Covid-19 lockdown effects on the seismic recordings of Central America

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Abstract. A noticeable decrease in seismic noise was registered worldwide during the lockdown measures implemented in 2020 to prevent the spread of Covid-19. In Central America, strong lockdown measures started during March of 2020. We have used seismic stations from Costa Rica, Guatemala, El Salvador, and Nicaragua to study the effects of these measures on seismic records by characterizing temporal variations in the high-frequency band (4-14 Hz) via spectral and amplitude analyses. In addition, we study the link between the reduction of seismic noise and the number of earthquake detections and felt reports in Costa Rica and Guatemala. We found that seismic stations near the capitals of Costa Rica, Guatemala, and El Salvador, presented a decrease in their typical seismic noise levels, from 200 to 140 nm, 100 to 80 nm, and 120 to 80 nm, respectively. Our results showed that the largest reduction of ~ 50% in seismic noise was observed at seismic stations near main airports, busy roads, and densely populated cities. In Nicaragua, the seismic noise levels remained constant (~ 40 nm) as no lockdown measures were applied. We suggest that the decrease in seismic noise levels may have increased earthquake detections and the number of felt reports of low magnitude earthquakes. However, the variations observed in several seismic parameters before and after the lockdown are not significant enough to easily untangle our observations or link them to other contributing factors. Our results imply that the study of seismic noise levels can be useful to verify the compliance of lockdown measures and to explore their effects in earthquake detection and felt reports.

1. Introduction

The seismic noise recorded by seismometers includes microseisms and atmospheric, anthropogenic or cultural noise (Nimiya, 2020). The anthropogenic seismic noise in urban areas tends to be rowdier and more complex than elsewhere. This includes seismic signals generated by human activities such as transportation and industrial activities (Gross and Ritter, 2009; Diaz et al., 2017; Hong et al., 2020). It is difficult to identify precisely at what frequencies and how different human activities are represented in seismic records (McNamara and Buland, 2004; Green et al., 2017; Lecoq et al., 2020a). Indeed, the seismic noise includes various anthropogenic noises as a function of frequency, time, and distance in a range usually between 1-40 Hz (Kuzma et al., 2009; Riahi and Gerstoft, 2015; Diaz et al., 2017).

A reduction in the seismic noise worldwide has been observed coinciding with the lockdown measures to prevent the spread of Covid-19, whose outbreak was declared pandemic in March 2020 by the World Health Organization (Sohrabi et al., 2020). This effect has been first described for Shillong (India) by Somala (2020), for Northern Italy by Poli et al. (2020), and by Lecocq et al. (2020a) at a global scale. Governments have tried to prevent or delay the spread of Covid-19 by forcing the social distancing through measures like limiting non-essential activities, closing schools and universities, restriction of the mobility of the citizens, and shutdown of workplaces (Piccinini, et al., 2020).

Central America has been severely affected by the of Covid-19 pandemic with an estimated death toll of 18,145 by the end of 2020 (SICA, 2020). This small land bridge (1400 km long, 80–400 km wide) between the Americas is home to about 50 million inhabitants. It is located mostly in the Caribbean Plate and the Panama Microplate, surrounded by four major tectonic plates: the Cocos plate to the southwest, the Nazca plate to the south, and the North American and South American plates to the north and southeast, respectively. The boundary between the Cocos and Caribbean plates occurs at the Middle America Trench (MAT), where the Cocos Plate subducts underneath the Caribbean Plate and the Panama Microplate. The North Panama Deformed Belt (NPDB) constitutes the Caribbean Plate-Panama Microplate boundary, and the Polochic-Motagua Fault System (PMFS) marks the Caribbean-North American Plate boundary (Figure 1) (e.g. Adamek et al., 1988; Kellogg and Vega, 1995; Trenkamp et al., 2002; Vargas and Mann, 2013). This complex and active tectonic setting in Central America generates high seismicity rates and volcanic activity. For instance, some of the deadliest earthquakes (Figure 1) were the 1910 M 6.4 Cartago earthquake in Costa Rica, the 1972 M 6.3 Managua earthquake in Nicaragua, the 1976 M 7.5 Guatemala earthquake, and the 1986 M 5.7 San Salvador earthquake in El Salvador, with ~600, ~20,000, ~23,000, and ~6,000 fatalities, respectively (Espinosa, 1976; Mann et al., 1990; Harlow et al., 1993; Alonso-Henar et al., 2013).

Seismometers in urban settings optimize the spatial coverage of seismic networks at these areas, and warn of local geological hazards, for example the amplification of seismic waves (Ashenden et al., 2011). Some of the main institutions in charge of the permanent monitoring of seismicity in Central America are: the National Institute of Seismology, Volcanology, Meteorology and Hydrology (INSIVUMEH) in Guatemala, the National Service for Territorial Studies (SNET in El Salvador), the Nicaraguan Institute for Territorial Studies (INETER) in Nicaragua, and in Costa Rica the National Seismological Network of the University of Costa Rica (RSN-UCR) and the Volcanological and Seismological Observatory of the National University of Costa Rica (OVSICORI-UNA). Belize and Honduras lack an official seismic service and Panama has several local networks, such as the Chiriqui and the University of Panama (UPA).

Because high levels of the root mean square (RMS) of the high-frequency seismic anthropogenic noise displacement (HFSAND-RMS) hampers the ability to detect signals from earthquakes and volcanic eruptions, its analysis and delimitation is of the utmost importance (Lecoq et al., 2020a). The objective of this work is to present the first study of HFSAND-RMS during Covid-19 in Central America. We have used seismic stations in Central America (Figure 1) to evaluate the effects of lockdown measures in the seismic record near urban centers of four countries in the region: Costa Rica, Guatemala, El Salvador, and Nicaragua. In addition, specific sites near populated centers and airports in Costa Rica and Guatemala are also analyzed. Finally, we explore the possible impact of the low noise levels on the capability of detecting earthquakes and on the number of felt reports during the lockdown.

2. Data and methods

2.1. Seismic Stations and Data

We consider data from vertical-component seismometers from 10 seismic stations located in Costa Rica, Guatemala, El Salvador, and Nicaragua. Four of them are operated by the RSN (Costa Rica), four more by the INSIVUMEH (Guatemala), one belongs to the MARN (El Salvador), and one to the INETER (Nicaragua) (Figures 1 and A1). Most of these stations have been selected within or near the capitals of each country, to obtain an overview of the changes in the seismic records induced by the lockdown measures. In Costa Rica and Guatemala, where we had more access to the records, we also selected three stations close-by other populated centers or airports.

The selected stations include both broadband seismometers (BB) and short-period geophones (SP). For Costa Rica, we use the TC.SJS1 station (BB, Guralp CMG-6TD) located at the main campus of University of Costa Rica in San Jose. This station is 3 meters below the ground level, and the sensor is installed in a concrete pillar. We also inspected the stations TC.BELE, TC.ERIA, and TC.ZEDO (SP, Sixaola instruments manufactured by Raspberry Shake), located in urban areas at fire station buildings at ground level, close to Juan Santamaria International airport, Liberia city in Northwestern Costa Rica, and in San Isidro city (Perez Zeledon) in Southeastern Costa Rica, respectively. For Guatemala, we used the GI.GCG4 station (SP, OSOP Sixaola) located in an urban area, close to the Aurora International airport. This station is 3 meters below the ground level, and the sensor is also installed in a concrete pillar. Furthermore, we analyzed the stations GI.HUEH, GI.RETA, and GI.CHIE (BB-Guralp CMG-3ESP), located in urban areas, close to local airports and Huehuetenango, Retalhuleu, and Esquipulas downtowns, respectively. These stations are at ground level inside a dedicated vault with a concrete pillar.

For El Salvador and Nicaragua, we use the stations SV.CEDA (BB, Nanometrics Trillium-120p), located close to the Panamerican highway at the city of La Libertad and NU.MGAN (BB, Streckeisen STS-2), located at INETER in Managua downtown. The continuous seismic data for Costa Rica and Guatemala were obtained directly from the seismological networks of each country (INSIVUMEH, 2013; RSN, 2017) and from IRIS for El Salvador and Nicaragua, via FDSN (International Federation of Digital Seismograph Network) web services (INETER, 1975; SNET, 2004). We analyzed data over a time span covering one year from November 1, 2019 to October 31, 2020.

2.2. Seismic noise analyses

A spectral and amplitude analysis was carried out to characterize temporal variations in high-frequency (4-14 Hz) seismic signals dominated by the anthropogenic noise via RMS. We computed the high-frequency seismic noise amplitude prior to and during the pandemic lockdown measures (before March 16, 2020). The results have been compared to the lockdown measures implemented by the governments for each country, as documented in Table A1 (SICA, 2020), and their compliance by the population.

The high-frequency seismic noise amplitudes have been computed following the method described by Lecoq et al. (2020a) and using the code provided by Lecoq et al. (2020b). In this technique, the method of Welch (1967) is applied, in which a power spectral density (PSD) is calculated for each 30-minute time-windows with a 50 percent overlap, converted into equivalent displacement, and combined into a single RMS value per time-window (Blackman and Tukey, 1958). This reduces the numerical noise in the power spectra at the expense of reducing the frequency resolution due to frequency binning, but this effect is minimized with a conservative smoothing parameterization (Lecoq et al., 2020a). Moreover, to highlight the general temporal pattern of the amplitude of the seismic noise, the displacement RMS time series with four samples per hour were averaged each day between 6h and16h, according to the local time (UTC-6). Additionally, for some stations in Costa Rica and Guatemala, the median displacement RMS of each hour was computed, for each day, comparing the result before and during the lockdown. Finally, an analysis of the percentage of change in the HFSAND-RMS was performed to obtain a median amplitude value for the whole period during the major restrictive measures, from March 16 to May 15, 2020, and to compare it with the median of the period before lockdown measures from January 15 to March 15, 2020.

2.3. Earthquake detection capability and felt reports

For Costa Rica and Guatemala, the effect of the reduction of HFSAND-RMS on earthquake detection was explored during the lockdown period, using the seismic catalogs of the RSN (Costa Rica) and the INSIVUMEH (Guatemala). In both observatories, earthquakes are located automatically by SeisComP3 (Gempa, 2019) and manually using the software SeisAn (Havskov et al. 2020). With this objective, a period before lockdown from November 1, 2019 to March 15, 2020 (4.5 months) was taken as a reference to compare with a proportional period during the confinement measures, from March 16 as of July 31, 2020 (4.5 months).

