Using Seismic Noise to Monitor COVID-19 Societal Response in Halifax

by

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ABSTRACT

Seismometers record signals from more than just earthquakes. Cultural noise, high-frequency seismic noise generated from human activities (e.g., traffic) produces a distinct diurnal signature in frequencies above 1 Hz due to how human activities change from day to night. To mitigate the spread of the coronavirus disease (COVID-19), public health regulations were imposed worldwide leading to an unprecedented global quieting in the seismic record. This unlocked a new pathway to explore the effects of anthropogenic activity on seismic noise. Cultural noise was analyzed in the month leading to and following the initial 2020 lockdown measures in Halifax, Nova Scotia, Canada, then compared with baseline data established from the year prior. Immediately following the lockdown, cultural noise (10-14 Hz) in Halifax dropped by 11.85% from the month prior. In comparison to 2019, seismic power had dropped by 17.19%. This suggests the pandemic itself, prior to lockdown measures, influenced human activities. In addition, annual holidays, such as Easter weekend and the tragic Nova Scotia Massacre, led to a reduction in seismic power relative to that of the initial lockdown. Overall, a correlation between cultural noise and human activity was found. Seismic data indicate that human activity decreased a fraction of that reported from major cities around the world, displaying how different municipalities can react to lockdown conditions. This study demonstrates the use of seismic cultural noise analysis as an independent way to quantify human mobility under government-mandated restrictions.

Keywords: cultural noise, COVID-19, signal processing, lockdown, computational seismology

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CHAPTER 1: INTRODUCTION

1.1 Motivation

Seismometers record signals from more than just earthquakes. High frequency seismic noise is generally correlated with human activities, such as noise generated from entertainment, railroads, and foot, local or highway traffic (Stutzmann et al., 2000; McNamara and Buland, 2004; Groos and Ritter, 2009; Green et al., 2016). In response to the COVID-19 pandemic, a series of public health regulations were issued in cities around the world to mitigate the spread of the disease. Researchers globally began to analyze patterns in seismic data captured from the longest quiet period on record. This research unlocks a new pathway to explore the effects of anthropogenic activity on seismic noise. To utilize this research for possible economic, political, or environmental applications, methods of characterizing this data and interpreting the results are necessary (Denolle & Nissen-Meyer, 2020). As the first of its kind to look at the effect of lockdowns on seismic noise in Atlantic Canada, this study seeks to characterize the patterns within frequencies attributed to cultural noise from before and after the first lockdown in Halifax on March 22, 2022. From a different view, we are going to quantitatively answer “How did Halifax respond to the restrictions?”

1.2 Background

Seismology is the study of earthquakes and seismic waves that move through and around the Earth. Seismic waves propagate from an impulse, traveling through the Earth (body waves), or moving along the Earth’s surface (surface waves). Seismograph units record relative changes in motion between itself and an internal component called a seismometer. The data produced is recorded in values and charted on a seismogram, a graph typically displayed on a time (seconds) vs. ground displacement (millimeters) (USGS, 2012).

A seismic wave has a frequency that is inversely proportional to its wavelength, i.e., high frequency equals a short wavelength (UCAR Center for Science Education, 2018). It is measured in hertz (Hz), an international unit of measure where one hertz is equal to one cycle, or complete wave, per second. Seismic waves transmit in the frequencies of 0.01 Hz (~100 seconds) to 50 Hz (0.02 seconds). Small ground vibrations (microseisms) are most prominent in the 0.1 to 1 Hz range (10-1 seconds), while frequencies generated by local sources can be up to 20 Hz (0.05

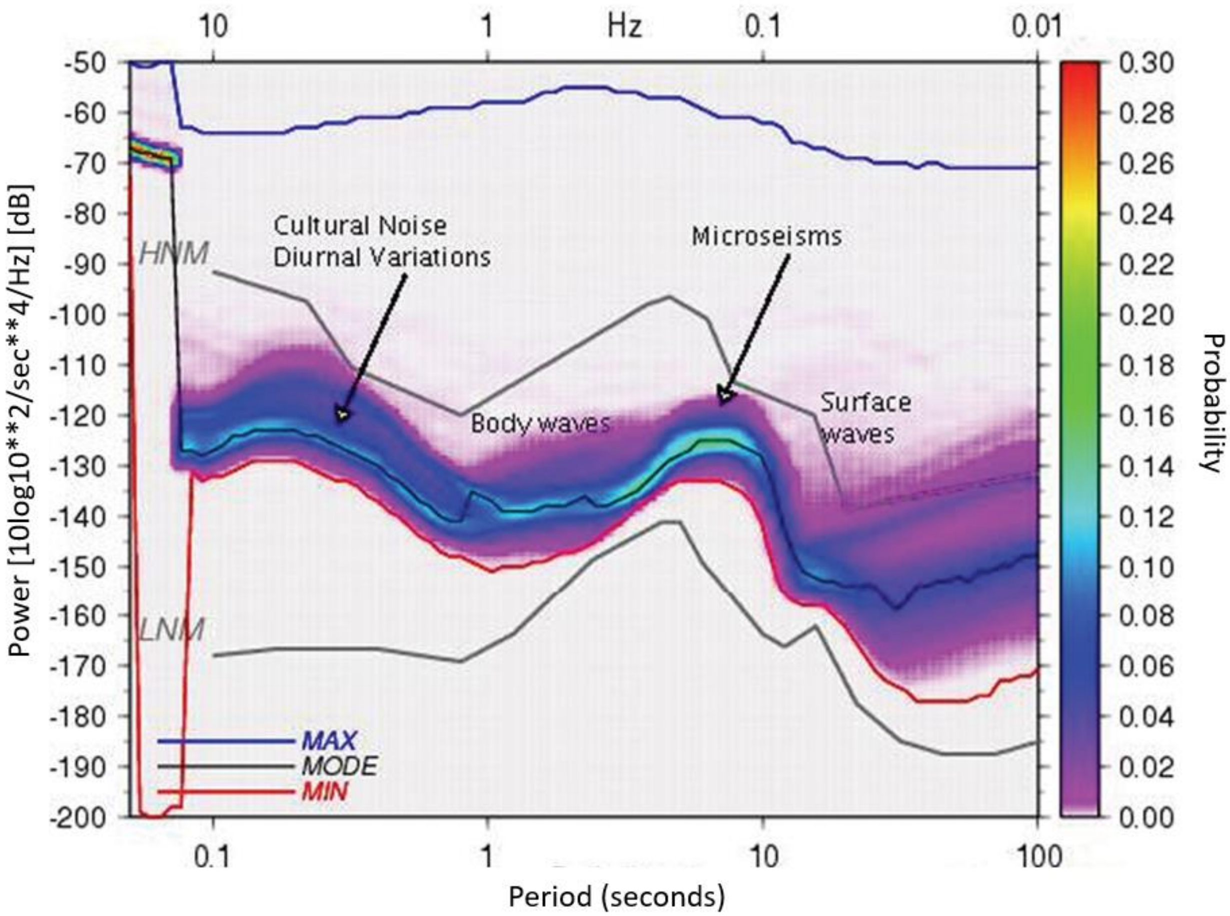

Figure 1.1 Example of seismic noise transmissions according to power and period. Figure visualizes the output of a common method of seismic noise analysis using probability density functions to visualize the distribution of seismic power spectral densities of broadband seismic data. In this case, cultural noise variations span the frequency range of >1 Hz to ~ 12 Hz. Body waves and surface waves (which dominate the spectrum above 1 second) are typically associated with tectonic activity. Figure adapted from D. McNamara (2005) and modified by IRIS (A Real-time Seismic Noise Analysis System for Monitoring Data Quality and Station Performance, n.d.) and author.

seconds) (*Earthquake – Properties of seismic waves*, n.d.). Frequency of seismic waves is an essential indicator to distinguish seismic sources.

Seismometers traditionally monitor seismic events such as earthquakes, but they also record near-continuous vibrations. Seismic noise, associated with man or man-made machinery such as power plants, factories, trains, highways, and even cattle, is generally referred to as cultural noise. Compared to earthquakes or other natural phenomena, seismic noise generated by human activities is relatively dominated by a higher frequency of > ~1 Hz, especially in urban areas (Figure 1). Thus, it is feasible to use seismic noise to monitor human activities.

Human activity has fluctuated significantly in response to the COVID-19 pandemic, from the first outbreak of the virus in late 2019, to ongoing virus prevention and mitigation by mid-2021. Patient zero of the novel coronavirus 2 (SARS-CoV-2) was initially found in Wuhan, China on

December 8, 2019 (Lu, 2020). Air travel quickly spread the virus globally. By January 27th, 2020, COVID-19, the disease developed from SARS-CoV-2, was confirmed within its first Canadian host in Toronto, Ontario. As reports of infections grew from major cities around the world, the World Health Organization (WHO) declared a public emergency. By March 11, 2020, the WHO announced that COVID-19 had infected more than 118,000 individuals within 114 countries and characterized the outbreak as a global pandemic (WHO). Days later, COVID-19 reached Nova Scotia. To help prevent the spread of the virus, the Government of Nova Scotia mandated physical distancing measures for businesses and organizations across the province (Roth et al., 2020) and universities converted to online delivery.

Figure 1.2. Location of the CN.HAL seismograph station at Dalhousie University, Halifax. The station is currently operated by members of the Department of Physics and Atmospheric Science. The red triangle is positioned at the location of HAL station. Map imagery is centered on the western flank of the Studley Campus. Inset photo obtained from Dalhousie University (Seismograph, n.d.); basemap imagery from Google Earth Pro (date accessed April 2, 2022).

