Reply to Reviewer #1 (Stephen Hicks)

1. SUMMARY

This manuscript by Cannata et al. analyses the effect of COVID-19 lockdowns on seismic noise in Sicily, Italy. Although this effect has been reported globally, this study is unique because uses a fairly dense regional seismic network to view the higher-order features of the anthropogenic lockdown signal and its spectral characteristics. The study finds quite a heterogeneous lockdown response, even on a relatively small island. Most interestingly perhaps, it is also found that the anthropogenic noise reduction might also have allowed for more detection of seismic arrivals from seismic events. I enjoyed reading this manuscript. The writing is very clear and contains minimal errors.

I congratulate the authors on a very nice study. Overall, the manuscript is in excellent shape, and aside from some minor comments detailed below, it should be close to publication-quality. My most significant comment is that I think the description of the seismicity detection results should be expanded a little.

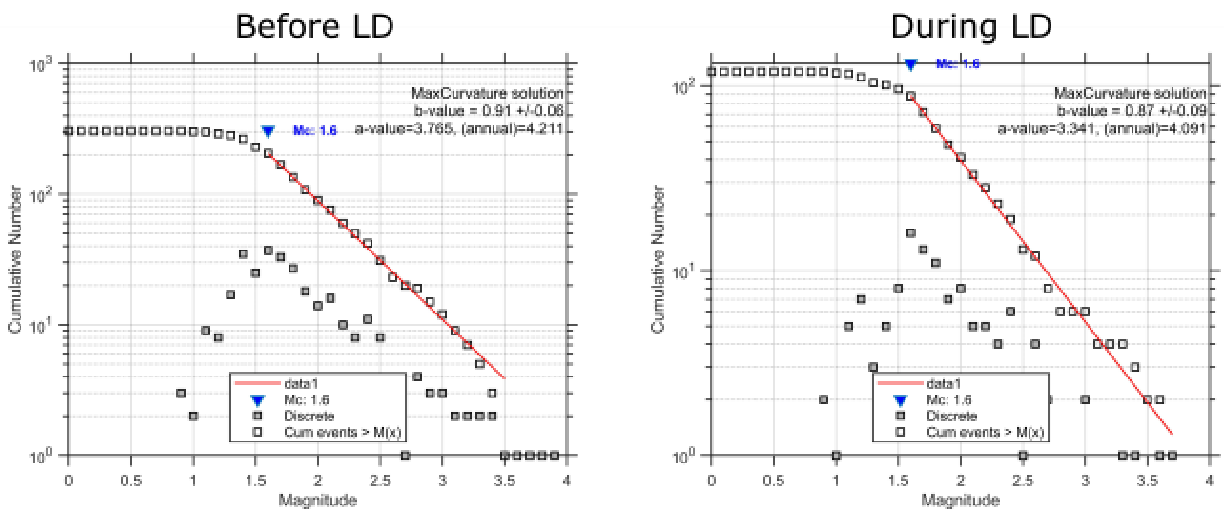
> *We thank the reviewer for the very positive comments.*

2. MINOR GENERAL COMMENTS

1) The analysis of the earthquake detections is interestingly, yet somewhat disappointingly short. I recommend a few things:

- First of all, this aspect of the paper is not yet mentioned in the abstract, so I would add some mention of it there.
- Second, I would recommend perhaps not having a separate methods subsection on the earthquake detection. I would move this short description of the detection system along with the results to a separate subsection of the Discussion called something like “Implications of the lockdown for detection of seismicity”.
- Finally, I think is much scope for further analyses of the seismicity detection changes. For example, for Figure 11, I could expect that if the improve the detectability of seismic phases during lockdown is robust, then it should be seen most clearly for seismic events occurring during the daytime. How does the correlation look if you only plot seismic events from during the daytime (e.g 0600-1800)? Also, if you were to assess a Gutenberg-Richter relationship and to compare pre- and during-lockdown, would you be able to infer a lower completeness magnitude? Finally, are you able to determine which stations had more P-picks during the lockdown, if so, were these the noisier stations, e.g. “EFIU”?

> *We tried to repeat the analysis by considering only earthquakes recorded during day-time and weekdays, but the number of events became very low (25 and 85, during and before lockdown, respectively), to be statistically significant. In addition, we also evaluated the Gutenberg-Richter relationship separately for earthquakes, taking place during and before lockdown, and we did not note any significant changes in the completeness magnitude, equal to 1.6 in both cases:*



Hence, these further analyses did not allow to get more robust results. Probably, this topic would need a more in-depth analysis. Following the advice of the reviewer #2, we decided to delete this section regarding the detection improvement and keep it for a next narrower, more focused study.

2) Is there any specific reason why your frequency analysis only goes up to 30 Hz, when your stations were sampling data to 100 Hz, so possibly allowing you to get close to 50 Hz? It might be interesting to see what his happening with the anthropogenic seismic wavefield at higher frequencies.

> Thanks for your advice. We extended our analysis up to 40 Hz, and consequently most of the figures/analyses have been updated. We could not go beyond 40 Hz, because of the digitizer anti-aliasing low-pass filter with cut-off frequency around 40-45 Hz (it depended on the station taken into account).

3. MINOR SPECIFIC COMMENTS

- L35: "Between 8-11 March, the entire country was put under lockdown (Gatto et al., 2020)". This phrasing makes it sound like the country was on lockdown for 3 days between the 8 and 11 March. Please rephrase, including the approximate total length of lockdown.

> Done, thanks.

- L55: I guess it would be good to use the opportunity in this paragraph to state why your study is different and complementary to the existing COVID-19 seismic noise studies. I guess yours is the first study that uses a fairly dense network from a local area in which lockdown restrictions were imposed uniformly. So, it gives us the opportunity to view higher-resolution details of the anthropogenic noise field (e.g. how the anthropogenic noise field propagates, site effects, frequency effects, etc.), with a uniform lockdown and independent of potential cultural variations.

> We added a sentence in that paragraph, highlighting the peculiarity of this study. Thanks for your advice.

- L65: You mention the seismometer instrument type, but it would be good to describe the station installation styles and environments given that you are looking at a local scale case study. Are all stations deployed in subsurface vaults? Or is there a more variable installation style? Are some stations located in populated areas, or are they in as remote regions as possible? Or is the installation style quite mixed over the network?
> The installation style is pretty uniform, all the considered stations are installed in shallow vaults (depth ~1.5 m) made of concrete. As for the site conditions (in terms of possible anthropogenic seismic sources), it is variable: some are close to towns or highways, others near agricultural areas, others in small islands or on the flanks of Mt. Etna. All these information have been added in the manuscript, as well as in the new Table 1.

- L170: I find this sentence a bit confusing: "The correction was performed by dividing the number of phases by the fraction of seismic data acquired by the network during the day when the earthquake took place, with respect to the data which would have been recorded in case of full operating state of the network (Figure 11b).". Does that mean the y-axis of Figure 11b is essentially a percentage value? Could you maybe please clarify this?
> As mentioned above, this topic would need a more in-depth analysis. Following the advice of the reviewer #2, we decided to delete this section regarding the detection improvement and keep it for a next narrower, more focused study.

- Figure 1: Some of the station text labels are quite small, overlapping, and so are hard to read. Please increase the font size and edit the label positions to make sure they do not overlap. -> Please also include a small inset map for readers who may not know where exactly Sicily is :) -> It might also be useful to include some topographic shading to emphasise the position and flanks of Mt. Etna.
> Done.

- Figure 2: -> If the paper is printed on A4 paper, some of the text labels could be very small. Maybe consider increasing each subplot size and reduce the whitespace between subplots? -> The "LD" label is very hard to see. Maybe increase the font and put this in a semi-transparent box. -> The x-axis tick intervals are a bit random. Maybe just show the 1st day of each month for clarity.
> Done.

- Figure 3: -> The "LD" label is very hard to see. Maybe consider increase the font and put this in a semi-transparent box.
> Done.

- Figure 4: -> What is the order of the stations on the y-axis? If these are in no particular order then maybe using alphabetic order might be useful so that readers can easily crosscheck the station results with other figures. -> The "LD" label is very hard to see. Maybe increase the font and put this in a semi-transparent box.
> The stations are sorted by decreasing latitude (it is indicated in the caption). We increased the font size of "LD" to make it more visible.

- Figure 5: -> Some of the station text labels are quite small, overlapping, and so are hard to read.
> Done.

- Figure 6: -> If the paper is printed on A4 paper, some of the text labels could be very small.
> Done.

Figure 7: -> If the paper is printed on A4 paper, some of the text labels could be very small.
> Done.

Figure 9: -> The figure resolution is very low so I cannot read the text labels in the legend.
> We increased the resolution, and changed a bit the figure based on the advices of the reviewer #2.

Figure 11: -> Change the y-axis labels from "# picking" to "Number of P-picks".

> As above mentioned, we deleted this section regarding the increased detectability of earthquakes, and then also the related figure.

Reply to Reviewer #2

This contribution describes the effect of quieting following the COVID19 lockdown measures on the noise level in a regional seismic network located around the Etna, Sicily, Italy. The subject is of interest, in particular in the framework of the "Social seismology" SE Special issue. The paper is well-written, the structure is in general well shaped and the figures are of good quality (although many labels should be enlarged). Therefore, I think that the manuscript deserves to be published in SE after minor to moderate revision. However, there are a number of point that, in my opinion, should be reworked in the final version of the manuscript.
> *We thank the reviewer for the positive comments.*

The most valuable contribution of the manuscript is documenting that a seismic noise reduction can be observed in areas far from large cities, where human activity still affect the background seismic noise via ship transit, touristic excursions etc.. Even some stations which seems to be installed at remote places reflect the decrease of activity following lockdown. I think that this point has to be highlighted through the manuscript and in particular in the abstract and conclusions.
> *Thanks for your advice, we added a couple of sentences about that in abstract, Results and discussion and conclusions sections.*

In general, the manuscript makes a good job in presenting the data, but tends to be too concise in the interpretation part. Sections 2.2 and 2.3 are merely descriptive of the results presented in the corresponding figures. The reader has to wait till section 3 to learn something on the information included in the figures. I propose to include here the discussion on the differences observed between sites, the tentative origin of noise at each site etc. included now at Section 3.
> *I see your point; however, we cannot write results in the "Materials and methods" section. Indeed, by putting only data and analysis descriptions in the "Materials and methods" section, the readers, not interested in the technical details, can skip such a part of the manuscript and still get all the information about the main paper results.*

Figure 6 and 7 provide essentially the same information that Figs 2 and 3, presented in a different way. I will appreciate a comment on which are the advantages of each kind of representation. Are there features only observed these representations and not in the RMS or spectra?? If yes, it will be interesting to comment. Otherwise, the figures can be seen as redundant.
> *Actually, figures 6 and 7 are necessary to explore the spectral content of the anthropogenic seismic noise and contain information not present (or at least not that evident) in both spectrograms and RMS amplitude time series. Hence, in our opinion, such figures cannot be considered redundant. Among the figures you cited,*

probably the one we commented less was Figure 2, showing the spectrograms. Hence, we added some comments about these at the beginning of the section 3.

Regarding the comparison with mobility data, I think that the message that seismic data is consistent with other data is best passed using a graphic as that presented at Suppl. Fig A2 than using just correlation coefficients. I suggest to start the section using a new figure composed by the a) subplot of Suppl fig. A2 and the submitted Fig. 10. The submitted Fig 9 will move to Fig 10. In this way the reader will first see an example of correlation between RMS and mobility data for specific station, then see the overall correlation and finally see the differences between stations and mobility data.

> Done, thanks for your advice.

The discussion on Spearman correlation and t-test and p-values is unclear. I think that the original Figure 9 has to be used shown the station with good or poor correlation with mobility data, in some graphic, easy to interpretate way.

> We changed a bit the discussion of these data. We hope that it is clearer now.

In the discussion (line 220) it is stated that only the ESAL/Facebook correlation does not match the criteria, but, in my opinion, some of the stations (EFIU, HSRS, ESML, HPAC) clearly show a good correlation between seismic RMS and quietening, while for the rest, the correlation is less clear. This point should be clearly stated, noting that the relationship seismic noise/mobility is not always clear. In the Conclusions section it is correctly stated that the effect is strongly station-dependent. I think that this dependency should be better described here. In any case I would enhance the fact that, even for stations with poor correlation there are evidences of changes in the seismic noise values.

