 2022 in Aguçadoura test site, in Portugal.

In Table 1, the exact location of the hydrophones as well as the temporal extent of their operation is shown.

Table 1. Spatiotemporal information of the January monitoring campaign in Aguçadoura.

Sampling station	Latitude [° N]	Longitude [° E]	Depth [m]	Deployment	Retrieval
H1	41.45791	-8.84222	21.75	17/01/2022 9:13	21/01/2022 10:26
H2	41.45612	-8.84235	21.75	17/01/2022 9:49	21/01/2022 10:48
H3	41.45587	-8.84113	21.75	17/01/2022 10:07	21/01/2022 11:11

During this period, the three hydrophones registered noise for 10 minutes every hour, with a sampling frequency of 576 kHz. The map of Figure 1 shows the relative location of the hydrophones as well as the bathymetry of the area of interest, which comprises shallow waters.

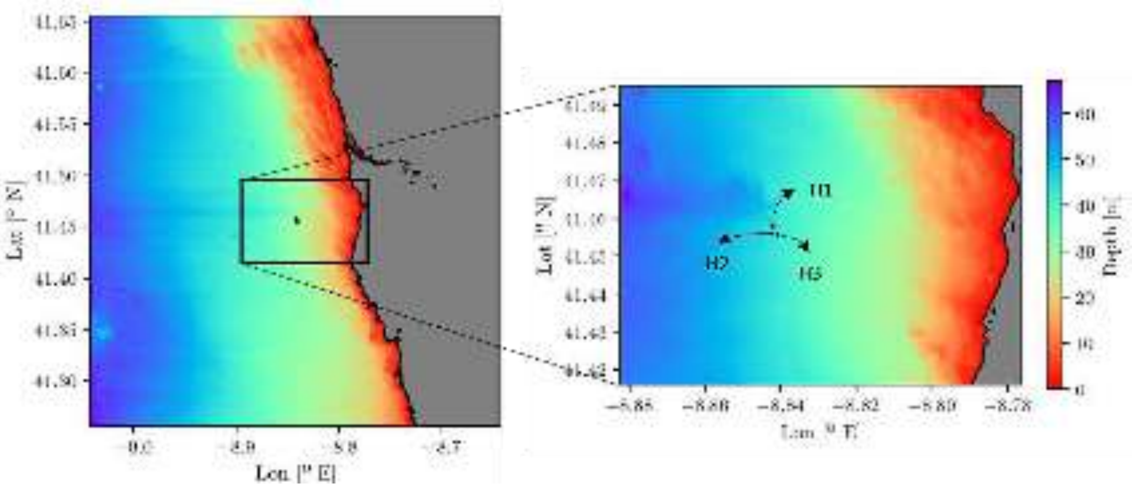

Figure 1. Sampling stations for acoustic monitoring in Aguçadoura.

2.1.2 Pre-installation campaign 2 (May)

In addition, a similar 3-day duration campaign was undertaken in May 2022, using the same hydrophones and sampling station locations, as specified by Table 2, recording 10 minutes every hour with a sampling frequency of 576 kHz.

Table 2. Spatiotemporal information of the May monitoring campaign in Aguçadoura.

Sampling station	Latitude [° N]	Longitude [° E]	Depth [m]	Deployment	Retrieval
H1	41.45791	-8.84222	11.75 (21.75)	04/05/2022 11:02	07/05/2022 11:29
H2	41.45612	-8.84235	11.75 (21.75)	04/05/2022 11:19	07/05/2022 11:36
H3	41.45587	-8.84113	11.75 (21.75)	04/05/2022 11:40	07/05/2022 11:47

Auxiliary time series characterizing sea state (significant wave height, wave period, wind speed) were obtained for these two periods, as can be seen in section 3.1.

2.1.3 Commissioning phase

In 2023, a first commissioning campaign was undertaken in September to test the different functions and modes of operation. This campaign lasted around nine days, and, the same hydrophones were deployed, configured to record 18 minutes every hour with a sampling frequency of 576 kHz.

Table 3. Spatiotemporal information of the September operational campaign in Aguçadaoura.

Sampling station	Latitude [° N]	Longitude [° E]	Depth [m]	Deployment	Retrieval
H1	41.458	-8.8445	11.75 (21.75)	24/09/2023 10:00	02/10/2023 10:30
H2	41.45631	-8.84211	11.75 (21.75)	24/09/2023 10:14	02/10/2023 10:46
H3	41.45523	-8.83975	11.75 (21.75)	24/09/2023 10:27	02/10/2023 10:56

Also, auxiliary data, such as time series characterizing sea state (significant wave height, wave period, wind speed) and a time series with the normalized power of the device.

By the time of writing the deliverable, no operational phase has been performed.

2.2 BiMEP (Spain)

In the case of the BiMEP test site, two distinct noise monitoring campaigns were carried out. Additionally, an airborne acoustic campaign was undertaken to further strengthen the acoustic analysis.

2.2.1 Pre-operational and installation phase

The first noise monitoring campaign took place before the operation of the device; that is, before *and* during its installation. In this case, just one hydrophone was set up to register 10 minutes each hour with a sampling frequency of 288 kHz from the 16/06/2021 until 10/08/2021, as defined in Table 4.

Table 4. Spatiotemporal information of the pre-operational and installation noise monitoring campaign in BiMEP. The specified depth is that of the hydrophone (in parenthesis the depth of sea in such coordinates).

Sampling station	Latitude [° N]	Longitude [° E]	Hydrophone Depth [m]	Seabottom Depth (m)	Deployment	Retrieval
WG1	43.46569	-2.87944	63	73	16/06/21 9:52	10/08/21 10:00

2.2.2 Operational phase

The main noise monitoring campaign was performed during the operation of the device, a few months after the pre-operational and installation phase campaign. Three hydrophones were deployed in the area and were set up to register 10 minutes each hour with a sampling frequency of 288 kHz from 11 November 2021 to 27 January 2022 as specified in Table 5.

Table 5. Spatiotemporal information of the noise monitoring campaign in the operation phase of the device, in BiMEP.

Sampling station	Latitude [° N]	Longitude [° E]	Hydrophone Depth [m]	Seabottom Depth (m)	Deployment	Retrieval
PE1	43.46443	-2.88482	62	72	11/11/2021 12:07	25/01/22
PE2	43.46423	-2.88140	61	71	11/11/2021 12:15	25/01/22
PE3	43.46253	-2.88412	58	68	11/11/2021 12:01	27/01/22

Visual information about the placements of the hydrophones is shown in Figure 2, as well as bathymetry of the area.

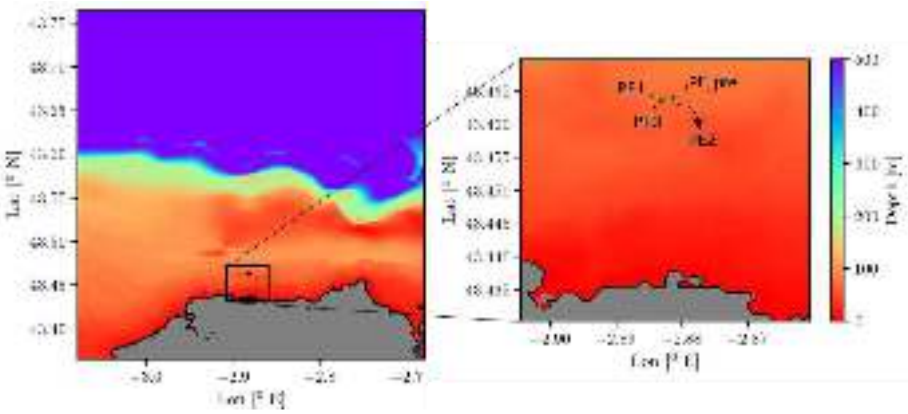

Figure 2. Sampling stations for all acoustic monitoring campaigns in BiMEP. The location of the WEC is denoted as an asterisk.

2.2.3 Airborne monitoring

As mentioned, an airborne acoustic monitoring campaign was carried out to further help in the assessment of the source level of the WEC. To do this, an acquisition system developed by CTN was deployed inside the WEC (see Figure 3), and continuously monitored the noise inside the device during the operational phase, recording audio for 10 minutes every hour.

Figure 3. Detail of the sound acquisition system installed in PENGUIN II.

2.3 Mutriku (Spain)

The other test site located in Spain is found in the village of Mutriku, in the Basque Country as well. One monitoring campaign was carried out from 16 March to 26 April 2022, in which three hydrophones were deployed and acquired data for 10 minutes each hour with a sampling frequency of 288 kHz.

Note that the positions of the sampling stations differ from those preliminarily referenced in D2.1 (Vinagre *et al.*, 2021) because of technical considerations regarding hydrophone safety (Figure 4).

Table 6. Spatiotemporal information of the noise monitoring campaign in Mutriku.

Sampling station	Latitude [° N]	Longitude [° E]	Hydrophone Depth [m]	Seabottom Depth (m)	Deployment	Retrieval
MT1	43.31252	-2.37358	13.5	17.5	16/03/2022 9:23	26/04/22 ---
MT2	43.31247	-2.37261	13.5	17.5	16/03/2022 9:28	26/04/22 ---
MT3	43.31230	-2.3706	14.5	18.5	16/03/2022 9:30	26/04/22 ---

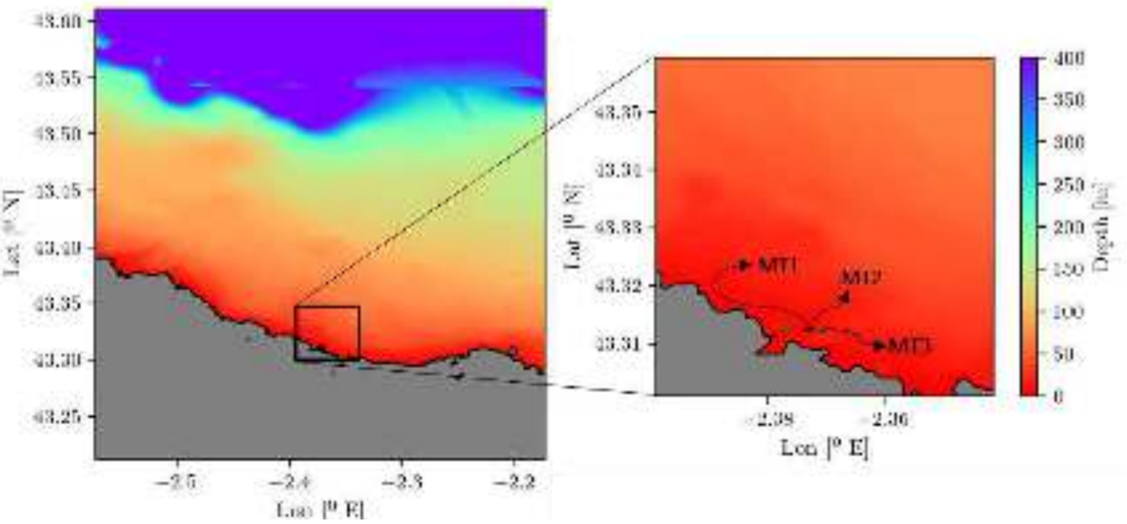

Figure 4. Sampling stations for acoustic monitoring in Mutriku. The location of the WEC is denoted as an asterisk. Note that the WEC is an onshore device, even though it appears in the sea on the map (because of plotting routine resolution).

2.4 SEM-REV (France)

2.4.1 First campaign

2.4.1.1 Operational phase

Regarding the acoustic monitoring in SEM-REV test site in Le Croisic (France), one noise monitoring campaign was carried out from 9th of July to 20th of August, in which three hydrophones were deployed around the device and acquired data regularly for 10 minutes each hour with a sampling frequency of 288 kHz, in this case solely during its operational phase, between 9 July and 20 August 2021 (see Table 7).

Table 7. Spatiotemporal information of the noise monitoring campaign in SEM-REV.

Sampling station	Latitude [º N]	Longitude [º E]	Hydrophone Depth [m]	Seabottom Depth (m)	Deployment	Retrieval
WG1	47.23436	-2.77954	23	33	09/07/21 10:51	20/08/21 16:30
WG2	47.23440	-2.78062	23.5	33.5	09/07/21 11:18	20/08/21 15:30
WG3	47.23609	-2.78107	24	34	09/07/21 12:00	20/08/21 16:00

In Figure 5 the location of the hydrophones and the bathymetry of the zone are shown. Here it is clear that it is one of the shallowest environments of the project, along with Mutriku and Aguçadoura.

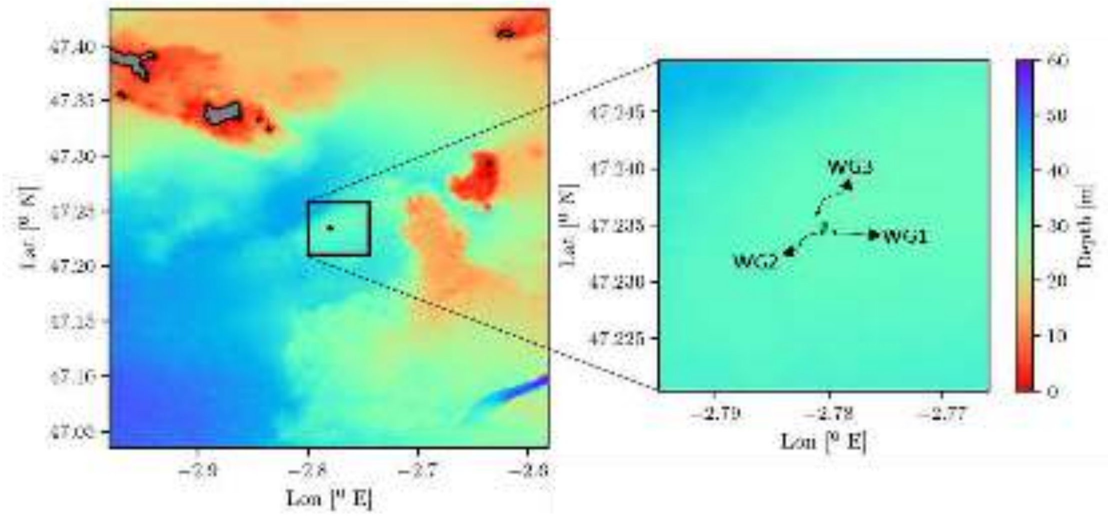

Figure 5. Sampling stations for acoustic monitoring in SEM-REV. The location of the WEC is denoted as an asterisk.

2.4.1.2 Airborne monitoring

Additionally, an airborne monitoring campaign was carried out to strengthen the acoustic analysis of the underwater campaign. It recorded data from 12th of August onwards. A similar acquisition system as the one used for the BiMEP test site was employed in this case, and was placed inside the WAVEGEM device, as illustrated in Figure 6.

Figure 6. Detail of the airborne sound acquisition system installed inside the WAVEGEM device.

2.4.2 Moving of the anchors campaign

After the first campaign, another noise monitoring campaign was carried out from 12th of May to 15th of June of 2023, in which three hydrophones were deployed to study the noise generated from the removal and installation of anchors in its new position. The hydrophones acquired data regularly for 10 minutes each 20 minutes with a sampling frequency of 288 kHz and in the same places than "first campaign" (see section 2.4.1).

Table 8. Spatiotemporal information of the noise monitoring campaign in SEM-REV.

Sampling station	Latitude [° N]	Longitude [° E]	Depth [m]	Deployment	Retrieval
WG1	47.23994	-2.78726	23 (33)	12/05/23 07:48	15/06/23 09:20
WG2	47.23982	-2.78164	23.5 (33.5)	12/05/23 08:00	15/06/23 09:57
WG3	47.23585	-2.7806	24 (34)	12/05/23 08:45	15/06/23 10:20

3. Collected data

In this section we show all collected data in the context of the acoustic characterization of the devices. This comprises, of course, the acoustic data collected during the campaigns, but also environmental data: mainly significant wave height, wave period and precipitation (if available) and operational data of the devices (e.g., kW output energy or an equivalent proxy, such as RPM of turbines).

It should be noted that not all these datasets were eventually used in the acoustic analysis.

3.1 Aguçadoura (Portugal)

As of the date of the publication of this deliverable, only pre-installation campaigns have been undertaken, thus only acoustic and sea state data was gathered, but no operational data.

3.1.1 Acoustics

3.1.1.1 Pre-installation campaign 1

During this campaign, a total of 268 sound files were acquired (about 90 per hydrophone), which translates into a total of about 44.6 hours of recordings.

Table 9. Characteristics of collected acoustic data in the pre-installation campaign 1, Aguçadoura.

Sampling station	Files	Monitoring start	Monitoring end
H1	89	2022/01/17 12:15:15	2022/01/21 04:15:15
H2	90	2022/01/17 11:51:33	2022/01/21 04:51:33
H3	89	2022/01/17 12:09:13	2022/01/21 04:09:13

3.1.1.2 Pre-installation campaign 2

During this campaign, a total of 210 sound files were acquired (70 per hydrophone), which translates into a total of about 35 hours of recordings.

Table 10. Characteristics of collected acoustic data in the pre-installation campaign 2, Aguçadoura.

Sampling station	Files	Monitoring start	Monitoring end
H1	70	2022/05/04 12:25:51	2022/05/07 09:25:51
H2	70	2022/05/04 12:06:45	2022/05/07 09:06:45
H3	70	2022/05/04 12:24:24	2022/05/07 09:24:24

3.1.1.3 First comissioning campaign

During this campaign, a total of 578 sound files were acquired, which translates into a total of around 173 hours of recording. However, only 10 minutes of every recording were used, leading into a total of about 96 hours.

Table 11. Characteristics of collected acoustic data in the operational campaign, Aguçadoura.

Sampling station	Files	Monitoring start	Monitoring end
H1	192	2023/09/24 09:46:06	2023/10/02 10:46:06
H2	194	2023/09/24 10:08:03	2023/10/02 11:08:03
H3	192	2023/09/24 10:20:19	2023/10/02 10:20:19

3.1.2 Sea state

Regarding sea state time series, wind speed and significant wave height (both hourly or every two hours resolution) data sets were gathered, obtained from WindGuru website.

3.1.2.1 Pre-installation campaign 1

The sea state data for the pre-installation campaign 1 is shown in Figure 7.

3.1.2.2 Pre-installation campaign 2

The sea state data for the pre-installation campaign 2 is shown in Figure 8.

3.1.2.3 First commissioning campaign

The sea state data for the first commissioning campaign is shown in Figure 9.

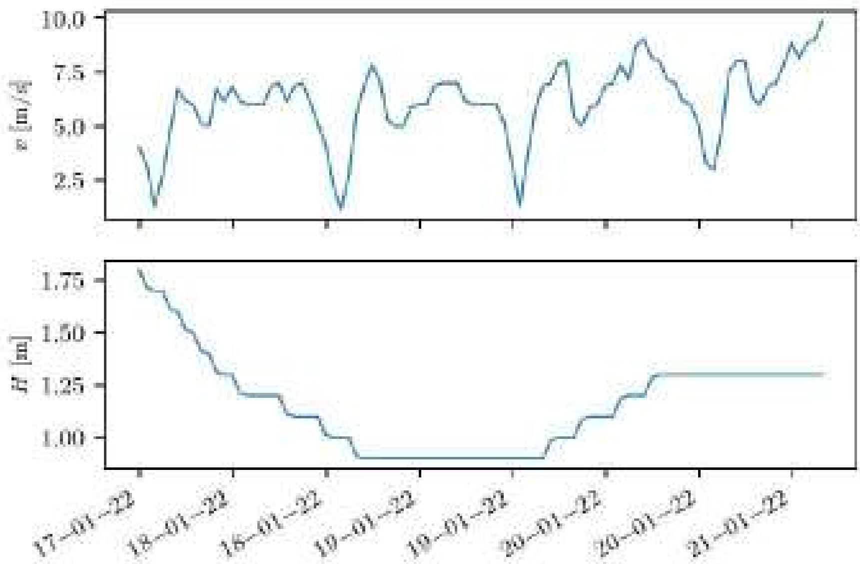

Figure 7. Time series of wind speed and significant wave height for the pre-installation campaign 1 in Aguçadoura.

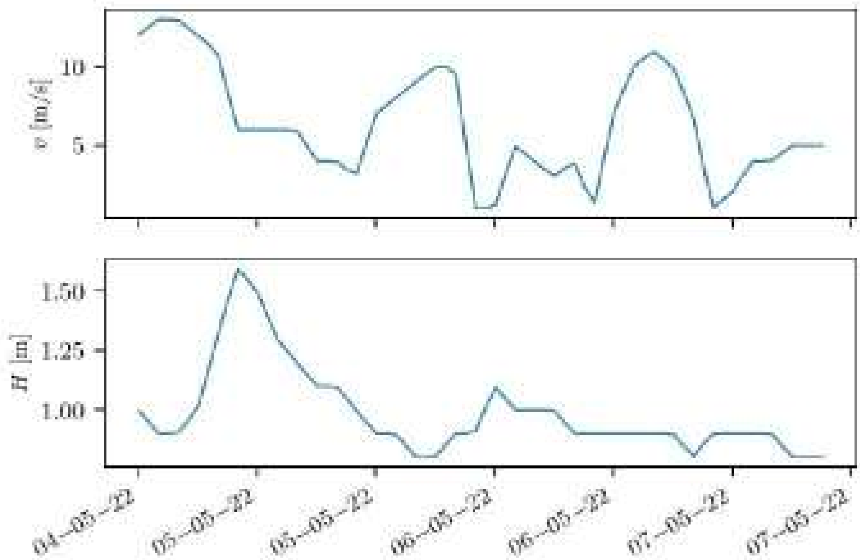

Figure 8. Time series of wind speed and significant wave height for the pre-installation campaign 2 in Aguçadoura.

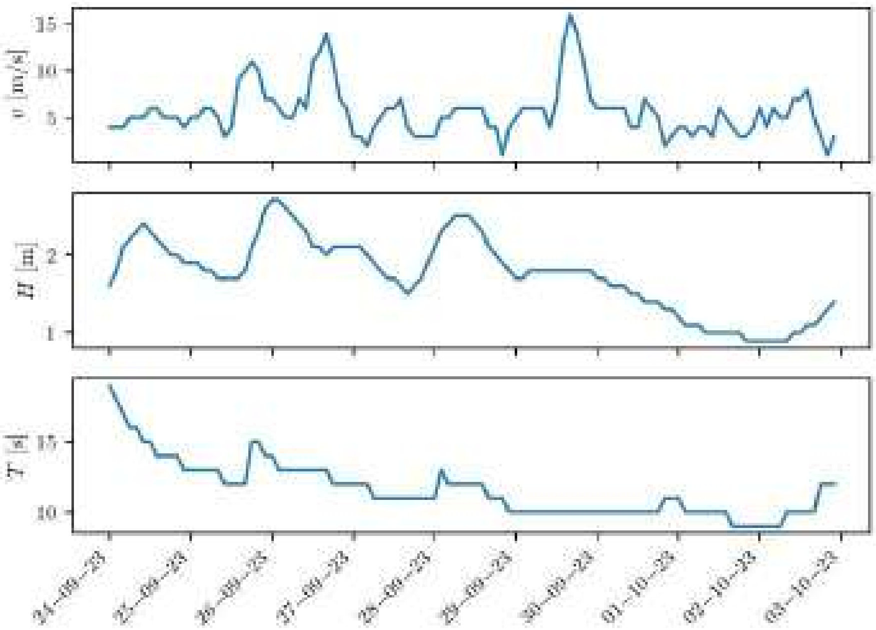

Figure 9. Time series of wind speed, significant wave height and wave period for the first commissioning in Aguçadoura.

3.1.3 WEC First commissioning regime

Data from the first commissioning phase of the C4 WEC was shared by CORPOWER. In order to maintain the industrial secret, the data was normalized with the following equation:

$$z = \frac{x - \mu}{\sigma}$$

Where x is the mean power over 1 h, μ is the mean of the power and σ is the standard deviation of the power. In Figure 10 and Figure 11, the distribution of the normalized data as well as the time series can be shown.

This data allowed to set a threshold to classify the operational regime as 'On' and 'Off'. This threshold was set as the median of the positive values of the distribution, thus ensuring that a significant amount of power (compared with the one from the operational campaign timespan) was being generated.

It is important to note that this data is not representative of the device operational modes. This first commissioning campaign aimed at testing the different functions and mode of operations of the WEC.

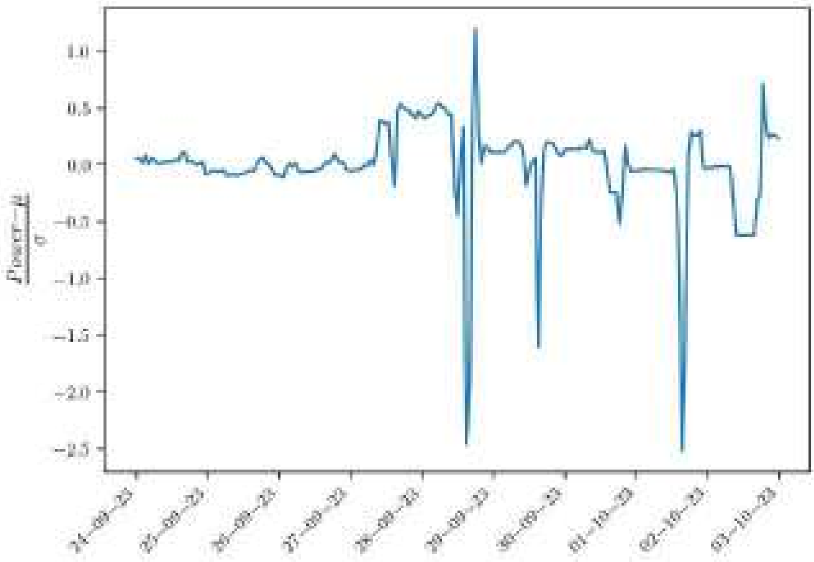

Figure 10. Normalized power generated time series of the Hi-Wave C4 WEC, Aguçadoura.

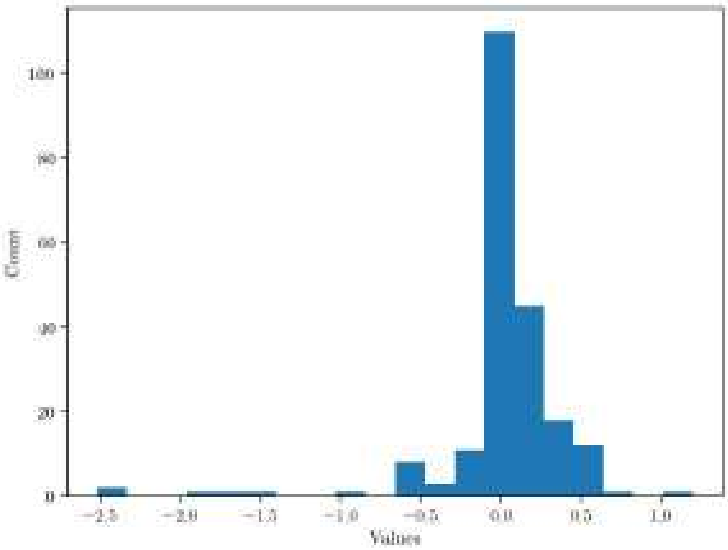

Figure 11. Distribution of normalized power data for the Hi-Wave C4 WEC, Aguçadoura.

3.2 BiMEP (Spain)

3.2.1 Acoustics

3.2.1.1 Pre-operational and installation phase

A total of 1073 sound files were recorded for this campaign, which ended after the device was deployed in the sea and before its operation.

Table 12. Characteristics of collected acoustic data in the pre-operational and installation phase in BiMEP.

Sampling station	Files	Hours recorded	Monitoring start	Monitoring end
PE_pre	1073	178.8	16/06/2021 07:31:22	30/07/2021 22:31:22

3.2.1.2 Operational phase

A total of 1294, 1064 and 1157 sound files were obtained from the sampling stations PE1, PE2, and PE3, respectively, with a total duration worth 586 hours. The first thing to note (see Table 13) is that the actual start and end of monitoring may differ from the timestamps shown in section 2.2 (Operational phase); this is the case if the acquisition system stops working or it is programmed to start before the actual deployment, among other causes. In any case, the relevant timestamps are always those coming from the actual sound files.

Table 13. Characteristics of collected underwater data in the operational phase in BiMEP.

Sampling station	Files (10 min)	Hours recorded	Monitoring start	Monitoring end
PE1	1294	215.67	11/11/2021 07:59:58	25/01/2022 04:59:58
PE2	1065	177.5	11/11/2021 07:59:58	25/01/2022 15:59:58
PE3	1157	192.83	11/11/2021 07:59:58	29/12/2021 12:59:58

3.2.1.3 Airborne

Regarding the airborne noise monitoring, a total of 9469 files of 1 min duration were obtained (10 each hour), accounting for a total of 157.8 hours' worth of recordings.

Table 14. Characteristics of collected airborne data during the operational phase in BiMEP.

Sampling station	Files (1 min)	Hours recorded	Monitoring start	Monitoring end
Airborne PE	9469	157.8	22/08/2021 14:00:00	19/12/2021 09:09:15

3.2.2 Sea state

Wind speed and wave parameters time series were downloaded from Puertos del Estado[4] (Bilbao-Vizcaya buoy) data service for the time range spanning all acoustic monitoring campaigns (Figure 12). Even though several wave parameters were included (significant wave height, peak period, mean period), only significant wave height time series was eventually used in the study. Even if the location of the buoy is not exactly the same as that of the hydrophones, it is close enough to the test site so as to be valid (this is confirmed in section 4.3).

