We thank the editor and the three reviewers for considering our manuscript for publication, and for their suggestions for improvement. Below are our replies to these comments and suggestions. We have taken all their comments on board in the revised manuscript, and a version with tracked changes highlights these. Below are the replies to the reviewers, which we will post as individual replies on the journal's online system.

1 Reviewer 1

`Overall, the manuscript is written well and provides interesting insights into seismic noise related to human activity. I have some minor comments.`

Thank you, reviewer 1.

`1. Frequency band.`

`A main frequency band is 0.1-50 Hz, which seems to include a variety of seismic noise including microseisms, local earthquakes, human activity. I wonder if the authors pro- vide several frequency bands (1-10Hz, 5-15 Hz, 10-30 Hz for example) that may allow us to understand the nature of the ambient seismic noise at the seismic stations.`

`2. Power spectral density plot.`

`Related to #1, I think it would be informative to include power spectral density (PSD) plots (with monthly to yearly data before the COVID-19 lockdown) for each station, which would provide the baseline of ambient noise level.`

To address the reviewers comments (echoed by the other two reviewers), we added PSD plots in an appendix to show that the anthropogenic component of the noise is at 1 Hz and higher. How high is not exactly clear, and probably varies a bit across the network, but it appears to approach the Nyquist frequency of 50 Hz. Because we are interested in earthquakes *and* volcano monitoring for the AVF, we analyse the entire frequency band of our recordings as one.

`3. Mobility data (work places)`

`I see the work places data show noise reduction over weekend before the level 4 COVID-19 lockdown but it appears that the work places data periodically increase weekend after the level 4? I may have missed but it would be good to have some comments in the revision.`

Yes, we added an explanation in the revised manuscript. The key is that the mobility data is presented as a "change" in mobility. Overall, work place activity dropped significantly during the lockdown, but essential services continued. During the weekend, essential services make up a large fraction of workplace activity during normal times, and this is even more so during a lockdown when non-essential services cease to happen. The text in the new manuscript reads:

"Because the mobility data is presented as a change in activity, the workplace activities dropped overall, but work deemed essential continues in the weekends, resulting in a temporary increase in weekend workplace activity during the lockdown period."

2 Reviewer 2

`I find this is a generally well-written manuscript and an interesting look into a unique period of seismic data.`

Thank you, Reviewer 2.

`I have two main suggestions for improvement that I think would strengthen this studys arguments significantly using the methods that theyve already demonstrated. First, I think that discussion of changes in earthquake detection during COVID lock- downs would be benefitted by the further context of comparison with other changes in anthropogenic seismic noise levels. Rather than only comparing lockdown to non-lockdown data, adding comparisons of night to day and weekend to weekday could give better insight into how anthropogenic noise affects event detection.`

We agree, and analyse the (anthropogenic) noise by looking at day and night-time differences as well (see Figure 2, and 3, for example), as well as weekdays versus weekends.

`The lockdown period is short enough (on the scale of earthquake occurrence rates) that Im not fully convinced by the authors claim that there was no change in detection rate during` that period, so it would be helpful to back that up through comparison to other low-noise times for which more data exist.

Indeed, we did not find more earthquakes during the lockdown than in the time before and after the lockdown, and agree with the reviewer that more can be done to explain this. Now, whether this is also true for christmas periods, for example, is for a special issue on christmas-holiday seismology! All jokes aside: because our analysis focuses on the efficacy of the matched-filter method, the detectability is affected by the noise-level in the cross-correlation sum. To demonstrate that we would not expect a change in detection-rate during lockdown we computed and plotted (now included in a new appendix of our revised paper) the network cross-correlation sum for one template between February 29th 2020 and May 8th 2020, alongside the multi-tapered power spectrum for this time series. Plotting the full sample-rate correlation-sum shows little power outside the 2-15 Hz range used, however computing the hourly mean correlation-sum provides more useful information regarding the variability in noise in the correlation sum. In this hourly correlation sum, reductions should correspond to reduced noise in the correlation sum and hence enhanced detectability. We find clear daily variations (evidenced by a peak in the amplitude spectra at 24 hour periods), however there is no clear reduction in background correlation values during lockdown. It is based on this evidence that we can be confident that there is no significant change in detectability during lockdown. Note also that our detection threshold is based on the daily median absolute deviation of the correlation sum which further smooths the daily variability in the correlation sum. The range of daily median absolute deviations upon which our threshold is based range from 0.234-0.254, with the lowest values falling outside the lockdown period.

Second, I believe that this study would be helped with further exploration (or at least explanation) into the frequency domain. The authors say that the 0.1-50 Hz range is of interest to volcano monitoring and contains anthropogenic seismic noise, but dont go into further detail and should at the very least provide more background on that choice of range and show a spectragram for at least one station. Dividing that range into a few smaller ranges and processing them individually would provide more information about the change in the seismic noise environment (e.g. deconvolving effects of changing wind and water vs changing anthropogenic activity), as well strengthen the authors arguments regarding those noise levels effects on event detection.

We agree that more details could be provided, and we have added spectragrams and text to further differentiate what we mean with anthropogenic noise, as well as our decision to treat these data mostly in one band, as the data frequency band for the different tasks of the AVSN (ie monitoring for impending volcanic unrest, as well as seismic imaging with local seismicity) overlap with the noise sources in question.

As for smaller technical corrections, the main things I found were: the authors need to ensure that all data in a figure is included in the one key (e.g. figure 7s key does not contain a red line for wind speed, and figure 8 has two keys instead of one), decide whether to use lock-down or lockdown, and ensure that figures are more colorblind-friendly (e.g. not using red and green for the two different lockdown levels).

We have fixed the lockdown/lock-down issue, and changed to line style for level 3 to distinguish it better from level 4. Figures 7 and 8 now have two keys (each), because there are two very distinct data sets displayed in these with separate y-axes.

3 Reviewer 3

In general, the manuscript reads well and the order of ideas and figures is well presented.

We thank reviewer 3 for this comment.

I would like the authors to edit or re-write to sentence starting in line 29. I would Line 44-45: The authors use the frequency band: 0.1 - 50 Hz assuming the cover the range of interest for volcano monitoring and seismic tomography, however, whiting this range, what frequency band is the most affected? It would be interesting to observe the results presented here using and plotting several frequency bands (5 or 6?) to understand better where the noise amplitudes show the maximum reduction and how they are related to different anthropogenic activities or sources (diffuse, harmonic, transient, etc) or/and natural processes (volcanic, wind, ocean, `etc.).`

We have rewritten this part in the revised manuscript, and added PSD plots to distinguish noise/signal in different frequency bands. What sets this study apart from previous studies on COVID-19 noise reductions is the presence of local seismicity and an active volcanic field. These require data to be used across a broad band of frequencies, where the frequencies of noise overlap with those for the signals of interest.

`Line 73: instead of multiplying by a factor of 25, why didnt the authors normalized the time series presented in figure 7? If i understand it correctly, the main idea of the figure is to compare the relative differences between the observed amplitudes at 3 different stations with the wind speed and more importantly evaluate their temporal correlations.`

Not only relative amplitudes matter and are informative; we are very much interested in the absolute value of the noise, so we can compare performance across the whole network. If we were to normalise the data in this figure, the reader loses perspective with the data from the stations not in Figure 7. Either way, the reader can appreciate how valuable it is to bury a station even by 10s of meters.

