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Solid Earth Discussions

Seismic noise variability as an indicator of urban mobility during COVID-19 pandemic in Santiago Metropolitan Region, Chile

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Abstract. On 3 March 2020, the first case of COVID-19 was confirmed in Chile. Since then, the Ministry of Health has imposed mobility restrictions, a global policy implemented to mitigate the propagation of the virus. The national seismic network operating throughout Chile provides an opportunity to monitor the ambient seismic noise (ASN) and determine the effectiveness of public policies imposed to reduce urban mobility in the major cities. Herein, we analyse temporal variations in high-frequency ASN recorded by broadband and strong-motion instruments deployed throughout the main cities of Chile. We focus on the capital, Santiago, a city with more than 7 million inhabitants, because it is seismically well-instrumented, and has high levels of urban mobility due to work commutes inside the region. We observed strong similarities between anthropogenic seismic noise and human mobility indicators, as shown in the difference between urban and rural amplitudes, long-term variations, and variability due to the COVID-19 outbreak. Our findings suggest that the initially implemented public health policies and the early deconfinement in mid-April 2020 in the metropolitan region caused an increase in mobility and virus transmission, where the peak in anthropogenic seismic noise coincides with the peak of the effective reproductive number from confirmed positive cases of COVID-19. These results confirm that seismic networks are capable of monitoring the urban mobility of population within cities, and we show that continuous monitoring of ASN can quantify urban mobility. Finally, we suggest to consider monitoring in real time the changes in ASN amplitudes to be included in the public policies about urban mobilities in Santiago as well as other high density cities of the world, as has been useful during the recent pandemic.

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1 Introduction

Since the propagation of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) which causes the coronavirus disease-2019 (COVID-19), countries have used various strategies to reduce the risk of the spreading of the virus. In Chile, the first case of COVID-19 was confirmed on 3 March 2020, and then the disease spread rapidly until the number of cases reached a peak on 14 June (Canals et al., 2020). The metropolitan region (hereafter MR) of Chile includes the capital, Santiago, a big city with 40% of the Chilean population. According to the 2017 Census (INE, 2017), the population of the MR reached 7,112,808 inhabitants with a density of 461.77 inhabitants per km2, and Santiago had the highest population density (Figure 1, Figure A1).

Ambient seismic noise (ASN) can be attributed to various sources depending on the frequency band analysed. At higher frequencies, above 1 Hz, ASN exhibits daily, weekly and holiday variations linked to human activities (e.g. Bonnefoy-Claudet et al., 2006; Groos & Ritter, 2009; Díaz et al., 2017). This high-frequency band, also called anthropic or cultural noise, registered on seismic data is quickly attenuated with distance at the order of a few km (Groos & Ritter, 2009; Boese et al, 2015; Green et al, 2017). The effects of COVID-19 outbreak and global mobility restrictions have created an opportunity to analyse the reduction and temporal variations in high-frequency ASN on seismological networks (e.g., Canatta et al., 2020; Dias et al., 2020; Lecocq et al., 2020; Poli et al., 2020; van Wijk et al., 2020; Xiao et al., 2020), GNSS Observations (Karegar & Kusche, 2020), and fibre-optic distributed acoustic sensing (Lindsey et al., 2020). These observations reveal the effect of mobility restrictions imprinted on geophysical measurements worldwide, and the pandemic caused one of the quietest recorded periods on Earth with a 50% reduction in seismic noise (Denolle & Nissen-Meyer, 2020; Lecocq et al., 2020). However, a deep analysis of temporal variations in ASN in each city/country could reveal ways to significantly advance the robust monitoring of urban mobility, especially during a pandemic.

Herein, we analyse the effect of temporal variations on ASN using the continuous recording data of the Chilean National Seismological (CSN) network. Our results show the difference between urban and rural ASN amplitudes, and the long-term temporal variations and reduction during holiday seasons as well as those due to the spreading of COVID-19 and mobility restrictions. Additionally, we studied the temporal variations due to the implementation of different public health policies in Chile. We identified an agreement between high-frequency ASN amplitudes and other mobility data within the MR, as well as an increase in epidemiological parameters of

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virus transmission on the dates of a peak in ASN. Our findings suggest that ASN analysis could be used to infer the dynamics of the population influenced by large and long-scale events, such as a pandemic.

2 Data and Methods

2.1 Seismic data

Since 2012 the CSN has deployed a large number of seismic stations throughout Chile, most of them in areas outside the main cities where there is a low signal-to-noise ratio to better record the regular seismicity (Barrientos et al., 2018; Leyton et al., 2018a; Leyton et al., 2018b). The CSN network is formed by 120 broad-band and accelerometer multi-parametric stations deployed at the same location, 300 accelerographs with trigger systems, and a few continuous recording strong-motion instruments. Herein, we focus on stations located inside or close to the principal cities. We analysed the data of 15 stations localised in the MR as well as 5 stations located in some cities within Chile (Iquique, La Serena, Valparaíso, Concepción, and Puerto Williams) (Figure 1, Figure A1). These places were selected because of their distance from the main cities, high-quality data, and short-time data gaps. We only analysed the vertical component of the data due to the similarities in the results observed using horizontal components (Lecocq et al. 2020). Most of the records correspond to broadband stations, except for the strong motion C.CCSP station localised in San Pedro - Concepción, and the strong motion C1.MT18 station localised in downtown Santiago (for MT18 station, we analysed both broadband and strong-motion records). For all stations we processed eleven months of data from 1 December 2019 to 1 October 2020 and three years of data from 1 October 2017 to 1 October 2020, for stations MT09 and MT18 located in the MR.

2.2 Seismic noise analyses

To investigate the temporal changes in the seismic signal, we followed the methodology used by Lecocq et al. (2020) considering continuous data. We computed a daily power spectral density in 30-min windows, where each windowed time series was calculated using Welch's method (Welch, 1967), therefore, the windowed segments were converted to periodograms. We estimated the displacement spectral power, from which we calculate the root-mean-square (RMS) of the time-domain displacement using a bandpass filter. To better address the corner

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frequencies of the bandpass filter, we tested the temporal changes in the normalised seismic RMS amplitude at the MT18 station (Figure 2). In the first order, the temporal changes are similar between the different corner frequencies applied, excluding the lower frequency bands such as 0.1-1 Hz, 1-3 Hz, and 3-5 Hz. At frequencies > 1Hz we can avoid records of microseism and observe important temporal changes in the normalised displacement. Consequently, we decided to filter the data between 4 and 14 Hz to obtain the RMS of the time-domain displacement or high-frequency ASN (Lecocq et al., 2020).

We calculated the RMS displacement variability for broadband and strong-motion records. Figure 3 shows the temporal changes in ASN amplitudes that are comparable between both instruments at station MT18. The median day-time amplitudes between 5h and 22h local time obtained from the seismometer and the accelerometer exhibits similar trends and behaviour. To analyse the seismic effects of lockdown in Santiago City, we calculated 24-h clock plots for station MT18 through which we observed the average displacement variation for weekdays and weekends for the period before Lockdown 1 (Figure 4a) and after Lockdown 1 (Figure 4b). In addition, the displacement noise evolution is shown in an hourly grid representation from January 2020 to August 2020 (Figure 4c). Although we observed a gradual reduction in ASN amplitudes on weekdays, a strong reduction was observed for weekends, especially between 11 h and 19 h, associated with social activities near the station in O'Higgins Park. We also distinguish the lockdown effect in the hourly grid representation, we observed a systematic behaviour of lower ASN amplitudes between 5 h and 22 h due to the imposed curfew between 22 h and 5 h, since Lockdown 1.

2.3 Other observables: Epidemiological and mobility data

Our study integrates epidemiological data available in official repositories from the Chilean Ministry of Science. One of the primary indicators of the spreading of viruses and contagion dynamics is the estimation of the effective reproductive number (Re) from confirmed positive cases of COVID-19 since the date of the beginning of symptoms. To control an epidemic outbreak, the Re parameter needs to be reduced below 1 (Riley et al., 2003). Herein, we used the estimation provided by ICOVID Chile (2020) who used the method proposed by Cori et al. (2013) only for the MR.

Related to mobility data, we analysed the data provided by Apple devices in Santiago City, which corresponds to the percentage of change in the public's walking and driving relative to the baseline value from 13 January (Apple, 2020). Moreover, we used the public transport transactions provided by the Chilean Ministry of Transport and the Instituto de Sistemas Complejos de Ingeniería (Ministerio de Ciencia, 2020). They account for the total number of transactions using a mobility card for public transport in the MR. Finally, we utilised local flight data provided by the Civil Aeronautics Board, which corresponds to the total number of passengers that departed from Santiago City or arrived there on national flights (Ministerio de Ciencia, 2020).

