The effect of confinement due to COVID-19 on seismic noise in Mexico

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Abstract. The world experienced the beginning of the COVID-19 pandemic by the end of 2019, beginning of 2020. Governments implemented strategies to contain it, most based on lockdowns. Mexico was not the exception. The lockdown was initiated in March 2020 and with it, a reduction on the seismic noise level was witnessed by the seismic stations of the national and the Valley of Mexico networks. Stations located in municipalities with more than 50,000 people usually experience larger seismic noise levels at frequencies between 1 to 5 Hz, associated with human activity. The largest noise levels are recorded in Mexico City, with the largest population in the country. The largest drop was observed in Hermosillo, Sonora, however, it was also the city with the fastest return to activities, which seems to correlate with a quick increase in confirmed COVID-19 cases. Mexico initiated a traffic-light system to modulate the re-opening of economic activities for each state. Therefore, since 1 June, noise levels reflect, in general, the colour of the state traffic light. Furthermore, the reduction in the noise level at seismic stations has allowed identification of smaller earthquakes without signal processing. Also, people in cities have perceived smaller or distant quakes.

1 Introduction

The World Health Organization declared a Public Health Emergency of International Concern to COVID-19, the disease generated by the SARS-Cov2 coronavirus, on 30 January 2020. The emergency was declared after the first case was reported in Wuhan, China, in late 2019 and had emigrated to other Asian and European countries. As a measure to stop the transmission of the virus, governments initiated strategies that involve confinement in our homes, reducing our mobility and with it that of the virus itself. This implied a decrease in activity in the cities, which seismologists immediately observed in their records (e.g., Lecocq et al., 2020). Specifically, in Mexico, the first case of COVID-19 appeared on 13 January (http://coronavirus.gob.mx/datos/, last accessed on 11 November 2020). Mexico's government decided to hold a daily press conference starting on 22 January with the Undersecretary of Health as the spokesman. At the press conference on Friday 13

March, the ‘Sana Distancia’ (Healthy Distance) program was presented. The strategy included the lockdown program named ‘#QuédateEnCasa’ (#StayAtHome). All non-essential activities were supposed to be either suspended or done remotely from home, starting 23 March. However, that weekend, the Secretary of Public Education announced that school activities would be suspended as of that date (14 March) and until after Eastern week. That is, there would be a probable return for dates after 20 April. Other institutions, both educational and businesses, also began to outline their strategies to migrate to online and remote operations and activities, inviting the population at risk not to return to their workplaces after 16 March, a holiday in Mexico. When the number of confirmed cases per day began to change its behavior and growth began to accelerate, officially on 24 March, the Secretary of Health declared the beginning of phase 2 of the contingency for the SARS-Cov2.

Phase 3, with 8,772 confirmed cases, was declared on 21 April. Lockdown was confirmed to last at least until May 30 (https://www.gob.mx/salud/prensa/110-inicia-la-fase-3-por-covid-19, last accessed on 23 November 2020). On 1 June, a traffic light system, with four levels (red, orange, yellow, green), was implemented at the state level to strategically and gradually open economic activities in each state. Mexico is a large country, integrated by 32 states (Figure 1) with very distinct economic and social conditions. Each state analyses its epidemic risk weekly based on ten indexes (Secretaría de Salud, 2020). All states started in red. The first state to go orange was Zacatecas on 15 June, and the first one to go yellow on 17 August and green on 28 September was Campeche. Some states lowered their risk level to increase it again, returning to a colour that represents the increased contamination risk. For example, Chihuahua went from red to orange on 19 October and went back to red on 26 October.

The Servicio Sismológico Nacional (SSN, National Seismological Service of Mexico) operates a national network that consists of 63 broadband stations (Pérez-Campos et al., 2018). There is at least one station in 30 out of the 32 states; 12 are located at a state capital. The stations are mostly concentrated in central and southern Mexico (Figure 1). Of the 63 stations, 29 are situated in municipalities with less than 50,000 inhabitants (Figure 2). The noise level at all stations is mostly within the noise-level model by Peterson (1993) (Pérez-Campos et al., 2018). The exception is a station located within Mexico City, where there is a high noise level at frequencies above 1 Hz (figures 1 and 2). The SSN also operates a regional network at the Valley of Mexico, where Mexico City is located. This network consists of 31 broadband stations (Quintanar et al., 2018); 24 are in Mexico City (Figure 1). The seismic noise level at these stations is high at frequencies above 1 Hz (Quintanar et al., 2018).

The effect of lockdown measures on seismic noise recorded by seismic stations in Mexico was immediate. A decrease in its levels began to be seen as of 14 March, but on 30 March, the reduction became more significant. This decrease coincided with the urgent call from the Undersecretary of Health to stay home on 29 March. The minimum seismic noise level was reached between 4 and 10 May. After that week, the seismic noise increased progressively, with different behaviors at each station. In this work, we analyse the variations in the seismic noise level as a response to the confinement measures, first dictated by the federal government and later by the state governments. As a result of the low levels of seismic noise at some stations, people were also able to perceive smaller earthquakes than usual, and SSN analysts have been able to analyse a seismic sequence close to the station located in the city of Zacatecas.