3.2.3 WEC operational regime

Data from the operational status of the PENGUIN II WEC was shared by WELLO. It is characterized by a binary variable that signals whether the generator is free to rotate or not (0: not operating; 1: operating). It is shown in Figure 13; in which it can be observed that the converter was operating about half of the time (irregularly from 22-11-2021 to 05-12-2021). This time series does not cover the whole monitoring period since the device had to be decommissioned before expected because of a leakage caused by some object striking the hull presumably during the extremely rough sea conditions that happened in early December of 2021.

[4] Link: https://www.puertos.es/es-es/oceanografia/Paginas/portus.aspx (last accessed 20-01-2023).

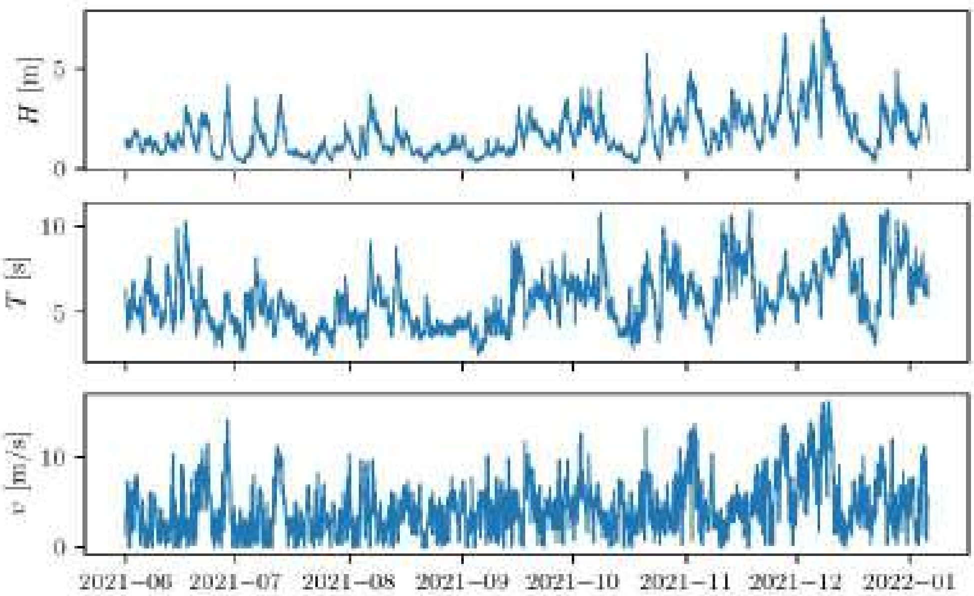

Figure 12. Significant wave height, wave mean period, and mean wind speed as monitored by the Bilbao-Vizcaya buoy.

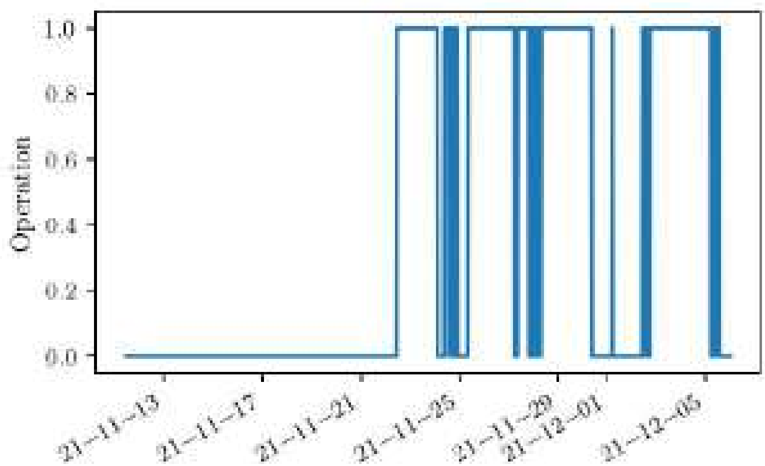

Figure 13. Operational regime of the WEC. 0: non-operating; 1: operating.

3.3 Mutriku (Spain)

3.3.1 Acoustics

A total of 272, 920 and 993 sound files were acquired for the MT1, MT2 and MT3 sampling sites, respectively (Table 15). Unfortunately, after a close inspection, data from MT1 is not only scarcer in quantity, but also in quality, as apparently the hydrophone did not work as intended and did not acquired data regularly during its operation.

Table 15. Characteristics of collected underwater data in Mutriku.

Sampling station	Files (10 min)	Hours recorded	Monitoring start	Monitoring end
MT1	272	272	16/03/2022 07:59:58	29/03/2022 12:08:39
MT2	920	153.3	16/03/2022 07:59:58	23/04/2022 14:00:17
MT3	993	165.5	16/03/2022 07:59:58	26/04/2022 09:59:58

3.3.2 Sea state

Historical hourly average data from the Spanish administration (Puertos del Estado[5]) was gathered for the studied period, corresponding to a point close to the test site ("Punto SIMAR 3171032"). As can be seen in Figure 14, there was a good variety of sea states during the monitoring period.

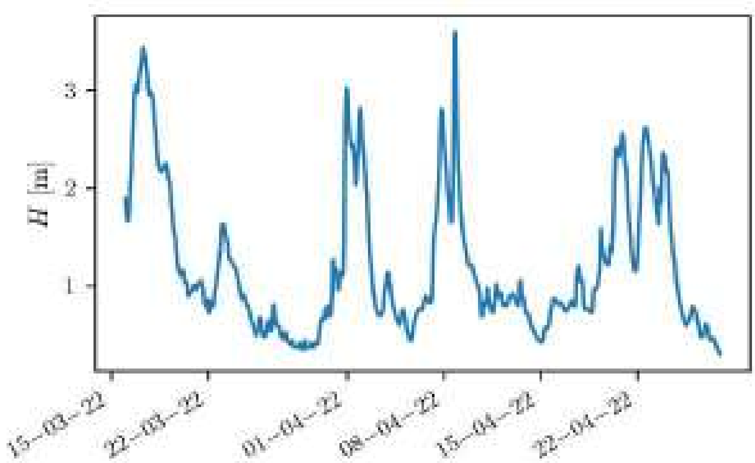

Figure 14. Significant wave height for the Mutriku test site.

[5] Link: https://www.puertos.es/es-es/oceanografia/Paginas/portus.aspx (last accessed 08/02/2023).

3.3.3 WEC operational regime

Operational data, in this case, revolutions per minute (RPM) from the Basque Country administration was supplied for the time period studied (Figure 16).

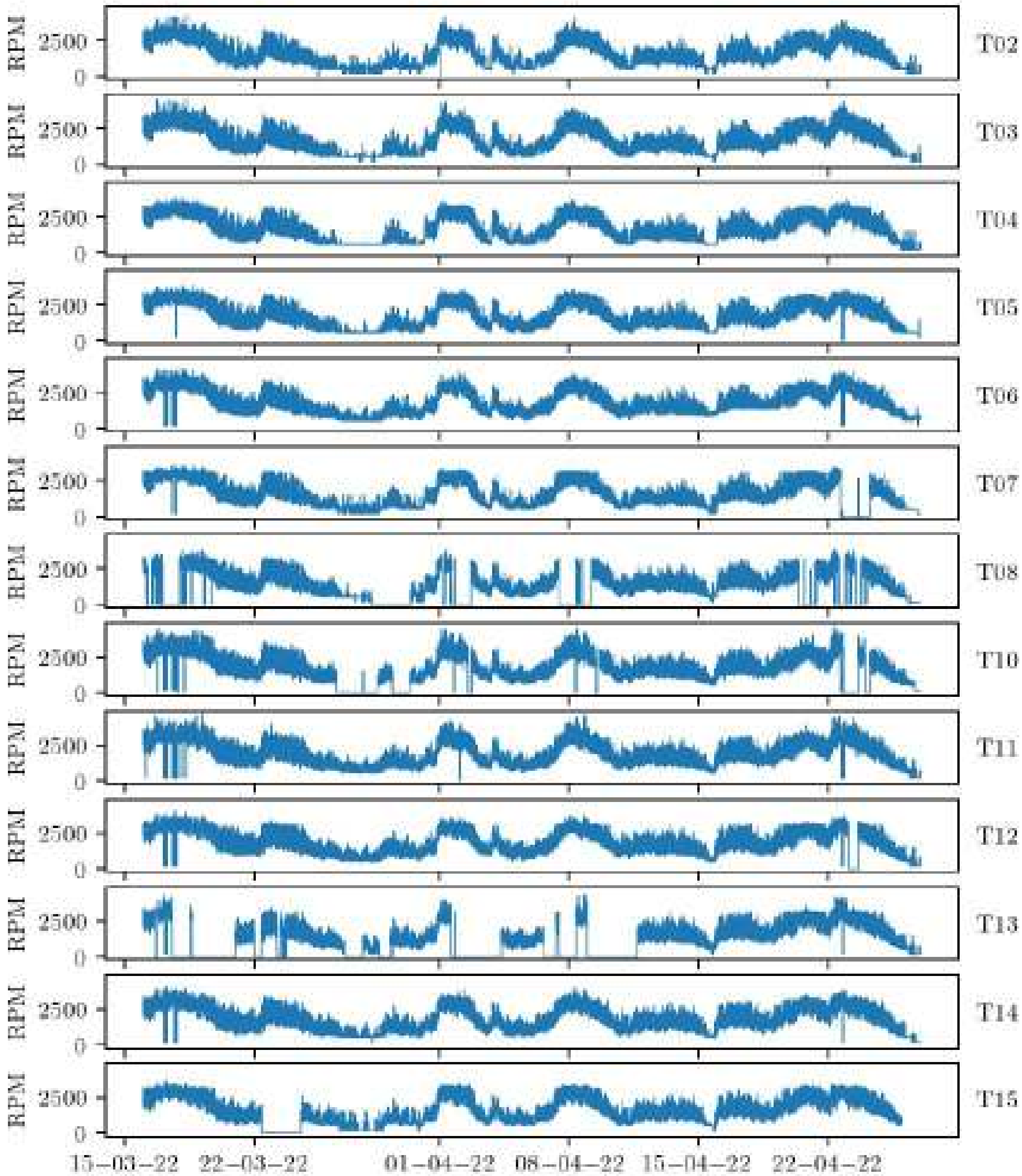

Figure 15. RPM time series for all turbines (indicated in the right column) in the Mutriku power plant.

3.4 SEM-REV (France)

3.4.1 First campaign

3.4.1.1 Acoustics

A total of 111, 1081 and 1023 sound files were obtained from the sampling stations WG1, WG2, and WG3, respectively, with a total duration worth 586 hours (see Table 16)

Table 16. Characteristics of collected underwater data in the operational phase in SEM-REV.

Sampling station	Files (10 min)	Hours recorded	Monitoring start	Monitoring end
WG1	111	18.5	09/07/2021 10:30:07	18/07/2021 10:04:26
WG2	1081	180.17	09/07/2021 07:59:58	23/08/2021 07:59:58
WG3	1023	170.5	09/07/2021 09:59:58	20/08/2021 23:59:58

It is worth mentioning that the hydrophone from WG1 stopped recording much earlier than expected (at about 10% the duration of the campaign), due to an unknown malfunctioning.

3.4.1.2 Sea state

Significant wave height as well as precipitation time series in the area were shared by staff from SEM-REV (Figure 16).

Eventually, only data from significant wave height was used in the analysis, as the classification of the SPL distribution was already scarce for some combination of operational regime and significant wave height (see section 4.5).

3.4.1.3 WEC operational regime

WEC operational regime (described as its generated power divided by the average power) was shared by staff from GEPS-Techno (Figure 17). Unfortunately, no data was available from the WEC for most of the monitoring campaign (from 09/07/2023 to 14/08/2023). However, the device was supposedly operating during this phase (but at unknown regime), so, as later explained in section 4.5.14.5, it is infeasible to assess the WEC acoustic signature.

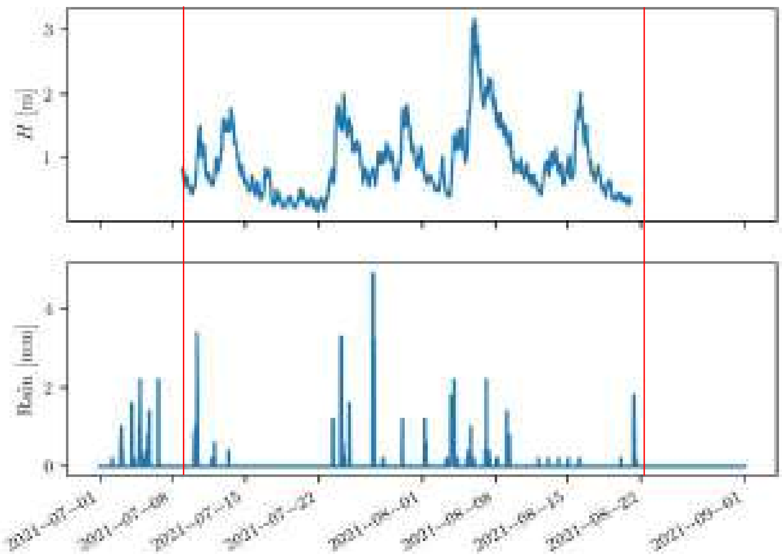

Figure 16. Significant wave height (from SEM-REV site wave buoy) and precipitation time series (from Meteo France portal[6], approximately 20nm from the site) for the acoustic monitoring campaign in SEM-REV. Red lines show the timespan where the sampling stations recorded acoustic data.

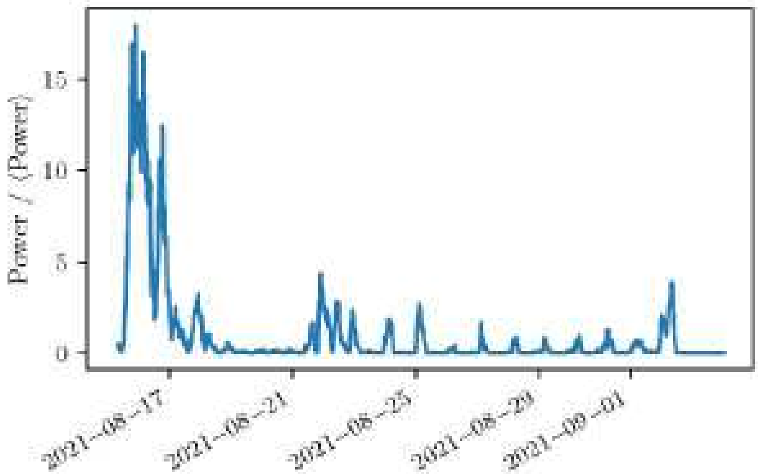

Figure 17. Normalized (with respect average) generated power of the WAVEGEM WEC.

[6] https://donneespubliques.meteofrance.fr/metadonnees_publiques/fiches/fiche_44184001.pdf

3.4.2 Second campaign

3.4.2.1 Acoustics

A total of 1027, 1021 and 1395 sound files were obtained from the sampling stations WG1, WG2, and WG3, respectively, with a total duration worth 574 hours (see Table 17)

Table 17. Characteristics of collected underwater data in the operational phase in SEM-REV.

Sampling station	Files (10 min)	Hours recorded	Monitoring start	Monitoring end
WG1	1027	171.17	12/05/2023 14:59:58	27/05/2023 08:19:09
WG2	1021	170.17	12/05/2023 14:59:58	26/05/2023 21:57:38
WG3	1395	232.5	12/05/2023 14:59:58	06/06/2023 20:20:24

It is worth noting that WG2 recorded 1026 files instead of 1021, but the last 5 files were discarded as those files were collected on 16/06/2023, when the hydrophone was recovered and out of the water.

3.4.2.2 Sea state

Sea state and wind speed time series were obtained from the SEM-REV site wave buoy (Figure 18).

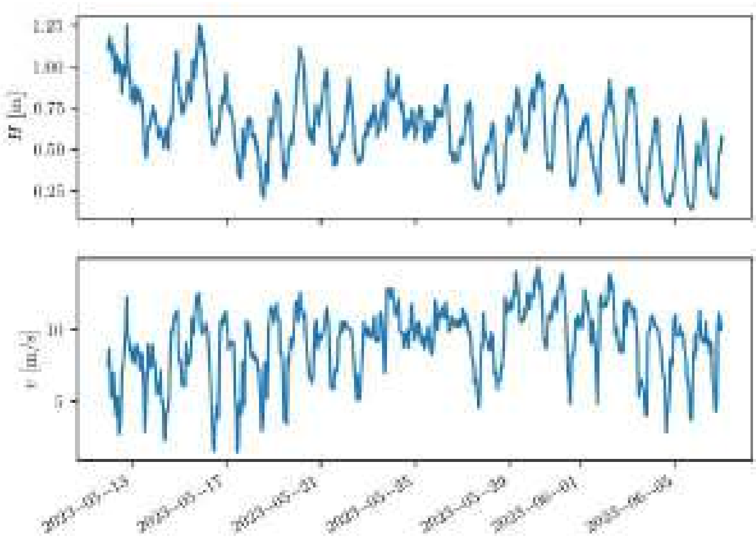

Figure 18. Sea state and wind speed time series (from SEM-REV site wave buoy).

4. Processed data

Finally, in this section, the results from the acoustic processing are presented and analysed.

4.1 Methodology

Once all necessary data is gathered, the proposed processing methodology in this project consists of three steps:

1) Obtain Sound Pressure Level (SPL) metric for all noise recordings: SPL distributions for each sampling station are obtained in 1/3 octaves from 15.625 Hz to 20 kHz.

2) Pre-process data: in this step the used datasets are cleaned to clear unreliable data[7]. Then, all datasets are interpolated to a common time vector that is defined by the most early (and late) date of sound measurements. This allows to work with simultaneous data without time-derived problems.

3) SPL distributions are flagged according to sea state (significant wave height) and operating regime (of WEC) time series, obtaining SPL for background and total noise for different sea states.

While we are not following any specific standard, the proposed methodology is based on current guidelines on noise monitoring reporting.

4.1.1 Sound Pressure Level

Given the particular importance of this metric in this study, this subsection is devoted to its definition and calculation.

Mathematically, the SPL is defined as:

$$\mathrm{SPL} = 20\log_{10}\left(\frac{p_{rms}}{p_{ref}}\right)$$

[7] Unreliable data is defined here as data acquired before/during (after) deployment (extraction) of hydrophones, data with saturated signal, and data with missing and/or wrong – outliers- values.

where p_{rms} is the root mean square of the pressure in some chosen interval of time and p_{ref} is a reference pressure (in water, $p_{ref} = 1$ μPa). The resulting SPL will slightly depend on such interval, that we will henceforth denote by Δt, and will be equal to 1 second in this study to balance the need for smoothing the signal without losing reliability and consistency. Given a pressure signal in the appropriate units, the processing scheme consists in the following steps (see Figure 19):

1. Truncate the signal to avoid artefacts at its beginning and end (about 5 seconds, artefacts which could directly be generated by the hydrophone itself). In this step it is also advisable to decimate the signal by some factor (between 4 and 8 in this study). This way, we significantly alleviate the computation cost. However, it must be ensured that the Nyquist limit frequency is respected.
2. Apply a bandwidth Butterworth filter to the signal in 1/3 centred octave bands, ranging from 15 Hz to 20 kHz (32 different bands), and discard the origin and ending parts of it, to avoid filtering artefacts.
3. Divide the signal in chunks of Δt seconds (1 second in this study).
4. Calculate the SPL of the individual sub-signals (for each frequency).

In the end, the obtained result is a multidimensional matrix consisting of the SPL of each sub-signal of every complete signal (e.g., sound file), such that we can associate a SPL value for each moment in time of the temporal monitoring. Every subsequent result will be based on a particular analysis of this very distribution.

More specifically, we will mostly work with the percentile distribution; and in particular, with the median, Q1 (percentile 25) and Q3 (percentile 75), employing both hourly and whole-period reductions of the distribution in time. In any case every result will be explained comprehensively. The analysis will be carried out in 1/3 octave bands centred in frequencies from 15.625 Hz to 20 kHz, but special emphasis will be placed on the central frequencies 62.5 and 125 Hz (following the recommendation of the MSFD), as well as 1 kHz, based on SafeWAVE expertise to characterize higher frequency noise.

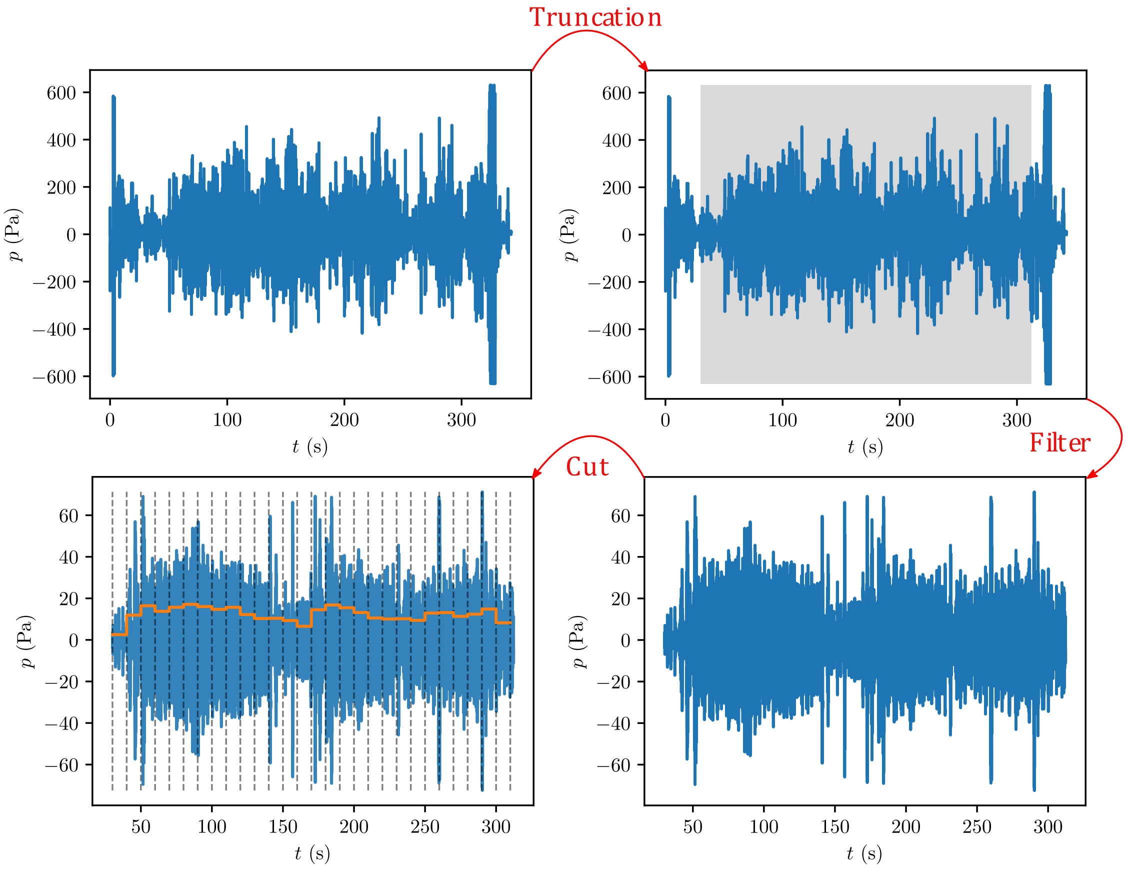

Figure 19. SPL processing scheme.

4.1.2 Acoustic signature assessment

Once the sound files are processed and the SPL is obtained, the following methodology is applied to obtain the contribution of noise from the WECs:

1) All time series (SPL, WEC operational regime, sea state) are interpolated to the same timestamps. They are also cleaned so that they can be properly used as input arguments of the functions involved in the analysis. This includes the replacement or deletion of invalid data.

2) Classify the state of operation of the WEC; usually, a binary class is used (Off, On). Moreover, classify the time periods by sea state (this allows an evaluation of the dependence of SPL on the state of the sea – here based on the wave height).

3) With this classification in mind, the percentile SPL distribution is calculated for all these cases. That is, for the baseline or background, and for the "On regime" (and possibly others, such as decommission activities, vessels activity, etc.). Depending on the case, note that baseline may stand for the existing noise when the device is not yet installed, while ambient noise refers to the existing noise when the device is installed but not yet operating.

4) The difference between cases is explored and serves as an assessment of the contribution of the radiated noise by the WECs to the background noise.

4.2 Aguçadoura (Portugal)

Following the aforementioned methodology, in this section the results from the Aguçadoura campaign are presented. Two short-duration monitoring campaigns were undertaken in this test site, both measuring the ambient noise in its waters (before the device installation).

4.2.1 Pre-installation campaign 1 (January)

As can be seen in Figure 20, overall SPL values are found around 95 dB re 1 µPa, with a spectrum quite constant in frequency, although both low (< 50 Hz) and high frequencies (>10 kHz) are in the lower side. While not identical, the spectrum for each hydrophone is quite similar. The significant wave height ranged from 1 to 1.8 m.

Next, in Figure 21 the SPL in the selected frequency bands is shown in more detail, for each sampling station distribution.

As it's clear, all hydrophones captured equivalent levels. Interestingly, these bands show very similar SPL values (between 105 and 85 dB re 1 µPa), which slightly decrease in time. The deviations, characterized using percentiles quartiles 25 and 75 (Q1 and Q3), are larger for the 62.5 Hz band.

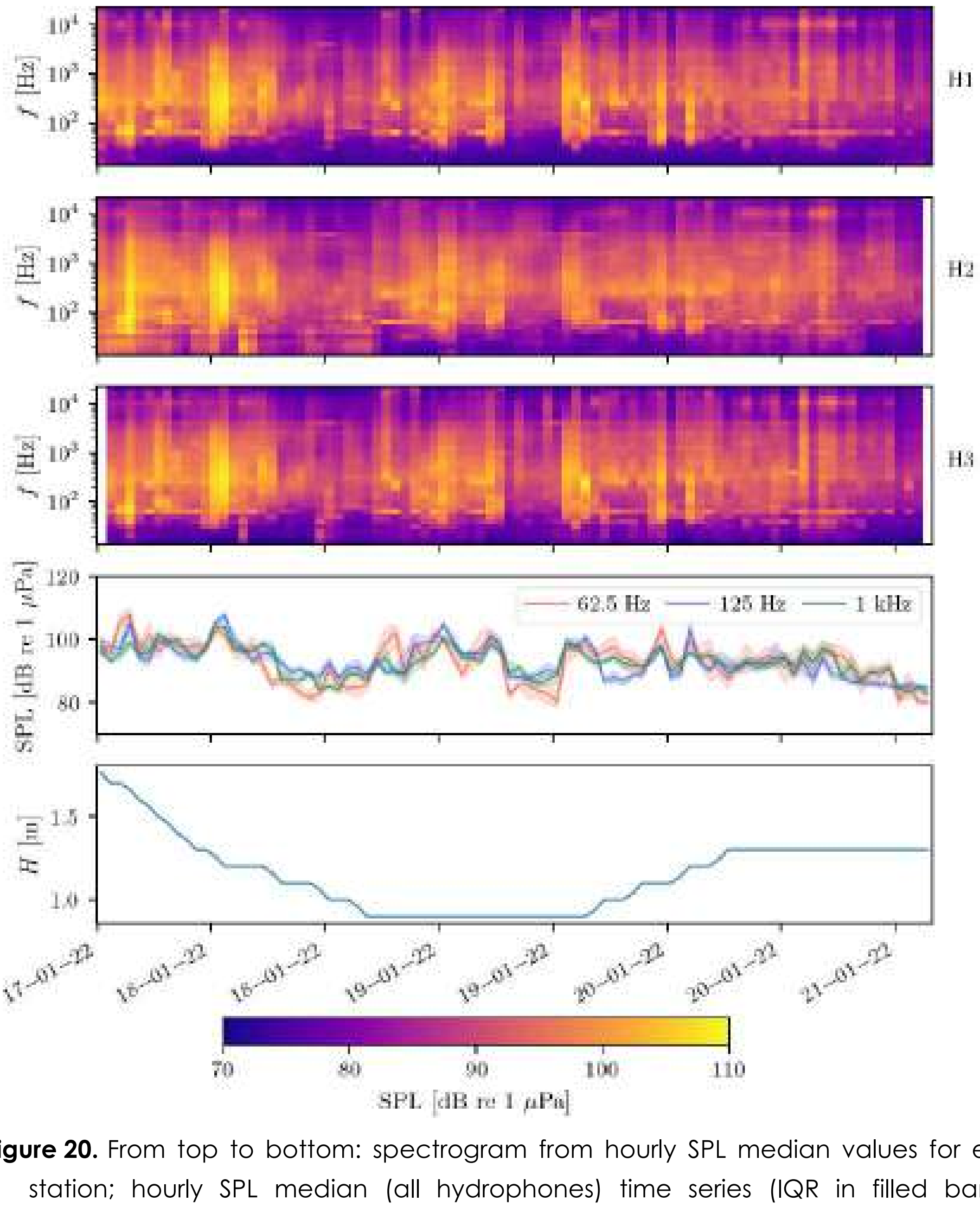

Figure 20. From top to bottom: spectrogram from hourly SPL median values for each station; hourly SPL median (all hydrophones) time series (IQR in filled bands); significant wave height.