3 Results

3.1 Variability between urban and rural areas in the Metropolitan region

Figure 5 shows the ASN variability over 3 years for two representative stations in MR, MT14 in Las Condes, and MT09 localised on an almost unpopulated area, near the town of Talagante. High-frequency ASN exhibits higher amplitude in urban stations than rural environments. MT14 presents larger temporal changes, for example during the summer holiday season (January-February). The same trends are observed in the three analysed years 2018, 2019, and 2020, and the lockdown restrictions are visible with clear changes in the mean of ASN. In contrast, the MT09 station located in a rural environment presents lower ASN amplitudes with few localised peaks due to local activity in the area.

Figure 6 shows the ASN variability in the six stations inside the urban ratio in the MR. In ten months of data, we can see the temporal changes in high-frequency ASN. MR had different lockdown protocols depending on each municipality; however, most of the changes started on 14 March 2020, where schools, universities, and institutes decided to shut down and stopped their activities to mitigate the spread of COVID-19. The first lockdown was in downtown Santiago (MT18, Figure 6b) and Las Condes (MT14, MT16, Figures 6c, 6d) on 26 March 2020, 23 days after the first case of positive COVID-19 and was lifted on 13 April (downtown Santiago, MT18) and 16 April (Las Condes, MT14, MT16). After that, ASN amplitudes increased until the second lockdown on 5 May (Santiago Centro, MT18) and 15 May (Las Condes, MT14, MT16) where immediately ASN amplitude decreased. These temporal restrictions were well recorded by seismic stations installed in urban areas and are useful for analysing urban mobility. Other sectors from MR such as Renca (MT05, Figure 6a), Peñalolén (MT03,

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Figure 6e), and Puente Alto (MT15, Figure 6f) also show strong variations in ASN because of lockdown restrictions. In contrast, the high-frequency ASN estimated for rural stations shows lower amplitudes and without conspicuous evidence of temporal variations due to mobility restrictions (Figure A2); as we mentioned previously, localised peaks are related to local activity in those areas and do not seem to follow a behaviour related to the anthropogenic ASN.

3.2 Correlation of lockdown, mobility restrictions, and epidemiological parameters with seismic noise amplitudes

We analysed the temporal variability of high-frequency ASN for station MT14, located in the Las Condes municipality within Santiago because this station lacked data gaps during 2020 and the area implemented different public policies for mitigating the effects of the pandemic. Figure 7 shows a strong correlation between the temporal changes in ASN amplitudes and the effective reproductive number (Re), especially from March to July, where we observed a peak in the number of positive COVID-19 cases (Canals et al., 2020). The peak for the Re parameter occurred after the end of Lockdown 1 and before Lockdown 2, a period in which the ASN amplitudes also increased. This observation is supported by mobility data such as Apple driving and walking data (Figure A4), the gradual increase in public transport transactions, and a gradual increase in the flight arrivals and departures from Santigo city (Figure A5).

After Lockdown 2 mitigated the propagation of SARS-CoV-2 virus, the Chilean government proposed a programme to gradually increase mobility in different counties as a public health policy in middle July 2020. The programme considers five phases, where the citizens progressively increase their mobility, and the advance or retreat of these phases is related to the epidemiological situation of each municipality. Las Condes (MT14) was the first territory in the MR in which the programme changed from Phase 1 to Phases 2 and 3. These mobility conditions explain the increase in high-frequency ASN amplitudes after 28 July (Phase 2) and 2 September (Phase 3) (Figure 7). These periods also correlate with the strong increase in the Apple mobility data. The Re parameter presents a gradual increase in this period and seems to oscillate around 1, similar to the period between May and June.

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3.3 Situation in other places along Chile

The variability in ASN amplitudes was observed in other populated cities of northern Chile, such as Iquique (TA02, Figure A3a) and La Serena (CO05, Figure A3b). In Iquique, the high-frequency ASN decreased after school closures until the end of April 2020, after which ASN increased to average levels. With the increase in the number of positive COVID-19 cases the government implemented the first lockdown in this city. In La Serena, the trends were similar, with a local ASN increase at the end of April. However, data gaps at station CO05 in La Serena do not allow further analysis. The Valparaíso station, along the coast of Central Chile (VA01, Figure A3c), showed high variation due to the influence of the ocean, and it is difficult to highlight the change in ASN associated with anthropogenic noise. In Central-South Chile in San Pedro, Concepción (CCSP, Figure A3d), we observed a strong reduction in ASN after school closures and the implementation of the first lockdown. Finally, in Puerto Williams (MG01, Figure A3e), a small town at the end of South America, temporal changes in ASN were also recorded, and this reduction coincided with the lockdown period and restriction of mobility and human activities.

4 Discussion

During 2020, the MR exhibited temporal changes in the amplitude of high-frequency ASN at all the stations near urban areas. However, we also identified temporal changes in the long-term variability of ASN, especially for stations deployed in urban areas than rural areas. Urban areas show larger RMS displacement amplitudes than rural areas located far from cities. We suggest that the variability in ASN amplitudes is a consequence of anthropogenic activities that affect higher frequencies (Díaz et al., 2017).

Since the implementation of lockdown measures in the MR, we observed a strong reduction in the amplitude of ASN similar to that observed by other authors in China, Italy, Brazil, and worldwide (Dias et al., 2020; Lecocq et al., 2020; Poli et al., 2020; Xiao et al., 2020). Due to the frequency band applied to obtain the RMS displacement, this ASN reduction indicates an intrinsic anthropogenic origin due to the variations in population mobility within cities. We described the temporal patterns and variations between weekdays and weekends, especially in station MT18 in the Santiago Centro, located near an amusement park with high levels of activity during the weekends observed in the seismic data before Lockdown 1 (Figures 3 and 4). After Lockdown 1, the activity on weekends abruptly decreased, whereas the activity during weekdays had a gradual reduction. As a public health policy,

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from 23 March the government imposed a curfew from 22 h to 5 h. The impact of this measure was recorded by most of the stations in urban areas, in which the ASN amplitudes decreased abruptly during the study period.

Temporal variations in ASN amplitudes coincide with the dates of changes in public health policies; variations due to lockdown and different phases of deconfinement are observed in the high-frequency ASN amplitudes. One of the most interesting examples in the MR corresponds to station MT14 in Las Condes (Figure 5a and 5b). Here, we observed a remarkable increase in ASN amplitudes between 16 April and 15 May, a period in which the government ended the first lockdown and started deconfinement in the eastern MR, raising the urban mobility and individual displacement of the population. Furthermore, this period corresponds to a higher Re value, an epidemiological factor that represents the velocity of propagation of viruses and increases with the transmission and overload of health systems (Caicedo-Ochoa et al., 2020). The mobility data gathered from Apple devices, public transport transactions, and flights (Figures A4, A5) confirm the increase of urban mobility in the period analysed. Other authors also suggest that small-area lockdowns and reductions in mobility can reduce the transmission of virus (Cuadrado et al., 2020). These observations indicate that ASN can act as an indicator of urban mobility and can be applied to monitor the dynamics of the populations within cities. The Re parameter increased during the periods of higher human activity and, therefore, ASN amplitudes increased in a period without strict management of the pandemic. The removal of lockdown protocols after 1 May resulted in an exponential increase in the number of positive COVID-19 cases, with a peak on 14 June and a 95% intensive care unit bed occupation (Canals et al., 2020). The 5 phases programme implemented in mid-July started a gradual decrease in the Re parameters, which oscillated around 1 since those dates, although the ASN amplitudes increased due to Phase 2 of deconfinement in eastern MR.

Finally, we show five examples within Chile of different temporal changes in high-frequency ASN amplitudes, in which the majority show similar patterns of gradual decreases in RMS displacements due to lockdowns or mobility restrictions. The cities like Iquique, La Serena, and Concepción are highly populated regions in Chile, whereas the temporal variations on ASN are comparable with other observations in the MR urban area. Valparaíso, the second most populated region only presents ASN dominated by the ocean in the frequency band analysed. In Puerto Williams, a small town in the extreme of South America, the decrease in ASN can be explained by the flight operation and restrictions, due to the closeness of the seismic stations and the local airport. Nonetheless, further analysis including other sources of mobility data and epidemiological parameters is needed.