`The fact that authors found 35 more earthquakes (a very low number of events) than Geonet during the lockdown, it doesnt mean they appear because of a reduction in anthropogenic noise, rather, they are found because of the use of a template matching algorithm, that is, systematically more efficient in finding earthquakes when compared with traditional human-based methods. Probably you also could find the same amount of events even without lock down measures. authors can add a sentence like this after line 105.`

We completely agree, and this was meant to be the message of this section: we find more earthquakes in general, because template matching is more sensitive than STA/LTA. We did *not* find more EQs during the lockdown than before or after the lockdown with this technique. For example, this is stated in the conclusions:

"However, the detection rate was not higher during the lockdown period than in the periods before or after the lockdown."

We hope the revised manuscript is more clear in this regard.

Seismic monitoring of the Auckland Volcanic Field during New Zealand's COVID-19 lock-downlockdown

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Abstract.

The city of Auckland, New Zealand (Tāmaki Makaurau, Aotearoa) sits on top of an active volcanic field. Seismic stations in and around the city monitor activity of the Auckland Volcanic Field (AVF), and provide data to image its subsurface. The seismic sensors – some positioned at the surface and others in boreholes – are generally noisier during the day than the night. For most stations weekdays are noisier than weekends, proving human activity contributes to recordings of seismic noise, even on seismographs as deep as 384 m below the surface, and as far as 15 km from Auckland's Central Business District. Lock-down Lockdown measures in New Zealand to battle the spread of COVID-19 allow us to separate sources of seismic energy and evaluate both the quality of the monitoring network, as well as the level of local seismicity. A matched-filtering scheme based on template matching with known earthquakes improved the existing catalogue of 5 known local earthquakes to 35 for the period between November 1st, 2019 and June 15th, 2020. However, the Level 4 lock-down lockdown from March 25th to April 27th – with its drop in anthropogenic seismic noise above 1 Hz – did not mark an enhanced detection level. Nevertheless, it may be that wind and ocean swell mask the presence of weak local seismicity, particularly near surface-mounted seismographs in the Hauraki Gulf that show much higher levels of noise than the rest of the local network.

1 Introduction

The Auckland Volcanic Field (AVF) is an active intra-plate volcanic field consisting of 53 known volcanoes Hopkins et al. (2020) (Hopkins et al., 2020). The last eruption ∼600 years ago is responsible for Rangitoto Island, a prominent geologic feature in the Hauraki Gulf, ∼10 kilometers from the Auckland Central Business District (CBD). Given the risk involved for the 1.5 million inhabitants of a city built on top of the AVF, a seismic network (AVSN, Figure 1 and Table 1) monitors for early warning signs of an impending eruption Sherburn et al. (2007)(Sherburn et al., 2007). However, seismic recordings in urban environments suffer from contamination by anthropogenic noise. To minimise the recording of anthropogenic noise in Auckland, seven of ten stations of the AVSN are installed in boreholes. This measure also reduces the recording of seismic signal

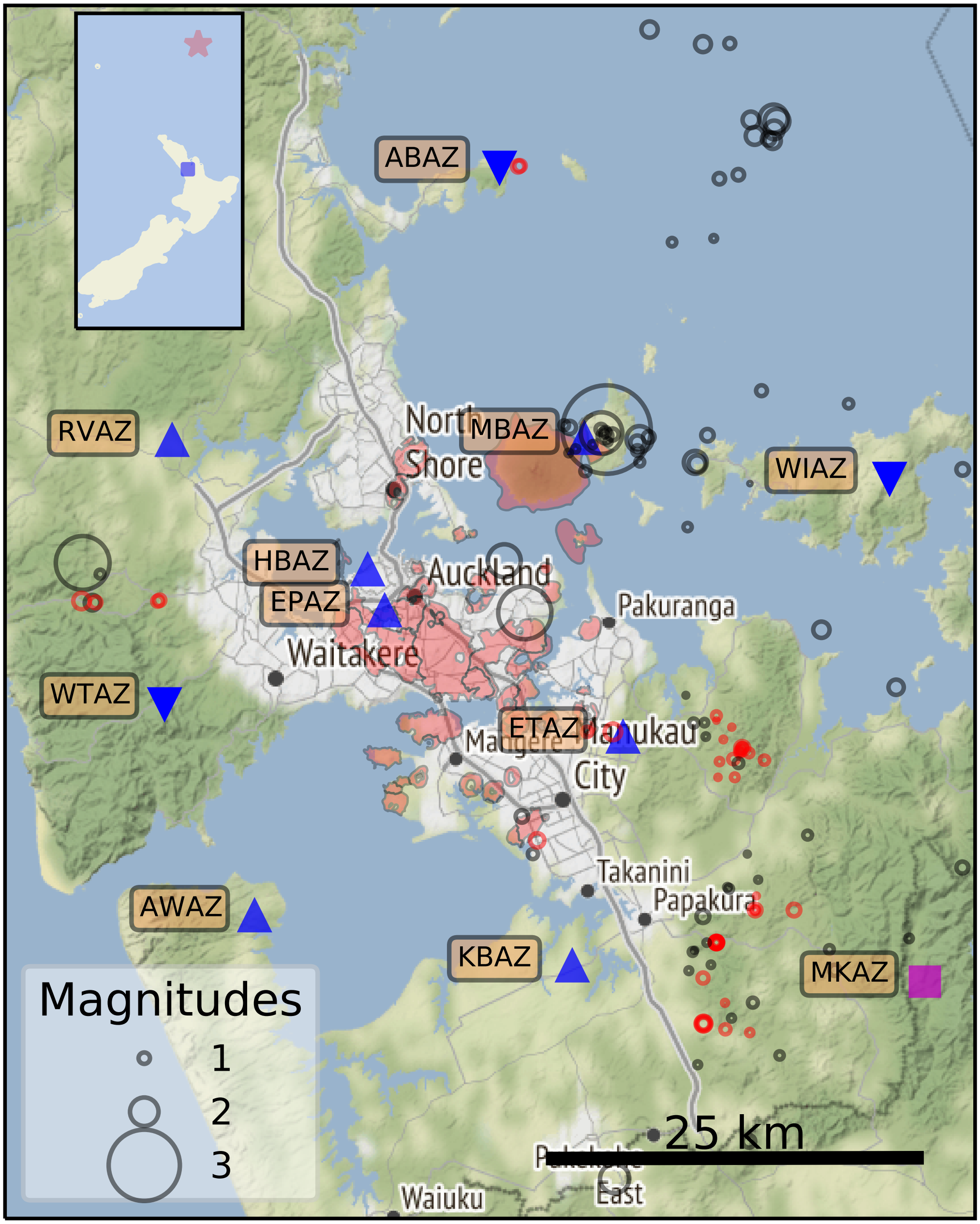

Figure 1. Terrain map of the greater Auckland area from OpenStreetMap with surface expressions of Auckland's volcanoes in pink from the Determining Volcanic Risk in Auckland (DEVORA) project. The stations of the Auckland Volcanic Seismic Network (AVSN, managed by Geonet) are presented as blue triangles (surface stations are inverted from the borehole station triangles). Station MKAZ (magenta square) is a broadband surface seismic station from the national seismic network. Earthquake epicentres (black circles) and quarry blasts (red circles) are from the Geonet catalogue from January 1st, 2011, to June 15th, 2020. The inset shows the position of Auckland in New Zealand, as well as the epicentre of an earthquake in the Kermadec Islands region (event ID us60008fl8).

