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Societal Impact of COVID-19 Crisis on the Ambient Seismic Noise in Metropolitan France

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Abstract The COVID-19 pandemic led to restrictions on human mobility worldwide. In France, numerous phases of lockdowns and curfews were instituted in an attempt to limit the consequences of this pandemic. Through these various phases of restrictions, we analyzed changes in human activity based on the study of the ambient seismic noise level in metropolitan France. We propose a different approach to previous studies, investigating variations in seismic noise levels between the pandemic years 2020 and 2021, as well as the post-COVID-19 period (2022-2023), using 2019 as the prepandemic reference year. We focused our work between 4 and 8 Hz, where human-induced noise sources are significant. We took advantage of the wide instrumental coverage of metropolitan France to distinguish the effects of restrictions in urbanized and rural areas. Whether in urban or rural areas, the effects of lockdowns and curfews coincide with the reductions in seismic noise levels. The magnitude of the noise level reduction is greater for the first lockdown than for the last. We also observe a signature of curfew periods and analyze variations according to time of day and day of the week. Changes in road traffic during lockdowns and curfews are shown to be a major factor contributing to observed variations in ambient seismic noise.

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1 Introduction

Numerous networks of permanent seismic stations spread across the globe now make it possible to continuously measure ground vibrations with great precision in a wide variety of contexts. The sources of these continuous vibrations are various and constitute a permanent background noise in seismic measurements (e.g. Nakata et al., 2019; Nishida, 2017; Brune and Oliver, 1959). The interaction of oceans with solid earth is an important continuous natural source in the 10-16 s (e.g. Hasselmann, 1963; Gualtieri et al., 2019) and 4-8 s (e.g. Longuet-Higgins and Jeffreys, 1950; Cessaro, 1994) period range. Human activities also contribute significantly. Road traffic, public transport, or machinery in factories contribute to ground vibrations, usually for frequencies above 1 Hz (e.g. McNamara, 2004; Coward et al., 2003; Díaz et al., 2017; Riahi and Gerstoft, 2015; Groos and Ritter, 2009).

In January 2020, the World Health Organization (WHO) declared a state of public health emergency of international concern due to the spread of the COVID-19 virus. This resulted in the implementation of strict sanitary measures to slow down the evolution of the pandemic around the world as described in the correspondence written by Cauchemez et al. (2020), leading to a sudden reduction in human activities throughout the world (Mofijur et al., 2021). Lecocq et al. (2020) studied the effects of this reduction in human activities on the evolution of seismic noise level on a global scale and observed a generalized decrease that could reach 50% at certain stations. Other studies have been carried out in more restricted areas, such as northern Italy (Poli et al., 2020), in Barcelona (Diaz et al., 2021), in Mexico city (De Plaen et al., 2021), in eastern Sicily (Cannata et al., 2021), or Romania (Grecu et al., 2021). They all observed a significant drop in seismic noise level during the first lockdown periods enforced in the studied area. These studies focus primarily on densely populated areas, where the effects of human activities are expected to be particularly significant.

In this study, we propose to look at the effects of government coercive measures (not only lockdown) on human activity between January 2020 and July 2021 at the scale of the entire permanent seismic network distributed throughout the territory of metropolitan France. The originality of this work lies in the numerous permanent stations in the area making it possible to study the evolution of seismic noise in a variety of contexts, in both rural and urban environments. To eliminate the usual variations in ambient seismic noise (night/day, weekend/week, school holidays, etc.), we work with relative variations compared to 2019,

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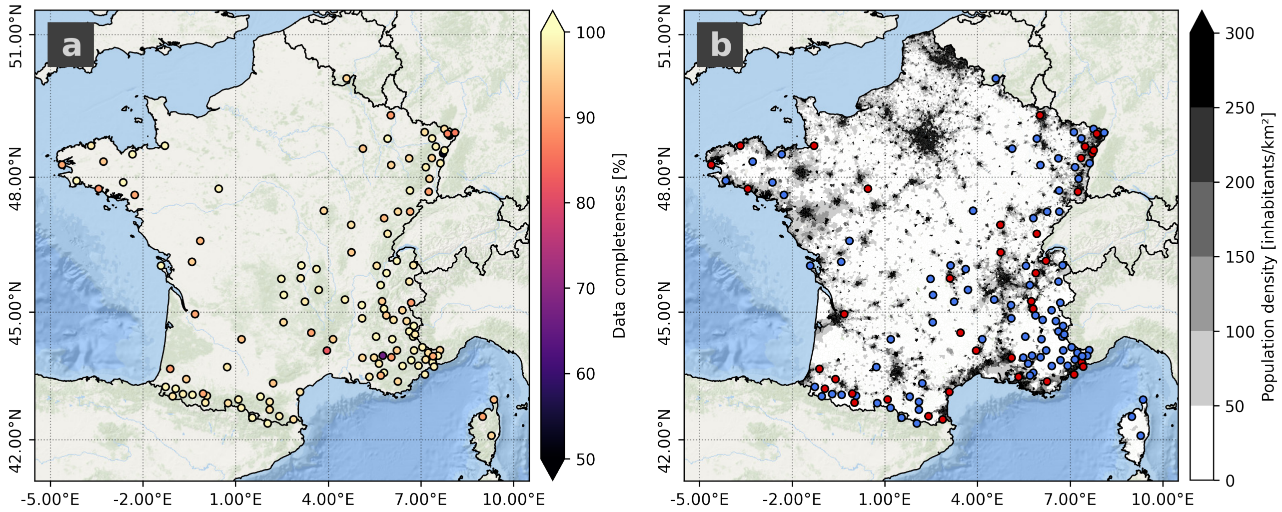

Figure 1 a) Location of the 127 stations used in this study with coloured dots representing the completeness of data between 01/01/2020 and 01/08/2021. b) Population density in metropolitan France. Coloured dots represent the 127 stations used in this study located either in urban (red dots) or rural (blue dots) environments.

before the COVID-19 pandemic, when there were no restrictive measures on human activities. Working with an entire network over this long period of time is intended to show the signature of the noise drop at the scale of a country over the various lockdowns and other restrictive measures and its recovery during the post-COVID period (2022-2023). In Section 2, we describe the ambient seismic noise datasets used for this study. Section 3 is dedicated to the overview of seismic noise variations during COVID-19 pandemic in metropolitan France and its hourly and daily evolution. In Section 4, we discuss the choice of the reference period, the origins of seismic noise variations in particular in terms of road traffic and the post-COVID-19 evolution.

2 Data and Methods

2.1 Seismological Network

In this study, we use data provided by the RESIF/EPOS-France research infrastructure through its FDSN webservices (https://ws.resif.fr) from permanent seismic stations in the French metropolitan area between 01/01/2019 and 01/08/2021. Those stations belong to the French permanent broadband network (Réseau large bande permanent - RLBP) that aggregates stations operated by regional observatories (FR, Epos-France, 1995), CEA/DASE (RD, RESIF, 2018), and GEOSCOPE (G, Institut de physique du globe de Paris (IPGP) and École et Observatoire des Sciences de la Terre de Strasbourg (EOST), 1982) networks. The RLBP network has been considerably densified in recent years to reach a more homogeneous distribution, with a higher density in the most active seismic regions (e.g., Alps, Pyrenees, Rhine graben, etc.), in order to better characterize the seismic hazard in France and to improve our knowledge on the deep structures. In this work, we take advantage of this densification to study the continuous seismological signal in various contexts, whether in urban areas or in environments more isolated from human activities. As is often the case, the choice of sites for the RLBP stations was a compromise between the sometimes conflicting constraints of geographic location, distance from the main sources of ambient noise, and ease of access to power and communications networks. As a result, some stations are located in very isolated areas, while others are close to human activities that generate ground vibrations. Only stations with at least 50% temporal coverage during the year 2019 and the period during the pandemic (01/01/2020 - 01/08/2021) were selected, representing a total of 127 stations illustrated in Figure 1a.

