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

Kasper van Wijk[1], Calum J. Chamberlain[2], Thomas Lecocq[3], and Koen Van Noten[3]

[1]Department of Physics, University of Auckland
[2]School of Geography Environment and Earth Sciences, Victoria University of Wellington
[3]Royal Observatory of Belgium

Correspondence: Kasper van Wijk (k.vanwijk@auckland.ac.nz)

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.

5 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 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

10 period between November 1st, 2019 and June 15th, 2020. However, the Level 4 lock-down from March 25th to April 27th – with its drop in anthropogenic seismic noise – 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.

15 ## 1 Introduction

The Auckland Volcanic Field (AVF) is an active intra-plate volcanic field consisting of 53 known volcanoes 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

20 impending eruption 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 from wind and ocean waves (see Table 1 and
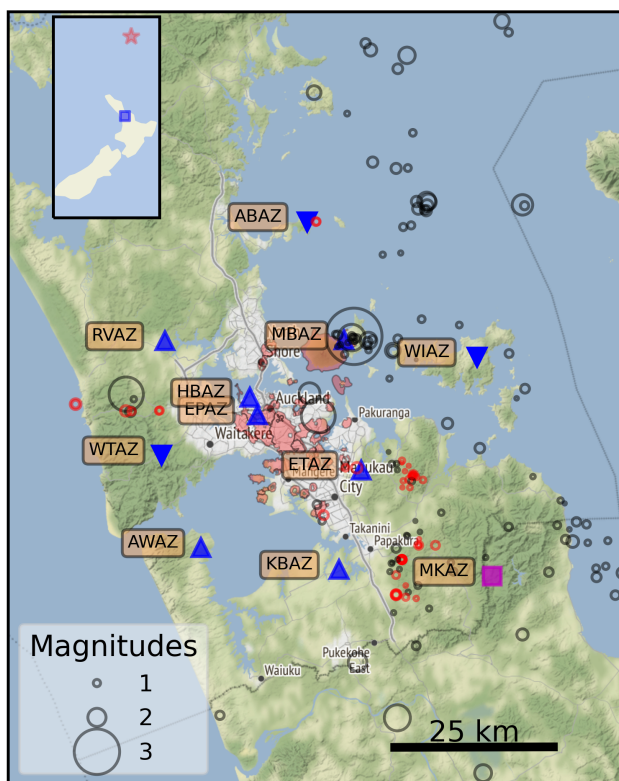
Figure 1. Terrain map of the greater Auckland area from OpenStreetMap with surface expressions of Auckland's volcanoes in pink from the Determining Volcanic Risk in Auckland (DEVORA) project. The stations of the Auckland Volcanic Seismic Network (AVSN, managed by Geonet) are presented as blue triangles (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

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.

25   New Zealand entered a Level 4 lock-down 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 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 on seismic recordings of the AVSN. Recent

30   studies have shown impact in the 1-10 Poli et al. (2020) and 4-14 Hz Lecocq et al. (2020) range, but as 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), our analysis includes seismic data from 0.1 to 50 Hz. In addition, we use this uniquely quiet period of Auckland in lock-down 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

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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