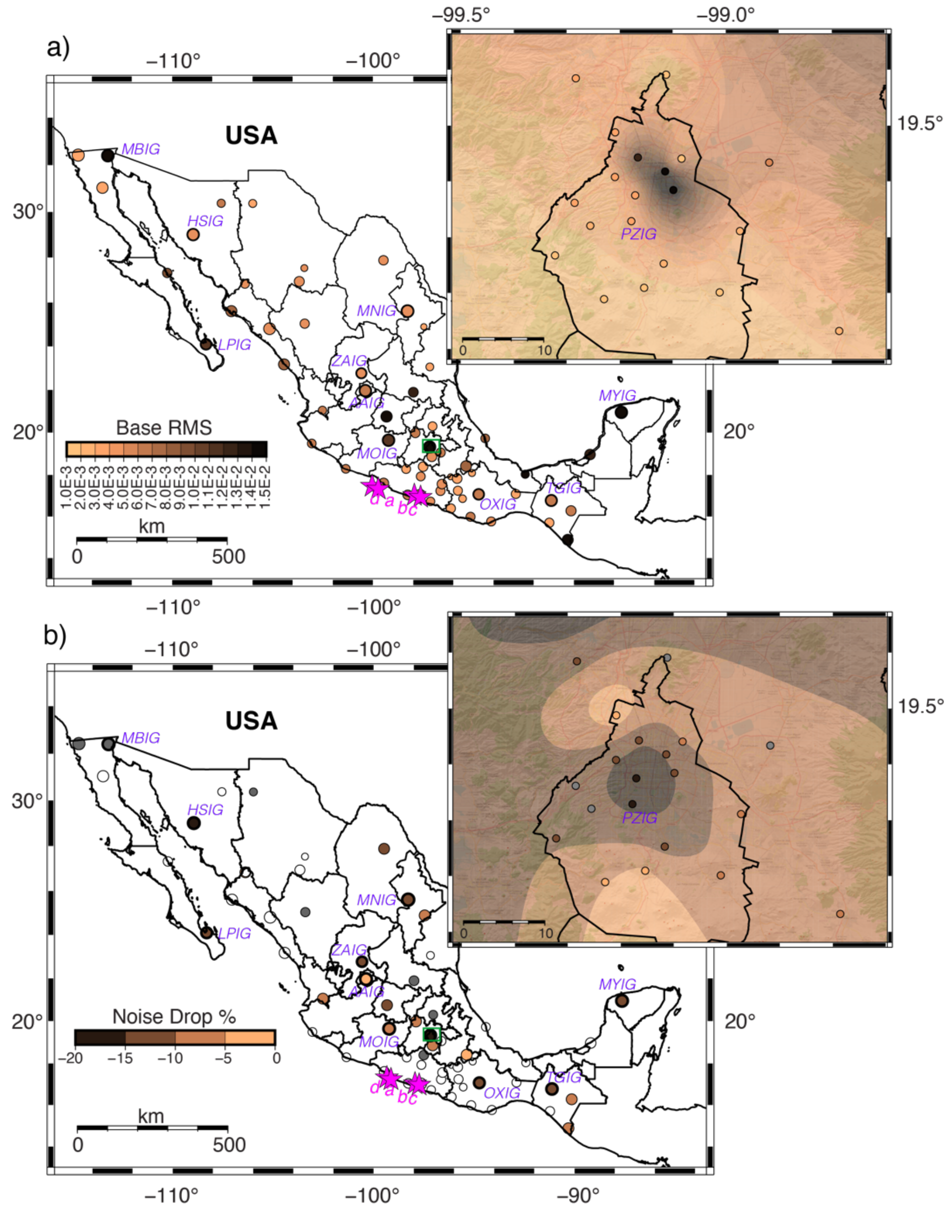


Figure 1: a) Noise RMS level and b) drop at seismic stations in Mexico. The pink stars indicate the location of the (a) 2020, M5.0, (b) 2019, M4.9, (c) 2017, M4.9, and (d) 2016, M5.0 earthquakes. The green box corresponds to the Valley of Mexico, shown in the inset. Symbol size is proportional to the municipality population (CEDRUS, 2019) where the station is located.