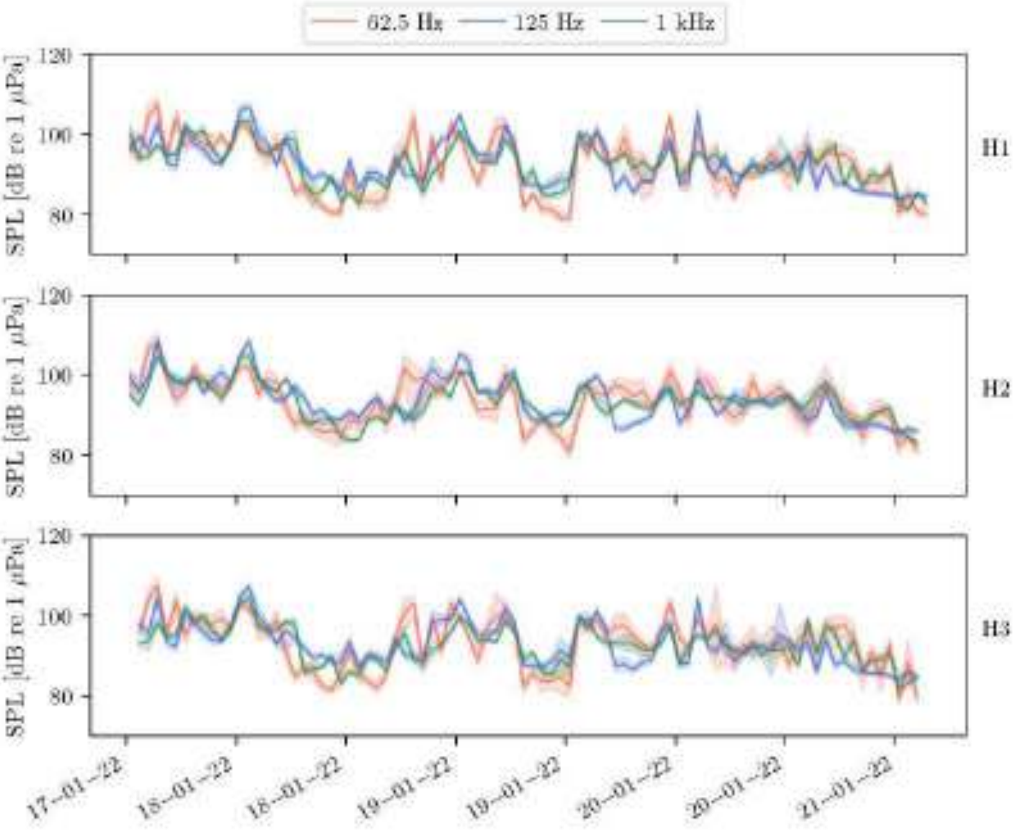

Figure 21. Median and Q1-Q3 (solid bands) for each sampling station.

To study the dependence of the SPL with sea state, the significant wave height time series is classified into the following bins (Figure 22): H_b = (0,1,2)

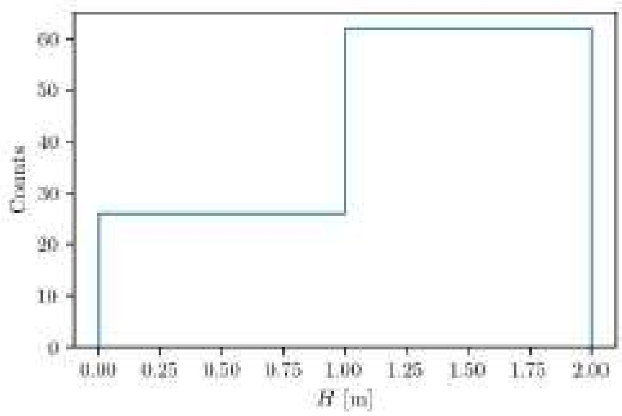

Figure 22. Histogram of H in the defined bins (0,1,2), for the pre-installation campaign 1, in Aguçadoura.

When classified into these bins, the SPL distribution ends up as it can be seen in Figure 23.

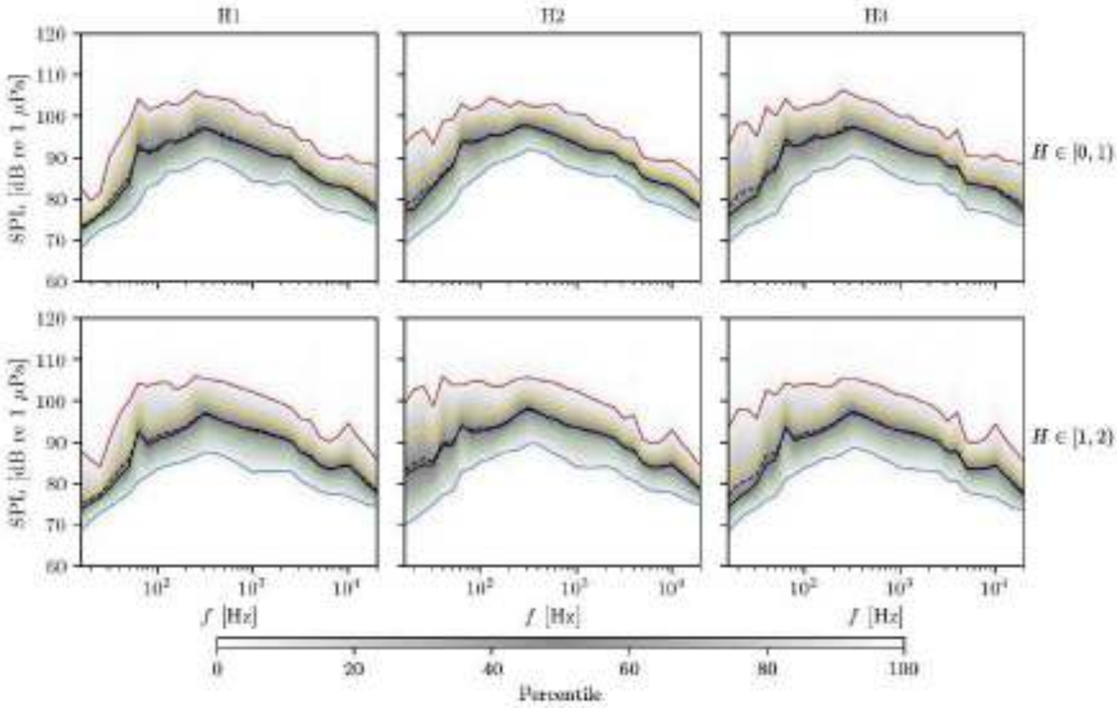

Figure 23. Percentile distribution of the SPL for each sampling station and sea state. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow and red lines, respectively. The mean is shown as a black dashed line.

4.2.2 Pre-installation campaign 2 (May)

In the second pre-installation campaign, carried out in May and set up in the same way as the January campaign (same hydrophone locations), some differences can be found.

As with the other campaign, the overall SPL values are found mostly within the 85-105 dB re 1 µPa range, although the values are slightly smaller for this campaign (Figure 24). There are some contributions to the noise that could be attributed to passage of vessels in which SPL reaches a maximum of ~110 dB re 1 µPa.

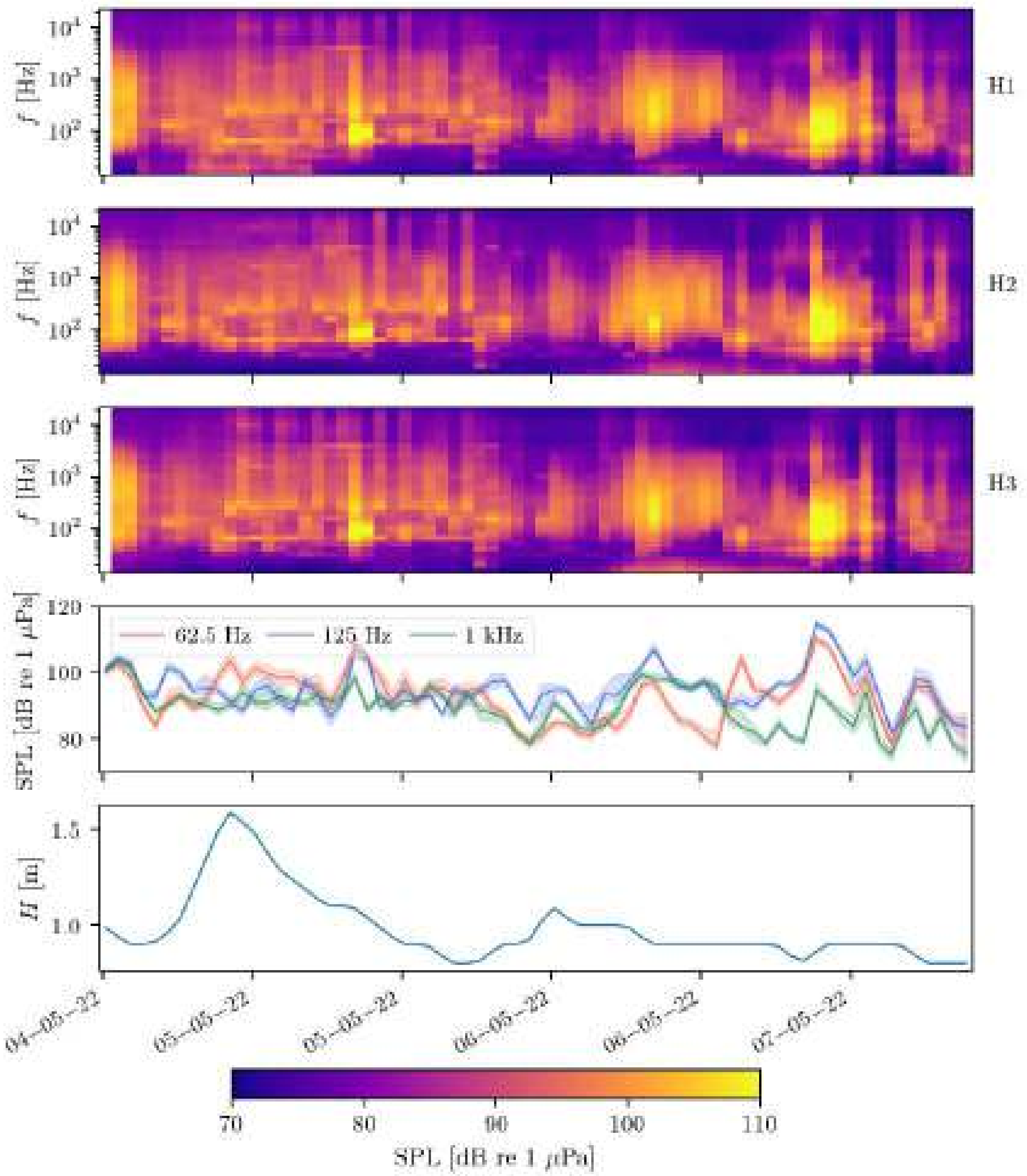

Figure 24. From top to bottom: spectrogram from hourly SPL median values for each station; hourly SPL median (all hydrophones) time series (IQR in filled bands); significant wave height.

As it can be seen in Figure 25, the difference between the sampling stations is quite small. The deviations are more unique to each station, as they capture transients that are more localized. They are however quite constraint, which denote small variance around the central values for each recording.

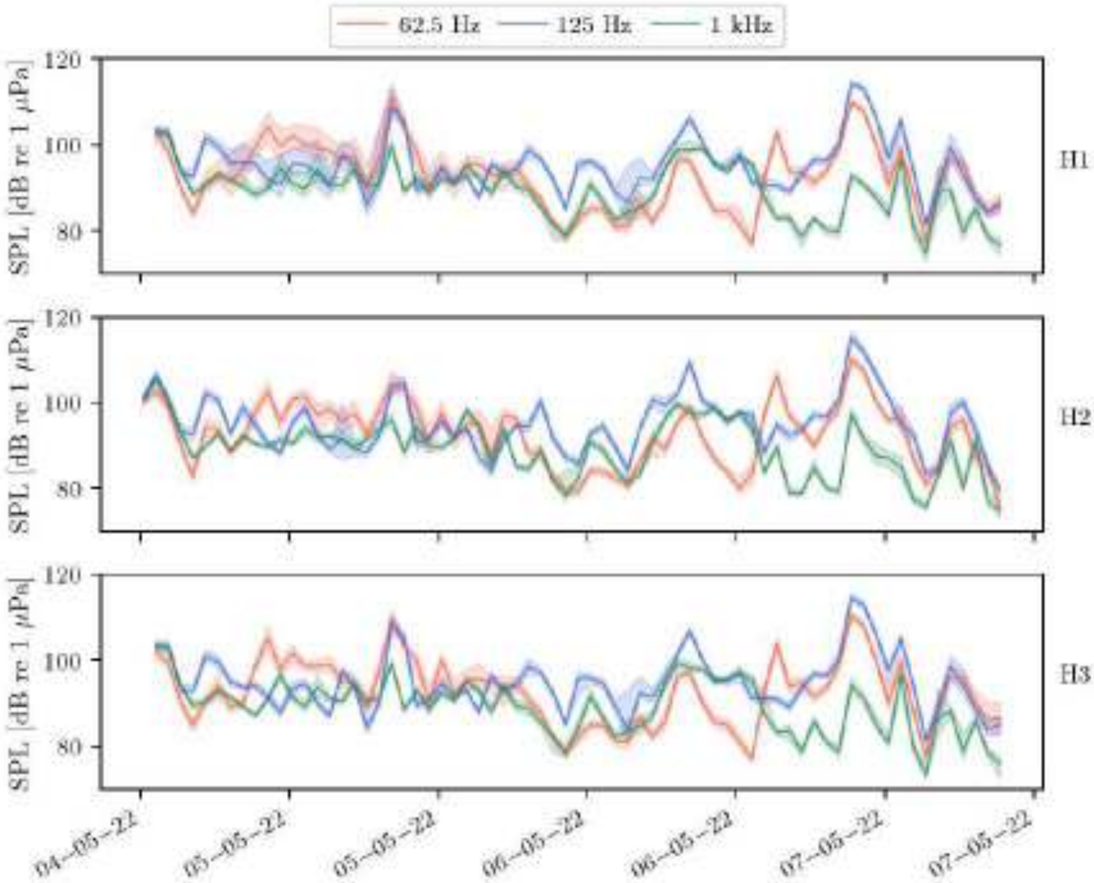

Figure 25. Median and Q1-Q3 (solid bands) for each sampling station.

In a similar fashion as before, significant wave heights are binned in the following values (in meters): H_b = (0,1,2). With that in mind, in the Figure 26 the counts in each bin are shown (47 (67.1 %), 23 (32.9 %)).

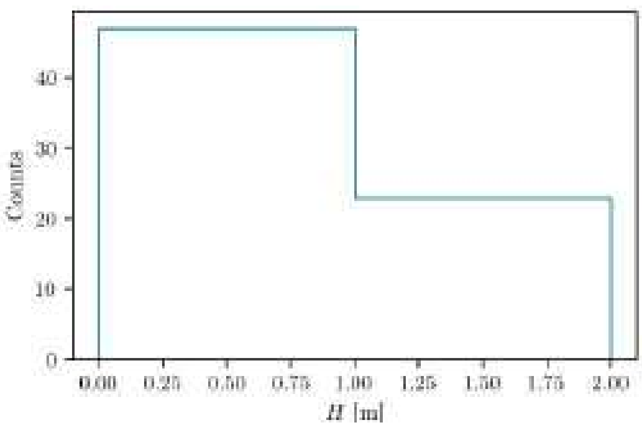

Figure 26. Histogram of H in the defined bins (0,1,2).

Using this classification, the percentile distribution of the SPL series for each sampling station and sea state are shown in Figure 27. The graphs show very similar distributions, with the main difference between sea states in the peaks at around 100 Hz and 4 kHz (which is attributed to noise from moorings chain lines).

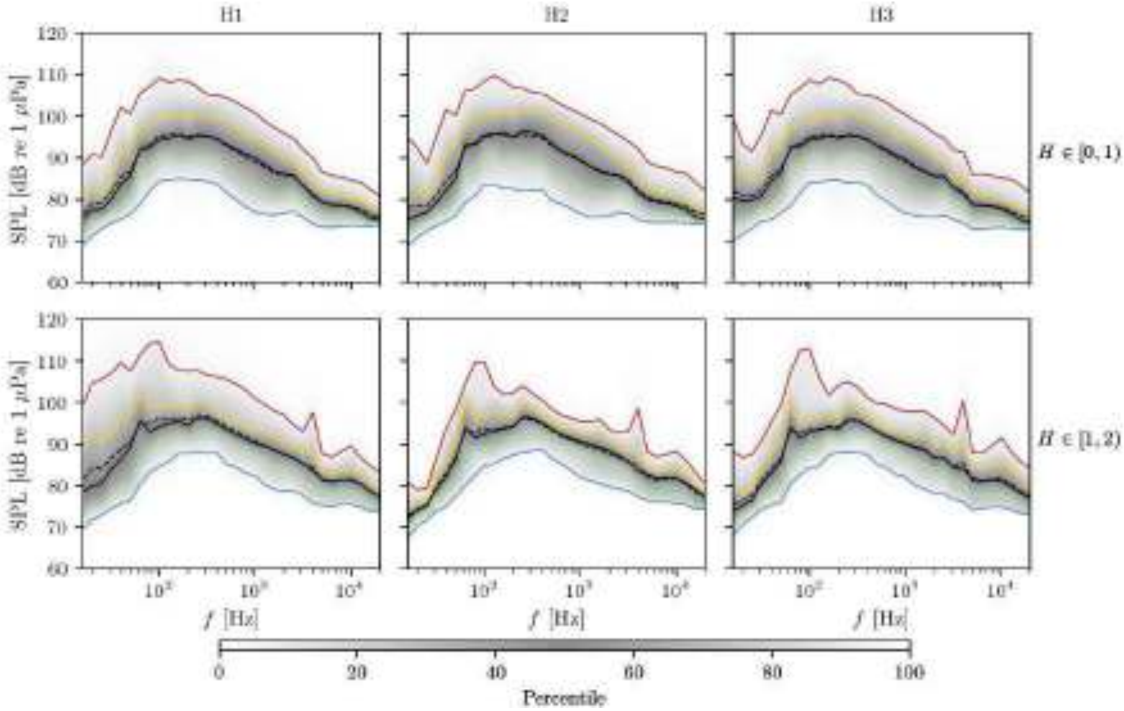

Figure 27. Percentile distribution of the SPL for each sampling station and sea state. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow and red lines, respectively. The mean is shown as a black dashed line.

4.2.3 First comissioning campaign

The monitoring campaign in this site was performed about 16 months after the pre-installation one, when the device was already deployed in the sea. The campaign was expected to be undertaken in 2022, but the harsh sea state conditions and the low sea windows. This campaign only lasted 9 days due to the sea conditions.

4.2.3.1 Underwater noise

The results of the processing of the data from the three deployed hydrophones is shown in this section. In Figure 28, the whole content of the

SPL distributions in both frequency and time is shown as spectrograms, which allows for a quick assessment of the most relevant acoustic signatures. Also, the global hourly median SPL values for the three key frequencies specified by MSFD are shown. Additionally, significant wave height with most relevant activities periods is plotted.

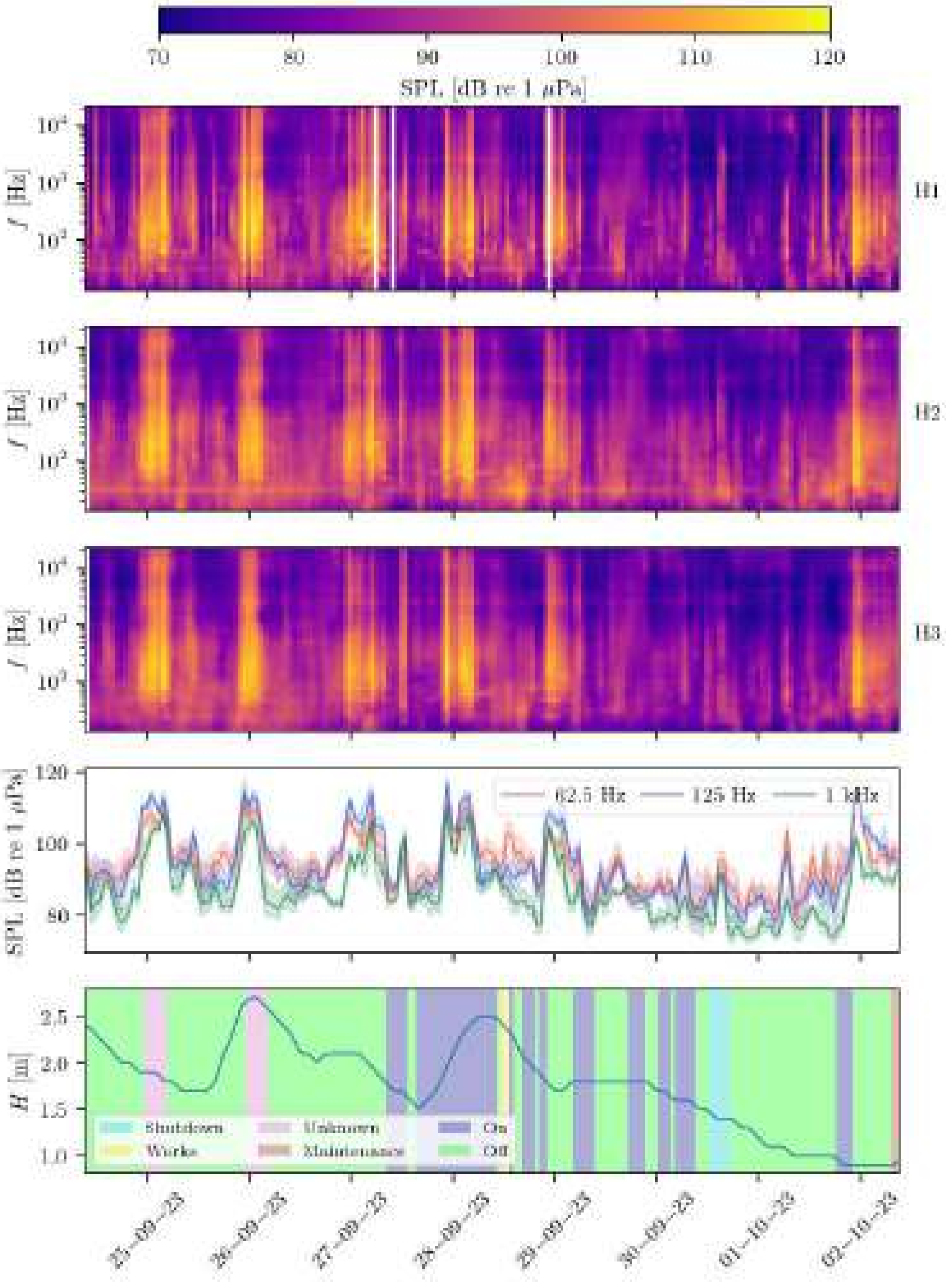

Figure 28. From top to bottom: spectrogram from hourly SPL median values; the corresponding IQR (Q3-Q1); hourly SPL median time series (IQR in filled bands); significant wave height and relevant periods of activity.

The three spectrograms show great similarity, well correlated with wave height (and vessel passings), and with levels between 75 and 118 dB re 1 µPa, depending on the frequency.

As can be seen, the most relevant acoustic signatures happened for the On and Unknown states. The 'Unknown' status refers to a sound discovered in the audios, which seems to come from interference between devices connected to the WEC at high frequency.

As these sounds were produced by the WEC in 'Off' state (almost no power was being generated), we decided to exclude it from the 'On' and 'Off' states, as theses sounds are not coming from the operational status of the WEC. In section X, the differences between these sounds and the 'Off' state are shown.

In Figure 30 the hourly median SPL time series for the key frequencies are plotted for each hydrophone.

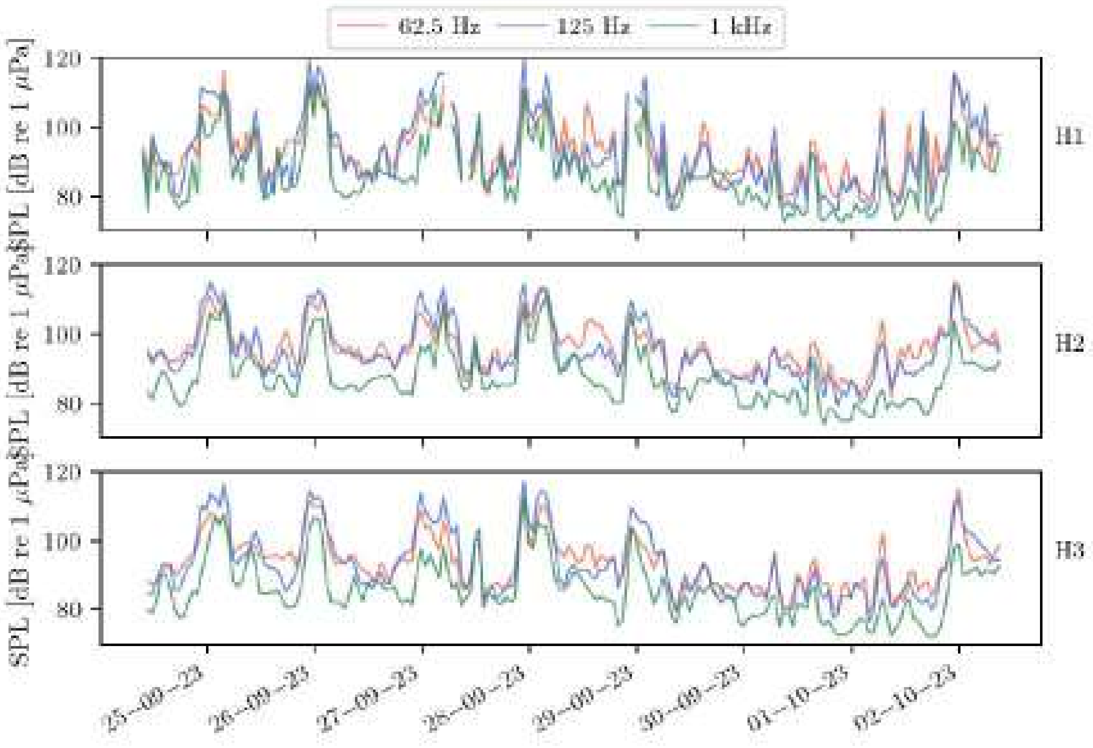

Figure 29. Median SPL time series for the three key frequencies per hydrophone.

It should be noted the discontinuities in the first hydrophone, which match with the blank spaces in the first spectrogram shown in Figure 28. These blank spaces were originated by some audio files being completely empty probably due to errors when decompressing from .sud to .wav format.

Four significant wave height values were selected to define ranges that, in addition to the operative regimes, allow for a detailed classification of the SPL distribution for all hydrophones. These bins are defined, as illustrated in Figure 30, (0.75, 1.5, 2, 2.5) meters.

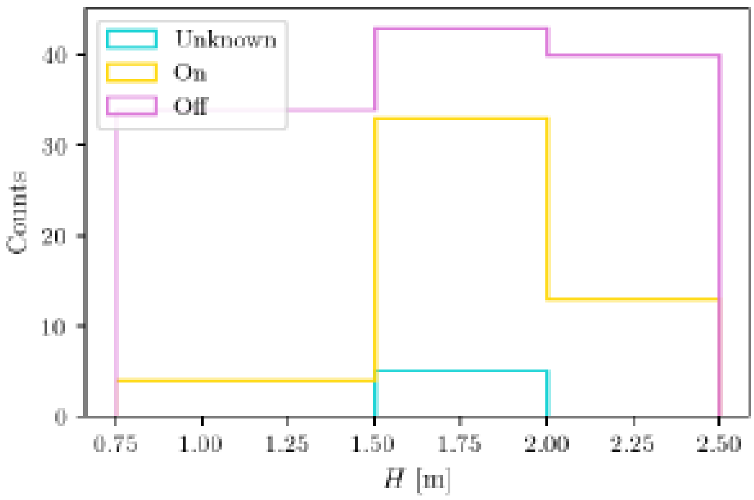

Figure 30. Histograms of significant wave height values for the different regimes.

The total count for the On, Off and Unknown states was, respectively, 50, 121 and 10 (as the unknown sound only appeared in a few audios). As expected, due to the short duration of the monitoring campaign, the wave heights are not sampled equally, nor are the On and Off states.

The subsequent illustrations (Figure 31 to 33) display the complete percentile distribution across all sampling locations. These figures highlight that certain data combinations are lacking, as previously explained. Generally, no significant differences are found between the On and Off state per hydrophone and wave height bin.

