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Monitoring human activity at a very local scale with ground motion records: the early stage of COVID-19 pandemic in California, USA, New York City, USA, and Mexicali, Mexico

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Abstract

During the global COVID-19 pandemic, governments took various social distancing measures to slow the spread of coronavirus. Many people moved their workplace back to their homes, and human activity slowed considerably. In this paper, we analyze the change in cultural (human-caused) seismic noise level, which we refer to as the Human Activity Index (HAI) through a survey of seismic stations in California, USA, New York City, USA, and Mexicali, Baja California, Mexico from early December, 2019 to late April, 2020. Some stations recorded a drop in the Human Activity Index during the COVID-19 pandemic, and the timing of the cultural noise decrease typically correlates with the timing of a strict curtailment of personal and economic activity issued by the local government; while in other locations, the drop in the HAI appears to be influenced by other regional factors, which we explore in detail. During our analysis we found that many stations did not record a drop during the early stage of COVID-19 pandemic. Of the 19 stations of the Southern California Seismic Network that were surveyed, we found that only five show a similar extent of drop in the Human Activity Index comparable to the Christmas holiday break in 2019. This suggests that human activity, such as traffic or industry tied to essential businesses, did not reduce during the COVID-19 pandemic in Southern California. Our results show that the cultural noise recorded by seismic stations is capable of being used as a Human Activity Index and that this metric is particularly powerful in measuring how localized communities initially responded to the COVID-19 pandemic. When combined with other measures of human mobility, the potential to carefully monitor cultural activity with seismic methods may have benefits to scientists and policy makers interested in understanding human responses to a pandemic.

Introduction

At the time of manuscript preparation (July 24, 2020), the total confirmed number of COVID-19 cases has reached 4.2 million in the United States with 74 thousand more new cases reported each day. This record breaking disease first struck the United States in late January, 2020 with its first arrival in the states of Washington and California. Soon, it developed into a nationwide pandemic in March, and New York State became the new "hotspot" of COVID-19. To prevent the overloading of hospitals, the state of California and New York took strong mitigation measures to enforce social distancing, hoping to slow the spread of virus and flatten the curve of daily confirmed cases (e.g., Matrajt et al., 2020; Thunström et al., 2020). At about the same time, the pandemic also spread in the neighbouring country of Mexico. In the current research, we revisit the early stage of the COVID-19 pandemic in California, USA, New York City, USA, and Mexicali, Baja California, Mexico with seismic cultural noise recorded by seismic stations.

The concerns regarding the COVID-19 pandemic escalated in all three locations in March, 2020, leading to the promulgation of strong social distancing edicts by the local governments. In California, Governor Gavin Newsom declared a state of emergency on March 4 (e.g., California Office of the Governor, 2020; Karlamangla et al., 2020; Budryk, 2020). In the following two weeks, numerous social distancing restrictions were issued at both local and state levels in California (e.g., De Atley, 2020; KSBY News, 2020; Hagan and Miller, 2020; Luna, 2020; Bizjak et al., 2020; Henderson, 2020; Bay City News, 2020; Public Health Department, County of Santa Clara, 2020; Lin, 2020; Romero and Ostly, 2020; Allday, 2020). As the number of confirmed coronavirus cases approached 1000 in

California, the Governor declared a statewide shelter-in-place order on March 19 (e.g., Casiano, 2020; Wick, 2020; Arango and Cowan, 2020).

In New York, Governor Andrew Cuomo declared a state of emergency on March 7 (e.g., New York Office of the Governor, 2020a; McKinley and Sandoval, 2020). Different levels of measures were taken in the following two weeks (e.g., NBC New York, 2020a; CBS New York, 2020a; Klebnikov, 2020; Kesslen, 2020; Shapiro, 2020; Mays and Goldstein, 2020; Gronewold and Hutchins, 2020). On March 20, Governor Cuomo announced a statewide stay-at-home order, also known as the New York State on Pause Program, with a mandate that all non-essential workers work from home starting on March 22, 2020 (New York Office of the Governor, 2020b).

Baja California is a Mexican state directly bordering the US state of California to the South. It was one of the first Mexican states affected by the COVID-19 pandemic in March, 2020. On March 21, the US-Mexico border was partially closed and all nonessential cross-border travel were restricted in an effort to slow the spread of the coronavirus (e.g., Solis and Fry, 2020; Hansen 2020; Ornelas, 2020). On March 30, a national health emergency in Mexico was declared by Secretary Marcelo Ebrard; all sectors in the country were urged to stop most activities (e.g., Valadez and Paola Wong, 2020; Eschenbacher et. al., 2020; Borunda, 2020). On the same day, Baja California Governor Jamie Bonilla announced a “stay-at-home” order (e.g., Lewis, 2020; Fry, 2020).

Human activity has a well demonstrated ability to generate seismic noise. Such noise can originate from traffic and machinery, and usually has frequency greater than 2–4 Hz (e.g., Stutzmann et al., 2000; McNamara and Buland, 2004; Havskov and Alguacil, 2015). Research has shown that the amplitude of human activity in a city can be correlated with the amplitude of seismic noise near the city (e.g., Lecocq et al., 2020; Gibney, 2020; Poli et. al., 2020; Xiao et al., 2020). Since cultural seismic noise is rapidly attenuated (on the scale of m to km from the source) due to its low amplitude and high frequency content, a seismometer is typically only sensitive to human activity within a range of a few kilometers (Havskov and Alguacil, 2015). Therefore, seismic data has the potential to provide us with unique information, which we can use to infer how a local community responds to the COVID-19 pandemic. In this study, we will refer to the amplitude of cultural noise as the Human Activity Index (HAI). Together with other datasets that reveal regional human activity, such as smartphone-based mobility metrics, we can obtain a comprehensive view of cultural responses to the pandemic at the metropolitan-to-regional scale, as well as at a highly localized scale.

In this paper, we compute the Human Activity Index (HAI) via the cultural noise amplitude at several seismic stations in California, USA, New York City, New York, USA, and Mexicali, Baja California, Mexico from early December, 2019 to late April, 2020, during which time cases of COVID-19 increased in the United States and Mexico, and strong social-distancing measures were taken by their respective governments. We will show that the seismic data derived Human Activity Index reflects the human activity specific to the surrounding local community. At some surveyed stations, a drop in seismic data derived Human Activity Index is observed concurrently with a social distancing measure in the area. This is consistent with the high frequency seismic noise quieting observed at global scale (Lecocq et. al., 2020). However, many stations we surveyed did not record a drop in Human Activity Index as had been expected, even though they were near population centers. In particular, most of the Southern California stations we study do not record a drop in Human Activity Index during the COVID-19 pandemic. In New York City and Mexicali, the stations we investigate record a drop in Human Activity Index that does not coincide with the regional shelter-in-place order or a drop in smartphone-based mobility metrics. These results suggest that the seismic derived Human Activity Index is strongly affected by the human responses at a very local scale. If interpreted properly, the seismic noise data could be very helpful for Public Health officials as they make critical decisions to combat the COVID-19 pandemic and potentially future pandemics.

Methods and data

Computing displacement root mean square amplitude

To measure ground vibration amplitude within a given time window (from t=0 to t=T) and frequency band (from f_1 to f_2), we compute the root mean square amplitude u_{RMS} of the displacement seismogram $u(t)$. $u(t)$ is filtered in the f_1-f_2 frequency band. A comprehensive description can be found in Havskov and Alguacil (2015). Here we will show a brief summary. The square of u_{RMS} can be defined as,

$$u_{RMS}^2 = \frac{1}{T}\int_0^T u^2(t)\mathrm{d}t$$

In practice, the root mean square amplitude u_{RMS} is usually computed by integrating the power density spectrum $P(\omega)$ of time series between t=0 and t=T, using Parseval's Theorem,

$$u_{RMS}^2 = \int_{f_1}^{f_2} P(\omega)\mathrm{d}\omega$$

To investigate how ground vibration amplitude changes with time at a given station, we use a 30-minute sliding window (i.e., T=30 minutes) to scan through its continuous record. Considering that anthropogenic seismic noise is usually found in a frequency range greater than 2-4 Hz (Havskov and Alguacil, 2015), we compute the displacement root mean square amplitude u_{RMS} in a 4-14 Hz frequency band ($f_1 = 4$ Hz, $f_2 = 14$ Hz). The sliding window is offset by 15 minutes every time it advances. To demonstrate the workflow with a simple example, we show a 1-hour seismic record (06:00-07:00) at station BK-BRK (at the University of California, Berkeley) in figure 1. In this case, the first time window is from 06:00 to 06:30, the second time window is from 06:15 to 06:45, and the third time window is from 06:30 to 07:00. Within each time window, the displacement root mean square amplitude u_{RMS} is computed between 4-14 Hz. The results are then used to represent the ground vibration level at the center of each time window, i.e., 06:15 for time window 1, 06:30 for time window 2, and 06:45 for time window 3.

To realize the process above, we use an open source python code SeismoRMS (Lecocq, A simple Jupyter Notebook example for getting the RMS of a seismic signal. Code package on Github, https://github.com/ThomasLecocq/SeismoRMS, accessed April 22, 2020) to compute the displacement root mean square amplitude u_{RMS}. The same code has been used to analyze the seismic noise drop in other places around the world (e.g., Lecocq et al., 2020; Gibney, 2020). SeismoRMS utilizes the freely available Python toolbox ObsPy to download the open-access seismic data and compute the corresponding power density spectra (Beyreuther, et al., 2010; Megies et al., 2011;

Krischer, et al., 2015). The ObsPy we use is version 1.2.0, and the Python we use is version 3.7.3.

All seismic data used are vertical records of either high broadband or broadband high gain channels (HHZ or BHZ). All the channels we used have a sampling rate of either 100 Hz or 40 Hz. The frequency band we are interested in is 4-14 Hz. The sampling rate of records are all higher than 40 Hz, such that the Nyquist frequency is higher than 20 Hz. In this paper, for convenience, we define the Human Activity Index (HAI) as the displacement RMS due to seismic cultural noise.