> As above mentioned, we have modified the discussion on these data. In particular, we have clearly written that correlation between seismic noise and human mobility is strongly station-dependent, some stations show very good correlations, others less. In any case, the p-value is lower than 0.05 in all the comparisons, suggesting how the obtained Spearman correlation coefficients are significantly different from zero. In addition, we performed again the analysis by using seismic RMS amplitude in the band 10-40 Hz (in place of 10-30 Hz). By doing so, the correlation ESAL/Facebook now also matches the criterion $p<0.05$.

I don't understand Suppl Fig A3; P-values are in the order of 0.005 for Google, 0.0002 for Apple and 0.02 for Facebook. Are those order of magnitude differences realistic?? The authors state the p-value of 0.05 is considered sufficient to reject the null hypothesis; while this particular number is chosen?

> The p-value threshold of 0.05 means that the probability, that the result of the statistical test is due to chance alone, is less than 5%, so it would occur once out of 20 times the study is repeated. The value of 0.05

is a commonly accepted significance level used for this statistic test. We added a couple of sentences about that in the section 2.3. As for the obtained differences in p-values, yes, they are realistic.

Noise level variations related to ship activity or touristic excursions is interesting and not often described. I suggest to give more weight to this funny observation.
> Agreed. Indeed, ship traffic data of Lipari port has been obtained and compared with seismic data acquired by ILLI station (installed in Lipari Island at about 2.7 km from the port). Hence, a new figure and several sentences have been added regarding this topic in sections 2.3 and 3. Furthermore, a couple of sentences about the fact that the seismic noise amplitude reduced even in stations installed in remote places have been added in abstract, Results and discussion and conclusions sections.

The section on the improvement on detection capability has a large potential interest, but it is not really developed here. In the main text, the authors just describe Figure 11 and the final discussion includes just a sentence on this subject. If the authors decide to keep the section, a significant improvement will be needed. Figure 11 shows that the number of pickings increase during lockdown, but the relevant information will be if more small magnitude events are detected or if the hypocentral determination is improved during lockdown. This analysis should be taken carefully, taking into account the epicentral distance of the events detected in each period, the occurrence of swarms/aftershocks that could perturb the comparison etc. Otherwise, a better option will be to keep the detection improvement discussion for a next paper focused on this subject.
> We totally agree with you. This topic would need a more in-depth analysis. Following your advice, we decided to delete this section regarding the earthquake detection improvement and keep it for a next narrower, more focused study.

Other points.
L. 31: Not sure that references to papers dealing with pharmacology are needed here
> The aim of lockdown measures, which influenced so unexpectedly the seismic signals, was just to slow down the COVID-19 epidemic to give more time to the pharmacological research to find a cure and/or a vaccine against COVID-19. This is the reasoning behind the references to papers dealing with pharmacology. So, in our opinion, they are needed here.

L. 65: The actual location setting of each location is hard to see in the small size screenshots in Supp Fig A1. I propose to summarize in this paragraph the different setting of the stations; how many are in towns, near roads, in small islands, in open nature etc Also a comment on the kind of installation used in each case will be useful; different installation types (vault, buried, building basement, insulation system etc) could affect the sensibility to human activity noise.

> We added a description of the installation, as well as the Table 1 summarizing the site conditions in terms of possible anthropogenic seismic sources.

Line 85: The authors should explain why they decided to use the 10-30 Hz band. I suggest to use the submitted Figure 8 to justify this choice.

> Exactly. We selected that frequency band according to both spectral ratio and spectral correlation with the human activity. However, reviewer #1 suggested to extend the analyses at higher frequencies, hence we chose the band 10-40 Hz, and performed again most of the analyses. We added a sentence in section 2.2 to justify our choice.

Fig 2 and 3: I will appreciate more conventional time labels (p.e. 1st and 15th of each month)

> Done.

Fig 2: The bars marking lockdown beginning is difficult to see.

> Done.

Fig. 6 and 7: Labels are too small.

> Done.

Fig. 10: The correlation is calculated between mobility data and a mean RMS profile using all the available data? Please clarify.

> We have rephrased the part of the manuscript, describing this analysis (Section 2.3). It should be clearer now.

L. 130: Using the Spearman correlation coefficient is really justified? Are the results using Pearson really different??

> As we explained in the Section 2.3, since we do not know whether the relationship between seismic noise and mobility data is linear or not, the Spearman correlation analysis is more recommended than the Pearson correlation.

L. 140. The reference to the critical p-value level to reject the null hypothesis should be better explained. As stated above, the numbers in the y-axis of Supp Fig A3 seems very different.

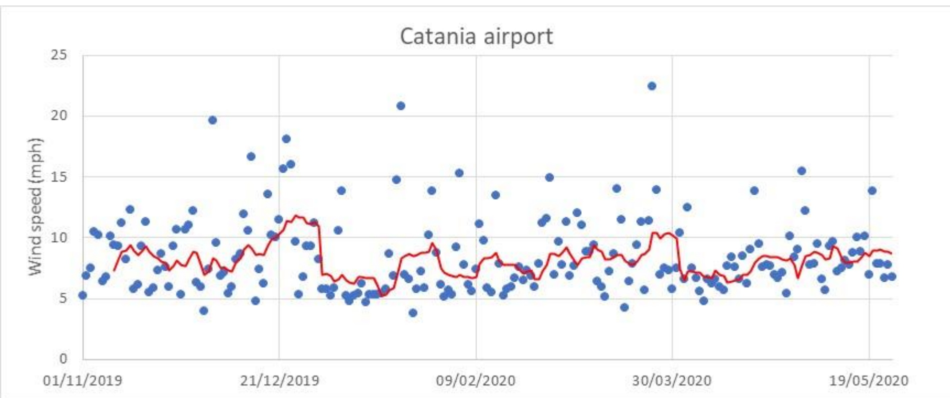
> Yes, they are. We checked the computations, and they are correct. In addition, we added a couple of sentences about the critical p-value level in the section 2.3.

Reviewer #3 (Kasper van Wijk)

"Seismic evidences of the COVID-19 lockdown measures: Eastern Sicily case of study" analyzes the data from the seismic network on Sicily during the lockdown. I am attaching an annotated pdf with smaller comments, mainly with some writing-related suggestions. In terms of the science, the analysis is thorough, and could be published in its current form. However, I wanted to propose something for the authors/editors to consider.
> We really thank the reviewer for the positive comments, as well as for the very helpful suggestions reported in the attached pdf.

To me, Figure 11 is the most exciting result: an increase in detection levels for earthquakes during the lockdown. I would provide more info (and data to show the increased S/N!) on this, and have a more focused build-up to this result, and have maybe less of the first 10 figures, as most of those observations were already reported in other settings in the existing published literature on this topic. If the authors agree, the abstract and conclusions should also highlight this result with quantitative information on this enhanced detection level.
> Following the advices of the other two reviewers, we repeated the earthquake detection analysis by considering only earthquakes recorded during day-time and weekdays, but the number of extracted events was very low (25 and 85, during and before lockdown, respectively), to be statistically significant. In addition, we also evaluated the Gutenberg-Richter relationship separately for earthquakes, taking place during and before lockdown, and we did not note any significant changes in the completeness magnitude, equal to 1.6 in both cases. Hence, we think that this topic would need a more in-depth analysis. Following the advice of the reviewer #2, we decided to delete this section regarding the detection improvement and keep it for a next narrower, more focused study.

Finally, I was wondering if weather data is available for the region? I say this, because it may be that winds could shake trees and buildings affecting seismic noise, even in the 10+ Hz band. If you agree, a correlation between wind speed (for example) and seismic noise levels may help build the case that enhanced detection level of earthquakes is due to anthropogenic quieting during the COVID-19 lockdown on Sicily.
> Actually, the period preceding the lockdown falls in winter, while the lockdown mainly in spring, so worse weather conditions (as well as the corresponding more intense seismic noise of meteorological origin) are expected in the former. However, in the following plot, we show daily wind speed data as recorded by a meteorological station installed in the Catania airport (red line is the moving average over 10 days). Such data do not show so evident changes in March 2020, to make you think that the observed seismic noise decrease could be due to meteorological variations.



In addition, the seismic noise amplitude started increasing again at the end of April, suggesting that the previous decrease cannot be due to variable weather conditions, but rather to anthropic activities. Finally, the correlation analysis between seismic data and human mobility confirms that the amplitude reduction is related to the decrease in anthropic activities. We added some sentences about this at the end of section 3.

Other comments in the attached pdf:

where does this very precise, but not round number come from? why not 82 seconds?

> Such a number is due to the fact that spectral analysis by FFT requires power of two for the number of data points; the signals are acquired at 100 Hz, and then 81.92 s corresponds with 8192 points (2^{13}).

how about a line for when the LD ended?

> We added a line in Figures 2, 3, 4 and 9a on 4 May 2020, when the first Presidential Decree, slightly releasing the lockdown measures, was issued.

you may have discussed this later in the paper, but how did weather affect this result? The island stations in the North seem to have a large reduction. Could this be that one of the periods had more wave action than the other?

> Sea wave action should create seismic noise (microseism) at low frequencies, below 1 Hz. In Figure 5 we showed the percent change of seismic RMS amplitude in the band 10-40 Hz. In addition, the seismograms shown in Figure A5(a) clearly show that the decrease in noise amplitude is not due to variations in a continuous signal (as microseism should be) but rather to the reduction in the occurrence rate of amplitude transients that in the Aeolian Islands are associated with ship activities. Finally, we added a reference, confirming that during the first period of COVID-19 pandemic marine traffic was affected by a dramatic decrease at the global scale, as well as ship traffic data of Lipari port, that correlate fairly well with seismic noise variations in ILLI station.

Seismic evidence of the COVID-19 lockdown measures: a case of study from Eastern Sicily (Italy)

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Abstract. During the COVID-19 pandemic, most countries put in place social interventions, restricting the mobility of citizens, to slow the spread of the epidemic. Italy, the first European country severely impacted by the COVID-19 outbreak, applied a sequence of progressive restrictions to reduce human mobility from the end of February to mid-March 2020. Here, we analysed the seismic signatures of these lockdown measures in the densely populated Eastern Sicily, characterised by the presence of a permanent seismic network used for earthquake and volcanic monitoring. We emphasize how the anthropogenic seismic noise decrease is visible even at stations located in remote areas (Etna and Aeolian Islands) and the amount of this reduction (reaching ~50-60%), its temporal pattern and spectral content are strongly station-dependent. Concerning the latter, we showed that on average the frequencies above 10 Hz are the most influenced by the anthropogenic seismic noise. We found similarities between the temporal patterns of anthropogenic seismic noise and human mobility, as quantified by the mobile phone-derived data shared by Google, Facebook and Apple, as well as by ship traffic data. These results further confirm how seismic data, routinely acquired worldwide for seismic and volcanic surveillance, can be used to monitor human mobility too.

1. Introduction

During the end of 2019, several cases of pneumonia, due to the novel coronavirus SARS-CoV-2, were identified in the city of Wuhan, China (Wang et al., 2020a). The disease due to this coronavirus, called COVID-19, then rapidly spread from China to other areas, as a pandemic wave (as declared by the World Health Organisation, WHO, in March 2020) currently affecting 216 countries with almost 14,300,000 confirmed cases (at the time of writing 21 July 2020; WHO, 2020). COVID-19 is considered the most severe global health crisis of our time and the greatest challenge human beings have faced since world war II (WHO, 2020).

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While huge efforts are being made to find pharmacological cures to heal the sick and to stop the spread of the disease (e.g. Cannata et al., 2020a; Graham, 2020; Wang et al., 2020b), most countries worldwide put in place social interventions, consisting of restricting the mobility of citizens, aimed at slowing and mitigating the epidemic (Pepe et al., 2020). Italy was the first country in Europe to be severely impacted by the COVID-19 pandemic wave at the end of February – onset of March 2020. Hence, Italy was also the first European country to apply a sequence of progressive restrictions to reduce both human mobility and human-to-human contacts. Restrictions were first implemented on 23 February 2020 in some regions of Northern Italy (Lombardy, Emilia-Romagna, Veneto, Friuli-Venezia Giulia, Piedmont, and Autonomous Province of Trento). On 11 March, the entire country was put under lockdown (Gatto et al., 2020) up to May, when the restrictions were gradually lifted.