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5 Conclusions

Although seismic data have been used to study wave propagation from seismic sources or to monitor different geological phenomena, temporal changes in the amplitudes of ASN have also been used to monitor population mobility within cities. We demonstrate that we can analyse the dynamics of the population and urban mobility through high-frequency ASN variations. The public health policies implemented to mitigate the spread of COVID-19 had an important influence on citizens mobility; lockdown, curfew, dynamic quarantines, and other restrictions affected the ASN amplitudes recorded by seismological stations. These temporal variations were also observed during the periods of lockdown and gradual deconfinement in the MR of Chile, in which a sharp decrease in ASN amplitudes was observed in the station within urban areas, in contrast to those in rural areas. Other mobility data were also compared with temporal variations in ASN amplitudes, showing good agreement with data from Apple devices, public transport transactions and national flights. In mid-April, during the rise of the number of positive COVID-19 cases worldwide, the government declared the end of the first lockdown in eastern Santiago. The public policy measure was followed by an increase in the citizen's mobility, a behaviour that was recorded by seismic stations. Most interestingly, during that period the effective reproductive number increased until it reached a maximum at the beginning of May. Thereafter, the Chilean government declared a second lockdown due to the increase in the number of positive COVID-19 cases in the MR. This observation suggests that the early end of the first lockdown in Santiago, while the pandemic situation was not controlled, increased the mobility within cities and promoted virus transmission in those weeks, reaching a maximum number of positive cases in mid-June in the MR. Finally, we showed the possibility of real-time monitoring of the population mobility dynamics through time variations of high-frequency ASN amplitudes in both broadband and accelerometer stations, which are typically used for the management of seismological networks in urban areas. The analysis of this study could be implemented in other high density cities of the world with important implications in our society directly or indirectly affected by the COVID-19 pandemic.

Code availability. All codes to analyse the seismic data are available in Lecocq et al. (2020)

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Data availability. The data shown in this study are available requesting from the authors. Seismic data from CSN are publicly available through the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC, last access: November 6th), Apple mobility data is available at https://covid19.apple.com/mobility (last access: October 2nd). Public transport transactions and flight data are delivered, and freely available at https://github.com/MinCiencia/Datos-COVID19 (last access: November 11th). Effective reproductive number estimation and other epidemiological parameters are available at https://www.icovidchile.cl/ (last access: October 2nd). Some figures were made using the Generic Mapping Tools (GMT) software version 5.3.1 (Wessel et al., 2013)

Author contribution. JO and SR wrote the manuscript and JO did the seismic noise analysis.

Competing interests. There are no competing interests

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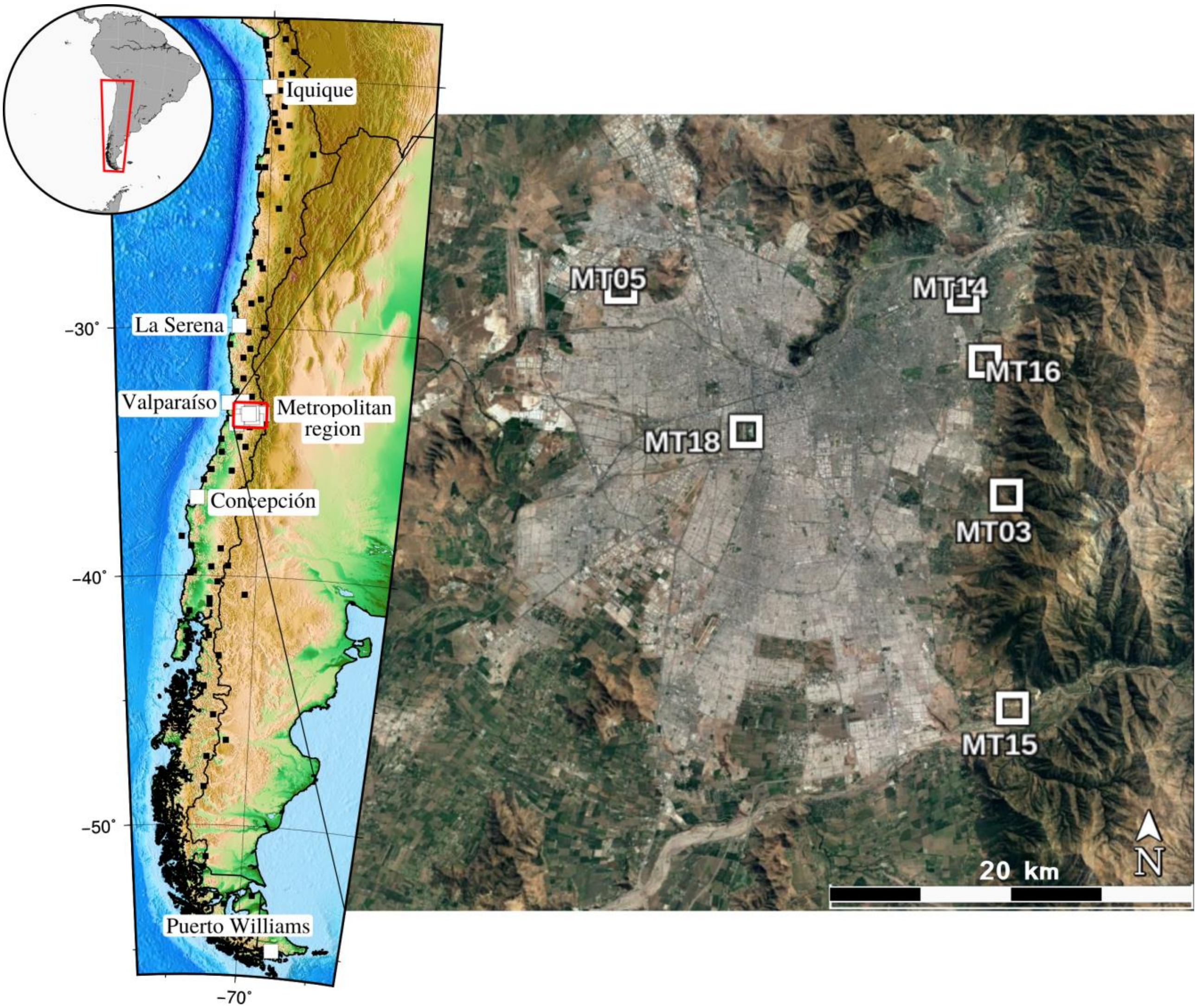

Figure 1. Location of the seismic stations of Chilean seismological network. Inset map shows the study location with reference to
415 **South America. The small black square corresponds to the broadband stations managed by CSN. White square corresponds to the five stations analysed in Iquique, La Serena, Valparaíso, Concepción, and Puerto Williams. The red rectangle shows the Metropolitan region with six stations localized in urban areas (squares with white contours). Photos from © Google Earth.**