Measuring daily "human activity" level with displacement RMS median

By scanning the continuous seismic data with the moving time window described above, we obtain a displacement root mean square time-series with a sampling interval of 15 minutes. This time series is capable of showing cultural noise variation within a day. If a station is capable of monitoring human activity level, its displacement root mean square amplitude in the daytime will typically be higher than in the night time (e.g., Lecocq et al., 2020; Havskov and Alguacil, 2015, Xiao et al., 2020). In this paper, the day versus night variation in displacement RMS is used as evidence to demonstrate that a station is sensitive to cultural noise.

However, the day-to-day variation of amplitude is not clear in the time series with a sampling rate of 15 minutes. In addition, short-duration (within a few seconds) tectonic events such as earthquakes can occur occasionally in the continuous dataset and make the direct analysis difficult. In order to compute the daily Human Activity Index (HAI), we take the median value of the 15-minutes-interval displacement root mean square (RMS) time-series of a certain day as the HAI of that day. We take the median of displacement RMS, rather than the average, to provide a representative value, since the median is less affected by outliers such as seismic events. In the daily median displacement RMS time series, we have a single data point per day (i.e., sampling rate is one day). By doing so we neglect the human activity variation within a day, and eliminate the influence of occasionally-occurring tectonic events.

Results

Seismic noise drop due to government restrictions: an example case in Berkeley, California

California was one of the first states in the United States to be affected by the COVID-19 pandemic. The first COVID-19 case was reported by the Center for Disease Control (CDC) on January 26, 2020 in Orange County (e.g., Linder, 2020; Wigglesworth et. al., 2020). As the pandemic intensified in early March, strong restrictions on human activities were ordered by both local and state governments to stop the spread of the virus (e.g., California Office of the Governor, 2020; Public Health Department, County of Santa Clara, 2020; Casiano, 2020; Wick, 2020). As we write this paper (July 24, 2020), the state has continued to report a record number of confirmed cases, however many of the earlier restrictions have been eased. As the COVID-19 pandemic intensified in California in early March, some of the seismic stations close to local communities witnessed this process.

In this section, we will demonstrate how the displacement RMS can be used as a Human Activity Index. We will investigate the area near the University of California, Berkeley (UC Berkeley) with the seismic record at station BK-BRK, which is on the UC Berkeley campus (figure 2a and 2b), located within the city of Berkeley in the Bay Area of California, one of the most densely populated areas in the United States. In figure 2, the blue circular shading denotes an area within 2 km of the station. This radius is a first-order empirical approximation of the range of cultural noise sources, as human activity is not observed in seismic noise beyond a few km from its source (Havskov and Alguacil, 2015). According to Berkeley News (2020), on March 10, UC Berkeley suspended most in-person classes. The school also cancelled or encouraged the cancellation of planned events depending on their gathering sizes. At midnight on March 17, a shelter in place order took effect in the Bay Area (Public Health Department, County of Santa Clara, 2020). One would expect that the cultural noise caused by the human activity near the Berkeley area would drop after the social-distancing restrictions described here.

Figure 2c shows the displacement RMS of station BK-BRK from Dec 1, 2019 to Apr 26, 2020. The thin black curves are the displacement RMS of the 30 minute-long sliding window, and the thick red curves show the median displacement RMS amplitude for the entire day. Before using the displacement RMS as a Human Activity Index, we need to first confirm that the ground vibration amplitude is primarily the result of cultural noise generated by human activity. We can confirm this cause by examining the periodic pattern of the displacement RMS time series. As shown in figure 2c, the 15-minute-interval displacement RMS time series shows a strong diurnal periodic pattern. For the month of February, 2020, within 24 hours, the ground vibration amplitude can have a high amplitude of about 2 nm during the daytime, and a low amplitude of about 1 nm during the nighttime. In addition, the daily median of displacement RMS shows a strong weekly periodic pattern: the ground vibration amplitude has a peak amplitude of about 1.5 nm during weekdays and a low amplitude of about 1.1 nm during weekends. This overall pattern reflects the mode of human activity: high on daytime/weekdays and low on nighttime/weekends. During the Christmas and New Year's holiday in 2019, the ground vibration amplitude dropped about 30%, and the weekly pattern was modulated by the holiday schedule, suggesting a significant decrease in human activity during the public holidays.

The result above implies that station BK-BRK is capable of recording human activity variation near the station, and we may use the displacement RMS amplitude as the Human Activity Index of the nearby area. Thus, we move forward to investigate the human activity change around the time when social distancing restrictions were issued in March, 2020. As shown in the daily median displacement RMS time series in figure 2c, the weekday daily median displacement RMS at station BK-BRK was about 1.5 nm in early December, 2019. It dropped to about 1 nm during the Christmas holiday and New Year's holiday. The weekday daily median displacement RMS gradually recovered back to its pre-holiday level in mid-January and stayed at that level until early March. On March 10, UC Berkeley suspended most in-person classes, and the Human Activity Index started to drop. At midnight on March 17, a shelter-in-place order took effect in the Bay Area, and the ground vibration amplitude went through a further drop to about 1 nm on weekdays. This level is comparable to that of the 2019 Christmas/New Year holiday. The daily/weekly periodic pattern still persisted afterwards, suggesting that cultural noise is still the major contributor of the displacement RMS.

In this section, the example of station BK-BRK demonstrates how we infer human activity change during the COVID-19 pandemic by analyzing the seismic record. We first confirm that the displacement RMS tracks the human activity by checking whether the displacement time series has a diurnal/weekly periodic pattern. If so, the displacement RMS can be treated as a Human Activity Index. Once that is confirmed, we investigate whether the Human Activity Index dropped when the local government issued a strong social-distancing order. As shown in the case of station BK-BRK, the daily median displacement RMS time series shows a clearer daily trend of human activity compared to the 15-minute-interval time series. In the remainder of this paper, we will only show the daily median displacement RMS time series. The 15-minute-interval time series is not shown although they were used to check if a diurnal periodic pattern exists.

Era of shelter-in-place vs. Christmas/New Year's Holiday in Southern California

Southern California is one of the most densely populated regions in the United States. It also has one of the densest seismic networks in the world due to the proximity of the San Andreas fault. The Southern California Seismic Network (Network code: CI) is the largest seismic network in Southern California, operated by California Institute of Technology (Caltech) and the United States Geological Survey (USGS) in Pasadena. Many stations within this network are close to or within significant population centers, and they provide a valuable dataset to study the human activity drop patterns in Southern California during the COVID-19 pandemic.

As an example, we analyze human activity during the early stage of COVID-19 pandemic at station CI-MSJ and station CI-RSS. As shown in figure 3a, CI-MSJ is located on the Mt. San Jacinto College (MSJC) campus and the CI-RSS station is located on the University of California, Riverside (UC Riverside) campus.

Figure 3b plots the daily median displacement RMS of these two stations. The top panel is CI-MSJ and the bottom panel is CI-RSS. Blue curves show the trends of the pandemic affected year (Dec 2019 to Apr 2020) and gray lines show the trends of previous year in the same period (Dec 2018 to Apr 2019). The weekly variation pattern and the amplitude drop during Christmas break suggest that the seismic records at these two stations are capable of reflecting human activity changes. As the COVID-19 situation intensified in early March, Mt. San Jacinto College closed its campus on Friday, March 13 (Schultz, 2020). On March 16, UC Riverside also closed its campus (Smith, 2020). Purple dashed lines denote the timing of when the two schools closed their campuses. The ground vibration records, however, show a significant drop in amplitude only on the CI-MSJ record, not on the CI-RSS record. Why does the human activity level not drop near UC Riverside?

One potential explanation is that the CI-RSS station at UC Riverside is not sensitive to human activity. This is probably not the case, though. The ground vibration amplitude at CI-RSS has a clear weekly periodic pattern: high on weekdays while low on weekends, which strongly indicates an anthropogenic origin. In addition, CI-RSS records a low level of vibration amplitude during the Christmas holidays in both 2018 and 2019, similar to CI-MSJ. These observations suggest that CI-RSS is definitely capable of measuring a drop in human activity.

Another explanation is that the human activity near UC Riverside did not decrease significantly during the COVID-19 pandemic, unlike during Christmas break. Students, faculty, and staff were not allowed to work or study on campus since the statewide shelter-in-place order began on March 19, so the high activity level is probably not caused by academic activities. One possibility is that much of the human activity recorded at this station is due to vehicular traffic, considering that the CI-RSS station is only 500m away from the junction of CA-60, CA-91 and I-215 freeways. It is possible that the highway traffic activity near UC Riverside did not drop as much during the COVID-19 lockdown as it typically does over Christmas. Another possibility is that the cultural noise recorded at the UC Riverside station CI-RSS is dominated by the building construction on campus. According to the UC Riverside news report, construction on UC Riverside campus continued at a regular pace as it was deemed an essential service under Governor Gavin Newsom's stay-at-home order (Ghori, 2020).

The analysis of CI-MSJ and CI-RSS data suggests that cultural noise recorded by seismic stations reflect variations in human behavior as part of the pandemic lockdown. Inspired by these results, we further investigate the human activity change at 23 seismic stations in Southern California, hoping to obtain a better picture of human activity change in the region. The locations of these analyzed stations are shown in figure 4. Out of the 23 stations we investigate, 19 of them show a diurnal/weekly cycle and a reduction of signal over Christmas, which is indicative of changes in human/cultural noise; while the other 4 stations (CI-DEV, CI-CJM, CI-IPT, and CI-PER) do not reflect obvious cultural noise characteristics (it is possible that other anthropogenic or natural noises may be responsible). To directly compare the 19 time series that reflect human activity, we scale them using the following method. For a given time-series, we define the “0” level as the mean vibration amplitude during Christmas/New Year break (12/21/2019 – 01/06/2020); meanwhile, we define the “1” level as the mean vibration amplitude during a non-holiday period (01/20/2020 – 02/29/2020). After that, the time-series is normalized using the pre-defined “0” and “1” level. If a time series has amplitude closer to 0 after California shelter-in-place order, it means that the human activity level near this station dropped to the “Christmas” level; Conversely, if a time series has amplitude closer to 1 after California stay-at-home order, it means that the human activity level near this station remained at the normal non-holiday level.