40   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.
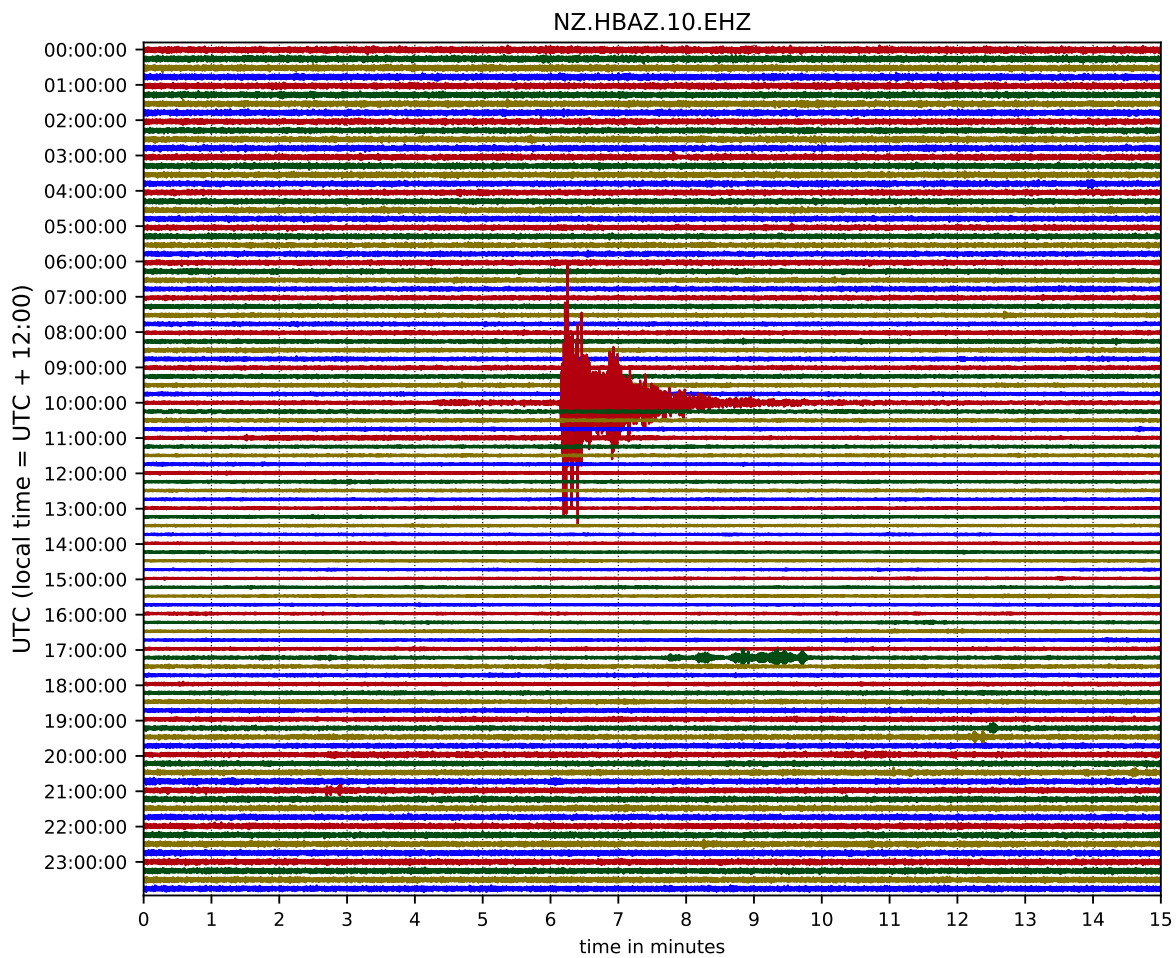
Figure 2. Vertical component of the seismic wavefield at borehole station HBAZ for March 14th, 2020. The signal with the largest amplitudes is from an earthquake in the Kermadec Islands region (event ID us60008fl8).
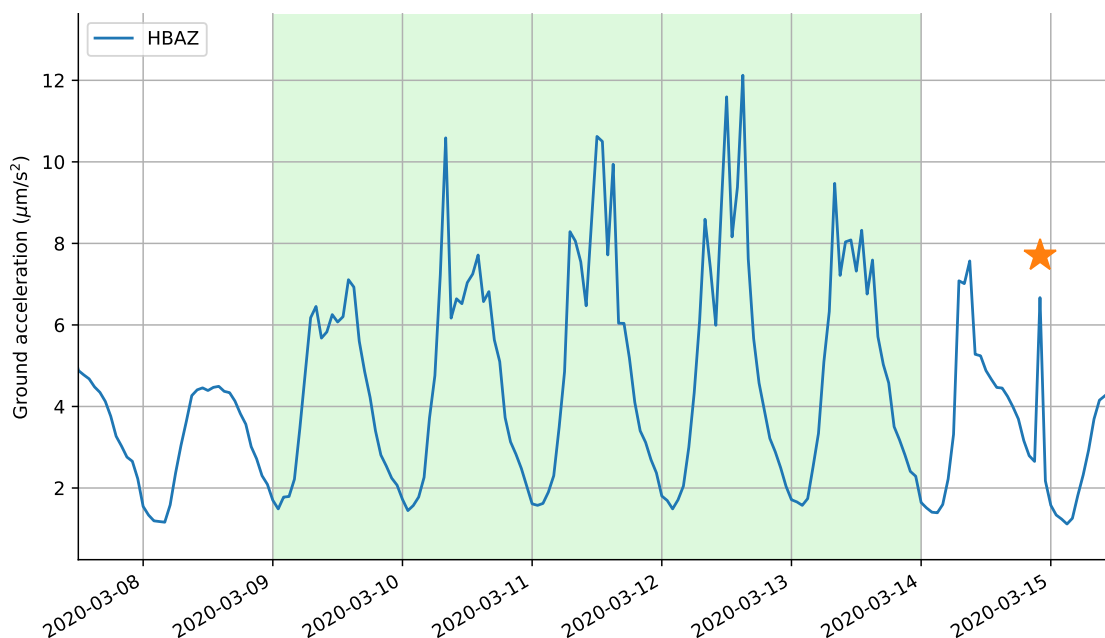
Figure 3. Standard deviation over 30-minute intervals of the ground acceleration of short-period borehole station HBAZ. Times are in local NZT, and weekdays have a green background. Note the lower night-time noise level compared to day-time, and quieter weekends. The origin time of the Kermadec Regions event ID us60008fl8 is annotated with a star.