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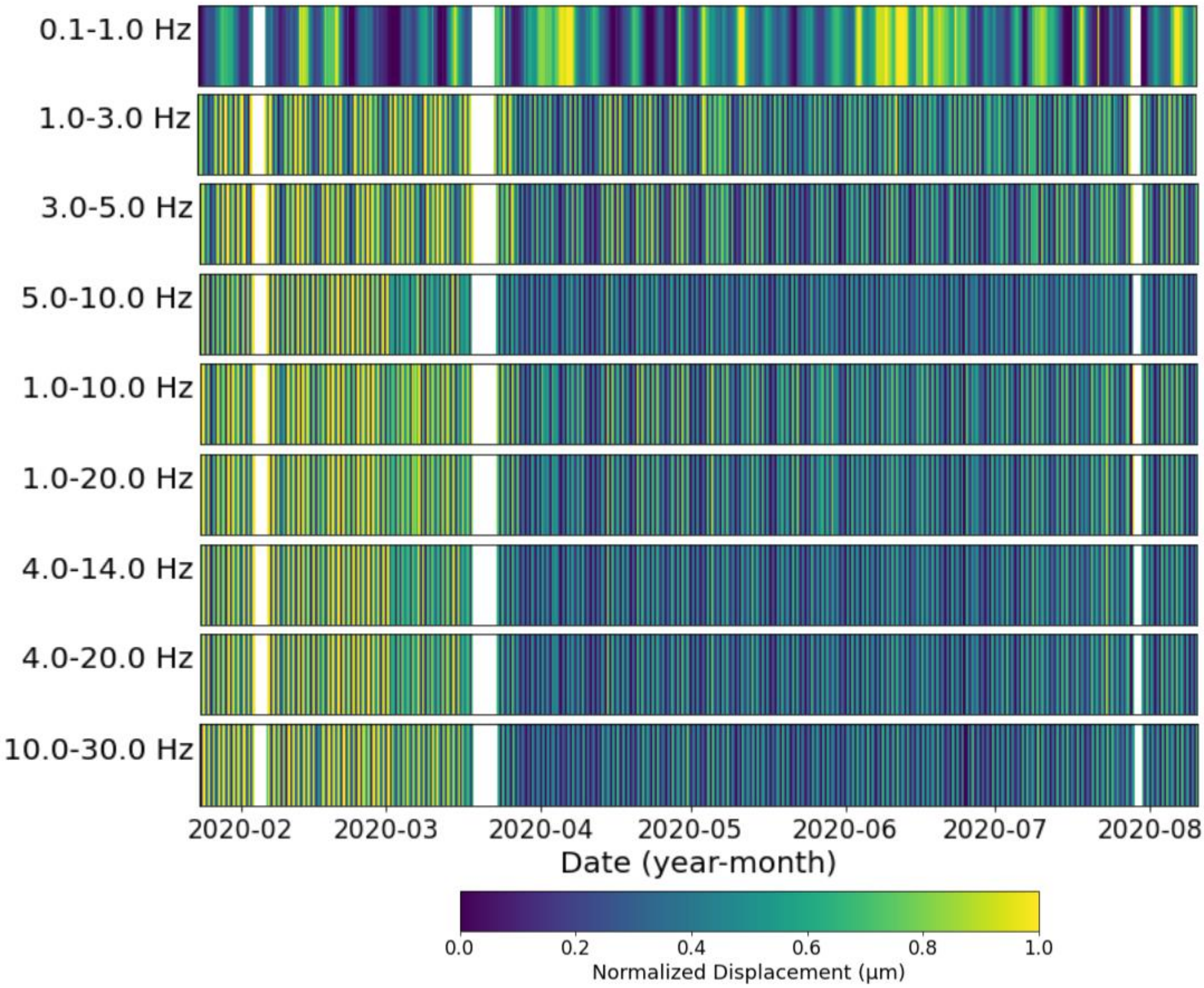

Figure 2. Normalised RMS amplitude at the vertical component of station MT18 in downtown Santiago. We tested nine bandpass filters between 0.1 to 30 Hz (see y-axis). White space corresponds to data gaps.

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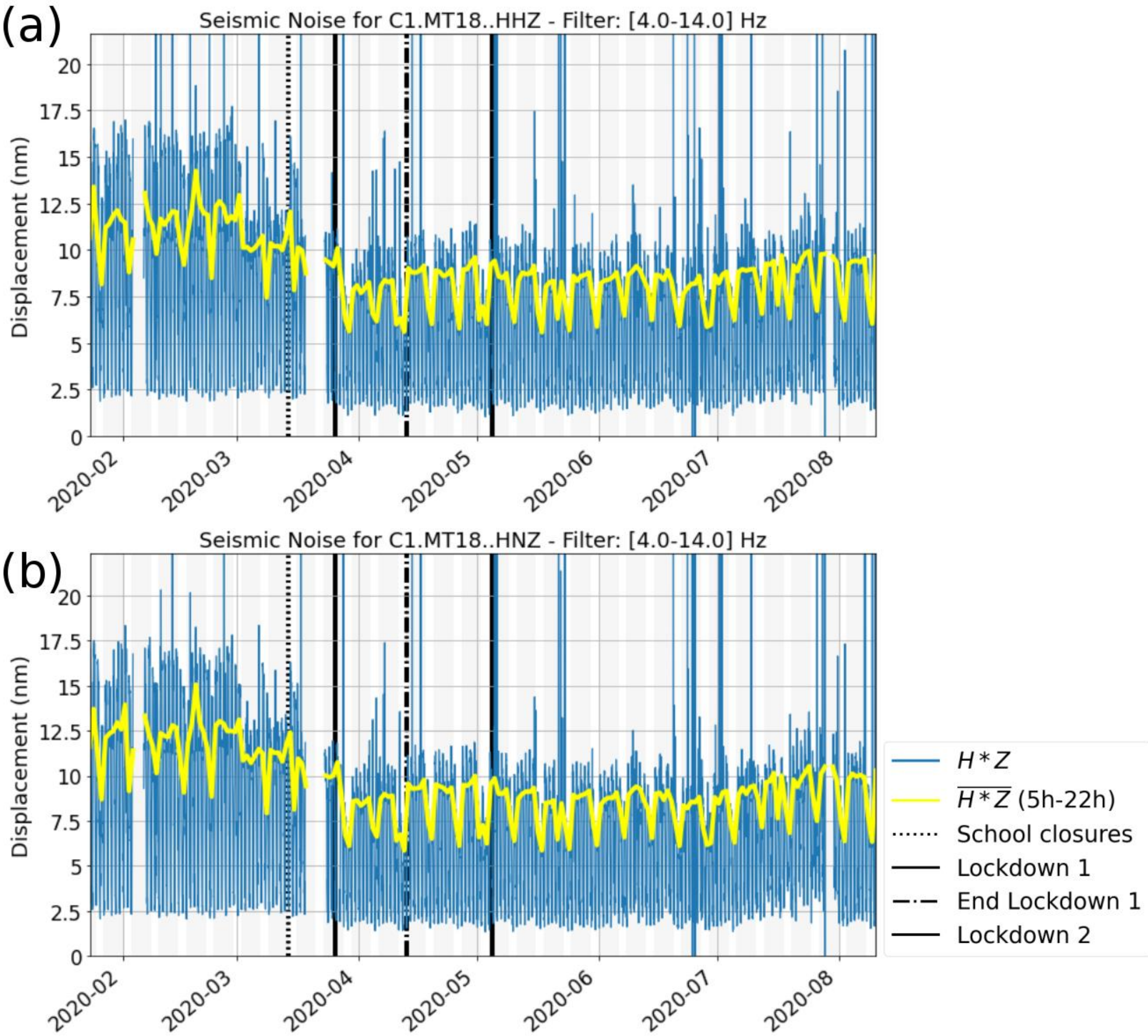

Figure 3. Comparison between (a) broadband and (b) strong-motion seismic noise amplitudes for station MT18 in downtown Santiago. The blue line corresponds to the RMS amplitude time series of the vertical component, filtered between 4-14 Hz, and the yellow line corresponds to median day-time, between 5h-22h local time. Gaps correspond to periods for which seismic data are unavailable. The vertical black lines indicate the time of public restrictions implemented in Santiago.

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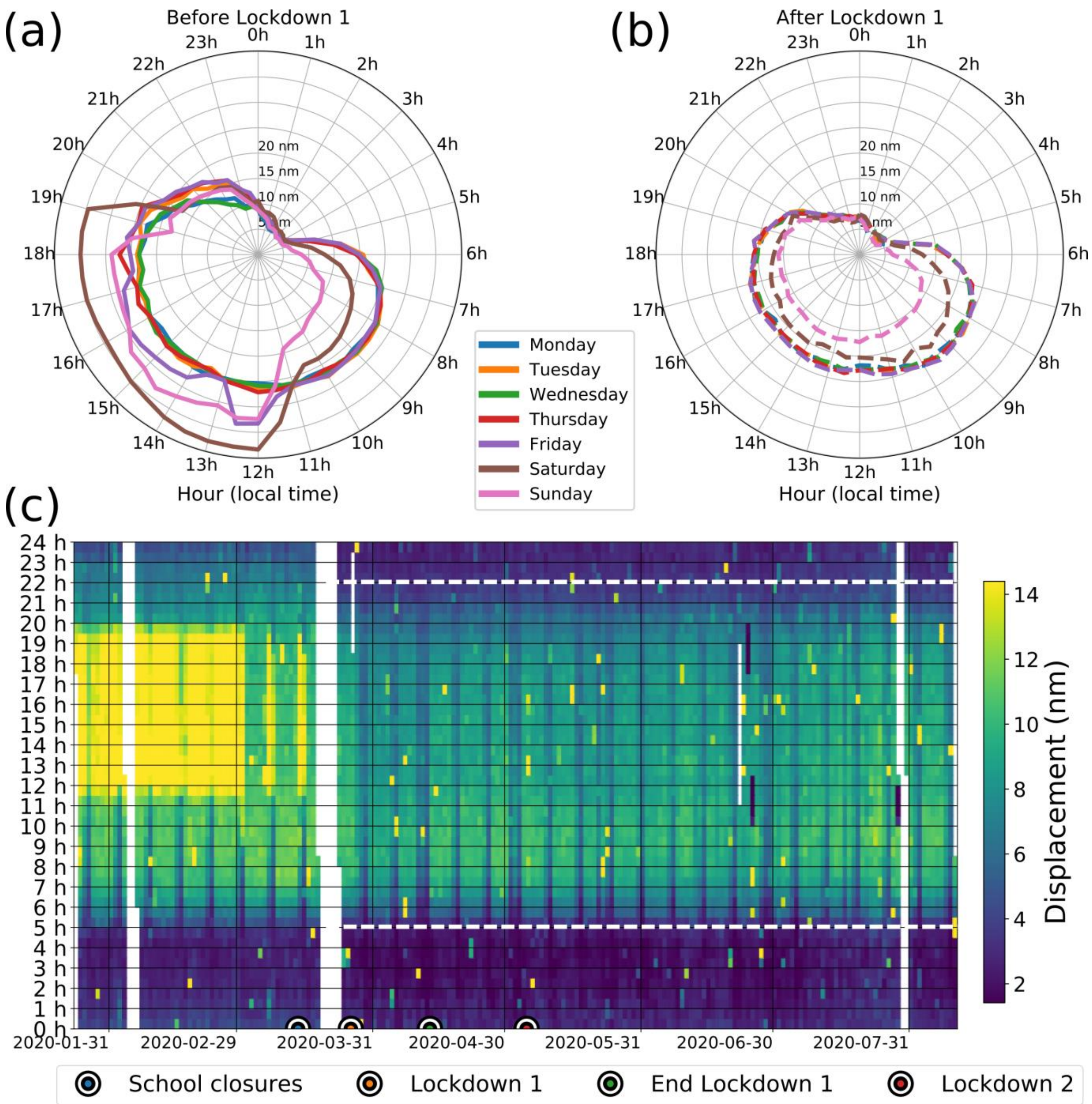

