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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 measurements of 2020 to prevent the 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 detection 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 the typical seismic noise level 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 were observed in 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 noted that the decrease in seismic noise levels allowed to improve earthquake locations and increment the number of reports of low magnitude felt earthquakes. Our results imply that seismic data can be useful to verify the compliance of lockdown measures and to explore effects of the decrease in the seismic noise in the earthquake detection and felt reports.

1. Introduction

The seismic noise recorded by seismometers includes microseisms and atmospheric, and anthropogenic or cultural noise (Nimiya, 2020). The anthropogenic seismic noise in urban areas tends to be louder 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 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 pandemic of Covid-19 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 maximize the spatial coverage of seismic networks and warn of local geological hazards as the amplification effect (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) seismic networks.

Because the measure 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 differentiation is of the utmost importance (Lecoq et al., 2020a). The objective of this work is to present the first study of HFSAND-RMS levels during Covid-19 in Central America. We have used seismic stations in Central American (Figure 1) to evaluate the effects of lockdown measures in the seismic record near urban centers, in the capitals of four countries in the region: Costa Rica, Guatemala, El Salvador, and Nicaragua. In addition, specific cases of stations near populated centers and airports of Costa Rica and Guatemala are analyzed. Finally, we show the impact of the low noise levels in the capability to detect earthquakes and the number of felt reports before and during the lockdown.

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2. Data and methods

2.1. Seismic Data

We consider data from the vertical component of 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). The stations have been selected within or near the capitals of each country, to obtain a general overview of the changes in the seismic records induced by the lockdown measures. In Costa Rica and Guatemala, where we have access to the records, we selected three more 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 in an urban area at the University of Costa Rica main campus, 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 Perez Zeledon city 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 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, the stations SV.CEDA (BB, Nanometrics Trillium-120p), located in an urban area, close to the Panamerican highway at La Libertad and NU.MGAN (BB, Streckeisen STS-2), located in an urban area at INETER, close to Managua downtown were used, respectively. 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 HFSAND-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 containment measures implemented by the governments of 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 used by Lecoq et al. (2020a), using the code provided by Lecoq et al. (2020b). In this way, using the method of Welch (1967), a power spectral density (PSD) is calculated for each 30-minute time-windows with a 50 percent overlap, converted into equivalent displacement, and combined in 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-16h, according to local time (UTC-6). Additionally, for Costa Rica and Guatemala, the median displacement RMS of each hour was computed, for each day, comparing the result before and during the lockdown for some stations in these countries. Finally, an analysis of the percentage change in the high-frequency seismic displacement RMS was performed. This allows to obtain a median amplitude value for the whole period during the major restrictive measures (March 16 to May 15, 2020) and to compare it with the median of the period from January 15 to March 15, 2020 (before lockdown measures).

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 analyzed during the lockdown period, using the seismic catalog 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). The lockdown measures and the seismic noise level reduction during this period motivated the systematic test of their influence on the amount and magnitude of earthquakes detected, as well as on the number of seismic phases that could be identified. 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 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.

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 and show the number of earthquakes reported as felt in different intervals of magnitude. In both countries, the population reports are done via telephone and through 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 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 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

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 mass events prohibition 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 suffered flexibilization and/or hardening along the pandemic evolution 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 (urban area, University of Costa Rica campus, San José), Guatemala (urban area, close to the Aurora International airport, Guatemala City), and El Salvador (urban area, close to the Panamerican highway) (Figure A1). This has been observed during the lockdown measures (March 16, 2020, 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 level. The graph clearly shows the stillness of the night (blue colors between 22h-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, these figures also show that the noise level is lower during the weekends. In these graphs, 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 a strict return of lockdown measures in Costa Rica (3) have been marked (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 used to be 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 in the city of La Libertad (Figure 2c and 3c), the usual displacement before the lockdown used to be on average about 120 nm, while these values decreased to 80 nm in average during the main measures of social distancing.

These displacement values, progressively, as the months go by, tend to return to their usual averages as the restrictive measures have been decreased. Even so, it can be clearly seen that the levels have not yet returned to the usual before the pandemic. As of November 2020, the average values shown are ~ 160 nm for San Jose, ~ 85 nm for Guatemala City, and ~ 110 nm for La Libertad, near San Salvador. This shows that some of the social distancing measures are still in place in most of the countries of the region (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 closer to the usual averages is La Libertad in El Salvador. Whereas, 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 little noisy station, with very low value compared to the other capitals, related to its site conditions that isolate it from environmental noise. Likewise, the most drastic effect of the limitation in the mobility of the inhabitants due to the measures against the Covid-19, added to the holidays of the time, was observed during Easter in April: ~60 nm in San José, ~50 nm in Guatemala City and near San Salvador, and ~25 nm in Managua.

To evaluate in detail the effects of variations in the HFSAND-RMS record in Costa Rica and Guatemala, more seismic data collected by three more stations in each of these countries were analyzed (Figure A1). For Costa Rica, the analysis was complemented with the stations TC.BELE, TC.ERIA, and TC.ZEDO (Figure 4a). In Guatemala, with the stations GI.HUEH, GI.RETA, and GI.CHIE (Figure 4b). 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). 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, vary according to the station considered.

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), where more than half of the country's population lives (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 all cases, 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 to "control" the mobility of the population, from 19h-5h in 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-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. The most outstanding seismic noise reduction due to the lockdown measures reached between 36-49% at the GI.RETA and TC.BELE stations. These values are explained by the aspects described above, affecting stations close to major cities, highways, and high-traffic airports. Other stations that also show a high decrease (between 26-35%), are GI.GCG4, SV.CEDA, and TC.SJS1. These changes are closely related to the proximity to the most important populated centers (Figure 1) of the capital cities of San José and Guatemala City, and to the Panamerican highway near San Salvador.

Intermediate values (between 16-25%) in the percentages of reduction of seismic noise 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, the lowest changes (6-15%) in terms of the percentage of decrease in seismic noise 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 to low population density, a less exposed station site, or lack of compliance with lockdown measures.