TABLE 1.1. Chronological list of dates significant to the COVID-19 initial lockdown in Halifax.

Date	Location	Date (yyyy/mm/dd)
Virus outbreak	Wuhan, China	2019/12/08
COVID-19 confirmed in Canada	Toronto, Ontario	2020/01/27
WHO declares global pandemic	Global	2020/03/11
COVID-19 confirmed in Nova Scotia	Nova Scotia, Canada	2020/03/15
Government of Nova Scotia declares state of emergency	Nova Scotia, Canada	2020/03/22
Multi-tier loosening of public health measures begins	Nova Scotia, Canada	2020/05/01

Nova Scotia declared its first state of emergency on March 22, 2020, a step which allowed the province to implement restrictions to its resident's mobility. Restrictions included a ban of non-essential travel outside of primary residences, closure of parks and beaches, and gatherings restricted to less than five individuals. This initial lockdown measure began on March 22, 2020 and continued to May 1, 2020 when a multi-tier loosening of public health measures began (Roth et al., 2020).

During the COVID-19 pandemic, public health measures abruptly shifted the way Canadians work, travel, and interact. Work from home arrangements that were implemented by necessity during the pandemic have normalized remote work (Fogarty et al., 2020), and thereby changed when and how Canadians travel. Travel during peak hours reduced and travel outside of normal peak hours increased (Luck, 2021) in response to more flexible work schedules, and a heavier reliance on ecommerce shopping versus brick-and-mortar store fronts for everyday goods (UNCTAD, 2020). Halifax's response to lockdown measures can serve as a proxy for future mandated restrictions. The response can provide trend data for models on the projected outlook of public health measures, visualize shifts in mobility patterns, and characterize behavioural responses to restrictions and changes. Currently, policy makers in Nova Scotia compare pre- and post-pandemic pedestrian, cyclist, and bridge traffic volume data through the city's Mobility Response Plan (Halifax Regional Municipality, 2021a). This project works to reduce the spread of COVID-19 by implementing temporary infrastructure changes such as expanding sidewalks, closing streets to road traffic, and changing available parking (Halifax Regional Municipality, 2021b). Cell tower-based location data were used during Nova Scotia's first lockdown to identify banned activity at beaches and parks (Luck, 2021), and it continued to be accessed by federal officials top indicator of COVID-19 transmission patterns in Canada in 2021 to track and predict community spread (Chandler, 2021; Woolf, 2022). However, within urban environments and economic hubs such as Halifax, an important registered change is not only where the activity is, but of what amplitude. High amplitude generators such as concerts and events, live-music, cruise ships, and tourist activity, and commuter trains such as Via Rail immediately halted with the onset of the pandemic. Yet, traffic still tended to bottleneck down narrow downtown streets and the city was still prone to groups congregating at outdoor facilities around the city. Utilizing the data generated by seismometers, graphs can be generated from seismogram data which show trends and allow an amplitude response to be quantified.

1.3 Summary of Literature (and Knowledge Gaps)

Seismic noise from anthropogenic sources has increased with the development of cities and towns, transportation networks, and growing populations worldwide (Denolle and Nissen-Meyer, 2020). Seismic noise produced from human activities produces a signal above 1 Hz and a diurnal periodicity due to day and night variations in cultural activities throughout a 24-hour period (Hong et al., 2020; Sheen et al., 2009). These signals are identified in global studies to analyze the effects of lockdown measures resulting from the COVID-19 virus on human

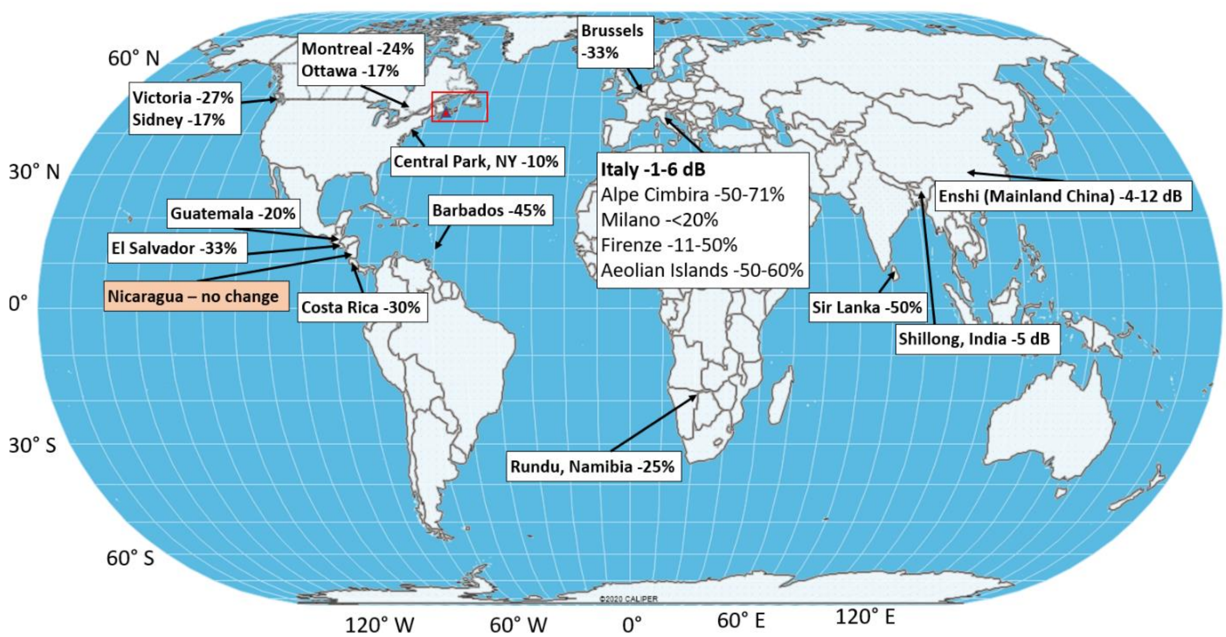

Figure 1.3. Summary of global findings in peer-reviewed papers reporting seismic noise changes related to COVID-19 lockdowns. Only findings from peer reviewed journals are included. Red triangle is approximate location of HAL station. Red box is unstudied area of interest (Maritime Canada and Newfoundland and Labrador). Noise fluctuations are reported in decibels or percent of change, depending on the method used by the authors. Basemap produced in Caliper Maptitude using a 10-degree grid area. Projection: Equal Area.

activities around the world (Figure 1.3). A reduction of up to 50% was reported in several major cities (Lecocq et al., 2020a), with dramatic reductions in noise associated with stricter public health measures (Xiao et al., 2020), and locations considered rural or remote (Piccinini et al., 2020). Major cities incurred a more progressive decline (Piccinini et al., 2020; Maciel et al., 2021) while stations positioned near transit hubs saw less of an impact (Piccinini et al., 2020). The type of noise sources and their proximity to the station location was as impactful on the change documented in the seismic record as the severity of lockdown measures for the specific location (Arroyo-Solórzano et al., 2021; Dupuis, 2020; Maciel et al., 2021; Xiao et al., 2020).

1.4 Introduction of the Study

In the Halifax region, an anthropogenic dampening of seismic activity is predicted to have followed mandated lockdowns (stay-at-home orders), school and business closures, and travel and social restrictions. Seismic noise analysis presents a unique window to monitor these changes as an overall societal response to government-mandated public health measures. While changes in seismic noise levels related to the COVID-19 pandemic have been documented in Asia, Europe, South America, and Canada, the impact of restrictions in Nova Scotia on seismic activity is so far unknown. The aim of this study is to characterize subsequent changes in noise levels in a subset region of the Halifax, the Halifax Peninsula, including their relationship to the onset of the first public health measures, and to correlate trends with public mobility and traffic data.

This study is interdisciplinary between geophysics (seismology), computer science (signal processing algorithms), and sociology (human movements and behaviours) (Figure 1.4). Geophysics characterizes subsurface conditions, and structures via seismic waves, which propagate through the Earth. Signal processing algorithms are applied to study the behaviour of those waves. The characterization of human social behaviour applies a sociological perspective to the study. It will seek to define high frequency seismic noise during a period of

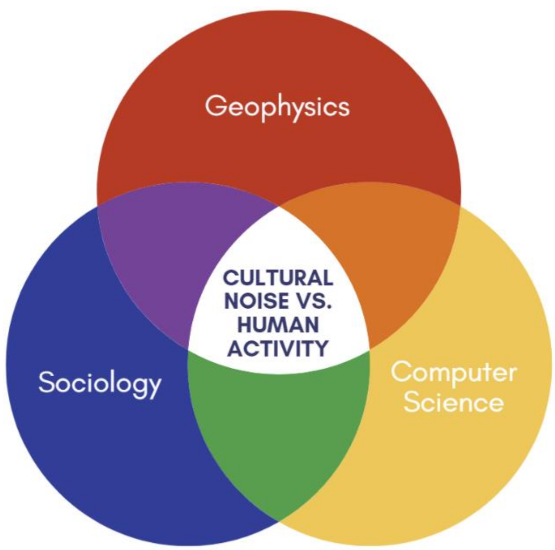

Figure 1.4: Representation of the multi-disciplinary nature of the study.

mass human immobilization, refining the link between human activities and changes in government restrictions. Not only will this determine the effect of the first phase of lockdown measures, but it will create a reference of seismic trends during the pandemic of which further studies can be conducted.