Figure 4. Analysis of station MT18 in Santiago Centro. (a, b) Clock plots showing an average of the displacement variability for each day of the week for the period (a) before Lockdown 1 and (b) after Lockdown 1 at station MT18 in downtown Santiago. (c) Displacement noise evolution is shown in an hourly grid representation. Gaps correspond to periods for which seismic data are unavailable. Blue, orange, green, and red circles below represent the time of public restrictions implemented in downtown Santiago. Horizontal dashed white lines show the curfew period imposed between 22 h - 5 h local time.

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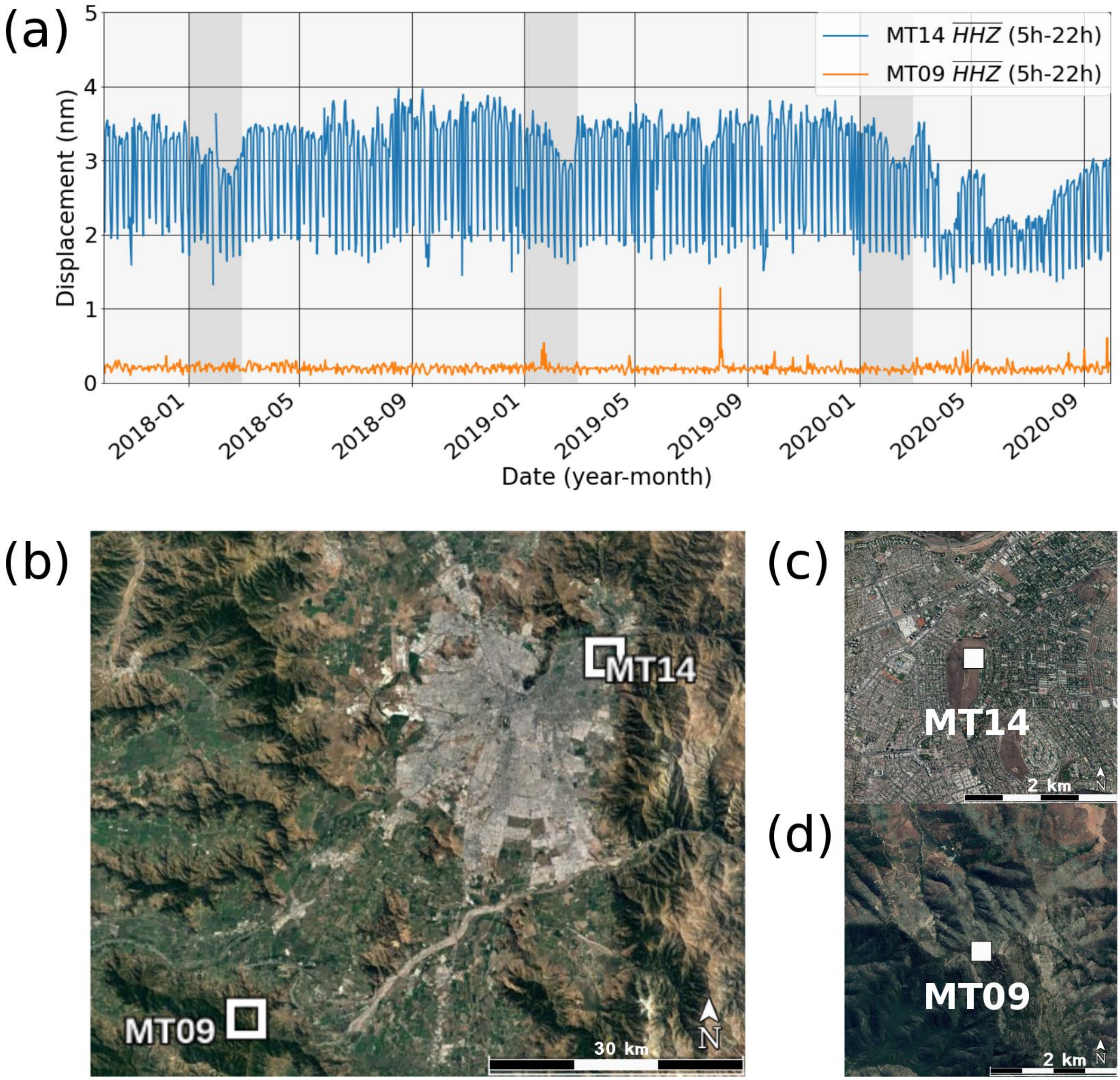

445 **Figure 5. Displacement noise evolution at urban and rural stations in the Metropolitan region for the period October 1st 2017 – October 1st 2020. (a) Long-term noise evolution in station MT14 (blue line) and MT09 (orange line). Grey areas correspond to summer vacations. (b) Map with the relative position of each station in the Metropolitan region, and the 2 km ratio of the station (c) MT14, and (d) MT09. Photos from © Google Earth.**

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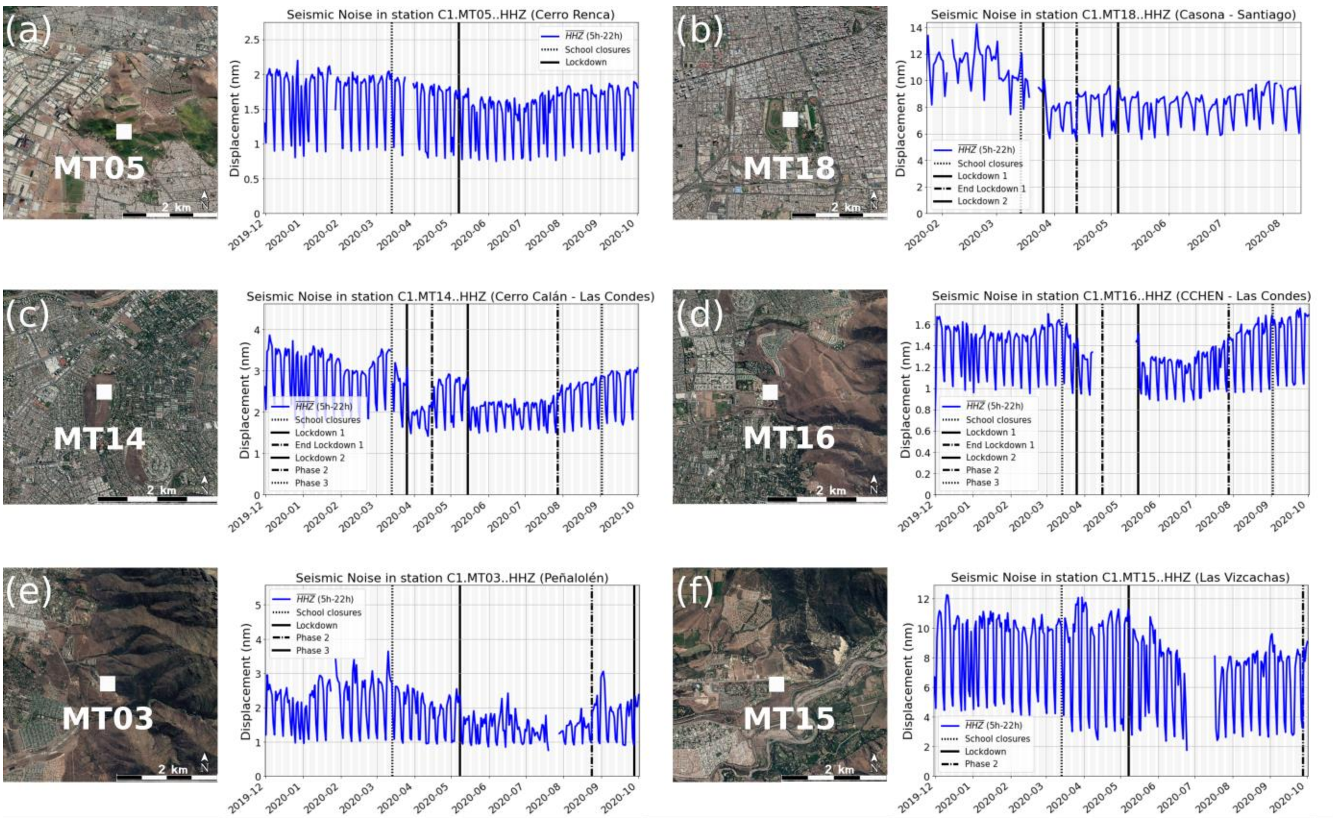