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 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

45   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 less noisy. RSAM for HBAZ varies between 6 and 12 μm/s^2 during the day on

50   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.
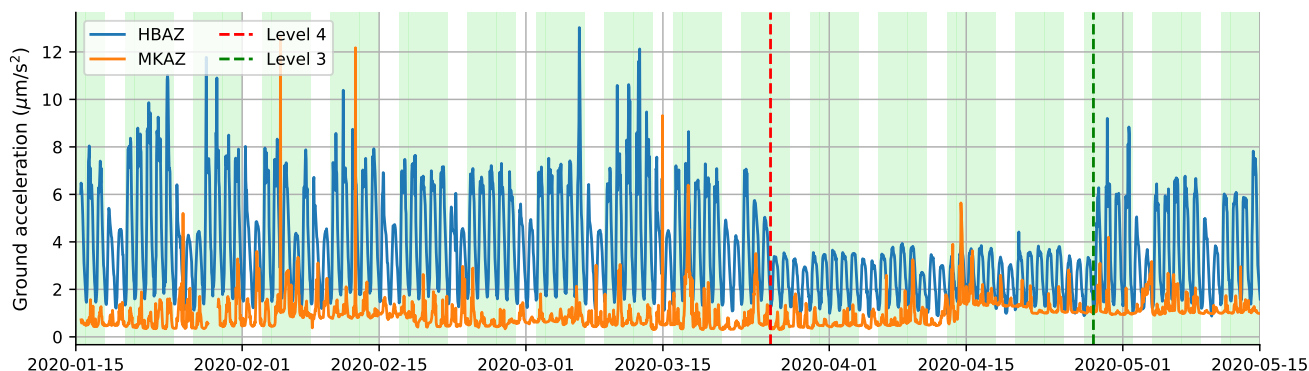
Figure 4. RSAM at short-period borehole seismometer HBAZ and the nearest broad-band station MKAZ. In addition to the contrasts in RSAM values for days, nights, weekends and weekdays, the Level 4 lockdown period is marked by lower RSAM values for station HBAZ.
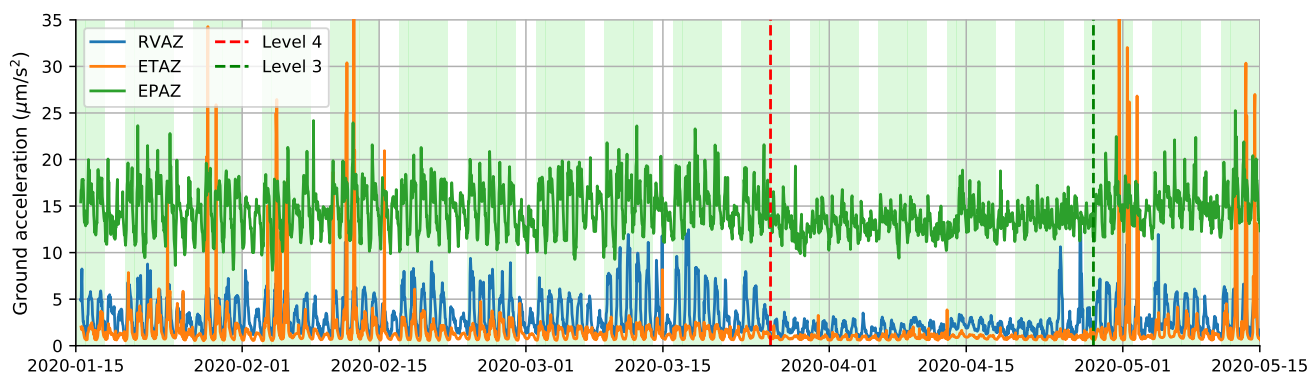
Figure 5. RSAM levels for three other borehole stations of the AVSN nearest to the Auckland CBD are reduced during the lock-down.