In figure 5a, we plot all the 19 traces together. The green horizontal dashed line denotes the Christmas/New Year holidays level, and the orange horizontal dashed line denotes the normal non-holiday level. As shown in figure 5a, the human activity patterns of all traces are very similar before the shelter-in-place order on March 19. However, human activity level at different stations starts to diverge after March 19. 14 of the 19 stations remained at the normal non-holiday level, like the CI-RSS station on UC Riverside campus, while the remaining 5 stations dropped close to the Christmas level, like the CI-MSJ station on Mt. San Jacinto College campus. In figure 5b, we plot the 5 stations that show an amplitude drop in red and the other 14 stations that do not show drop in black. The 5 stations have very similar trends to the other 14 stations before the shelter-in-place order in California.

The results above demonstrate that the human activity level at most locations in Southern California surveyed in this study did not decrease after the “stay-at-home” order, in contrast to the well-resolved reduction in human activity observed during the

Christmas/New Year's holiday. Since cultural noise mainly originates from traffic and machinery (e.g., Stutzmann et al., 2000; McNamara and Buland, 2004; Havskov and Alguacil, 2015), it implies that the traffic or industrial activities in Southern California did not significantly change after the "stay-at-home" order was enacted. We will further discuss these results in the discussion section.

Monitoring local human activity with seismometers

The results above suggest that the cultural noise amplitude recorded by a seismometer can be used as a Human Activity Index for the nearby community. It is worth noting that the Human Activity Index at many stations in Southern California did not show a drop concurrent with the timing of California's "stay-at-home" order. This result highlights a unique benefit of the seismic derived Human Activity Index in that it reflects the human activity specific to the surrounding local community, instead of the whole city or state. In this section, we extend our investigation to two other stations outside California: station LD-CPNY in Central Park in New York City (figure 6a) and station BC-UABX on the campus of Autonomous University of Baja California (UABC) near downtown Mexicali, Baja California, Mexico (figure 6b). We will show that the drop in Human Activity Index at these two stations does not perfectly coincide with the regional shelter-in-place order or the drop in smartphone-based mobility metrics.

Similar to California, New York state began to see growth in COVID-19 confirmed cases in March, 2020. The disease spread most rapidly in the New York City metropolitan area, which has the greatest population density in the United States. By April 10, 2020, New York had more confirmed cases than any other entire country (Dzhanova, 2020). On

March 7, New York state Governor Andrew Cuomo declared a state of emergency (New York Office of the Governor, 2020a). On March 20, New York state announced its "Stay-at-home" order, which went into effect on March 22 (New York Office of the Governor, 2020b).

Baja California is a state in Mexico that borders California to the south. The city of Mexicali is a border town located immediately south of Calexico, CA and approximately 90 miles east of Tijuana, Mexico. Baja California confirmed cases of COVID-19 in mid-March, 2020. On March 21, the US-Mexico border was partially closed and all nonessential cross-border travel was restricted in an effort to slow the spread of the coronavirus (e.g., Solis and Fry, 2020; Hansen 2020; Ornelas, 2020). On March 30, a "stay-at-home" order was issued in Baja California (e.g., Lewis, 2020; Fry, 2020).

We compute the Human Activity Index of station LD-CPNY and BC-UABX with their displacement RMS. For reference, we compare them with the Human Activity Index of station BK-BRK in Berkeley, California, which is discussed earlier in this paper. Figure 6c plots the daily median displacement RMS from Dec-01 to Apr-26 of these three stations. In the panel for each station, blue curves show the trend of the pandemic-affected year (Dec-2019 to Apr-2020) and gray curves show the trend of the previous year (Dec-2018 to Apr-2019) as a comparison. Vertical lines of different colors (numbered in a chronological order) denote the dates when potential human-activity-related measurements were issued, such as a "school closure" order or a "shelter-in-place" order.

Before we use the displacement RMS as Human Activity Index, we need to confirm that the seismic record is subject to human activity. All three stations show a weekdays-weekend variation pattern in displacement RMS records. At station BC-UABX, a decrease in amplitude is concurrent with the Christmas (December 25) and New Year holiday (January 1) for both years. At LP-CPNY a decrease in amplitude during this same period is not observed, although the weekday/weekend periodicity does appear to be modulated, suggesting rapidly fluctuating changes in human activity. These results indicate that ground motion records of these three stations are subject to nearby human activity and therefore are capable of reflecting human activity change. A more speculative reading of our results suggests that individual locations may respond to specific events differently, resulting in differences in the seismic noise record. As an example, we see that amplitude of seismic noise near Central Park (LD-CPNY) does not drop off near the Christmas holidays, in contrast to stations BC-UABX and BK-BRK. This might be due to the fact that human activity near the park did not decrease during holidays.

We then further investigate the human activity change before and after the COVID-19 pandemic. Before March 2020, the Human Activity Index at these three stations are very similar to the same period in the previous year. As the COVID-19 pandemic intensified in March 2020, displacement RMS began to drop to a level lower than in the previous year. Station BK-BRK on the UC Berkeley campus records a drop in ground vibration amplitude starting from March 10 when UC Berkeley was closed, and continued to drop when the shelter-in-place order was issued in the Bay Area on March 17. At Central Park in New York City, station LD-CPNY records a slight drop of ground vibration amplitude a few days before Governor Andrew Cuomo signed the ‘New York State on PAUSE’ executive order on March 20, closing 100% of non-essential businesses statewide. Displacement RMS decreased further when the order took effect on March 22.

One week later, on approximately March 27, the ground vibration amplitude of LD-CPNY dropped to its lowest level.

In the border town of Mexicali, station BC-UABX records a drop in ground vibration amplitude on March 17. This drop occurred almost concurrently with the state-wide shelter-in-place order in California issued on March 19. On March 30 a shelter-in-place order was also issued in Baja California (the Mexican state where Mexicali is located), almost two weeks after the recorded human activity dropped in Mexicali. This result shows that the change in the Human Activity Index in downtown Mexicali is correlated with the shelter-in–place order in California, rather than the shelter-in-place order in Baja California. It suggests that human activity in Mexicali is strongly influenced by the bordering US state of California. We will further discuss this result in the Discussion section.

An independent data set on human activity is provided by smartphone based mapping services. For example, Apple Inc. has released its Mobility Trends Reports before and after the COVID-19 pandemic (https://www.apple.com/covid19/mobility, accessed May 02, 2020), which include requests for directions in Apple Maps. The data show a relative volume of direction requests per country/region, sub-region or city compared to a baseline volume on January 13th, 2020. Cities are defined by their greater metropolitan areas, and their geographic boundaries remain constant across the data set. In figure 7, we compare the displacement RMS of the three stations with the driving index in Apple Mobility Trend of the larger metropolitan area that the stations belong to. For station BK-BRK, we use the Apple Mobility Trend of “San Francisco – Bay Area”. For station LD-CPNY, we use the Apple Mobility Trend of “New York City”. For station BC-

UABX, we use the Apple Mobility Trend of “Baja California”. From top to bottom are BK-BRK, LD-CPNY and BC-UABX, respectively. In each sub panel, blue curves show the trends of daily median displacement RMS from Dec-2019 to Apr-2020, and orange curves show the Apple Mobility Trend in the same period. The displacement RMS should reflect the human activity level in the local area (within several kilometers), while the Apple Mobility Trend should reflect the human activity in the larger metropolitan area.

As shown in figure 7, the Human Activity Index drops recorded by seismometers are in general consistent with the decrease in regional human activity determined by Apple Mobility Trend data. The differences in details may reflect the particular conditions in the local area near the seismometer. For example, the Apple Mobility Trend in Baja California started to drop several days earlier than the Human Activity Index in downtown Mexicali. Likewise, the Apple Mobility Trend data in New York City shows a minimum in activity on around March 20, while the seismic Human Activity Index near Central Park reached its lowest level one week later on around March 27. This is probably because people were still flocking outdoors for exercise and leisure as the stay-at-home order did not force people to stay indoor (e.g., Passy and Honan, 2020; Yuan, 2020; Fitz-Gibbon, 2020). To prevent people from gathering, the New York government announced additional warnings to the public in the following week and issued several stronger social distancing measures, such as closing parks, playgrounds, and streets. (e.g., Marsh and Meyer, 2020; NBC New York, 2020b; Lovelace, Feuer et. al., 2020; Kelley, 2020; Taylor et al., 2020; Lovelace, Mangan et. al., 2020). We also notice another interesting fact that station LD-CPNY is less than 500m away from the emergency tent hospital in Central Park, which was built over the weekend from March 28 to March 29 and was open in the following week (e.g., Holcombe et al., 2020; Griffith, 2020; CBS New York, 2020b). Surprisingly, the emergency tent hospital did not seem to affect the Human Activity Index at LD-CPNY, which suggests that the construction and operation of the tent hospital did not make much seismic noise. A future in-depth study is needed to fully address this observation.

In both Central Park and in Mexicali, the differences in the Apple Mobility Trend data and our calculated Human Activity Index suggest that the independent measures of human activity are sensitive to different but complementary aspects of the pandemic response. The displacement RMS should reflect the human activity level in the local area (within several kilometers), while the Apple Mobility Trend should reflect the human activity in the larger metropolitan area. By considering both the similarities and differences it may help us to better characterize human behavior to the pandemic.

Discussion

Why do most surveyed seismic stations in Southern California show no change in the Human Activity Index in response to the COVID-19 pandemic?

In the previous section we show that most of the surveyed stations in Southern California do not record a significant drop in human activity during the COVID-19 pandemic with respect to the Christmas period. Since cultural noise in the seismic record mainly originates from traffic and machinery (e.g., Stutzmann et al., 2000; McNamara and Buland, 2004; Havskov and Alguacil, 2015), this result implies that traffic and/or industrial activity in Southern California, such as factory operations, building construction, and cargo transportation, did not drop significantly during the COVID-19 lockdown. This inference is supported by the fact that 3 of the 5 stations that show a drop in ground vibration amplitude are located on a school campus (CI-MSJ, CI-USC, CI-CLT), and that the other 2 stations are relatively far away (greater than 2km) from the major highways (CI-DEV, CI-RUS).