Table 1. Coordinates of the AVSN short-period seismometers, and the broadband station MKAZ.

Station	Latitude	Longitude	Depth (m)
ABAZ	-36.600	174.832	0
AWAZ	-37.064	174.643	371
EPAZ	-36.875	174.744	383
ETAZ	-36.953	174.928	347
HBAZ	-36.850	174.730	380
KBAZ	-37.095	174.889	160
MBAZ	-36.769	174.898	93
MKAZ*	-37.10413	175.16117	0
RVAZ	-36.770	174.579	250
WIAZ	-36.793	175.134	0
WTAZ	-36.932	174.573	0

from wind and ocean waves (see Table 1 and Ashenden et al., 2011; Boese et al., 2015). The seismic data from the AVSN are hosted by GeoNet (https://www.geonet.org.nz/), and publicly available in near-real time.

New Zealand entered a Level 4 ~~lock-down~~ lockdown to combat the spread of COVID-19 at 23.59pm on the 25th of March, 2020 (local time). Schools were closed, work was halted or moved to home, and travel reduced to trips to the doctor and the supermarket. A limited workforce continued to work and commute if their profession was deemed "essential." On the 27th of April, New Zealand lowered this ~~lock-down~~ lockdown to Level 3, which meant mobility of Aucklanders was increased, and construction work, for example, resumed. The following results present the impact of the ~~lock-down~~ lockdown on seismic recordings of the AVSN. Recent studies have shown impact in the 1-10~~Poli et al. (2020)~~ Hz (Poli et al., 2020) and 4-14~~Hz Lecocq et al. (2020) range, but as the~~ Hz (Lecocq et al., 2020) range. The AVF is an active volcanic field with ongoing efforts to image the subsurface ~~Ensing et al. (2017); Ensing and van Wijk (2018); Ensing (2020)~~(Ensing et al., 2017; Ensing and van Wijk, 2018; with seismic data that spans the entire seismic data spectrum. Therefore, our analysis includes the impact of the lockdown on seismic data from 0.1 to 50 Hz. In addition, we use this uniquely quiet period of Auckland in ~~lock-down~~ lockdown to 1) evaluate the sensitivity of the AVSN and 2) explore the (a-)seismicity of the Auckland Volcanic Field by increasing the earthquake catalogue with a matched-filtering technique with known template earthquakes.

2 Results

Figure 2 displays 24 hours of the vertical component of particle velocity measured on station HBAZ, a short-period seismometer installed in a borehole, 380 m underground in Herne Bay, Auckland. The dominant feature in this seismogram is signal at 10:06UTC from a M6.4 earthquake in the Kermadec Islands region (event ID us60008fl8). In general, however, the seismogram is less noisy during the (local) nighttime than during the daytime. As a result, signals associated with the smallest earthquakes

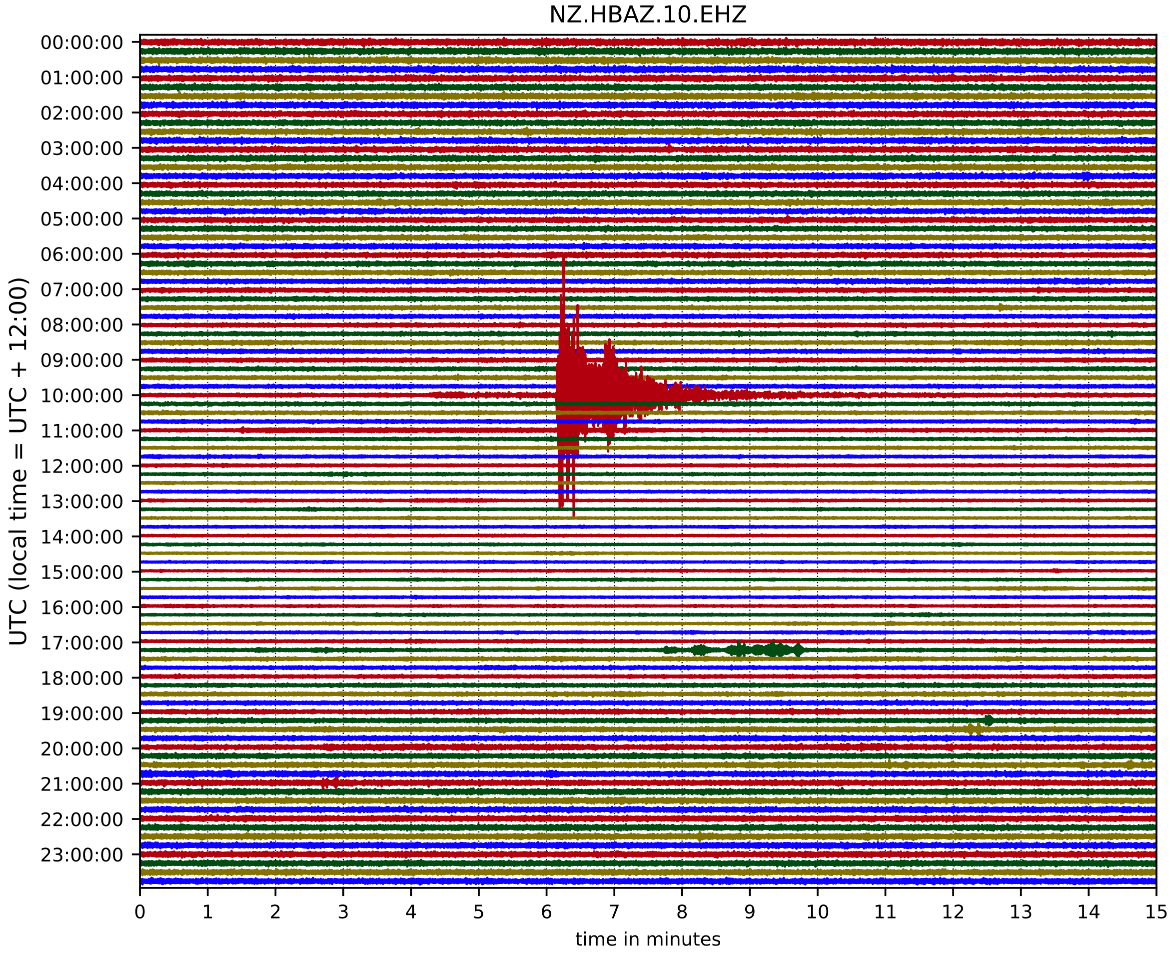

Figure 2. Vertical component of the seismic wavefield at borehole station HBAZ for March 14th, 2020. The signal with the largest amplitudes is from an earthquake in the Kermadec Islands region (event ID us60008fl8).