3.2. Effects of the lockdown in earthquake detection and felt reports

During the time range analyzed, there were no significant earthquakes in Costa Rica and Guatemala. Before lockdown in Costa Rica, the biggest earthquakes were two events with 5.6 Mw on 21-01-2020 and in Guatemala a 6.2 Mw earthquake occurred on 19-11-2019, near Mexico. During lockdown, a 5.5 Mw earthquake on 15-04-2020 and a 5.7 Mw earthquake on 26-03-2020 took place in Costa Rica and Guatemala, respectively. All these events were offshore earthquakes related to the interplate seismogenic zone. Accordingly, we conclude that the seismic rates during the two time periods considered in this work were not affected by any specific large event.

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 magnitude every 0.5, for earthquakes with a moment magnitude (Mw) between 2.0 and 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. On the other hand, Figure 7b shows the average number of seismic phases per earthquake of the same magnitude on the vertical axis and the respective magnitudes on the horizontal axis, for earthquakes ≤ 4.0 Mw. Although the difference in the number of P wave arrivals before and during the pandemic is not (between 1 and 5 picks for magnitudes between 1.8 to 4.0), the values are consistently higher during the pandemic, especially for the lower magnitudes (≤ Mw 3.5). This suggests that the decrease in HFSAND-RMS during lockdown may have had a direct positive effect on the earthquake detection capability of the RSN.

Figure 7c shows the number of felt earthquakes reported through social networks or telephone calls on the vertical axis and the range of magnitude of those earthquakes on the horizontal axis, grouped in intervals of magnitude every 0.5, for earthquakes with magnitude less than Mw 2.0 to greater than Mw 5.5. This graph shows that there were a greater number of earthquakes with Mw > 3.0 reported as felt before the lockdown measures, but during the confinement, a greater number of reports for low magnitude earthquakes (Mw < 3.0) were collected. In addition, based on reports through the RSN application *"¿Lo Sentiste?"*, Figure 7d shows the average number of reports for seismic events (Mw < 5.0) in a magnitude interval on the vertical axis and the respective interval of magnitude on the horizontal axis. The trend lines in this graph show how the application *"¿Lo Sentiste?"* collected, on average, more felt reports for magnitudes Mw < 5.0 during the lockdown measures. These figures show a greater sensitivity of the population to low magnitude earthquakes, possibly because longer stays in their homes, favored by the implementation of home office and restrictions of mobility, allowed them to perceive events and make their reports.

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 may be a factor contributing to more small earthquakes being reported by the community. This is also spatially observed with the higher magnitude earthquakes (M > 4.5) before lockdown (20) than during it (11), occurred 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. It 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

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urban area in Southeastern Costa Rica (TC.ZEDO). While there were 25 earthquakes reported as felt for Central Costa Rica before lockdown, 17 of them of low magnitude ($M < 3.5$), during lockdown there were 36 felt earthquakes, 28 of them 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). Additionally, in Figure 8 we show the hour of the day when the felt earthquakes occurred. As expected, more events (63% before and 74% during lockdown) were perceived during the night hours (blue earthquakes, from 18h-6h).

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 "normal" conditions can be very difficult.

In Figure 9, a comparison between the statistics before and during the lockdown measures is presented, where the number of earthquakes is on the vertical axis and the range of magnitude of these on the horizontal axis, grouped in intervals of half a unit of magnitude. The graph clearly shows that a higher number of low-magnitude events was recorded during the lockdown measures. Moreover, the average number of seismic phases per event of the same magnitude increases for magnitudes lower than 3.0 during the lockdown (Figure 9b). The effect of seismic noise reduction on earthquake detection is stronger in Guatemala than in Costa Rica, probably because of the much lower seismic station density in Guatemala.

Furthermore, it should be noted that the measures implemented by the Guatemalan government were some of the most drastic in the region. Moreover, the number of events reported by the population as "felt" earthquakes shows an interesting trend of a general increase during the lockdown period (Figure 9c), even considering that reporting an earthquake as "felt" has many variables such as the seismic activity itself.

Figure 10 shows the distribution of the felt earthquakes reported to INSIVUMEH by the population (Figure 9c) before and during the lockdown in Guatemala. Before the lockdown, a total of 34 seismic events were reported as felt, 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 (Figure 10b), 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. This behavior indicates a good correlation with the quiescence of the environment and low-magnitude events felt during the lockdown period (Figure 10).

From the spatial distribution of felt earthquakes during lockdown, we observed that, unlike before, 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 confinement measures cause an improvement on the detection capacity of the network. Finally, most of the earthquakes felt in Guatemala (~60%) occur mostly during not working hours (blue and light blue earthquakes, from 18h-6h) both before and during the lockdown periods (Figure 10).

4. Conclusions

An important decrease in the high-frequency seismic noise was detected in stations of three Central American countries during the lockdown measures adopted to prevent the 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 (40 nm).

There is a good agreement between certain measures and the reduction in the seismic noise levels. The greatest impact was observed in connection with 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 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 in stations near airports, busy roads, and densely populated cities.

In Costa Rica, the lower levels in seismic noise allowed the detection of a higher number of seismic phases 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, the reduction of seismic noise levels also induced an increase in the amount of the phase picking per event and, therefore, it was possible to detect a significantly higher number of low magnitude earthquakes (< 2.5) than before the lockdown. In addition, there were more felt reports during lockdown. For both countries, a spatial correlation was found between felt earthquakes reported during lockdown and the decrease in seismic noise, mainly in the urban areas of Central and Southeastern Costa Rica, and Guatemala City and Huehuetenango in Guatemala.