Using curves of earthquake magnitude-frequency distribution, we inspected earthquakes with moment magnitude (Mw) $\leq$ 4.0 before and during lockdown, because small events reflect better the variations in the detection capability. Furthermore, we quantified the average number of seismic phases per earthquake as function of the magnitude, obtaining linear regressions for the two data sets. In addition, to explore the increase in the number of earthquakes detected as a function of magnitude, we calculated the Gutenberg-Richter relationship (Gutenberg and Richter, 1944) before and during the lockdown (Figure A2). To calculate these seismic parameters and their uncertainties, we used the classical maximum likelihood technique of Aki (1965) modified by Weichert (1980). To run this methodology, we used the OpenQuake software (GEM, 2020). The magnitude of completeness (Mc) was estimated by the MAXC method, which corresponds to the maximum point in the non-cumulative graph of the Gutenberg-Richter relationship (e.g. Wiemer and Wyss, 2000; Woessner and Wiemer, 2005).

We have also investigated the effect of lockdown measures on the number of earthquakes felt by the population. For both, Costa Rica and Guatemala, we counted the number of felt earthquakes in different magnitude intervals. In Costa Rica and Guatemala, the population reports via smartphones and social networks. Further, to analyze if there is a correlation between the decrease in HFSAND-RMS and the increase in low-magnitude felt events, and between the low-magnitude felt events and the hour of the day, we explored the spatial context of these events with a map of felt seismicity and its occurrence hour, before and during lockdown.

Additionally, the RSN maintains an interactive application for smartphones called “RSN”, which includes the module *"¿Lo Sentiste?"* (Linkimer and Arroyo, 2020), also available at the RSN website. This app was developed by the RSN based on the questionnaire *“Did you feel it?”* of the United States Geological Service (USGS) (Atkinson and Wald, 2007; Wald et al., 2011), which was translated to Spanish and simplified and adapted to Costa Rica. The users access the app and answer 12 simple questions (Table A2) and obtain a quick estimation of the intensity determined by the community decimal intensity (CDI), which is an aggregate of the average sums of the indexes associated with the questions (Dengler and Dewey, 1998). All the reports are shown in an emoticon map that updates continuously and can be accessed in real time in the app or in the RSN website. Finally, after enough (> ~300) reports and outliers have been manually removed, an average intensity map is generated (Linkimer and Arroyo, 2020). We use this tool to complement the felt earthquakes analysis in Costa Rica, collecting the number of felt earthquakes reported through this app, before and during lockdown, including only the events with at least three reports and with Mw < 5.0. These events were also averaged by magnitude intervals.

3. Results and discussion

3.1. Seismic noise and lockdown measures

The stronger lockdown measures in Central America started on March 16. In Costa Rica, some of the main restrictions implemented by the governments were the closure of borders, schools, non-essential stores, and beaches, as well as massive public events prohibition (concerts, soccer games, etc.) and home-office implementation. Although in Costa Rica no curfew was imposed on citizens, a strict vehicle mobility restriction has been maintained during the whole pandemic. For Guatemala and El Salvador, the lockdown measures were very similar to those implemented in Costa Rica, but in some cases included restrictions on citizen mobility and curfews. These measures have been softened or hardened as the pandemic evolved in each of these countries (Table A1). Very few lockdown measures were taken in Nicaragua to prevent the spread of Covid-19 and there were no specific measures applied to restrict social mobility.

An important decrease in the HFSAND-RMS is shown in seismic stations located near the capitals of Costa Rica (University of Costa Rica campus, San José), Guatemala (close to the Aurora International airport, Guatemala City), and El Salvador (close to the Panamerican highway) (Figure A1). This has been observed during the lockdown measures (Table A1 and Figures 2 and 3), except for Nicaragua (urban area, at INETER, Managua).

Figure 2 shows the time of day on the vertical axis, the period analyzed on the horizontal axis, and the high-frequency displacement RMS in colors, blue for the lowest level and yellow for the maximum. The graph clearly shows the stillness of the night (blue colors between 22h and 5h), the relative quiet of weekends (vertical blue bars that alternate periodically), and the hustle and bustle from day to day (in yellow colors). Figure 3 shows the displacement on the vertical axis and time on the horizontal axis. The orange line represents the median recorded displacement, which usually has its maximum during the hours of the day, when there is more seismic noise, and its minimum during the nights. In addition, Figure 3 also show that the noise level is lower during the weekends. In these figures, we marked the beginning of the social distancing measures on March 16 (red line), the period of the end of the year holidays 2019 (1), Easter 2020 (2), and a brief period in July 2020 when there was a strict return of lockdown measures in Costa Rica (3) (Table A1).

In both types of graphs (Figures 2 and 3), for the stations in Costa Rica, Guatemala, and El Salvador, the effect of the social distancing measures can be clearly seen beginning on March 16, as a notable drop in seismic noise (displacement). At the station in Managua, Nicaragua, where no important measures were adopted to limit urban mobility and economic activities, there is no change in the seismic record (Figures 2d and 3d). In Costa Rica, Guatemala, and El Salvador, the seismological stations show that the measures of social distancing produced a decrease in the seismic noise levels similar to those observed in the 2019 New Year holidays.

For the TC.SJS1 station in San Jose, Costa Rica (Figure 2a and 3a), the displacement during a typical working day before the lockdown used to be up to 200 nm, while during the social distancing measures, these values decreased to 140 nm on average. In the case of the GI.GCG4 station in Guatemala City (Figure 2b and 3b), the usual displacement before the lockdown was 100 nm on average, and during social distancing measures, these values decreased to 80 nm on average. At the SV.CEDA station, near San Salvador (Figure 2c and 3c), the usual displacement before the lockdown was on average about 120 nm, while these values decreased to 80 nm on average during the lockdown.

The lower displacement values, tended to return to their usual averages values as the restrictive measures were progressively eliminated. Even so, the values have not yet returned to the usual pre-pandemic levels by November 2020, when the average values were ~ 160 nm for San Jose, ~ 85 nm for Guatemala City, and ~ 110 nm near San Salvador. This shows that some of the social distancing measures were still in place by November 2020 (Table A1) or other factors are affecting the station environment (permanent or long-term activity loss, e.g., company shutdown) (Figures 2 and 3). The place location where the level is closer to the usual averages is at La Libertad near San Salvador. The most drastic effect of the limitation in the mobility of the inhabitants was observed during Easter in April of 2020. The values observed were: ~60 nm in San José and ~50 nm in Guatemala City and near San Salvador.

In the case of the NU.MGAN station in Managua, Nicaragua (Figures 2d and 3d), the registered displacement values have remained constant before and during the pandemic, without any variation with respect to the usual displacement records of this station (40 nm). It is a low-noise site compared to the other capitals because it has particular conditions that favor its isolation from the environmental noise.

Results for Costa Rican stations TC.BELE, TC.ERIA, and TC.ZEDO are presented in Figure 4a and Guatemalan stations GI.HUEH, GI.RETA, and GI.CHIE in Figure 4b. All these stations also show a decrease in displacement RMS since the application of lockdown measures. However, the reduction, as well as the pattern of the displacement RMS time series is very specific to each station. For Costa Rica (Figure 4a), the largest percentage difference in the station record is found in the TC.BELE station, located near (~3 km) the country's main airport and in the Great Metropolitan Area (GAM) (Figure 1). This station varied from ~40 nm before lockdown to ~20 nm during the lockdown measures. For Guatemala (Figure 4b), a similar behavior was observed in the GI.RETA station, towards the western part of this country, which is one of the most touristic regions. This station varied from ~100 nm before lockdown to ~50 nm during the lockdown measures.

In addition, the daily variation of the average seismic noise per weekday, before and during the pandemic, was inspected for the station TC.SJS1 in Costa Rica (Figure 5a) and for station GI.RETA in Guatemala (Figure 5b). In both stations, the typical pattern of HFSAND-RMS is also shown, with minimums during weekends and nights, and maximums during the week and day (Figure 5). This is also highlighted during the lockdown, due to the measures adopted by each country (Table A1). Costa Rica, despite not imposing a curfew, established measures of vehicular restriction from 19h to 5h at its most strict stage. This is highlighted in the station TC.SJS1, showing a great decrease in HFSAND-RMS during these hours (Figure 5a). For Guatemala, the station GI.RETA clearly shows the effect of the curfew in its most restrictive stage, imposed from 17h to 5h (Figure 5b).

The percentage of HFSAND-RMS decrease was determined for the 10 stations analyzed here, in the same frequency band (4-14 Hz). Figure 6a shows the change obtained for the stations in Guatemala and El Salvador and Figure 6b shows the percentage obtained for the stations in Nicaragua and Costa Rica. Four categories of seismic noise reduction were identified: very high (36-49%), high (26-35%), intermediate (16-25%), and low (6-15%). The most outstanding seismic noise reduction (very high) due to the lockdown measures were obtained at the GI.RETA and TC.BELE stations. These values are explained by the site characteristics described above, strong sources of noise at stations close to major cities, highways, and high-traffic airports. The stations that show a high decrease were GI.GCG4, SV.CEDA, and TC.SJS1. These changes are closely related to the location of these sites at the populated capital cities of San José and Guatemala City, and to the Panamerican highway near San Salvador (Figure 1). Intermediate decrease values were identified in the stations GI.HUEH, GI.CHIE, and TC.ERIA. In this case, these values are associated with cities with less population density (Figure 1) but significant activity and proximity to touristic airports, such as Liberia city, in northwestern Costa Rica. Finally, low changes were identified in the NU.MGAN and TC.ZEDO stations. In Managua, this is due to the lack of social distancing measures and in the case of Perez Zeledon (Costa Rica), it could be related a lower population density, a station site building more confined, less exposed to population and environment dynamics, or lack of compliance with lockdown measures.

3.2. Possible effects of the lockdown in earthquake detection and felt reports

There were no significant earthquakes in Costa Rica and Guatemala during the time this study was conducted. Before lockdown in Costa Rica, the biggest earthquakes had a Mw of 5.6 on 21-01-2020 and in Guatemala a Mw of 6.2 on 19-11-2019. During lockdown, the largest events were a Mw 5.5 earthquake on 15-04-2020 in Costa Rica and a Mw 5.7 on 26-03-2020 in Guatemala. All these events were offshore earthquakes related to the interplate seismogenic zone. We conclude that the seismic rates during the time periods considered in this work were not affected by any specific large event..In Table A3 we summarize the main observations when comparing the earthquake detections and felt reports from the time before the lockdown and during lockdown for Costa Rica and Guatemala.