To understand the societal response to COVID-19 restrictions in the region, we need to ask two critical questions: first, *did seismic noise levels in the Halifax Peninsula change during the first COVID-19 lockdown;* and second, *is there a correlation between seismic trends and human activity?* Based on available reports from global studies (Xiao et al., 2020; Lecocq et al., 2020a; Piccinini et al., 2020; Poli et al., 2020), the population of the region (Statistics Canada, 2017), and the unique geographic elements of a growing coastal city (Boulos, 2016), mobility restrictions emplaced by the Government of Nova Scotia are predicted to have caused a seismic noise reduction of 20% from pre-pandemic levels in Halifax. Seismic trends in the region of frequencies

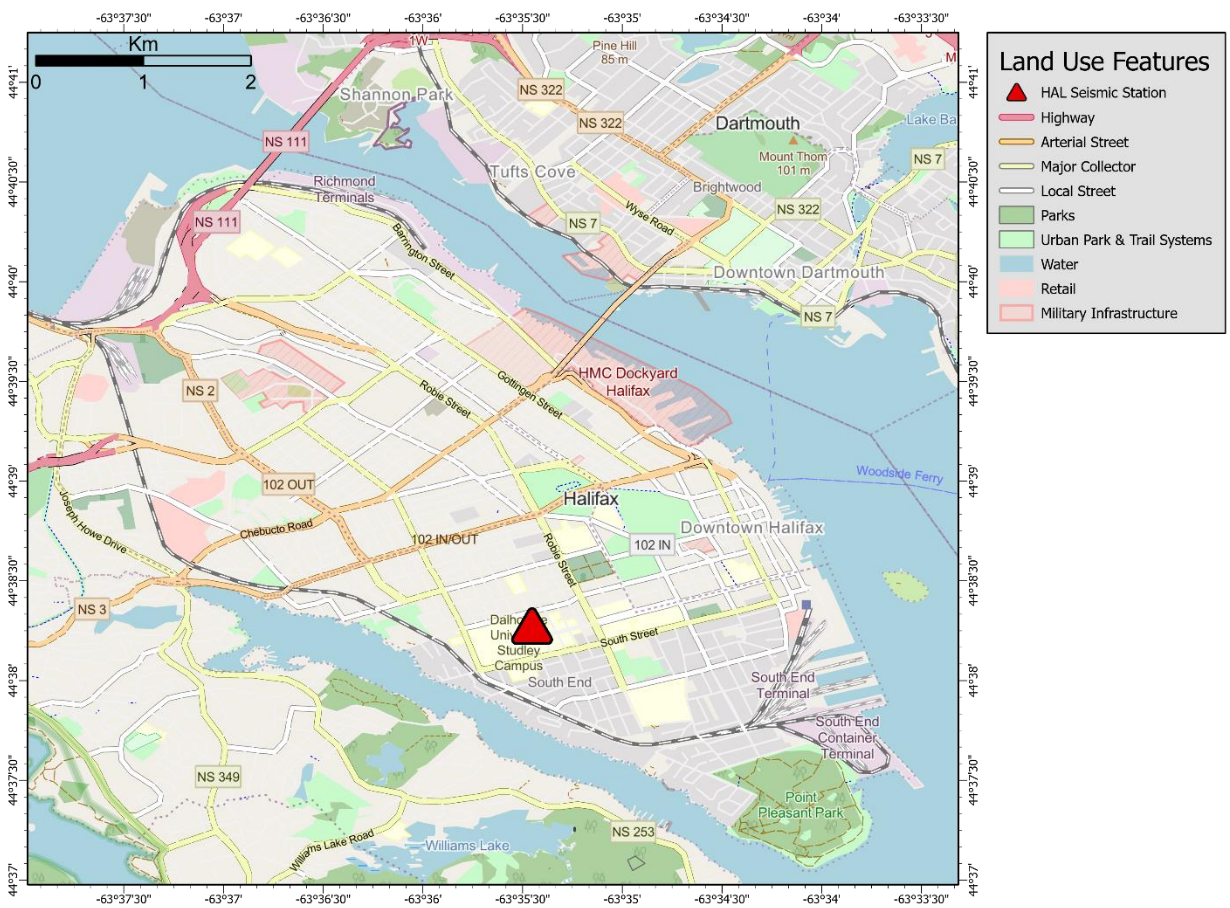

Figure 1.5. Street map of the Halifax Peninsula. Predicted sources of noise generated by human activity (regional and urban parks, roadways and local streets, retail stores and shopping centers, and military buildings) are identified. Map produced in ArcGIS Pro 2.7.3, projected in coordinate system WGS 1984 Web Mercator (auxiliary sphere). Sources: OpenStreetMap base map (ESRI, 2020); Street Centrelines shapefile (HRM Open Data, 2022).

above 1 Hz, generally representing cultural noise, are predicted to follow the ebb and flow of public health measures. Therefore, a reduction of seismic noise and cultural activity is predicted to follow activation of the initial lockdown. Additionally, seismic trends are predicted to correlate with anonymized public mobility and traffic data fluctuations.

The Halifax Peninsula has been selected as a study area to represent the trends of the Halifax region. It is home to 78.6% of Halifax residents (Statistics Canada, 2017) and is the economic hub of the province, therefore, it is expected to emphasize changes in bus, train, car, and foot traffic following pandemic-related restrictions. The urban study area (Figure 1.1) is closed off by Joseph Howe Drive as it transects the Halifax Peninsula from Mainland Halifax. Even the furthest extents of the peninsula are within a 4.63 km radius of the CN.HAL seismic station, constraining the study extent. The study area is limited by water bordering three sides of the study area, providing an ideal, and somewhat bounded environment to study cultural noise in the Halifax Peninsula. Seismic wave propagation and its velocities depend on the properties of the material it passes through, fluctuating as it moves through varying compositions, densities, and temperature and pressure conditions. Cultural noise is mainly consisted of high frequency surface waves, which are dominated by shear components and cannot travel through liquids or gases (e.g., water). Thus, cultural noise out of the study area should not significantly contribute to the waveform data.

This study ranges temporally between February 22, 2020, and April 22, 2020. A baseline of pre-pandemic seismic noise is established from the year prior (February 22-April 22, 2019), to provide a reference for comparison of seismic trends and human activities without a lockdown within a same seasonal period. To differentiate human activity from background noise, the frequency limits of the study are 1 Hz to 20 Hz (Xiao et al., 2020).

1.5 Summary of Approach

To provide a baseline for research, continuous seismic waveform data from the HAL seismic station, on the Studley Campus of Dalhousie University, is used to establish a seismic record for the Halifax Peninsula for a set period before pandemic-related restrictions began. The baseline data is then compared with seismic noise activity recorded during the initial lockdown measure instituted in Nova Scotia. This response will determine the overall effect of COVID-19 restrictions on seismic noise levels in the Halifax Peninsula. Trends within the data will also be compared with available mobility and traffic volume data. The results of this study will describe seismic trends, analyze variables for each segment, and provide observations of the data and results via visualization and discussion.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

This review will focus on the defining concept of cultural noise with a specific focus on the application of such to COVID-19 lockdown measures. It will discuss the signature of cultural noise and the correlation of high-frequency seismic noise with human activity related to public health mandates. Given the global nature of studies in the field of cultural noise, a variety of journals have been referenced including Science, Seismological Research Letters, Solid Earth, Geophysical Research Letters, Geophysical Journal International, New Scientist, Geophysics, PLOS One, Natural Hazards, Bulletin of the Seismological Society of America, and Earth, Planets and Space. Knowledge gaps concerning the study of cultural seismic noise in Atlantic Canada will be discussed, and partly addressed within this study.

2.2 The Signature of Cultural Noise

Seismic noise from anthropogenic sources has increased dramatically in the last few decades (Denolle and Nissen-Meyer, 2020). As populations, cities, and transportation networks grow, so does the amplitude of the noise (Shannon et al., 2015). The definition of ‘anthropogenic