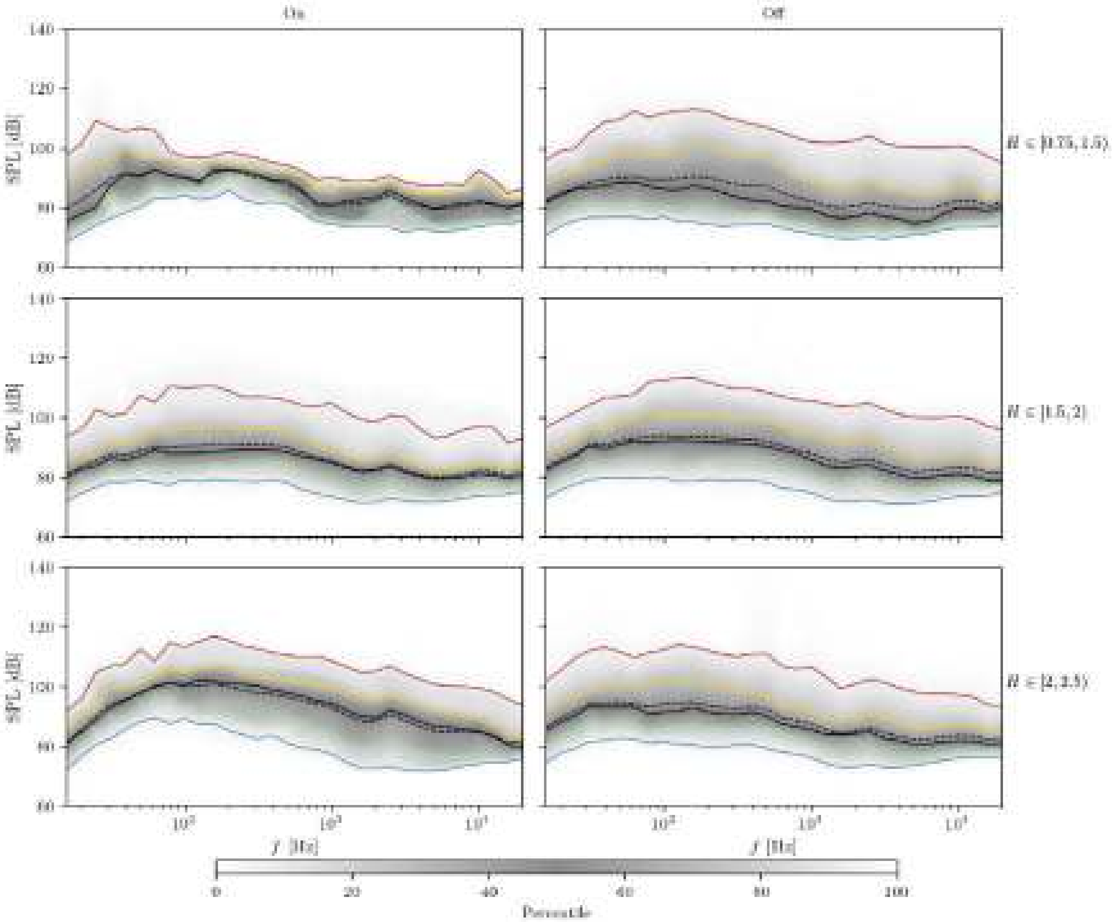

Figure 31. Percentile distribution of the SPL for each sea state (for the H1 sampling site). Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The mean is shown as a black dashed line.

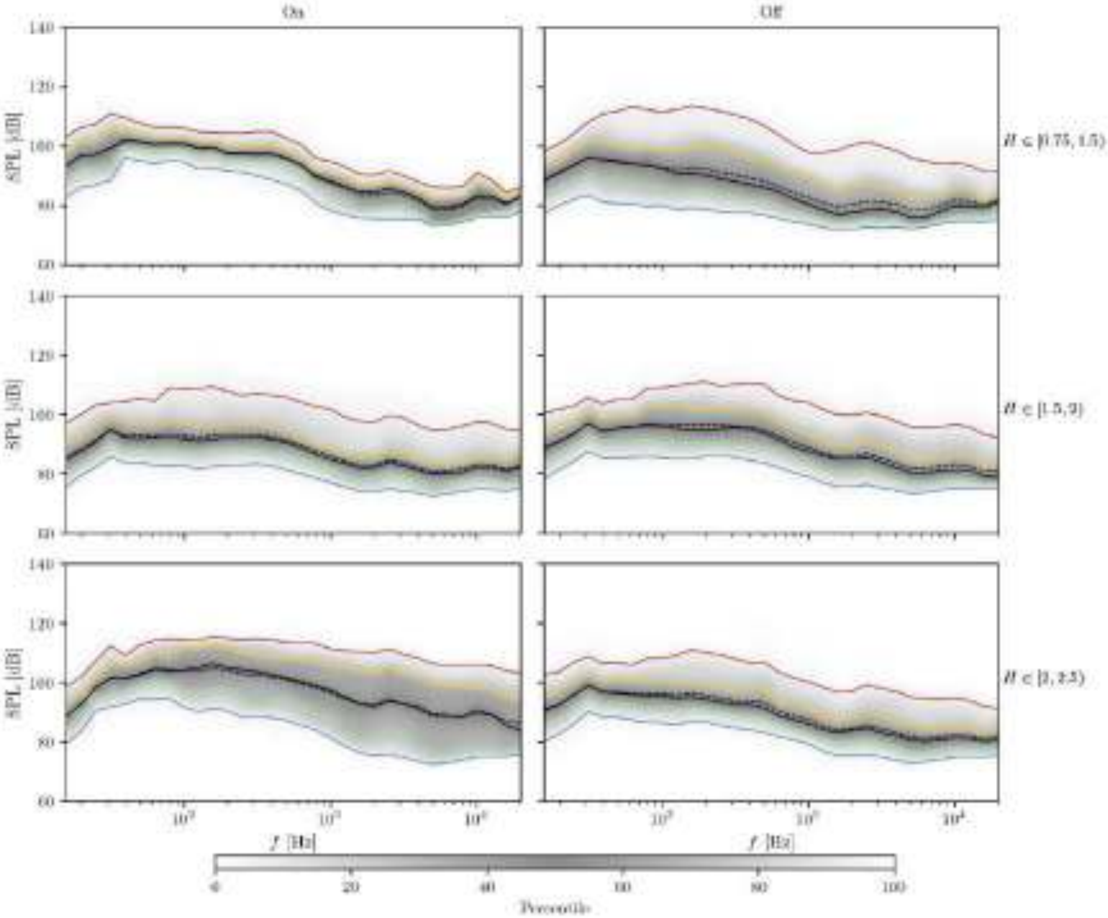

Figure 32. Percentile distribution of the SPL for each sea state (for the H2 sampling site). Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The mean is shown as a black dashed line.

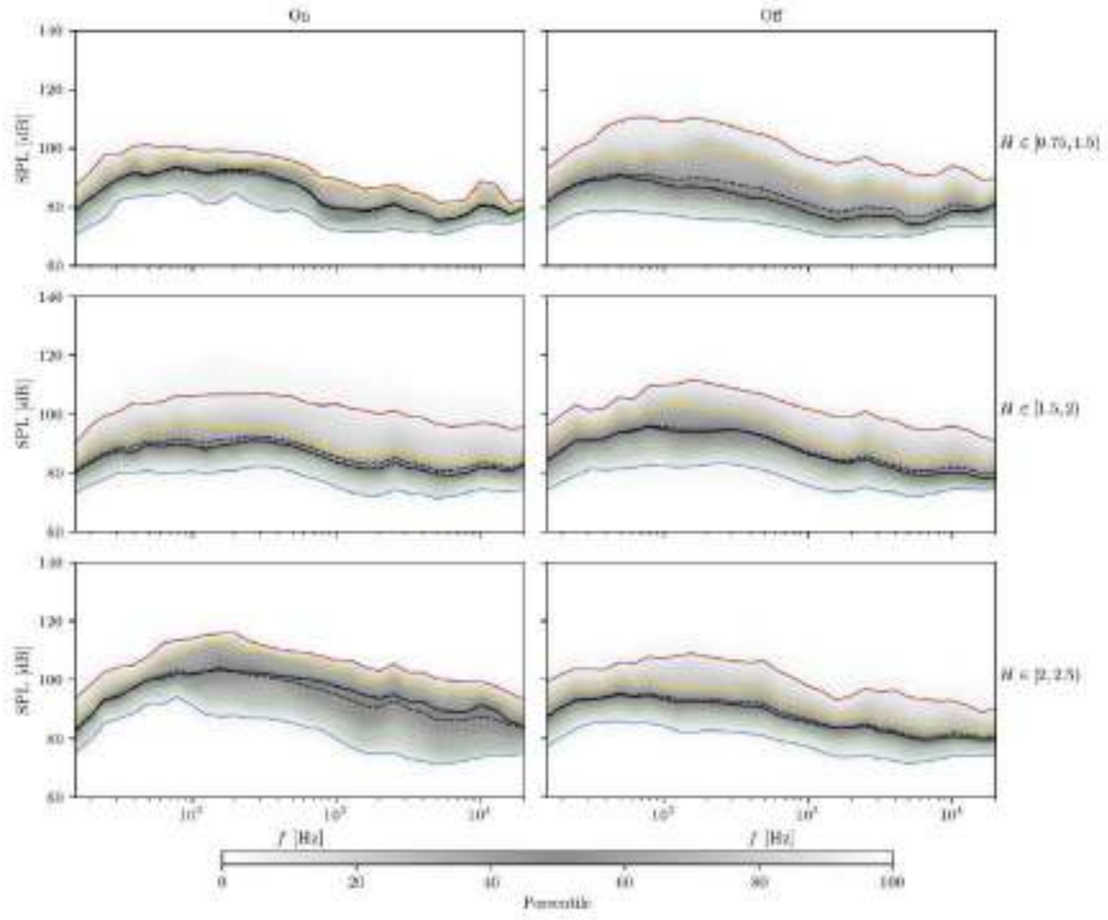

Figure 33. Percentile distribution of the SPL for each sea state (for the H3 sampling site). Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The mean is shown as a black dashed line.

These values can be better compared in the Figure 34, in which the median curves corresponding to all wave height bin are plotted against each other.

No significant differences are found between the On-Off state, except for the [2, 2.5) m bin, where around 125 Hz a difference of approximately + 8 to 10 dB is observed for the On state specially for H3 and H1.

This can definitely be checked in Figure 35, in which the actual differences are computed and shown for all sampling sites, regimes, and wave height bins, in which the deviations are calculated using equation (1).

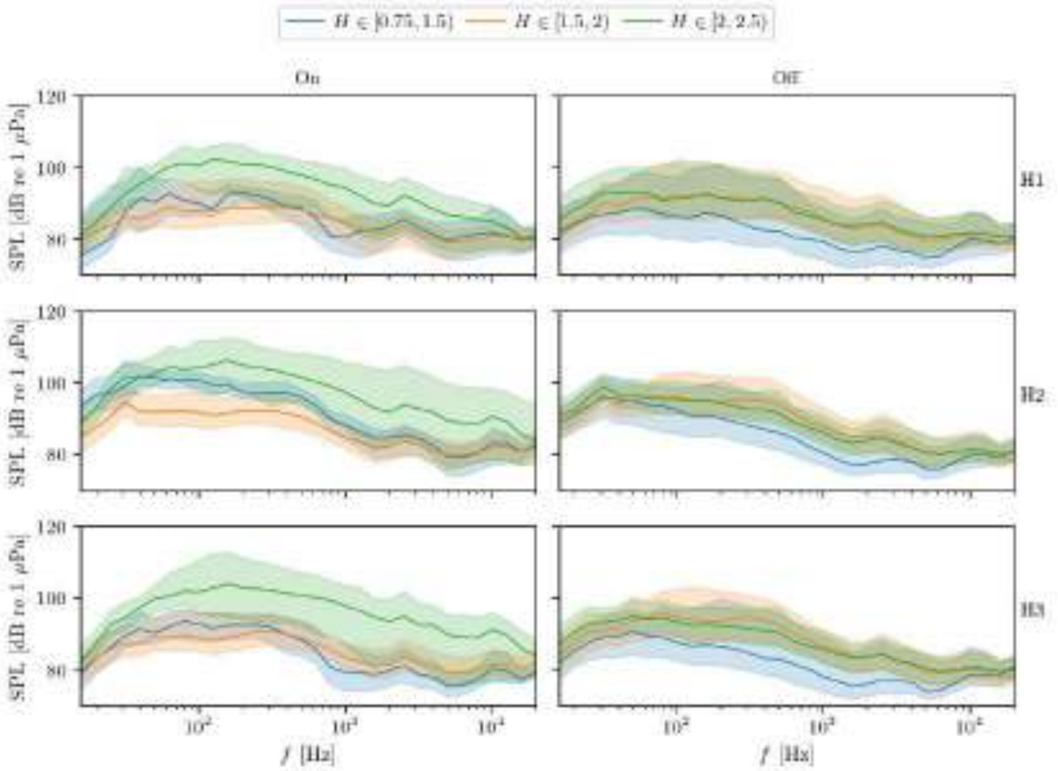

Figure 34. Median, and Q1-Q3 (bands around) for all sampling sites, regimes, and wave heights for the Operational phase monitoring campaign in Aguçadoura.

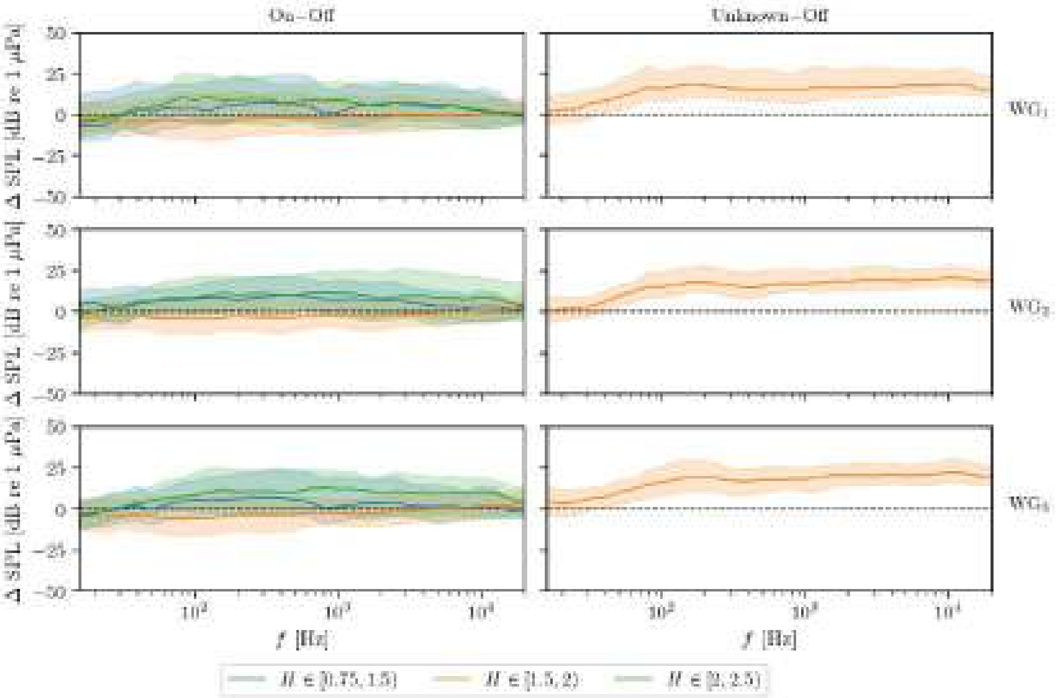

Figure 35. Median (Q1-Q3 in solid bands around) SPL differences between regimes, for all wave heights, as function of frequency.

As specified above, no significant differences are found between On and Off states for the wave height bin [1.5, 2). Only for the wave height bin [0.75, 1.5) and, specially, [2, 2.5), some differences can be appreciated. These differences are present over the whole spectrum analysed for the [2, 2.5) bin and between 40 Hz and 1 kHz for the [0.75, 1.5) bin.

Also, a comparison with the sound during the Unknown state and the Off state was performed. As depicted above, a constant difference of around +15 dB is registered between 100 Hz and 10 kHz.

4.2.4 Conclusions

For both **pre-installation campaigns,** the noise levels (as dictated by the median values) were similar, with levels ranging from 75 (for the extreme of the frequency range) to 105 dB re 1 µPa (for the band centred around 200 Hz). The effect of the sea state is most reflected on the high frequencies, (4 kHz and 10 kHz for the campaign 1 and campaign 2, respectively), as well as on the frequencies around 100 Hz for the campaign 2.

For the **first commissioning phase**, there seem to be little to no contribution of the WEC operation to the background noise. Only some differences can be found for the wave heights bin [2, 2.5), where differences up to 10 dB re 1 µPa are found over the whole spectrum. In this regard, the difference from the high frequencies could be mostly originated by the moving of the mooring lines with the waves. Also, the Unknown sound was reported to Corpower, and as appreciated in that small number of audios, the sound contributes to the background in around 15 dB re 1 µPa.

To conclude this case, it should be considered that the duration of the campaign is approximately one week, which means that this analysis should be taken as a first approximation and that the WEC went through its first commissioning phase, which means the data recorded are not representative of an operational mode of the WEC, since there is not enough data available to draw significant conclusions.

4.3 BiMEP (Spain)

4.3.1 Pre-operational and installation phase

Following the chronological order, the pre-operational and installation phase of the BiMEP campaign is analysed and its results are shown. In Figure 36 the main results are plotted, in various ways, as a comprehensive synthesis of the acquired information.

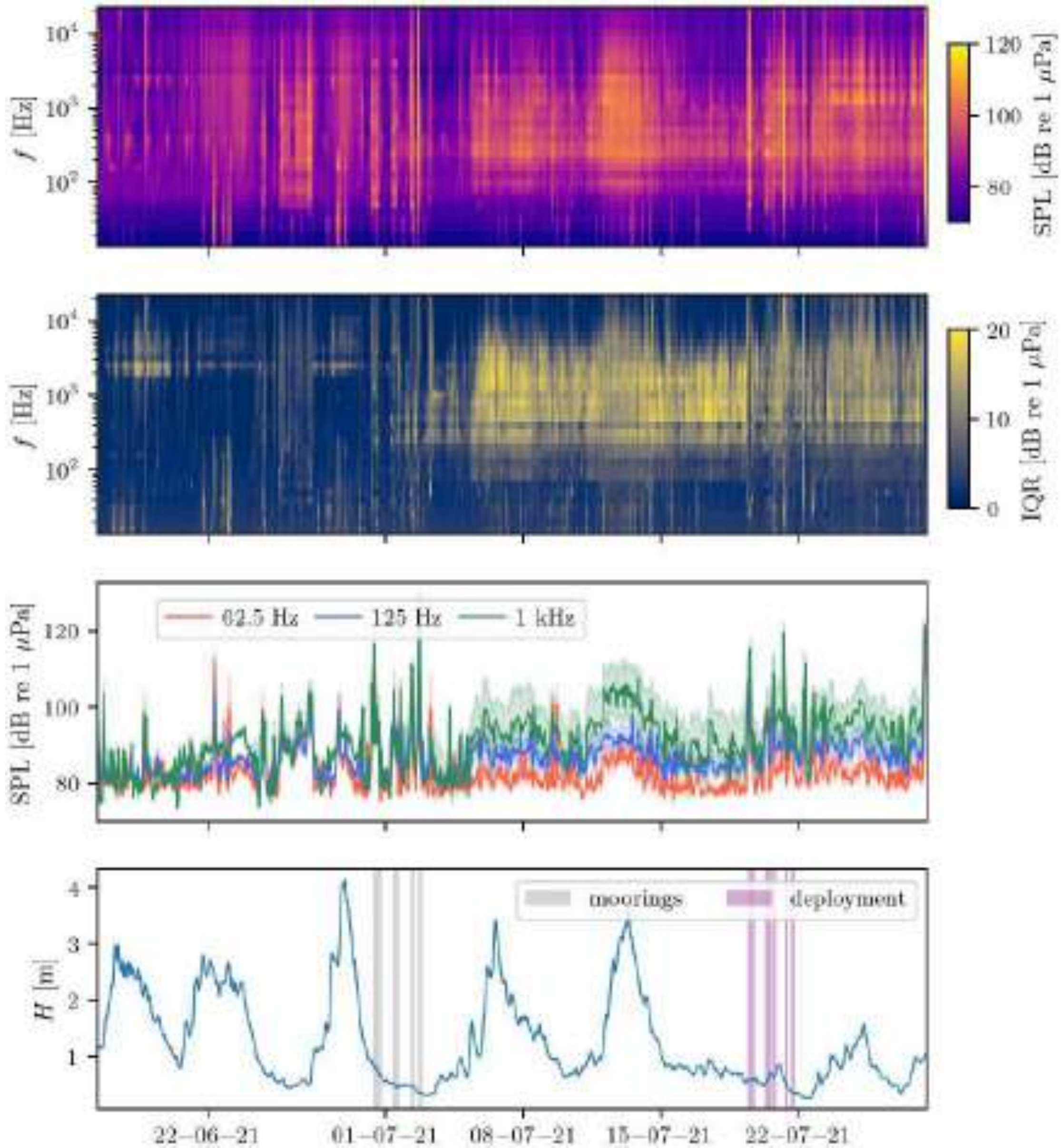

Figure 36. From top to bottom: spectrogram from hourly SPL median values; the corresponding IQR (Q3-Q1); hourly SPL median time series (IQR in filled bands); significant wave height and relevant periods of activity.

As it can be seen in Figure 36, it is particularly noticeable the change brought about by the installation of the mooring lines around the 3rd of July 2021. The noise from vessels during the installation (moorings) and the deployment of the device can also be clearly detected. Although barely visible in the bottom graph, the device was deployed in the end of the monitoring period (around the 28th of July).

To characterize the noise in different regimes, time periods are classified according to two activities or states, namely, "Installation activities" and "Background".

Installation activities comprise both "moorings" and "deployment" periods from Figure 37, as they were the main periods in which vessels operated in the area performing field work.

Background noise is further classified into pre-moorings and post-moorings periods (meaning before – and after - full deployment of mooring lines), in order to distinguish the contribution of mooring lines to ambient noise. This classification is binned in sea states (i.e., significant wave height) to later find the dependence of SPL with this variable. This is summarized in Figure 37, in which the three regimes are classified in the wave heights defined by the following values:

$$H_b = (0, 0.75, 1.5, 2.5, 4,5)$$

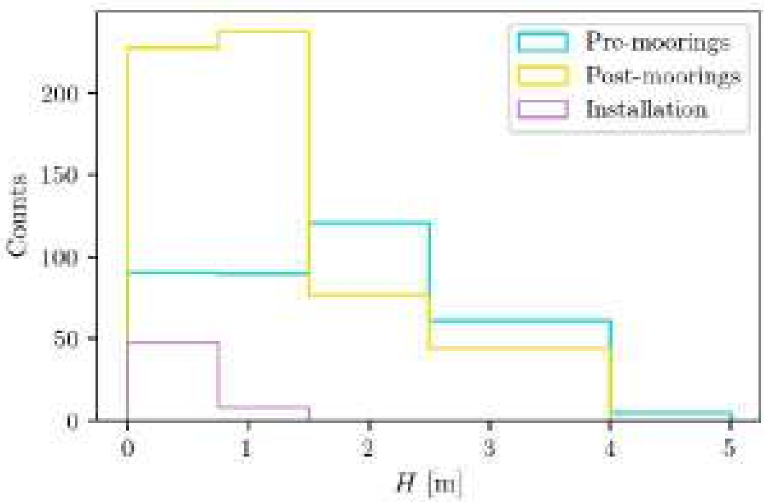

Figure 37. Histograms of significant wave height values for the different regimes.

The total counts of "Installation", "Post-moorings", and "Pre-moorings" are 368 (36.40 %), 643 (58.06 %), 56 (5.54 %), respectively. With this classification in mind, in the Figure 38 the full percentile distributions are shown. Note that the blank graphs are due to absence of data in the given regime.

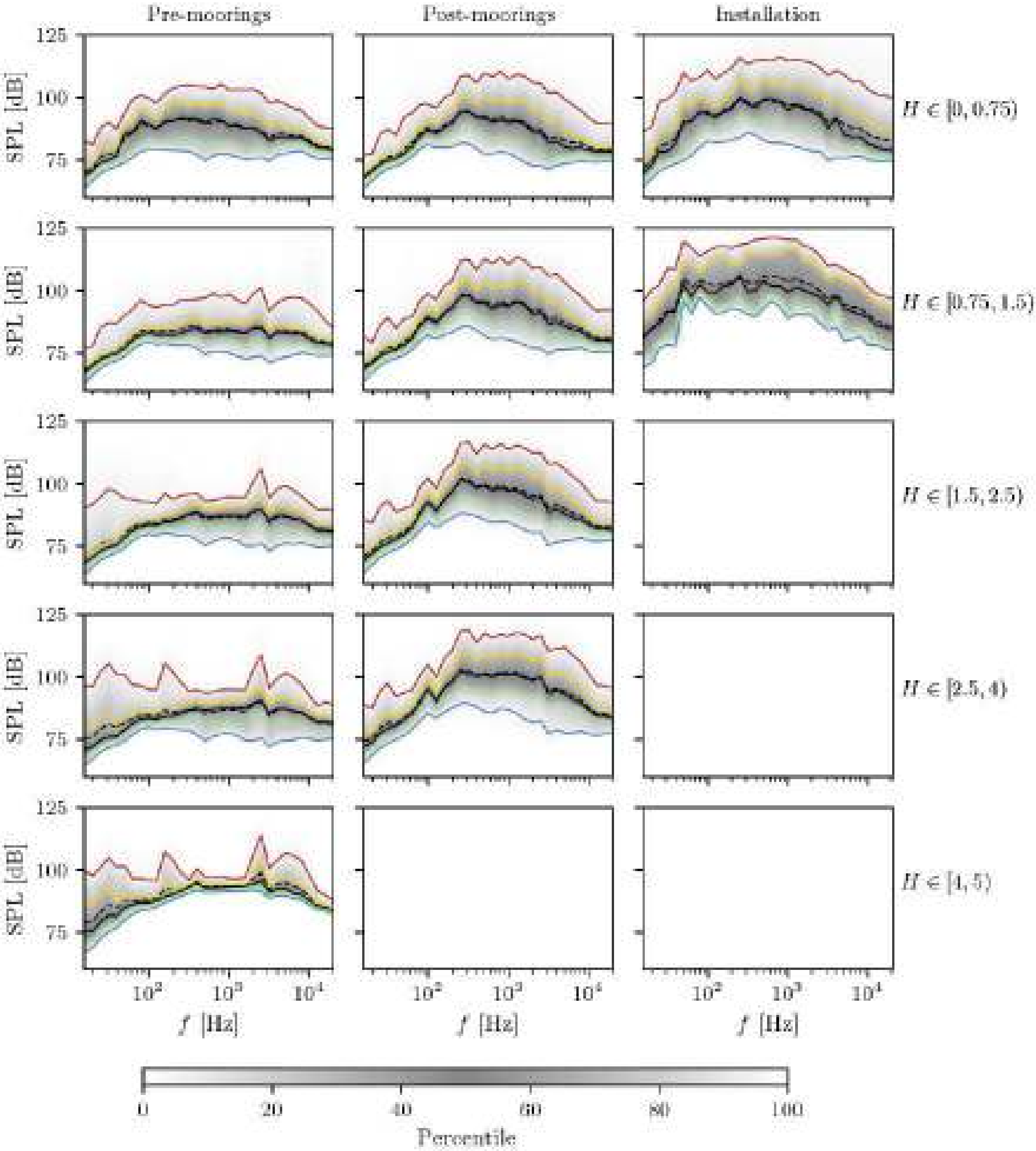

Figure 38. Percentile distribution of the SPL for each regime and sea state. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow and red lines, respectively. The median is shown as a dashed line.

The differences between all regimes are quite noticeable. Overall, noise levels are higher during installation activities (even though data is only limited to wave heights less than 1.5 meters). Post-moorings noise is also consistently higher than that of the pre-moorings period, especially in the mid frequencies and for stronger sea states (Figure 39).

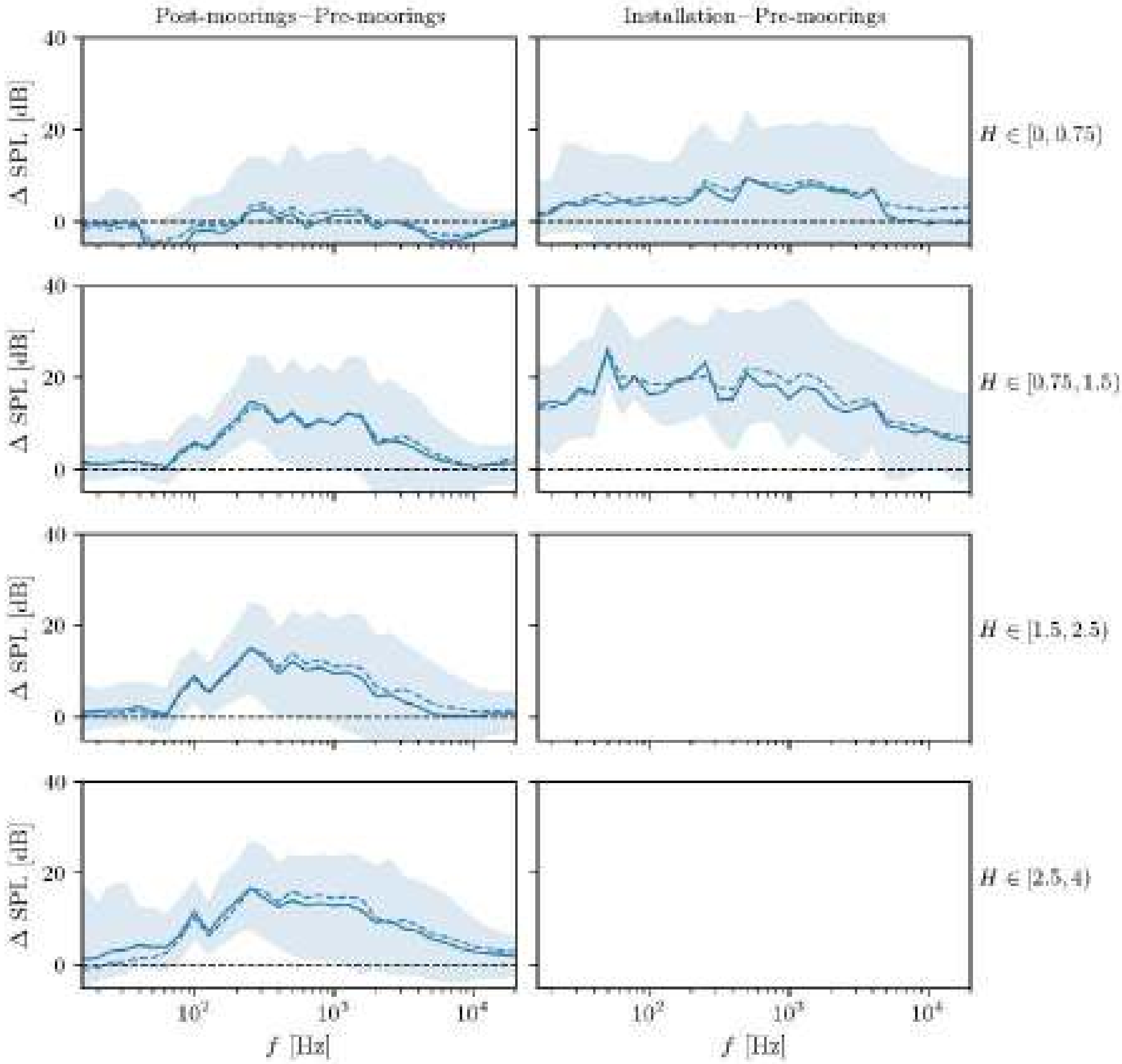

Figure 39. Difference in median SPL for between Installation and Pre-moorings (left) as well as Post-moorings and Pre-moorings (right). The null value is highlighted as a dashed black line, as well as the arithmetic mean of the distribution. Key: median (solid line) and mean (dashed line).