To provide information about the effectiveness of the quarantine measures during COVID-19 emergency, Apple, Facebook and Google made available mobility data, mostly based on mobile phone locations, for almost every country in the world (Apple, 2020; Facebook, 2020; Google, 2020). At the same time, different studies showed the effectiveness of seismic noise monitoring as a tool to quantify human activity and its changes over time (Dias et al., 2020; Hong et al., 2020; Lindsey et al., 2020; Lecocq et al., 2020; Poli et al., 2020). Indeed, the Earth is continuously vibrating due to a wide spectrum of elastic energy sources including tectonic forces (Stein and Wysession, 2003), volcanic processes (Chouet and Matoza, 2013), ocean (Cannata et al., 2020b) and human (Diaz et al., 2017) activity. As for the latter, it typically generates a high-frequency continuous signal (> 1 Hz), called anthropogenic or cultural seismic noise, associated with phenomena such as traffic, construction, industrial operations and mining (Diaz et al, 2017; Hong et al., 2020). Recent papers identified clear seismic signatures of the lockdown measures applied by different countries (Lindsey et al., 2020; Lecocq et al., 2020; Piccinini et al., 2020; Poli et al., 2020; Xiao et al., 2020). For instance, Lindsey et al. (2020) showed a 50% decrease in vehicle count in Palo Alto area (California) immediately following the lockdown order by using fiber-optic distributed acoustic sensing connected to a telecommunication cable. Lecocq et al. (2020) performed a global-scale analysis of anthropogenic seismic noise using hundreds of seismometers located around the world, which evidenced how the 2020 lockdown period has produced the longest and most dramatic global anthropogenic seismic noise reduction on record. Poli et al. (2020) and Piccinini et al. (2020) analysed the anthropogenic seismic noise reduction following the lockdown for the Northern Italy area and its socio-economic implications.

In this work, we analyse the seismic signatures of the lockdown measures in the highly populated Eastern Sicily (Italy), which benefits from the presence of a dense permanent seismic network used for both seismic and volcanic monitoring. Hence, this is the first study to show the effects of uniform lockdown measures in the seismic noise acquired by a so dense seismic network. In particular, we investigate the decrease in the anthropogenic seismic noise amplitude, characterise its spectral content, and compare the observed changes with mobility data.

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2. Materials and methods

2.1 Data

The seismic data was recorded by 18 stations, located on the Eastern part of Sicily and belonging to the seismic permanent network, run by Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (INGV-OE) (Table 1, Figures 1 and A1). These stations, selected both for the good data continuity and the even spatial distribution on the investigated area, are equipped with broadband (40 s cutoff period), 3-component Trillium Nanometrics™ seismometers, acquiring at a sampling rate of 100 Hz. The stations are installed in shallow vaults (depth ~1.5 m) made of concrete, and show very different site conditions in terms of possible sources of anthropogenic seismic noise; some are close to towns, highways or industrial plants, others near agricultural areas, others in small islands or on the flanks of Mt. Etna volcano (see Table 1). The analysed time interval was 1 November 2019 – 23 May 2020.

Table 1. List of the seismic stations used in this work, with information about location and site conditions in terms of possible sources of anthropogenic seismic noise.

Station name	Latitude (degree)	Longitude (degree)	Altitude (m a.s.l.)	Site conditions
AIO	37.9713	15.233	794	close to small towns and a few roads
CAGR	37.622	14.4999	548	close to small towns, a few roads and agricultural areas
EFIU	37.7896	15.2103	97	close to towns, roads and highway
EMFS	37.7196	14.9979	2507	on the flank of Mt. Etna, close to country roads
ESAL	37.7551	15.1345	768	close to small towns and a few roads
ESML	37.6181	14.8794	408	close to towns and roads
ESPC	37.6925	15.0274	1655	on the flank of Mt. Etna, close to country roads
HAGA	37.2858	15.1552	176	close to town, roads and industrial plants
HLNI	37.3486	14.8719	133	close to towns, roads, agricultural areas and industrial plants
HPAC	36.7085	15.0372	70	close to small towns, roads and agricultural areas
HSRS	37.0928	15.222	100	close to towns, roads, highway and industrial plants
IFIL	38.5642	14.5753	269	on an island, close to a port
ILLI	38.4457	14.9482	277	on an island, close to a port
ISTR	38.7867	15.1918	114	on an island, close to a port
IVCR	38.4096	14.961	172	on an island, close to a port

MSFR	38.0339	14.5916	723	close to small towns and a few roads
MSRU	38.2639	15.5083	401	close to small towns and a few roads
MUCR	38.043	14.8739	1042	close to small towns and a few roads

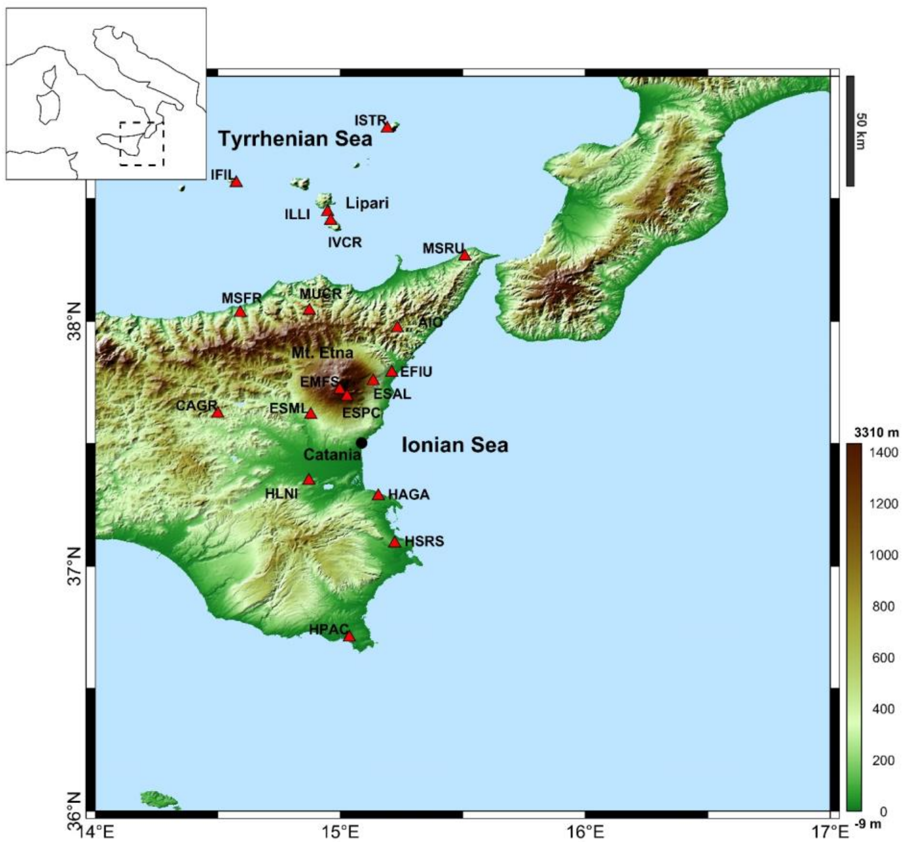

Figure 1. Map of the Eastern Sicily with the location of the seismic stations (red triangles) used in this work. **The top left panel shows where the area is located in Italy. Map was drawn by using NASA Shuttle Radar Topography Mission (SRTM) data and readhgt.m Matlab® function (Beauducel, 2020).**

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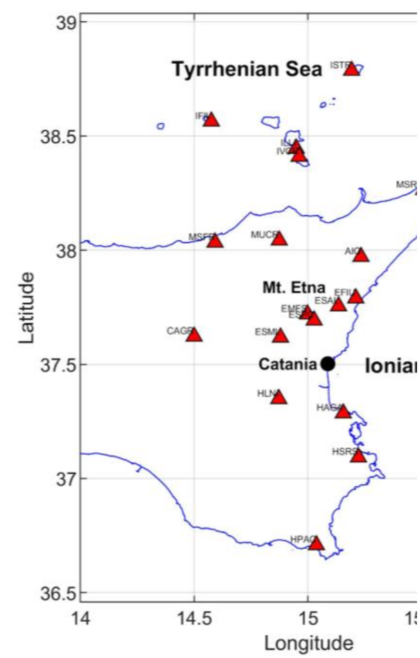

2.2 Spectral and amplitude analysis

Both spectral and amplitude analyses were carried out to characterise the temporal variations of the seismic noise features. As for the former, the daily spectra of the vertical component of the seismic signal were calculated by using Welch's method (Welch, 1967) with windows of 81.92 seconds. All the daily spectra were gathered and visualized as spectrograms, with time on the x-axis, frequency on the y-axis, and power spectral density (PSD) indicated by a color scale (Figure 2). It is worth noting that the sharp decrease in the spectral amplitude, evident at frequencies above 40 Hz, is due to the digitizer anti-aliasing filter. Hence, the following analyses have been performed at frequencies up to 40 Hz.

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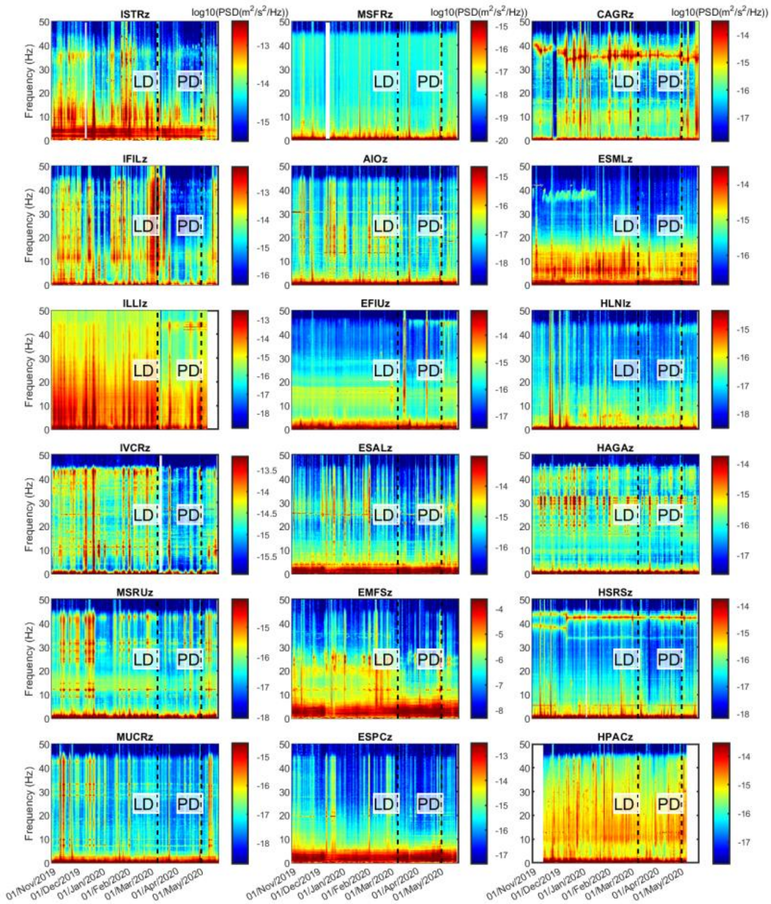
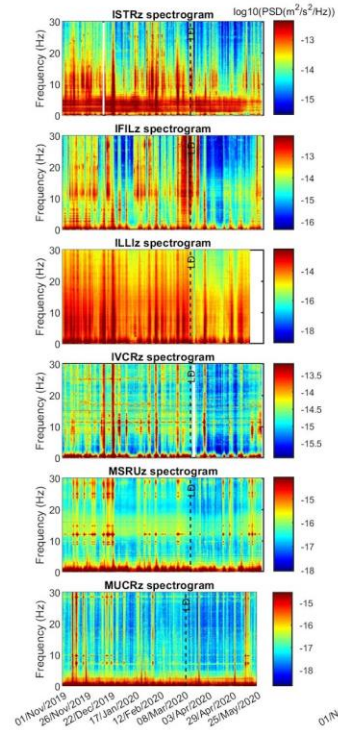


Figure 2. Spectrograms of the vertical component of the seismic signals. The vertical dashed lines and the labels "LD" and "PD" indicate the times when the national lockdown measures were implemented in Italy (11 March 2020) and when first Presidential Decree, slightly releasing the lockdown measures, was issued (4 May 2020), respectively. The stations are sorted by decreasing latitude from upper left to bottom right.