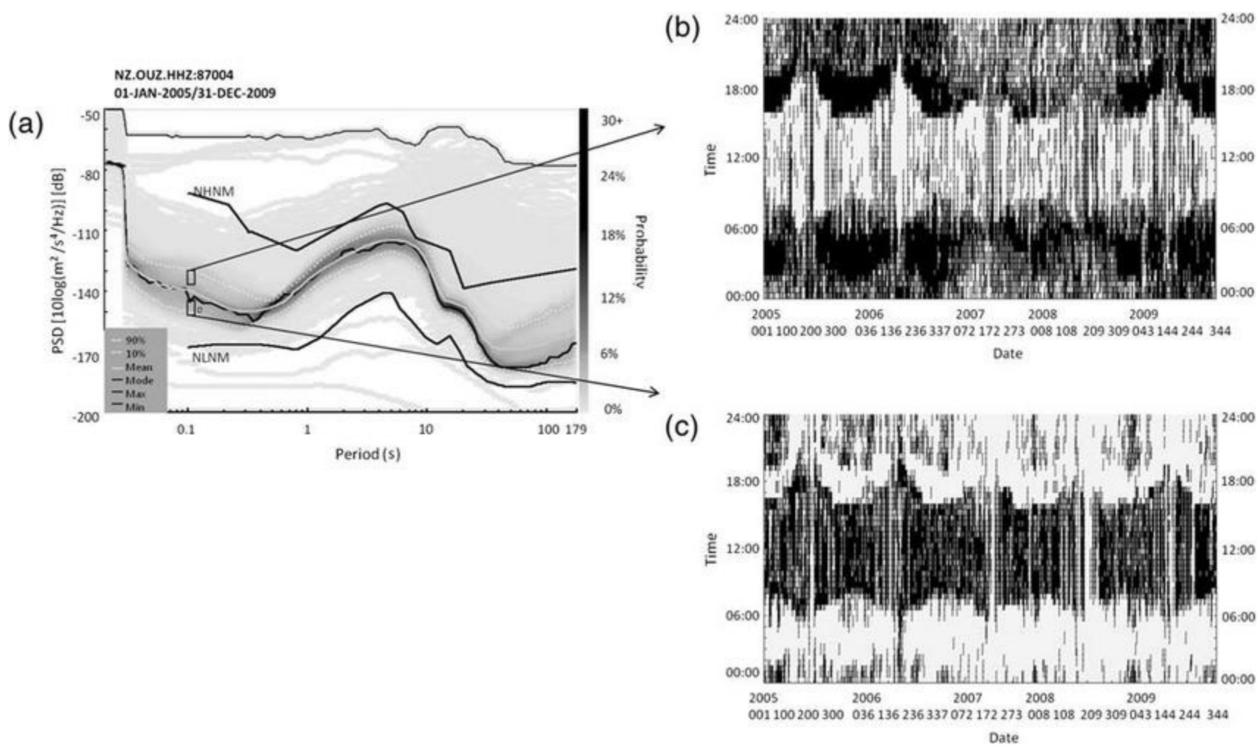

Figure 2.1 An example of diurnal variation in cultural noise energy. **A** (left): Black boxes indicate the diverging components of the cultural noise band, which are visualized in closer detail on the right (**B & C**, right). Image source: Rastin et al. (2012).

noise' can vary by discipline. In oceanography, biology, or environmental science, the term is used to describe noise pollution affecting wildlife or outdoor environments (Hildebrand, 2004; de Soto et al., 2013). In surveying, cultural noise is considered undesirable energy that interferes with the recorded signal (*Cultural Noise*, 2022). In seismology, seismic signals generated by anthropogenic sources are generally called cultural noise, which shows peak energy in high frequencies (>1 Hz). Cultural noise produces a distinct signature in the seismic record due to the diurnal periodicity of the signal (Hong et al., 2020; Sheen et al., 2009). Diurnal variations refer to the fluctuations that occur during the day and the variations from those values that are produced in the night. In cultural noise, the different seismic frequencies produced create a time-dependent distribution in the seismic record (Scafetta & Mazzarella, 2018). When visualized in a non-temporal capacity, diurnal variations produce a diverging signal at the same period (Figure 1.6).

2.3 Seismic Fluctuations Related to COVID-19 Lockdown Measures

Lockdown measures implemented globally have introduced a new application of seismic monitoring to patterns in anthropogenic activities. Variations in seismic noise have been documented globally (Lecocq et al., 2020a), in India (Somala, 2020; Roy et al., 2021; Pandey et al., 2020), China (Xiao et al., 2020), Japan (Yabe et al., 2020), Italy (Xiao et al., 2020; Cannata et al., 2021; Piccinini et al., 2020), Belgium (Gibney, 2020), South America (Maciel et al., 2021; Dias et al., 2020; Arroyo-Solórzano et al., 2021), Nepal (National Geographic, 2021), and in Canada (Kuponiyi & Kao, 2021; Lecocq et al., 2020a) (Figure 1.3). Changes in seismic noise are not provided in a standard unit across studies and can be provided in dB or percent. Available studies suggest that the frequency band in which the most impact occurred differs by location and its local environments (e.g., rural area or urban area).

Within a global study conducted by the 76 authors in 27 countries of Lecoq et al. (2020a), high-frequency seismic noise was analyzed and a reduction of up to 50% in select urban locations was observed. Similar findings were reported across several studies. Populated city centers often rendered significant noise reductions (Xiao et al., 2020; Cannata et al., 2021; Poli et al., 2020; Lecocq et al., 2020a; Kuponiyi & Kao, 2021; Arroyo-Solórzano et al., 2021), however some densely populated, highly active urban zones experienced a negligible decrease (Piccinini et al., 2020; Dupuis, 2020; Arroyo-Solórzano et al., 2021). Little or no change found is attributed to a lack of lockdown measures in the region, influence from major highway or road traffic, or the location of a station near a transit hub (Dupuis, 2020; Piccinini et al., 2020; Maciel et al., 2021). Decreases occurred progressively in large city centres (Piccinini et al., 2020; Maciel et al., 2021), and sharply in remote locations (Piccinini et al, 2020). For example, Italy's seismically active region utilized a dense network of seismic stations (Poli et al., 2020) to link noise reduction to the location of key activities: a 71% reduction was observed at a popular ski district, up to a 50% reduction was reported from the tourist city of Firenze, and only a moderate drop (-20%) was recorded at a station in Milan where the largest transit network in Italy continued to run (Piccinini et al., 2020). Remote stations and those installed in deep boreholes were likely to see little to no change (Gibney, 2020; Roy et al., 2021), yet a lockdown signature could still be identified in in select boreholes and remote areas (Piccinini et al., 2020; Dupuis, 2020; Cannata et al., 2021). Maciel et al. (2021) found that the spectra of cultural noise recorded from a seismic station is dependent on the noise sources within the vicinity, however, the character and type of noise would be constant into the lockdown.

2.4 Knowledge Gaps

Nationally, research on the effects of lockdown measures on cultural noise has been published on station data from major city centres in Western and Eastern Canada (Kuponiyi & Kao, 2021; Dupuis, 2020; Lecocq et al., 2020a). Studies have not yet been published from Maritime Canada (Nova Scotia, New Brunswick, Prince Edward Island) or Newfoundland and Labrador (Figure 1.3, red box) on the topic of cultural noise or lockdown-related seismic activity. In response, this study seeks to describe the impact of lockdown measures on human activity while producing a reference of cultural noise trends in the region.

2.5 Conclusion

Cultural noise is defined as seismic activity resulting from anthropogenic sources. The signature of seismic noise related to cultural activities is identified by its distinct diurnal behaviour in the seismic record at frequencies above 1 Hz. Global studies detected greater seismic reductions in locations with stricter lockdown mandates and identified progressive declines in seismic noise within highly populated areas versus sharp declines in more remote regions. The effect on the Halifax region is unknown as studies characterizing cultural noise in the province or describing the effects of public health measures on seismic activity has not been documented for Nova Scotia or the surrounding provinces.

CHAPTER 3: METHODOLOGY

3.1 Overview

This study seeks to describe the seismic trends of high frequency noise recorded in the Halifax Peninsula in the month prior, and following, the initial onset of public health measures in Nova Scotia. The Halifax Peninsula, which is the economic and transit hub of the province, is used as a proxy for activity in the Halifax region. The study analyzes cultural noise variations (between the frequency bands 1 to 20 Hz) before and after lockdown restrictions were emplaced to help curtail the spread of the disease in Halifax. A time series of continuous noise activity is generated from February 22 to April 22, 2020, marking March 22, 2020, as the “Lockdown Date”. Pre-lockdown and post-lockdown time series are produced from seismic data between February 22 to March 21, 2020, and March 22 to April 22, 2020, respectively. Then, a second time series is produced for the study period between February 22 to April 22, 2019, to define a reference for comparison in the same seasonal period of a year, and to aid in identifying potential seasonal changes by human activities that occur outside of a lockdown.

A seismic noise analysis is conducted to estimate the distribution of power within the frequency band using power spectral density (PSD) calculations. Standard plots are used to visualize probability density functions using period vs. amplitude. Components of the seismic noise spectrum are identified to aid in isolating the anthropogenic frequencies. Root mean square (RMS) displacement values are extracted from PSDs to produce an array of graphic visualizations of the seismic data in hourly and/or daily formats for both 2019 and 2020. The RMS in time domain, as used here, represents the square root of the integral of the power spectrum.

Various frequency bandpass filters between the range of 1 Hz to 20 Hz are evaluated to determine which filters produce non-seasonal, clear seismic change that best reflects the region’s cultural response to the lockdown measures. The displacement values produced from the waveform files (miniseed format) are used to quantify seismic noise variations in amplitude following the lockdown within selected frequency bands. Several daytime time range windows were tested; the 7:00AM to 9:00 PM time range window provided the best performance in this study for the CN.HAL station. With the frequency parameter selected, data analysis figures of noise distribution over the time of day and the displacement per date are used to identify trends.

The time series are compared to determine the overall effect of COVID-19 restrictions on cultural activity in the Halifax Peninsula. Cultural noise patterns in each time series are compared with anonymized public mobility and traffic data to characterize overall trends in human behaviour during this period.

3.2 Procedures

Seismic waveform and metadata were retrieved from the Canadian National Seismograph Network (CNSN) via the Incorporated Research Institution for Seismology (IRIS). The Data Management Center (DMC) of IRIS Data Services (IRISDMC) is an online data repository that provides open and free access to high-quality seismic data. Python code was used to automate the download of miniseed waveform data from a broadband seismic station (network: CN; station: HAL) from IRISDMC. Time series data are retrieved for the pre-lockdown period (February 22 to March 21, 2020) and post-lockdown period (March 22 to April 22, 2020), and for the reference period of February 22 to April 22, 2019. Waveforms are obtained in Coordinate Universal Time (UTC) and converted to the local time zone by the ObsPy UTCDateTime function. Three-component 100 Hz seismograms (HHE, HHZ, and HHN) retrieved from CN.HAL station are analyzed. HHE is a trace captured by the instrument vibrating in an east-west horizontal direction; HHN moves north-south horizontal; and HHZ indicates vertical sensor motion. To provide a complete picture of the wave motions captured at the HAL station, data captured from all three instruments are used.