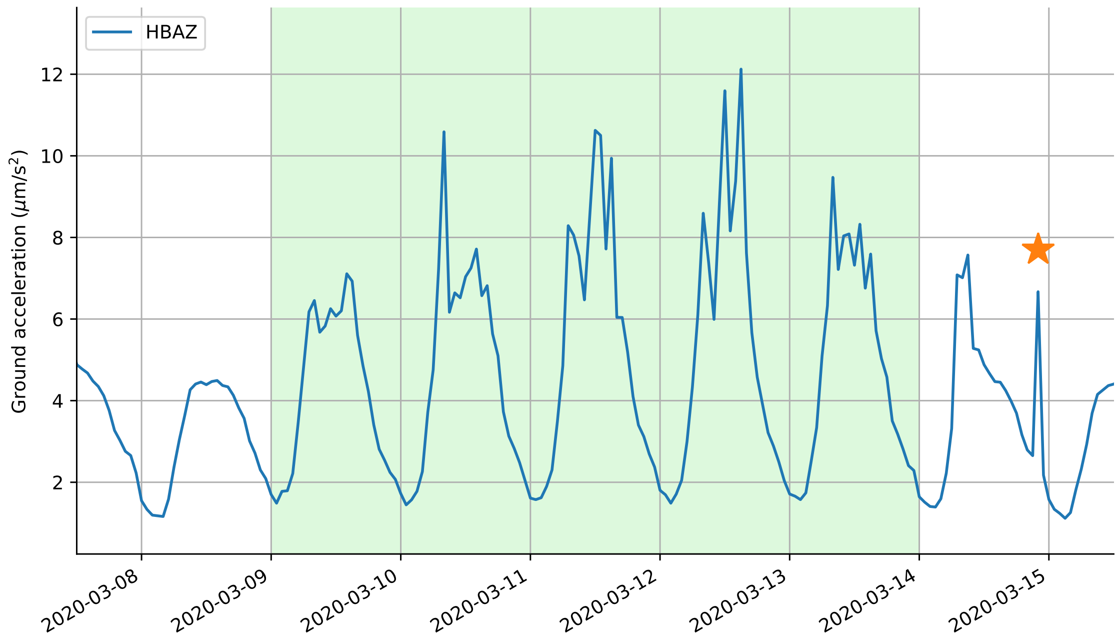

Figure 3. Standard deviation over 30-minute intervals of the ground acceleration of short-period borehole station HBAZ. Times are in local NZT, and weekdays have a green background. Note the lower night-time noise level compared to day-time, and quieter weekends. The origin time of the Kermadec Regions event ID us60008fl8 is annotated with a star.

detectable at night could be masked by noise during the day. An example is the small event around 17.23(UTC, in green), which may have been obscured by day-time noise levels.

To study seismic signal levels over longer time periods, we compute the standard deviation in 30-minute time windows, after an instrument correction to acceleration~~. This is similar to~~ , as defined in the volcano monitoring technique called Real-Time Seismic Amplitude Measurement (RSAM, Endo and Murray, 1991). We ~~decided to~~ filter the data between 0.1 Hz and 50 Hz to both cover the range of frequencies of interest in volcano monitoring and in seismic tomography. ~~From here on, we'll refer to the resulting values as "RSAM".~~ Figure 3 displays the standard deviation from the 8th to the 15th of March (2020) on station HBAZ in local time. From here on, all time scales are in the local time zone and week-days are marked by a light green background. In addition to a difference between day- and nighttime noise, there is a clear distinction between weekdays and weekends: especially data on Sunday ~~appears~~ appear less noisy. RSAM for HBAZ varies between 6 and 12 μm/s^2 during the day on weekdays, while the night-time RSAM values are less than 2 μm/s^2. The narrow spike late on the March 14th is due to the previously mentioned earthquake in the Kermadec Islands region.

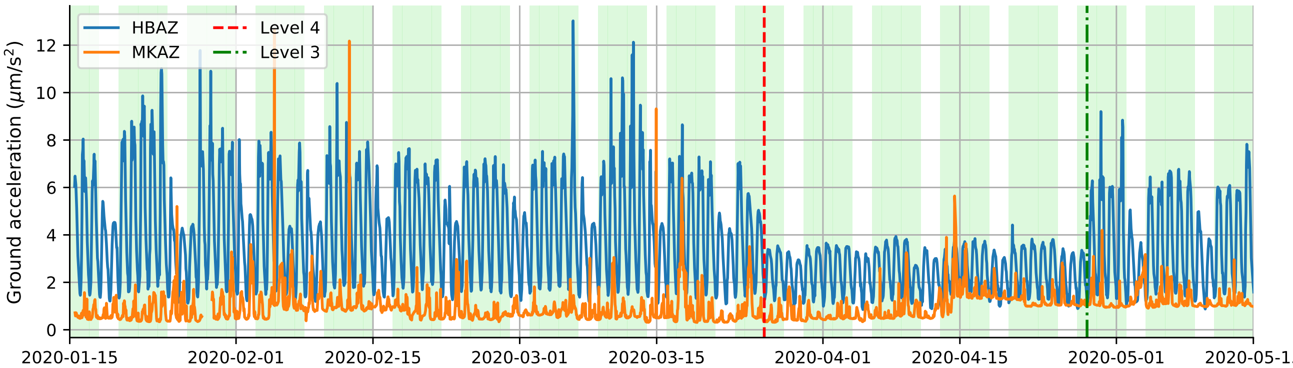

Figure 4. RSAM at short-period borehole seismometer HBAZ and the nearest broad-band station MKAZ. In addition to the contrasts in RSAM values for days, nights, weekends and weekdays, the Level 4 lockdown period (its start marked by a red dashed line and the transition to Level 3 is annotated by a green dash-dotted line) is marked by lower RSAM values for station HBAZ.

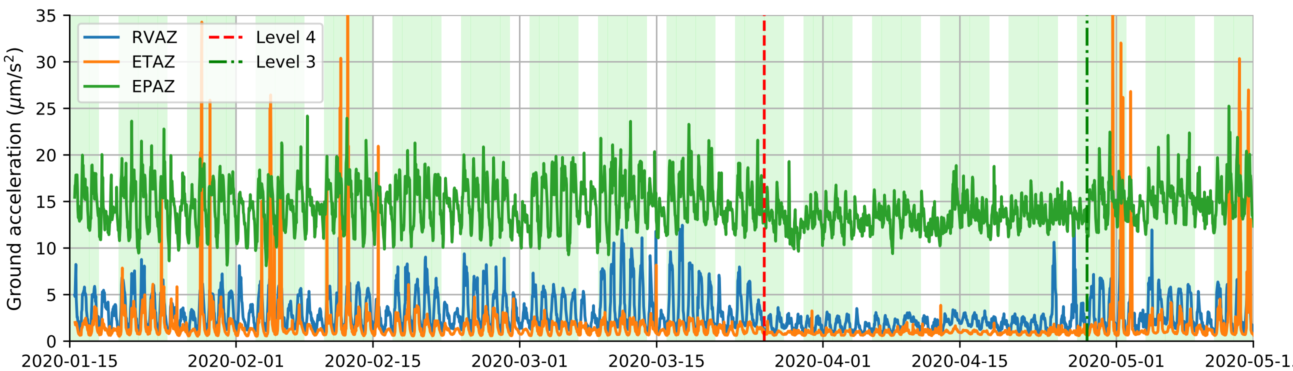

Figure 5. RSAM levels for three other borehole stations of the AVSN nearest to the Auckland CBD are reduced during the ~~lock-down~~lockdown.