Figure 6. Changes in high-frequency seismic ambient noise amplitudes at stations (a) MT05, (b) MT18, (c) MT14, (d) MT16, (e) MT03, (f) MT15. The vertical black lines indicate the time of public restrictions implemented in the Metropolitan region. Each municipality inside the region had different lockdown periods or phases, despite the proximity between them. Photos from © Google Earth.

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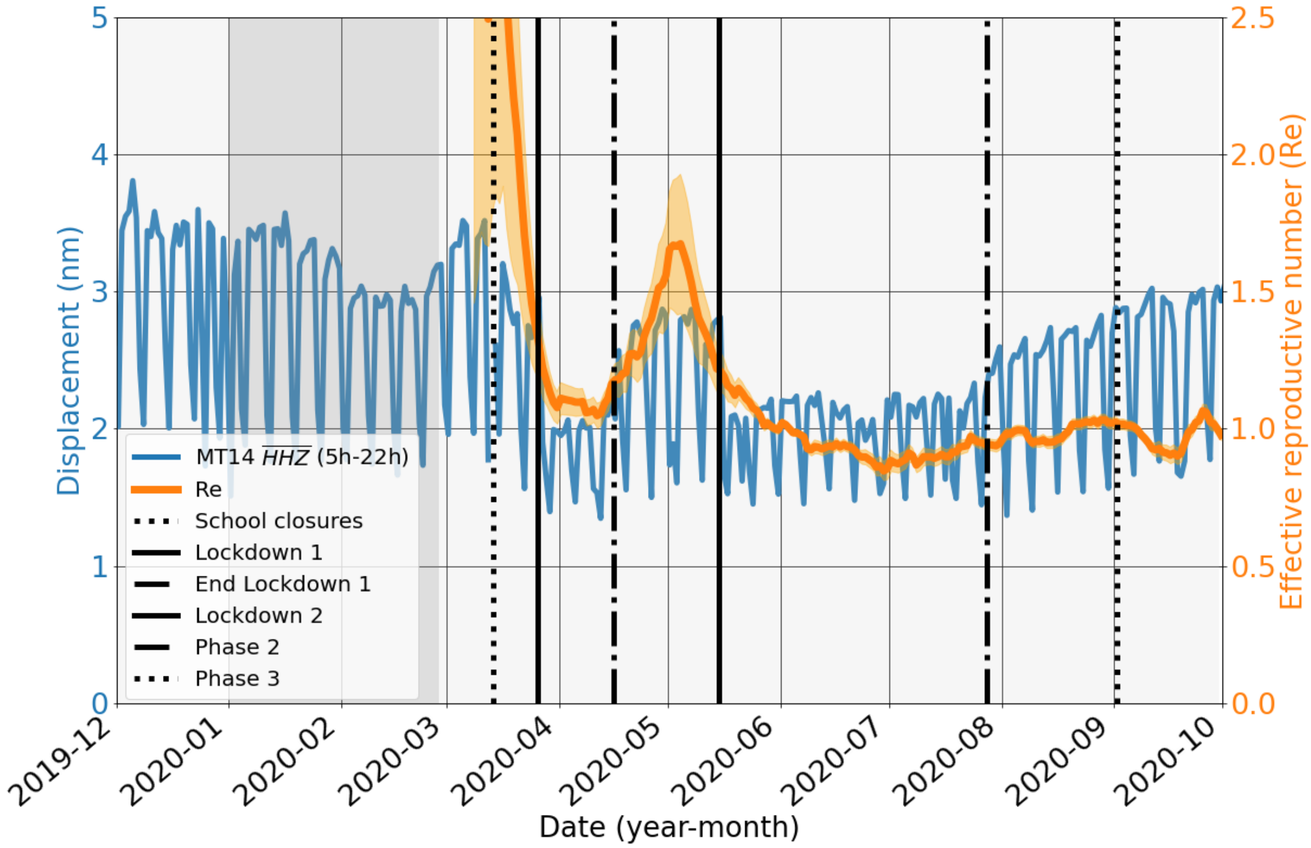

Figure 7. Comparison between noise evolution of station MT14 (blue line), the epidemiological factor of the effective reproductive number (Re) over a time is shown (orange line) with their 95% confidence intervals (thin orange lines). The vertical black lines indicate the time of public restrictions implemented in Las Condes.

Appendix A: additional figures

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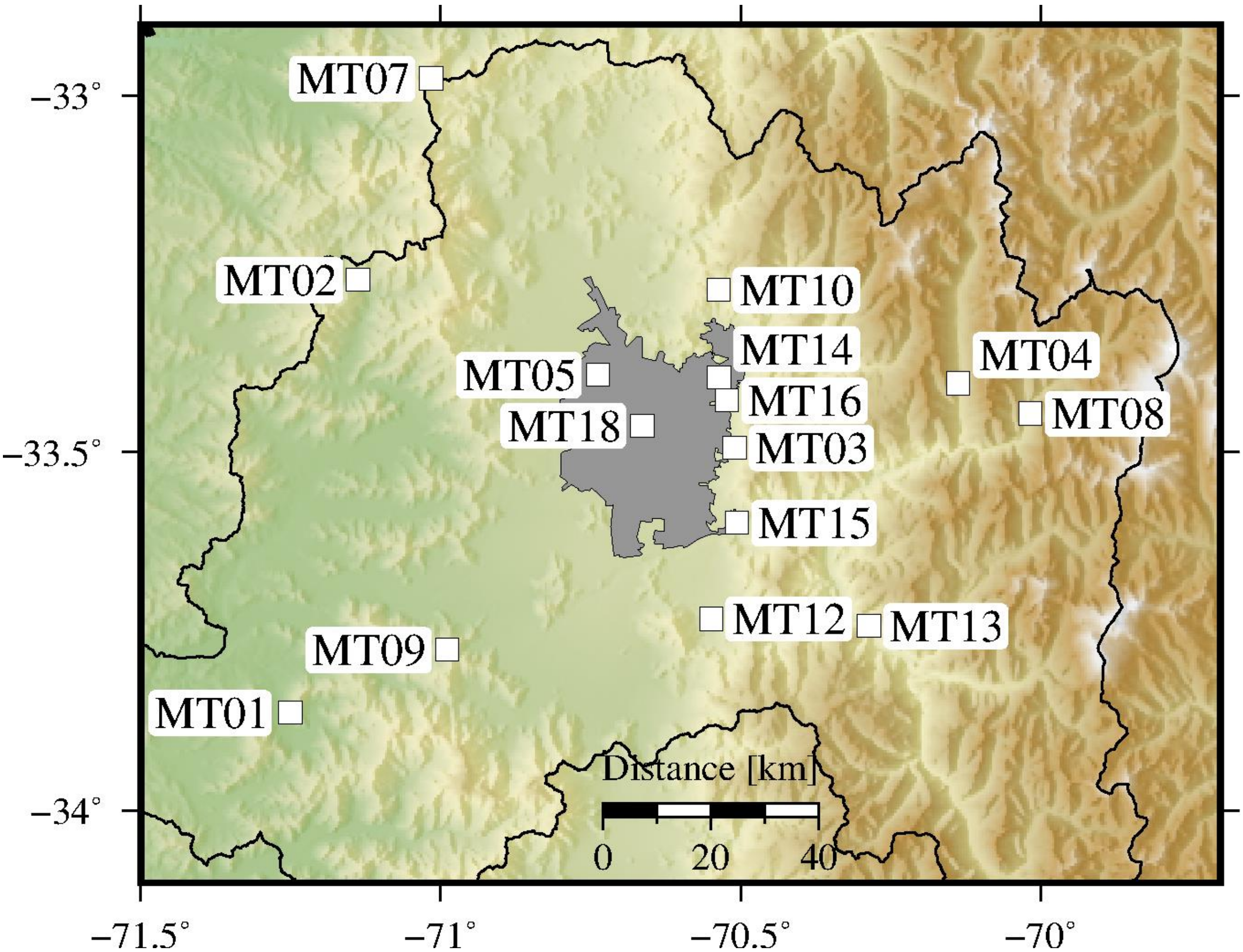