2.2 Population Density Data

To take into account the environment in which seismological stations are installed, we classified the stations into two categories: rural or urban. This classification is based on population density data for metropolitan France for the year 2020, publicly available from the Observatoire des Territoires (www.observatoire-des-territoires.gouv.fr), providing the population density of each town in France. This data is illustrated in Figure 1b. We define a station as urban when the population density exceeds 200 inhabitants per km² within a 5 km radius of the station. The results of this classification are illustrated in Figure 1b with a total of 41 urban stations and 86 rural stations.

2.3 Ambient Seismic Noise Processing

The processing of this velocimetric data is inspired by the work of Lecocq et al. (2020). Using Obspy (Beyreuther et al., 2010), we first correct from the instrumental response, remove the trend, and apply a taper on every one hour segment, overlapping over 30 minutes, and then compute the spectrum using the Fast Fourier Transform. We then compute the power spectral densities (PSDs) following McNamara (2004).

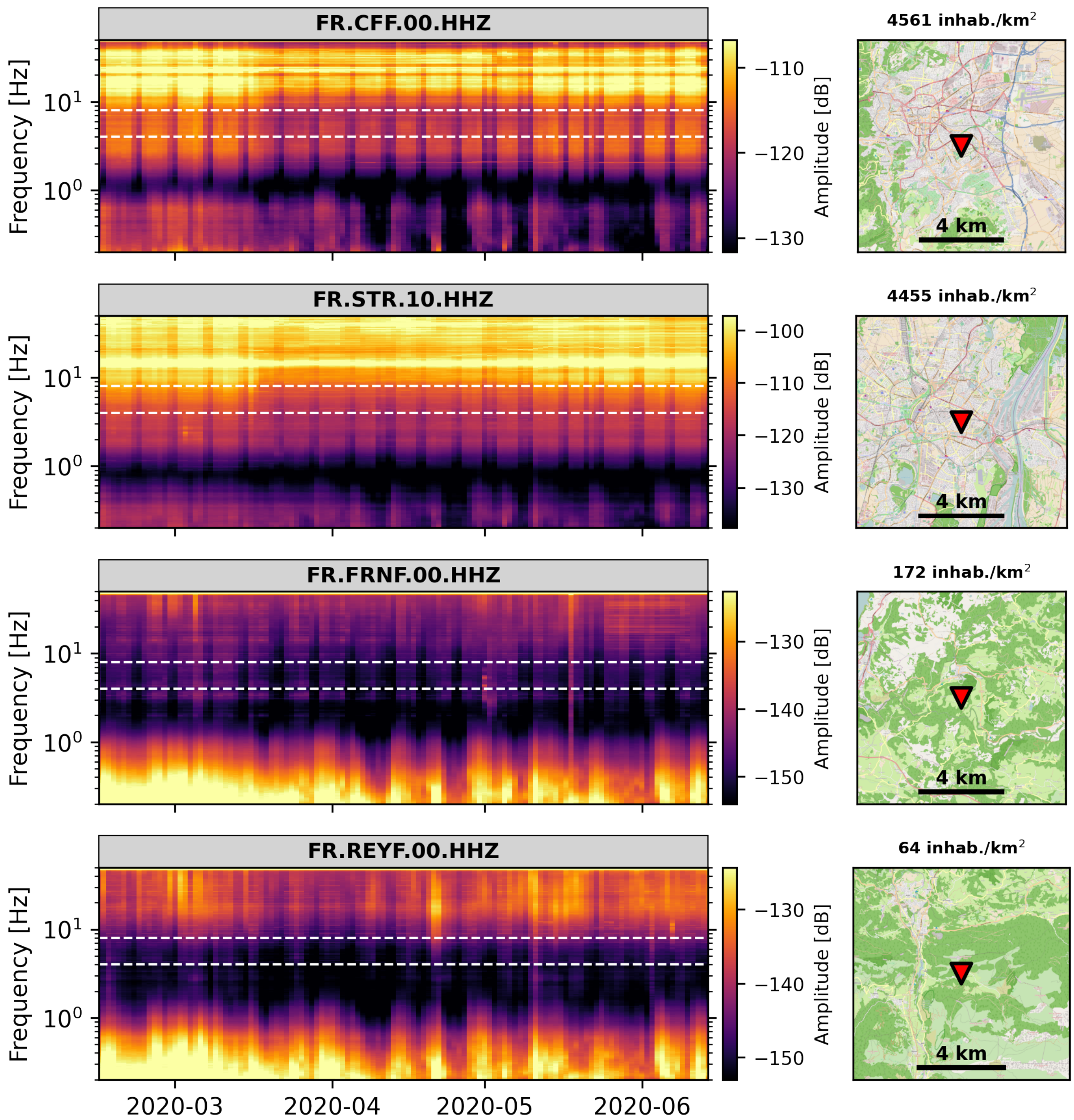

Figure 2 (Left) Spectrograms of stations located in urban (FR.CFF and FR.STR) and rural (FR.FRNF and FR.REYF) environments between February and July 2020. The two horizontal white dashed lines indicate the frequency band of this study (4 to 8 Hz). (Right) Map of the environment around the station (www.openstreetmap.fr). The station location is indicated by the red triangle. Population density near the station is mentioned above each map.

The Root Mean Square (RMS) displacement for each time window is estimated from the square root of the integral of the power spectrum. This procedure is applied to all the stations in the study.

The effect of human activities is known to usually be visible at frequencies above 1 Hz (e.g. McNamara, 2004), which correspond to noise induced, for example, by factories (e.g. Hong et al., 2020) and vehicles (e.g. Coward et al., 2003; Fuchs et al., 2018). Some studies use a frequency content between 4 and 20 Hz to emphasize human activities during the COVID-19 pandemic (e.g. Hong et al., 2020; Lecocq et al., 2020; McNamara, 2004). Here, we use data from stations sampled at 20, 100, 125 or 200 sps (samples per second). To avoid both aliasing effects and very local high-frequency sources in the vicinity of the stations, we set the upper frequency of the Butterworth filter at 8 Hz. To define the lower frequency, we analyzed the spectrograms of the various stations used. Some examples are shown in Figure 2, in both urban (top) and rural (bottom) contexts. For stations located in urban environments, anthropogenic imprints are particularly visible above 1 Hz, with a weekly drop in noise level during weekend days (Saturdays and Sundays). Weekly changes are more difficult to observe for stations located in rural environments, but are most of the time visible for frequencies above 4 Hz. To take into account the variety of contexts in which stations are installed, we have chosen a lower frequency of 4 Hz. The final frequency band is between 4 to 8 Hz and is indicated by white