Another piece of evidence that supports this inference comes from the comparison with precipitation data. In figure 8, we compare the average displacement RMS with the average daily precipitation in Southern California during the same period. We download the precipitation data of all 14 areas that are covered by the National Weather Service (NWS) Office in Los Angeles/Oxnard and in San Diego: Long beach, LA downtown, LA airport, Santa Maria, Burbank Glendale, Camarillo, Oxnard, Lancaster, Palmdale, San Diego, Palm Spring, Riverside, Ramona, and Escondido. The average of the 14 time series is then considered as the average daily precipitation of Southern California.

All of the seismic stations sensitive to human activity, whether their displacement RMS dropped during the COVID-19 lockdown or not, show a drop during the second week in April (April 05 – April 11). This drop correlates with a period of heavy precipitation in Southern California (figure 8a). The drop in seismic Human Activity Index could be possibly due to a reduction in industrial activity (such as construction) and/or highway traffic caused by an unfavorable weather condition. In the same period, the four stations that do not appear to be sensitive to human activity variation show no drop in ground vibration amplitude (figure 8b), meaning that the drop of displacement RMS amplitude in figure 8a during the week of April 05 through April 11 probably is not due to a change in subsurface seismic structure induced by the increase of rainfall.

In summary, our results suggest that traffic and/or industrial activity considered essential by the state of California during the pandemic, plays an important role in generating seismic noise characterized by our Human Activity Index. To determine the specific cause of the noise, a site-specific study may well be necessary.

Is the change in the Human Activity Index in Mexicali, Baja the result of the shelter-in-place order of California, USA?

In the results section, we show that the decrease in human activity in Mexicali, Baja California correlates well with the mitigation measures in California. This result suggests that physical proximity could be a more influential factor than the political boundaries for Mexicali in terms of COVID-19 pandemic. To test this hypothesis, we compare the Human Activity Index of station BC-UABX in Mexicali with the Human Activity Index of station CI-DRE near Imperial, California. Station CI-DRE is located in the Desert Research and Extension Center of University of California (figure 9a), and it is one of the few Southern California stations we investigated in the previous section that records a significant drop in Human Activity Index after the state-wide shelter-in-place order in California. Station CI-DRE is approximately 10 km away from station BC-UABX to the north, but is located north of the Mexico-USA border. If the human activity in Mexicali is more affected by the bordering US state of California, we would expect the Human Activity Index of both BC-UABX and CI-DRE to record a drop at approximately the same time.

In figure 9c, we compare the seismic-data-derived Human Activity Index of BC-UABX in downtown Mexicali with station CI-DRE. As a reference we also plot the total confirmed COVID-19 cases by population in the greater metropolitan area for which these two stations belong to. For BC-UABX, we choose the COVID-19 data of Baja California; for CI-DRE, we choose the COVID-19 data of California. As shown in figure 9c, the Human Activity Index of both BC-UABX and CI-DRE show a drop after the shelter-in-place order in California, although the magnitude of drop was smaller in CI-DRE, likely the result of its location in a less populated area. We do not observe a change in human activity for either station around March 30, when the shelter-in-place order was issued for Baja California.

The "geographical control" hypothesis is also, to a certain degree, supported by the COVID-19 data. In figure 9b, we compare COVID-19 data for Baja California with Chiapas, the southernmost state in Mexico, in figure 9b. We plot the total confirmed COVID-19 cases per million between four political regions: California, Baja California, Mexico (whole country), and Chiapas state in southern Mexico. This figure shows that the trajectory of the COVID-19 pandemic development in Baja California correlates more with California, rather than with Chiapas or the average of Mexico.

The similarity between seismic-data-derived Human Activity Index of both station BC-UABX and station CI-DRE suggests a potential geographical control on human activity, rather than a political control, in Mexicali. Considering that cultural noise mainly originates from traffic and machinery (e.g., Stutzmann et al., 2000; McNamara and Buland, 2004; Havskov and Alguacil, 2015), this result is probably due to the fact that much of the industry or traffic in Mexicali is cross-border, and thus is affected strongly by the US. The similarity of COVID-19 confirmed cases trend between Baja California and California implies that the progress of the pandemic is similar in these two neighbouring states. However, there are intrinsic uncertainties in the COVID-19 data, as we do not know how much they are affected by the testing capacity and related policies. A thorough analysis of the geographical control is subject to a future study.

Do regionally-based mitigation measures influence the course of the COVID-19 pandemic?

How will regionally-based mitigation measures influence the course of the COVID-19 pandemic? This is an important question for both governments and academia (Anderson et al, 2020). We have shown in the previous sections that ground displacement root mean square (RMS) is capable of monitoring local human activity changes. The seismic data-derived Human Activity Index suggests that the mitigation measures in many regions have indeed reduced the human activities in local communities. Did these measures successfully mitigate the development of the COVID-19 pandemic?

One way to address this question is to compare the seismic data-derived Human Activity Index with COVID-19 data. In figure 10, we plot the daily median ground displacement RMS at UC Berkeley, the Central Park in New York City, and downtown Mexicali against the total confirmed COVID-19 cases by population in the greater metropolitan area they belong to. The blue curves denote the daily median displacement RMS and the yellow curves denote the COVID-19 trends. We compare the UC Berkeley station human activity with the COVID-19 data of the 9 California counties in the Bay Area (Alameda, Contra Costa, Marin, Napa, San Mateo, Santa Clara, Solano, Sonoma, and San Francisco, ~7.75 million people). The Central Park in New York City human activity is compared with the COVID-19 data in New York City (~8.34 million people), and the Downtown Mexicali human activity is compared with the COVID-19 data of Baja California

(~3.32 million people). Baja California is a much larger area than the other metropolitan areas. However, much of its population is concentrated in the North in a much smaller area, near Tijuana and Mexicali.

As shown in figure 10, all three metropolitan areas experienced a rapid increase in COVID-19 numbers before human activity dropped to its reduced level. Note that the COVID-19 cases number are plotted in logarithmic scale, so an exponential growth in COVID-19 cases should correspond to a straight line. After human activity decreases, the exponential growth rate appears to slow and become steady after a few weeks. This result suggests that the mitigation measure did indeed attenuate the spread of the virus. However, it is also possible that this is because the testing data lagged behind new COVID-19 cases in March and April, 2020. With limited knowledge about the nature of COVID-19 data, it is difficult to draw firm conclusions on causality.

Conclusions

In this article, we use seismic data to extract information on human activity changes during the early stage of the global COVID-19 pandemic in California, USA, New York City, USA, and Mexicali, Baja California, Mexico. The Human Activity Index derived from seismic data has the ability to monitor human activity at a very local (several kilometers range) scale. While these data are to first-order consistent with mitigation measures of the greater metropolitan area, the ground motion data reveal unique information about the local area. In Southern California, we observe that while some stations record a drop in human activity comparable to the Christmas holiday period, most stations do not. One potential interpretation is that the traffic and/or industrial activity in

Southern California associated with essential activities, such as factory operations, building constructions, and cargo transportation, did not drop during the COVID-19 lockdown.

We investigate two other stations outside California, USA: station LD-CPNY in Central Park, New York City, USA and station BC-UABX near downtown Mexicali, Baja California, Mexico. The drop in the seismic Human Activity Index of LD-CPNY near the Central Park area in New York City is delayed by approximately one week from the decrease in human activity in New York City determined by the Apple Mobility Trends Reports. We hypothesize that this is due to people continuing to utilize outdoor space even after the restriction on non-essential businesses was issued in New York. Station BC-UABX records a drop in human activity during the COVID-19 pandemic. However, the timing of its drop is better correlated with the shelter-in-place order in its neighboring US state California, rather than the shelter-in-place order in Mexico, indicating a potential geographical control on human activity, rather than a political control, in Mexicali. These results suggest that the seismic Human Activity Index is sensitive to very localized human activity change and is thus capable of helping us better characterize the human behavior in response to COVID-19 pandemic.

Although a seismometer is best known for its ability to record earthquake shaking, it is also capable of recording ground movements caused by human activity, as we explore in this article. Especially, we have shown that the seismic derived Human Activity Index is particularly sensitive to the human activity changes at a very local (several kilometers range) scale. From an earth science point of view, the reduction in human activity during the pandemic offers us a chance to explore the nature of cultural noise in the seismic record, such as its physical origins and its attenuation distance. From a public health point of view, the advancements of open-access seismic data make it possible for a daily monitoring of human activity via cultural noise. As we write this paper (July 24, 2020), the total number of COVID-19 cases is still growing rapidly. If interpreted properly, the seismic noise data can provide valuable information on local human activity and could be very helpful to policy makers and scientists as they make critical decisions to combat the COVID-19 pandemic and potentially future pandemics.

Data and Resources

All seismic data we used are open-access at different data centers and can be accessed through the Incorporated Research Institutions for Seismology (IRIS) website (www.iris.edu, last accessed June 2020). The data of Southern California Seismic Network (CI) is downloaded from the Southern California Earthquake Data Center (SCEDC). The data of Berkeley Digital Seismograph Network (BK) is downloaded from the Northern California Earthquake Data Center (NCEDC). The data of Lamont-Doherty Cooperative Seismographic Network (LD), CICESE's Seismic Network (BC) and Mexican National Seismic Network (MX) are downloaded from the IRIS Data Management Center (IRISDMC). Precipitation data in Southern California is downloaded from the National Weather Service (NWS) Office website (https://w2.weather.gov/climate/xmacis.php?wfo=lox for Los Angeles/Oxnard Office data; https://w2.weather.gov/climate/xmacis.php?wfo=sgx for San Diego Office data, last accessed June 2020). The COVID-19 data in United states are obtained from the COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns

Hopkins University (Dong et al., 2020), and the COVID-19 data in Mexico are obtained from the Coronavirus webpage on the Government of Mexico website (https://coronavirus.gob.mx/datos/, last accessed June 2020). The population data of "San Francisco Bay Area", "New York City", and "California" are obtained from the United States Census Bureau. The population data of "Baja California", "Chiapas", and "Mexico (whole country)" is obtained from the National Institute of Statistics and Geography in Mexico. All maps in the paper are made with Google Maps (https://www.google.com/maps, last accessed July 2020).