465 **Figure A1: Map of Metropolitan region with 15 stations analysed in this study. Note that only stations MT05, MT18, MT14, MT16, MT03, and MT15 are stations in the Santiago city urban area (grey surface).**

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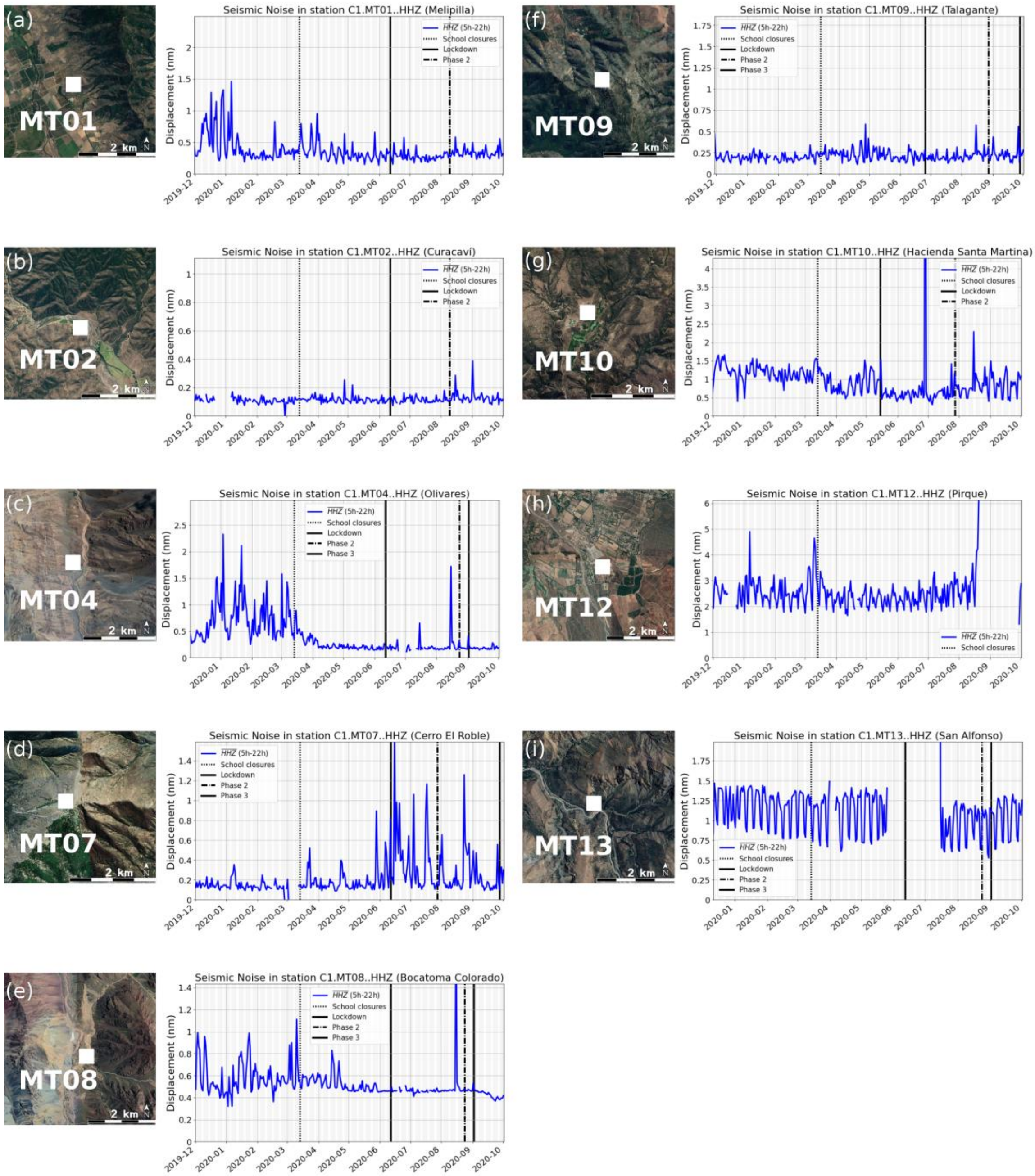

Figure A2. Changes in high-frequency seismic ambient noise amplitudes at stations (a) MT01, (b) MT09, (c) MT02, (d) MT10, (e) MT04, (f) MT12, (g) MT07, (h) MT13, and (I) MT08. The vertical black lines indicate the time of public restrictions implemented in the Metropolitan region. Each municipality inside the region had different lockdown periods or phases despite the proximity between them. Photos from © Google Earth.

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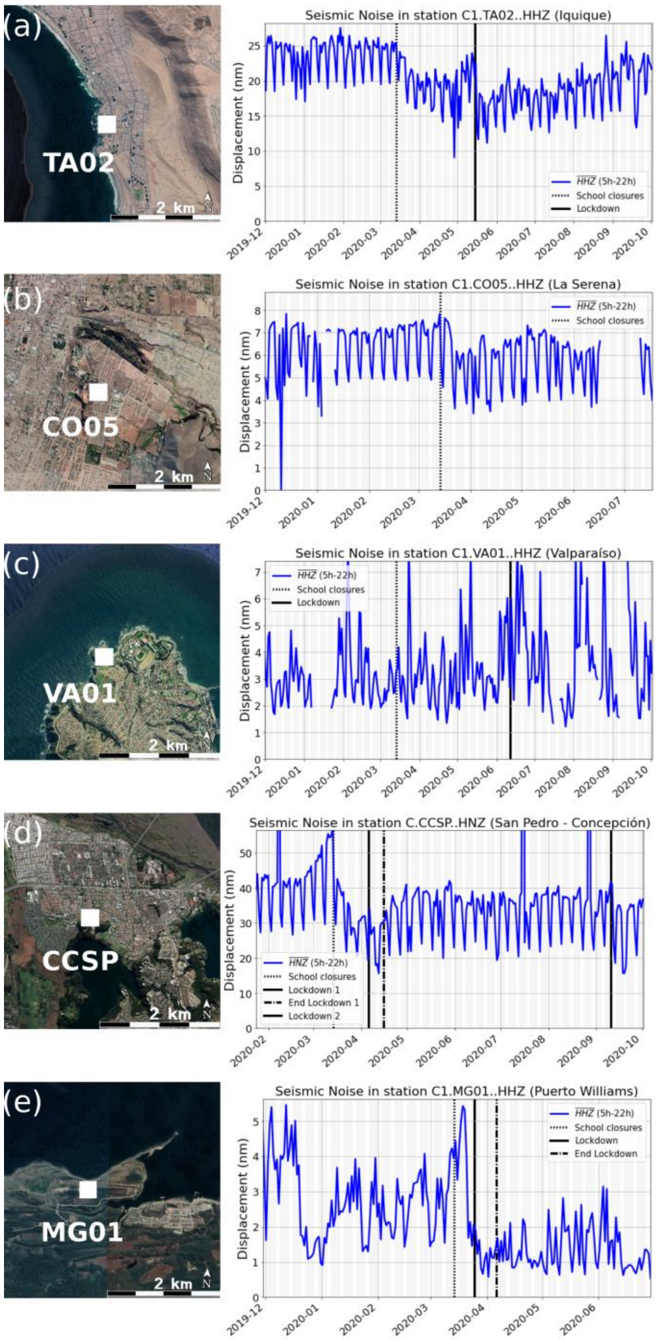

Figure A3. Changes in high-frequency seismic ambient noise amplitudes at stations (a) TA02, Iquique, (b) CO05, La Serena, (c) VA01, Valparaíso, (d) CCSP, San Pedro Concepción, and (e) MG01, Puerto Williams. The vertical black lines indicate the time of public restrictions implemented in each region. Photos from © Google Earth.