Felt events corresponded mainly to the higher magnitudes ($M > 4.5$) earthquakes, but low-magnitude felt events ($M < 3.5$) presented a high correlation with the quiescence of the environment. A higher sensitivity of the population to low magnitude earthquakes was found in Costa Rica and Guatemala, possibly because longer stays in their homes, favored by the implementation of home office and restrictions on mobility, allowed them to perceive events and make their reports. 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 effects of the decrease in the seismic noise in the 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

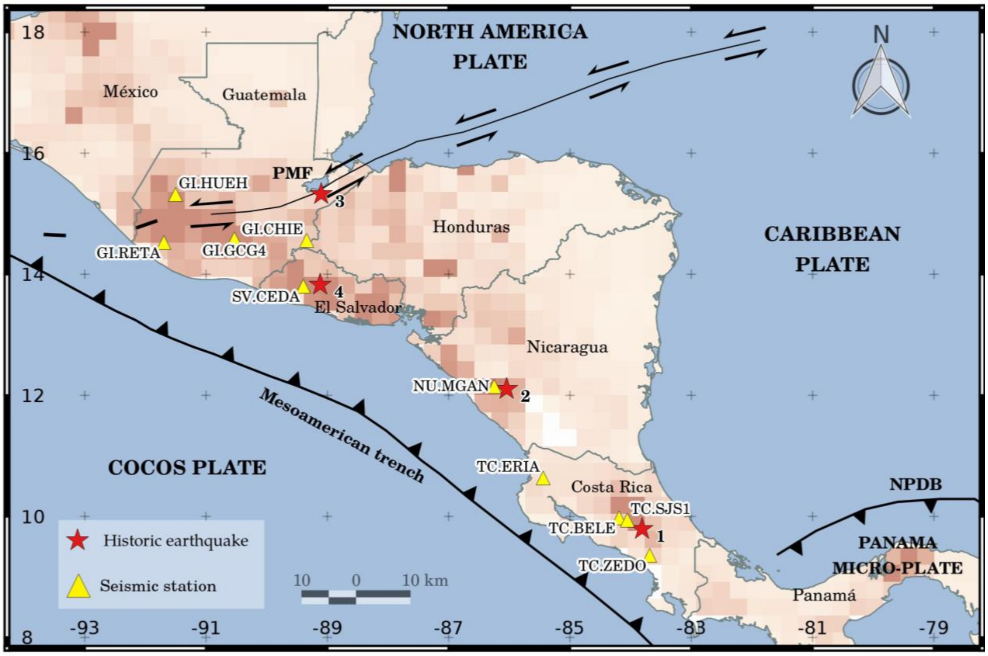

Figure 1. Map of Central American and location of the selected seismic stations from Costa Rica, Guatemala, El Salvador, and Nicaragua, used in this work. The map shows the approximate location of the North Panama Deformed Belt (NPDB) and the Polochic-Motagua Fault (PMF). Darker red tones indicate areas 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).

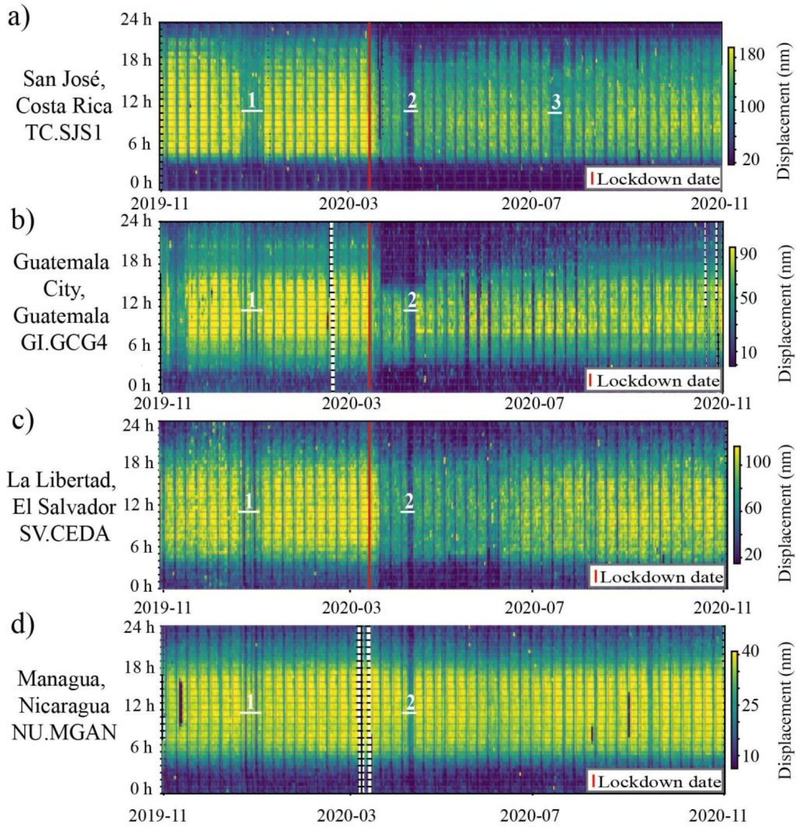

Figure 2. HFSAND-RMS evolution near capitals of the countries studied in an hourly grid representation. a) TC.SJS1 station in San Jose, Costa Rica. b) GI.GCG4 station in Guatemala City, Guatemala. c) SV.CEDA station, near San Salvador in the city of La Libertad. d) NU.MGAN station in Managua, Nicaragua. Gaps correspond to periods for which seismic data are 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.