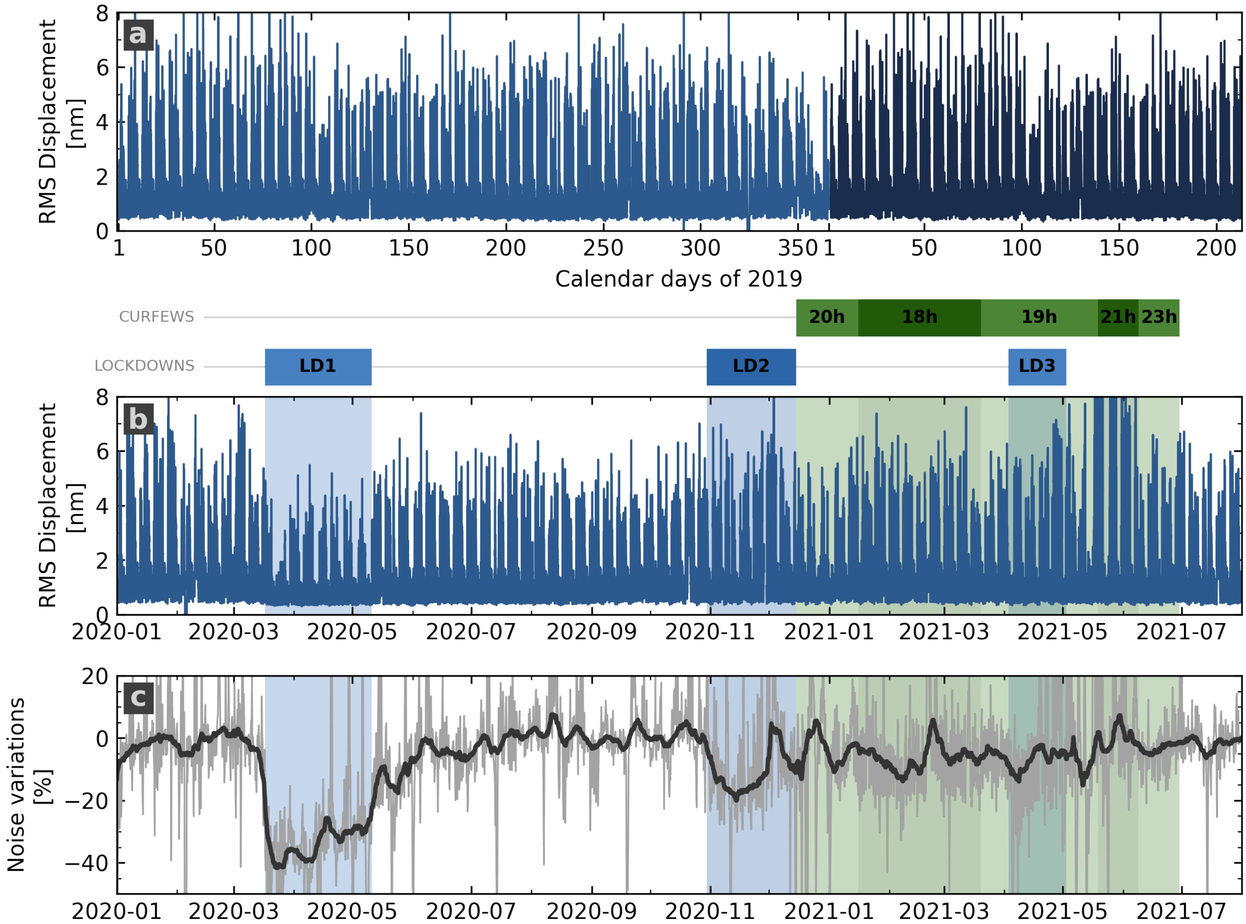

Figure 3 a) RMS displacement to the Clermont-Ferrand station (FR.CFF) over the year 2019. The x axis represents the calendar days from 01/01/2019. b) RMS displacement at the same station over the years 2020 and part of 2021. The vertical bands indicate the various restriction periods during the pandemic (blue for lockdowns; green for curfews with start time indicated). c) Un-smoothed (gray line) and 7-day smoothed (black line) variations of the RMS displacement relative to the reference noise level (year 2019).

dashed lines in Figure 2.

Studies carried out on the impact of the COVID-19 crisis on seismic noise level generally focus on the period associated with the pandemic only, using a median noise level reference computed from the weeks preceding the first lockdown (Lecocq et al., 2020; Cannata et al., 2021; Diaz et al., 2021). This approach has the disadvantage of superimposing the variations in noise levels associated with the pandemic to intrinsic variations in human activities over the course of the day, week, or year (vacations, bank holidays, etc.). We present here another approach, taking the variations during the whole year of 2019 as a reference. Data samples for each year of the present study (2019-2023) are counted in calendar days, considering the first calendar day as the first Monday of the year. The noise level variations are then calculated as the difference, for every 30-minute sample, between the noise level for the calendar days of the reference year, 2019, and the noise level for the calendar days of years 2020 and 2021 covering the pandemic period. Figure 3 illustrates this method for the FR.CFF station, located in the city of Clermont-Ferrand, France. Figure 3a clearly shows that for the reference year in 2019, there are strong variations in seismic noise level between weekdays and weekends, on public holidays and during vacations (for example, during the Christmas period from calendar day 355 onward). A significant difference can be observed between the reference year, 2019, and the period during the COVID-19 pandemic, by comparing Figure 3a and 3b. The seismic noise level drops drastically during the first lockdown, but we do not observe a significant drop during the second and third ones (Figure 3b). Figure 3c clearly highlights the drops in noise level for the first and second lockdown, but does not show any drop for the third one. It can also be noted that the effects linked to weekends, with regular drops in noise levels every Saturday and Sunday, are removed with our approach. The same is true for the period around Christmas and New Year, which have a lower noise level each year.

2.4 Mobility Restrictions During the COVID-19 Pandemic

In order to relate the key periods of the COVID-19 pandemic with the variations in the ambient seismic noise level, we consider the main periods and type of restriction during the pandemic in metropolitan

Date	Details
17 March 2020	Beginning of the first lockdown across the whole territory, closure of schools and "non-essential" businesses such as places of sociability and non-food retail stores. People need a certificate to go outside.
11 May 2020	End of the first lockdown. Reopening of non-essential shops and gradual reopening of places of sociability starting in June 2020.
30 October 2020	Beginning of the second lockdown. Schools remain open (except for universities), and many sectors can maintain their activities.
15 December 2020	End of the second lockdown. Universities, high schools, sports halls and restaurants remain closed.
16 January 2021	Introduction of a curfew between 18:00 and 06:00. Closing of places of sociability.
20 March 2021	Curfew starting at 19:00 and ending at 06:00.
3 April 2021	Beginning of the third lockdown. Curfew continues. Ability to circulate in a restricted area during the day. Closure of schools and non-essential businesses.
3 May 2021	End of the third lockdown. Curfew continues, but end of certificates to go outside during the day and circulation beyond 10 km authorized. Reopening of schools and gradual reopening of places of sociability.
19 May 2021	Reopening of places of sociability. Curfew starting at 21:00.
6 June 2021	Curfew starting at 23:00.
30 June 2021	End of curfew and night certificates.

Table 1 Key dates used in this study related to the COVID-19 pandemic in France (Wikipedia contributors, 2024).

France. The French government introduced three phases of lockdown during which human mobility was drastically reduced. In addition, several phases of curfews at varying times were established, from the end of the second lockdown until several weeks after the third one. All the key dates used in the following are summarized in Table 1.