To confirm these findings in more detail, in Figure 39 the difference (between regimes) in noise levels is explored, for the considered sea states. Using the median (solid line) and mean (dashed line) as central values and the Q1 and Q3 to describe the deviation.

The combined Q1 and Q3 are obtained using the following equations:

$$\begin{aligned} Q1 &= (Q2_1 - Q1_1) + (Q2_2 - Q1_2) \\ Q3 &= (Q3_1 - Q2_1) + (Q3_2 - Q2_2) \end{aligned} \qquad (1)$$

Where Q2 is the median, while the subindices denote the subset of values.

This figure confirms the previous results, that is, levels are higher after deployment of moorings, and even higher during the installation phase. The differences can be up to 20 dB re 1 µPa. If we consider the interquartile range as a measure of uncertainty, for the post-mooring – pre-mooring difference the main relevant frequencies (> 0 dB) are found within the 100-300 Hz (up to 1 kHz for the strongest sea state). On the other hand, during the installation activities the difference was more broadband (except for frequencies above 5 kHz).

4.3.2 Operational phase

The main monitoring campaign in BiMEP was performed about 4 months after the pre-installation one, when the device was already deployed in the sea. This campaign consisted of both underwater and airborne monitoring.

4.3.2.1 Underwater noise

Here we show the results of the processing of the data from the three deployed hydrophones. In Figure 40, as has been done so far, the whole content of the SPL distributions in both frequency and time is shown as spectrograms, which allows for a quick assessment of the most relevant acoustic signatures. For comparison, airborne SPL is also shown here for the duration that it existed (about one month), as well as the global hourly median SPL values for the three key frequencies. Additionally, significant wave height with most relevant activities periods is plotted.

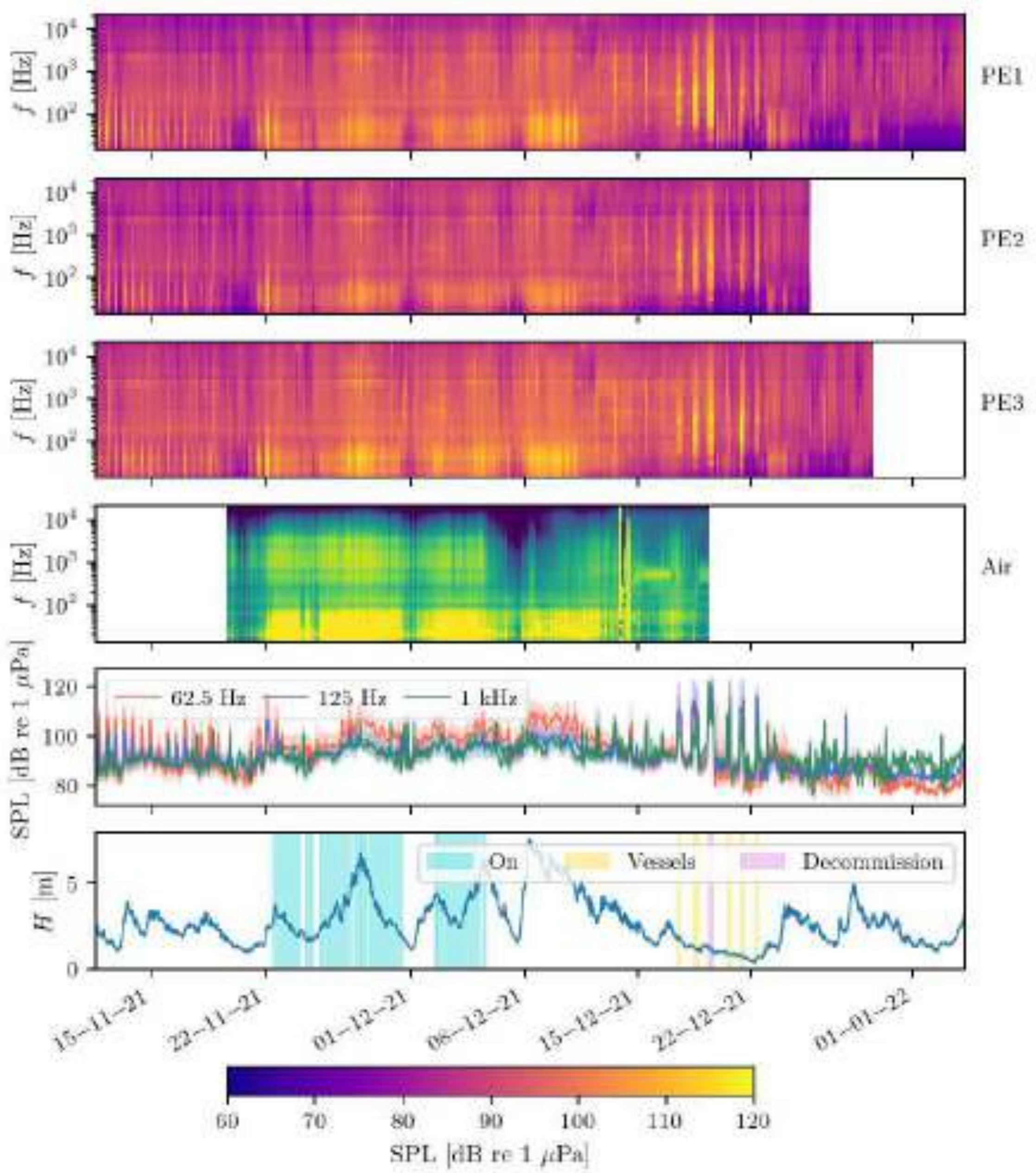

Figure 40. From top to bottom: spectrogram from hourly SPL median values; the corresponding IQR (Q3-Q1); hourly SPL median time series (IQR in filled bands); significant wave height and relevant periods of activity.

The three spectrograms show great similarity, well correlated with wave height (and vessel passings), and with levels between 80 and 105 dB re 1 μPa, depending on the frequency. The airborne SPL is also well correlated with wave height.

Although they were originally configured to do so, note that not all hydrophones registered noise for the same extent in time; in any case, all of them acquired data for more than one month. One should note that the device was removed from the test site the 19 of December of 2021 (that is the reason the operational status time series does not exist beyond that date – same goes for the airborne SPL). Different activities are also identified in this graph, that is, "On" (meaning WEC operating), "Vessels" (meaning nearby passage of vessels), and "Decommission" (meaning the activities related to the dismantling of the WEC).

In Figure 41 the hourly median SPL time series for the key frequencies are plotted for each hydrophone.

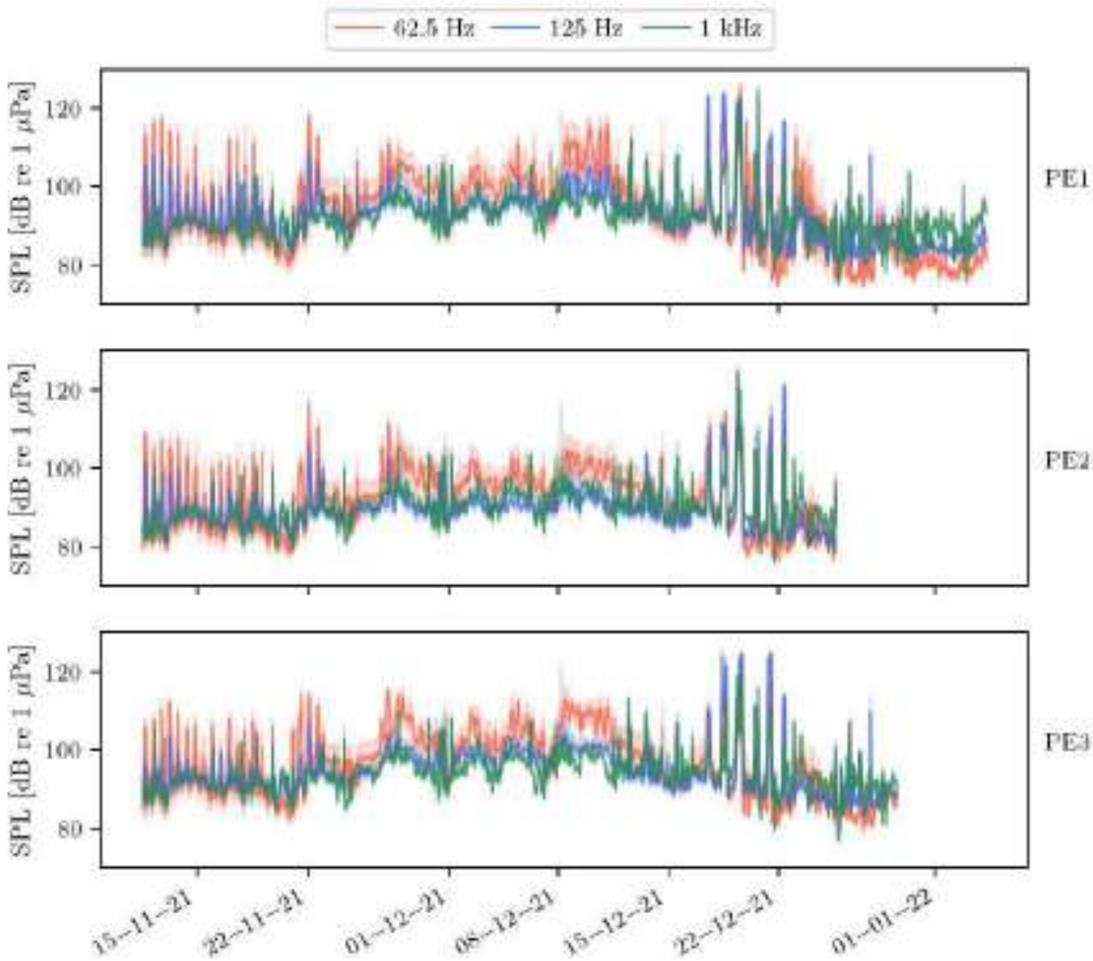

Figure 41. Median (Q1-Q3 shown as bands around) SPL time series for all hydrophones and 62.5, 125 and 1000 Hz.

Five significant wave height values were selected to define ranges that, in addition to the operative regimes, allow for a detailed classification of the SPL distribution for all hydrophones. These bins are defined, as illustrated in Figure 42, (0, 0.75, 1.5, 2.5, 4, 8) meters.

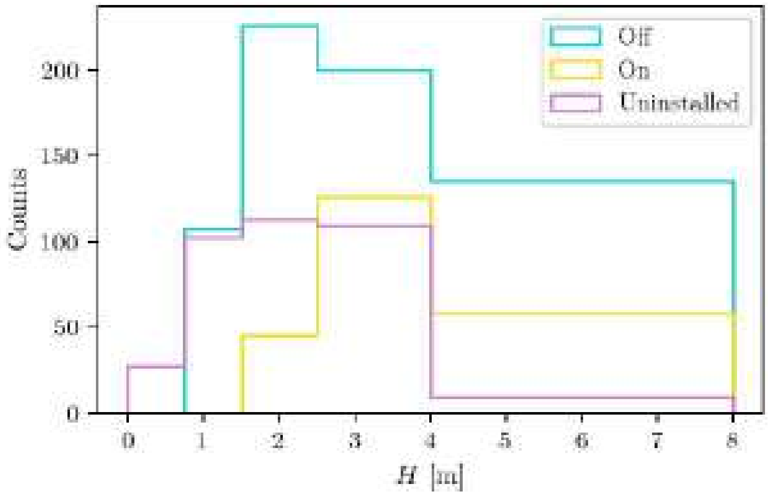

Figure 42. Histograms of wave significant height for Off, On and Uninstalled regimes.

It is difficult to sample all periods with similar wave height ratios; in this sense, lower wave heights (<0,75 and < 1.5 m, respectively) are absent in the Off and On regime, respectively. Inversely, the highest wave heights were very infrequent during the Uninstalled period. The total counts were 220 (17.4 %), 669 (53 %), and 373 (29.6 %), for the Off, On and Uninstalled (after decommissioning) regimes, respectively.

In the following figures (Figure 43 to 45) the full percentile distribution for all sampling sites are presented. As can be seen in them, for some combinations there are no available data (for the reasons discussed above). SPL values are generally (for all sampling sites) higher during the On regime, specially in the lowest frequencies, although the difference is slight with the Off regime (it's more pronounced with respect the Uninstalled). There seem to be a contribution from the mooring links at around 2.5 and 5 kHz for all cases, specially for higher wave heights (>1.5 m).

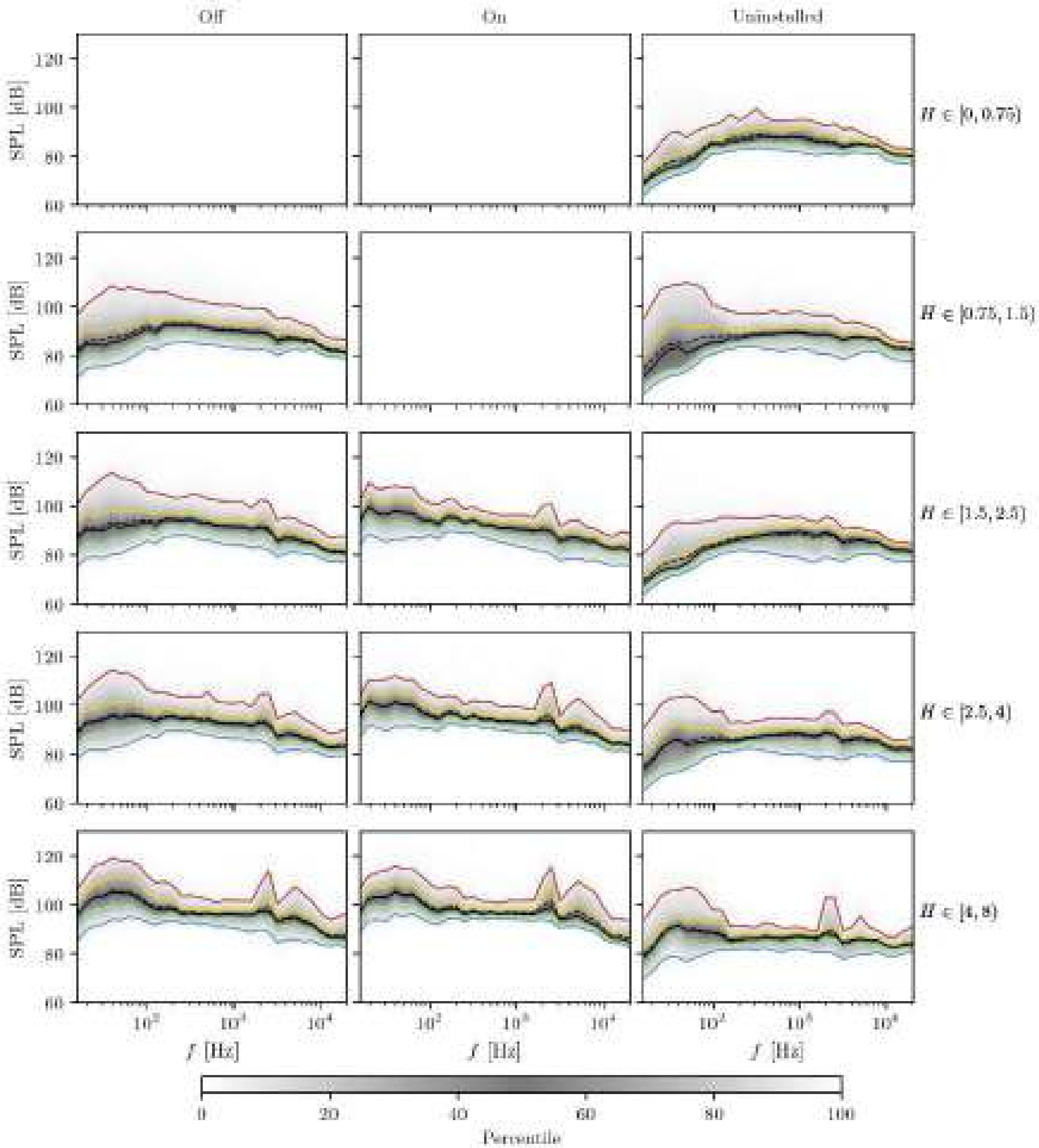

Figure 43. Percentile distribution of the SPL for each sea state (for the PE1 sampling site). Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The mean is shown as a black dashed line.

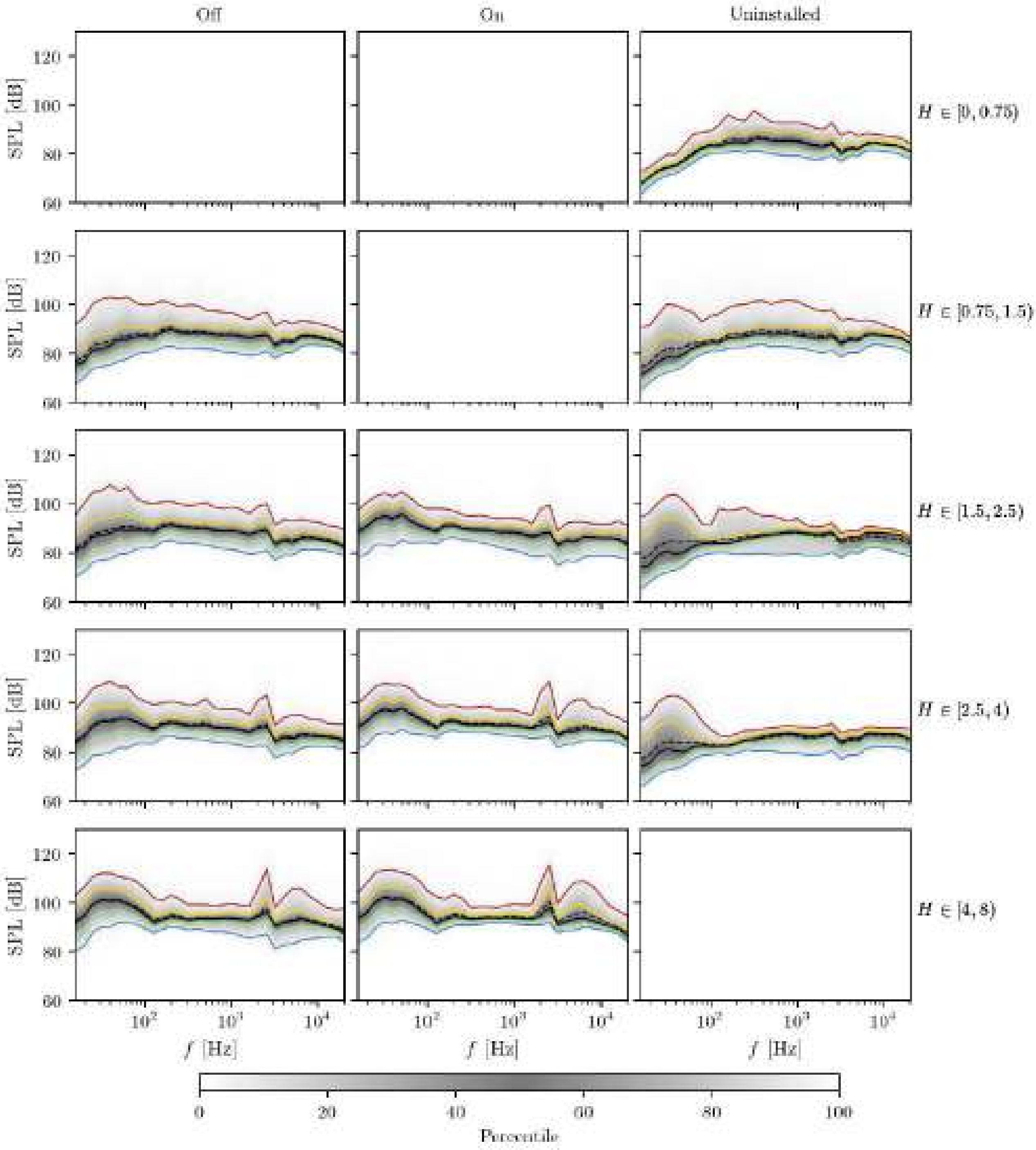

Figure 44. Percentile distribution of the SPL for each sea state (for the PE2 sampling site). Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The mean is shown as a black dashed line.

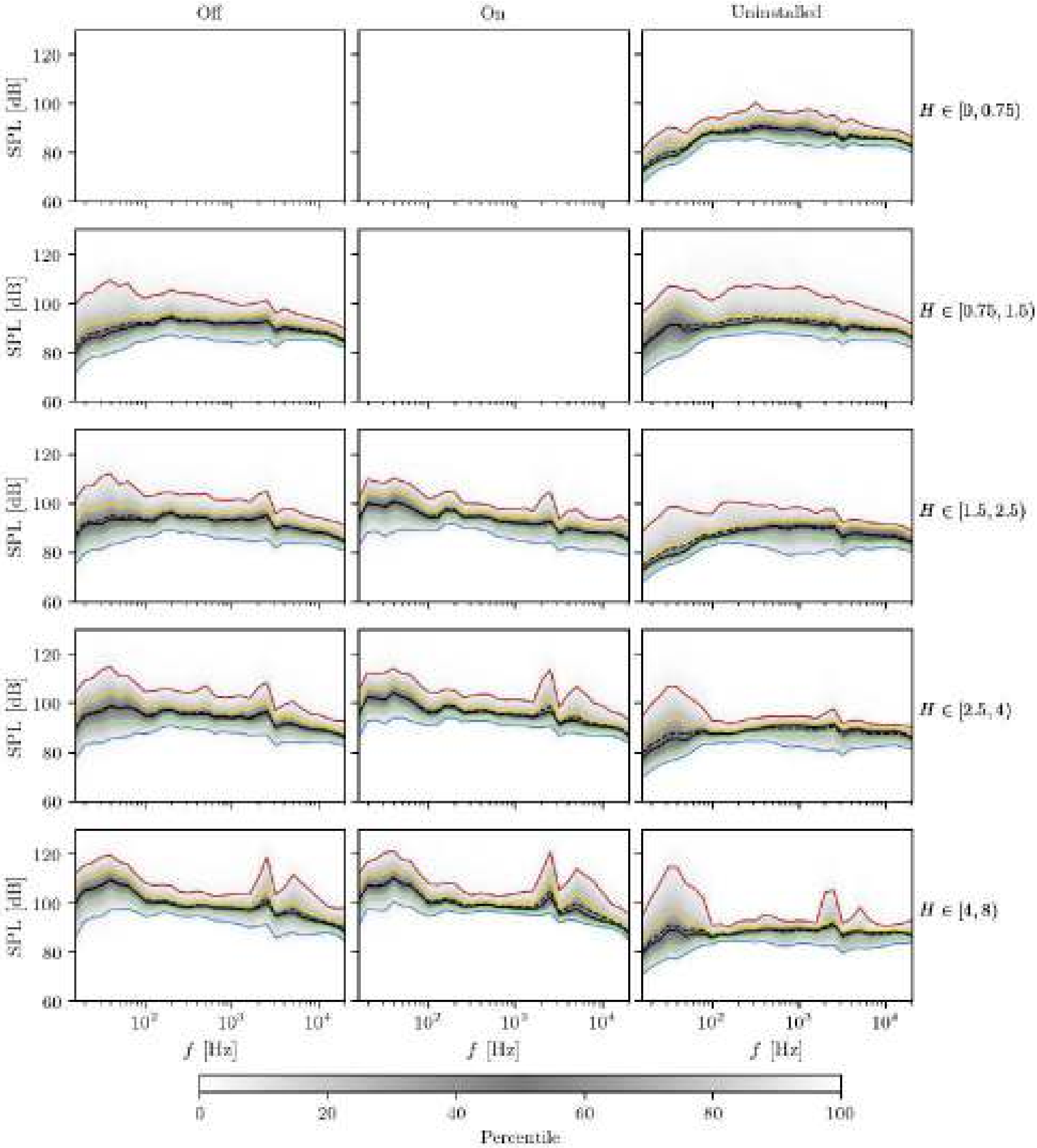

Figure 45. Percentile distribution of the SPL for each sea state (for the PE3 sampling site). Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The mean is shown as a black dashed line.

These values can be better compared in the Figure 46, in which the median curves corresponding to all wave height bin are plotted against each other.

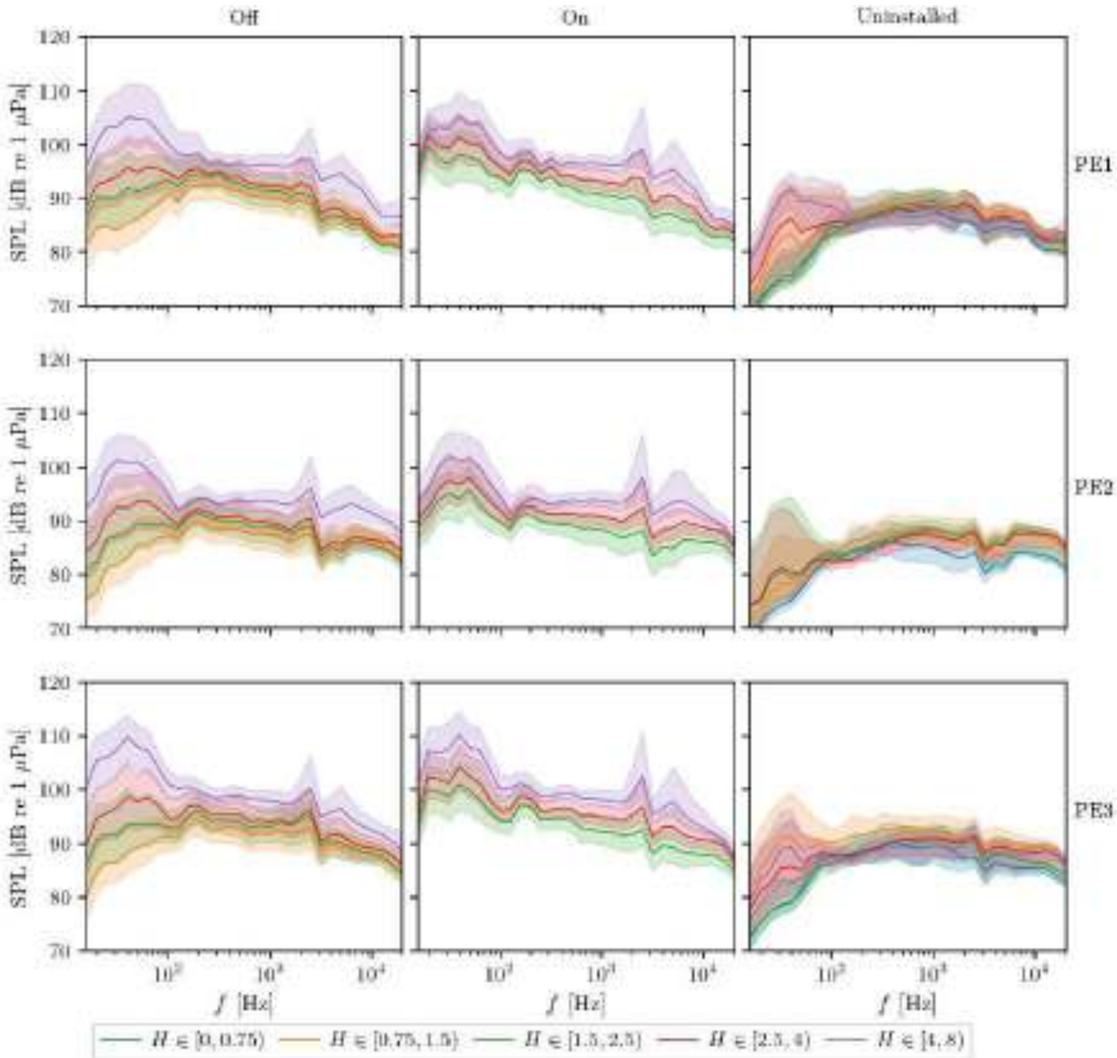

Figure 46. Median, and Q1-Q3 (bands around) for all sampling sites, regimes, and wave heights for the Operational phase monitoring campaign in BiMEP.

The effect of the wave height is clear here, as it raises levels across all frequencies. One should also note that there were few samples during the "Uninstalled" regime with high wave heights, especially for the PE2 sampling site. The most visible difference in SPL between regimes is found in the lowest frequencies. This can definitely be checked in Figure 47, in which the actual differences are computed and shown for all sampling sites, regimes, and wave height bins, in which the deviations are calculated using equation (1). As expected, differences of up to 28 dB re 1 μPa can be found when comparing On-Uninstalled regimes (for PE1). If we take into account the deviations, the significant differences are indeed found for the On-Uninstalled and Off-Uninstalled regimes. In average, the more energetic sea states (and the lower the frequency), the bigger the difference in SPL.