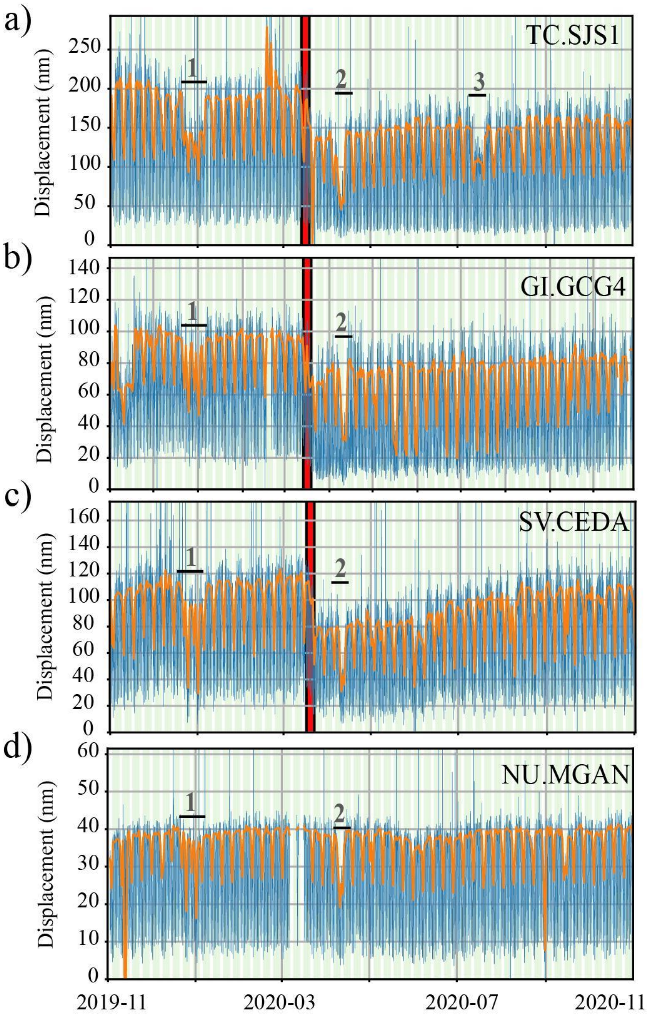

Figure 3. HFSAND-RMS evolution at the seismic stations near capitals of the countries studied. a) TC.SJS1 station in San Jose, Costa Rica. b) GI.GCG4 station in Guatemala City, Guatemala. c) SV.CEDA station, near San Salvador in the city of La Libertad. d) NU.MGAN station in Managua, Nicaragua. The blue line corresponds to the RMS amplitude time series of the vertical component, filtered between 4-14 Hz, and the orange line corresponds to median day-time, between 6h-16h local time. Gaps correspond to periods for which seismic data are 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.

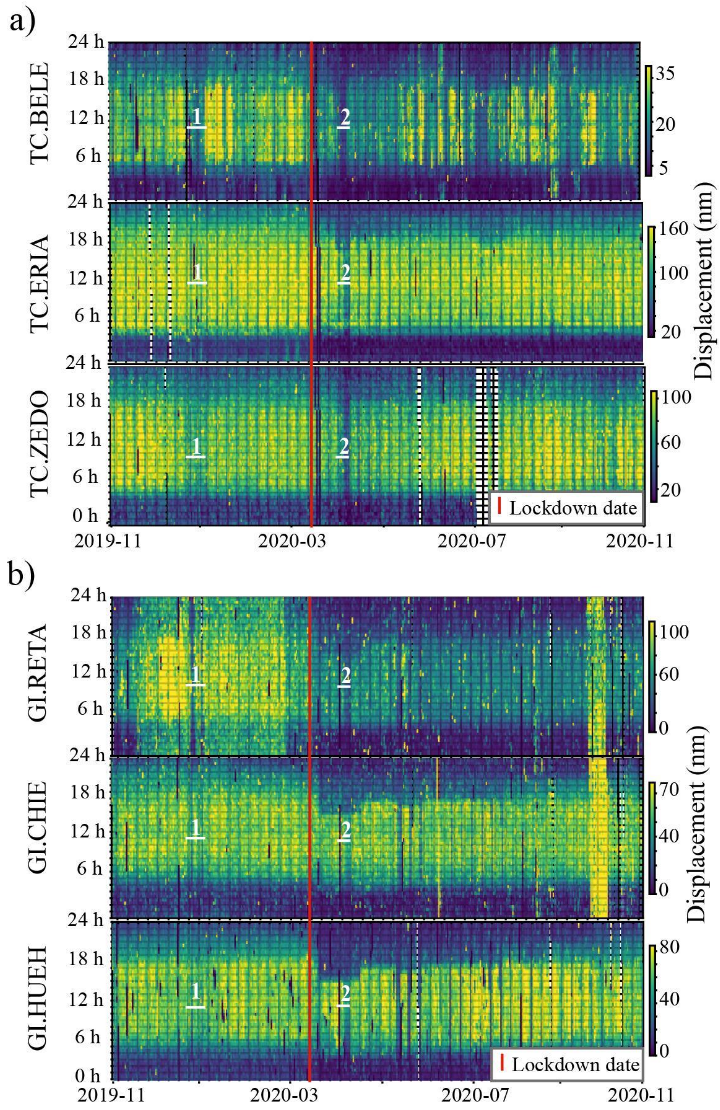

Figure 4. HFSAND-RMS evolution for specific sites in Costa Rica and Guatemala in an hourly grid representation. a) TC.BELE (central Costa Rica, near Juan Santamaria international airport), TC.ERIA (northern Costa Rica, urban area), and TC.ZEDO (southern Costa Rica, urban area). b) GI.HUEH (northwest of Guatemala, urban area), GI.RETA (southwest of Guatemala, urban area), and GI.CHIE (east of Guatemala, urban area). Gaps correspond with periods for which seismic data are 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.