2.1 Seismic noise levels during a Level 4 ~~lock-down~~lockdown

Restrictions during a level-4 ~~lock-down~~ lockdown to combat the COVID-19 pandemic in New Zealand resulted in a reduction of weekday day-time RSAM values on HBAZ (Figure 4). Before the ~~lock-down~~lockdown, indicated by the red vertical dashed line, the periodicity of RSAM follows the familiar day/night and weekend/weekday pattern from Figure 3, but after the ~~lock-down~~ Level 4 lockdown ended (at the dash-dotted green vertical line) weekday daytime RSAM levels resemble those of a typical Sunday. For comparison, the nearest broadband station south of Auckland, MKAZ, generally has lower RSAM levels and appears unaffected by the NZ ~~lock-down~~lockdown.

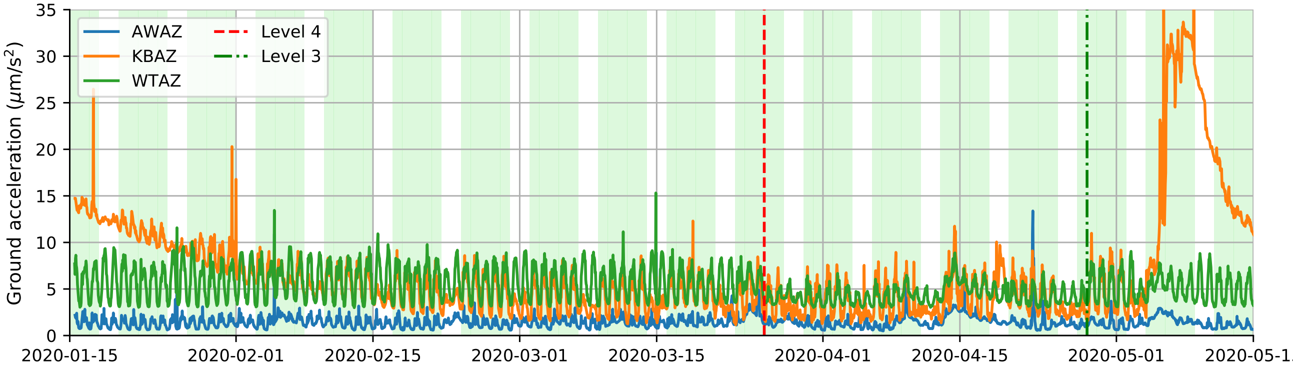

Figure 6. RSAM levels at three AVSN stations Southwest of Auckland's CBD. Only RSAM levels on station WTAZ dropped during the ~~lock-down~~lockdown.

The ~~lock-down~~ lockdown measures affect AVSN data in different ways. Stations EPAZ, RVAZ and ETAZ are – as station HBAZ – in a borehole near or in the CBD. And similarly to station HBAZ, their RSAM values captured in the top panel of Figure 5 are reduced at the start of the Level 4 ~~lock-down~~ lockdown and increased to ~~pre-lock-down~~ pre-lockdown levels after the severest restrictions were lifted in Level 3. In addition, station EPAZ located under Eden Park Stadium suffers from a continuous source of high-frequency (~50 Hz) noise, which results in elevated RSAM values at all times. Figure 6 contains RSAM values for stations to the Southwest of the Auckland CBD. WTAZ data are less noisy during the ~~lock-down~~lockdown, despite not showing a significant weekday/weekend signature. Conversely, KBAZ has quieter weekends, but no reduction in RSAM during the ~~lock-down~~lockdown. Furthermore, the data for KBAZ are marked by extended periods of larger RSAM values in the beginning of January and mid-May. Even though KBAZ and WTAZ are borehole stations, the least noisy station of these three is station AWAZ, located in a borehole on the Awhitu Peninsula. The data from this station do not show the weekend/weekday signature, nor a ~~lock-down~~ lockdown reduction in RSAM values.

2.1.1 The influence of wind

Figure 7 presents the RSAM values for three seismic stations in the Hauraki Gulf. The two seismic surface stations ABAZ and WIAZ are approximately 25 times noisier than the other stations in the AVSN. To compare the features in the RSAM data for all three stations, the MBAZ signal is multiplied by a factor of 25. Station MBAZ is in a borehole on Motutapu Island in the Hauraki Gulf; a seismically quiet location. There are no distinctions between weekdays and weekends, but still a small reduction in noise levels during the ~~lock-down~~ lockdown is evident in the data. Figure 7 includes the running average of wind speed over a 72-hour window from Auckland's Sky Tower in the CBD. Correlation between the noisiest periods and the wind is strongest for the surface stations, for example during high-wind times in the middle of February and April, as well as in early May.

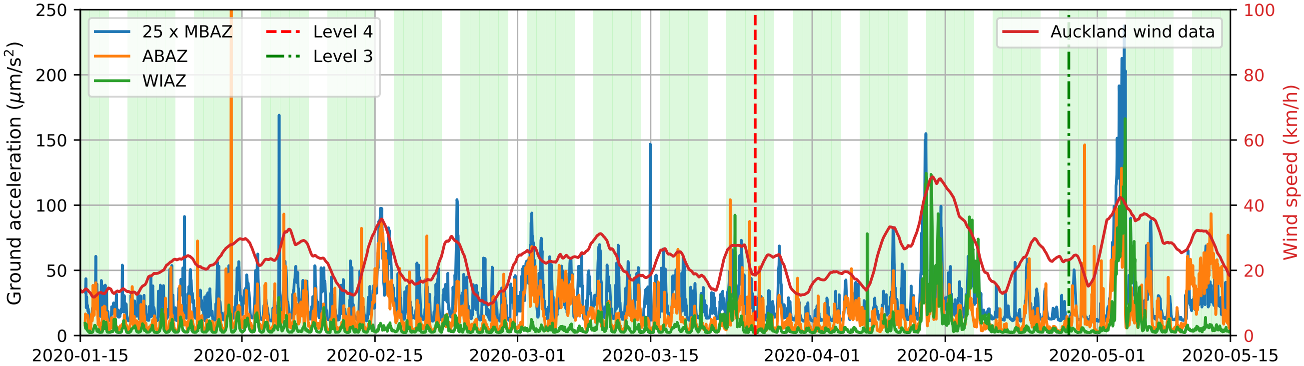

Figure 7. RSAM values for stations east of Auckland CBD, on the Hauraki Gulf. Only the borehole RSAM data from MBAZ, artificially multiplied by 25 for visual purposes, correlate with the Level 4 ~~lock-down~~ lockdown in New Zealand.

2.1.2 Mobility data

Figure 8 contains the same RSAM values for HBAZ as in Figure 4, but filtered between 1-14 Hz. This frequency band has previously proved to be most sensitive to human activity ~~Dias et al. (2020)~~(Dias et al., 2020), but is also in the range of frequencies of interest for seismic monitoring of volcanic unrest. Figure A1 shows that RSAM values drop for even higher frequencies, possibly as high as the Nyquist frequency in the data (50 Hz). The right vertical axis is for Google's public mobility data for Auckland ~~last accessed June 2020~~(last accessed June 2020). The mobility data are broken down into different human activities. Prior to the ~~lock-down~~lockdown, the strongest correlation between mobility data and seismic noise levels is seen in the Work Places category; in both cases, the weekend leads to a drop in noise and work-place activity. Not surprisingly, all but the residential activity (movement inside the home) dropped significantly during the ~~lock-down~~lockdown, but the correlation between seismic noise on HBAZ and mobility associated with "grocery and pharmacy" is particularly strong. Because the mobility data are presented as a change in activity, the workplace activities dropped overall, but work deemed essential continues in the weekends, resulting in a temporary increase in weekend workplace activity during the lockdown period.