Power spectral densities (PSDs) are computed to estimate the power distribution within the frequency bands using the plotting script by Thomas Lecocq (Belgian Observatory, open-source codes at https://github.com/ThomasLecocq/SeismoRMS). Welch's method (Solomon, 1991; Lecocq et al., 2020b) is used to estimate power spectra to convert the signals from the time domain to the frequency domain. First, each PSD is compiled from a 50% overlap of data to reduce noise in the signal (Xiao et al., 2020; Lecocq et al., 2020b). Data points are divided into 30-minute windows with overlapping 15-minute intervals (Lecocq et al., 2020b). Secondly, the time series are tapered with this window function (in time domain) at the beginning and end of the time series to improve frequency resolution and provide leakage protection (prevent a loss of data). Lastly, a common type of frequency analysis, Fourier transform, is applied to transition from the discrete time domain to the discrete frequency (Lecocq et al., 2020b; Vibration Analysis and Signal Processing in LabVIEW, 2020). This method can remove random noise corrupting the signals and isolate its frequency components.

In signal processing, the power of a signal as a function of frequency is commonly used (*Fourier Transforms - MATLAB & Simulink*, n.d.). The time series are converted into a periodogram (an estimate of the spectral density of a signal or the power of a signal) by squaring the amplitude of the signal's Fourier transform. The result is a PSD, which is used to identify amplitudes of seismic signals in specific bands and to characterize temporal changes in the seismic noise (Rakhman et al., 2020).

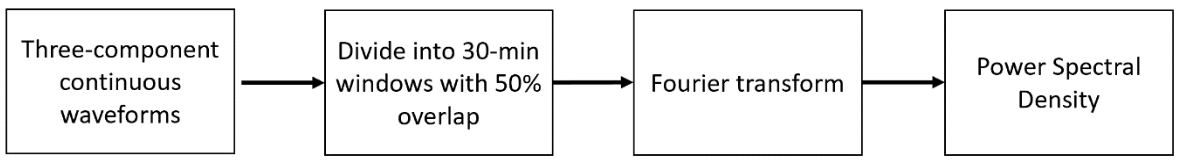

Figure 3.1. General workflow of PSD calculations using Welch's Method. Process is executed using the plotting script by Thomas Lecocq (Belgian Observatory, https://github.com/ThomasLecocq/SeismoRMS).

The probability density function is a method developed by McNamara & Boaz (2006) to display the PSD. It is graphed with period (in seconds) and frequency (in Hz) as the independent variables, and amplitude ($m^2/s^2/Hz$) as the dependent. The output of the probability density function will be used to identify the anthropogenic component of the seismic noise spectrum (Kuponiyi et al., 2021). Previous studies identified cultural noise change due to lockdown measures at varying frequencies (Lecocq et al., 2020; Dias et al., 2020; Cannata et al., 2020; Xiao et al., 2020). As period is inversely related to frequency (frequency = 1/period), the range of the anthropogenic component is identified and used to narrow the frequency bands of interest.

PSDs are processed to extract the root mean square (RMS) displacement values for various frequency bands between 1 Hz to 20 Hz, in a two-step calculation (Lecocq et al., 2020b). Power spectral amplitude (D_{pow}) is calculated using the PSD's acceleration values in decibel (A_{dB}) (Equation 1). Then, Parseval's identity is used to calculate the RMS of the time-domain displacement (d_{rms}) using a bandpass between f_{min} and f_{max} and D_{pow} (Equation 2).

$$D_{pow}\,(f) = \frac{A_{pow}(f)}{(2\pi f)^2} = \frac{10^{\left(\frac{A_{dB}\,(f)}{10}\right)}}{(2\pi f)^2} \qquad (1)$$

$$d_{rms}\,(t) = \sqrt{\int_{f_{min}}^{f_{max}} D_{pow}\,(f)df} \qquad (2)$$

The RMS displacement values are fed into several functions using ObsPy implementation to visualize noise variations. Plots, reflecting changes per day of week & time of day, are produced from three typical frequency bandpass filters (4-14 Hz, 10-14 Hz, 8-18 Hz). The plot outputs are analyzed to determine which bands are stable, i.e., seismic trends are more associated with the lockdown than the hourly and daily changes by the natural environment (e.g., wind, ocean wave, etc.). The displacement changes are used to quantify seismic noise variations (% change) within the selected frequency bands. The average of mean PSD outputs from HHZ, HHN, and HHE traces are calculated and compared to pre-lockdown and baseline (2019) values to determine the percent change for set date ranges. A summary of how each period is compared is provided in Table 3.1.

Plots are produced from median displacement values during those time windows and are used to isolate peaks and trends which may be suppressed in visualized data spanning the full 24-hour period. Final plotted data is visualized with 24-hour data and median values for each time range window. As with frequency bands, a time range window is chosen to best reflect the impact of the lockdown measures.

With the waveform data isolated to the most suitable frequency band and time range window for analysis, various data analysis figures are used to demonstrate noise variations over time. Outputs from the seismic noise analysis are characterized and compared to mobility reports and traffic volume data to identify trends in human activity. Mobility data is retrieved from

Table 3.1. Chart of ratio variables used to generate change (in percent) between 2019 and 2020 temporal periods. Calculations represent power fluctuations from previous periods within the same year, or between 2019 to 2020 in select frequency bandpass filters.

Year	**Date Range**	**Dates (inclusive)**	**Compared to**
2020	Month prior	February 22 to March 21, 2020	N/A
	Month after	March 22 to April 22, 2020	Month prior
	Week pre-lockdown	March 15 to March 21, 2020	N/A
	W_1	March 22 to March 28, 2020	Week pre-lockdown
	W_2	March 29 to April 4, 2020	Week pre-lockdown
	W_3	April 5 to April 11, 2020	Week pre-lockdown
	W_4	April 12 to April 18, 2020	Week pre-lockdown
2019	Month prior	February 22 to March 21, 2019	2020 Month prior
	Month after	March 22 to April 22, 2019	2020 Month after
	W_1	March 22 to March 28, 2019	March 22 to March 28, 2020
	W_2	March 29 to April 4, 2019	March 29 to April 4, 2020
	W_3	April 5 to April 11, 2019	April 5th to April 11, 2020
	W_4	April 12 to April 18, 2019	April 12 to April 18, 2020

Google's anonymous, aggregated data sets (https://www.google.com/covid19/mobility, last accessed March 2022), generated from Google users who have Location History settings activated (Overview - Community Mobility Reports, 2020). Google's COVID-19 Mobility reports are compiled using SQL syntax reflective of the requested parameters to query using BigQuery BI Engine (used for interactive data analysis) and Data Studio (a data visualization reporting tool). COVID-19 Mobility KPI reports on bridge traffic and public transit volumes are obtained from the Halifax Regional Municipality in partnership with Halifax Harbour Bridges, Downtown Halifax Business Commission, Develop Nova Scotia, and Dalhousie Transportation. Seismic noise trends are correlated to external data sources reflecting human activity during the temporal period, to assist in characterizing Halifax's response to the lockdown.

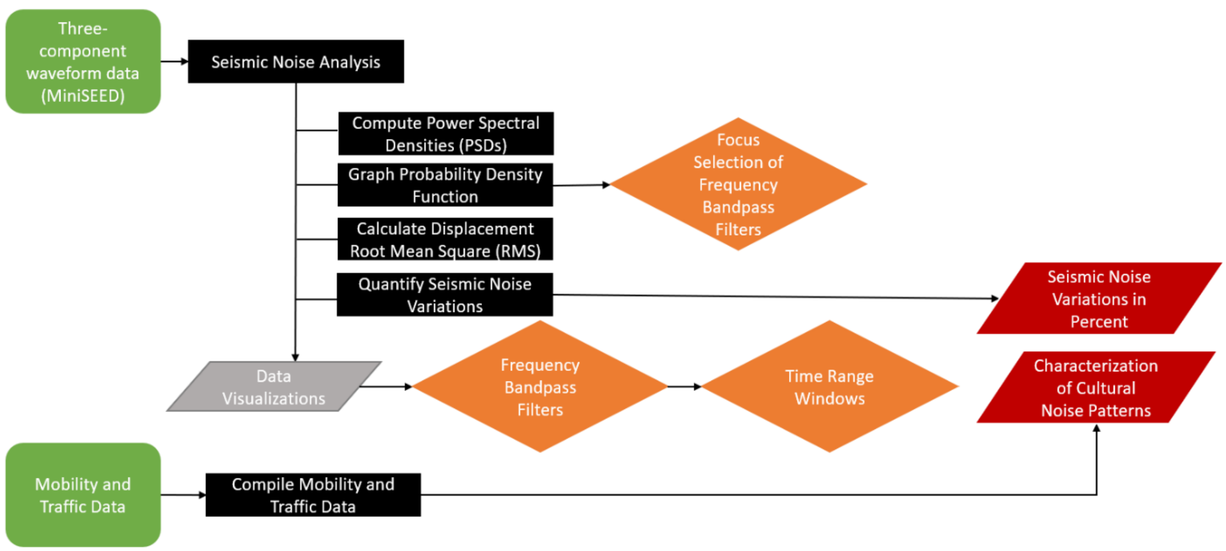

Figure 3.2. Workflow of study design. Chart summarizes a high-level view of the methods of the study. Green box indicates input, black rectangle indicates a process, orange diamond indicates a decision, red parallelograms indicate output. Outputs align to, and seek to partly answer, research questions.