Costa Rica

Since 2018, the RSN network consists of around 160 sites, qualifying as a robust network with a high capacity for detecting low-magnitude earthquakes (Linkimer et al., 2018). Figure 7 shows the comparison of the number of seismic events recorded by the RSN and the reports of earthquakes felt before and during the lockdown measures.

Figure 7a shows the number of earthquakes on the vertical axis, and the range of magnitude on the horizontal axis, grouped in intervals of 0.5, from Mw 2.0 to 5.5. The graph shows that there is no increase in the capacity to detect earthquakes during the lockdown measures, and it even seems that more seismicity was detected in the period before lockdown, possibly due to higher seismic productivity in that period. The Mc shows that the impact of the lockdown measures in the detected earthquakes is not significant as Mc varies from 2.9 before to 3.0 during lockdown (Figure A2a and A2b). Also, the a- and b-values obtained were very consistent and similar to recent studies for Costa Rica (i.e., Arroyo and Linkimer, 2021). The a-value decreased slightly during the lockdown from 3.62 to 3.56, showing a general decrease in the seismic rate. On the other hand, the increase in the b-value from 0.76 to 0.77 could be explained as an increment in the number of low-magnitude earthquakes compared to the number of higher magnitudes. This b-value could support the idea that more low-magnitude earthquakes were detected during the lockdown period (Table A3). However, as it can be seen the variations very small to allow strong conclusion. The observed variations could also be explained due to other contributing factors or even as random coincidence.

In Figure 7b we show the average number of P-wave phases per earthquake for earthquakes with $M \leq 4.0$. Although the difference in the number of P-wave arrivals before and during the pandemic is not too much (between 1 and 5 picks for magnitudes between 1.8 and 4.0), the values are consistently higher (on average ~20%) during the pandemic, especially for the lower magnitudes ($M \leq 3.5$). This additional observation also favors the idea that the decrease in HFSAND-RMS during lockdown may have had an effect on the earthquake detection capability of the RSN (Table A3).

Figure 7c shows the number of felt earthquakes reported through social networks or telephone calls with respect to a range of Mw from 2.0 to 5.5. This graph shows that there were a greater number of earthquakes with Mw > 3.5 reported as felt before the lockdown measures, but during the confinement, a greater number of reports for low magnitude earthquakes ($M < 3.5$) were collected (Table A3). In addition, based on reports through the RSN application *"¿Lo Sentiste?"*, we present in Figure 7d the average number of reports for $M < 5.0$ by magnitude intervals. The trend lines in this graph show how the application *"¿Lo Sentiste?"* collected, on average, more felt reports for magnitudes $M < 5.0$ during the lockdown measures. These figures suggest a greater sensitivity of the population to low-magnitude earthquakes, possibly because the longer stays in their homes and the implementation of home office and restrictions of mobility, allowed them to perceive more events and also to report them to seismic agencies (Table A3).

Figure 8 shows the geographical distribution of felt events reported by the RSN (Figure 7c) before (1 Nov 2019-15 Mar 2020) and during (16 Mar-31 Jul 2020) lockdown measures in Costa Rica. Even though the number of earthquake reports was higher before (99) than during (74) the lockdown measures, the percentage of low magnitude (M < 3.5) felt earthquakes was clearly higher (46%) during the lockdown than before it (only 27%). These numbers suggest that the quiescence of the environment could be an important contributing factor to more small earthquakes being reported (Table A3). Another aspect is that there were a greater number of higher-magnitude earthquakes (M > 4.5) before the lockdown (20) than during it (11), and these events were located onshore and closer to population centers (Figure 8).

We also checked the correlation between felt events, before and during lockdown, and the decrease in the HFSAND-RMS of the four seismic stations analyzed in Costa Rica. There seems to exist a correlation in three of them, two located in the metropolitan area of Central Costa Rica (TC.SJS1 and TC.BELE) and the other in an urban area in Southeastern Costa Rica (TC.ZEDO). There were 25 felt earthquakes for Central Costa Rica before the lockdown and 17 of them had a low magnitude (M < 3.5). These numbers are lower than those during lockdown, when there were 36 felt earthquakes, including 28 of low magnitude (Figure 8). For Southeastern Costa Rica, near the Perez Zeledon urban area (TC ZEDO), just five felt earthquakes were reported before the lockdown, all of them with M > 3.5, but during lockdown seven events were reported as felt, four of them of low magnitude (Figure 8 and Table A3). Then, again, these observations suggest an increase in felt reports from small earthquakes in these regions as well. These felt events, as expected, were more perceived during the night hours, from 18h to 6h (Figure 8).

Guatemala

The INSIVUMEH seismic network is still under development. This network consists of 24 seismic stations, most of them Guralp broadband sensors, some installed inside the main military detachments or national airports, while others are installed in the main tourist cities of the country. For this reason, these stations can reach high levels of seismic noise, which is why detecting low-magnitude earthquakes under pre-pandemic conditions were challenging.

In Figure 9a, we present a comparison between the statistics before and during the lockdown measures. Similar than Costa Rica, for Guatemala this graph shows that a higher number of events was recorded during the lockdown measures (Table A3). However, the analysis of other seismic parameters are not conclusive: Mc varies only slightly from 3,7 7o 3,8 from before to during the lockdown, which does not imply a significant increase in earthquake detection (Figure A2c and A2d). But the a- and b-values seem to suggest an increment in low magnitude earthquake, changing from 4.43 to 4.63 for the a value and from 0.87 to 0.91 for the value, for the periods of before and during the lockdown.

In Guatemala, the average number of seismic phases per event of the same magnitude increases clearly for magnitudes lower than 3.0 during the lockdown (on average ~40%) (Figure 9b). Then, the possible effect of the lower levels in seismic noise for detecting more low-magnitude earthquakes could be stronger in Guatemala than in Costa Rica (Table A3). This may be related to the much lower seismic station density of Guatemala.

Furthermore, it should be noted that the lockdown measures implemented by the Guatemalan government were more drastic than in Costa Rica. Moreover, the number of felt events reported by the population shows again the interesting trend of a general increase during the lockdown period, but in the case of Guatemala this is visible for $M \geq 3.5$ (Figure 9c and Table A3).

Figure 10 shows the distribution of the felt earthquakes reported to INSIVUMEH (Figure 9c) before and during the lockdown. Before the lockdown, a total of 34 seismic felt events were reported, while during lockdown that number increased to 47. The earthquake magnitudes were higher before lockdown (Figure 10a) with 21 earthquakes above M 4.5 (62% of the total felt events in this period) than during lockdown, with 19 earthquakes above M 4.5 (40% of the total felt events in this period). Hence, during the lockdown there were more felt earthquakes of lower magnitude ($M < 4.5$), including three earthquakes below M 3.5, in contrast to just one before the lockdown. Once more, this trend suggests a correlation between the quiescence of the environment and and increment in low magnitude felt events during the lockdown (Figure 10 and (Table A3). These felt events, as expected, were more perceived during the night hours, from 18h to 6h (Figure 10).

Finally, from the spatial distribution of felt earthquakes during lockdown, we observed that, unlike the time before the pandemic, there are more events originated onshore and mainly close to the populated places, such as Guatemala City and Huehuetenango. These are epicentral locations near two of the seismic stations for which the decrease in the HFSAND-RMS was observed: GI.GCG4 and GI.HUEH, respectively. In a seismic network under development like the INSIVUMEH, with fewer stations, a high percentage of the low-magnitude seismicity is likely not detected due to ambient noise, but the observations provided above seems to support the idea that the lockdown measures cause an improvement in the detection capacity of this network.

4. Conclusions

An important decrease in the high-frequency seismic noise was detected at stations of three Central American countries during the lockdown measures adopted to prevent the spread of Covid-19. In Costa Rica, Guatemala, and El Salvador, the measures of social distancing produced seismic noise levels comparable to those observed during the New Year holidays from previous years. The displacement observed decreased from 200 to 140 nm in San Jose, from 100 to 80 nm in Guatemala City, and from 120 to 80 nm in the city of La Libertad near San Salvador. In Nicaragua, with very few measures in place, there were no effects on the seismic noise levels of the station analyzed, which also happens to be a quiet site (40 nm).

The decrease in the high-frequency seismic anthropogenic noise displacement is strongly dependent on the location of the station and on the lockdown measures. Four categories of seismic noise reduction were identified (very high, high, intermediate, and low), with significant values of ~50% decrease were observed in stations near airports, busy roads, and densely populated cities. The greatest impact in the noise levels started on March 16 and was specially related to the closure of educational centers and non-essential stores, the curfew from 17h to 5h in Guatemala, and the restriction on vehicular mobility from 19h to 5h in Costa Rica. The most drastic effect of the limitation in the mobility of the inhabitants was observed during Easter in April of 2020, when the values observed were as low as ~60 nm in San José and ~50 nm in Guatemala City and near San Salvador.

We suggest that in Costa Rica, the lower levels in seismic noise allowed the detection of a higher number of seismic phases (~20% more per magnitude) and therefore, the location of more small earthquakes than usual, as well as more low magnitude earthquakes (M < 3.5) reported as felt. Similarly, in Guatemala, where the seismic network is still under development, we suggest a similar effect with an increase of ~40% in the amount of the phase picking for low magnitude events and, the detection of a higher number of low magnitude earthquakes (< 2.5) than before the lockdown. In addition, there were more felt reports during lockdown in both countries, mainly in the urban areas of Central and Southeastern Costa Rica, and in Guatemala City and Huehuetenango. Although we present some evidences to link the reduction in seismic noise and the increase in earthquake detections and felt reports, the variations in the magnitude of completeness and the a- and b- values are not significant enough before and during the lockdown to confirm that connection or to discriminate other possible contributing factors.

Finally, we suggest that there could be a connection between the lockdown measures and the number of felt reports for smaller earthquakes (M < 3.5) in Costa Rica and Guatemala. This possible effect may have been induced by a more quiescence environment, more people with home office measures and longer time at homes, which might have stimulated a higher sensitivity in the population to feel low magnitude earthquakes and to report them to the seismic agencies. This work demonstrates that seismic networks can monitor population mobility and consequently can be used to verify the compliance of lockdown measures and to explore the consequences of reducing seismic noise in earthquake detection and felt reports.