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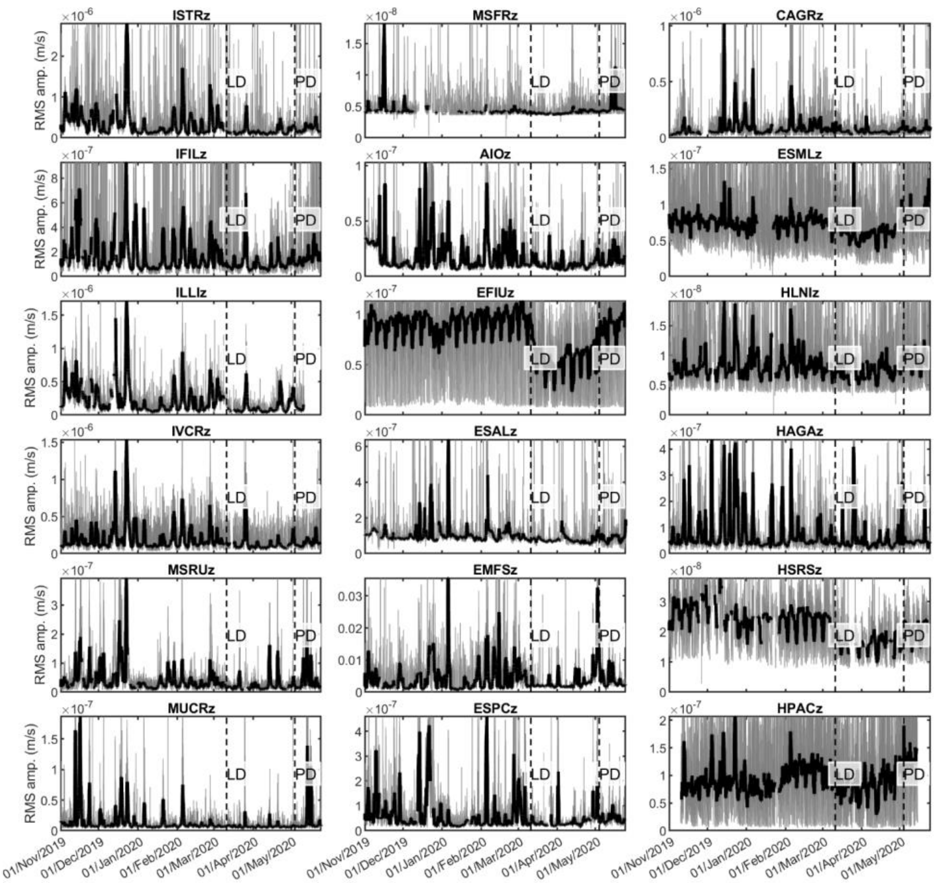
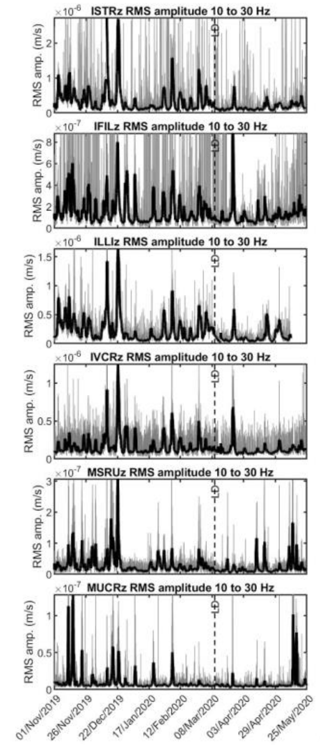


Figure 3. RMS amplitude time series of the vertical component of the seismic signals, filtered in the band 10-40 Hz (grey line) and corresponding moving median computed on 1-day-long sliding windows (thick black line). The vertical dashed lines and the labels "LD" and "PD" indicate the times when the national lockdown measures were implemented in Italy (11 March 2020) and when first Presidential Decree, slightly releasing the lockdown measures, was issued (4 May 2020), respectively. The stations are sorted by decreasing latitude from upper left to bottom right.



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Concerning the amplitude analysis, the time series of the root mean square (RMS) amplitude of the seismic signal, filtered in the band 10-40 Hz, were obtained on 15-minute-long sliding windows (Figure 3). This frequency band was chosen because, as it will be shown in the section 3, it is the most influenced band by the anthropogenic seismic noise. To visually show the general temporal pattern of the seismic noise amplitude in Eastern Sicily, the RMS amplitude time series were averaged on 3-day-long sliding windows, normalised, gathered and represented by a colored checkerboard plot (Figure 4). To make the changes of the noise background level as clear as possible in the checkerboard plot, the normalization was performed by: i) setting all the values greater than the 90th percentile, equal to the 90th percentile, ii) subtracting the minimum value, and iii) dividing by the maximum value. In addition, the percentage change in seismic RMS amplitude in the band 10-40 Hz in the period 11 March - 11 April 2020 was calculated by using the RMS amplitude during 20 January - 20 February 2020 as baseline (Figure 5).

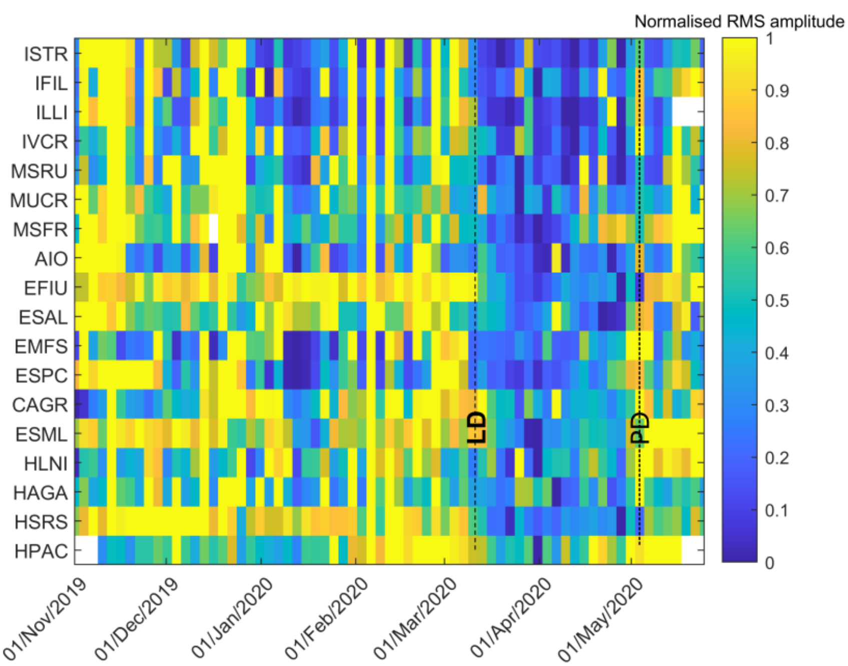

Figure 4. Temporal changes of the normalised seismic RMS amplitude at 18 seismic stations sorted by decreasing latitude (see labels close to the left y-axis). Data gaps are coloured white. The vertical dashed lines and the labels "LD" and "PD" indicate the times when the national lockdown measures were implemented in Italy (11 March 2020) and when first Presidential Decree, slightly releasing the lockdown measures, was issued (4 May 2020), respectively.

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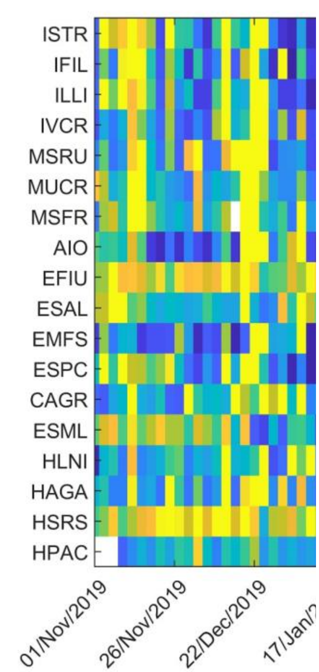

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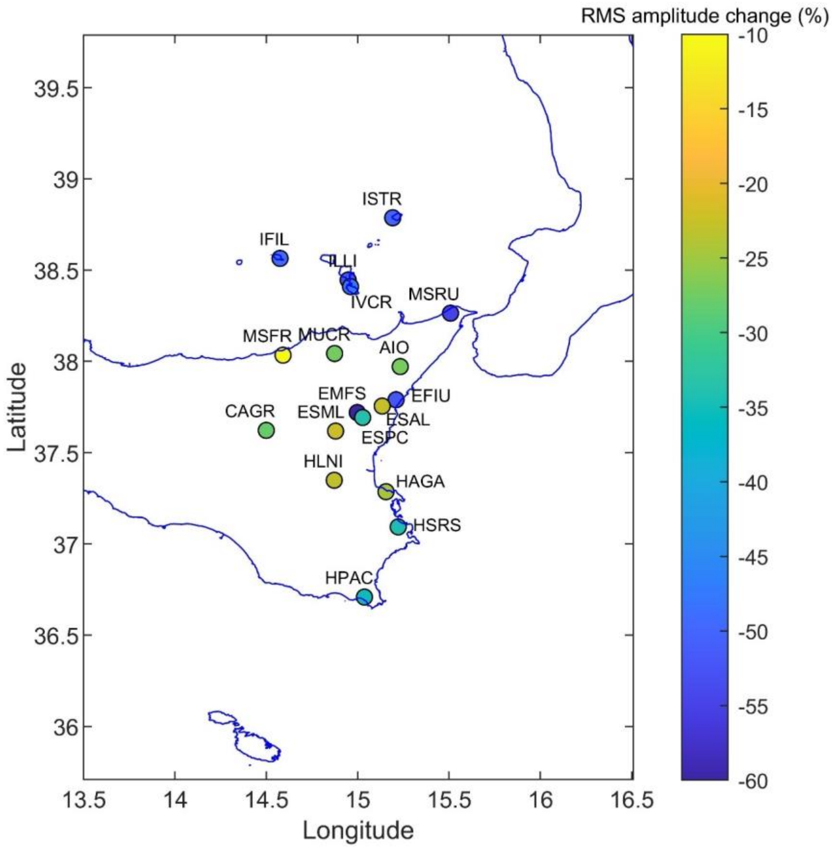

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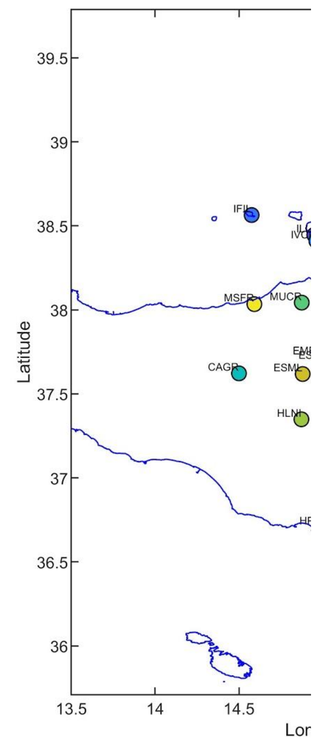

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Figure 5. Percent change of seismic RMS amplitude in the band 10-40 Hz during the period 11 March - 11 April 2020 (right after the lockdown measures entered in force) with respect to the interval 20 January - 20 February 2020.

Finally, to highlight the frequency band showing the most evident amplitude changes due to the lockdown, two 20-day-long time windows, extracted before (1-20 February) and during (11 March – 1 April) the lockdown, were considered. Two average spectra, representing the seismic spectral content before and during the lockdown, were computed on the two windows, and, successively, a ratio between them was calculated (Figures 6 and 7). All the ratios were stacked and the result is shown in Figure 8.