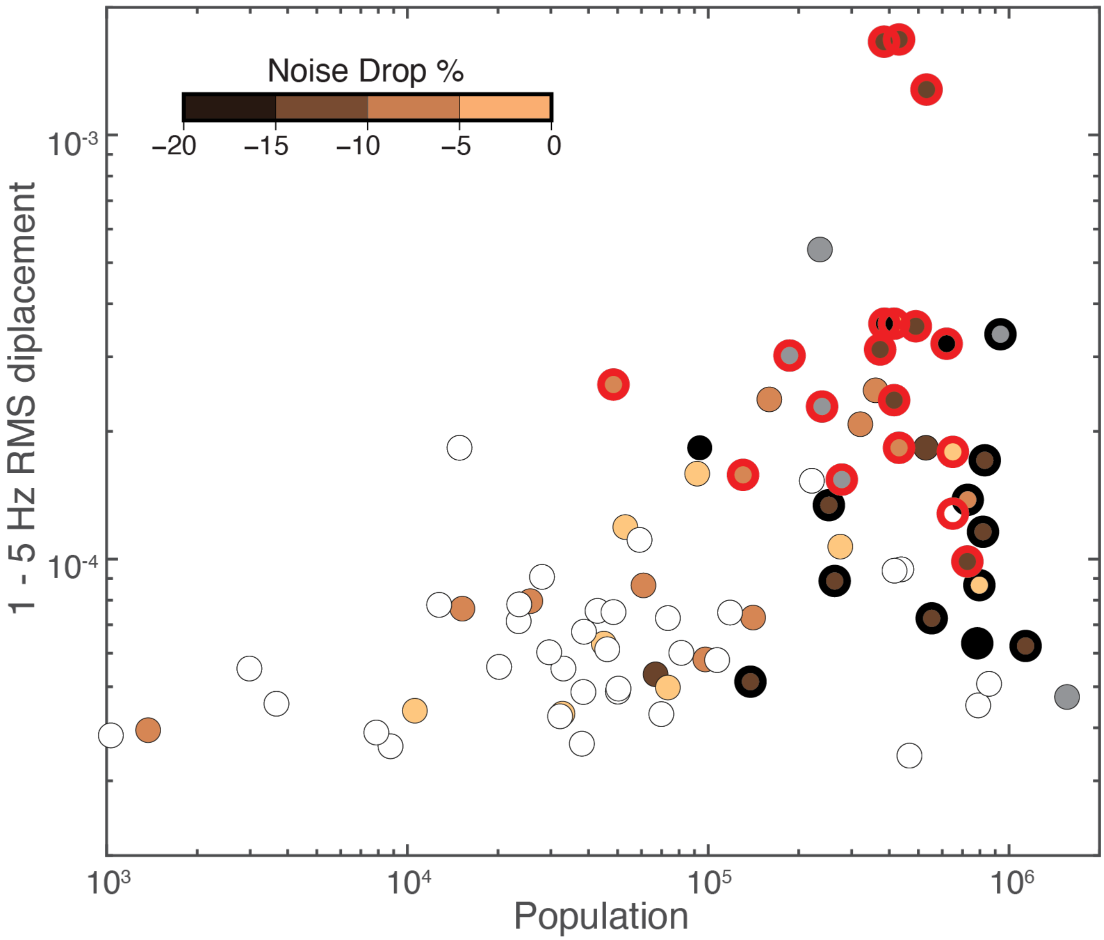


Figure 2. Noise RMS level and drop with respect to population. The outline symbols denote stations located in capital cities; the ones in red are in Mexico City. The white circles correspond to stations where no weekly cycle was observed; the grey ones, to stations where it was not possible to identify a drop in the noise level.

2. Materials and Methods

2.1 Data

We analyse the data received in real-time for 60 stations of the national seismic network and 24 of the Valley of Mexico seismic network (Figure 1). We removed the instrument response for all of them. The national network stations have a 120 s broadband seismometer, an accelerometer, and 42 of the stations also have a GNSS receiver. In the case of the Valley of

Mexico seismic network, we use 24 stations, 18 of them located in Mexico City (Figure 1). They are equipped with a 30 s seismometer, and eight of them also have an accelerometer. We analyse the data for 2019 and 2020, up to 14 November, to analyse the variations in the seismic noise as a response to the confinement measurements. Unfortunately, during the lockdown, some seismic stations malfunction, and it was not possible to service them (Pérez-Campos et al., 2020), losing real-time data.

2.2 Spectral and Amplitude Analysis

For each day, we obtain the power spectral density of 60-second windows. Then, we obtain the median of their distribution (McNamara and Buland, 2004). We plotted this daily median for 2019 and 2020. We observed a weekly variation at frequencies higher than 1 Hz at 49 stations, indicating human activity as a possible noise source (e.g., Groos and Ritter, 2009; Boese et al., 2015). These stations are mainly located in municipalities with more than 50,000 inhabitants (Figure 2). For the rest of the stations, this cycle was not evident. The only station at a municipality with less than 10,000 inhabitants, and a low RMS displacement, that shows an evident weekly cycle is within a university campus.

We obtain the root mean square (RMS) displacement at four frequency bands (1 – 5 Hz, 5 – 10 Hz, 10 – 20 Hz, and > 20 Hz) to select which one better-mapped variation of human activity and the variations associated with the confinement. In most of the stations, the band between 1 and 5 Hz showed a clearer weekly cycle and more evident noise reduction. This band is mostly related to pedestrians (Alyamkin and Eremenko, 2011) and low-speed urban road traffic (Green et al., 2017). Moving vehicles on the freeway can be detected at distances between 5 to 8 km away, but their frequency range is higher, 10-20 Hz (Long, 1971). Most of the national network stations are located far away from freeways. Within Mexico City, the speed limit is 80 km/h in the fastest avenues, which is rarely reached due to the constant traffic. Therefore, we base our analysis on this frequency band between 1 and 5 Hz.