Code availability

All the codes used to analyze the seismic data are available in Lecocq et al. (2020b).

Data availability

The data is available by FDSN web services for INSIVUMEH and RSN-UCR seismic networks.

Author contributions

MA designed the study and wrote the paper with contributions from all co-authors. MA and DC processed the seismic data and made figures. All the authors interpreted and analyzed the results and revised the article.

Competing interests

There are no competing interests.

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Figures

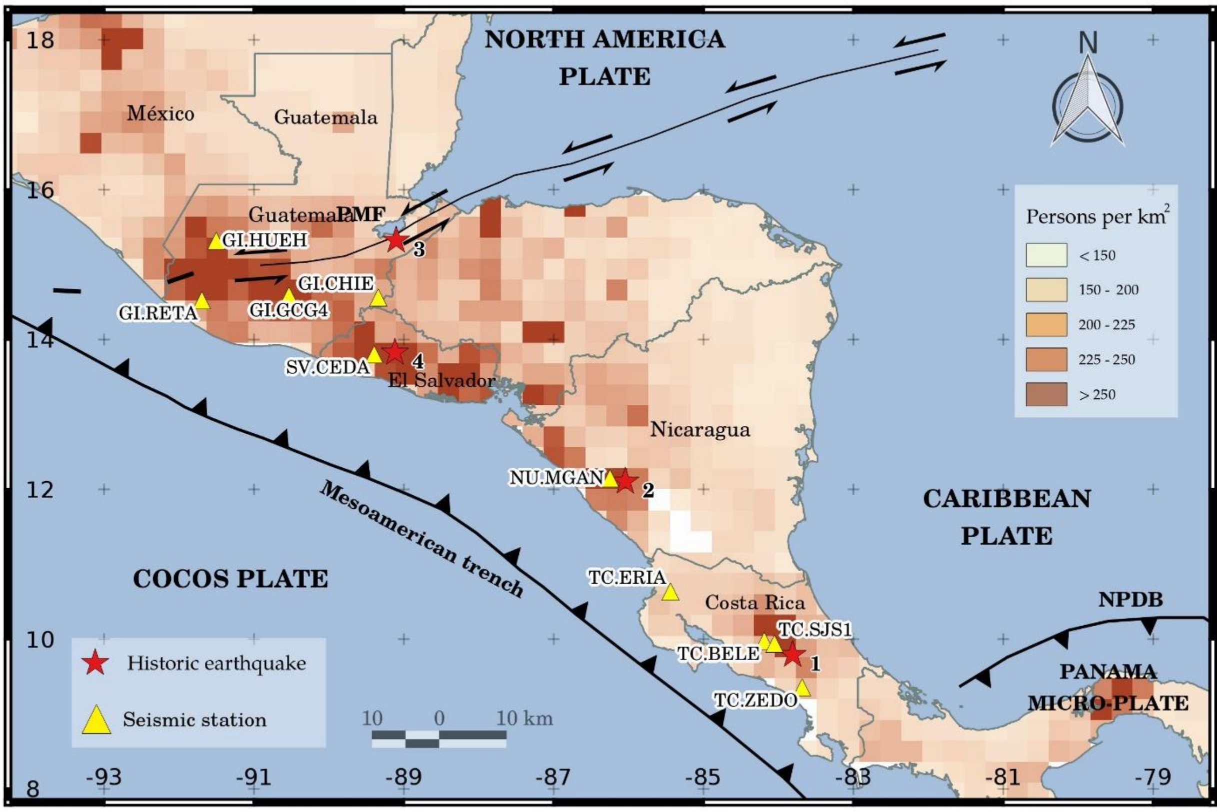

Figure 1. Map of Central American and location of the selected seismic stations from Costa Rica, Guatemala, El Salvador, and Nicaragua, used in this work. The map shows the approximate location of the North Panama Deformed Belt (NPDB) and the Polochic-Motagua Fault (PMF). Darker red tones indicate areas with higher population density. The numbered stars represent the historic deadliest earthquakes mentioned in the text: 1) 1910 M 6.4 Cartago, Costa Rica, 2) 1972 M 6.3 Managua, Nicaragua, 3) 1976 M 7.5 Guatemala, and 4) 1986 M 7.5 San Salvador, El Salvador. © ESRI and its data partners (ArcGis Services).

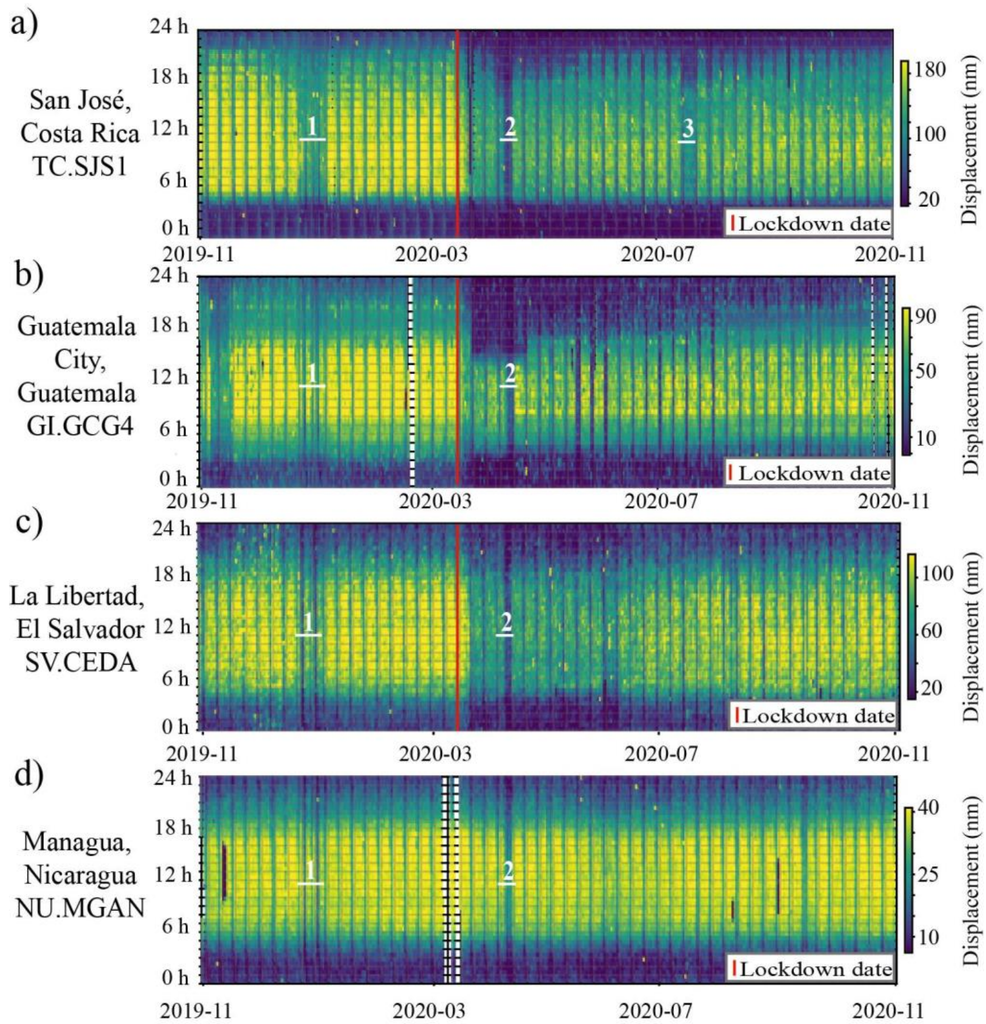

Figure 2. High-frequency seismic anthropogenic noise displacement (HFSAND-RMS) evolution near capitals of the countries studied in an hourly grid representation. a) TC.SJS1 station in San Jose, Costa Rica. b) GI.GCG4 station in Guatemala City, Guatemala. c) SV.CEDA station, near San Salvador in the city of La Libertad. d) NU.MGAN station in Managua, Nicaragua. Gaps correspond to periods for which seismic data were unavailable and the vertical red lines indicate the time when the first lockdown measures started in Central America. The numbers 1, 2, and 3 show the New Year holidays of 2019, Easter of 2020, and a brief period in July 2020 when a strict return of lockdown measures was implemented in Costa Rica, respectively.