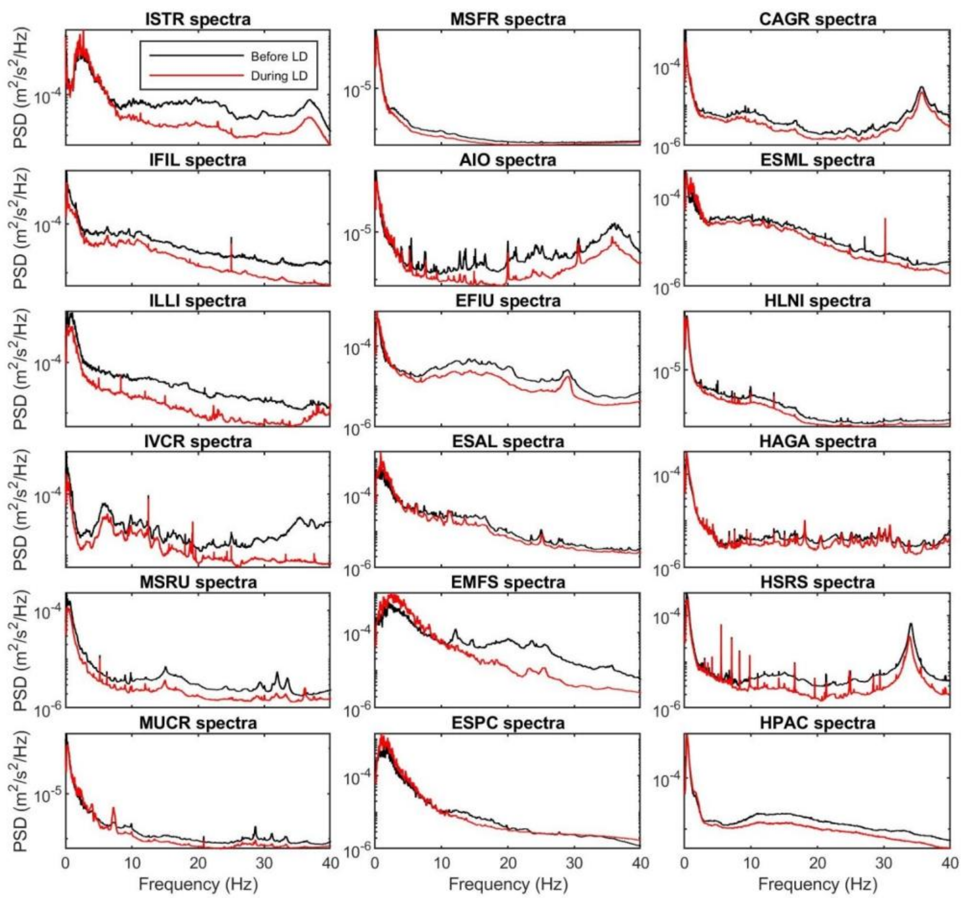
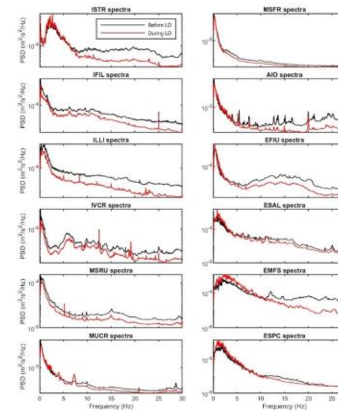


Figure 6. (a) Spectra of the vertical component of the seismic signals recorded during two 20-day-long time windows, extracted before (black line; 1-20 February) and during (red line; 11 March – 1 April) the lockdown. The stations are sorted by decreasing latitude from upper left to bottom right.



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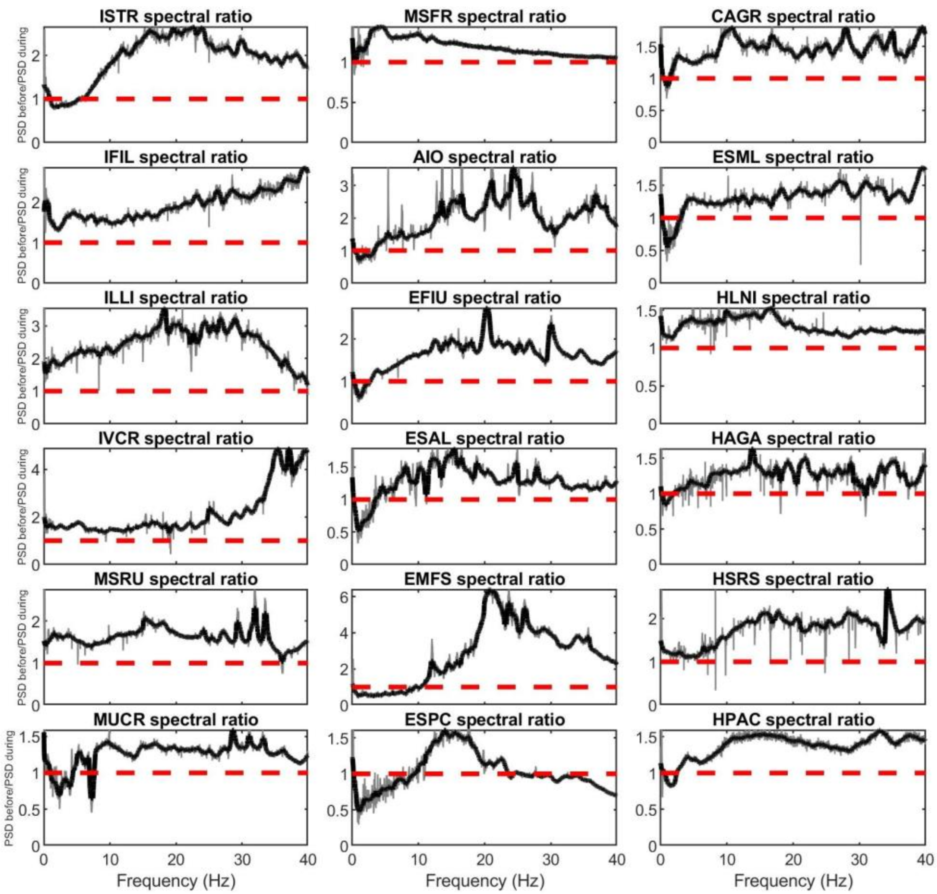
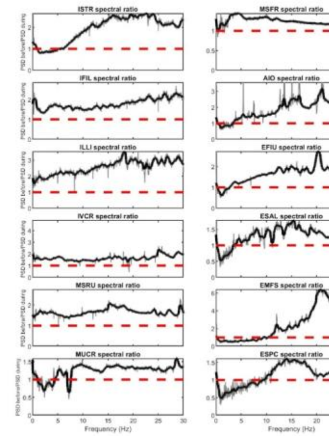


Figure 7. Ratios between the spectra of the vertical component of the seismic signals, recorded during two 20-day-long time windows, extracted before (1-20 February) and during (11 March – 1 April) the lockdown (grey lines; see Figure 6) and corresponding moving median over 0.6 Hz (black thick line). The red horizontal dashed lines indicate ratio values equal to 1. The stations are sorted by decreasing latitude from upper left to bottom right.



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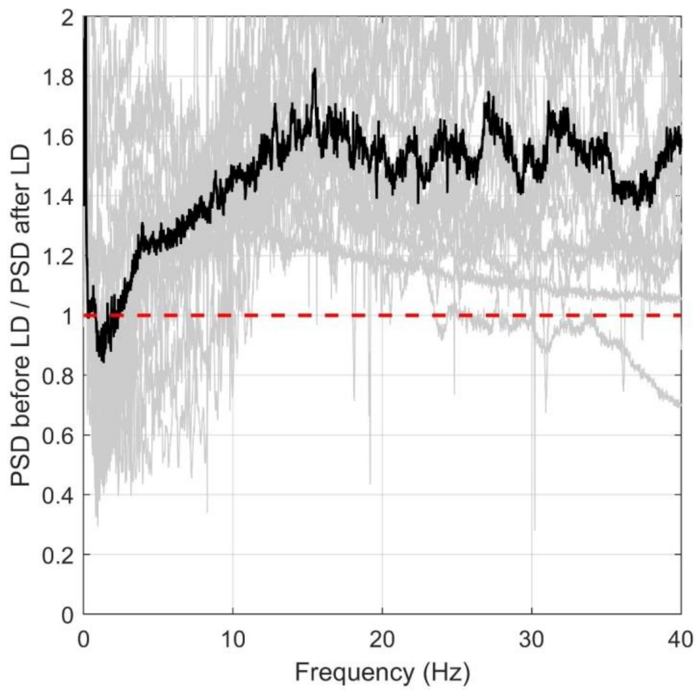

Figure 8. Ratios between the spectra computed before and during the lockdown (grey lines; see Figure 7) and the corresponding stacked ratio (black line). The red horizontal dashed line indicates a ratio value equal to 1.

2.3 Comparison with mobility data

Google, Apple and Facebook made human mobility data available for almost every country worldwide as support for public health policy during the COVID-19 crisis. For our study area, Google and Facebook provided aggregated data for the Sicily region, Apple shared data for Catania City, which is the main city in Eastern Sicily (Figure 1). The Google community mobility corresponds to the percentage of change relative to a baseline defined as the median value of the corresponding day of the week, during the period 3 January – 6 February 2020. The data are structured in categories to group some of the places with similar characteristics: grocery stores and pharmacy, parks, transit stations, retail and recreation places, residences and workplaces (Google, 2020). Apple shared information about the percent change of public's walking and driving compared with

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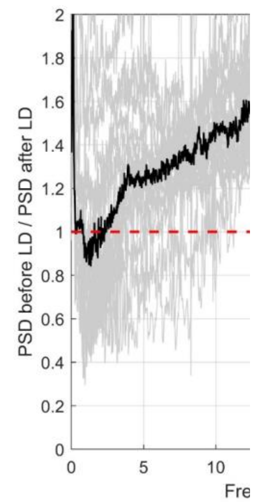

the baseline value from the 13 January (Apple, 2020). Finally, Facebook provided data regarding the human movement percent changes measured throughout March, April, and May 2020 relative to a baseline value in February (Facebook, 2020).

To understand how much the seismic noise could reflect the society mobility level, a preliminary visual comparison between time series of the seismic RMS amplitude and the corresponding above mentioned community mobility data was performed (Figure 9a). Then, to quantify the similarity, a correlation analysis was performed. In place of using the more common Pearson correlation coefficient, we made use of the Spearman correlation coefficient, allowing to compare series which do not have a normal distribution, as well as to explore nonlinear relationships (e.g. Craig et al., 2016; Cannata et al., 2019). To identify the frequencies that better correlate with the human mobility data, we performed the correlation analysis between all the time series of seismic RMS amplitudes, filtered in narrow bands (bandwidth = 1Hz, 4th order Butterworth filter; Lyons, 2004) around the integer frequencies between 1 and 40 Hz, and the community mobility datasets provided by Google, Apple and Facebook. Successively, we computed an average value of the Spearman correlation coefficients of all the stations per each frequency band (Figure 9b). In addition, to show how the correlation changes at the different considered stations, the Spearman correlation coefficient was calculated between the seismic RMS amplitude time series of each station in the 10-40 Hz range and the community mobility datasets (Figure 10). To verify if the obtained Spearman correlation coefficients are significantly different from zero or not (null hypothesis), the t-test was performed and the p-value (probability value) was calculated (Figure A3). p-values lower than the significance level of 0.05 were considered sufficient to reject the null hypothesis. Such a value, which means that the probability that the result of the statistical test is due to chance alone is less than 5%, is a commonly accepted threshold for this statistic test (e.g. Anthony et al., 2017).

In addition, since some seismic stations are located on the Aeolian Islands (ISTR, IFIL, ILLI, IVCR), we took into account ship traffic data from Lipari port (~2.7 km from ILLI station; see Figure 1), provided by FleetMon.com, containing information about the daily number of port calls of all the boats, as well as each boat category (passenger, highspeed, tanker, cargo and yacht) and their gross tonnage. All these data were compared with the seismic RMS amplitude time series of ILLI station in the 10-40 Hz band again by Spearman correlation coefficient (Figure 11a-d). As the only parameters showing p-values lower than 0.05 were the overall daily gross tonnage and the daily number of port calls of tanker, the frequency dependence analysis shown above was repeated on these two time series (Figure 11e).