Figure 3 shows the process for station PZIG, located in the main university campus in Mexico City, at the School of Veterinary, 500 m away from the Monitoring Centre of the SSN. The station is located only 500 m away from the campus limits and about 1 km from a very busy subway station. At this station, the noise due to human activity is evident. Daily influx through the campus is estimated to be of more than 300,000 people among students, teachers, researchers, workers, and the general public. The undergraduate population at UNAM is about 116,000 students (UNAM, 2020). Therefore, it is expected that despite the instruments being installed 20 m below ground, the noise level at frequencies above 1 Hz is high during the day and on weekdays. The lower levels are observed weekly on Sundays when the university campus is fully closed. Saturdays show a medium level since the campus is open half day for classes. The holiday periods are evident due to the low noise levels. One can also notice the periods of student vacations since the RMS displacement is not as high as for a weekday.

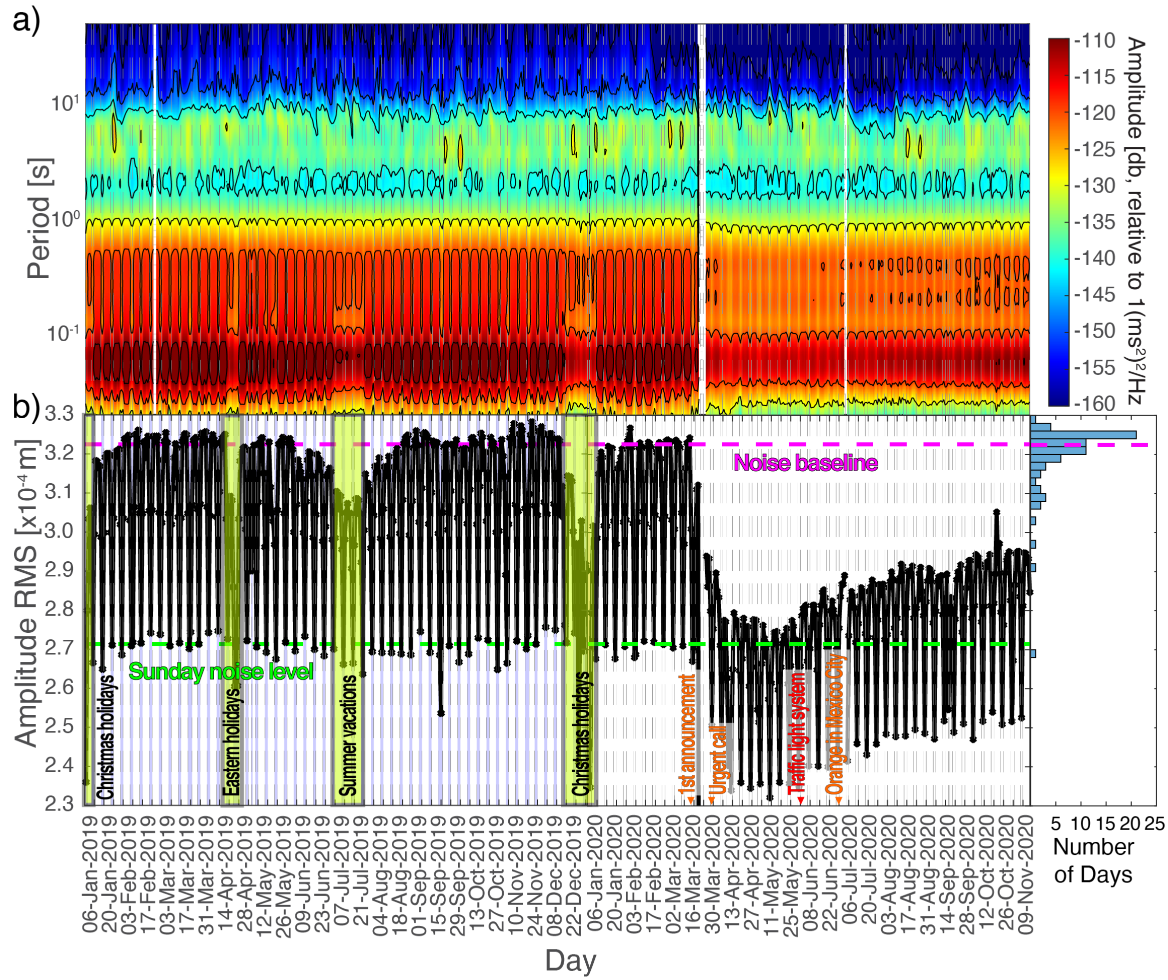


Figure 3: a) Daily median power spectral density for station PZIG. b) Daily RMS noise level for frequencies between 1 to 5 Hz.

As the base noise level, we set the RMS displacement median at frequencies 1 – 5 Hz for all weekdays during 2019 (Figure 3), including vacations. In general, the larger the municipality population where the station is installed, the larger the noise level (Figure 2). We set this level as 100% and compare the RMS displacement for each day of 2020, until 15 November, to obtain the daily percentage of the noise drop at each station.