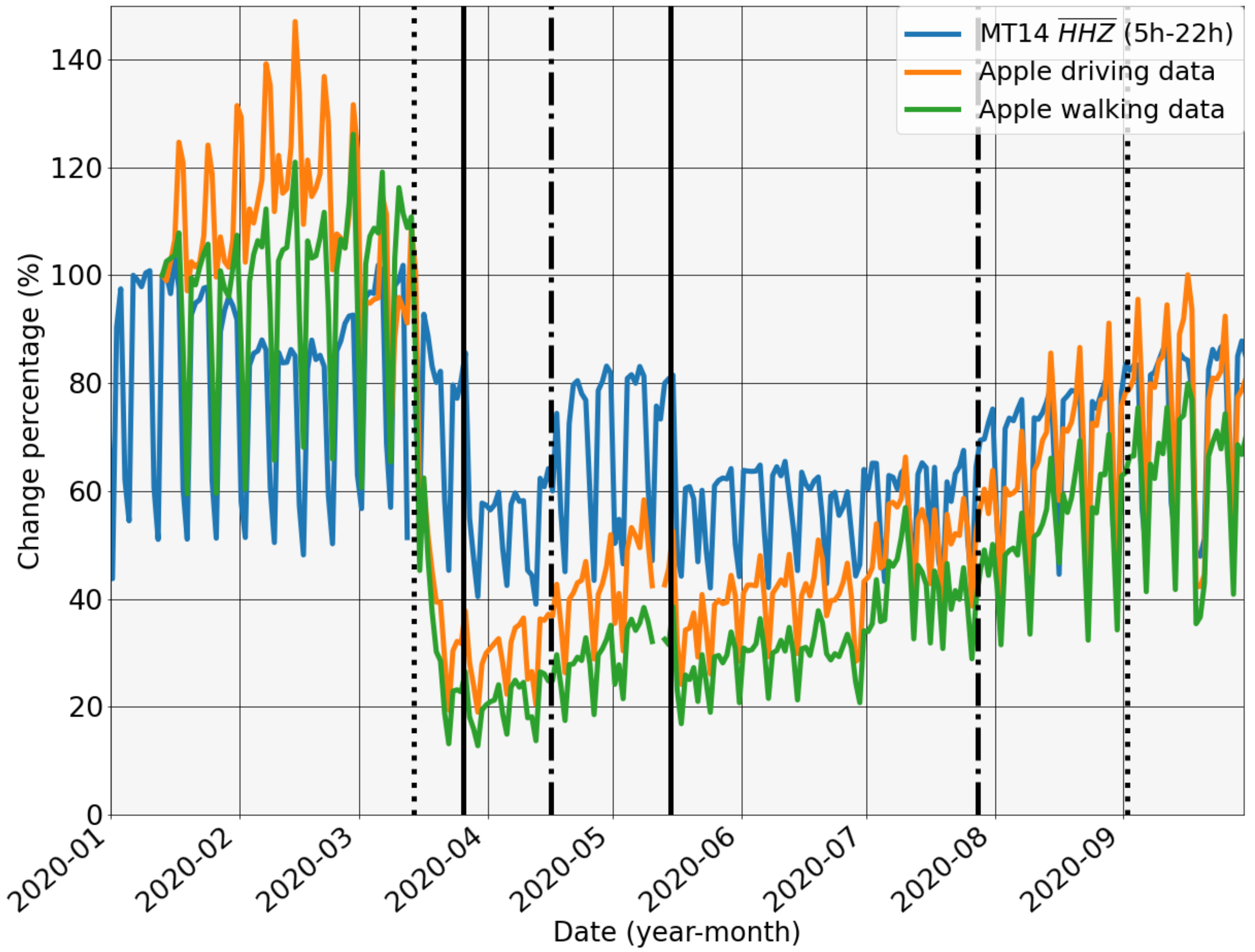

Figure A4. Comparison between noise evolution of station MT14 (blue line) and the Apple mobility data, specifically driving (orange line) and walking data (green line). The vertical black lines indicate the time of public restrictions implemented in Las Condes.

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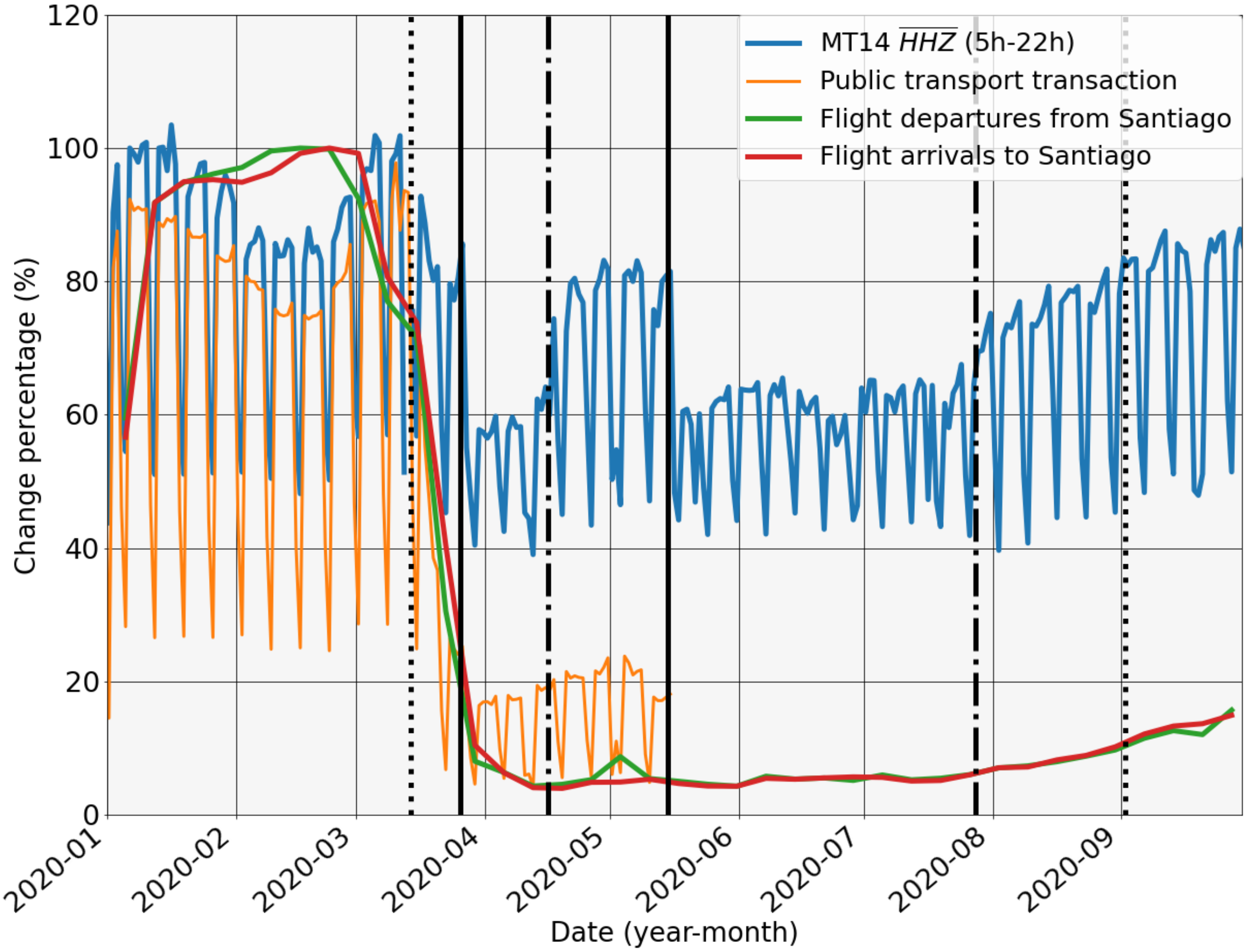

Figure A5. Comparison between noise evolution of station MT14 (blue line) and other mobility data, specifically public transport transactions (orange line), flight departures from Santiago (green line), and flight arrivals to Santiago (red line). The vertical black lines indicate the time of public restrictions implemented in Las Condes.