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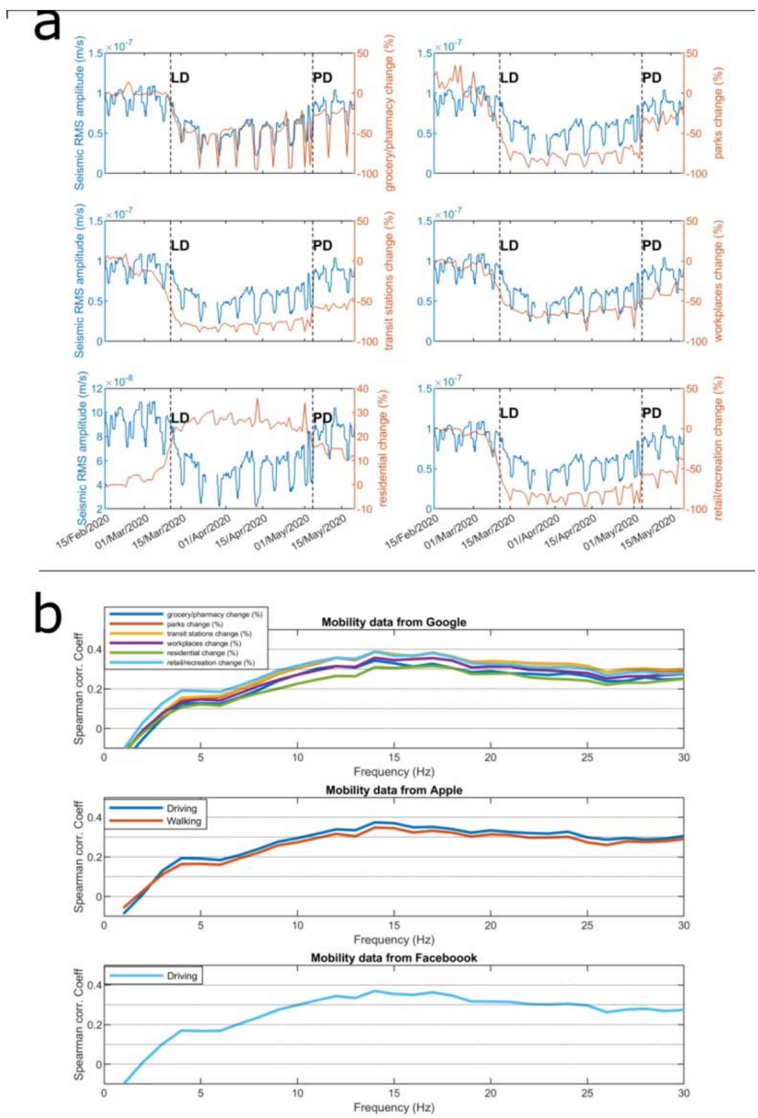

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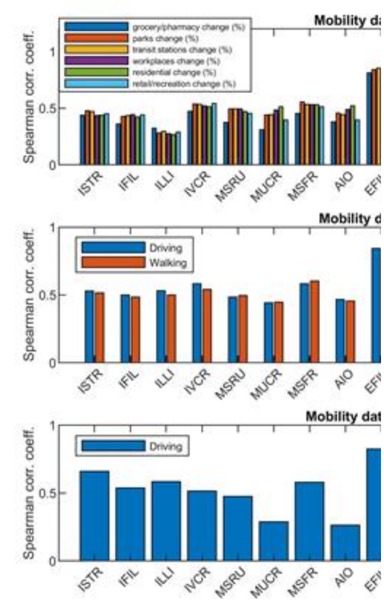

Figure 9. (a) Time series of RMS amplitude of the vertical component of the seismic signal recorded by EFIU station and filtered in the band 10-40 Hz (blue line) and the different categories of human mobility as provided by Google (red line). The vertical dashed lines and the labels “LD” and “PD” indicate the times when the national lockdown measures were implemented in Italy (11 March 2020) and when first Presidential Decree, slightly releasing the lockdown measures, was issued (4 May 2020), respectively. (b) Spearman correlation coefficient, calculated between seismic RMS amplitude at the different stations and the mobility parameters, as a function of the frequency band of the seismic noise. The Spearman correlation coefficient obtained for the residential change (top plot in (b)) was multiplied by -1 to make it positive.

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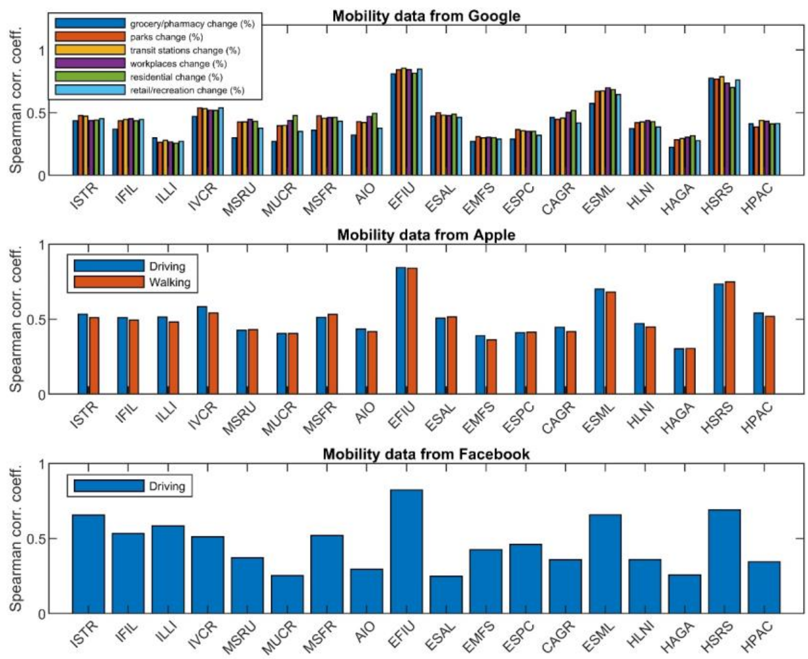

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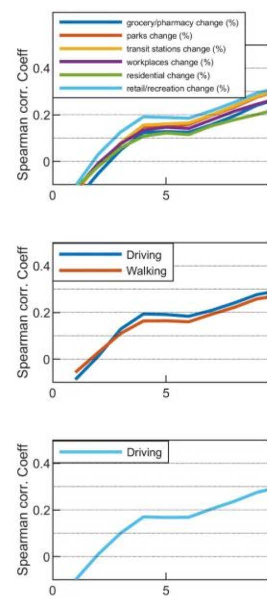

Figure 10. Spearman correlation coefficient calculated between seismic RMS amplitude at the different stations in the band 10-40 Hz and the mobility parameters, as provided by Google, Apple and Facebook. The Spearman correlation coefficient obtained for the residential change (see top plot) was multiplied by -1 to make it positive.

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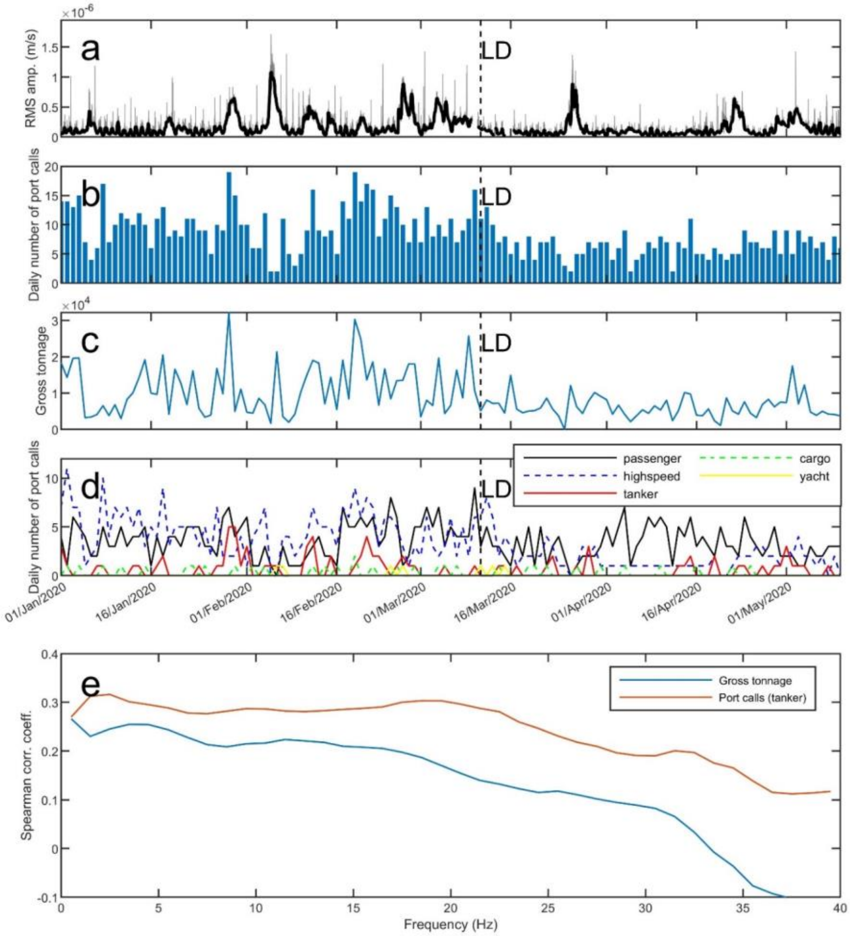

Figure 11. (a) RMS amplitude time series of the vertical component of the seismic signal, recorded by ILLI station and filtered in the band 10-40 Hz (grey line) and corresponding moving median computed on 1-day-long sliding windows (thick black line). (b) Daily number of port calls in the Lipari port. (c) Daily overall gross tonnage in the Lipari port. (d) Daily number of port calls in the Lipari port, separated on the basis of the boat category. (e) Spearman correlation coefficient, calculated between seismic RMS amplitude at ILLI and two ship traffic parameters (see the legend in the upper right corner), as a function of the frequency band of the seismic noise. The vertical dashed line and the label "LD" in (a-d) indicate the time when the national lockdown measures were implemented in Italy (11 March 2020).

3. Results and discussion

The seismic data, collected by 18 stations located in Eastern Sicily during 1 November 2019 – 23 May 2020, was analysed. The spectrograms show a wide variety of spectral features, as well as their variability over time (Figure 2). Some stations show broad spectra with significant amplitude up to 30-40 Hz (such as ISTR and IVCR), others narrower spectra with almost no energy above 10 Hz (such as MSFR and ESPC). In addition, very stable spectral peaks are evident in some stations (such as IVCR, ESAL and HAGA) probably due to continuously active seismic noise sources. More interestingly, a general reduction in the amplitude of seismic noise at all the stations, even at the ones located in remote areas such as Mt. Etna flanks and the Aeolian Islands, is observed following the enforcement of lockdown measures (on 11 March 2020; Figures 2-5). However, the amount of reduction, as well as the pattern of the investigated seismic RMS amplitude time series varies significantly in function of the station considered. For instance, the stations located close to towns and infrastructures such as busy roads, highways, industrial plants and agricultural areas (EFIU, ESML, HSRS, HPAC; Table 1), show the typical temporal pattern of the anthropogenic seismic noise with minima during the weekends and the night-time, and maxima during the weekdays and the day-time (Figure A4; Lecocq et al., 2020; Xiao et al., 2020). Focusing on the frequency band 10-40 Hz, the amplitude noise reduction due to the lockdown measures reaches ~50% at EFIU station (Figure 5), which also shows a slight amplitude decrease (~10%) during the Christmas - New Year holidays. This station is close to towns, as well as to a busy highway called A18 (Figure A1 and Table 1). Other stations show less regular patterns with clear peaks interspersed throughout the time series, whose origin depends also in this case on the station considered. In the stations located in the Aeolian Islands (ISTR, ILLI, IVCR, IFIL), the peaks are closely related to the ships rather than to road traffic or industrial activities (Figure A1 and A5, Table 1). The amplitude and rate of occurrence of those peaks also clearly decreased right after the implementation of the lockdown measures. Indeed, after March 2020 marine traffic was affected by a dramatic decrease at the global scale, that was particularly marked in the Mediterranean Sea (March et al., 2020; Figure 11b-d). Overall, the reduction in seismic noise in the band 10-40 Hz in the Aeolian Islands ranges between ~40% - 50% (Figure 5). At stations EMFS, ESPC, located on the flanks of Mt. Etna, the anthropogenic seismic noise is mostly related to tourists' excursions, as both stations are located close to country roads used to bring tourists to the top of the volcano (Figure A1 and Table 1). These excursions were suspended on 9 March following the COVID-19 outbreak, leading to a decrease in the seismic noise in the band 10-40 Hz of 30% and 60% for ESPC and EMFS, respectively (Figure 5). Some notable increases in seismic amplitudes, visible in more than one stations at the same time, are not caused by human activities but rather due to bad weather conditions. For instance, the amplitude increase on 25-26 March, visible at almost all the stations (Figures 2 and 3), was associated with bad weather conditions, which affected the whole Southern Italy. The amplitude of the anthropogenic seismic noise interestingly increased again at the end of April (Figures 3 and 4), a few days before the introduction of the first Presidential Decree, slightly releasing the lockdown measures (4 May 2020), and many days before the following Presidential Decree lifting those measures for many economic activities (18 May 2020).