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Figure captions

Figure 1. An example of a seismic record demonstrating how the sliding time-windows are used to compute displacement root mean square (RMS) time series. The seismogram in red is 1 hour of a vertical component seismogram (HHZ) at station BK-BRK filtered at 4-14 Hz (from 2020-05-20, 6am to 7am, local time). The blue, cyan, and brown horizontal lines below the plots denote the three, 30 minutes long overlapping sliding time windows within this one hour.

Figure 2. (a) Small scale map showing the regional context of station BK-BRK (Berkeley, CA, US). Blue circular shade denotes an area within 2 km of the station. The human activity induced seismic waves that are detected by the stations are mostly generated within the shaded area. **(b)** Large scale map showing the area near station BK-BRK . **(c)** Displacement RMS of BK-BRK station from Dec 1, 2019 to Apr 26, 2020. Thin black curves show the displacement RMS of the 30 minute-long sliding window, and thick red curves show daily median displacement RMS amplitudes.

Figure 3. (a) A map showing the area near station CI-MSJ and CI-RSS (Hemet area and Riverside area, California, United States). Blue circular shading denotes an area within 2km range of the station. The human activity induced seismic waves that are detected by the stations are mostly generated within the shaded area. **(b)** daily median displacement RMS time series of CI-MSJ (upper panel) and CI-RSS (lower panel) from Dec 1 to Apr 26. In each sub panel, blue curves show the trends of the current year (Dec-2019 to Apr-2020) and gray curves show the trends of the previous year (Dec-2018 to Apr-2019).

Vertical lines of different colors denote the dates when a potential human-activity-related restriction was issued, such as “school close order” or “shelter-in-place order”.

Figure 4. Locations of 23 seismic stations investigated in Southern California. Purple pins denote the 5 stations that record a drop in human activity during COVID-19 lockdown. Red pins denote the 14 stations that are capable of reflecting human activity variation but did not record a drop in human activity during COVID-19 lockdown. Green pins denote the 4 stations that are not capable of reflecting human activity variation.

Figure 5. (a) Scaled daily median displacement RMS time series of the 19 stations that show the capability of detecting human activity change. All 19 time series are plotted in black. Green horizontal dashed line denotes the Christmas/New Year break level, and Orange horizontal dashed line denotes the normal period level. Vertical purple line denotes the day when California issued a state-wide “shelter-in-place” order. **(b)** Same as figure 7a, except that the 5 stations that show an amplitude drop for Covid-19 are instead plotted in red while the other 14 stations that do not show drop remain plotted in black.

Figure 6. (a) Map showing the area near station LD-CPNY (Central Park, New York City, NY, United States). Blue circular shade denotes an area within 2km range of the station. The human activity induced seismic waves that are detected by the stations are mostly generated with the shaded area. **(b)** A map showing the area near station BC-UABX (downtown Mexicali, Baja California, Mexico). Blue circular shaded area as above. **(c)** daily median displacement RMS time series of BK-BRK (upper panel), LD-CPNY (middle panel) and BC-UABX (lower panel) from Dec 1 to Apr 26. In each sub panel, blue curves

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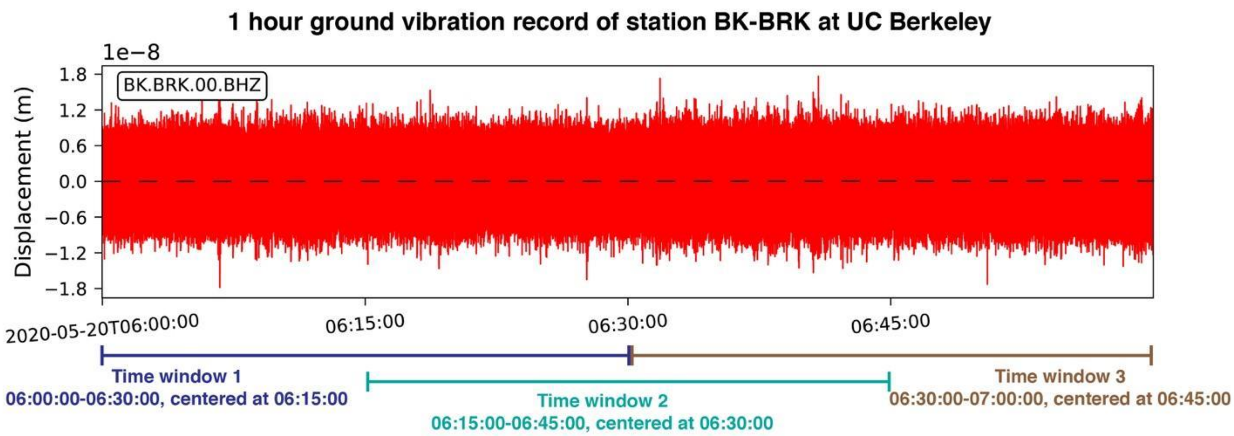
Figure 7. Comparisons between the ground vibration amplitude and the Apple mobility driving index. From top to bottom are BK-BRK, LD-CPNY and BC-UABX, respectively. In each sub panel, blue curves show the trends of daily median displacement RMS from Dec-2019 to Apr-2020, and orange curves show the Apple mobility driving index trends in the same period.

Figure 8. (a) Comparisons between the average daily precipitation in Southern California and the 14 daily displacement RMS time series that do not show a significant drop in amplitude after the “shelter-in-place” order. Gray thin curves are the individual time series of the 14 stations. Purple curves are the mean variation of the 19 individual time series. Green curves are the average daily precipitation time series over the 14 areas that are covered by the National Weather Service (NWS) Office in Los Angeles/Oxnard and in San Diego: Long beach, LA downtown, LA airport, Santa Maria, Burbank Glendale, Camarillo, Oxnard, Lancaster, Palmdale, San Diego, Palm Spring, Riverside, Ramona, and Escondido. **(b)** Comparisons between the average daily precipitation in Southern California and the 4 daily displacement RMS time series that are not reflecting human activity variations. Gray thin curves are the individual time series of the 4 stations. Purple curves are the mean variation of the 5 individual time series. Green curves are the average daily precipitation time series in Southern California (same as figure 8a).

Figure 9. (a) A map showing the area near station BC-UABX and CI-DRE. Blue circular shading denotes an area within 2km range of the station. The human activity induced seismic waves that are detected by the stations are mostly generated within the shaded area. **(b)** The total confirmed COVID-19 cases per million in population between four political regions: California, Baja California, Mexico (whole country), and Chiapas state in southern Mexico. The COVID-19 confirmed cases data are plotted in logarithmic scale. **(c)** Daily median ground displacement RMS at downtown Mexicali (BC-UABX, upper panel) and near Imperial, California (CI-DRE, lower panel) against the total confirmed COVID-19 cases by population in the greater metropolitan area it belongs to. The blue curves denote the daily median displacement RMS and the yellow curves denote the COVID-19 trends. The COVID-19 confirmed cases data are plotted on a logarithmic scale. Red and purple vertical lines denote the timing of “shelter-in-place” order in California, USA and Baja California, Mexico (numbered in chronological order).

Figure 10. Daily median ground displacement RMS at UC Berkeley (BK-BRK, upper panel), Central Park in New York City (LD-CPNY, middle panel), and downtown Mexicali (BC-UABX, lower panel) along with the total confirmed COVID-19 cases per million in population in the greater metropolitan area in which it belongs. The blue curves denote the daily median displacement RMS and the yellow curves denote the COVID-19 trends. The COVID-19 confirmed case data are plotted on a logarithmic scale. Vertical dash lines denote the dates when a potential human-activity-related restriction was issued.

Figures



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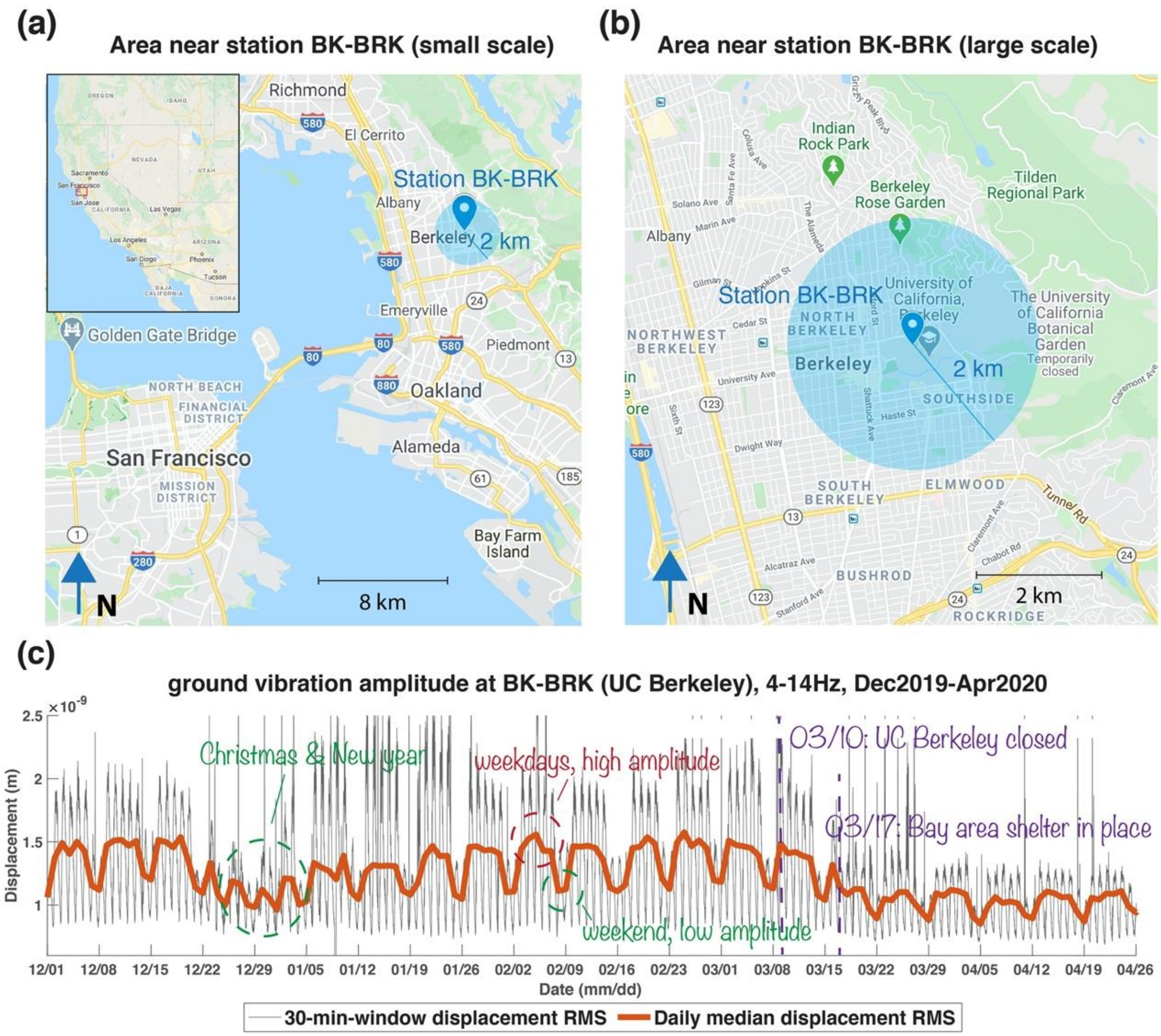