3.3 Tools

Digital signal processing is conducted within a high-performance programming environment hosted by ACENET – Computer Canada, a CentOS 7 high-performance computer cluster installed at Memorial University. Within this project, eight nodes (purchased by Dalhousie Quake Group), each containing 40 cores, with 6 x 32GB and 6 x 16GB DIMMs for a total of 288GB of memory per node are available for job scheduling. The Project Space filesystem is engaged for processing and file management. Termius, an SSH client, is used to manage the virtual environment. Globus Connect is used for the transfer of research data between systems. For high volume modifications (adjusting graph outputs, etc. in Jupyter Notebook), PowerShell Prompt, PyCharm, and Jupyter Notebook are used on PC with Anaconda Individual Edition, Windows 64-bit distribution. Python 3.9.6 with required dependencies (ObsPy, NumPy, Matplotlib, Jupyter Notebook, pandas, tqdm) were loaded into environments on Siku and Anaconda.

3.4 Limitations and Reliability

Expansion of the study to include additional seismic stations in the region could enhance the visibility, and reliability, of patterns within the data, and allow interpretations to include a comparison of neighbouring (possibly, similar sociological) regions (Nimiya et al., 2021; Xiao et al., 2020). CN.HAL is one of three federal seismograph stations in Nova Scotia, and the sole federal seismograph station within the Halifax Regional Municipality. This study concentrates on the characterization of cultural noise fluctuations in Halifax, therefore, data analysis within this study is restricted to recordings obtained from CN.HAL.

The data itself holds limitations within the calculations, as the trace obtained from the HHE component for the 2020 temporal period contained only 5797 out of 5845 segments (data loss of 49 segments). The small fraction of waveforms is not available to the study may be a result of a power outage or maintenance (white bars within Figure 4.3 indicate a lack of data).

The Halifax Peninsula acts as a central transportation hub for commercial and commuter activities, including public transit, long-distance trains, the largest shipyard in Canada, and an 8,000-foot container terminal (*South End Container Terminal (PSA Halifax),* 2016). Although a reduction in activity is expected across all business and non-business activities in the region in response to lockdown measures, any continuance, or increase, in activity on the Halifax Peninsula may inhibit the reliability of the seismic noise signature extracted from the data. In this study, mobility and traffic data are analyzed in conjunction with seismic noise to better characterize fluctuations, or a lack thereof.

Construction activity in Halifax increased by 5.5% from the year prior, and construction investment increased by 11% (only 15.3% of the 11% was residential). (*Nova Scotia Department of Finance - Statistics*, 2021). The increase in construction during the pandemic's lockdown measures could result in a lower net change in seismic noise and may reduce the reliability of the data. To mitigate these limitations, isolating frequencies and noise signatures associated with each activity (either prior to study, or on an ongoing basis) could allow for their specific influence to be quantified within the data. Facilities Management at Dalhousie University was queried to determine if any construction projects or maintenance were ongoing at the university during the study period, to correlate with peaks within the seismic data, however, records were not available. In this study, daily displacements are calculated from median PSDs to disregard skews within the data caused by noise sources unrelated to the study, such as construction or tectonic activity (Nimiya et al., 2021).

A substantial benefit of comparing trends in human activity year-over-year is the ability to identify seasonal patterns. Removing seasonality from the trends observed within the data would allow fluctuations pertaining to lockdown measures to be more clearly observed. Google's mobility data poses several limitations. Public access to the data is restricted to February 15, 2020, onward, thereby precluding its inclusion within the study and limiting the ability to identify seasonal trends from mobility reports. Additionally, data from this source is restricted to people in Halifax with Location Settings activated, and who carry their phone with them into stores, restaurants, or into parks. As a result, a bias exists within data which likely projects into how the visualized data is interpreted.

Bridge and pedestrian traffic data is available to the public on the Halifax COVID-19 Mobility website for the day of, and the aggregated data is reported annually in simplified figures. As a result, limitations exist in the use and manipulation of this data alongside seismic trends.

CHAPTER 4: RESULTS AND DISCUSSION

The results of this study are presented in three stages. The first stems from PSD calculations and their quantified and/or visual changes over time. It displays outputs from the test period (February 22 to April 22, 2020), including probability density function results, change in seismic power per frequency band (Table 4.1 and 4.2), and temporal visualizations of seismic noise change over time (Figure 4.2 to 4.7) which are often segmented into pre- and post-lockdown periods. The second provides a comparison of 2019 to 2020 time series data, with temporal visualizations of seismic change over time for 2019 found in Figures 4.8 to 4.9. The final stage presents mobility and traffic data and patterns significant to this study.

4.1. Seismic Noise Analysis of 2020 Time Series

A two-month seismic record (February 22 to April 22, 2020) was compiled from CN.HAL data to characterize the effect of the initial set of COVID-19 restrictions on seismic noise levels on the Halifax Peninsula. A probability density function was produced to isolate the components of the seismic noise spectrum (Figure 4.1). Due to increased cultural noise at

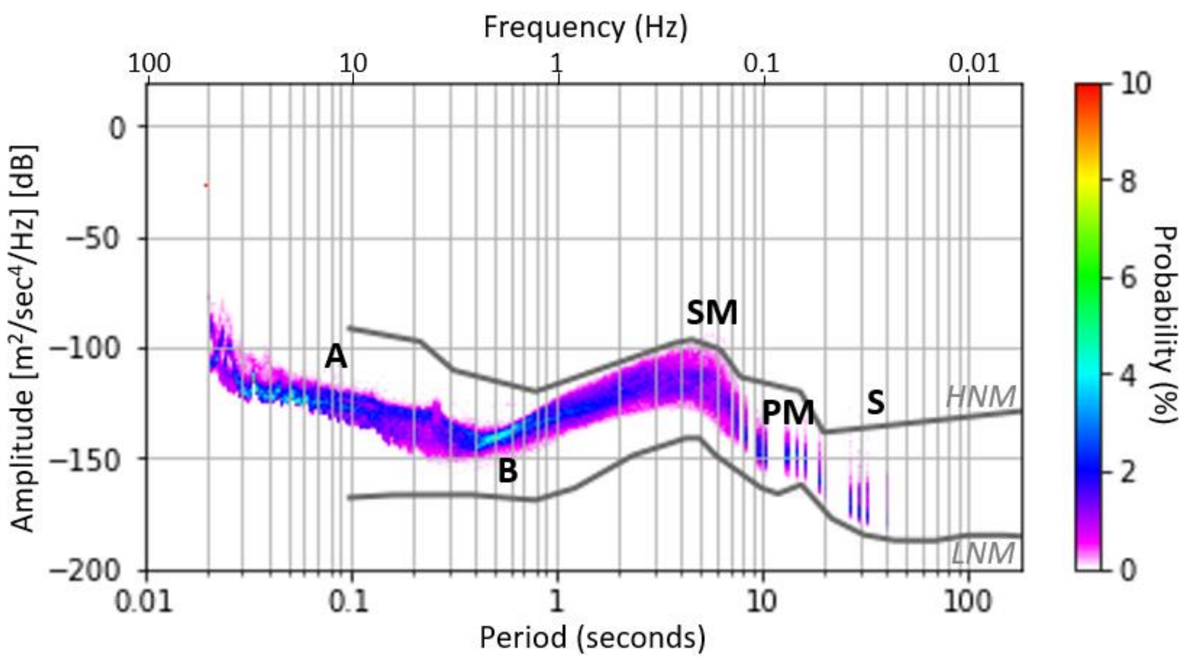

Figure 4.1. Probability density function of seismic noise captured by the CN.HAL seismic station for February 22, to April 22, 2020. Function was constructed with 5845 segments. The probability of occurrence of the given power (shown in amplitude) at a particular period is represented by colour, shown on right. Grey lines bound the high-noise (HNM) and low-noise (LNM) extents of the signals according to models defined in Peterson (1993). The components of the seismic noise spectrum are identified with letters: A, anthropogenic noise; B, body waves, SM, secondary microseism; PM, primary microseism; S, surface waves. Body waves and surface waves (which dominate the spectrum above 1 second) are typically associated with earthquake activity.