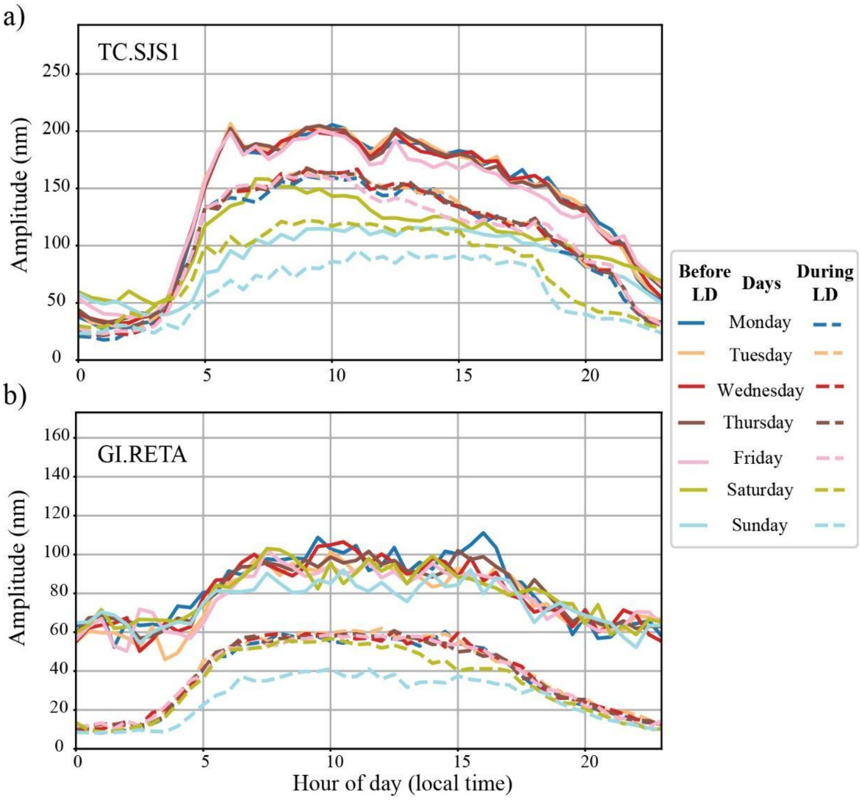

Figure 5. Daily variation of the median seismic noise per weekday, before and during the pandemic. a) TC.SJS1 station in San Jose, Costa Rica. b) GI.RETA station in Retalhuleu, southwest of Guatemala. LD means “lockdown”.

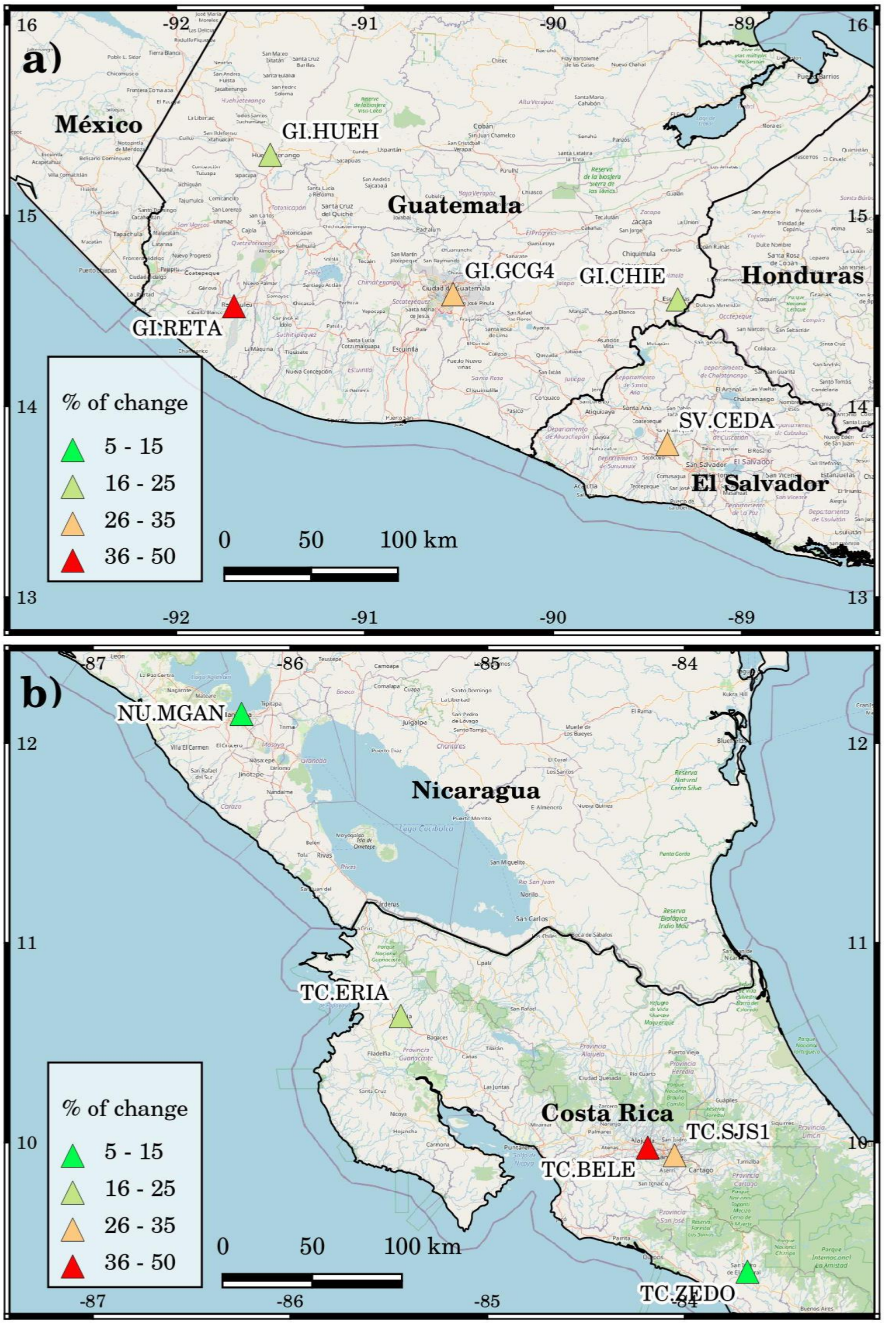

Figure 6. Percent of change of HFSAND-RMS in the band 4-14Hz during the period January 15 to March 15, 2020 (before lockdown measures) with respect to the interval March 16 to May 15, 2020 (after the lockdown measures entered in force). a) Percent of change in seismic stations of Guatemala and El Salvador. 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.