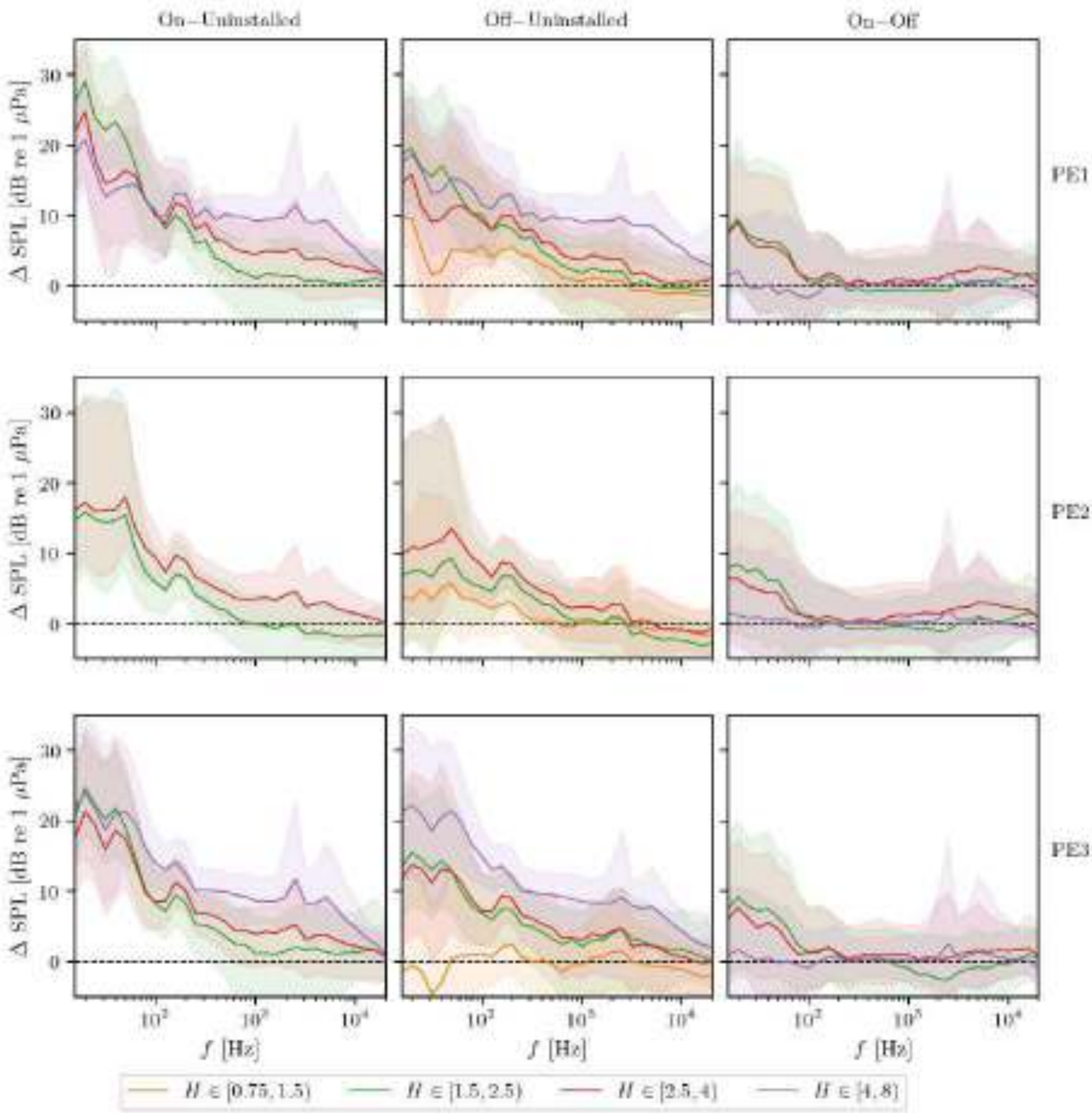

Figure 47. Median (Q1-Q3 in solid bands around) SPL differences between regimes, for all wave heights, as function of frequency.

Additionally, the percentile SPL distribution corresponding for the period of decommission is shown in Figure 48, which show the highest overall levels during the whole campaign, with median values surpassing 120 dB re 1 µPa for the band centred in 300 Hz.

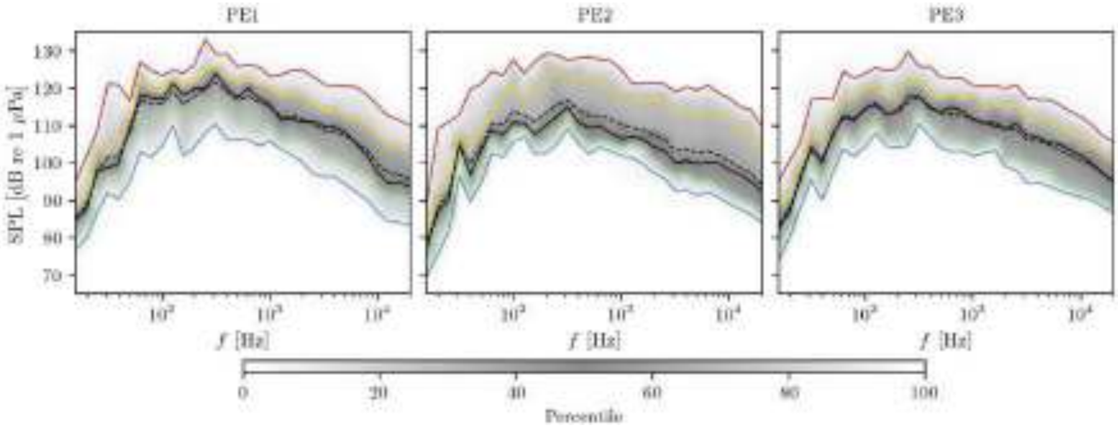

Figure 48. Percentile distribution of the SPL for each sea state and sampling sites, for the "Decommission" period. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The mean is shown as a black dashed line.

4.3.2.2 Airborne noise

In this section, the airborne noise, as registered by the microphone inside the WEC, is briefly analysed.

In the Figure 49, the airborne median SPL and interquartile range is shown for both Off and On regimes and all wave heights. During the On regime, all levels are almost independent of wave height, in comparison with the Off regime, which show great dependence with this variable, especially for the lower frequencies (up to ~200 Hz).

When visualizing the actual SPL difference (see Figure 50), it is clear that most cases are not much significative when taking into account the interquartile range. The difference seems to be inversely proportional to the wave height in the lowest frequencies, with the higher values corresponding to the wave height range between [1.5, 2.5) m, but proportional from 100 Hz upwards (with the higher values corresponding to the wave height range between [4,8] m). In particular, the most significant differences are found in these cases, with values of Q1 above the abscissa axis.

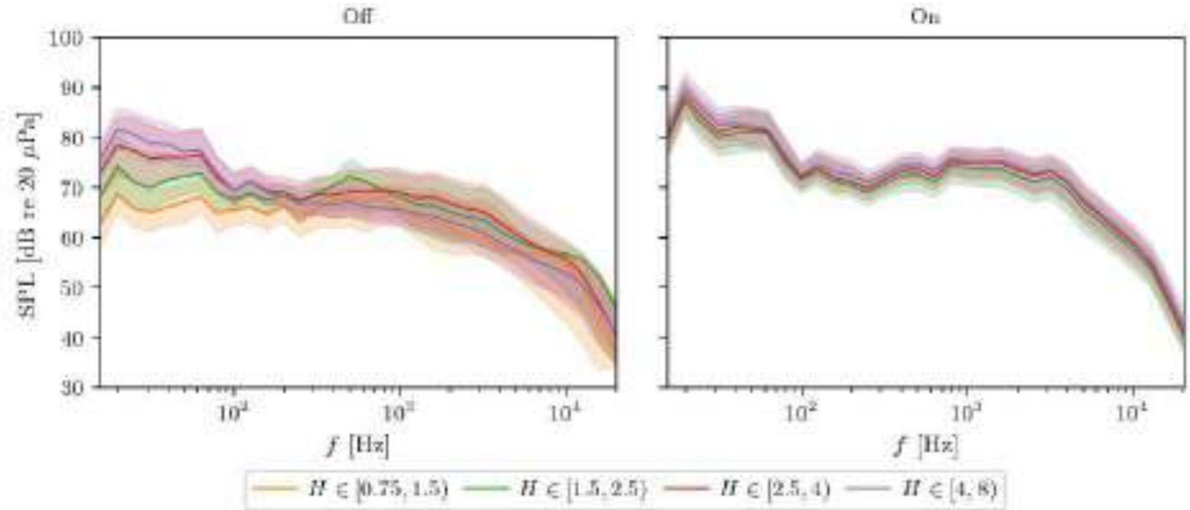

Figure 49. Airborne median (Q1-Q3 in bands around) SPL for Off and On regimes.

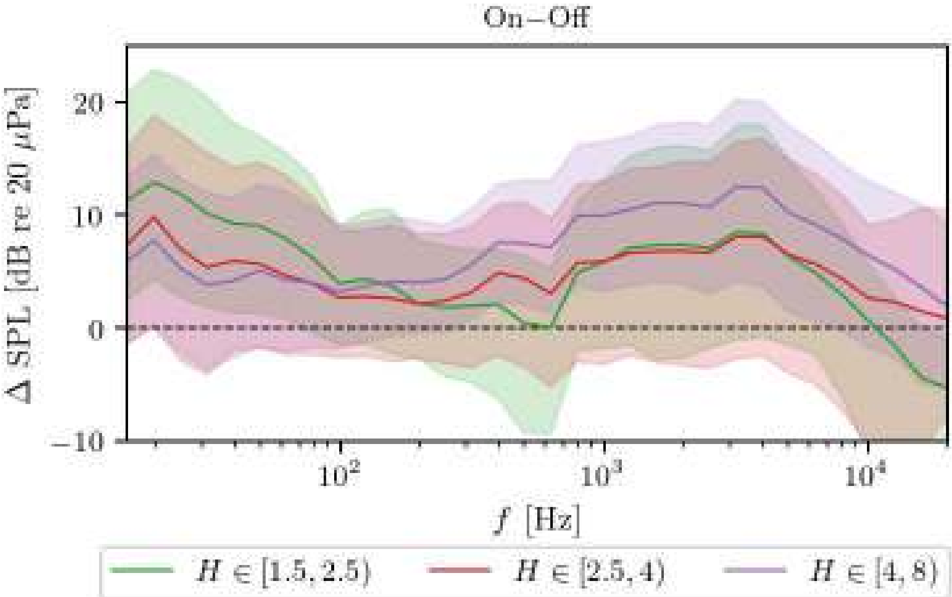

Figure 50. Difference between airborne median SPL spectrum for the On and Off regimes, for all wave heights.

4.3.3 Conclusions

For the **pre-operational and installation** phase, we see an increase in the SPL after deployment of moorings (+15 dB re 1 μPa for high wave heights), and even a greater increase during the installation phase (differences up to 20 dB re 1 μPa). If we consider the interquartile range as a measure of uncertainty, for the post-mooring – pre-mooring case the main relevant frequencies (> 0 dB) are found within the 100-300 Hz (upper bound rising up to 1 kHz for the strongest sea state). On the other hand, during the installation activities the difference was more broadband (all spectrum except frequencies above 5 kHz).

For the **operational** (and decommission) **phase**, there seem to be some contribution of the WEC operation to the background noise. In this regard, all sampling sites and regimes show a similar behaviour, with the lower frequencies showing the greater differences in SPL. Separating in cases:

- On-Uninstalled: all wave height bins show significant (e.g., lower bound above 0 dB) differences (up to 28 dB re 1 μPa that approximately lineally decrease with frequency) in SPL up to 300 Hz (for $H \in [1.5,2.5)$, which is the minimum case) or up to 20 kHz (for $H \in [4,8)$, which is the maximum case).
- Off-Uninstalled: similarly to what happens with the case before, generally all SPL in wave height bins show a resemblance in their behaviour with the frequency. The differences are less significant than with respect to the On-Uninstalled case, but still significant for the stronger sea states. Stronger sea states lead to higher differences, with the bin $H \in [4,8)$ causing all frequencies to show a significant increase in SPL (~20 dB re 1 μPa for low frequencies).
- On-Off: in this case the differences are much smaller, and in fact, there is no frequency for which the difference can be deemed as significant by our criterium.

- The decommission period was acoustically characterized by the highest values of SPL found in the campaign, with values over 120 dB re 1 µPa (centred around 300 Hz).

From the analysis of **airborne sound**, the difference between the On and Off regimes are characterized by:

- $H \in [1.5, 2.5)$: below 70 Hz the difference in SPL is found to be between 8 and 13 dB re 20 µPa.
- $H \in [4, 8)$: from 300 Hz up to 8 kHz, the difference in SPL is found to be between 4 and 13 dB re 20 µPa.

It is worth noting that the increase in the lowest frequencies is consistent to what is found for the underwater case.

4.4 Mutriku (Spain)

4.4.1 Operational phase

The next test site that we consider is the Mutriku power plant. As mentioned in section 3.33.3.1, as the acoustic dataset from MT1 was deemed invalid, the analysis only used data from MT2 and MT3 stations.

In the Figure 51 the main results of the processing are presented. Both hourly median spectrograms and time series curves indicate a strong daily periodicity. Low frequency components depend clearly on the sea state, with values surpassing 100 dB re 1 µPa in all sampling stations in periods of high waves (> 3 m).

Indeed, there is a clear daily periodicity in the noise levels for most of the frequency range, as Mutriku is a very busy location (in terms of human coastal activity), but most noticeable in the lower spectrum (~100-1000 Hz). It is interesting to note that SPL values are higher during the night in the case of the higher frequencies. In this context, it was considered useful to classify the period in day and night, as most anthropogenic coastal activity is carried out in daylight. The effect of sea state is most clear in the lower frequencies (< 200 Hz).

As a proxy of operational activity of all turbines, the average of all RPM time series is considered (denoted as Ω in Figure 51). As expected, Ω is higher the greater the wave height.

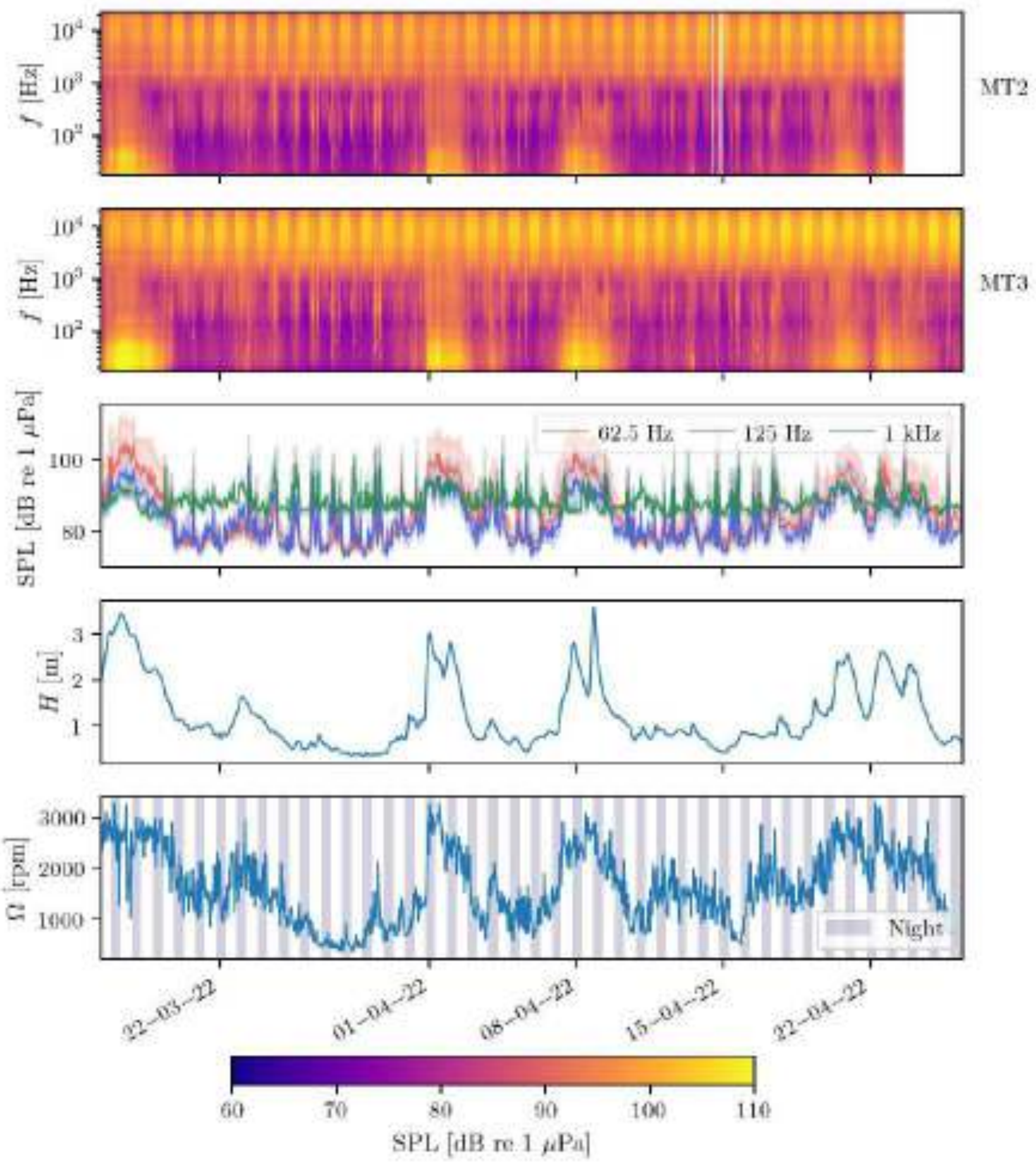

Figure 51. From top to bottom: spectrogram from hourly SPL median values; hourly SPL median (across all hydrophones) time series; significant wave height; mean RPM (all turbines), with night periods.

The evolution of the SPL for the key frequencies is shown in more detail in Figure 52 separately for both hydrophones. The behaviour in both cases is very similar, with a clear dependence with wave height for all frequencies, but more so for 62.5 and 125 Hz, as expected.

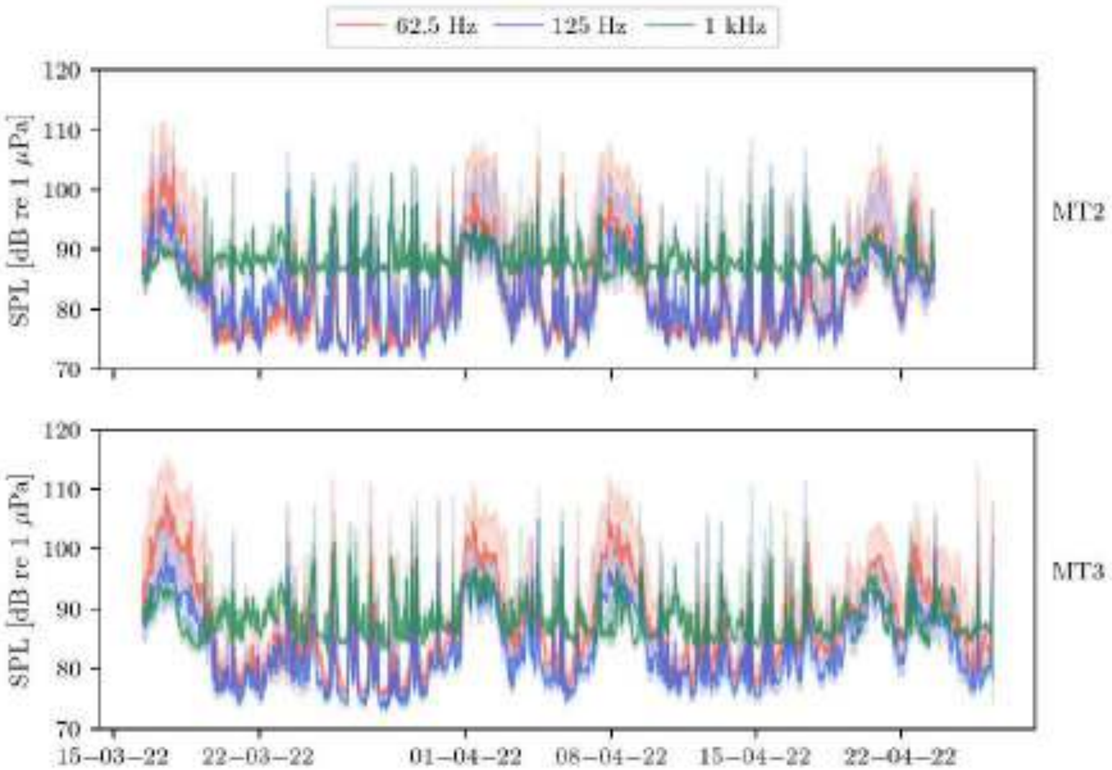

Figure 52. Hourly median SPL time series for 62.5, 125 and 1000 Hz.

In Figure 53 and 54, the full percentile distribution (for each frequency) is represented. The dependence with wave height is clear in the Night case, as there are few, if any, vessels passing through the area, showing a strong correlation up to around 1 kHz. For the stronger sea states, however, the difference between day and night is negligible except from 1 kHz upwards.

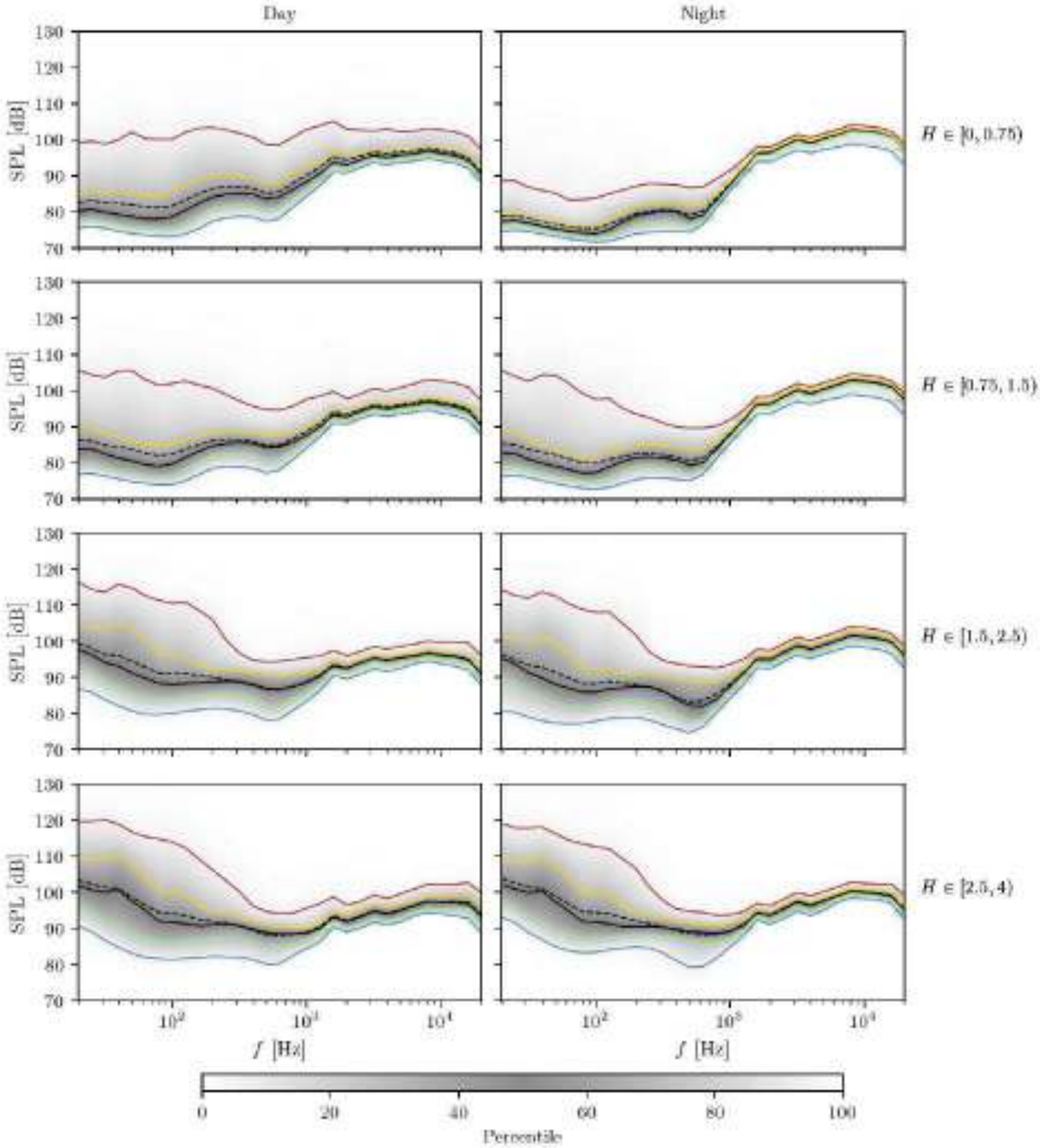

Figure 53. Percentile distribution of the SPL of MT2 for each regime and sea state. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The median is shown as a dashed line.

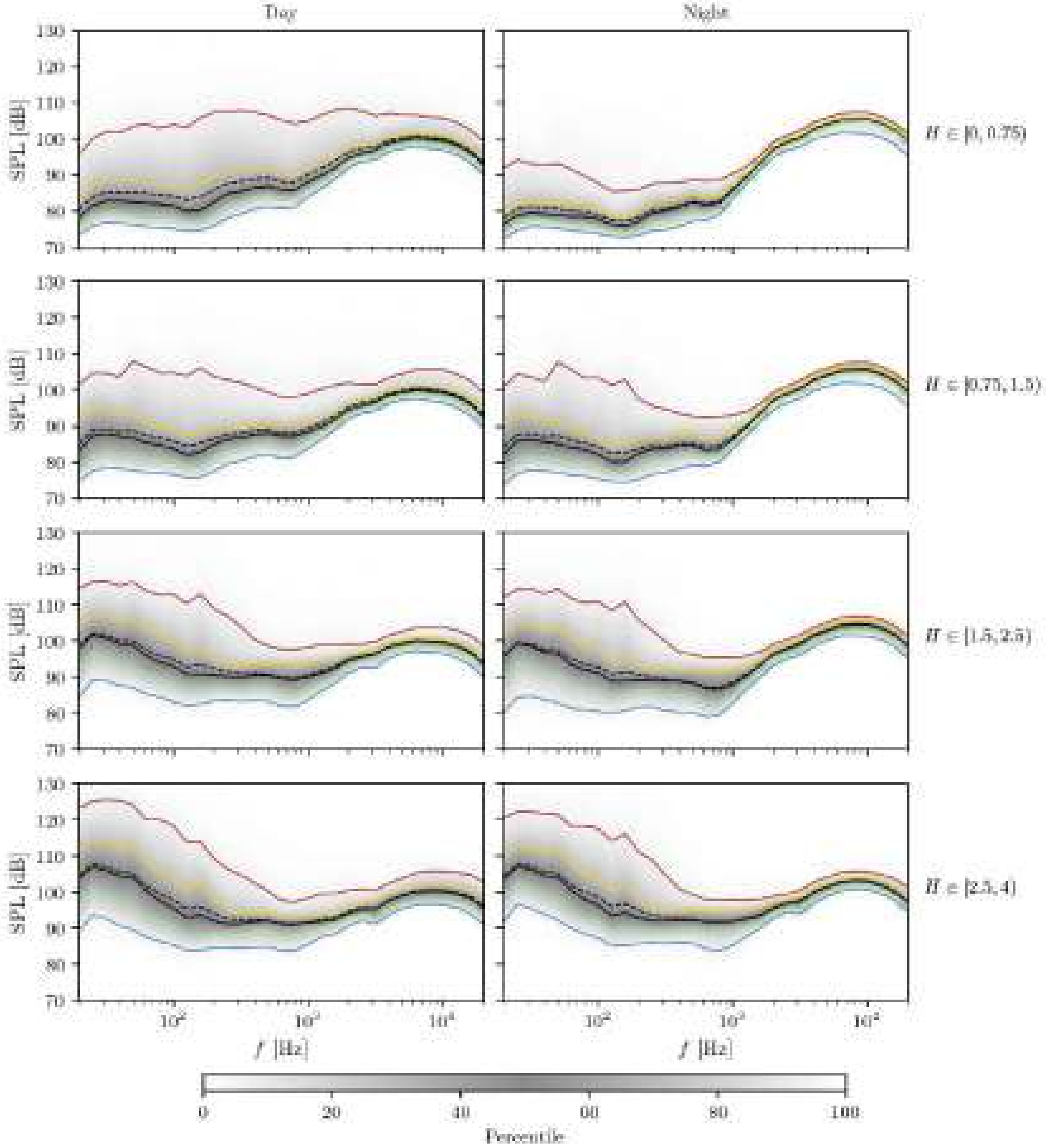

Figure 54. Percentile distribution of the SPL of MT3 for each regime and sea state. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The median is shown as a dashed line.

The higher frequencies are practically independent of wave height, with levels about 100 dB re 1 μPa (a little higher for the night periods), but for the lower frequencies, levels rise up to 108 dB re 1 μPa ($H \in [2.5,4)$) from 82 dB re 1 μPa ($H \in [0,0.75)$). In any case, both types of spectrums are very similar, as can be better identified with Figure 55, and even more in Figure 56, in which the actual differences between SPL distributions for periods and wave heights are shown in more detail.