3 Results

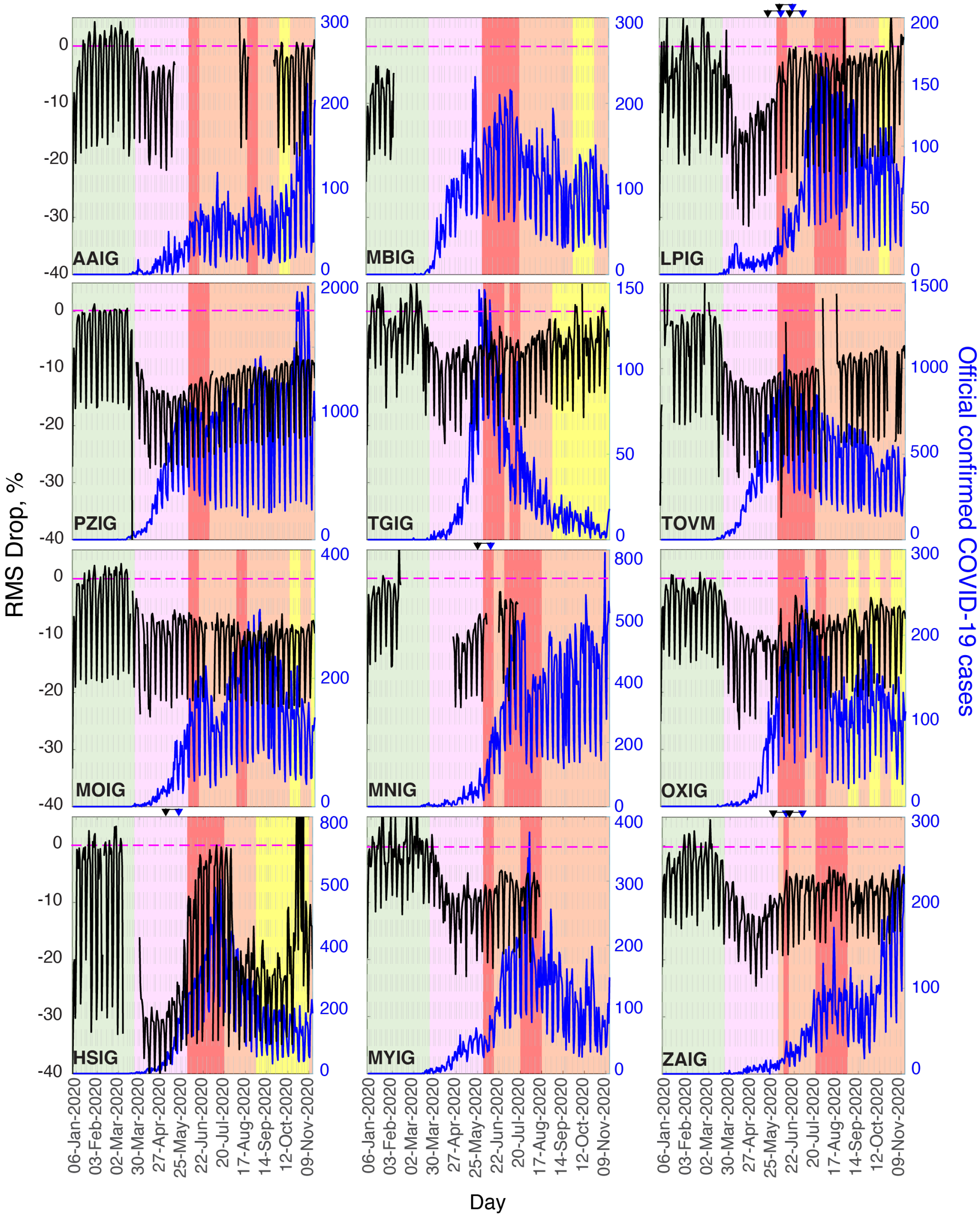
3.1 Seismic noise in Mexican cities

Figure 1 shows the noise level for each station of the national and the Valley of Mexico seismic networks. In general, the larger the population, the higher the noise level at frequencies between 1 and 5 Hz. Those stations located in a municipality with a large population but with low seismic noise are installed in remote places within the cities. The highest seismic noise levels are observed in Mexico City, which is the capital and the most populated city in the country. Unfortunately, only one-third of the capital cities have a national network station.

By analysing the daily RMS displacement for frequencies between 1 and 5 Hz, we selected only 49 stations where the weekly cyclic behavior is evident and chosen as a proxy for human activity. We then divided this set into two groups: 1) clear seismic noise reduction with the beginning of the national lockdown; and 2) no evidence of seismic noise reduction.

For the first set (Figure 4), we can observe that despite the official beginning for the lockdown was 23 March, the reduction in seismic noise started on 17 March, since many education institutions and companies started their transition to home-office as a response to the announcement by the federal government on 13 March. A steady decrease in the noise level continues for seven weeks, reaching its minimum in the week of 4 May. The reduction in noise level was not as strong as in other countries (e.g., Cannata et al., 2021); the maximum reduction was observed at station HSIG, located in Hermosillo, capital of Sonora, a state in the northwest of Mexico. The minimum noise level coincides with the dates announced by the Undersecretary of Health as the period when the maximum of the pandemic was going to be achieved in Mexico. After that week, the seismic noise level started increasing. The rate of increase varies significantly in different cities. At some, such as Hermosillo (station HSIG), and La Paz (station LPIG), capital of Baja California Sur, the noise level quickly went back to baseline level by 1 June, despite, the traffic light for these states remained red. In some countries, seismic noise levels have been strongly correlated with the lockdown phases (e.g., Díaz et al., 2021; Ojeda and Ruiz, 2021); however, in Mexico the lockdown is not imposed, and a weak correlation is observed between the noise variation and the lockdown phases. This suggests that at some cities people did not fully followed the recommendations of lockdown.