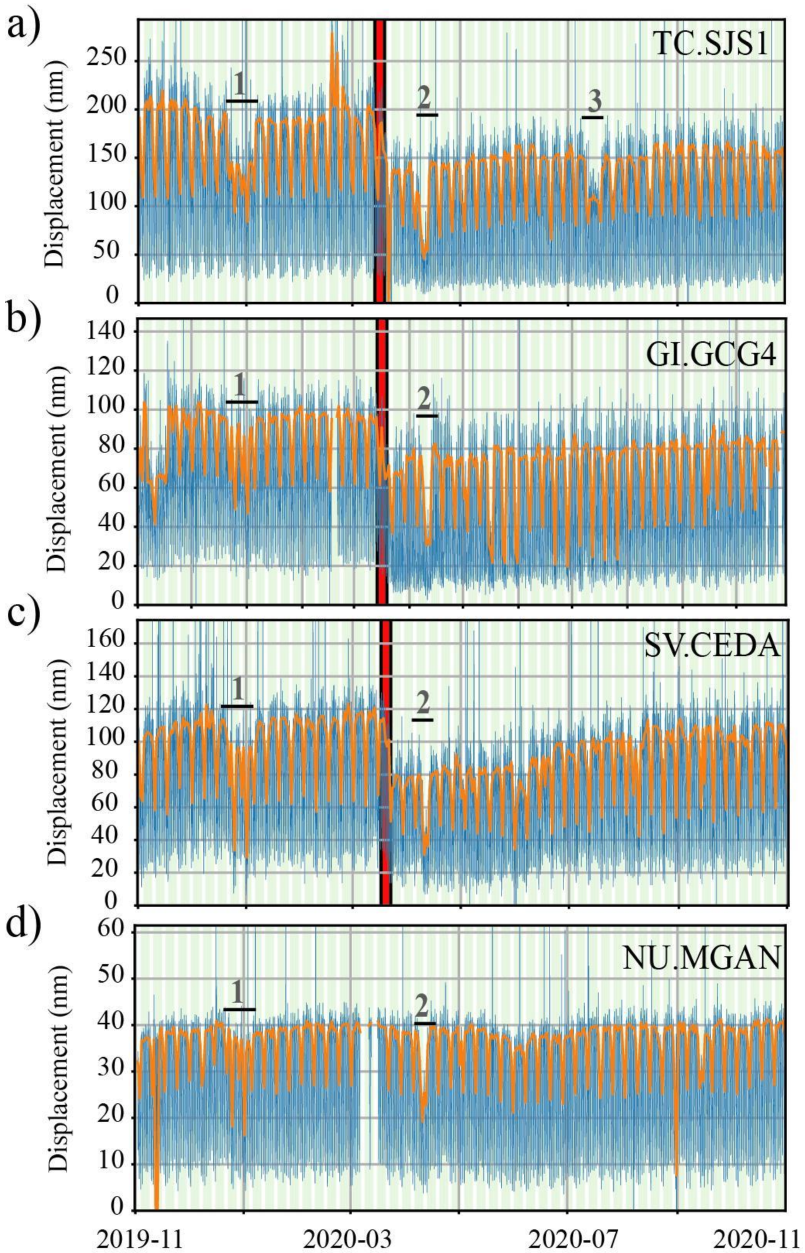

Figure 3. High-frequency seismic anthropogenic noise displacement (HFSAND-RMS) evolution at the seismic stations near capitals of the countries studied. a) TC.SJS1 station in San Jose, Costa Rica. b) GI.GCG4 station in Guatemala City, Guatemala. c) SV.CEDA station, near San Salvador in the city of La Libertad. d) NU.MGAN station in Managua, Nicaragua. The blue line corresponds to the RMS amplitude time series of the vertical component, filtered between 4 and 14 Hz, and the orange line corresponds to median day-time, between the 6 and 16 hours of local time. Gaps correspond to periods for which seismic data were unavailable and the vertical red lines indicate the time when the first lockdown measures started in Central America. The numbers 1, 2, and 3, show the New Year holidays of 2019, Easter of 2020, and a brief period in July 2020 when a strict return of lockdown measures was implemented in Costa Rica, respectively.

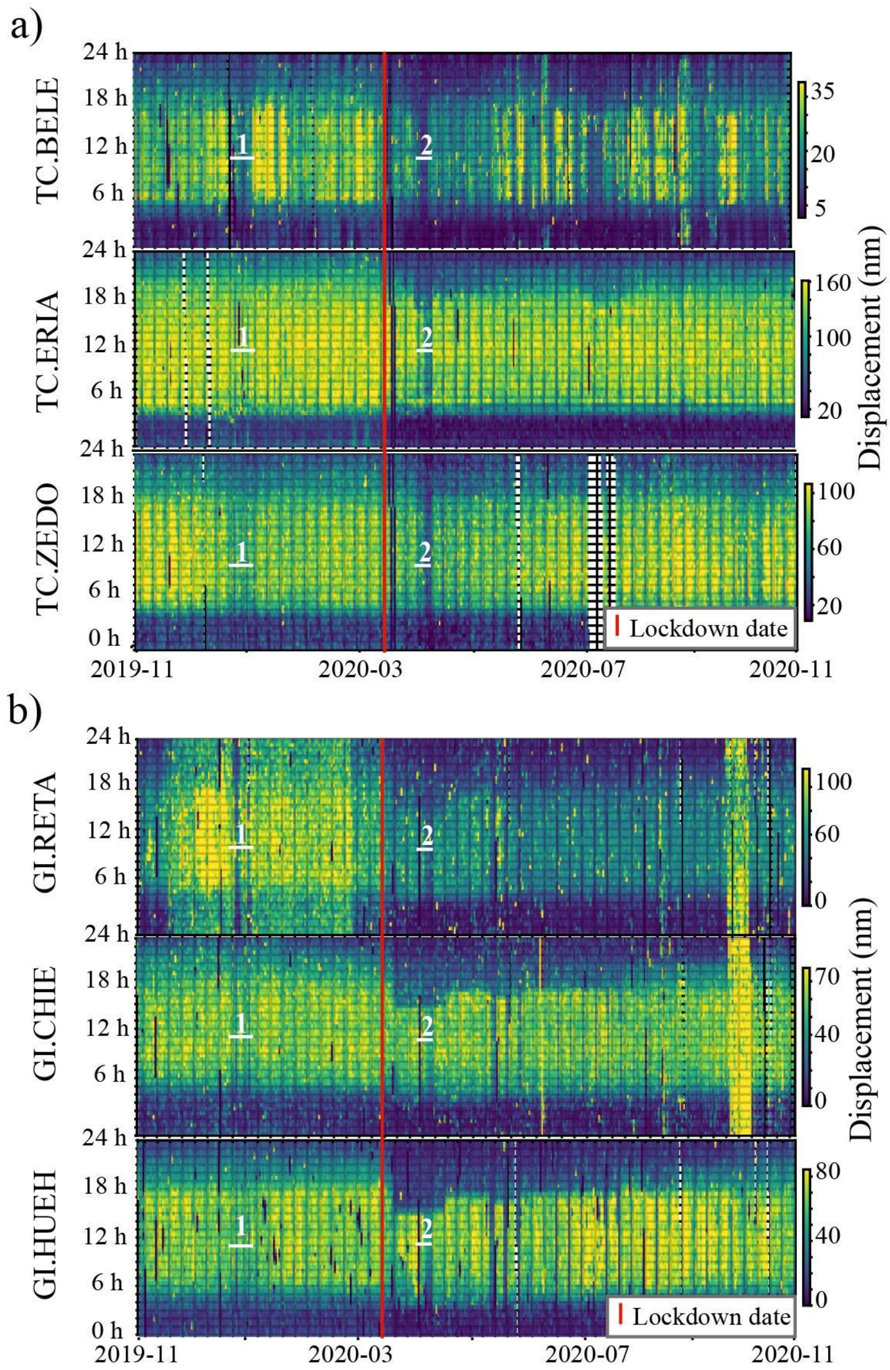

Figure 4. High-frequency seismic anthropogenic noise displacement (HFSAND-RMS) evolution for specific sites in Costa Rica and Guatemala in an hourly grid representation. a) TC.BELE (central Costa Rica, near Juan Santamaria international airport), TC.ERIA (northern Costa Rica, urban area), and TC.ZEDO (southern Costa Rica, urban area). b) GI.HUEH (northwest of Guatemala, urban area), GI.RETA (southwest of Guatemala, urban area), and GI.CHIE (east of Guatemala, urban area). The gaps correspond to the time periods for which seismic data were unavailable and the vertical red lines indicate the time when the first lockdown measures started in Central America. The numbers 1 and 2 show the New Year holidays of 2019 and Easter of 2020, respectively.

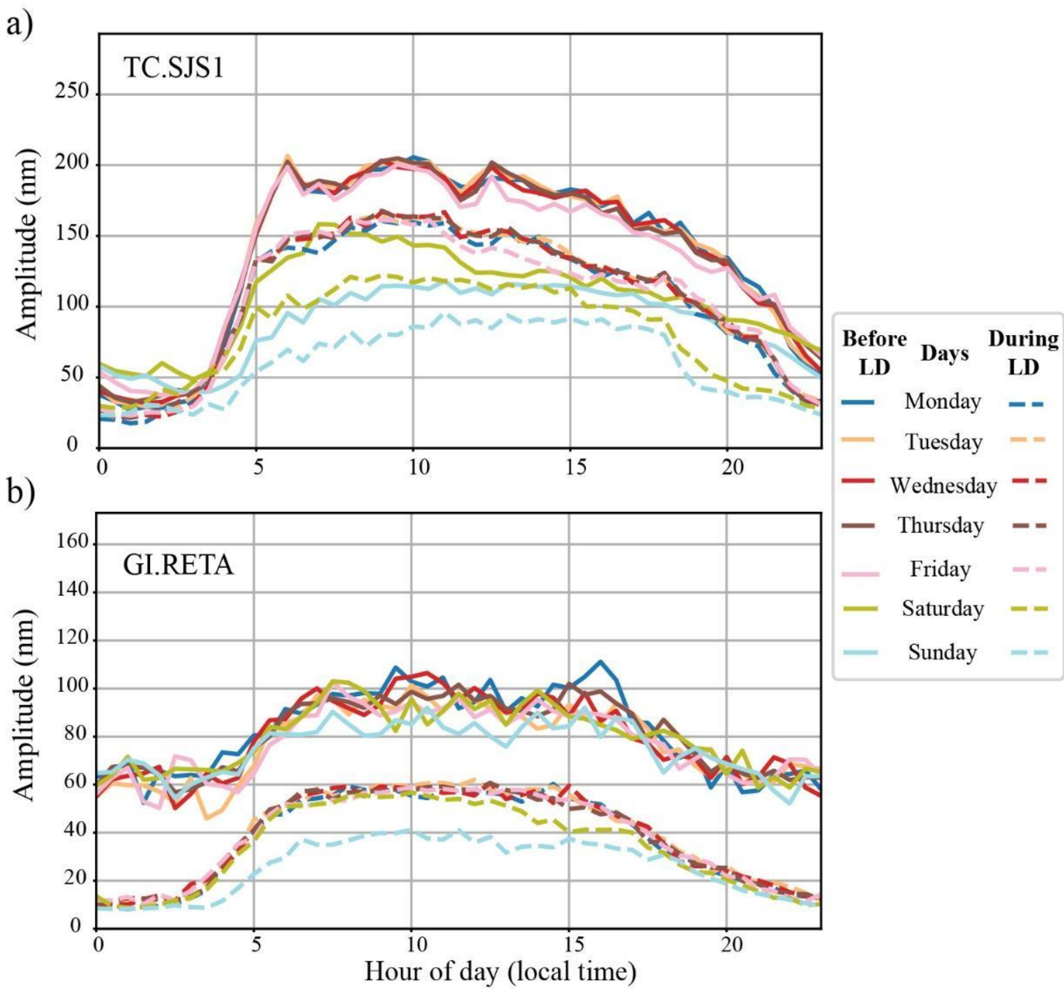

Figure 5. Daily variation of the median seismic noise per weekday, before and during the lockdown (LD). a) TC.SJS1 station in San Jose, Costa Rica. b) GI.RETA station in Retalhuleu, southwest of Guatemala.