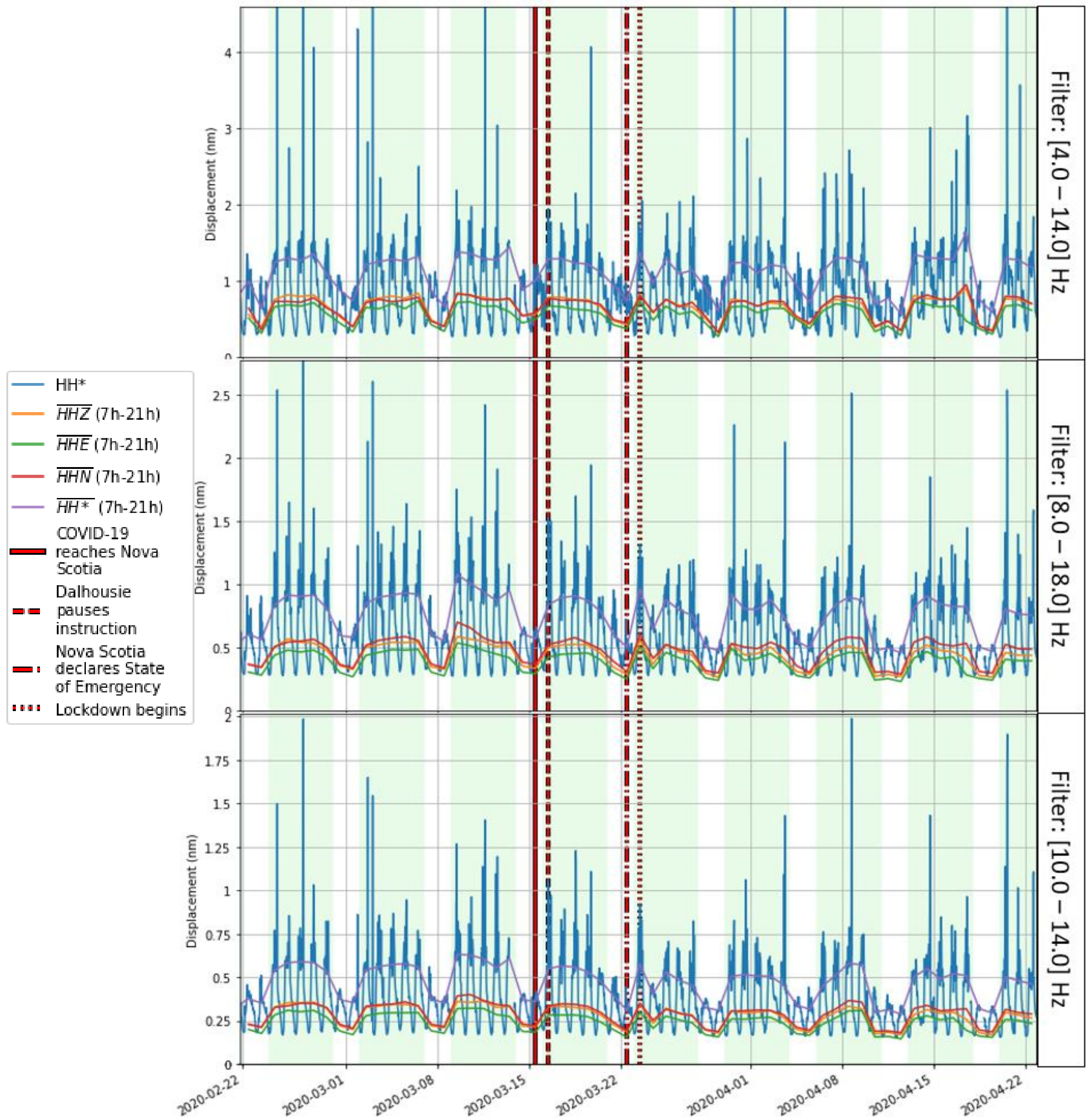

Figure 4.2. Temporal variations of PSD for pre- and post-lockdown months in 2020. Significant dates are shown in red bands. The start of public health mandates (March 22, 2020) is denoted in short red dashes (final vertical red bar). Normal business days are shown in green. Mean displacement values (nm) from HHZ, HHE, and HHN traces are in blue (HH*). Mean horizontal and vertical traces are shown in orange, green, and red thin lines. Purple line (mean HH*) provides a smoothened trend line from median HH* values. Note the variations in y-limits; although adjustments were made to include the peaks within graphs, in some cases peaks are truncated by the extent of the graph to preserve the visual representation of the bulk of the data points.

periods >0.3 seconds, the highest probability power levels (HNM) are significantly higher than the lowest probability model (LNM). Body waves and microseisms dominate the spectrum

TABLE 4.1. Signal variations in pre- and post-lockdown phases in 2020 within selected frequency bandpass filters.

Date Range	Relation to Lockdown	$\overline{4-14\text{ Hz}}$	Change	$\overline{8-18\text{ Hz}}$	Change	$\overline{10-14\text{ Hz}}$	Change
Month	Prior	4.96E-10	-1.74%	3.66E-10	-10.70%	2.30E-10	-11.85%
	Following	4.85E-10		3.28E-10		2.04E-10	
Week	Prior	4.93E-10	-5.27%	3.52E-10	-7.95%	2.22E-10	-10.35%
	Following	4.72E-10		3.24E-10		2.02E-10	

from 0.2 – 20 seconds. Ocean interactions in coastal waters are typically responsible for generating primary and secondary microseisms (Kuponiyi et al, 2021), and are characterized by double peaks (McNamara and Buland, 2004; Peterson, 1993). Microseisms, primary and secondary, peak in the spectrum at 10-12 seconds and 5 seconds, respectively (Figure 4.1). Surface waves, which typically generate longer period waves at above 20 seconds (McNamara and Buland, 2004), show few waves in the spectrum due to filtering of low frequency components. Coinciding with findings from Somala (2020), the anthropogenic noise component (denoted with 'A') is in the high-frequency range (>10 Hz). Cultural activity exhibits a typical diurnal pattern (Rastin et al., 2012), and is visible around ~0.1 seconds/10 Hz. Frequency bandpass filters of interest were narrowed to signals within the vicinity of 10 Hz. To capture fluctuations in seismic noise related to human activities (typical range for cultural noise: 1 – 20 Hz), PSDs were generated for three typical frequency bandpass filters: 4-14 Hz, 10-14 Hz, and 8-18 Hz. PSDs were held within the memory of the program to calculate RMS displacement values. Plots visualizing displacement values (nm) over the test period display a range of spectral and temporal patterns (Figure 4.2). Signal variations between pre- and post-lockdown phases (month and week calculations) are quantified within Table 4.1. Power levels in each of the four weeks following the lockdown date are compared to pre-lockdown seismic power levels and reported in percent change (Table 4.2). A moderate decrease in seismic power is visible in all bands, but lacks the sharp decrease observed in studies for major cities in Canada and globally (Figure 1.3, Table 4.2). A progressive decline is observed in the power spectrums from the first case of COVID-19 reported in Nova Scotia (March 15, 2020) to the province declaring a state of emergency (March 22, 2020). The immediate impact level of the lockdown measures on seismic levels depends on the frequency bandpass filter applied, as they are not equal in the type and amount of cultural noise captured.

TABLE 4.2 Seismic power fluctuations in the weeks following lockdown measures vs. pre-lockdown noise in selected frequency bandpass filters, shown in percent.

Frequency Band	**Week No.**	**Mean Displacement (nm)**	**Change (%)**
4-14 Hz	W_1	4.74E-10	-5.46%
	W_2	4.83E-10	-2.33%
	W_3	4.70E-10	-5.32%
	W_4	5.03E-10	1.25%
8-18 Hz	W_1	3.27E-10	-8.05%
	W_2	3.36E-10	-4.94%
	W_3	3.19E-10	-10.62%
	W_4	3.31E-10	-7.01%
10-14 Hz	W_1	2.02E-10	-10.35%
	W_2	2.08E-10	-6.82%
	W_3	1.99E-10	-11.92%
	W_4	2.05E-10	-9.09%

reported in percent change (Table 4.2). A moderate decrease in seismic power is visible in all bands, but lacks the sharp decrease observed in studies for major cities in Canada and globally (Figure 1.3, Table 4.2). A progressive decline is observed in the power spectrums from the first case of COVID-19 reported in Nova Scotia (March 15, 2020) to the province declaring a state of emergency (March 22, 2020). The immediate impact level of the lockdown measures on seismic levels depends on the frequency bandpass filter applied, as they are not equal in the type and amount of cultural noise captured.

In the first month following the lockdown, an immediate reduction in seismic power of 11.85% was observed within the band 10-14 Hz. Comparatively, drops observed in bands 4-14 Hz and 8-18 Hz were -1.74% and -10.70%, respectively. A significant decrease is observed in all bands during the week following the lockdown. Signal variations between pre- and post-lockdown phases (month and week calculations) are quantified within Table 4.1. Power levels in each of the four weeks following the lockdown date are compared to pre-lockdown seismic power levels and reported in percent change (Table 4.2).

With the 4-14 Hz filter applied, mild, but visible, drops in power are observed. No peaks above 4 nanometers (nm) occur, a trend present at least once for each week in the month prior. The weekends of March 21-22nd and March 28-29th produced a higher rate of fluctuations (remaining below 1 nanometer) than viewed in the 8-18 Hz and 4-14 Hz bands. A rainstorm on March 20th was followed by an above average temperature of 10.2°C on March 21st; the day before lockdown measures were emplaced. March 28-29th saw similar temperatures of 10.1°C