3 Results

3.1 Overview of Seismic Noise Variations During COVID-19 Pandemic in France

We analyze the temporal variations of the seismic noise level during the COVID-19 period, relative to the year 2019, as shown in Figure 4. It represents the median noise level variations at all the stations, as well as the associated error bars defined by the 10th and 80th percentiles. A smoothing of the data was also carried out over 7 days in order to better highlight general trends (e.g. Lecocq et al., 2020). Noise-level variations are also represented for each of the stations studied.

Following the first lockdown measures put in place by the French government on 17 March 2020, 109 stations (86%) show a decrease in seismic noise level. The stations with the greatest decrease in noise levels during the first lockdown are mainly urban, although rural stations can also record large decreases. 22 stations (17%) show a noise reduction of more than 30%. Some stations highlight an increase in seismic noise level during the first lockdown, which is probably related to changes in noise sources in the vicinity of the stations or a decrease in seismic noise during the reference period, resulting in a relative increase during the COVID-19 pandemic. For instance, some of these stations are located near a dam (e.g. FR.RSL; FR.SMPL), or near torrents (e.g. FR.OGAG; FR.OGCE; FR.ENAUX), which can have a direct impact on noise levels. The noise level in metropolitan France remains low about 4 weeks after the end date of the first lockdown, and returns to an equivalent level to the reference year after July 2024. During the second lockdown, a smaller decrease in median noise level is observed and fewer stations observe it. This decrease seems to extend after the second lockdown, since we observe that the seismic noise level remains low until the implementation of a curfew at 18:00 for some stations. Finally, the third lockdown presents an even smaller decrease in noise level. The sorting of the amplitude of noise level decrease during the first lockdown does not apply for the other two lockdowns. The stations that recorded the largest decrease during the first lockdown are not necessarily those recording the largest decreases during the second and third lockdowns.

To get an overview of the geographical variation in the seismic noise level during the pandemic on the scale of the whole network, we illustrate in Figure 5 the median variations in noise level, compared to the year 2019, at each station and for each of the three lockdowns.

During the first lockdown, there is a median decrease in noise level across the entire network of about 15.3% compared to 2019. The median decrease is twice greater for urban stations (24.4%) than for rural stations (12.2%). Most stations show a decrease in noise level, although some rural stations presented an increase during this first lockdown. During the second lockdown, the reduction in noise level is only around 7.6% (7.0% and 7.7% for urban and rural stations, respectively), and 4.2% (7.4% and 3.6% for urban and rural stations, respectively) during the third one. The difference in noise level reduction between the first lockdown and the following ones correlates with the less restrictive governmental measures (Table 1).

3.2 Variation in seismic noise level with the time of day

The restrictions placed to combat COVID-19 have led to drastic changes in working conditions, human mobility, and hours of human activity. We study here the hourly variations of the seismic noise level encompassing the different phases of lockdowns or curfews put in place.

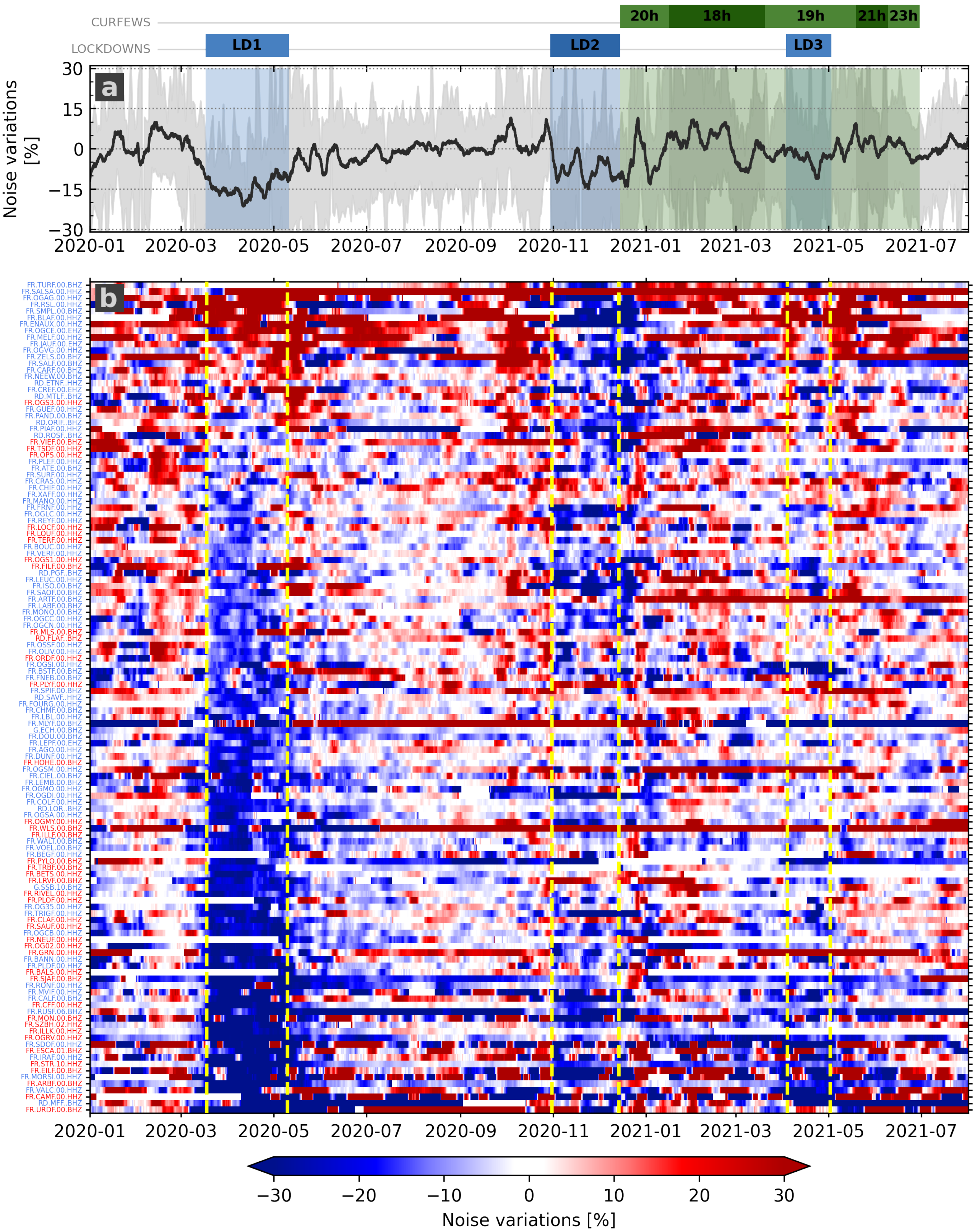

Figure 4 (a) Median noise level variations at all stations used in this study compared to the median noise level of the same calendar day in 2019 (dark grey), smoothed by a moving window of 7 days (black) and the distribution of percentiles 10% and 80% around the median value (grey). The vertical bands indicate the various restriction periods during the pandemic (blue for lockdowns; green for curfews with start time indicated). (b) Noise level variations for all stations compared to the median noise level of the same calendar day in 2019. The stations are sorted in ascending order from the station having the smallest decrease in noise level during the first lockdown to the one having the strongest decrease. Station name is either red (urban stations) or blue (rural stations). Vertical yellow dashed lines indicate lockdown dates during the COVID-19 period (see Table 1 for details).