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2.4 Effects on earthquake detection capability¶
The impact of the reduction of anthropogenic seismic noise during the lockdown period on the detectability of the earthquakes was analysed, by using the catalogue of the earthquakes automatically detected for the INGV-OE control room. The system, routinely applied at INGV-OE to monitor the mostly local seismicity in Eastern Sicily, is called *Kataloc* and uses the STA/LTA algorithm (short time average / long time average; Trnkoczy, 2012) to automatically pick the P seismic phases. The ability for this technique to detect amplitude transients in the real-time streaming of seismic data closely depends on the signal to noise ratio (e.g. Trnkoczy, 2012). The reduction of seismic noise during the lockdown period therefore motivated the analysis of its influence on the performances of this system. ¶
We emphasized this influence by plotting the number of automatically detected P seismic phases per earthquake versus the earthquake magnitude before the lockdown (from 1 November 2019 to 10 March 2020) and during the lockdown period (from 11 March to 15 May 2020). We then performed linear regressions on the two sets of data, made up of 287 and 119 earthquakes, respectively (Figure 11a). Finally, since the number of detected seismic phases is strongly affected by the number of properly working seismic stations, we repeated the same analysis by using a number of detected P phases corrected according to the operating state of the seismic network. The correction was performed by dividing the number of phases by the fraction of seismic data acquired by the network during the day when the earthquake took place, with respect to the data which would have been recorded in case of full operating state of the network (Figure 11b).¶
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As for the frequency content analysis, the spectral ratios show that the band characterised by anthropogenic seismic noise is strongly station-dependent (Figures 6 and 7). Indeed, the frequency with the maximum ratio value, coinciding with the frequency most affected by the anthropogenic noise, ranges from a few Hz (i.e. MSFR) to 20 Hz or even more (i.e. EFIU, ESML). Besides, the maximum ratio value, which indicates the amount of anthropogenic noise affecting the station, shows a fairly wide variability, from 1.5 (i.e. ESPC, HPAC) to 6 (EMFS). It is also noteworthy that some stations show a ratio lower than 1 at low frequencies (<5 Hz), indicating that the seismic amplitude was higher during the lockdown than before. The stations on or around Mt. Etna (ESPC, ESAL, EFIU, AIO, EMFS, ESML), as well as the station on Stromboli island (ISTR), exhibit this behaviour due to the increase of volcanic tremor amplitude in both volcanoes during the second analysed time window (11 March – 1 April) with respect to the first one (1-20 February). Indeed, Mt. Etna and Stromboli volcanoes are characterised by continuous volcanic tremor, with energy mainly radiated in the band ~0.5-5.5 Hz (e.g. Cannata et al., 2010; Falsaperla et al., 1998). In addition, the variability of the spectral ratio values below 1 Hz is not related to temporal changes in anthropogenic noise but rather to the variations in the amplitude of microseism, the most continuous and ubiquitous seismic signal on Earth, generated by ocean wave energy coupling with the Earth's ground (e.g. Longuet-Higgins 1950; Hasselmann, 1963; Ardhuin et al., 2015). Finally, the spectral ratio derived from stacking the spectral ratio plots of all the considered stations clearly shows that the frequency band most affected by the anthropogenic seismic noise (that is, the one showing the highest ratio values) is above 10 Hz (Figure 8).

Concerning the comparison between the time series of seismic noise and human mobility, these are positively correlated, suggesting that seismic noise amplitude increases with increasing human mobility, with the exception of the residential visit changes provided by Google (Figure A2). Indeed, this category quantifies the change in duration of time spent at places of residence, which, unlike the other categories, increased during the lockdown period. We obtained a wide range of Spearman correlation coefficients, whose absolute values range from 0.25 to more than 0.85 according to the considered station and mobility parameter (Figure 10). In particular, stations EFIU, ESML and HSRS, displaying the typical temporal pattern of the anthropogenic seismic noise with minima during the weekends and maxima during the weekdays, showed the highest correlation coefficients. The similarity between seismic noise and human mobility patterns is remarkably high at station EFIU characterized by correlation coefficients higher than 0.8 (Figures 9a and A2). For other stations (e.g. EMFS, HAGA, MUCR), the correlation is not as clear. However, even if the correlation between seismic noise and human mobility is strongly station-dependent, p-values lower than 0.05 were obtained in all the comparisons (Figure A3), suggesting how the obtained Spearman correlation coefficients are significantly different from zero. This confirms that seismic data from all the considered stations contain plenty of information about human mobility. The seismic noise frequencies better correlated with human mobility data turned out to be above 10 Hz (maximum values are reached in the band 11 - 18 Hz; Figure 9b). This result, in line with the information obtained by computing the ratios between the seismic spectra before and during the lockdown (Figure 8), shows how the seismic frequency band most affected by the human activities is above 10 Hz. As for the comparison between the time series of seismic noise at ILLI station in the band 10-40 Hz and ship traffic data of Lipari port, only daily overall gross tonnage

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and the daily number of port calls of tanker showed p-values lower than 0.05 (with Spearman correlation coefficients equal to 0.18 and 0.25, respectively). In this case, the seismic noise frequencies better correlated with ship traffic data were below ~25 Hz. This analysis, focused on ship traffic data, highlight how particular types of boats (likely the ones with higher gross tonnage, among which the tankers) are mainly responsible of the seismic noise generation recorded close to ports. In addition, the frequency band most affected by such a seismic noise seems to be different (in particular lower) from the band most influenced by the other human activities (see Figures 9b and 11e).

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Since the general reduction in the amplitude of seismic noise at all the stations in mid-March took place at the end of the winter - beginning of the spring and then when the meteorological conditions improved, such a decrease could also be interpreted as due to weather changes. Indeed, wind generates a broadband seismic noise with frequencies from ~0.5 Hz up to ~60 Hz (e.g. Bormann and Wielandt, 2013). However, we exclude such a possibility on the basis of: i) the increase of seismic noise amplitude, observed again at the end of April; ii) the correlation analysis results, that confirm how the amplitude reduction in mid-March is related to the decrease in human mobility.

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4. Conclusions

The amplitude reduction of the anthropogenic seismic noise, due to the lockdown measures restricting the mobility of citizens during the COVID-19 pandemic, gave the opportunity to investigate in detail the characteristics of such an anthropogenic signal in Eastern Sicily.

We emphasize how the seismic amplitude decrease is visible even at stations located in remote areas, such as Mt. Etna volcano and the Aeolian Islands. The amount of the amplitude reduction, its temporal pattern and spectral content proved to be strongly station-dependent. As for the former, we found decreases of 30-60% in most of the considered stations, located close to towns and busy highways, as well as on the flanks of Mt. Etna where country roads are used to bring tourists on the top of the volcano, or in the Aeolian Islands following to ship traffic reduction. Regarding the temporal patterns of seismic noise amplitude, the stations installed close to towns or infrastructures (like busy roads and highways) showed the typical pattern of the anthropogenic seismic noise with minima during the weekends and the night-time, and maxima during the weekdays and the day-time. Other stations show less regular patterns with clear peaks interspersed throughout the time series. Concerning the spectral content, the frequency band most affected by anthropogenic seismic noise ranges from a few Hz to more than 20 Hz, depending on the station. On average, the frequencies above 10 Hz are the most influenced by anthropogenic seismic noise. We found that human mobility influenced the seismic noise mostly in frequencies above 10 Hz with remarkably high correlations between them observed at some stations. Furthermore, the comparison between seismic noise data acquired at ILLI station (located in Lipari; Aeolian Islands) and ship traffic data from Lipari port highlighted a significant correlation,

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especially in case of ships with high gross tonnage. These results further confirm how seismic data, routinely acquired worldwide mainly for seismic and volcanic surveillance, can also be used to monitor human mobility, especially during emergency periods such as the COVID-19 pandemic. As highlighted by Lindsey et al. (2020), seismic data also present the advantages over mobile phone-derived information of being natively anonymous and not affected by biases due to data sampling according to socio-economic class, age and region.

Data availability

The data that support the findings of this study are available on request from the corresponding author.

Author contributions

A.C., F.C. and T. L. designed the study. All the Authors analysed the seismic data. A.C., F.C., R.D.P., G.D.G. wrote the paper. All the Authors interpreted the results and revised the article.

Competing interests

The authors declare that they have no conflict of interest.

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Appendix A: additional figures

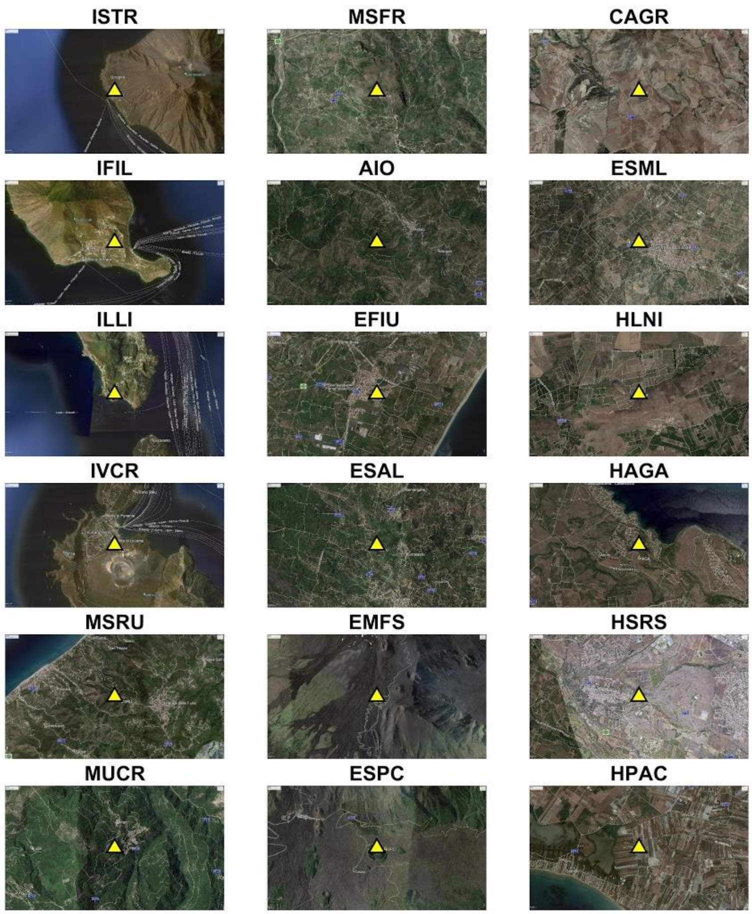

Figure A1. Photos from © Google Earth of the installation site areas of the seismic stations (yellow triangles) used in this work. The width of the area shown in each picture is ~5 km. The stations are sorted by decreasing latitude from upper left to bottom right.