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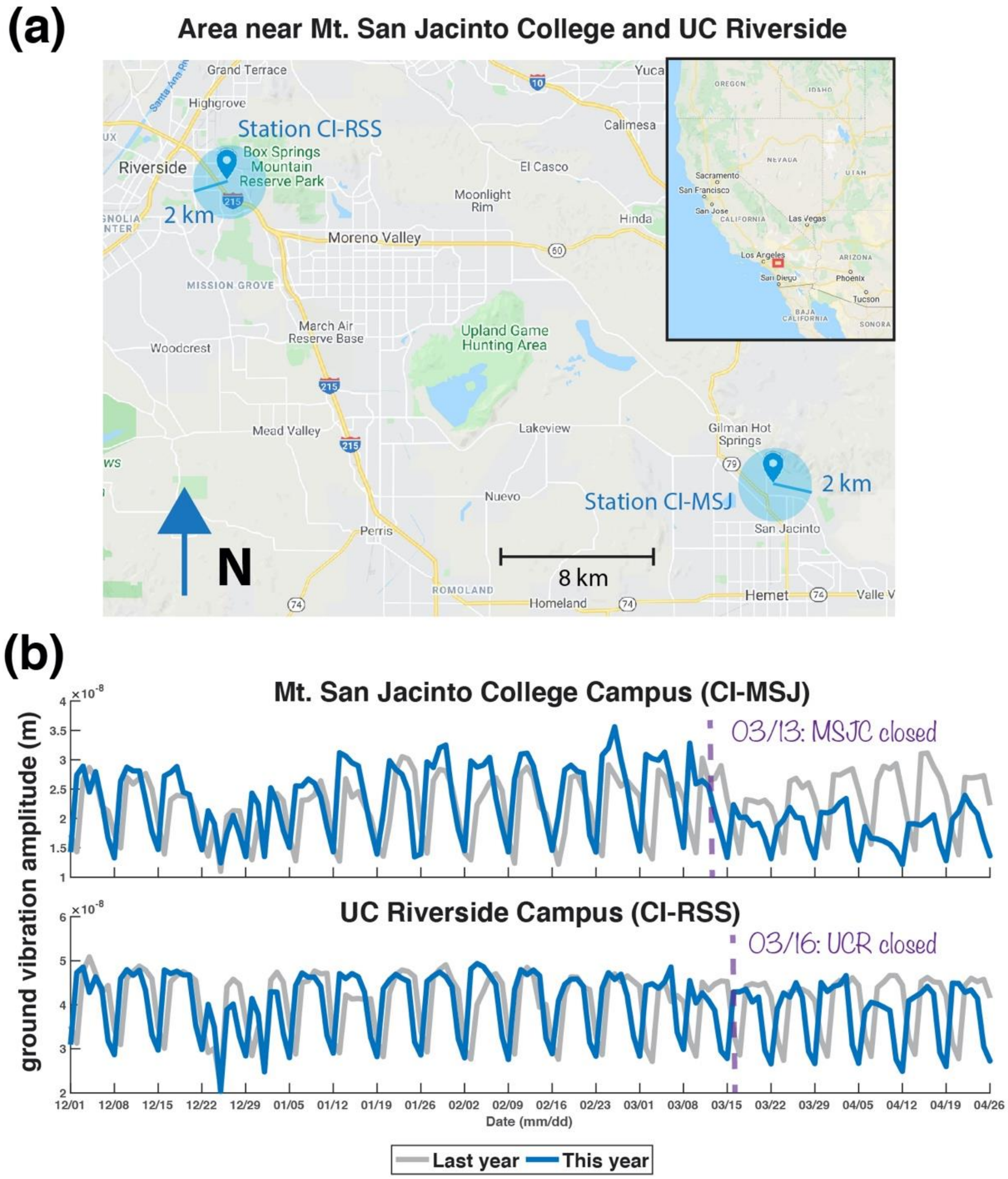

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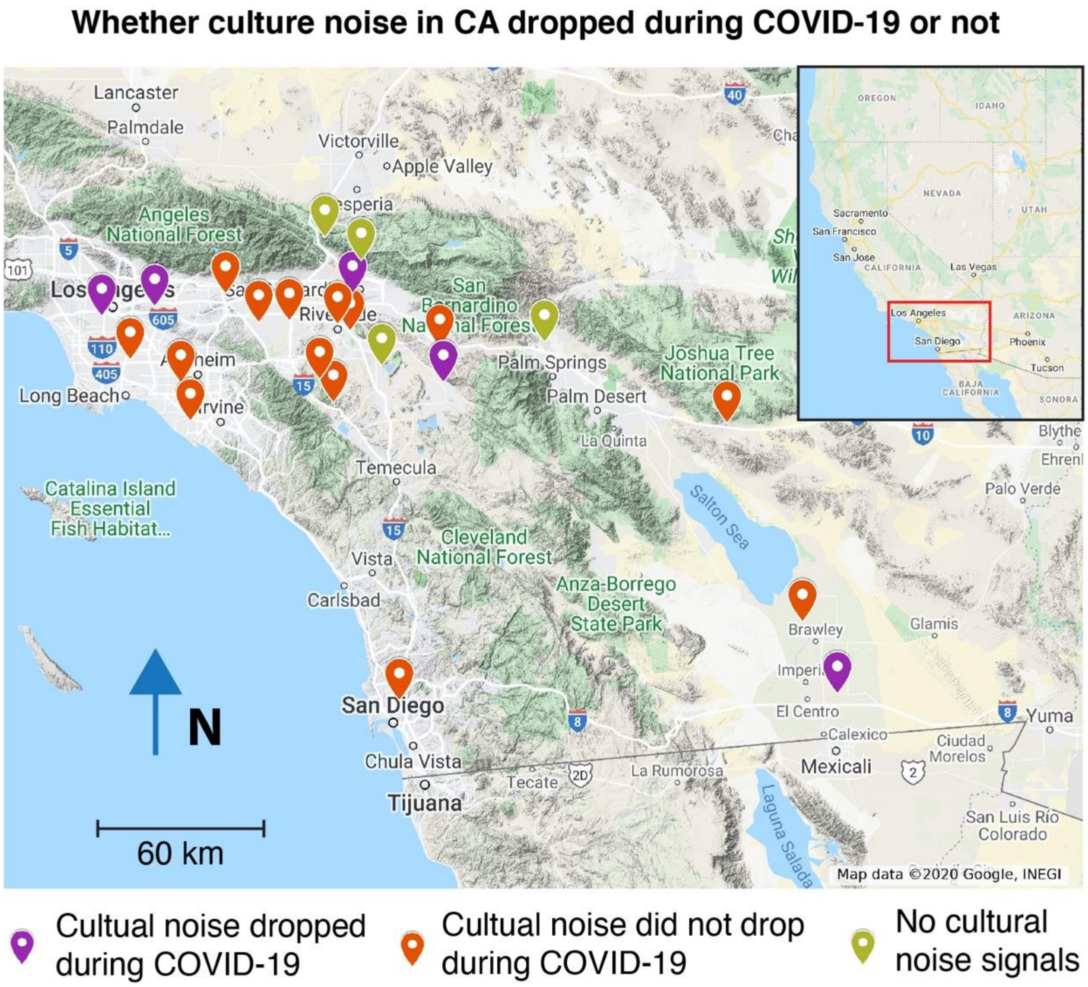