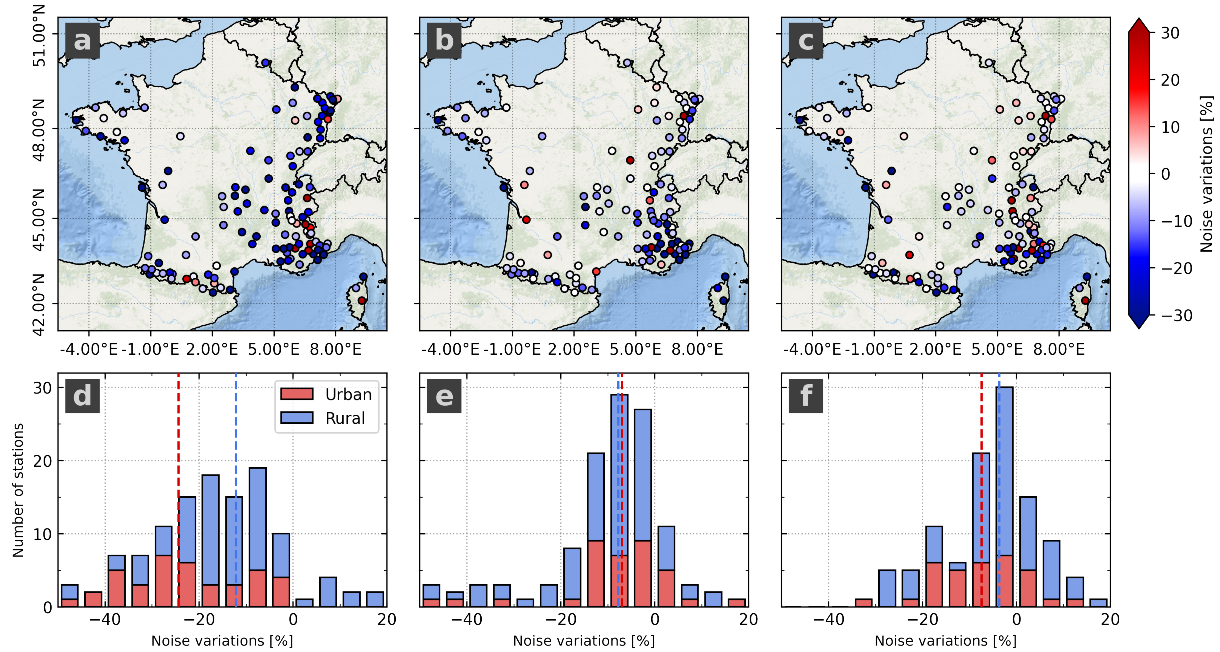

Figure 5 (Top) Map of the median noise level variations for all stations in the metropolitan area during (a) first lockdown, (b) second lockdown and (c) third lockdown, compared to the reference year 2019. (Bottom) Distribution of noise level variations over the whole network zoomed between -50% and +20% of noise variations during (d) first lockdown, (e) second lockdown and (f) third lockdown. The histogram is shown in red for urban stations and blue for rural stations. The median noise level variation is represented by the red (urban stations) or blue (rural stations) dashed lines.

The time series of median noise variations at all stations for each half-hour of the day is presented in Figure 6 using local time.

During the first lockdown, the seismic noise level decreased sharply at all hours by at least 15%, with the exception of nights at the beginning and end of the lockdown, with a slighter decrease (about 5% to 10%). After the end of the first lockdown, the noise level gradually increases and finally exceeds the noise level of 2019, the month before the second lockdown. This return to normal seems to occur more quickly during daytime hours than during night time hours.

The second lockdown is also clearly visible in this figure, with a clear decrease of about 10-15% of the noise level during the night. During the day, the drop of noise is barely visible, which reflects the second lockdown well, where schools were open and people were allowed to work during the day but stayed at home in the evenings and at night because public places such as restaurants or cultural places were closed. Just after the second lockdown the noise level remains low with a decrease of 5% of the noise level for all hours of the day. This low level of noise can be explained by a tense situation due to the strong presence of the virus despite the lockdown. We also note that bars, restaurants, and cultural spaces were still closed at that time.

The third lockdown also shows a drop in noise of about 5% during the day, but with a higher drop of up to 15% between 19:00 and 07:00, which fits the curfew in place before the third lockdown. Figure 6 also shows a noise drop during the evenings which matches the evolution of the curfew start time, as shown by the black horizontal lines in Figure 6.

We can also see in Figure 6 three periods with an important increase in noise level compared to 2019. The first two periods of high noise level occur during weeks before the first and second lockdowns. The third high-noise-level period occurs between mid-January and end of February 2021 between the second and third lockdown. This high period of noise is even higher during the night with an increase of around 10 to 15% through a curfew.

3.3 Variation in seismic noise level depending on the day of the week

In this section, we analyze the impact of the COVID-19 restrictions on the seismic noise level depending on the day of the week. Based on Figure 6, we split the 2020-2021 dataset into eight different periods: before the beginning of the first lockdown, during each of the three lockdowns, during the three periods of curfews without lockdown and after the release of all restrictions. For each of them, we represent the median ambient noise variation of all stations for each day of the week and each half-hour of the day (Figure 7).

This mode of representation indicates that:

- The increase in seismic noise level observed before the first lockdown occurs mainly during the night from Monday to Tuesday and to a lesser extent during the night from Tuesday to Wednesday.
- During the first lockdown, the decrease in ambient noise is weaker during the nights from Sunday evening to Wednesday morning (around 5%). During the first lockdown, ambient seismic noise decreases at all hours of the day and every day of