2.1 Seismic noise levels during a Level 4 lock-down

Restrictions during a level-4 lock-down 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, indicated by the red vertical line, the periodicity of RSAM

55 follows the familiar day/night and weekend/weekday pattern from Figure 3, but after the lock-down 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.

The lock-down 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 Fig-

60 ure 5 are reduced at the start of the Level 4 lock-down and increased to pre-lock-down 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-
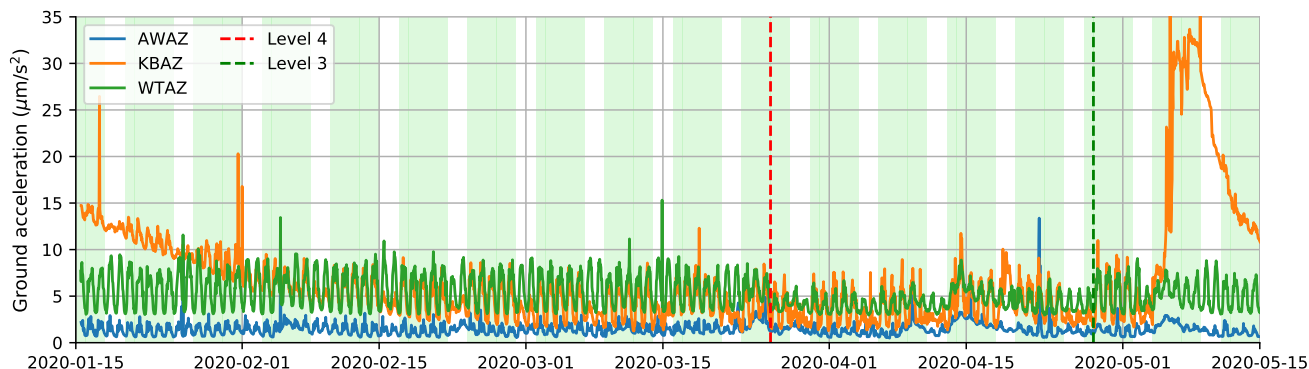
Figure 6. RSAM levels at three AVSN stations Southwest of Auckland's CBD. Only RSAM levels on station WTAZ dropped during the lock-down.

frequency ($\sim$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, despite not showing a significant weekday/weekend signature. Conversely, KBAZ has quieter weekends, but no reduction in RSAM during the lock-down.

65 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 reduction in RSAM values.

2.1.1 The influence of wind

70 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 is evident in the data. Figure 7 includes the running average of wind speed over

75 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.

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), but is also in the range of frequencies of interest for