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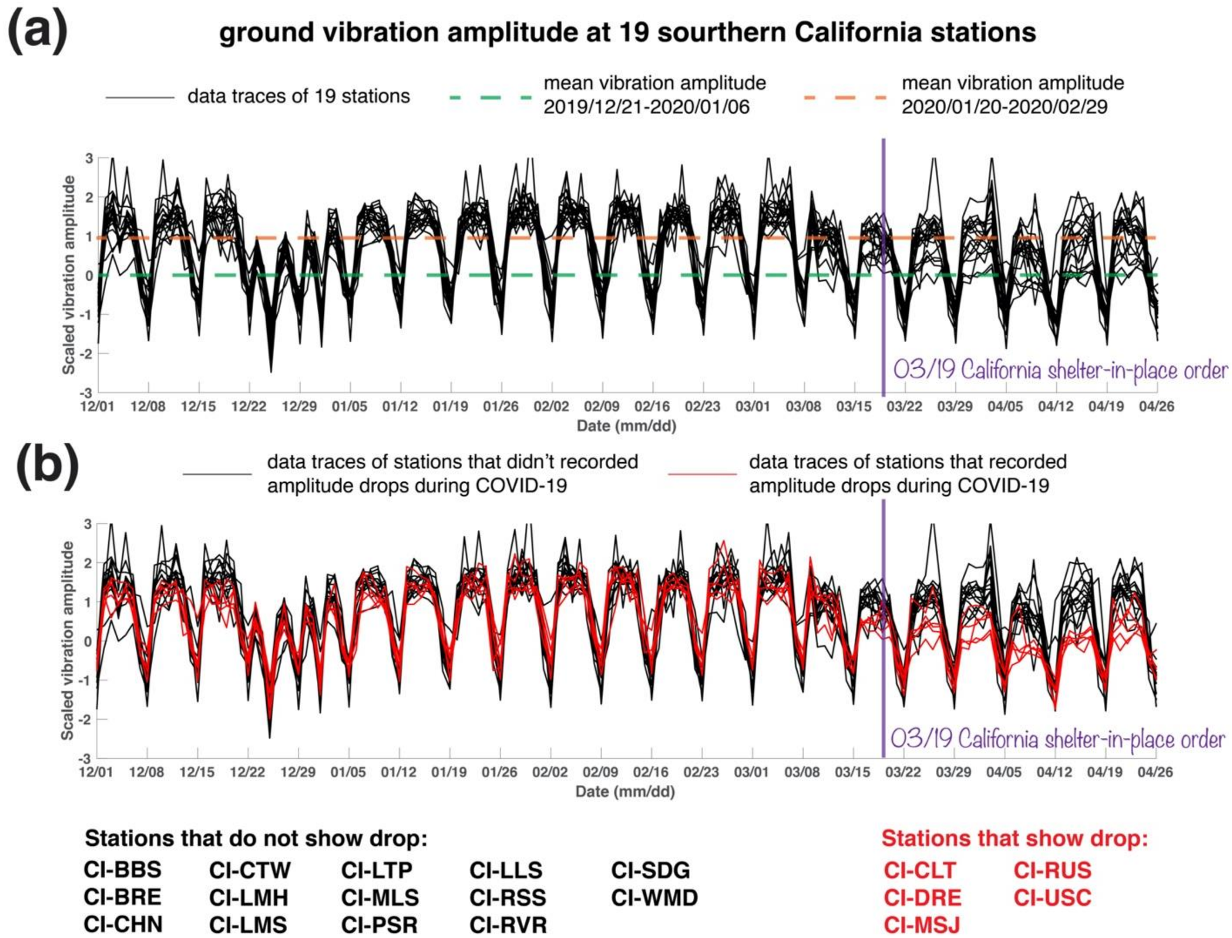

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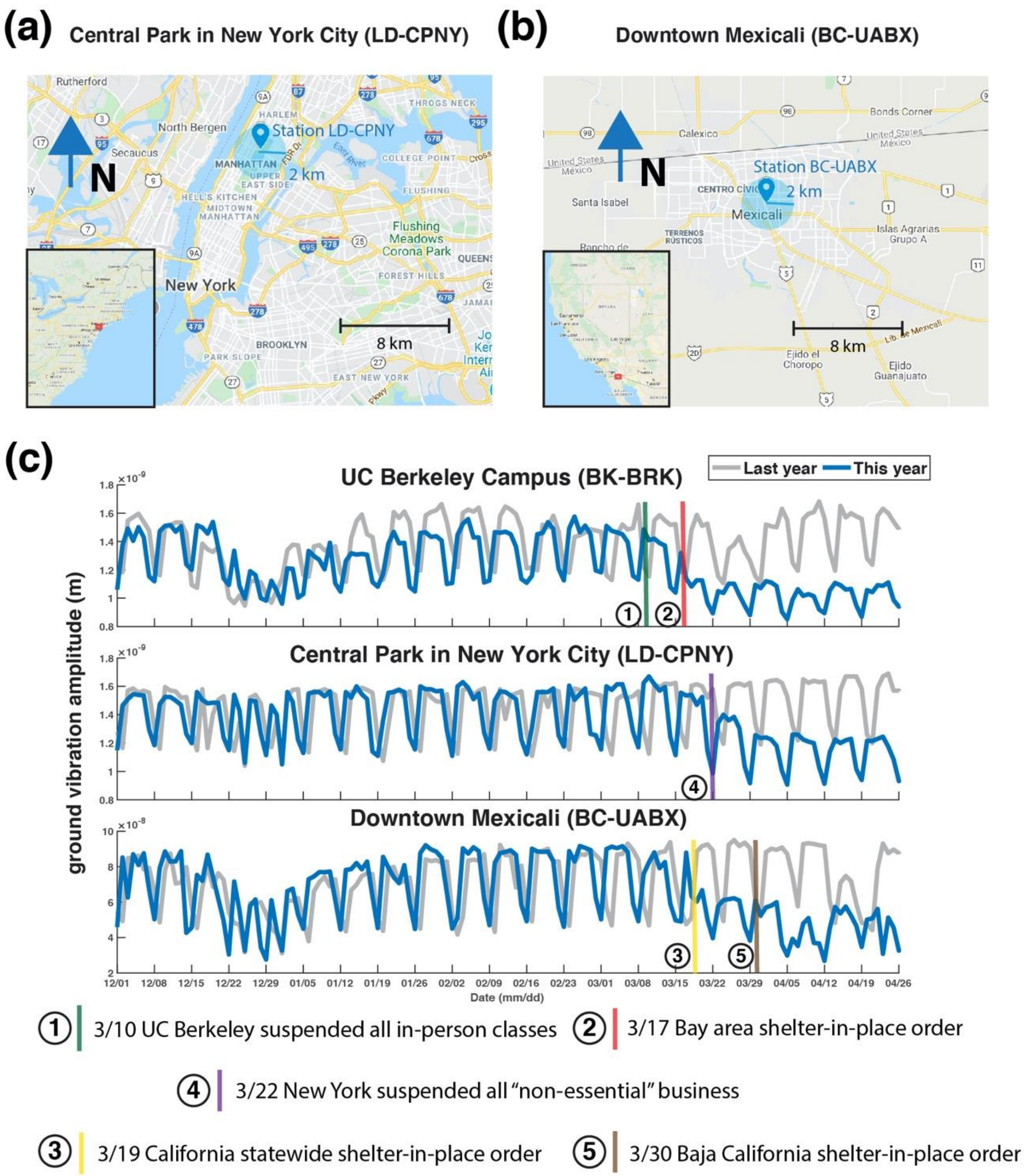

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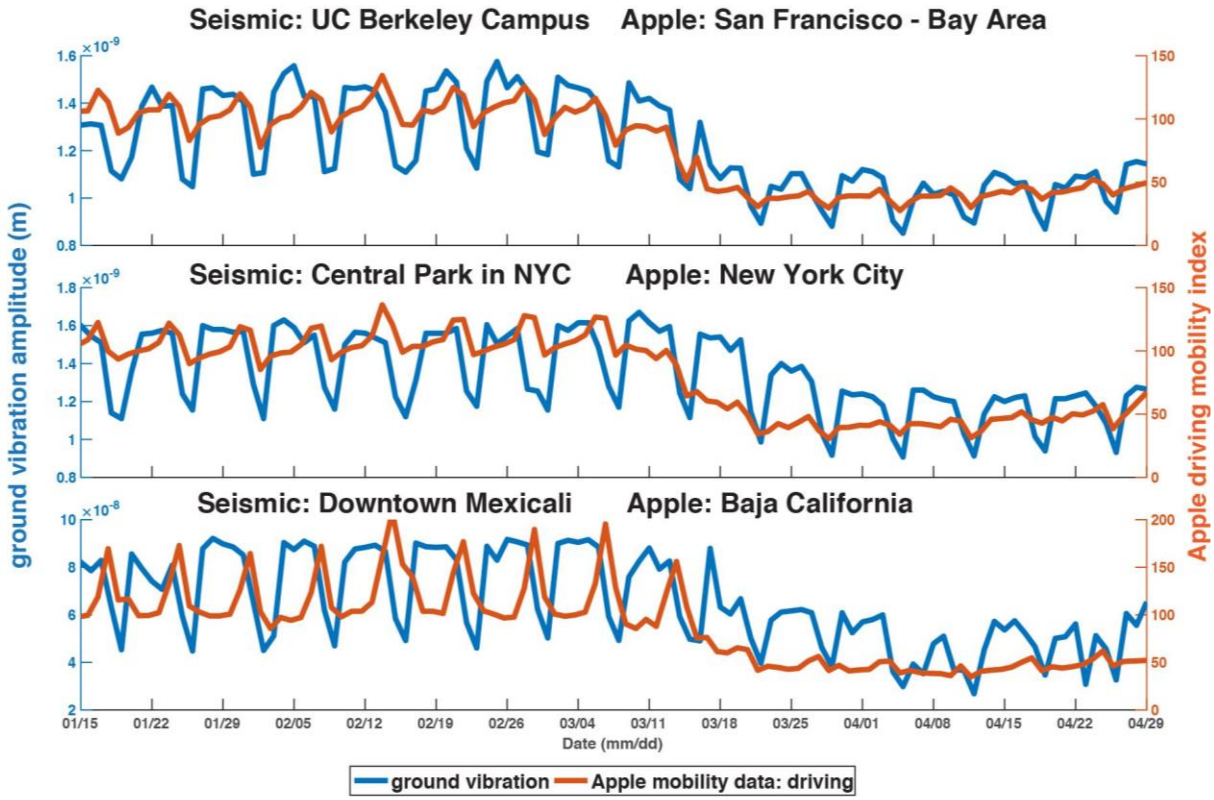