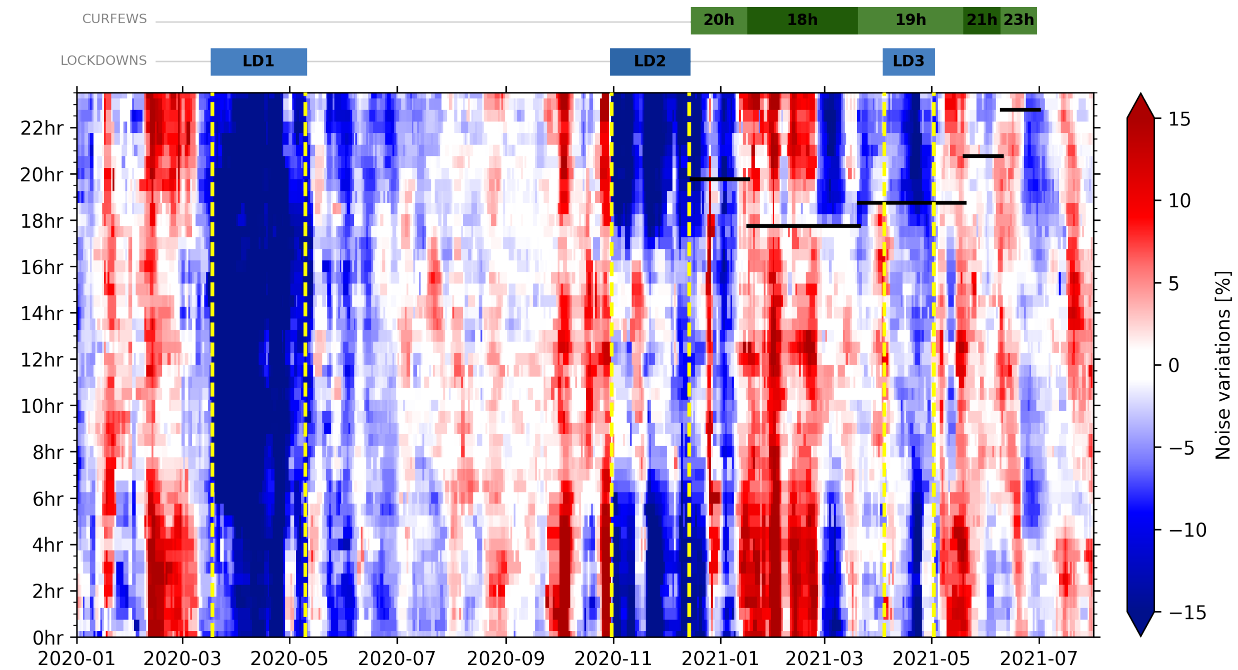

Figure 6 Median noise level variations at all stations used in this study, relative to the median noise level of the same calendar day in 2019, for each half-hour of the day using local time. The reference noise level is specific to each half-hour of the day. Vertical yellow dashed lines indicate the three lockdown periods during the COVID-19 crisis (see Table 1 for details). The top panel indicates the various restriction periods during the pandemic (blue for lockdowns; green for curfews with start time indicated). Horizontal black lines indicate the beginning of curfew hours.

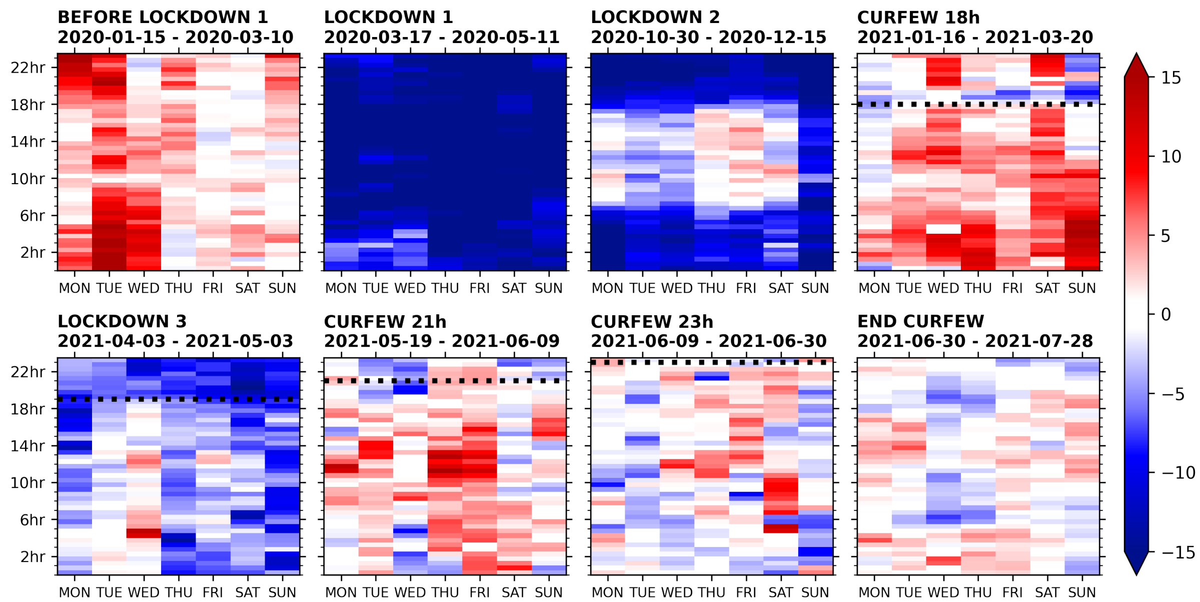

Figure 7 Median noise level variations at all stations used in this study compared to the median noise in 2019 depending on the hour of the day (local time) and the day of the week for eight distinct periods during the COVID-19 pandemic (see Table 1 for details). Curfew starting hour is indicated by horizontal black dashed lines for concerned subplots.

the week. This decrease is less pronounced at the end of the night (00:00 to 05:00) between Mondays and Wednesdays.

- During the second lockdown, there are weak changes in seismic noise during working hours between 06:00 and 18:00, with a slight increase on Monday, Thursday, Friday, and Saturday, and a slight decrease on Tuesday and Wednesday. This can be explained by weaker restrictions during the second lockdown. More people could go to work at their workplace compared to the first lockdown. However, there is a significant drop of more than 10% in the evening, at night, and all day on Sunday, as all restaurants and places of sociability were still closed during the second lockdown.

- During the period of the first curfew starting at

18:00, there is an increase in noise level for all days of the week at all hours, except between 18:00 and 19:00 when there is a slight decrease before a further increase in the evening. The decrease is more pronounced between Wednesday and Sunday around 18:00, with a more significant decrease during the evening on Sunday. This may be explained by the usual larger night activity at the end of the week than during the beginning of the week. As all bars, restaurants, and nightclubs were closed during the first lockdown, none of this activity was possible, so it showed a bigger decrease for the end of the week (from Wednesday evening to Sunday evening).

- During the third lockdown, we observe a greater reduction in noise level in the evening and at the end of the week, up to 10 to 15%. There are almost no variations in the morning and during the day from Monday to Wednesday, and a decrease of about 5% in the morning the rest of the week. It appears that the variations are less marked by working hours than during the second lockdown.
- During the period with a 21:00 curfew, there is an overall increase, slightly higher during working hours.
- Regarding the curfew periods at 23:00 and after the lifting of sanitary measures, we did not notice any particular trend and the noise level was quite similar to that of 2019 for the same period of time.

4 Discussions

4.1 Consistency and New Insights in Seismic Noise Studies

Numerous studies have been carried out to investigate seismic noise levels in different countries and cities. Our work is consistent with the results observed in other urban contexts (e.g. Cannata et al., 2021; De Plaen et al., 2021; Diaz et al., 2021; Grecu et al., 2021; Poli et al., 2020), with significant decreases in noise levels when local authorities implement lockdown measures. However, for stations located in environments far from cities, the effects have not been widely studied. It can be seen that Grecu et al. (2021) observed the effects of lockdowns in Romania even for stations located far from cities. In metropolitan France, we also observed that many stations located in rural environments measured the effects of lockdowns and other restrictions.

Some studies have observed that during the COVID-19 pandemic, there were also variations in noise levels that were not necessarily related to coercive measures, such as holiday periods (e.g. Diaz et al., 2021; Poli et al., 2020), which can sometimes make interpretation difficult. By working in relative terms with respect to a reference year, here 2019, we are no longer sensitive to these periodic or seasonal variations. This is why, for example, we are not sensitive in our results to the effects of holiday periods.

4.2 Influence of the Reference Period

In this work, we decided to compute the noise level during COVID-19 relative to the day-by-day reference noise level during the year 2019. Care must be taken when interpreting the variations observed, as changes in noise level can occur during the COVID-19 period in 2020 and 2021, or during the reference year in an opposite manner. However, the temporal correlation of the drop in seismic noise level with lockdown and curfew phases averaged at the scale of the entire metropolitan network are quite strong and tend to suggest that these results are robust. To estimate the effect of choosing a reference averaged over several years, Figure 8 illustrates where each reference year has been set to start on the first Monday of the corresponding year to average for identical weekdays. For both stations, the choice of several reference years reduces the number of narrow peaks visible when using only 2019 as the reference. These variations were probably related to particular activities close to the stations in 2019 for the corresponding days. However, we did not observe significant differences and bias for the general trend of the ambient noise variations when choosing a longer reference period, and the main observations reported before remain valid. Our choice to use only the year 2019 as a reference is due to the relative youth of most of the permanent broadband stations in metropolitan France. Extending the reference time to the 2016-2019 period and selecting only the stations with at least 50% of data for each year of this period, would reduce the number of available stations to 60 instead of the 127 stations when using only the year 2019 as a reference. We believe that this leads to less significant results in terms of geographic coverage and estimation of median values of the ambient noise variations at the scale of the entire network.