2.1.3 Earthquake detection

To test whether the reduction in noise during ~~lock-down~~ lockdown affects the detectability of local seismicity, we employed a network matched-filter detector ~~Gibbons and Ringdal (2006)~~(Gibbons and Ringdal, 2006) to construct a catalogue of the AVF. The matched-filter method complements standard energy-based detection methods that rely on variations in waveform amplitude and are therefore strongly controlled by background noise-levels. Matched-filters commonly provide robust earthquake detections at lower amplitudes (and therefore magnitudes) than standard detectors, often generating catalogues with one magnitude unit lower completeness (around 10 times more earthquake detections Warren-Smith et al., 2018; Shelly and Hardebeck, 2019; Ross et al., 2019). All codes to generate the following results can be retrieved from Chamberlain and van Wijk (2020).

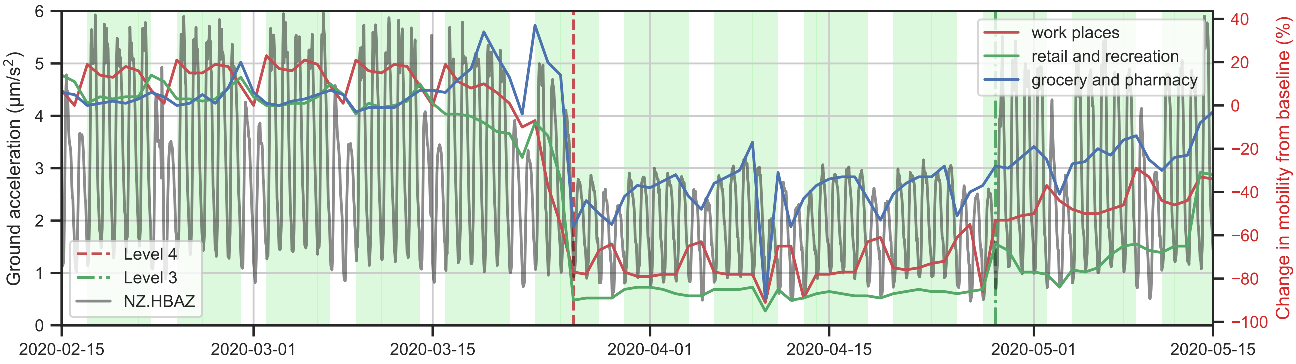

Figure 8. RSAM values for station HBAZ, compared to Google's mobility data for Auckland.

We made earthquake templates from the Geonet catalogue with 59 events between 1st January 2011 and 15th April 2020 that had picks on at-least five stations of the AVSN. Templates are constructed by re-sampling the seismic data to 50 Hz and filtered between 2–15 Hz using a fourth-order Butterworth band-pass filter. Template waveforms were cut to 6 s length starting 0.5 s before P-wave picks on vertical channels and 0.5 s before S-wave picks on horizontal channels. We required a minimum signal-to-noise ratio of 5 to retain waveforms in the templates. All 59 templates were correlated with data processed with the same parameters between the 1st of November 2019 and the 15th of June 2020 using EQcorrscan ~~Chamberlain et al. (2018)~~ (Chamberlain et al., 2018). Detections are made when the network sum of the normalised cross-correlations exceeds 9 times the median absolute deviation (MAD) of the cross-correlation sum for that day ~~Warren-Smith et al. (2017)~~(Warren-Smith et al., 2017) . If more than one detection occurs within 2 s of another detection, the detection with the highest average correlation value is retained.

To improve the quality of the resulting catalogue, we computed cross-correlation derived pick-corrections for each detection using the method ~~Warren-Smith et al. (2017)~~ (Warren-Smith et al., 2017) with a minimum normalised cross-correlation value of 0.4 required for each pick. We retained detections that were picked on at least three stations, resulting in a final catalogue of 40 events. One of these events is a quarry blast, and a further four events are not related to visible phase-arrivals. In the same time-period in which we detect 35 earthquakes, the GeoNet catalogue contains five earthquakes (which are a subset of the events in Figure 9).

3 Discussion

Seven of the ten stations of the AVSN are installed in boreholes, reducing the impact of environmental and anthropogenic noise sources. For example, station AWAZ at 371 m below the surface is inline with the runways of the Auckland airport, and appears insensitive to airplane noise, compared to surface station WTAZ. Nevertheless, borehole stations closest to the CBD ~~are still prone to record~~ remain sensitive to anthropogenic noise, which was reduced during the level 4 ~~lock-down.~~ lockdown.

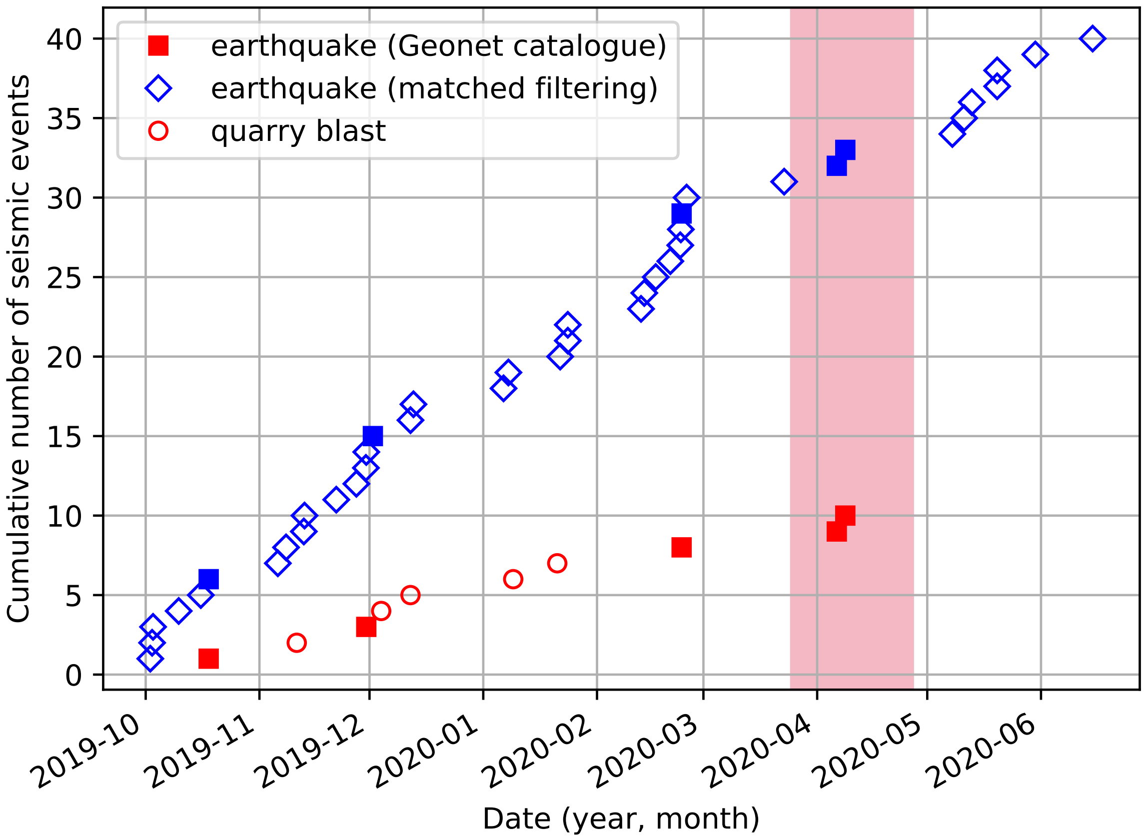

Figure 9. Matched filtering with templates built from Geonet-catalogued earthquakes results in 40 events between October 1st, 2019, and June 15th, 2020. Of these 40 events, 35 are identified as local earthquakes, including the five earthquakes in the Geonet catalogue for the same period.