In contrast with the analysis by Ojeda and Ruiz (2021) for Santiago, Chile, only few studied Mexican cities show a strong correlation of seismic noise variations and epidemiological factors (Figure 4). For example, Sonora had only 2561 confirmed COVD-19 cases by 1 June, but the daily confirmed cases had a rapid increase until the first week of August when the rate decreased (Figure 4). The decrease in COVID-19 confirmed cases correlates with a drop in the seismic noise level on the first week of August. In the case of La Paz, the seismic noise level increase also coincides with a quick rise in COVID-19 confirmed cases. Later, the seismic noise level had a small decrease that has not dropped down again (Figure 4).



60 **Figure 4: RMS noise for frequencies 1 to 5 Hz (left axis, black lines) at stations located in capital cities. The right axis (blue line) indicates the number of official confirmed COVID-19 cases. Triangles on top of selected stations indicate when the RMS noise starts an increase tendency (black triangle) and when the COVID-19 cases start a fast grow (blue triangle). The lag between these triangles is two weeks.**

Stations that belong to the second set are installed at municipalities with less than 100,000 inhabitants or located at remote places within cities. In general, the base RMS displacement is below 1.1×10^{-4} m/s (Figure 1).

3.2 Seismicity detection and perception

As a result of the seismic noise reduction, we observe two notable effects: 1) perception of people to vibrations due to earthquakes; and 2) easier identification of earthquakes. At the SSN, automatic earthquake detection is done using SeisComP3 (Pérez-Campos et al., 2020); however, it is configured for the detection of earthquakes with a magnitude, M, larger than 4.0. Analysts routinely identify smaller earthquakes. Reports of perceptions are received through two channels: social networks (mainly Twitter), and the survey '¿Sintió un sismo?' (Did you feel an earthquake?, Montalvo-Arrieta et al., 2017, 2019).

On 6 April 2020, an M 5.0 earthquake hit the coast of Guerrero (Figure 1). Earthquakes like this one are frequent; in the last four years, three other earthquakes have happened close by and with similar magnitudes (Figure 1; Table 1): 4 June 2019, M 4.9; 13 February 2017, M 5.0; 2 December 2016, M 4.9. For the 2020 quake, 114 surveys were received against 29, 84, and 49 received for the other three earthquakes, respectively, despite having similar magnitudes. In the four events, obtained macroseismic intensities vary from II to V in the Mercalli Modified Intensity (MMI) scale, only for the 13 February 2017 earthquake, two values of VI in MMI were reported. The distribution of the macroseismic intensities values shows that during the 06 April 2020 earthquake, user reports were considerably more in central Mexico, located approximately 250 km from the epicenter, compared to other earthquakes that occurred previously to the COVID-19 lockdown. The ground-shaking experienced by citizens was mainly weak (values of II - III in MMI), however, the number of felts reports of intensity values of II and III were, respectively, approximately 2.5 and 2.9 times greater during the lockdown than for previous events. We conclude that the increase in the surveys received in ¿Sintió un Sismo? is the result of the seismic noise reduction mainly in urban centers. These events were recorded at stations up to Mexico City. The 2020 event, as mentioned by Lecocq et al. (2020), was visible without any signal processing at local seismic stations in Querétaro, north of Mexico City, since the noise in these stations was lower than usual.

We analyse the SSN catalogue (SSN, 2020a) for the last five years to identify variations in the minimum reported magnitude (Figure 5). We chose this period since the network grew considerably from 2006 to 2015 (Pérez-Campos et al., 2018); the last station of the national network was installed in 2015. Also, the Valley of Mexico seismic network increased the number of stations between 2010 and 2015 (Quintanar et al., 2018). Pérez-Campos et al. (2019) present a spatial distribution of the minimum magnitude reported in the SSN catalogue and able to detected by the 2019 network configuration. From this analysis, it is evident that the detection level, and therefore completeness magnitude, is heterogenous at the national level. The minimum reported magnitude for 2015-2020 is 1.0, reported in Mexico City. Three seismic swarms can be identified: 1) 2019 Mexico City, 2) 2020 Uruapan, and 3) 2020 Zacatecas. The first one has been studied by Singh et al. (2020), the second one was reported by the SSN (SSN, 2020b), and the third one occurred during the lockdown and a low level of seismic noise at the station ZAIG, located within the city of Zacatecas. People from Zacatecas reported feeling some of the events, which pointed the SSN analysts to analyse the data from this station carefully. Similar to van Wijk et al. (2021), due to the reduced noise levels, we were able to identify a template. With it, we have analysed the data for earlier months, and 120 events have been identified using a cross-correlation algorithm (Yoon et al., 2015). Eighty-seven of these events can be visually identified but were not previously reported since in the daily analysis they were discarded due the large noise level. Figure 6 shows the signals for two days, the first one on 27 January (Sunday 19:11:59, local time), M 1.4, and the second one on 21 June (Sunday, 18:08:59 local time), M 1.2. The signal is clearly less contaminated with high frequencies for the record in June 2020.