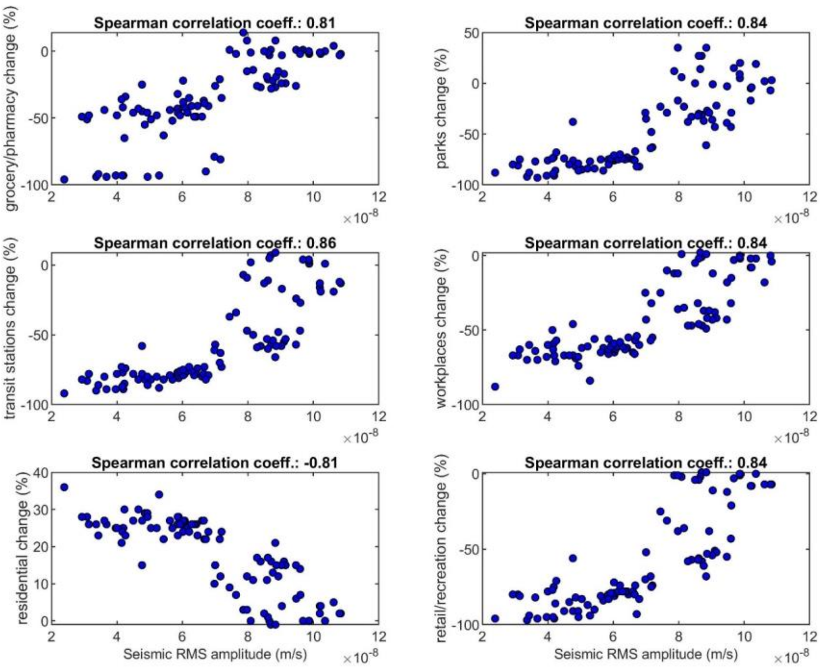

Figure A2. **Cross-plots showing the seismic RMS amplitude of EFIU station in the band 10-40 Hz in the x-axis and the different categories of human mobility from Google in the y-axis from 15 February to 20 May 2020. The values of the Spearman correlation coefficient, computed between the time series plotted in the graph, are shown in the title.**

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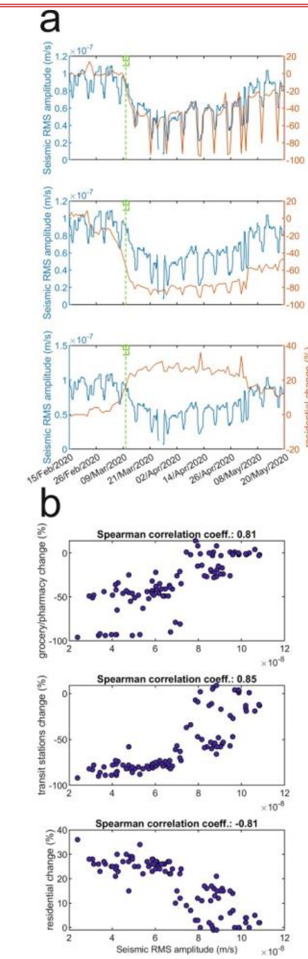

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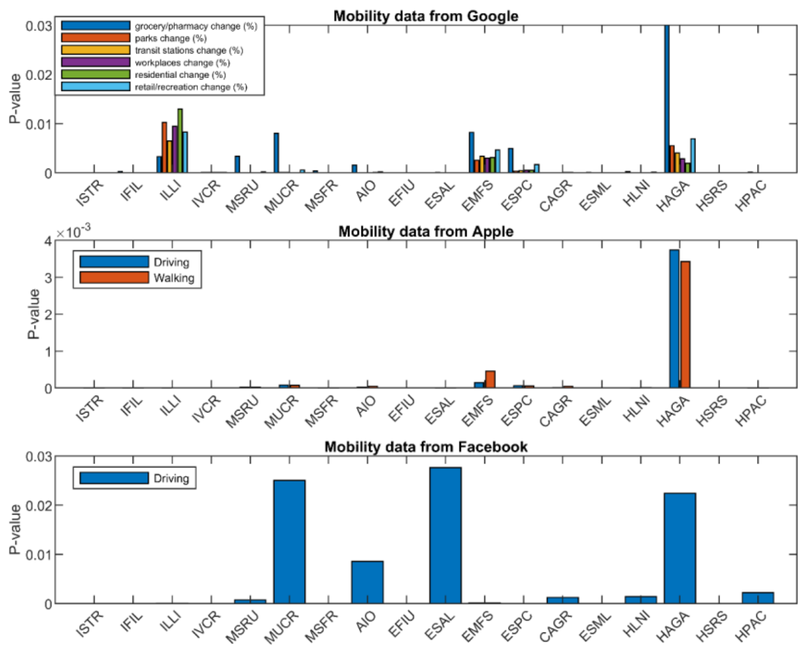
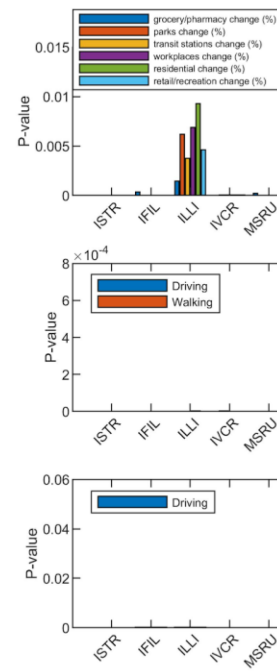


Figure A3. Probability values (p-values), obtained by the Spearman correlation analysis performed between seismic RMS amplitude at the different stations and the human mobility parameters, as provided by Google, Apple and Facebook.



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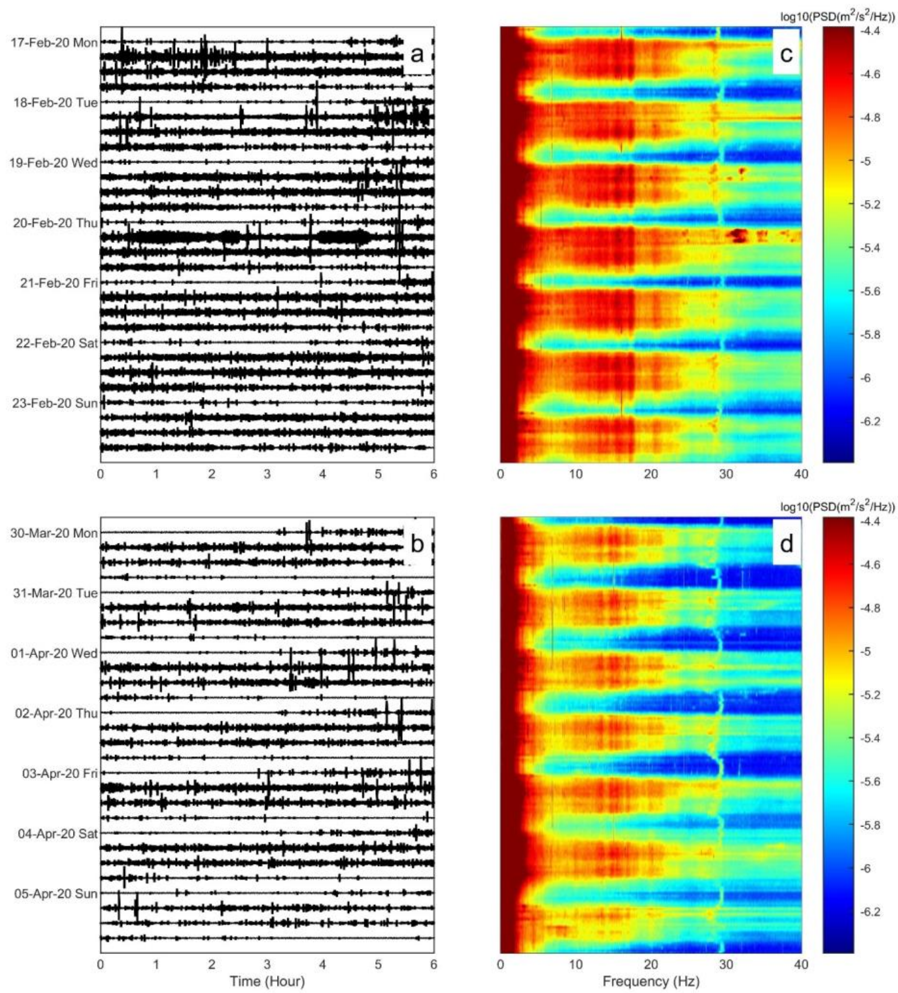
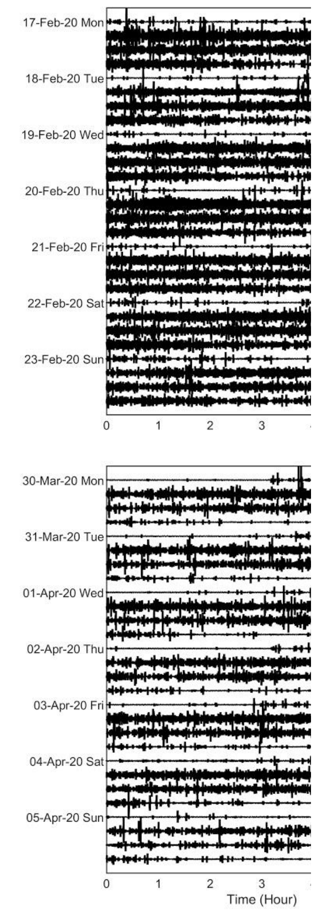


Figure A4. (a) Seismogram showing the seismic signal recorded by the vertical component of the station EFIU and filtered in the band 10-40 Hz during the week 17-23 February 2020 and (c) the corresponding spectrogram of the non-filtered signal. (b) Seismogram showing the seismic signal recorded by the vertical component of the station EFIU and filtered in the band 10-40 Hz during the week 30 March - 5 April 2020 and (d) the corresponding spectrogram of the non-filtered signal.



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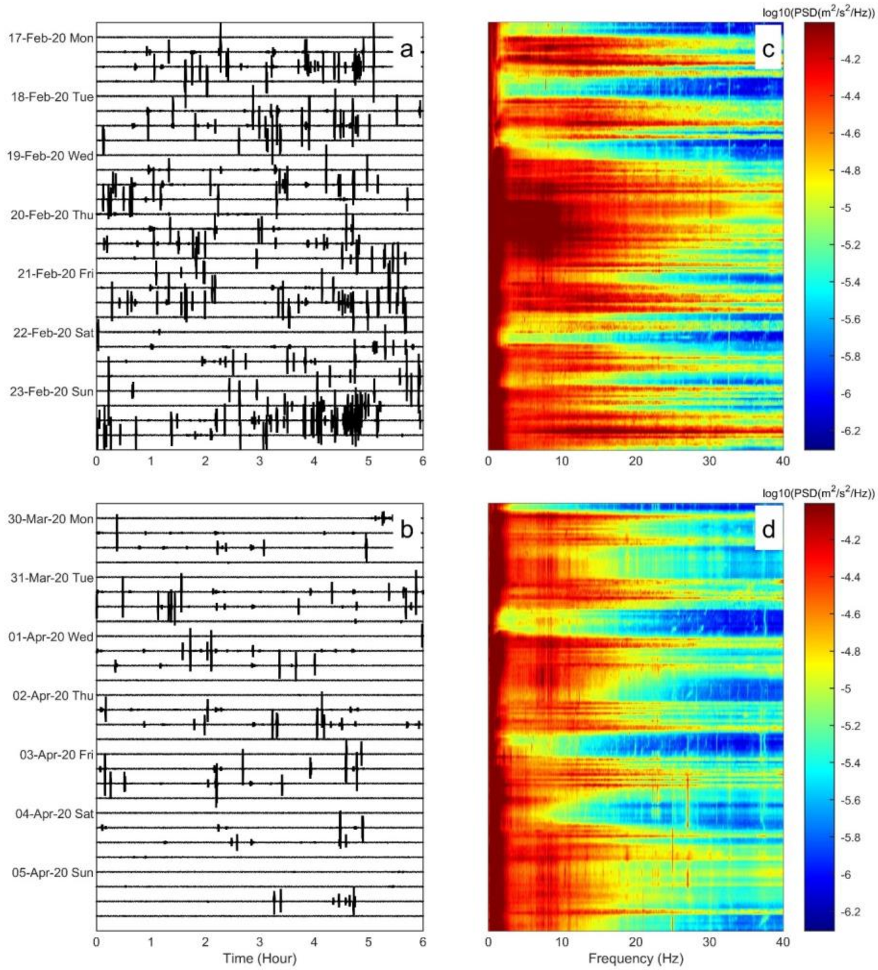
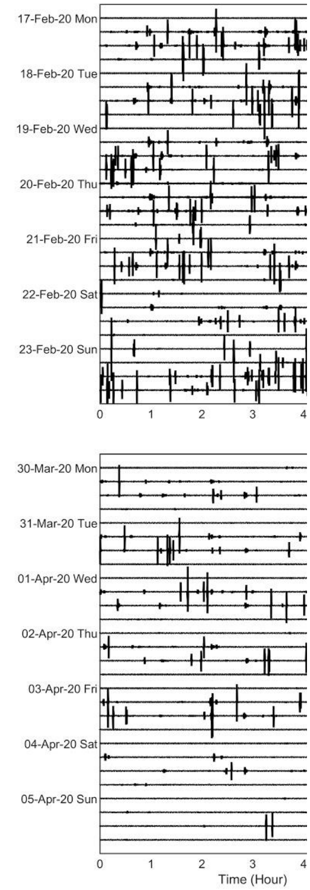


Figure A5. (a) Seismogram showing the seismic signal recorded by the vertical component of the station ILLI and filtered in the band 10-40 Hz during the week 17-23 February 2020 and (c) the corresponding spectrogram of the non-filtered signal. (b) Seismogram showing the seismic signal recorded by the vertical component of the station ILLI and filtered in the band 10-40 Hz during the week 30 March - 5 April 2020 and (d) the corresponding spectrogram of the non-filtered signal.



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