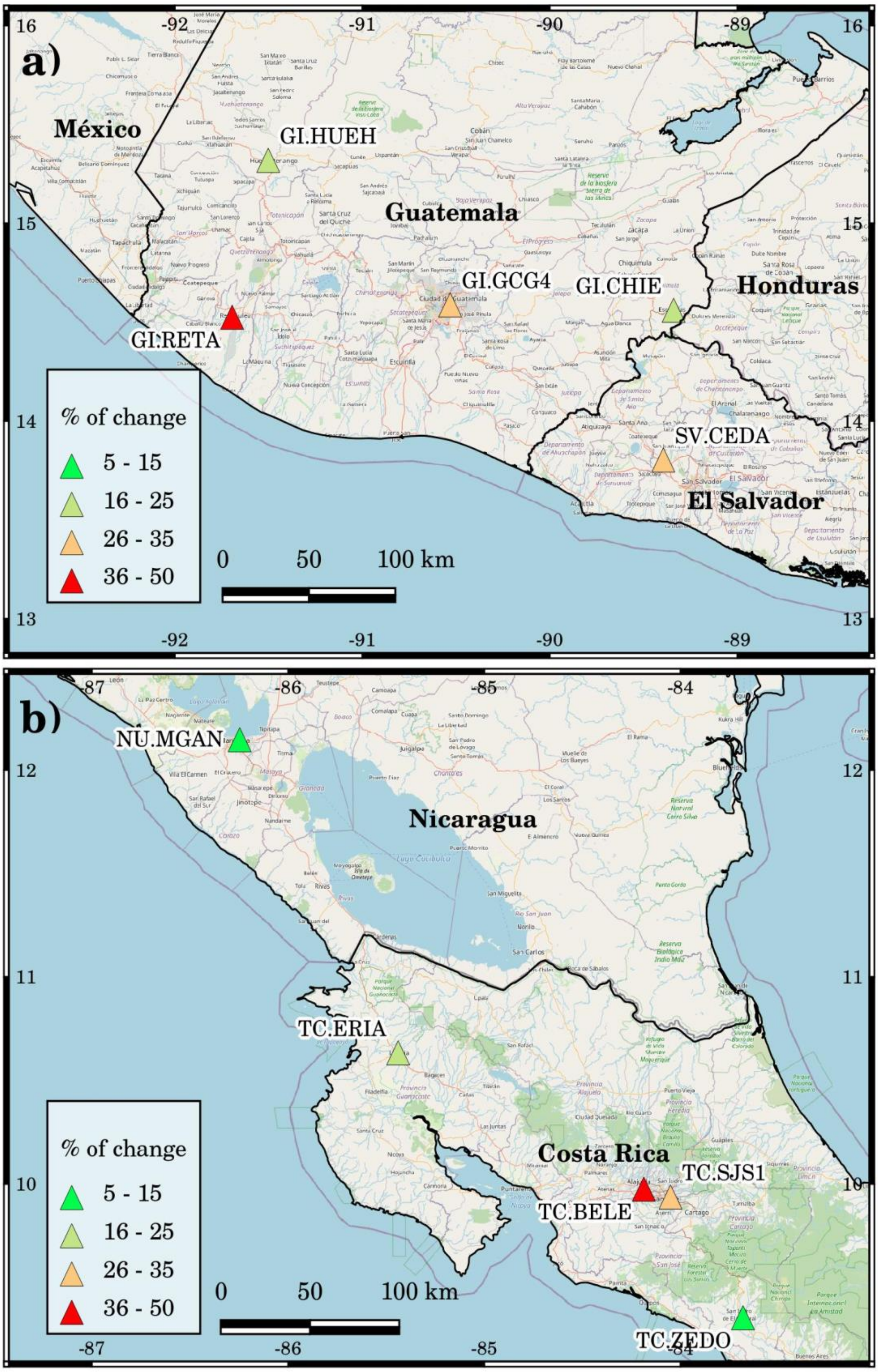

Figure 6. Percent of change of the high-frequency seismic anthropogenic noise displacement (HFSAND-RMS) in the band 4-14Hz during the period from January 15 to March 15, 2020 (before lockdown measures) with respect to the time interval from March 16 to May 15, 2020 (after the lockdown measures were applied). a) Percent of change in seismic stations of Guatemala and El Salvador. b) Percent of change in seismic stations of Nicaragua and Costa Rica. © OpenStreetMap contributors 2020. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

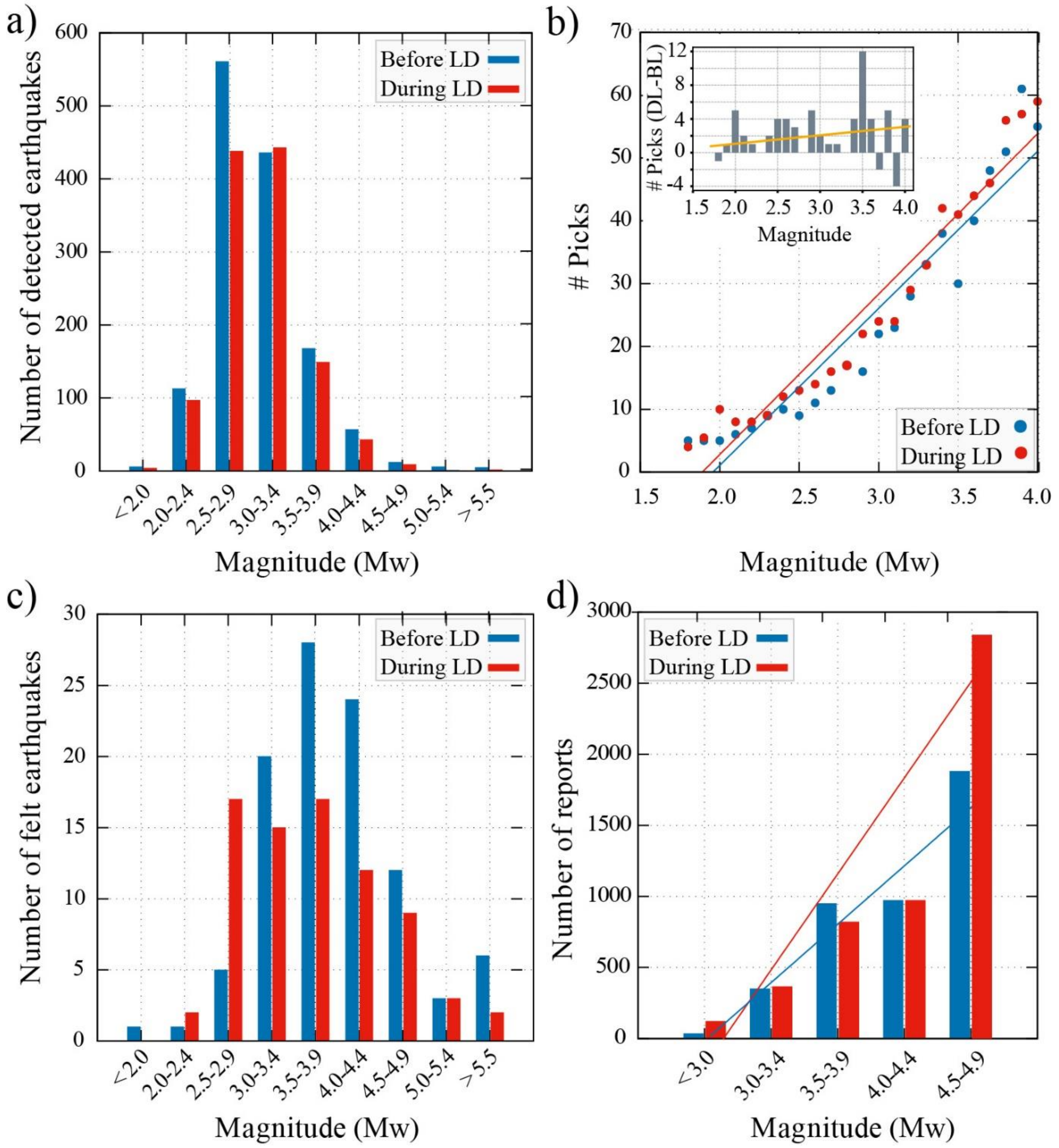

Figure 7. Event detection and felt earthquakes reported in Costa Rica before (1 Nov 2019-15 Mar 2020) and during (16 Mar-31 Jul 2020) lockdown (LD) measures. a) Number of detected earthquakes. b) Earthquake magnitude versus the average number of P-wave picks per Mw for the events with Mw < 4.0, and the corresponding linear fits. The inset graph shows the average difference in the number of picks for magnitude bins for the time periods before (BL) and during (DL) the lockdown. c) Number of felt earthquakes in Costa Rica. d) Magnitude versus the number of reports from the population through the RSN application for smartphones *"¿Lo Sentiste?"* for events with Mw < 5.0, and the corresponding linear fits.