Table 1: Earthquakes at the Guerrero coast from 2016-2020, at similar distances from Mexico City and similar magnitudes.

Date	Local Time	Day of the week	Magnitude	Number of surveys received
6 April 2020	20:52	Monday	5.0	114
4 June 2019	14:12	Tuesday	4.9	29
13 February 2017	01:29	Monday	5.0	84
2 December 2016	07:57	Friday	4.9	49

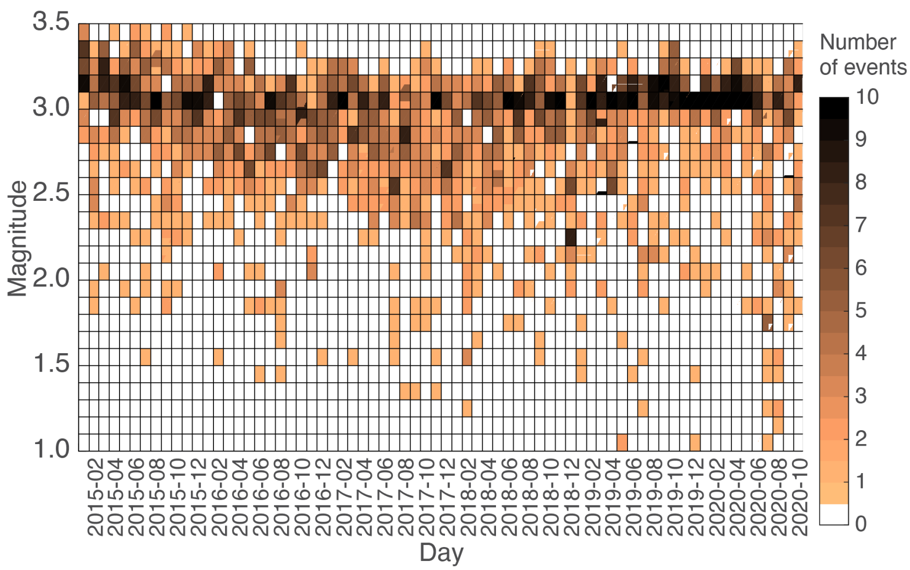


Figure 5: Minimum magnitude reported by the SSN per month.

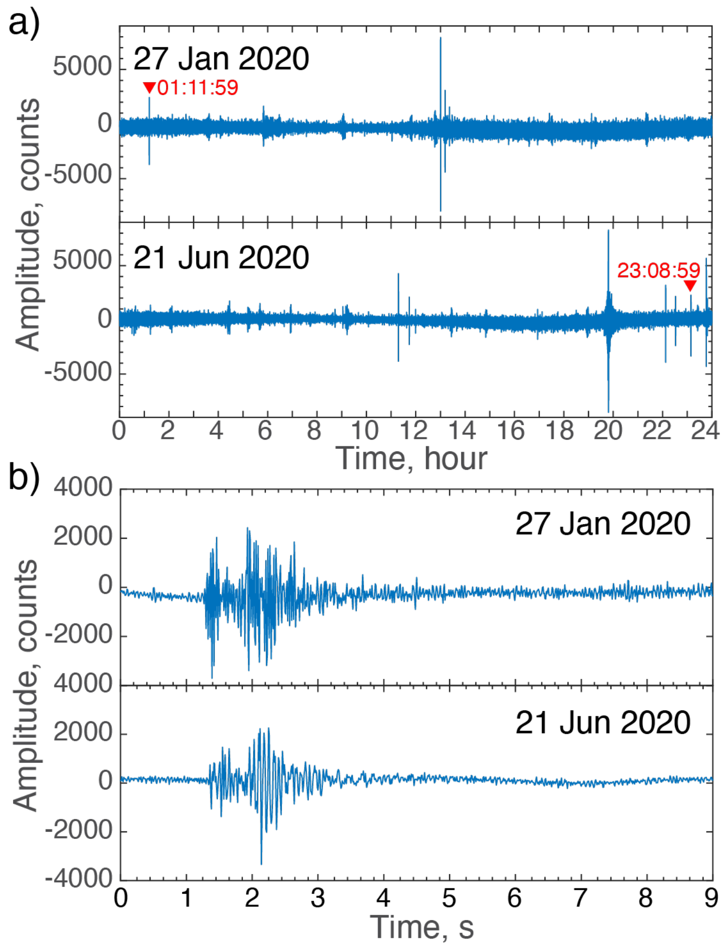


Figure 6: Record comparison for a day with the usual (top panels, 2020-01-27) and a reduced (lower panel, 2020-06-21) seismic noise at station ZAIG. a) 24-hour record. b) Event window. Both events are M 1.2.