80 seismic monitoring of volcanic unrest. The right vertical axis is for Google's public mobility data for Auckland last accessed June 2020. The mobility data are broken down into different human activities. Prior to the lock-down, the strongest correlation
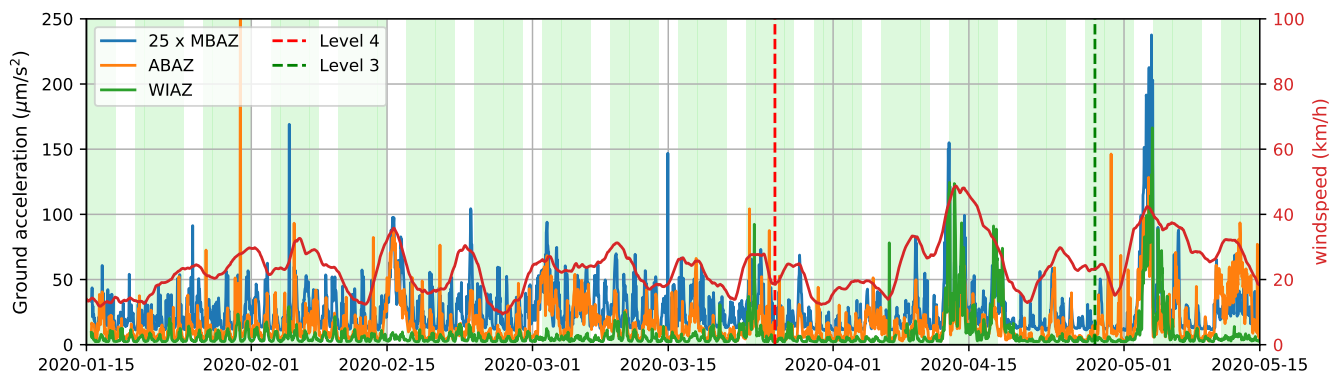
Figure 7. RSAM values for stations east of Auckland CBD, on the Hauraki Gulf. Only the borehole RSAM data from MBAZ, artificially multiplied by 25 for visual purposes, correlate with the Level 4 lock-down in New Zealand.
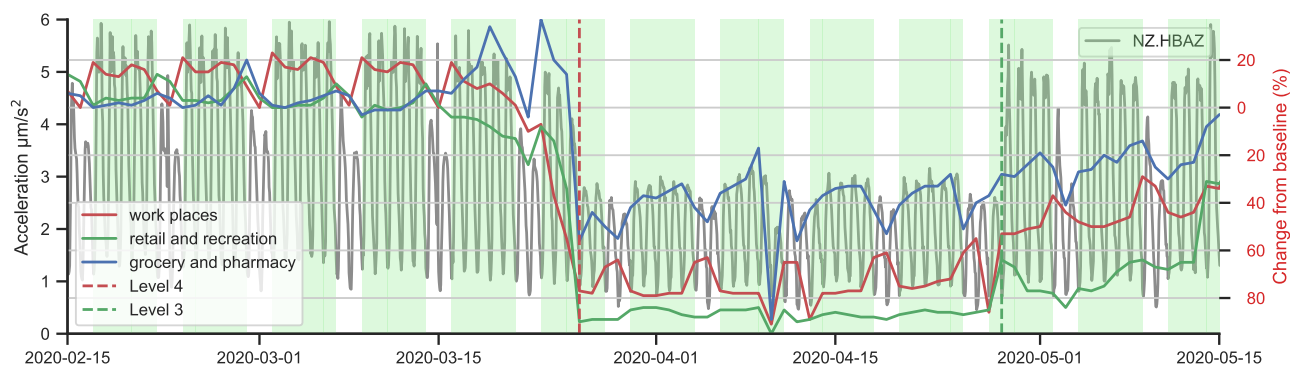
Figure 8. RSAM values for station HBAZ, compared to Google's mobility data for Auckland.

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, but the correlation between seismic noise on HBAZ and mobility associated with "grocery

85 and pharmacy" is particularly strong.

2.1.3 Earthquake detection

To test whether the reduction in noise during lock-down affects the detectability of local seismicity, we employed a network matched-filter detector Gibbons and Ringdal (2006). 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.

90 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)