4.3 Origins of Seismic Noise Variations

The sudden cessation of human activities is particularly significant in cities, although we observe that the drop in seismic noise levels is visible throughout the territory, even at stations located in rural areas and far from urban centers. Studying the signal at high frequency (above 1 Hz) makes the analysis highly sensitive to effects in the vicinity of the stations. Even if a station is located in a rural environment, nearby anthropogenic sources (road, building site, factory, etc.) can exist and will have a strong impact on the recorded signal. However, the low level of seismic noise typical of rural stations makes it possible to observe the evolution of more distant anthropogenic sources than for urban stations. This is why, even for apparently isolated stations, a drop in noise levels has been observed.

Although noise level variations can originate from a variety of sources around each station, we took a closer look at the contribution of road traffic to these observations. We retrieved road traffic data made publicly available by Cerema (Center for studies and expertise on risks, the environment, mobility and development) via the French government website (https://trafic-routier.data.cerema.fr). This data consists

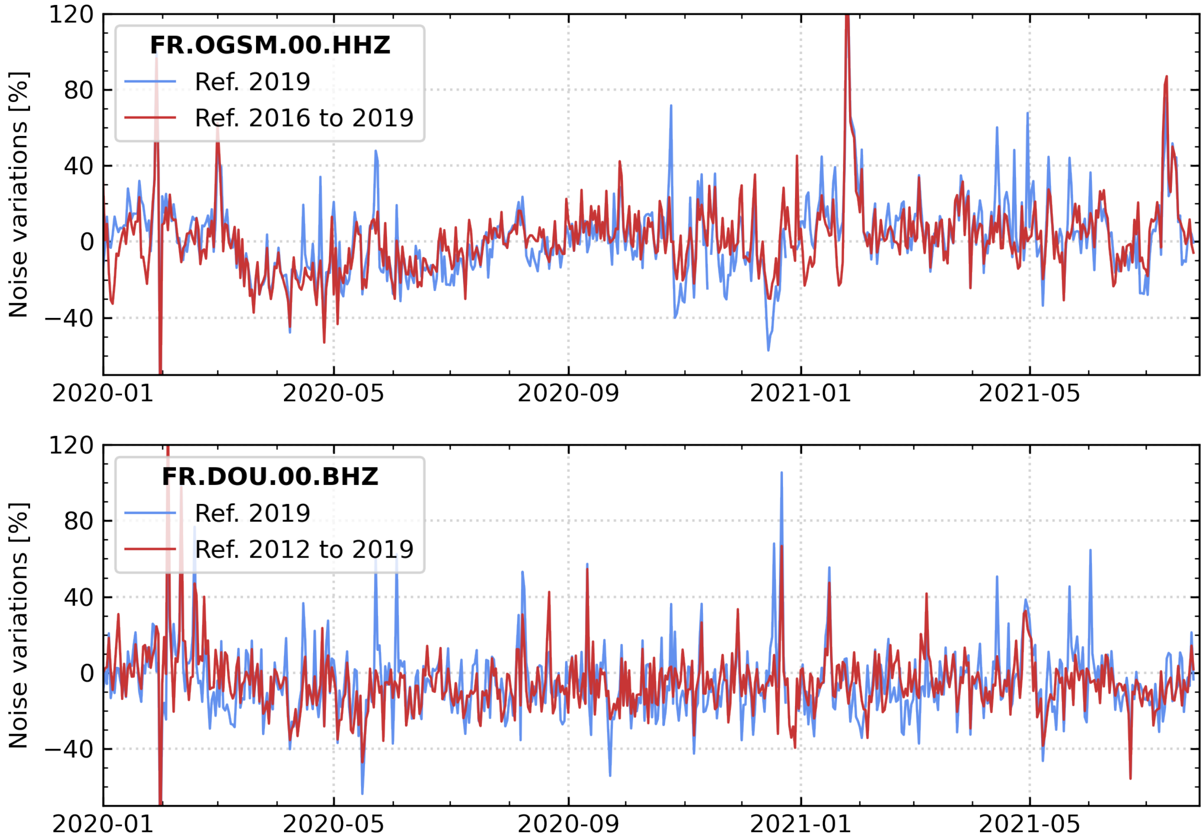

Figure 8 Noise level variations at FR.OGSM (top) and FR.DOU (bottom) stations relative to a reference. (Blue line) Reference year 2019 only (Red Line) reference built by averaging noise level from 2016 (FR.OGSM) or 2012 (FR.DOU) to 2019.

of vehicle counting stations on major roads, mainly located in the north-west of mainland France. We analyzed road traffic variations in a similar way to ambient seismic noise variation data, using the year 2019 as a reference. The results are shown in Figure 9. We only keep the seismological and road traffic stations less than 15 km apart to avoid statistical bias due to the highly heterogeneous spatial distribution of publicly available road traffic counting stations in metropolitan France (see Figure 9d).

Figure 9a shows very clear decreases in road traffic during the three lockdowns with variable amplitude, similarly to variations in the seismic noise level (see Supplemental Figure S1, which was derived from Figure 6 by considering only the stations shown in Figure 9d). On the scale of hourly variations, Figure 9b shows very precisely the three lockdowns and the successive phases of curfews implemented by the French government. These results are very similar to those shown by the seismic noise level variations in Supplemental Figure S1. In general, road traffic variations appear to be linearly related to ambient seismic noise level variations (Figure 9c) although there is obviously a large dispersion around the best linear trend. This confirms that, on a first-order and large geographical scale, road traffic is a major contributor to the seismic noise level in the 4-8 Hz frequency band. The additional complexity observed in the seismological recordings can be explained in several ways. First, by selecting only the road traffic counting and seismological stations located within 15 km, it is possible that the seismological station is sufficiently far from the counting station to be sensitive to different environments (e.g. different roads near the seismological stations) in the 4-8 Hz frequency band. In addition, the ambient seismic noise also includes other man-made contributions (factories, turbines, etc.) that could explain these discrepancies. Seismological data provides a less biased view, spatially integrating all sources of human socio-economical activities contributing to seismic noise in the target frequency band, with road traffic being only one of them.