4 Discussion and Conclusions

Seismic noise has been correlated with mobility data published by Google, Apple, or social networks, such as Twitter and Facebook. In some countries, this correlation seems high (Lecocq et al., 2020; Cannata et al., 2021). Tracking mobility this way might represent a challenge in countries like Mexico, where there is a heterogeneous adoption of the internet and smartphone nationally and within cities. In general, they can reach up to 71.2% and 77.7% in urban areas, respectively, whereas for rural areas, it can be as low as 39.2% and 53.8%, respectively (Martínez-Domínguez and Mora-Rivera, 2020). Mexico is considered 76.83% urban. Mexico City is 99.5% urban, while the Oaxaca state is 47.3% (INEGI, 2015). Also, the distribution of seismic stations, as seen in Figure 2, is mostly at urban centres (> 2,500 inhabitants). Unfortunately, in most cities, there is only one seismic station rather than a network. Therefore, the seismic noise is only representative of a ~5 km radius of the seismic station. Mexico City is an exception since the station distance there is ~5 km. Therefore, the seismic noise of the network can be representative of the city activity. This is also the case for Querétaro city, where a low-cost Raspberry Shake network has been recently installed. The effect of lockdown on seismic noise in this city has been analysed by De Plaen et al. (2020). They also analysed the correlation of the median seismic RMS to community mobility reported by Google. They analysed six categories, obtaining the minimum correlation for residential areas. Unlike some European or American cities, Mexican cities are not spatially distributed in a business district or residential neighborhood. Most of the cities are a mix and mingle of economic activities and residences. Furthermore, non-formal commerce represents 56.1% of the Mexican economy (Secretaría del Trabajo y Previsión Social, 2020). This activity does not take place in establishments but rather in the city streets. This is the scenario for Mexico City. As suggested by Díaz et al. (2021) for Barcelona, Spain, Cannata et al. (2021) for Sicily, Italy, and Ojeda and Ruiz (2021) for Santiago, Chile, seismic noise can be used to monitor urban mobility. However, the seismic noise levels for Mexican cities seem to be weakly modulated by the state traffic-light system.

Some state capitals concentrate more than 50% of the state population; such is the case for Aguascalientes (station AAIG) and Toluca (TOVM); whereas others barely reach 30%; such as Mexicali (MBIG), Tuxtla Gutiérrez (TGIG), Morelia (MOIG), Oaxaca (OXIG), and Zacatecas (ZAIG). The daily confirmed COVID-19 cases presented in Figure 4 correspond to the state total; however, in most cases, despite the low percentage of the state population, it was in the capital city where most cases have been confirmed. Comparing the daily COVID-19 confirmed cases with the daily RMS noise at frequencies from 1 to 5 Hz (Figure 4), a rapid increase in the seismic noise (i.e., a quick return to city activities) have coincided, with a two-week lag, with a rapid increase in daily confirmed cases; for example in La Paz (LPIG), Monterrey (MNIG), Hermosillo (HSIG), and Zacatecas (ZAIG). On the other hand, state strategies for a progressive return to economic activities, such as in Mexico City (PZIG), have shown a slow increase in the rate of daily confirmed cases.

In general, we can confirm that Mexican citizens responded to the government call for lockdown without any coercive measure. The lockdown resulted as an effective control at the beginning of the pandemic in Mexico. However, in a country where poverty prevails, and 56.1% of the economy is not formal, a very restrictive lockdown might have represented serious problems. Therefore, state-level strategies for reopening economic activities have been modulating the contagion rate, and the seismic noise allowed us to observe the response of the cities where the seismic stations are located. The evolution of the confirmed cases might eventually not correspond to the seismic noise behavior since other measures can be implemented, such as the generalized use of a mask, or ultimately, vaccination.

Code availability

Data preparation was done using Seismic Analysis Code (SAC; Goldstein et al., 2003). Data processing and analysis have been done using codes written in MATLAB by the first author. Codes are available upon request (xyoli@igeofisica.unam.mx). Figure 1 was made using the Generic Mapping Tools (GMT) software version 6.0.0 (Wessel et al., 2013). Figures 2 through 6 were made in MATLAB through an academic licence of the Universidad Nacional Autónoma de México.

Data availability

Data for the national network is available and can be obtained upon request, following the instructions at http://www.ssn.unam.mx/doi/networks/mx/ (DOI: https://doi.org/10.21766/SSNMX/SN/MX). Data for the Valley of Mexico seismic network can be obtained upon email request to Dr. Luis Quintanar (luisq@igeofisica.unam.mx). Catalogue data can be downloaded at http://www2.ssn.unam.mx:8080/catalogo/ (DOI: https://doi.org10.21766/SSNMX/EC/MX).
Data regarding COVID-19 in Mexico can be downloaded at https://datos.covid-19.conacyt.mx/#DOView.

Author contribution

XPC, VHMR, and RDP designed the study. XPC analysed the seismic data and wrote the paper. VHE and DGA analysed the Zacatecas seismic sequence and the mínimum reported magnitude data, BZF analysed the population and COVID-19 data and generated some maps, JCMA analysed the ¿Sentiste un sismo? Survey data, LQ analysed the Valley of Mexico data. All authors revised the article.

Competing interests

The authors declare that they have no conflict of interest.

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