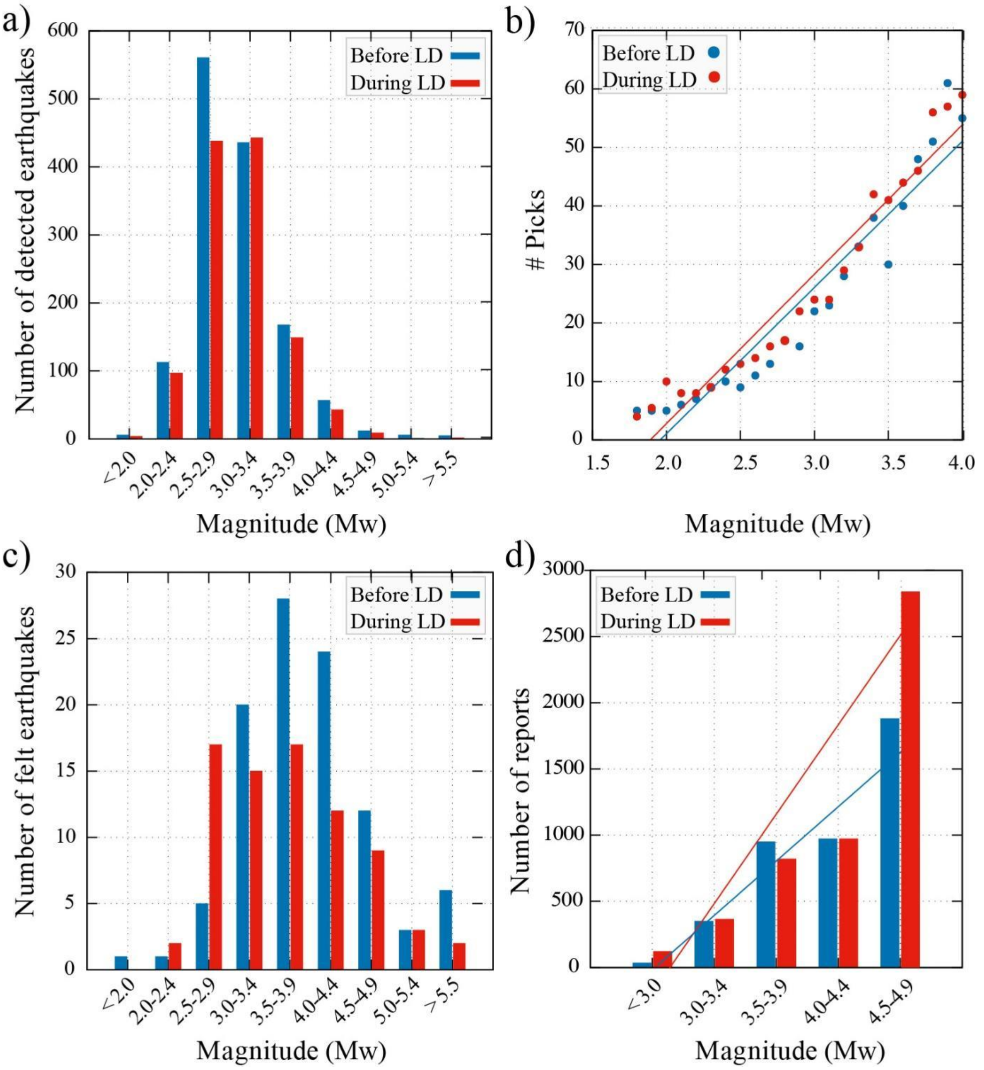

Figure 7. Event detection and felt earthquakes reported in Costa Rica before (1 Nov 2019-15 Mar 2020) and during (16 Mar-31 Jul 2020) lockdown measures. a) Number of detected earthquakes. b) Earthquake magnitude versus the average of P seismic phases per magnitude for events with Mw < 4.0, and the corresponding linear fits. 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. LD means "lockdown".

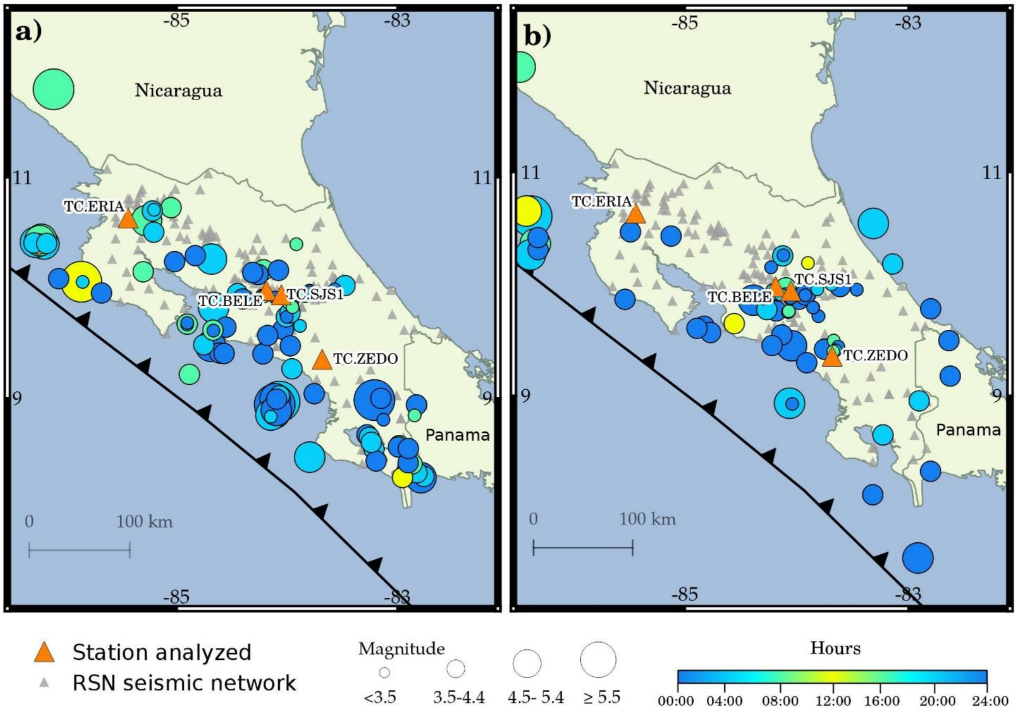

Figure 8. Map of felt earthquakes reported in Costa Rica. a) Before lockdown measures (1 Nov 2019-15 Mar 2020). b) During lockdown measures (16 Mar-31 Jul 2020).