We made earthquake templates from the Geonet catalogue with 59 events between 1st January 2011 and 15th April 2020
95   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).
100   Detections are 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). 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) with a minimum normalised cross-correlation value of 0.4 required for each pick.
105   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
110   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 anthropogenic noise, which was reduced during the level 4 lock-down. Correlation of RSAM values during the lock-down 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.
115   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 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
120   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.
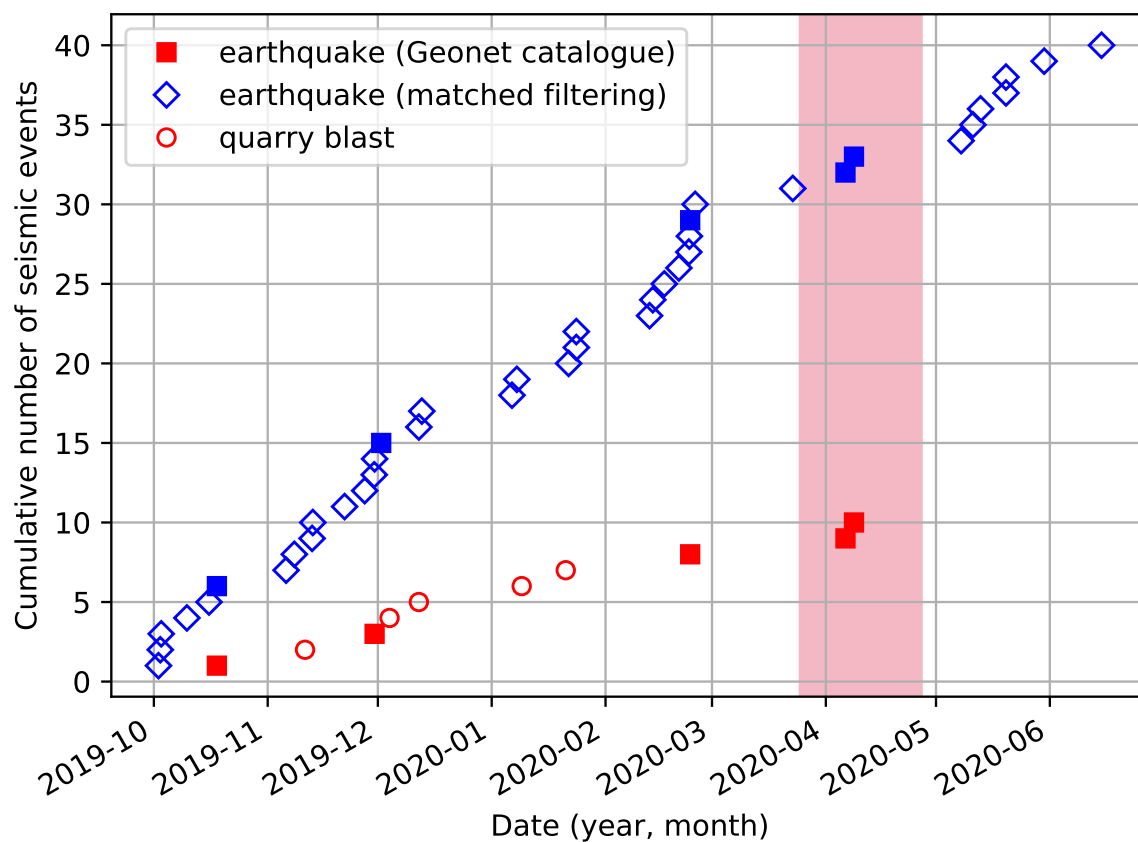
Figure 9. Matched filtering with templates built from Geonet-catalogued earthquakes results in 40 events between October 1st, 2019, and June 15th, 2020. Of these 40 events, 35 are identified as local earthquakes, including the five earthquakes in the Geonet catalogue for the same period.

Large amplitudes in RSAM for station KBAZ in January and May 2020 cannot be linked to storms or lock-down effects, and may be the result of local farming activity. Additional variations in weekday/weekend RSAM signals are robust even in

125 the presence of the lock-down. 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 in seismic noise throughout New Zealand's level 4 lock-down 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

130 shows little variation in this detection statistic, 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 to combat the COVID-19 pandamic in New Zealand, six of the ten seismometers that monitor

135 the Auckland Volcanic Field display reduced seismic noise levels. 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 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 period allowed us to explore for local earthquakes that are

140 smaller than normally would be detectable. A first attempt at template matching resulted in the detection of 34 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. 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)

145 *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

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150   Government through its agencies: Earthquake Commission (EQC), GNS Science and Land Information New Zealand (LINZ). The wind speed data were made available by NIWA. Data processing was done in ObsPy (Krischer et al., 2015), and data visualisation with Matplotlib (Hunter, 2007) and Cartopy (Met Office, 2010 - 2015) in Python.

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