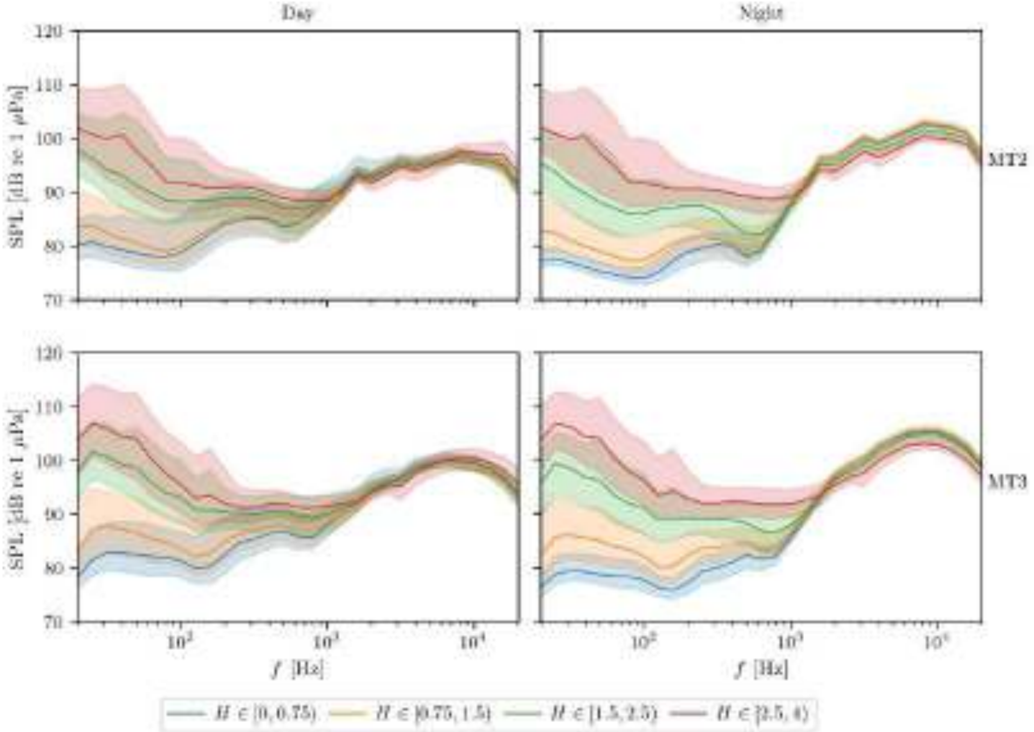

Figure 55. Median, and Q1-Q3 (bands around) for all sampling sites, regimes, and wave heights.

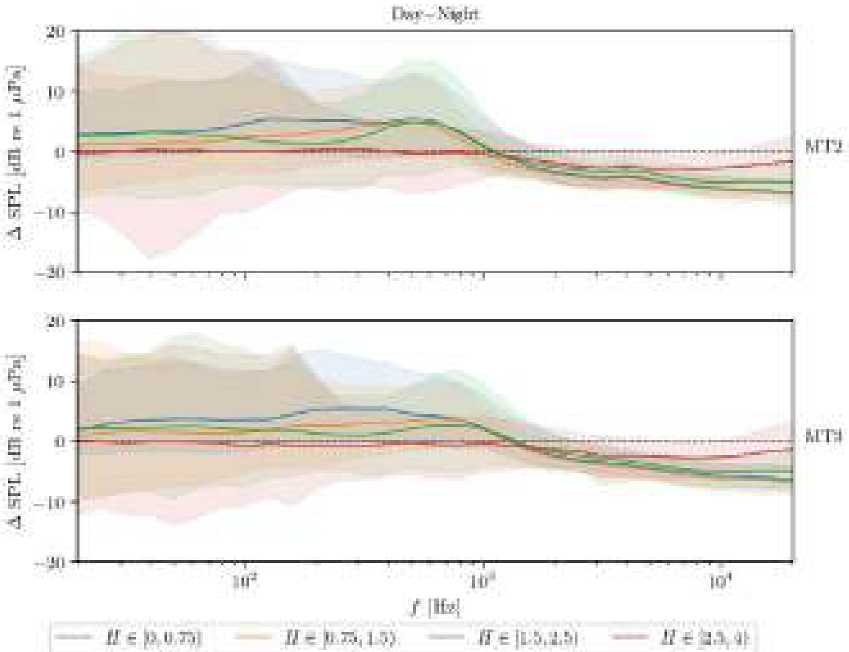

Figure 56. Median (Q1-Q3 in solid bands around) SPL differences between Day and Night, for all wave heights, as function of frequency.

All in all, the differences seem not significant between day and night, and in any case would be positive (meaning levels during daylight are higher than at night). Therefore, we can presumably say that the noise generated by the power plant is below background noise (assuming that it would be the main anthropogenic source of noise during the night).

An as extra step, a causality analysis was carried out to explore the causal dependences between SPL, significant wave height and operation of the power plant (RPM of turbines). For this purpose, the PCMCIplus algorithm (Runge, 2020) was used, which assess causal links between time series.

The results can be seen in Figure 57 for both sampling stations. The frequencies with a p-value under a significance level of 0.05 (95% probability) indicate a statistically significant causal relation. Apparently, significant wave height causes SPL for all frequencies except 110-120 Hz, and those above 1 kHz, which is expected and reasonable (those low frequencies are dominated by vessel-related noise). This variable also has a directional link with the average RPM[8]. Most importantly, the average RPM shows no causality with respect to the SPL in any frequency.

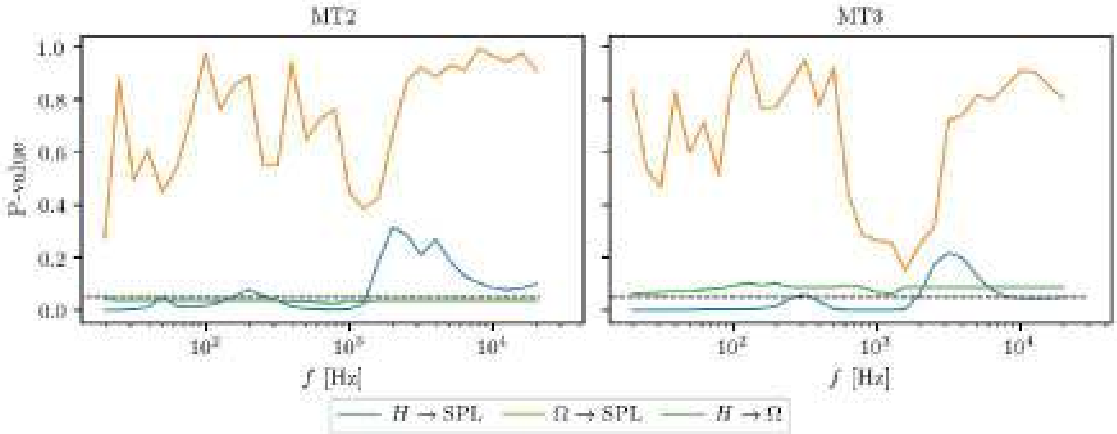

Figure 57. P-values from the PCMCIplus causal inference algorithm, showing causal links between hourly median SPL, significant wave height, and average RPM time series for all frequencies.

[8] Note that for this pair of variables there is no defined frequency dependence *per se*, but as the method takes into account all time series simultaneously, therefore, the results are frequency dependent.

There should be noted that because shallow waters act as a low frequency filter, the lowest components cannot efficiently propagate from the source. In this case, as the bathymetry ranges from few meters to about 20 meters in the first kilometre of distance. This would imply a cut-off frequency from ~150 Hz to 36 Hz. Mutriku is the most extreme case of this phenomena among all test sites, being an onshore device.

4.4.2 Conclusions

The conclusions for the Mutriku test site are the following:

- Being Mutriku a busy coastal site, there is a clear difference between day and night distributions of SPL, with higher values during the day for frequencies below 1 kHz, and lower values during the day for frequencies above 1 kHz; the deviation is very low above this frequency for all cases. SPL values range between 77 and 105 dB re 1 μPa for the greatest and lowest wave heights, respectively.
- There are no apparent signs of noise coming from the Mutriku power plant, as indicated by the difference between day and night levels, as well as the causality analysis between SPL, significant wave height and average RPM time series. This is consistent with two facts: noise generated by Mutriku power plant turbines is centred in the lower spectrum (2000 RPM is equivalent to approximately 33 Hz), and the very shallow waters of the area lead to a low-frequency filter of considerable value (of the order of 100 Hz).

4.5 SEM-REV (France)

4.5.1 Operational phase

4.5.1.1 Underwater noise

The results from the monitoring campaign undertaken in the SEM-REV test site are presented in the present section. Similarly to what happened with the Mutriku campaign, one hydrophone did not operate as expected (it sampled for about 4 days, as shown in Table 16), so the results (see Figure 58) are referenced only to WG2 and WG3.

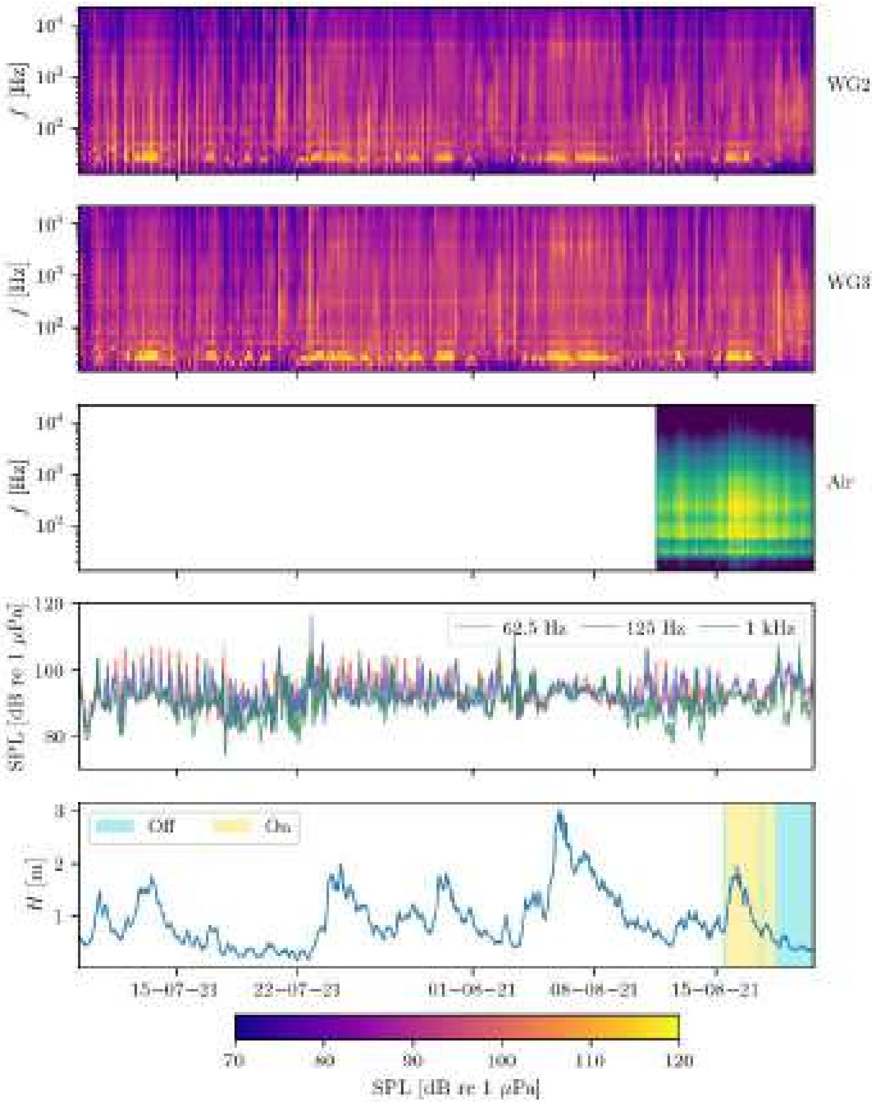

Figure 58. From top to bottom: hourly SPL spectrogram; hourly median airborne spectrogram (inside WEC); hourly SPL median (across all hydrophones) time series; significant wave height with relevant regime periods.

The spectrograms show very localized peaks in frequency, strongest during rough sea states, but also broadband peaks most probably due to vessel activity. Both sampling stations show similar values; however, WG2 seemed to be closer to vessel routes. Airborne noise was monitored for about a week and a half; and it shows good correlation with wave height.

In Figure 59 the evolution of the SPL can be observed in more detail. Indeed, WG2 shows more daily peaks (most probably due to vessel activity in the vicinity or by the tides modifying the sensor setup). All frequencies show similar baseline levels, around 80 and 95 dB re 1 µPa depending on the sea state, with maximum levels occasionally above 115 dB re 1 µPa.

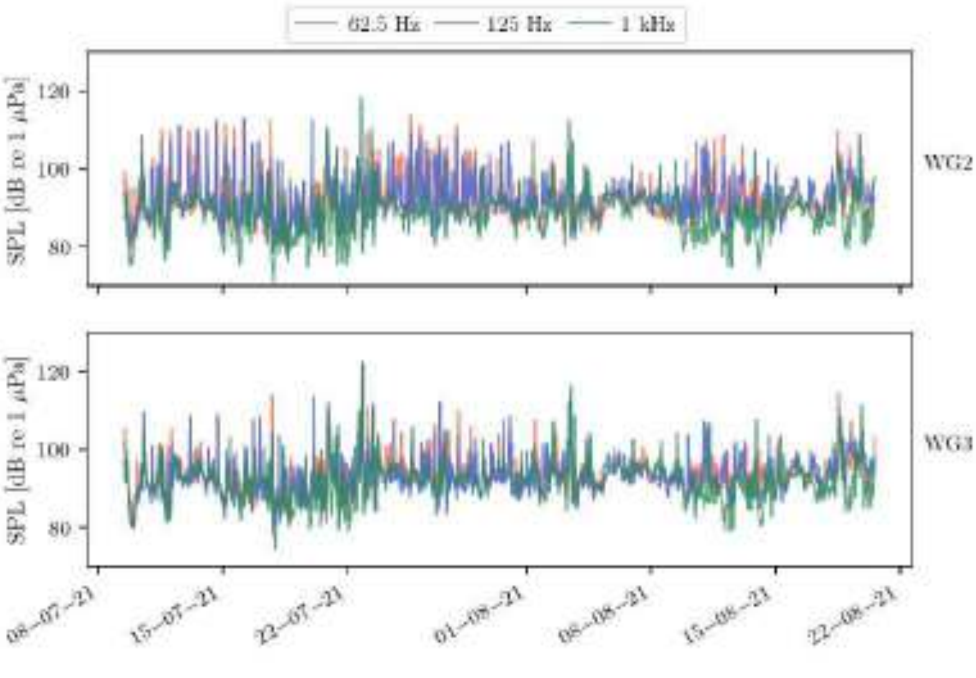

Figure 59. Hourly median SPL time series for 62.5, 125 and 1000 Hz.

Three regimes were identified: “Off”, “On”, and “Other” (meaning the rest of the time). It is worth recalling that the device was supposedly operating during the Other regime, but without more details on the operating regime, hence it cannot be considered as background noise as understood in this work. As there is not much data on the operation of the device, Off and On regimes were defined using as threshold the normalized power values under and above 0.5, respectively (1 equals the average power output during the period). The significant wave height time series were classified according to these regimes and a number of bins, defined as

$$H_b = (0, 0.75, 1.5, 2.5, 4)$$

Number of samples for Off, On and Other regimes were 62 (6.3 %), 63 (6.4 %), and 855 (87.3 %) counts, respectively, as depicted in Figure 60. Not all wave heights are equally represented in this classification, as Off regime periods were (not coincidentally) characterized by the calmest sea states.

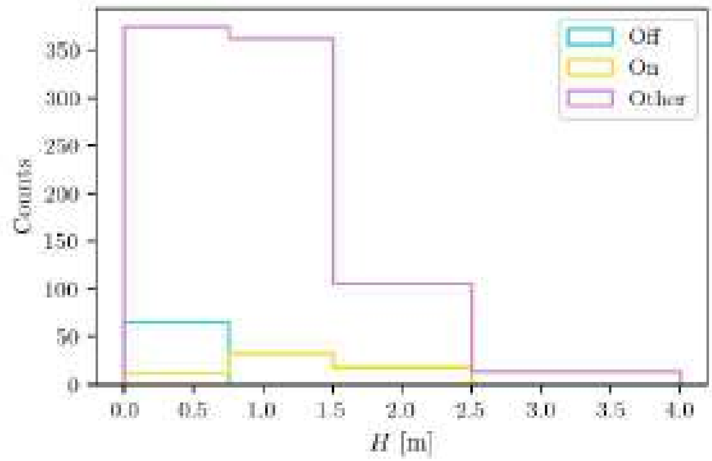

Figure 60. Histogram of significant wave heights depending on the regime.

With this classification in mind, the full SPL distribution is shown in Figure 61 and Figure 62. In these figures the dependence with respect wave height is most clear in the lowest and highest frequencies, in which most of the energy of the spectrum of the naturally occurring wave-induced noise and the moorings is located, respectively. In this sense, it shows a similar behaviour as the BiMEP test site. Moreover, the effect of the sea state impacts to a greater extent in the bands between 25 and 50 Hz and, through the movement of the moorings, in the bands between 3 and 4 kHz.

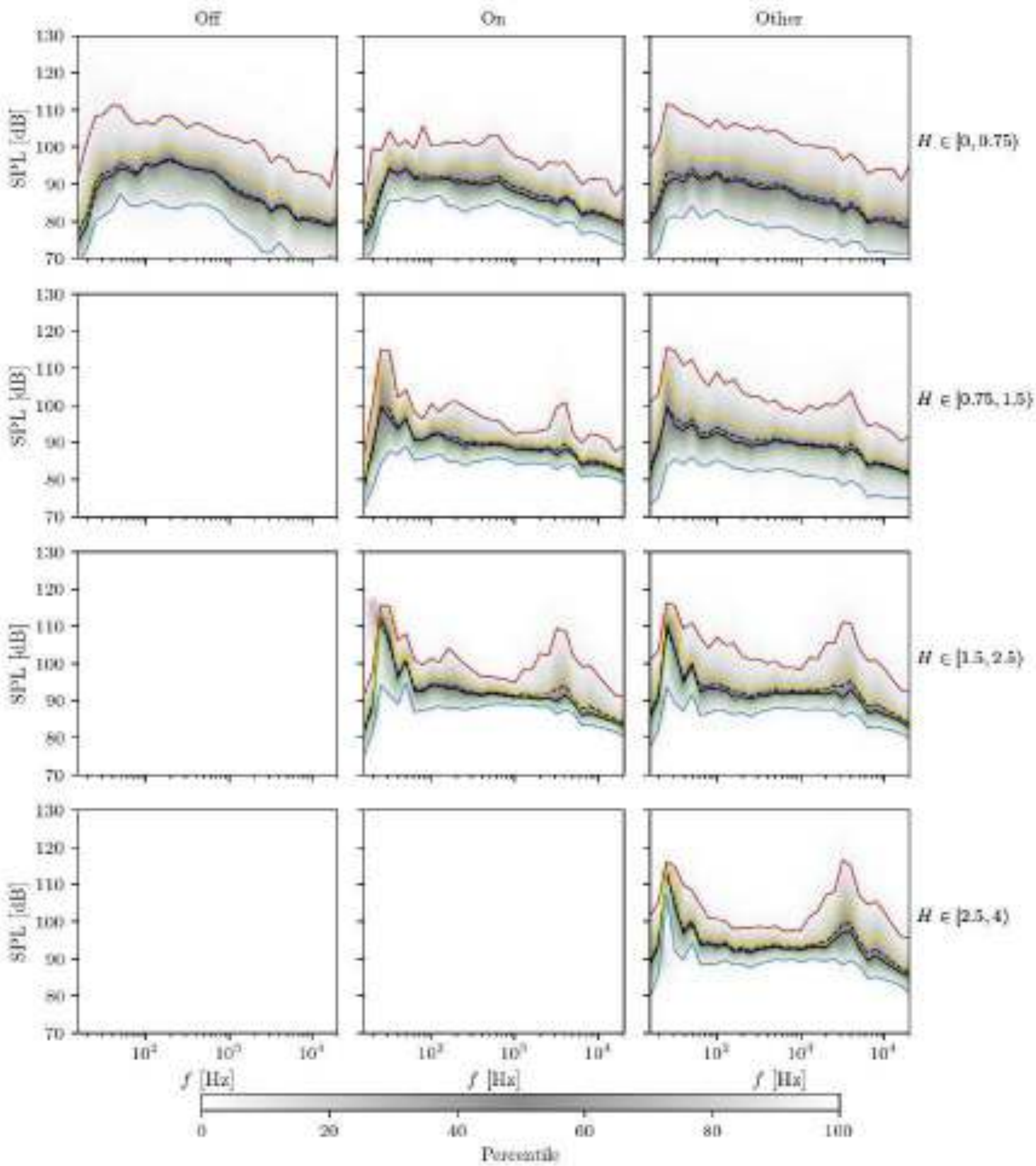

Figure 61. Percentile distribution of the SPL of WG2 for each regime and sea state. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The median is shown as a dashed line.

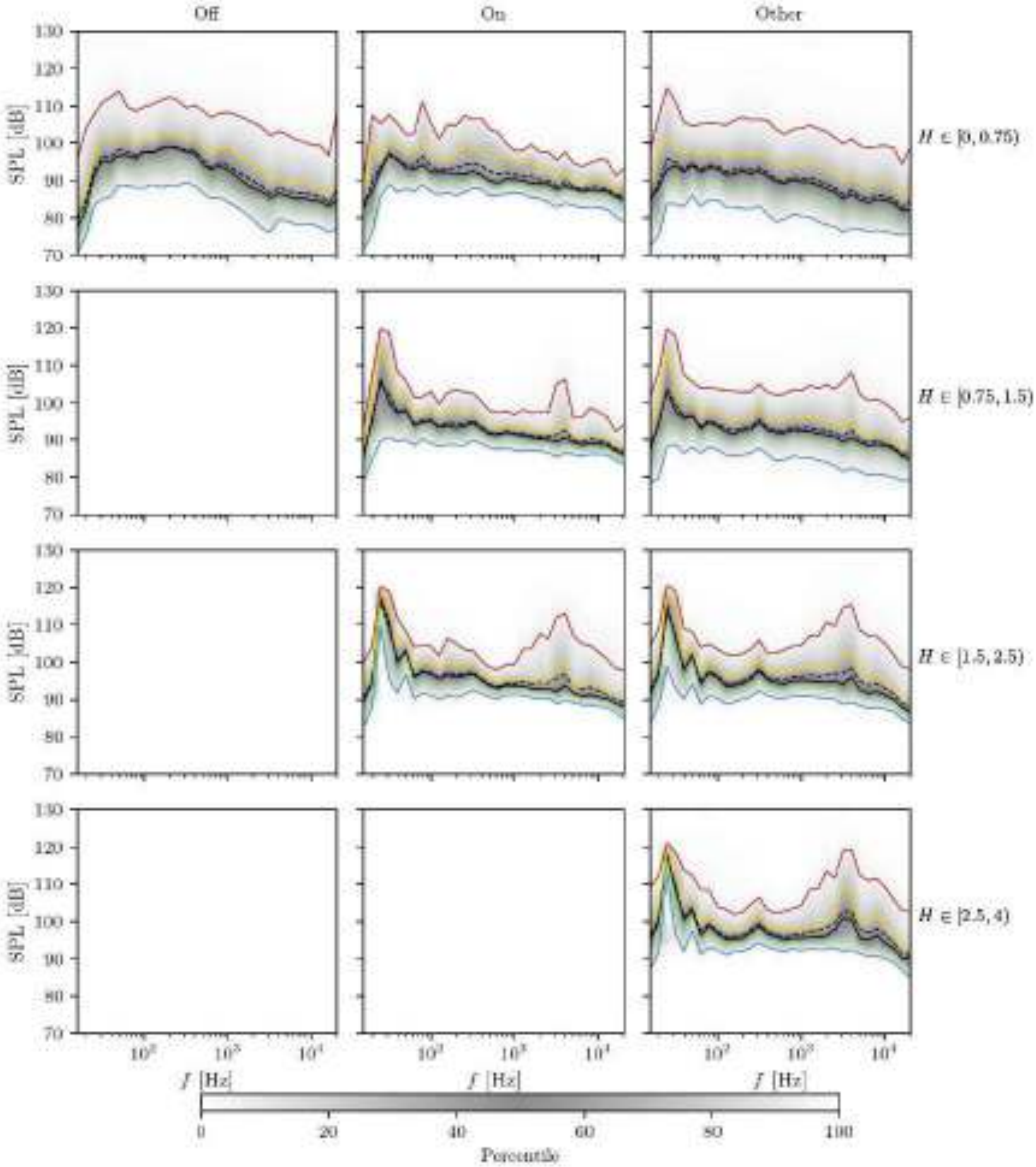

Figure 62. Percentile distribution of the SPL of WG3 for each regime and sea state. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The median is shown as a dashed line.

In Figure 63 the median SPL values can be observed with the explicit dependence on the significant wave height, for all regimes. Here the already mentioned effect of the sea state is confirmed, with a clear increase in the levels with rougher sea states. The higher levels are found around the 30 Hz band, reaching almost 120 dB re 1 µPa.

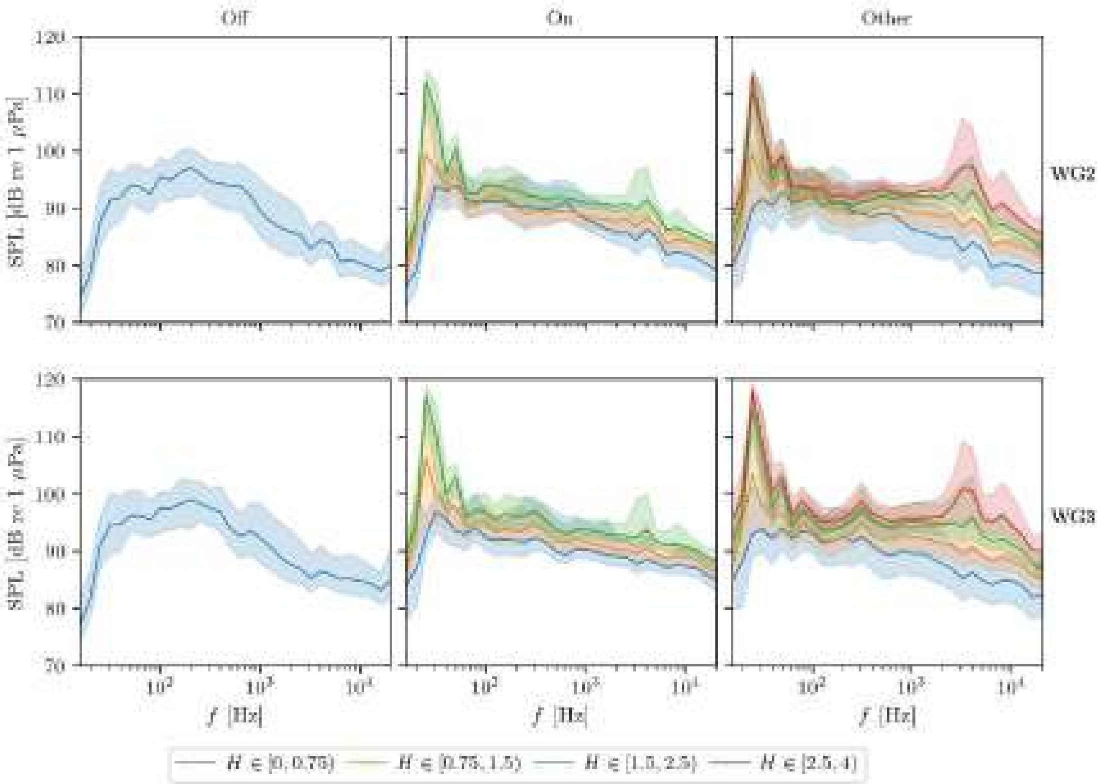

Figure 63. Median, and Q1-Q3 (bands around) for all sampling sites, regimes, and wave heights.

Finally, the differences between regimes are explored in Figure 64. As expected from earlier results, there is no significative difference in the levels between different regimes. In particular, for the On-Off case, even if there are some frequencies for which the difference is positive, the corresponding deviation is large enough to override any effect. This signals that the acoustic signature of the WEC is not perceptible (cannot be distinguished from background noise) at the distances of the hydrophones.

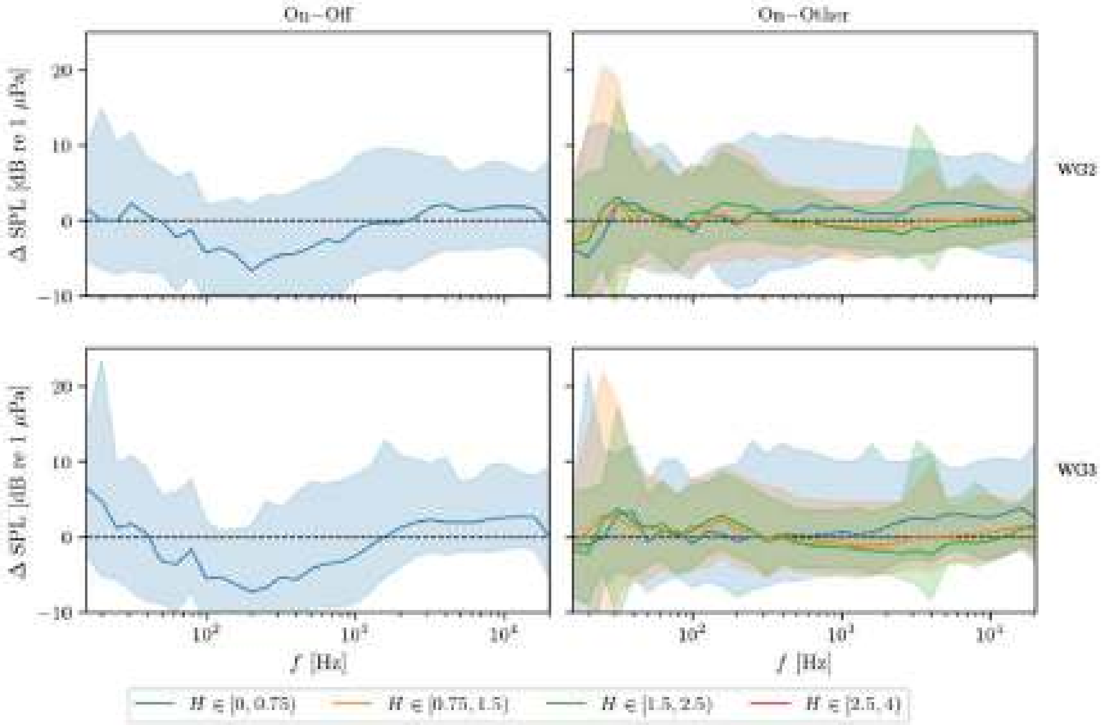

Figure 64. Median (Q1-Q3 in solid bands around) SPL differences between selected regimes, for all wave heights, as function of frequency.