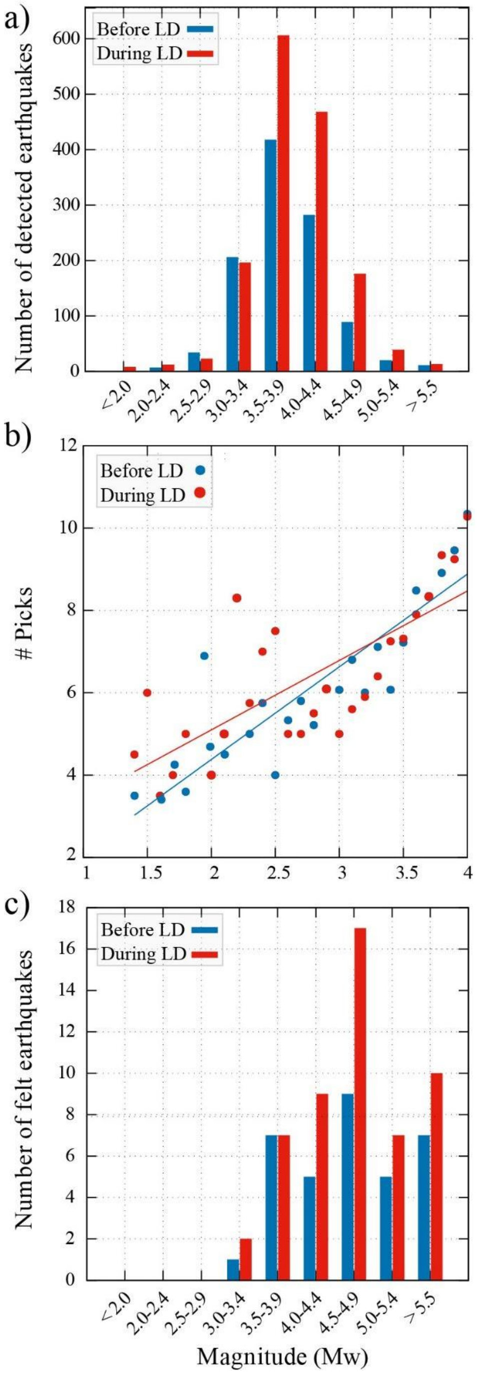

Figure 9. Event detection and felt earthquakes reported in Guatemala before (1 Nov 2019-15 Mar 2020) and during (16 Mar-31 Jul 2020) lockdown measures. a) Number of detected earthquakes. b) Earthquakes magnitude versus the average of P seismic phases per magnitude for Mw < 4.0 events, and the corresponding linear fits. c) Number of felt earthquakes in Guatemala. LD means "lockdown".

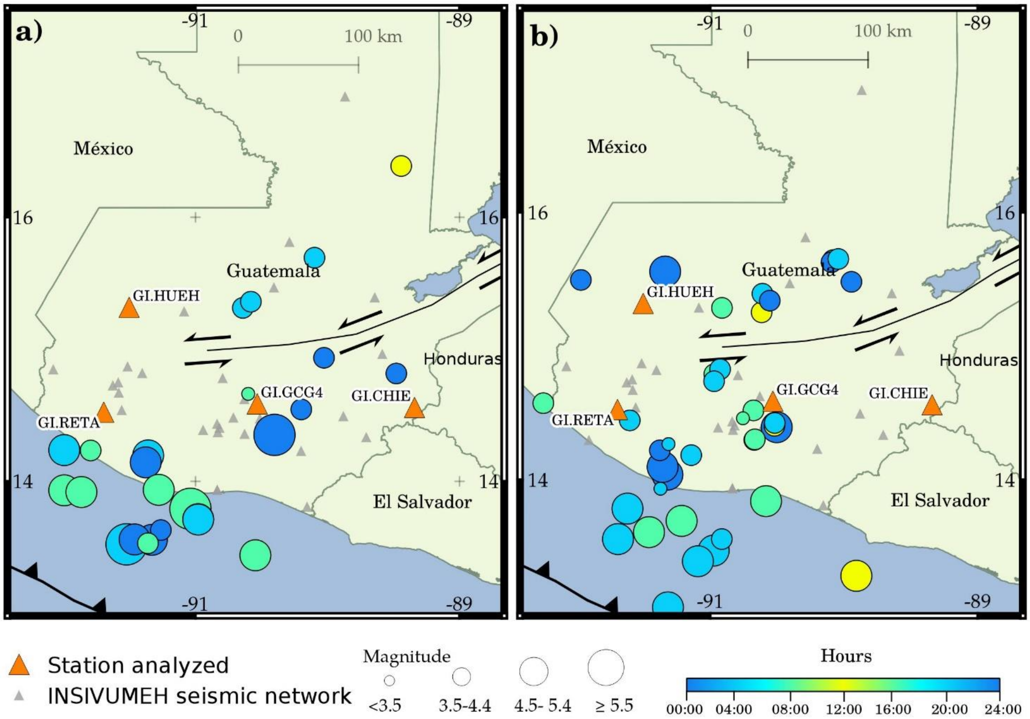

Figure 10. Map of felt earthquakes reported in Guatemala. a) Before lockdown measures (1 Nov 2019-15 Mar 2020). b) During lockdown measures (16 Mar-31 Jul 2020).