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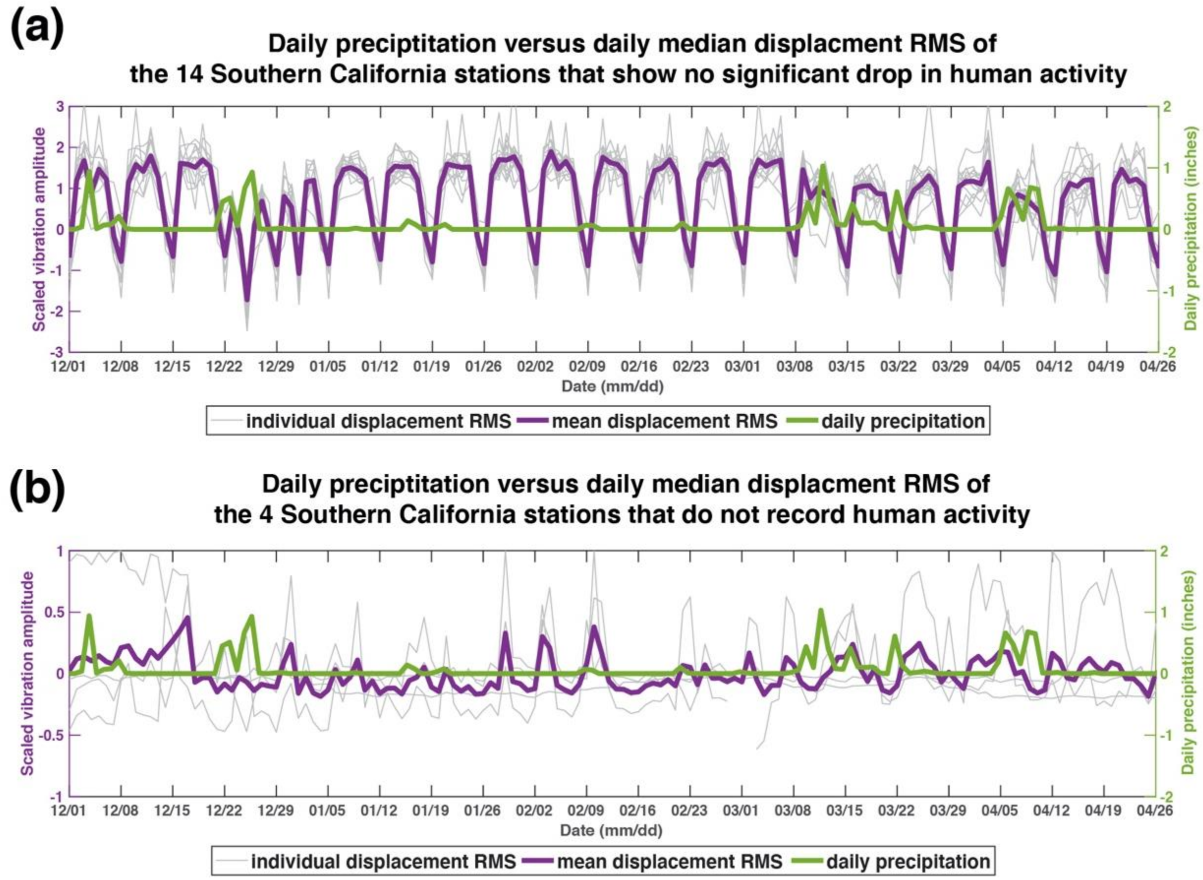

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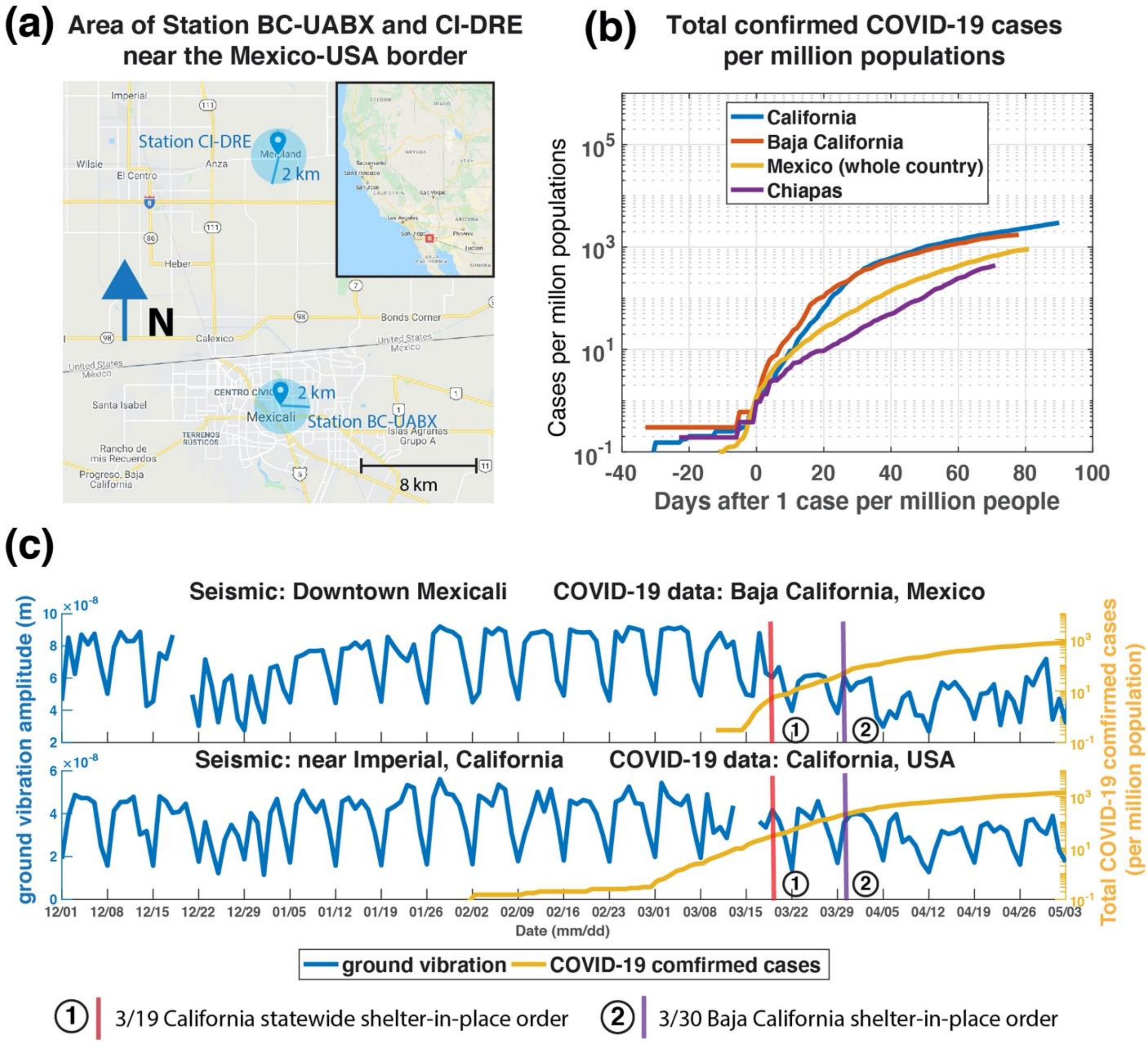

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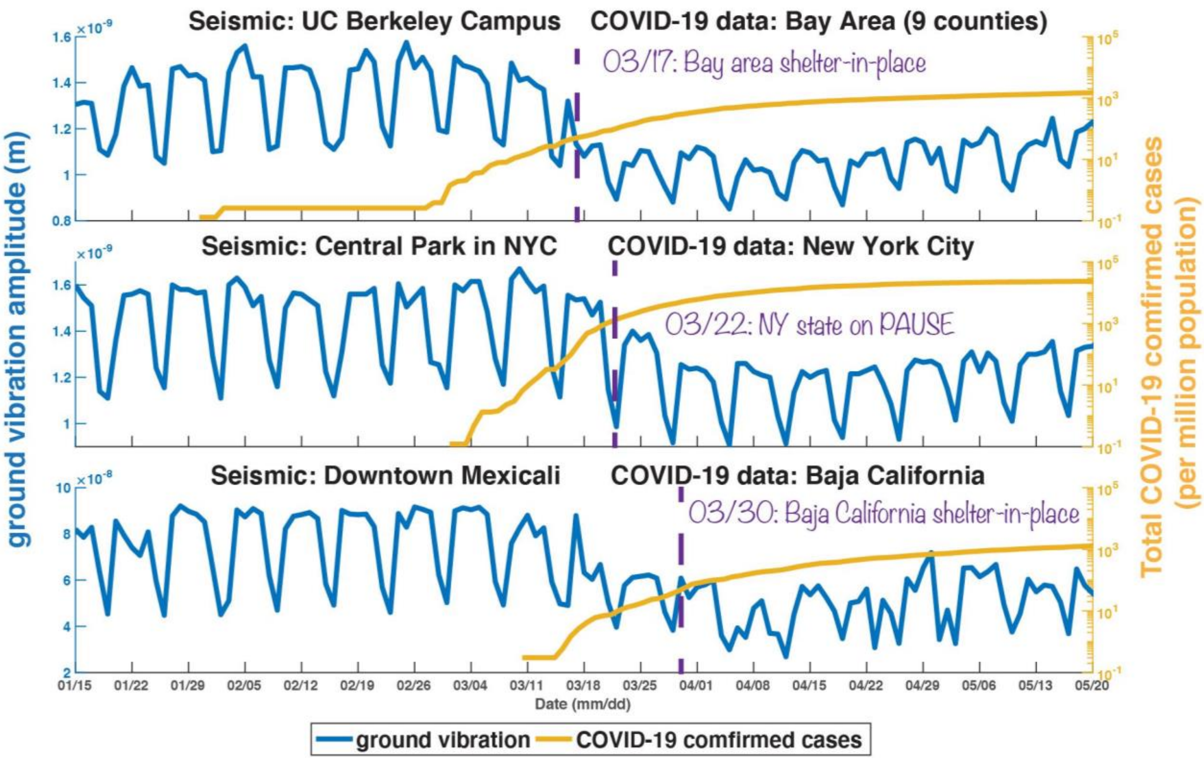

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