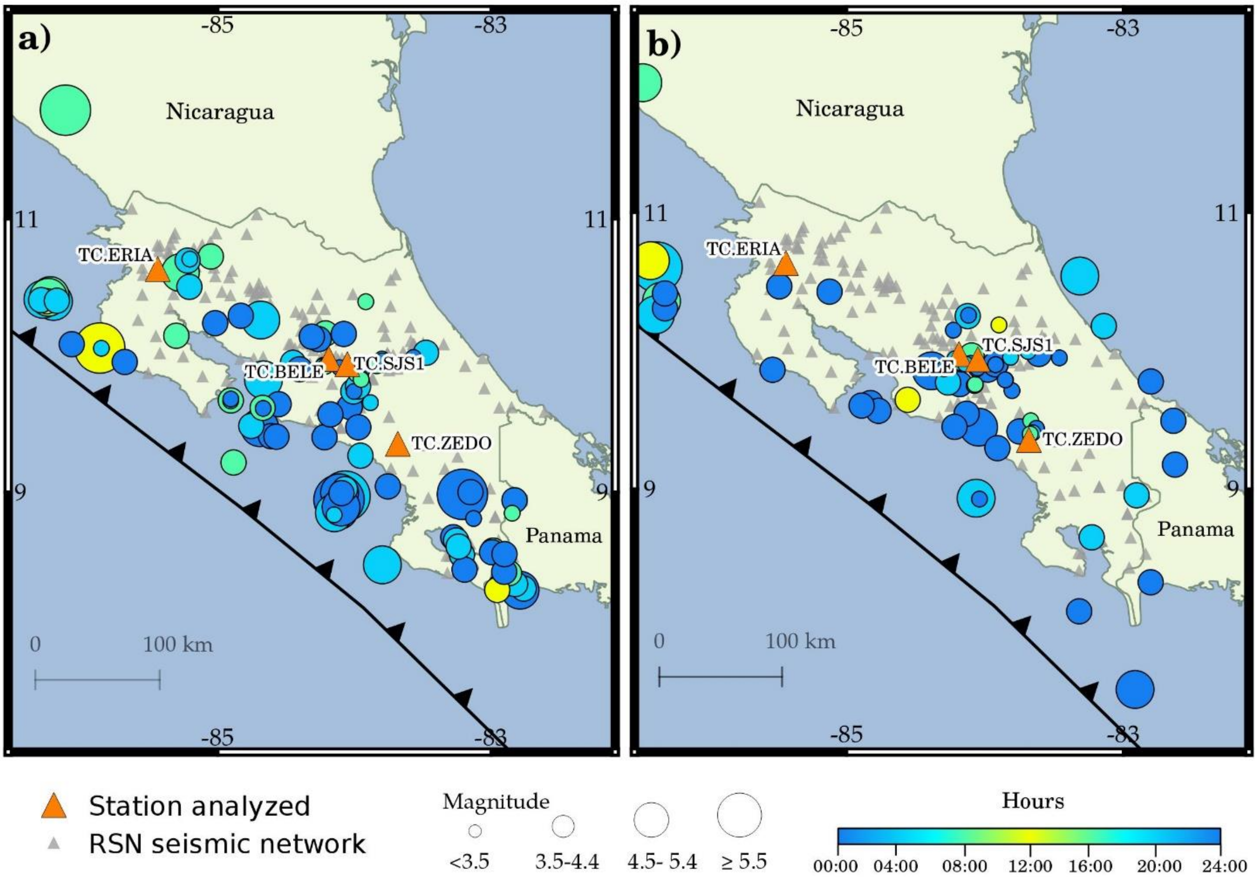

Figure 8. Map of felt earthquakes reported in Costa Rica. a) Before lockdown measures (1 Nov 2019-15 Mar 2020). b) During lockdown measures (16 Mar-31 Jul 2020).

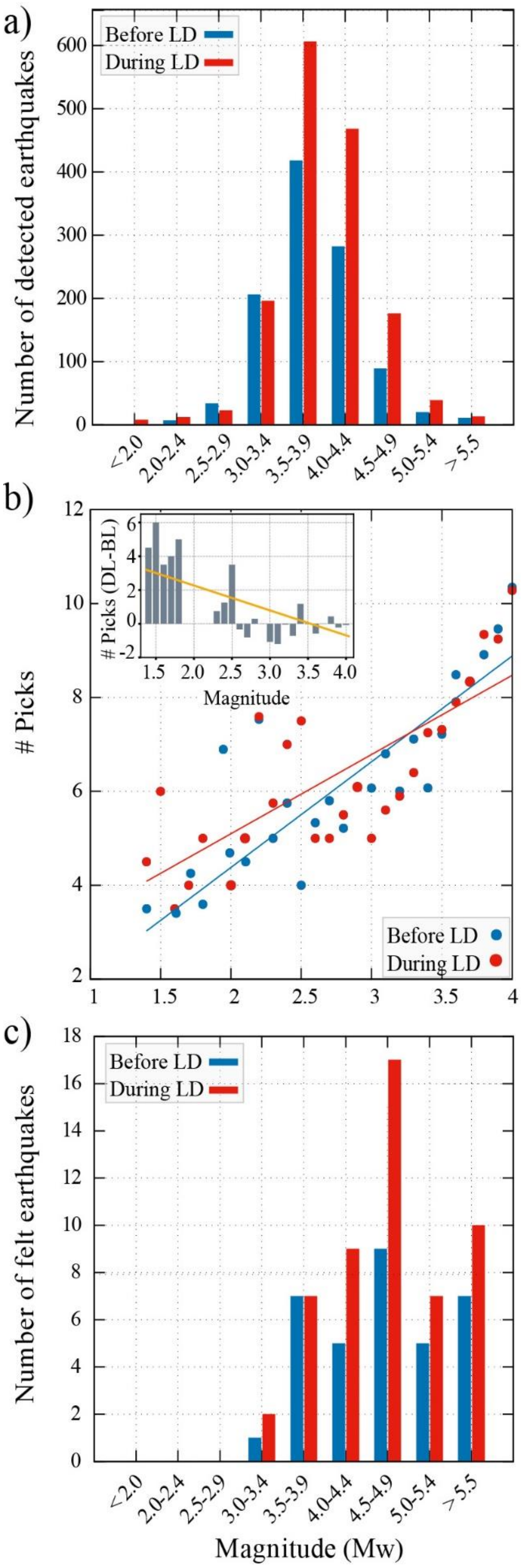

Figure 9. Event detection and felt earthquakes reported in Guatemala before (1 Nov 2019-15 Mar 2020) and during (16 Mar-31 Jul 2020) lockdown (LD) measures. a) Number of detected earthquakes. b) Earthquakes magnitude versus the average number of P-wave picks per Mw for the events with Mw < 4.0, and the corresponding linear fits. The inset graph shows the average difference in the number of picks for magnitude bins for the periods before (BL) and during (DL) lockdown. c) Number of felt earthquakes in Guatemala.

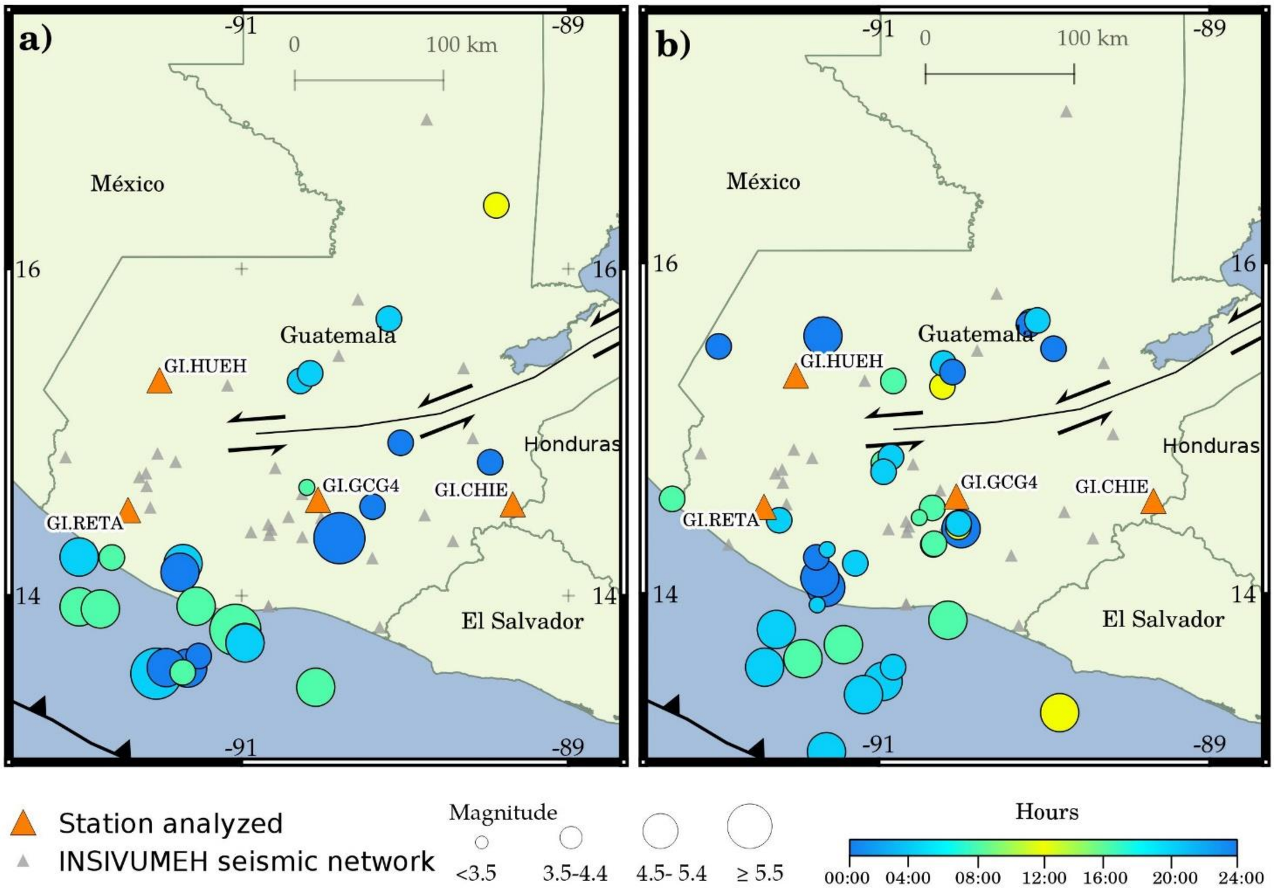

Figure 10. Map of felt earthquakes reported in Guatemala. a) Before lockdown measures (1 Nov 2019-15 Mar 2020). b) During lockdown measures (16 Mar-31 Jul 2020).