A particular analysis was performed in the 50-1000 Hz, given the negative difference between the On-Off states. In order to explain this negative difference, a regression experiment was performed between Power and SPL values in the band for the On and Off states. In Figure 65, the relationship between power and SPL for both On and Off is explored. A **strong positive correlation (Pearson coefficient = 0.72)** can be found for the On state case, suggesting that as the device consumes more power, the noise it generates (as measured by SPL) tends to increase. On the other hand, when the device is Off, we found a **weak negative correlation (Pearson coefficient = -0.24)** between power and SPL. This weak correlation implies that when the device is Off, the power consumption has very little influence on the sound levels. The noise detected in the Off state is likely caused by other factors such as the water sloshing on the tanks.

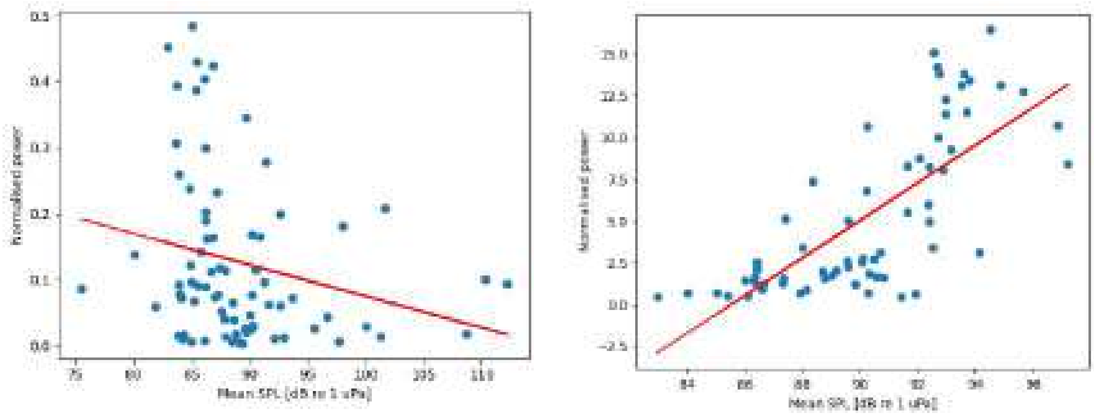

Figure 65. From left to right: Mean SPL vs Normalised power for the Off state and mean SPL vs Normalised power for the On state.

4.5.1.2 Airborne noise

When analysing the airborne SPL distribution for both Off and On regimes, there seems to be no significant frequencies that characterize the device operation, as can be observed in Figure 66.

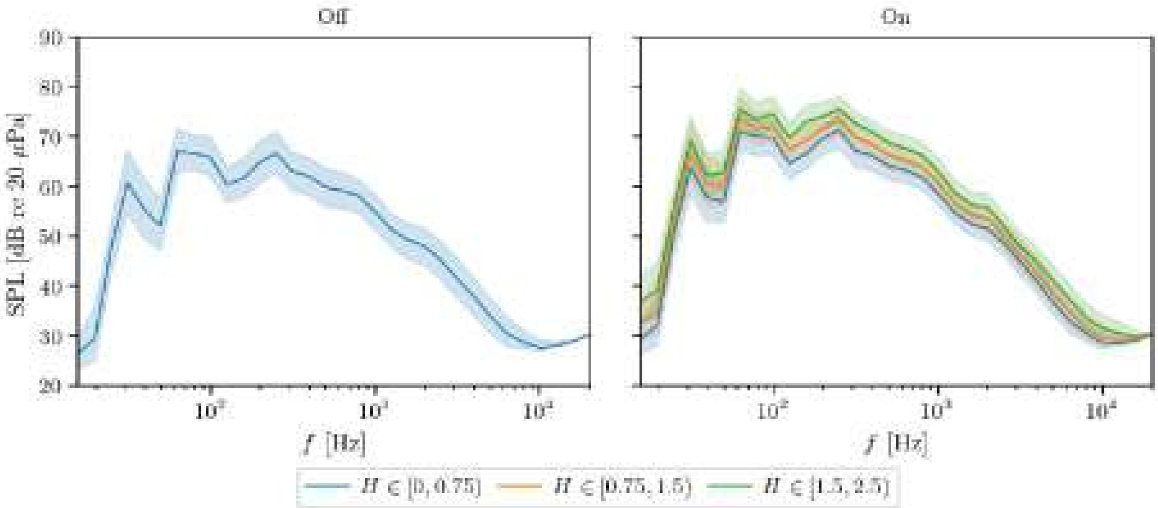

Figure 66. Median, and Q1-Q3 (bands around) for the regimes and wave heights of the airborne noise campaign.

All levels increase homogeneously with significant wave height, in contrast to the underwater case. The increase in each consecutive significant wave height is small (about 2 dB re 20 µPa). The actual differences between regimes in this case are plotted in Figure 67. As was expected, even though the difference is positive, the deviation is big enough as to mask any statistical significance.

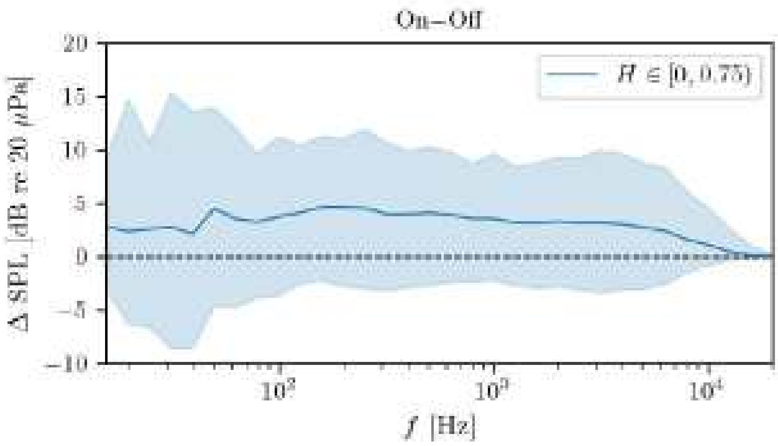

Figure 67. Difference (between On and Off regimes) of the median SPL for the airborne noise.

4.5.2 Second campaign (removal and installation of anchors)

The spectrograms are well correlated with the key acoustic events during the campaign, which were the installation and removals of the 4 anchors on the test sites, along with the WEC hook-up (Figure 68). As can be seen, the SPL increases over the whole spectrum during these key periods, but especially at 62.5 Hz, which is one of the key frequencies specified by MFSD. It should be noted that there is no remarkable difference between the 3 spectrograms, since the noise generated during the key events was large enough to cover the distances to the 3 hydrophones. It is also important to note that the WG3 audios were discarded because the background was already characterized and there was no need to analyse it until the end of the campaign.

From the SPL median time series, it can be extracted that the values when no key event was happening were around 90 dB but with peaks up to 110 dB. Also, the highest levels of the campaign found on the key events were up to 135 dB.

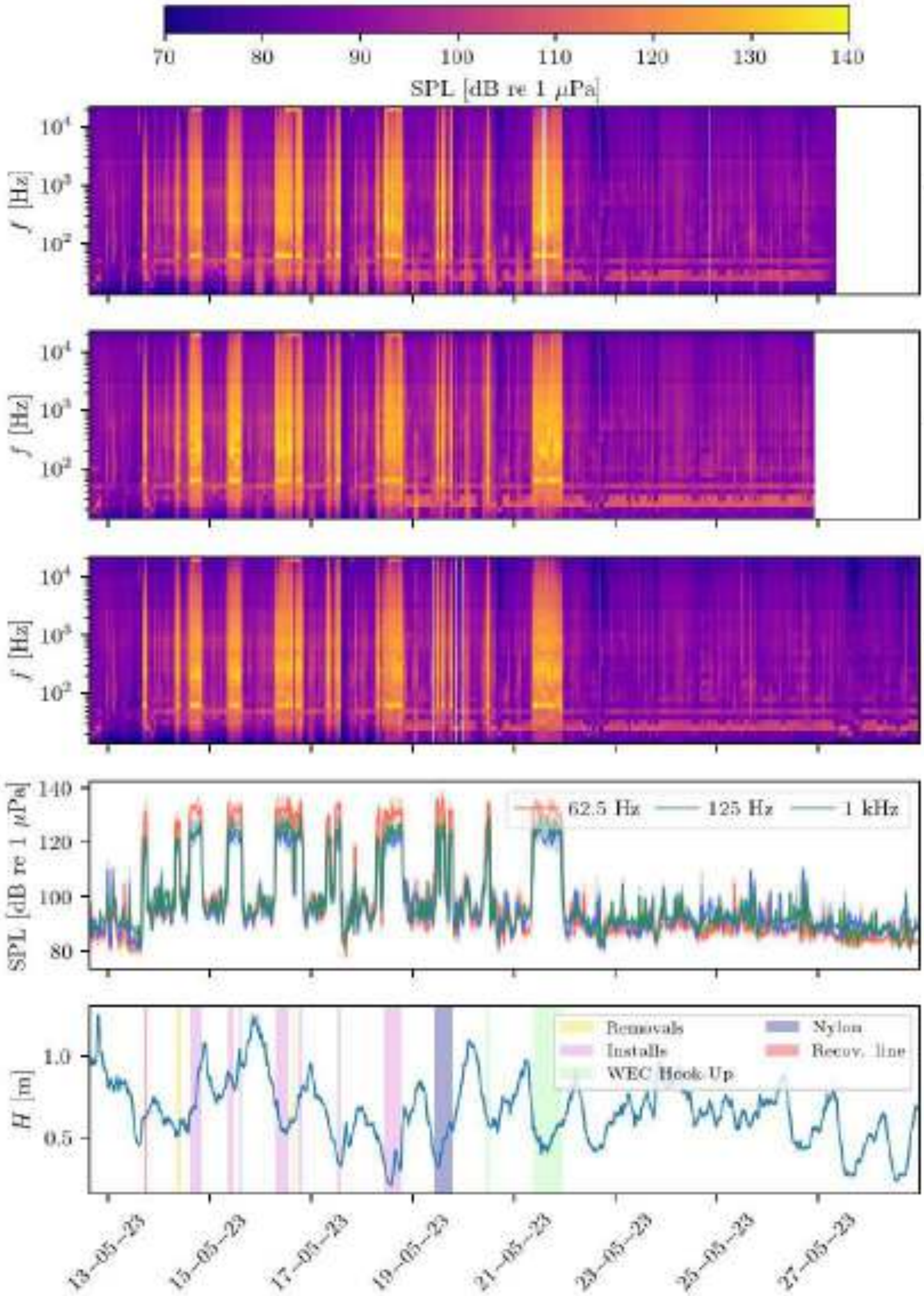

Figure 68. From top to bottom: hourly SPL spectrogram; hourly SPL median (across all hydrophones) time series; significant wave height with relevant regime periods.

In Figure 69 the evolution of the SPL can be observed in more detail. All frequencies show similar baseline levels, around 90-95 dB re 1 µPa, with maximum levels occasionally above 115 dB re 1 µPa. It can be seen that the highest values are up to 135-140 dB re 1 µPa for every key acoustic event.

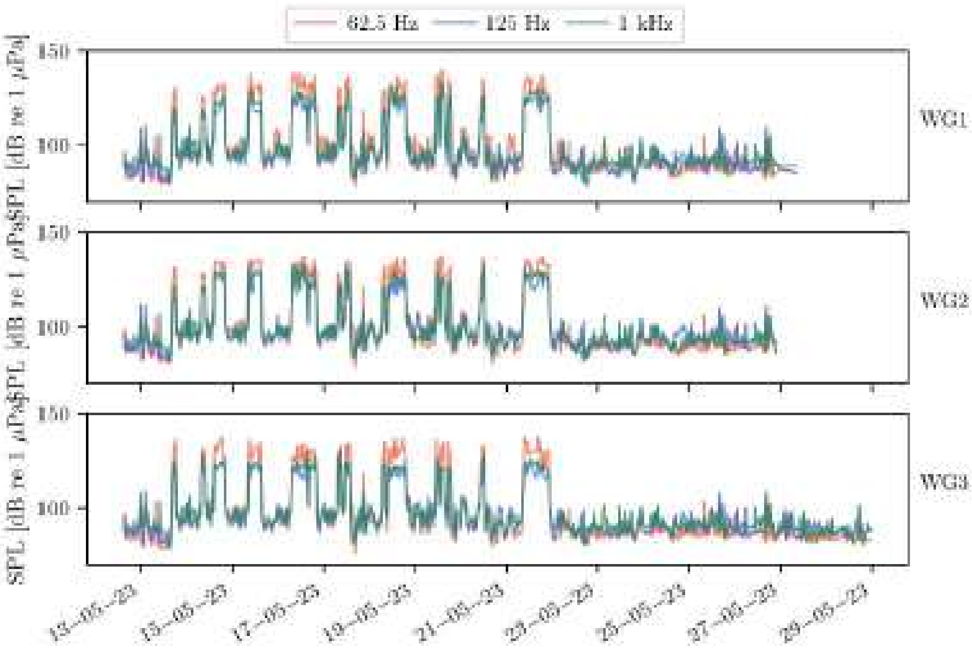

Figure 69. Hourly median SPL time series for 62.5, 125 and 1000 Hz.

Three key events were selected from the list of acoustics events: “Removals”, “Installs”, and “WEC Hook-Up”. The significant wave height time series were classified according to these regimes and a number of bins, defined as

$$H_b = (0, 0.75, 1.5)$$

Number of samples for Removals, Installs and WEC Hook-Up regimes were 9 (6.7 %), 79 (59.4 %), and 45 (33.83 %) counts, respectively, as depicted in Figure 70. It should be noted that for security stuff, these three events were carried out on calm sea states, being that the reason why there are no high wave heights information.

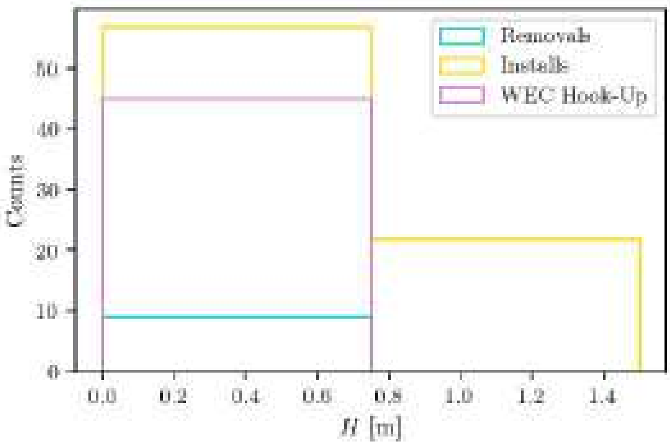

Figure 70. Histogram of significant wave heights depending on the regime.

As no high wave heights values were found for the key events, and the main goal of this second campaign was to characterize the noise emitted during the works on the area instead of characterizing the noise emitted by the WEC, the wave heights were not taken into account for the analysis.

The full SPL distribution is shown in Figure 71 to 73. As can be seen, the highest values are found for Installs and WEC Hook-Up.

As explained before, no significant differences are appreciated between hydrophones due to the high intensity of the acoustic waves, and due to the proximity of the hydrophones to the working area.

The high values of the percentile 95 for the background case should be noted. These values could appear due to vessels movement on that "background" state. In addition, the 'background' condition was selected by eliminating the periods during the campaign when there was construction work, but it should be noted that during the period from 21-05-23 a low frequency anthropogenic noise (~15/20 Hz) is visible (probably linked to the wind turbine), reaching 110 dB most of the time. In addition, mooring lines can be clearly heard at around 3-4 kHz during this period, which seems to indicate that, given that the WEC device was not at sea during this period and the wind turbine was, a small part of the noise measured in the same band during the first campaign was due to the mooring lines of the wind turbine installed close to the hydrophones.

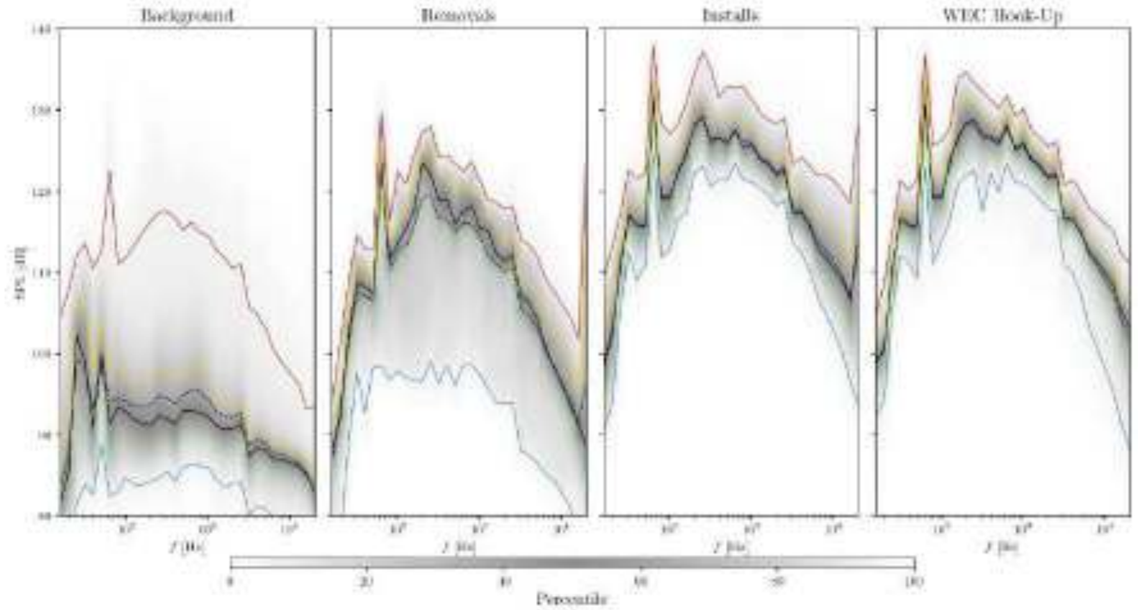

Figure 71. Percentile distribution of the SPL of WG1 for each key event. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The median is shown as a dashed line.

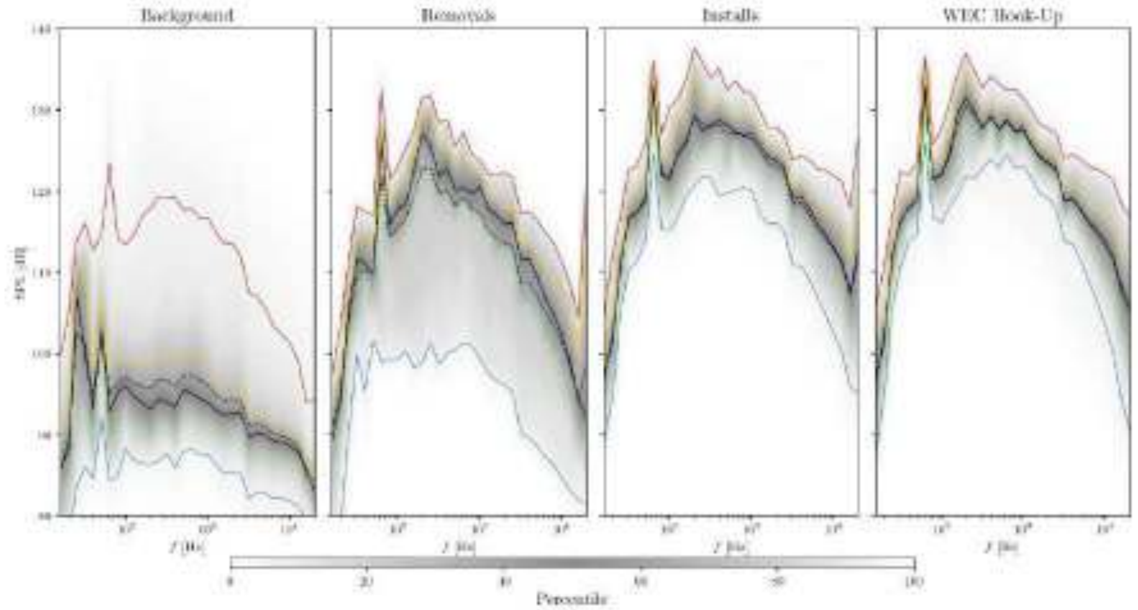

Figure 72. Percentile distribution of the SPL of WG2 for each key event. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The median is shown as a dashed line.

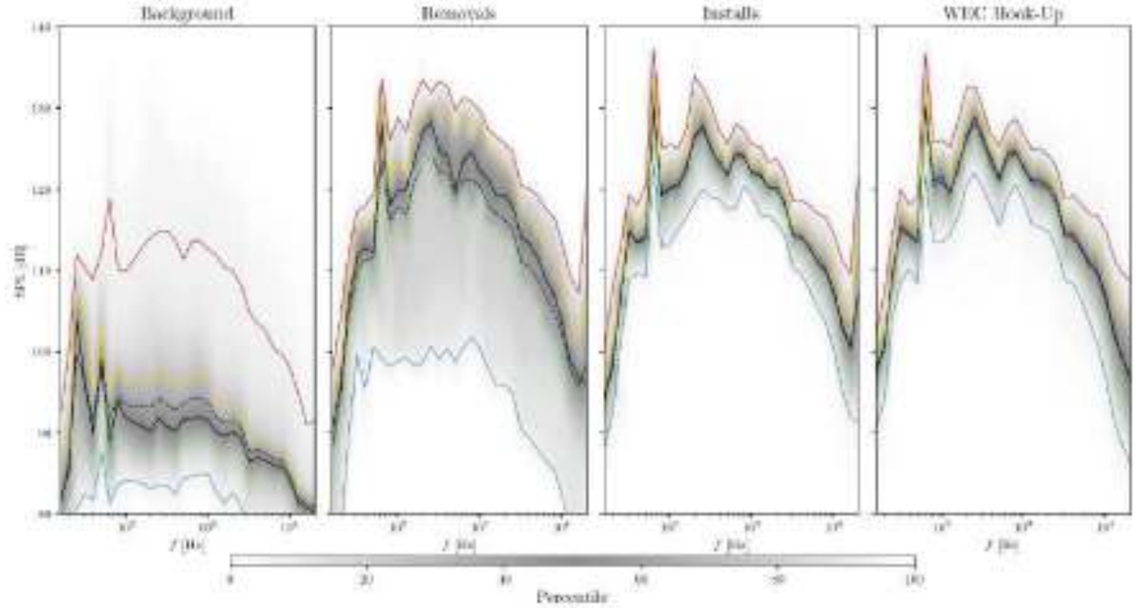

Figure 73. Percentile distribution of the SPL of WG3 for each key event. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The median is shown as a dashed line.

It should also be noted the high component in 62.5 Hz, especially in the “Installs” and “WEC Hook-Up” states, which will probably be originated by the devices used on the works.

Finally, the differences between regimes are explored in Figure 74. As expected, a high difference between the key acoustics events and the background is found over almost the whole spectrum.

Highest difference values (almost 40 dB) are found at 63 Hz. It should be noted that at 25 Hz, no difference is found between the key events selected and the background.

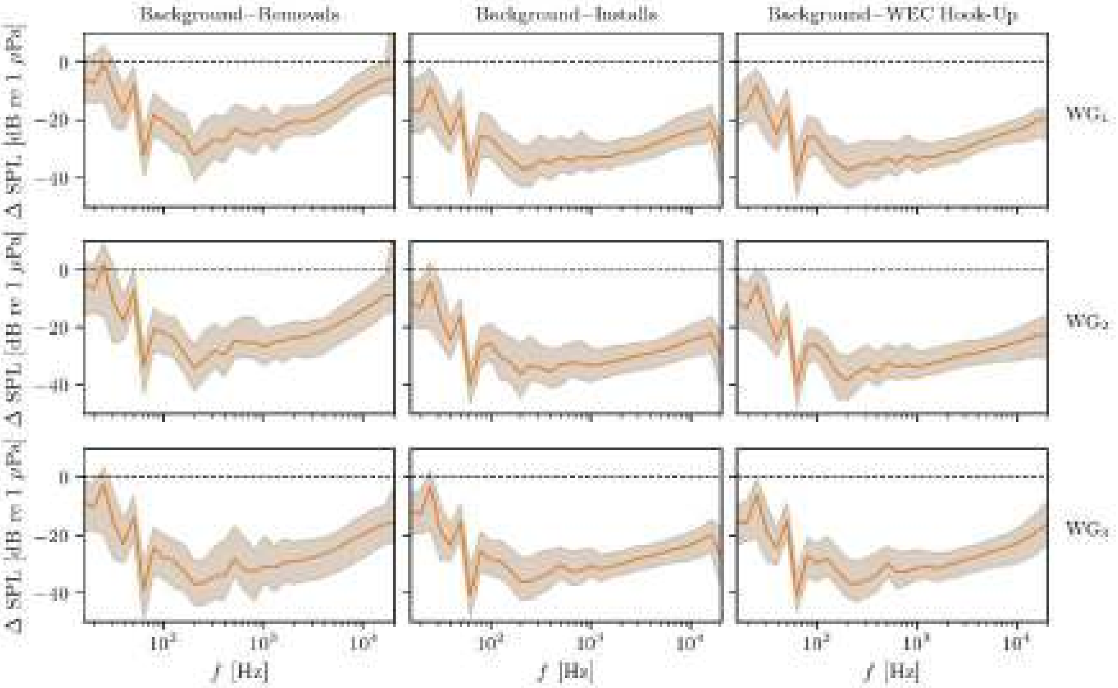

Figure 74. Median (Q1-Q3 in solid bands around) SPL differences between selected regimes, as function of frequency.

4.5.3 Conclusions

There seems to be no significant contribution of the WEC to the ambient noise in the SEM-REV test site. However, it should be highlighted that the amount of available operation data is very small, that when coupled with the fact that there is no background noise levels assessment, limits the scope of the outcome in this test site. Additionally, the acoustic signature of the mooring chains that are in the area can be detected, as a peak localised in the band centred in 4 kHz that increases in magnitude with the wave height.

Finally, the highest values in SPL are localized in a narrow band centred in in 30 Hz, with values reaching almost 120 dB re 1 μPa. This peak could be caused by the WEC, when forced by strong waves, but without more operating data or a baseline campaign this remains a hypothesis.

For the second campaign, the key acoustic events were selected as "Installs", "Removals" and "WEC Hook-Up" and the differences between the background noise (no activity on the test site) and these events were investigated. The largest differences were found across the spectrum, but particularly at the frequency specified by MSFD (62.5 Hz), where there was almost a 40 dB difference.

5. Conclusions

From all devices monitored during operation (PENGUIN II, Mutriku Power Plant, WAVEGEM, and CorPower C4 WEC, located in BiMEP, Mutriku, Nantes, and Aguçadoura, respectively), we can conclude that only in the case of PENGUIN II there is some kind of acoustic contribution to the background noise. However, this happens whether the device is operating or not (higher when operating though), and only when the comparison is made with respect to the baseline levels existing after decommissioning. The device is a floating asymmetric hull containing a rotating mass which drives a generator. When device was off (not generating or operating) the rotator was unlocked so it actually could rotate. What it did, it short circuited the generator so that movement was generating the current in coils which was generating magnetic field opposing the movement of mass rotator. There was also a pin locking device, but if that was operated, it needed to drive the mass rotator on certain location and then pin actuated. But that was only used on during deployment of the device. When device was off (not generating), there might have been also cooling fan and cooling circuitry making some noise. All these factors could explain why sound levels where similar whether the device was operating or not.

In this case sound levels increase more than 20 dB re 1 µPa in the lowest frequencies. This seems to indicate that the presence of the device itself implies noise disregarding its operation state when compared to the existing soundscape when there is no device.

The rest of the wave energy devices showed no significant acoustic signature. In the case of the WAVEGEM device, it was suspected that there was an above-background component localized in the lowest frequencies (~ 30 Hz), but the limited operation data, in conjunction with the absence of preinstallation underwater noise assessment, did not allowed for a conclusive outcome. The background noise was later obtained on the second campaign, selected as the noise when no works were being performed, and allowed to conclude that no significant difference was being made by the operation of the WEC, and also, that both the moorings from WAVEGEM and the wind turbines near were contributing to the noise at the 3-4 kHz band.

In the other hand, there is another WEC-related element with a detectable acoustic signature, which is the system of moorings that can be found both in the BiMEP and SEM-REV test sites. When significant wave heights are above ~1 meter (and thus the moorings are displaced), a high frequency (between 3 and 5 kHz) component in the SPL spectrum is observable. Same effect occurred for the C4 device in Aguçadoura, where there is a slight increase at around 2 kHz.

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