Appendix: additional figure and table

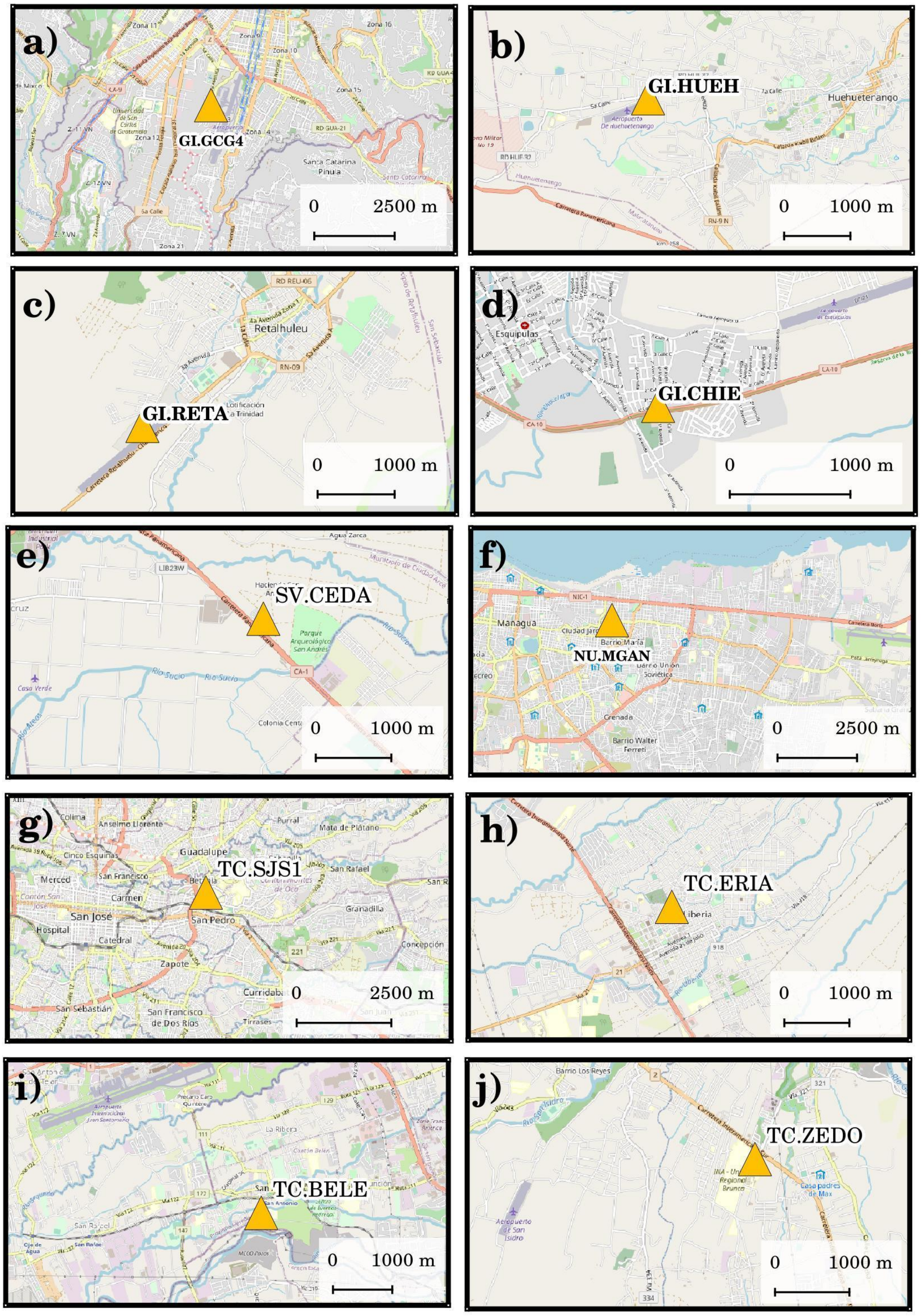

Figure A1. Images from Open Street Maps of the site areas of the seismic stations (orange triangles) used in this work. © OpenStreetMap contributors 2020. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

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; therefore, it is not included in this table. 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**, suspension 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. Total closure of air and land borders is declared	**Day 11**, suspension of educational activities **Day 16**, suspension 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**, air reserve to monitor borders. **Day 9**, suspension of 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-19h. **Day 16**, vehicle restriction is maintained from 5h-19h. Opening of hotels with a capacity of 50%. Opening of some national parks (50%). Beaches are open Monday-Friday from 5h-8h.	**Day 4,** opening of shopping malls with few stores. Activities and public transport, as well as classes are suspended. Curfew from 18h-4h. Prohibition of transit between departments. **Day 14**, cantonal and municipal markets can open Monday, Wednesday, and Thursday from 6h to 13h, as well as supermarkets and convenience stores, from 9h-16h. Closure of the country under restriction of total mobilization. **Day 25**, curfew 17h-5h with vehicle restriction between 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.

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Preprint. Discussion started: 14 June 2021

June 2020	**Day 1**, tourist transport is enabled with restrictions and special measures. Operation of gyms, cafes, 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 country's 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-17h 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 cantons with orange alert	**Day 13**, curfew is established from Monday to Friday from 18h-5h and Saturdays from 14h-5h. **Day 26**, vehicle restriction by license plate is eliminated and the curfew is modified from 21h-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 1 hour and a limit of attendees. **Day 26**, reopening of the La Aurora Zoo.	**Day 9**, personal clusters are established: groups that do not exceed 10 people are allowed to socialize. **Day 24**, beginning of the "Transitory Phase" in the process of 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-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-5h.	**Day 1**, El Salvador begins a new phase of economic reopening that includes public transportation and a good part of economic activities.
October 2020	**Day 1,** opening of borders for travelers from California, Mexico, Jamaica, and Ohio. **Day 15,** opening of flights from Central America. **Day 26,** foreign travelers not required 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 open. Opening of stadiums and public shows with a distance between people of two meters, trips to the beach at restricted hours, museums, cinemas, and hotels with capacity reduced to 50%. The public sector in general returns to work.