Appendix: additional figures and tables

Figure A1. Images from Open Street Maps of the site areas where the seismic stations (orange triangles) used are located. © OpenStreetMap contributors 2020. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

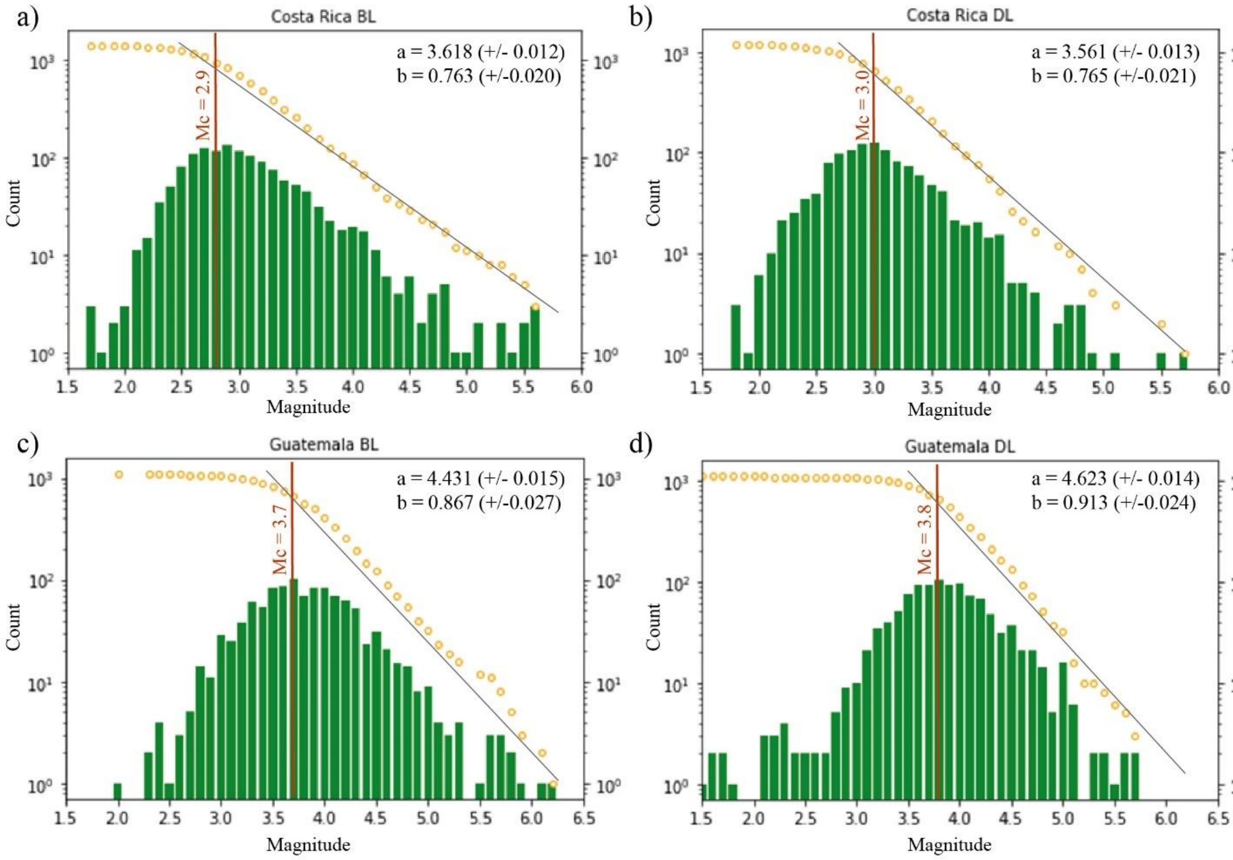

Figure A2. Magnitude-frequency distribution for earthquakes. a) Costa Rica before lockdown. b) Costa Rica during lockdown. c) Guatemala before lockdown. d) Guatemala during lockdown. Green bars represent the incremental (non-cumulative) number of earthquakes and yellow circles the cumulative distribution of events. The grey solid line fits the data points for the cumulative distribution above the magnitude of completeness (Mc). Vertical lines indicate the Mc estimated from the maximum curvature (MAXC) method.

Table A1. Main mobility lockdown measures between March and October 2020, in Costa Rica, Guatemala, and El Salvador during the Covid-19 pandemic according with the "Sistema de Integracion Centroamericana" (SICA), (2020). Nicaragua did not establish lockdown measures for social mobility. On March 18 the first positive case of Covid-19 was found in Nicaragua.

Month	Costa Rica	Guatemala	El Salvador
March 2020	**Day 6**, the first positive case for Covid-19 is detected. **Day 9**, the National Emergency Commission (CNE) and the Ministry of Health declare a yellow health alert. **Day 12**, closure of schools at risk; 50% reduction in capacity in meeting spaces; suspension of trips abroad for public employees. **Day 16**, a state of national emergency is declared. **Day 17**, closure of public and private educational centers, closure of non-essential stores, prohibition of mass events and total closure of beaches throughout the country. **Day 24,** vehicle mobility restriction from 22h to 5h.	**Day 6**, red alert is extended to the entire country after the first positive case for Covid-19 is detected **Day 16**, classes are suspended and the borders with El Salvador are closed. **Day 17** interruption of work activities in the public and private sectors, suspension of public transport, prohibition of meetings of any kind, religious and sport activities, closing of shopping centers. The total closure of air and land borders is implemented.	**Day 11**, interruption of educational activities **Day 16**, discontinuation of public and sport shows, closing of bars and gyms and non-essential shops. **Day 17**, El Salvador International Airport closes operations. **Day 18**, first positive case for Covid-19 detected. **Day 22**, mandatory 30-day quarantine and ban on crowds.
April 2020	**Day 1**, during Easter the daytime vehicle restriction was in place from 5h-17h. Vehicular traffic was allowed only one day per week according to the license plate number to make essential purchases. **Day 11**, a nighttime vehicle restriction is established 19h-5h until May 15.	**Day 1**, Greater air monitoring at Borders. **Day 9**, break in school lessons for the whole month.	**Day 3**, no circulation on beaches, rivers, lakes, spas, or tourist centers in the country. **Day 13**, entire population to be kept in compulsory home security with some exceptions, extended until April 28.
May 2020	**Day 1**, all public spaces and shops work at 50%; gradual reactivation of work centers from 5h to 19h. **Day 16**, vehicle restriction is maintained from 5h to 19h. Opening of hotels with a capacity of 50%. Opening of some national parks (50%). Beaches are open Monday-Friday from 5h to 8h.	**Day 4,** opening of shopping malls with few stores. Activities and public transport, as well as classes are suspended. Curfew from 18h to 4h. Prohibition of transit between territorial departments. **Day 14**, markets can open Monday, Wednesday, and Thursday from 6h to 13h, as well as supermarkets and convenience stores, from 9h to 16h. Closure of the country under restriction of total mobilization. **Day 25**, curfew 17h-5h with vehicle restriction between territorial departments. Total closure of the country.	**Day 7**, restriction of mobility between municipalities, people can circulate according to their occupation. **Day 10**, public transport may only circulate to mobilize duly identified health personnel.

June 2020	**Day 1**, tourist transport is enabled with restrictions and special measures. Operation of gyms, restaurants, and museums with a capacity of 50% **Day 20**, access to beaches from 5h-9:30h **Day 26**, mandatory use of masks is established.	**Day 15**, mobilization according to the last digit of the car plate in the territorial departments.	**Day 16**, restriction of mobility according to the last number of the identity document.
July 2020	**Day 3**, public parks, bars and massive events closed. **Day 11,** vehicle restriction for the whole country from 5h to17h according to license plate number. **Day 14,** increase in the capacity in public transport from 20% to 50% in routes shorter than 75 km. **Day 20**, vehicle restriction from 17h-5h according to license plates, but only in areas of orange alert.	**Day 13**, curfew is established from Monday to Friday from 18h to 5h and Saturdays from 14h to 5h. **Day 26**, vehicle restriction by license plate is eliminated and the curfew is modified from 21h to 4h.	**Day 6**, high restrictions are extended for 15 days, due to the increase in infections and deaths from Covid-19. **Day 29**, beginning of a new phase of economic reopening.
August 2020	**Day 1**, opening of commercial flights with limited routes from Europe. **Day 31**, Costa Ricans who return to the country may not quarantine. New vehicle restriction for weekdays 5h-22h and weekends 5h-20h.	**Day 24**, religious activities are reestablished with a maximum of one hour and a limit of attendees. **Day 26**, reopening of the La Aurora Zoo.	**Day 9**, personal clusters are established with groups not exceeding ten people. **Day 24**, beginning of the "Transitory Phase" in the process of the gradual reactivation of the economy.
September 2020	**Day 9**, temporary suspension of activities that involve massive movements of people. Controlled opening of economic activities.	**Day 6**, public servants work hours from 7h to 15h. **Day 18**, international airport reopens. Entry to the country conditioned to a negative PCR test. **Day 28**, vehicle restriction from 9h to 16h. Prohibition of alcohol sale between 19h and 5h.	**Day 1**, start of a new phase of economic reopening which includes public transportation and and most of economic activities.
October 2020	**Day 1,** opening of borders for travelers from California and Ohio and Mexico and Jamaica. **Day 15,** opening of flights from Central America. **Day 26,** foreign travelers are not required to present a negative Covid-test. **Day 27**, permission to use outdoor spaces for recreation.	**Day 1**, reopening of higher education centers and technical training centers. **Day 7**, hotel and tourism workers are allowed to hold events with restricted capacity.	**Day 3**, cultural spaces re-open. Opening of stadiums and public shows with social distancing (two meters) and beach trips at restricted hours. Opening of museums, cinemas, and hotels with capacity reduced to 50%. The public sector in general returns to work.

Table A2. Questions on the RSN module *"¿Lo Sentiste?"* (Linkimer and Arroyo, 2020).

Number	Question
1	Did you feel it?
2	What were you doing?
3	Where were you?
4	Did others nearby feel it?
5	How would you describe the shaking?
6	How did you react?
7	Was it difficult to stand and/or walk?
8	Did light objects move or fall from the shelves?
9	Did pictures on walls move or get knocked askew?
10	Did the furniture fall, overturn or fall?
11	Was there any damage to the buildings?
12	Additional comments on effects in nature, such as landslides, cracks in the ground, among others?

Table A3. Summary of observations when comparing the earthquake detections and felt reports from the time before the lockdown (BL) and during lockdown (DL) for Costa Rica and Guatemala (see also Figures 7, 8, 9, 10 and A2). The observations that favor an increase in lower magnitude earthquakes (LM) are marked.

Observations	Costa Rica		Guatemala	
	$M \leq 3.5$	$M > 3.5$	$M \leq 3.5$	$M > 3.5$
Number of detected earthquakes	Slightly decrease	No change	Slightly increase (LM)	Increase
Number of picked phases	~20% increase (LM)	Slightly increase	~40% increase (LM)	No change
Number of Felt earthquakes	Increase (LM)	Decrease	No change	Increase
Number of felt earthquakes reports	No change	Increase	-----	
Mc	Slightly increase		Slightly increase	
a-value	Slightly decrease		Increase (LM)	
b-value	Slightly increase (LM)		Slightly increase (LM)	