Correlation of RSAM values during the ~~lock-down~~ lockdown at station HBAZ are strongest with the “grocery and pharmacy” category of Google mobility data. This station is 380 m underground, but the local grocery and medical centre are less than 2 km away.

Surface stations on Waiheke Island (WIAZ) and on the Whangaparaoa peninsula (ABAZ) are the noisiest stations, and RSAM values correlate with wind speed. In fact, the wind data ~~is a sliding~~ are the result of a moving average of 72 hours of data during which winds ~~actually~~ vary significantly. Therefore, we believe the correlation between seismic noise and this averaged wind speed indicates the correlation is more related to the ocean swells associated with storms. In fact, we believe all the seismic stations of the AVSN are sensitive to ocean swell, indicated by variations in RSAM amplitudes between day and night. Installing WIAZ and ABAZ in boreholes would reduce their noise floor by one or two orders of magnitude, based on RSAM values on nearby borehole station MBAZ and others, improving sensitivity of the AVSN network for both volcano monitoring and seismic tomography.

Large amplitudes in RSAM for station KBAZ in January and May 2020 cannot be linked to storms or ~~lock-down~~ lockdown effects, and may be the result of local farming activity. Additional variations in weekday/weekend RSAM signals are robust even in the presence of the ~~lock-down~~lockdown. We attribute this to the proximity of one of the main highways that carry transport of (essential) services in and out of Auckland.

The ~~variation~~ reduction in anthropogenic noise is noted in the frequency band from 1 Hz and up, possibly all the way to the Nyquist frequency in the data, 50 Hz (see Figure A1 in Appendix A). Anthropogenic noise in this frequency band affects both volcano monitoring with RSAM, as well as its ability to detect weak and local seismicity. Nevertheless, the reduction in seismic noise throughout New Zealand’s level 4 ~~lock-down~~ lockdown does not appear to have affected our ability to detect earthquakes in this seismically quite part of New Zealand. By employing a matched-filter approach, we limit the sensitivity of our detector to variations in noise amplitude. Analysis of the cross-correlation sums for the full period studied shows little variation in this detection statistic (see Figure B1 in Section B), resulting (combined with low seismicity rates) in little change in detection rate. In contrast, classic earthquake detectors dependent of ratios of seismic amplitudes, would be sensitive to this variation in noise. This highlights the efficacy of matched-filter detectors for consistent detection capability during periods of variable noise.

4 Conclusions

During the Level 4 ~~lock-down~~ lockdown to combat the COVID-19 pandamic in New Zealand, six of the ten seismometers that monitor the Auckland Volcanic Field display reduced seismic noise levels above 1 Hz. One seismic station has low levels of noise all the time (AWAZ), and one station (KBAZ) appears to be affected by local farming and a motorway supporting essential services. Two other (surface) stations (WIAZ and ABAZ) in the Hauraki Gulf have Real-Time Seismic Amplitude Measurement (RSAM) values that are one to two orders of magnitude greater than the rest of the AVSN, and show the strongest correlation with ocean swell.

Besides analysing the sensitivity of the network, the ~~lock-down~~ lockdown period allowed us to explore for local earthquakes that are smaller than normally would be detectable. A first attempt at template matching resulted in the detection of ~~34~~ 30 new local events in the time where the Geonet catalogue contains only five local earthquakes. However, the detection rate was not higher during the ~~lock-down~~lockdown period than in the periods before or after the lockdown. More advanced matched-filtering detection efforts with existing data are underway, but re-installing surface stations WIAZ and ABAZ in boreholes can improve seismic monitoring and tomography of the AVF.

Code availability. All codes for the event detections are available from Chamberlain and van Wijk (2020)

Author contributions. All listed authors wrote the manuscript. KvW did the seismic noise analysis. The original idea to analyse seismic data during the COVID-19 pandemic is from TL and KVN, EQcorrscan analysis by CJC

Competing interests. We note no competing interests

5 Acknowledgements

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Appendix A: Spectrograms

Figure A1 contains the spectrograms for every station of the AVSN, plus the broadband station MKAZ of the national seismic monitoring network. The spectrograms are built using the continuous seismic records. The data is split in windows of 30 minute duration that overlap by 50%. The PSD of each window is calculated using MSNoise (Lecocq et al., 2014),which relies on the Probabilistic Power Spectral Densities (PPSD) implementation of ObsPy (Krischer et al., 2015). the frequency binning is by 1.25% of an octave (default 12.5%, or 1/8) and the PSDs are smoothed over 2.5% of an octave (default 100%, or 1 octave) around the central frequency of each bin. The amplitudes of the PSDs are binned in 0.25 dB bins.

All the stations have a distinct spectral signature near (but just above) 0.1 Hz for event ID us60008fl8. The period between the black vertical dashed lines marks the extent of the lockdown in New Zealand. For most stations, anthropogenic noise is reduced for frequencies from 1 Hz to the Nyquist frequency of 50 Hz. However, the effect of the lockdown is not equally clear in all stations: wind noise on stations on the Hauraki Gulf (WIAZ and ABAZ) dominates over any anthropogenic noise, as previously seen in the seismograms.

Appendix B: Matched filtering details

The lockdown period is short, especially when compared to seismogenesis in this relatively low seismicity region. Because our template analysis focuses on the efficacy of the matched-filter method, the detectability is affected by the noise-level in the cross-correlation sum. To demonstrate why we do not expect a change in detection-rate during lockdown, we computed and plotted the network cross-correlation sum for one template (GeoNet publicID: 3469372) between February 29th 2020 and May 8th 2020, alongside the amplitude spectra for this time-series (Figure B1. Plotting the full sample-rate correlation-sum shows little power outside the 2-15 Hz range used, however computing the hourly mean correlation-sum provides more useful information regarding the variability in noise in the correlation sum. In this hourly correlation sum, reductions should correspond to reduced noise in the correlation sum and hence enhanced detectability. We find clear daily variations (evidenced by a peak in the amplitude spectra at 24 hour periods), and some variability, however there is no clear reduction in background correlation values during lockdown. It is based on this evidence that we can be confident that there is no significant change in detectability during lockdown. Note also that our detection threshold is based on the daily median absolute deviation of the correlation sum which further smooths the daily variability in the correlation sum. The range of daily median absolute deviations upon which our threshold is based range from 0.234 to 0.254, with the lowest values falling outside the lockdown period.