4.4 Seismic noise level during the post-COVID-19 period

We extended the analysis to 2022 and 2023 in order to identify whether any post-COVID-19 effects were visible in the seismological data. We reproduced Figures 4, 6, and 9 between January 2020 and December 2023, included in the Supplementary Material (Supplemental Figures S2, S3, S4, respectively) for readability reasons. The seismic noise level after the lockdown and curfew phases exhibits contrasted features: a general decrease in 2022 in noise level with respect to 2019 (numerous blue domains in Supplemental Figure S3) and an overall increase in 2023 (numerous red domains in Supplemental Figure S3). However, we note that in Supplemental Figure S2, significant decreases in the seismic noise level of about 20% are visible toward

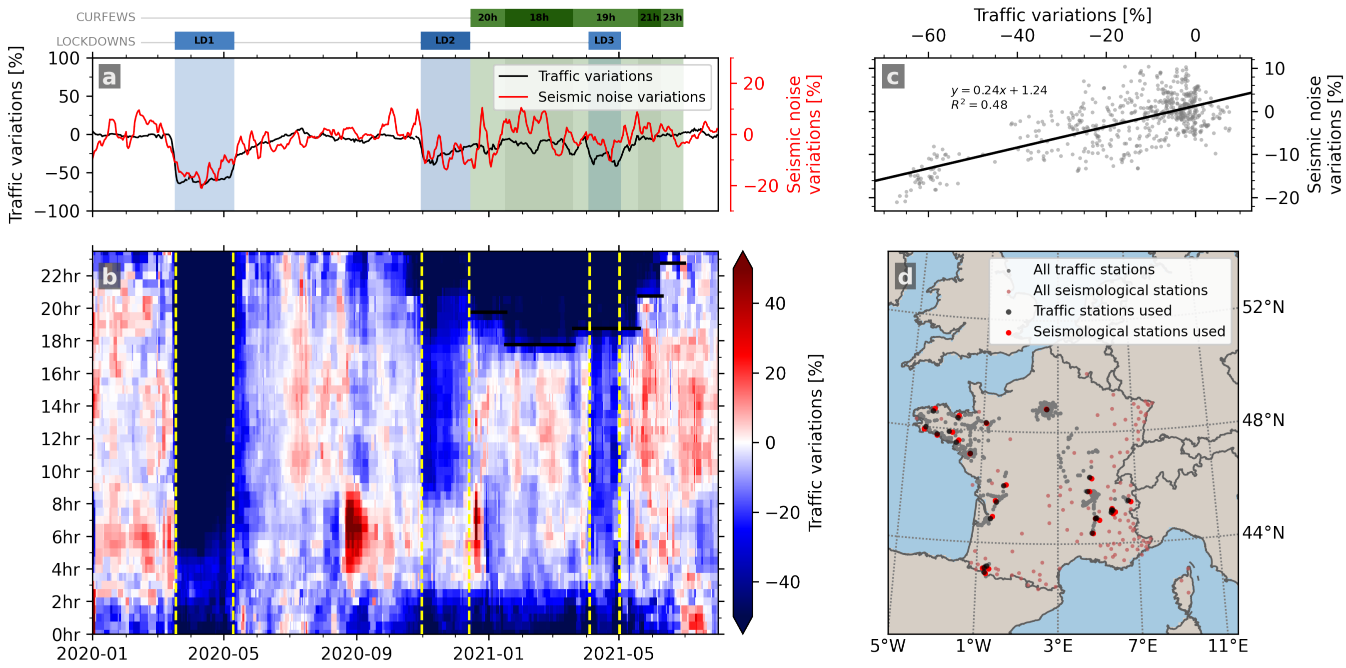

Figure 9 a) Median noise level variations (red) and median traffic variations (black) with a 7 days moving window stack. The vertical bands indicate the various restriction periods during the pandemic (blue for lockdowns; green for curfews with start time indicated). b) Median traffic variation with respect to the hour of the day. The reference is specific to each half-hour of the day relative to the year 2019. Vertical yellow dashed lines indicate lockdown phases during the COVID-19 period (see Table 1 for details). c) Noise level variations with respect to traffic variations. The thick black line is the best fitting line. d) Public traffic stations and seismological stations used in this comparison.

the end of the years 2021 and 2022 around November and December, particularly for rural stations. This observation is confirmed in Supplemental Figure S5, which compares the median seismic noise level at urban (red) and rural (blue) stations, with a greater decrease for rural stations. We compared these results with the median variations in temperatures across metropolitan France (Supplemental Figure S5b), relative to 2019, by collecting the data produced by Météo France and distributed by the French government (https://www.data.gouv.fr/datasets/donnees-climatologiques-de-base-quotidiennes/). The temperature variations show positive strong variations, compared to 2019, which coincide with the drops in the seismic noise level. These variations are also visible at the end of 2023, but with positive amplitudes for the seismic noise level. The strongest temperature variations compared with 2019 occur during the periods when absolute temperatures are the lowest (*i.e.* in winter). Seismic noise level variations are thus observed during periods of extreme cold and may correspond either to a low seismic noise level recorded in the reference year or to low noise levels measured between 2021 and 2023.

We also note that in Supplemental Figure S3, there appears to be a reduction in the level of seismic noise of about 10% in the evening and at night, which persists after the COVID-19 restriction phases, until 2023. This can also be seen in the road traffic data (Supplemental Figure S4). The origin of this decrease is not clear, but could reflect potential changes in human mobility that do not return to a pre-COVID-19 state (*i.e.* before the restriction phases). This analysis paves the way for more in-depth studies to understand these changes, particularly with regard to the sociological aspect, in order to identify which post-COVID-19 sociological behaviors have been observed and would make it possible to understand the changes in seismic noise level.

5 Conclusions

The COVID-19 period and the various phases of human activity restrictions in metropolitan France have shed light on the ability and sensitivity with which seismological data can be used to monitor human activity. Permanent seismic networks provide spatially integrated information in the station environment, taking into account all the human activities that generate ground vibrations, and enable long-term monitoring of these activities. Here, we analyzed the ambient noise level variations at the scale of a whole metropolitan French territory without explicit selection of stations, for example, based on their proximity to human activities (towns, roads, etc.). To remove periodic and seasonal variations of human activity, we determined noise level variations of the years 2020 and 2021 compared to a reference year 2019, not affected by the pandemic.

We observed a significant effect of lockdowns, with a drop in the seismic noise level at all hours of the day during the first lockdown (an average of 15.3% over the whole network). The second and third lockdowns led to a smaller reduction in noise levels (7.6% and

5.2%, respectively) occurring outside working hours. The decrease in noise level was on average greater for stations located near urban centers (24.4% during the first lockdown), although stations located in rural areas observed significant decreases (12.2% during the first lockdown). In addition, we highlight the coincidence of noise level decreases with successive phases of curfews. Our dataset provides relevant information on human activity with half-hour precision that highlights how human activity evolved on the scale of a whole country for each of the successive curfews implemented by the French government. Our work presents results consistent with previous studies on the subject (e.g. Cannata et al., 2021; De Plaen et al., 2021; Diaz et al., 2021; Grecu et al., 2021; Poli et al., 2020), but we also show that the effects of lockdowns and curfews are visible even for stations located in rural environments. The evolution of road traffic during lockdown and curfew periods is a major contributor to the observed variations in ambient seismic noise over the 4-8 Hz frequency range. However, changes in other types of human socio-economical activities during this period are also observed in seismic data.

Our study paves the way for an in-depth analysis of seismological noise after the restriction phases, as certain post-COVID-19 changes are observed, but which require a close link with the sociological community to be properly understood.

Finally, this work demonstrates the numerous possibilities of seismological data to study other sites, other periods, or other socio-cultural contexts, comparing cultural rhythms between different countries or even in other types of social containment.

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Data and code availability

All waveforms from the French (FR), GEOSCOPE (G) and CEA/DASE (RD) networks are available through FDSN webservices on RESIF data center https://seismology.resif.fr. All data recovery and some processing have been performed using the Obspy Python package (Krischer et al., 2015) and codes from Lecocq (2020) available on Zenodo. Road traffic data are available online at https://trafic-routier.data.cerema.fr. Population density data are available online at www.observatoire-des-territoires.gouv.fr.

Competing interests

The authors declare no conflict of interest.

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