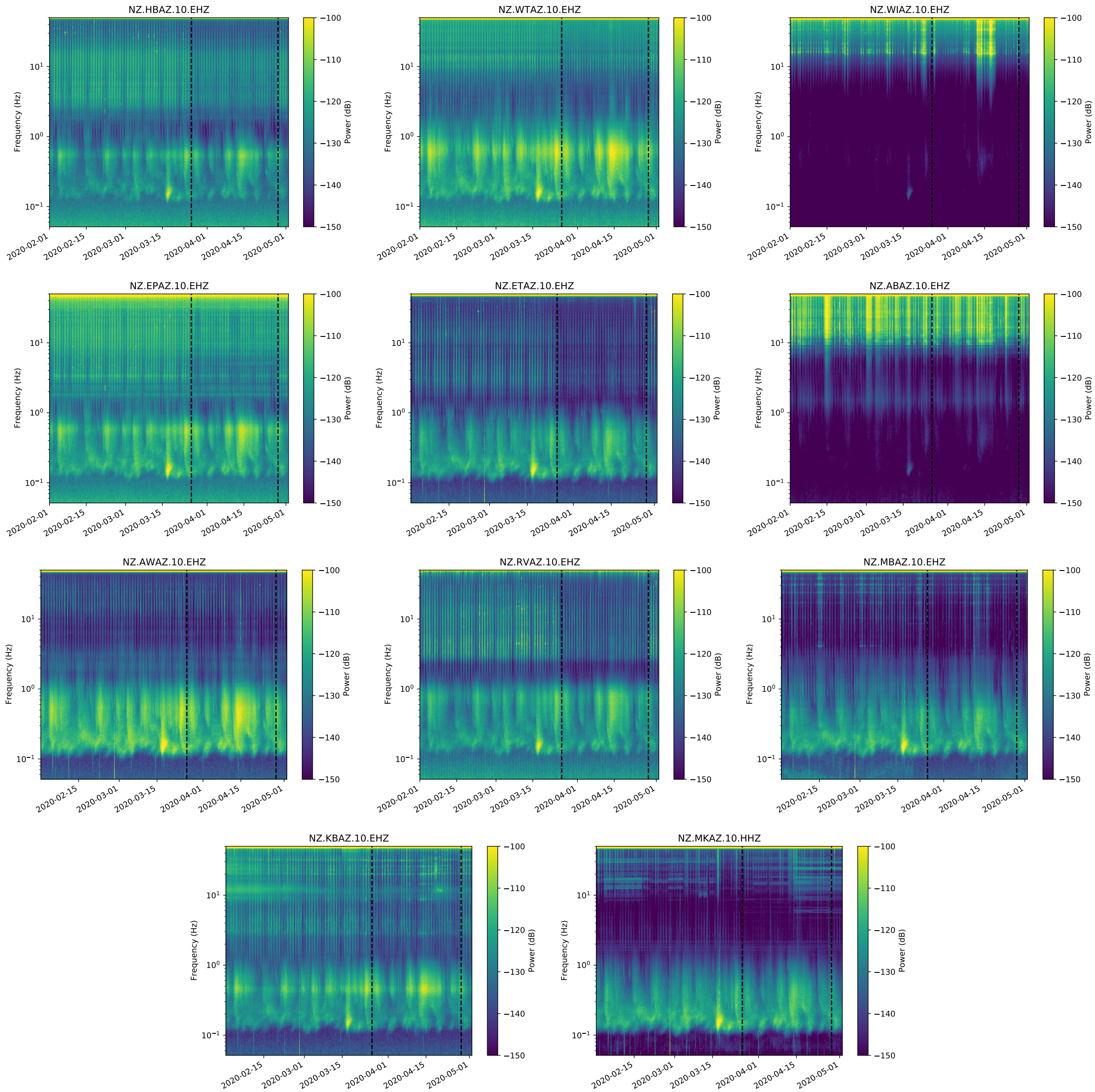

Figure A1. Spectrograms for the seismic data of the Auckland Volcanic Seismic Network. The vertical dashed lines indicate the start and end date of the COVID-19 lockdown in New Zealand.

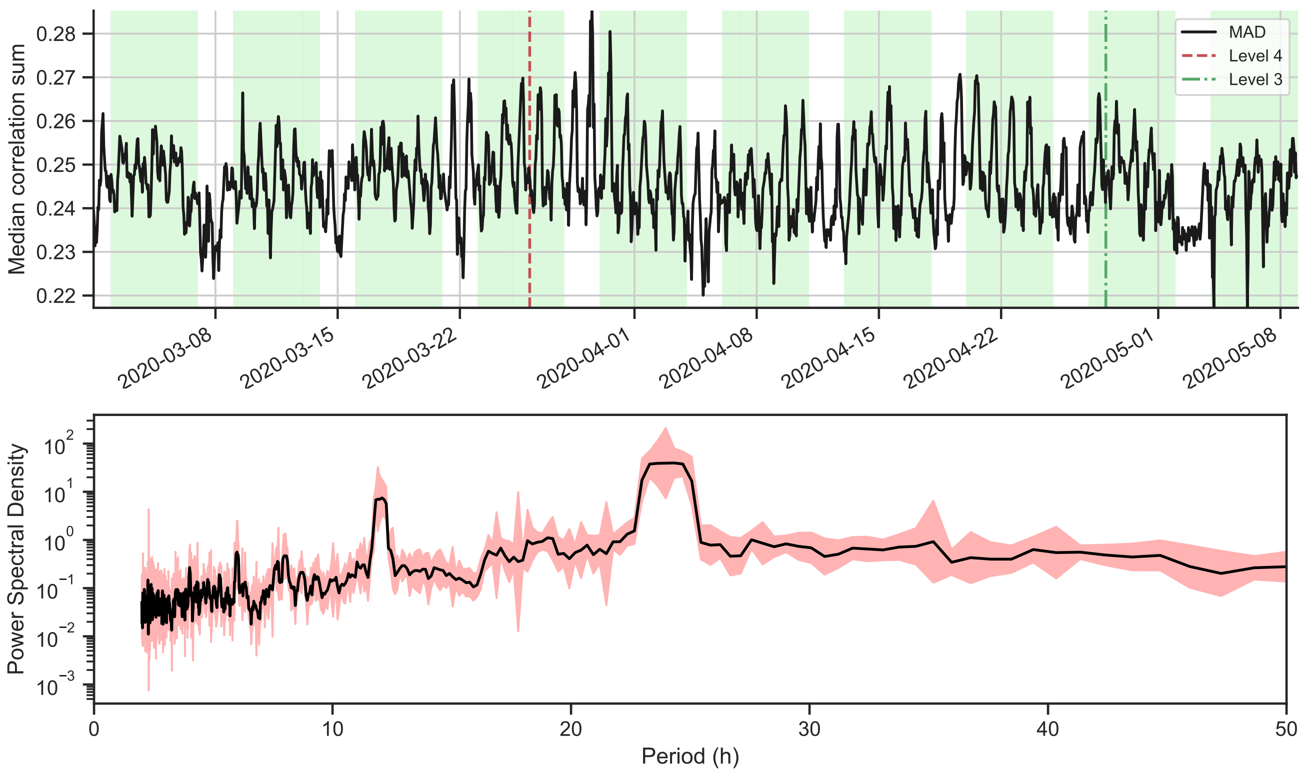

Figure B1. Top: the median crosscorrelation sum for the AVSN against a template of one of the Geonet-located earthquakes, showing no reduction in this value for the lockdown period. Bottom: weighted multitaper spectrum with 5 and 95 percent confidence intervals of the top panel time series. Spikes at 12 and 24 hours confirm the noise is dominated by the difference between night and day noise levels.