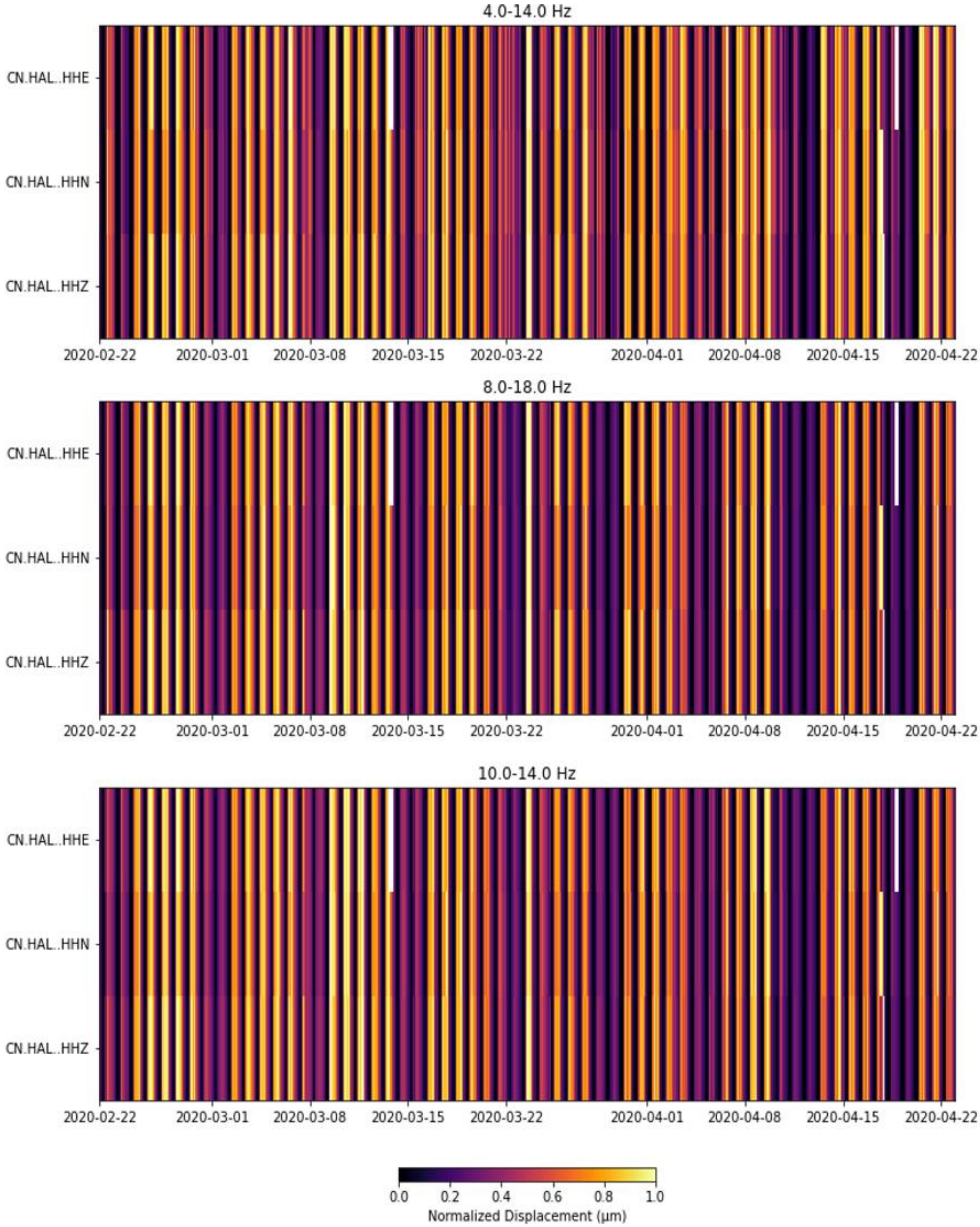

Figure 4.3. Colourmapped plot of normalized displacement (μm) over time. Three-component traces are shown in three bars for each frequency bandpass filter: HHE top, HHN middle, HHZ bottom. A clear increase in normalized displacement is visible in the day following lockdown measures (March 23, 2020). The start of the first public health measures in Halifax, March 22, 2020, is positioned in the center of the figures. White bands indicate a loss, or lack, of data.

and 11.1°C (precipitation and climate data was obtained via the Meteorological Service of Canada for the Halifax Windsor Park station, located on the peninsula 2.25 kilometers from CN.HAL). All three represent the highest temperatures recorded since December 15, 2019. These temperature variations would not directly impact the seismic record; the seismic signature of rain is found in frequencies above 80 Hz (Dean, 2017). However, human activity is likely to vary with changes in weather and produce changes in the cultural noise spectrum. The repeated fluctuations indicate at least several short periods of suppressed noise on both Saturday and Sunday, combined with periods of registered activity in the 4-10 Hz range. In the subsequent week (W_2), four weekdays peak above 2 nm, with Monday and Friday reaching above 4.5 nm. Still, on average, the power density is lower than pre-lockdown levels by 2.33% (Table 4.2). Week 3 (W_3) following the lockdown displays a moderate drop in seismic noise from pre-lockdown levels by 5.32%, -3.02% less than W_2 levels. Seismic power rebounded in W_4, exceeding pre-lockdown power by 1.25%. A colourmapped plot of normalized displacement values over time reveals that many of the trends existing in the pre-lockdown data continued after the lockdown. Bands of 0.0 – 0.2 normalized displacement (μm), unique to the post-lockdown period, are observed but not only exist but are more prominent within the 8-18 Hz and the 10-14 Hz bands.

With the 8-18 Hz filter applied, a more pronounced change in seismic power is observed (-10.70% in the month following). A clear, gradual decrease visible from early March to the beginning of April contrasts with the expected increase in human activity with the transition into warmer weather conditions. Week two (W_2) reflects a slight rebound. The Monday peak is also observed in the 4-14 Hz band but at a higher displacement. Power levels are ~0.65 nm displacement for this date in the 10-14 Hz band, indicating most of this noise registered in the 8-10 Hz band.

The 10-14 Hz band displayed the most consistent reduction in three out of the four weeks (slight rebound in W_2). In the week immediately following the lockdown, a 10.35% decrease was experienced. Like the 8-18 Hz band, the maximum reduction is reached in the third week (10-14 Hz band W_3: 11.92%). Several peaks observed in other bands were present in the 10-14 Hz filter, indicating many of the peaks registered at some frequency in the range of 10-14 Hz (the range shared by all three bands). The 10-14 Hz band saw the greatest reduction in seismic power on

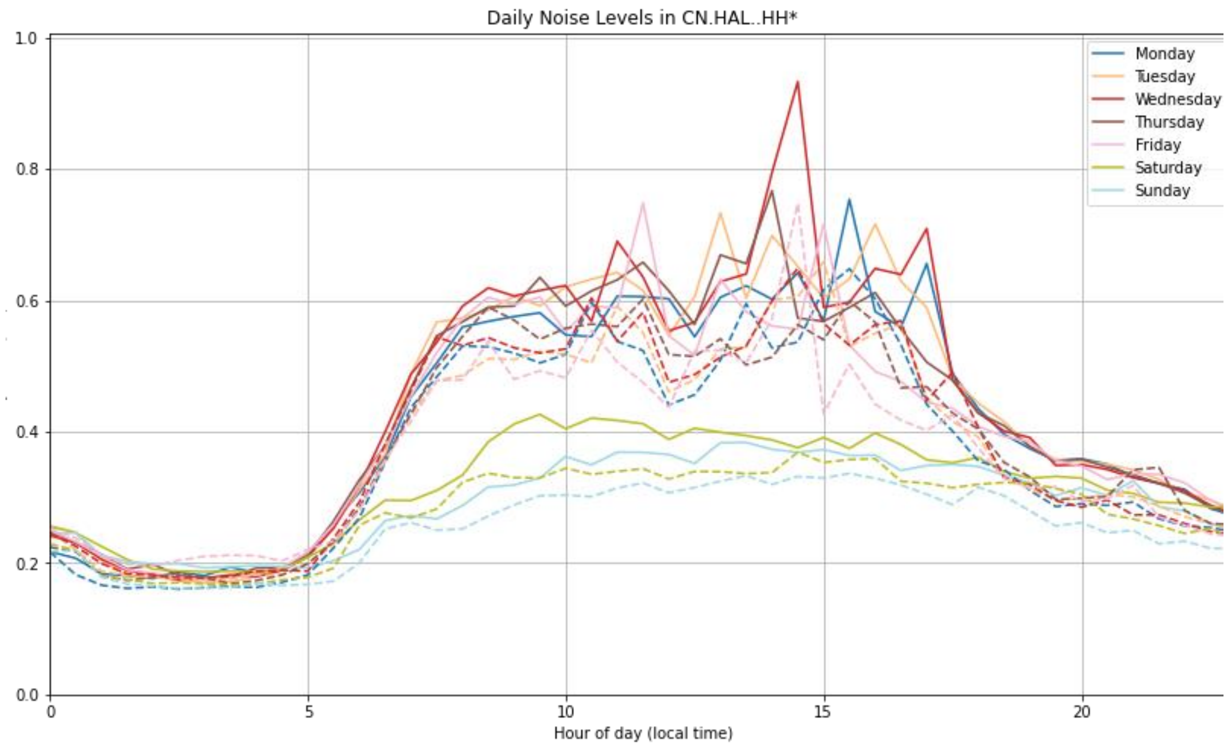

Figure 4.4. Radial map of hourly cultural noise distribution over time of day for February 22 to April 22, 2020. Daily median noise graphed by day (local time) vs. seismic power in amplitude. Median power levels, which exclude isolate peaks and outlier values, range from 0.2 to 0.5-0.6 nm displacement for pre- and post-lockdown power levels.

weekdays, visible by the increasingly wide purple bands (normalized displacement >0.2 µm) in Figure 4.3. The 10-14 Hz band exhibits a steady and distinct impact to the initial lockdown measures on the Halifax Peninsula. Therefore, in culmination of the seismic noise analysis on all three bands, the 10-14 Hz frequency bandpass filter best represents variations in cultural noise in Halifax. Accordingly, analysis and discussion of cultural noise within this study are centred on patterns and fluctuations within the 10-14 Hz range.

The rebound in seismic noise within the second week after lockdown (W_2) is a pattern observed in all three filters. This rebound was produced from peaks in the data on both Monday (March 30) and Friday (April 2) of that week. Major nearby construction projects resulted in traffic delays and road detours, which may have impacted the cultural noise spectrum (Shore Road Bridge Replacement and Paving Project, 2020; St. Margarets Bay Road - Traffic Delay, 2020).

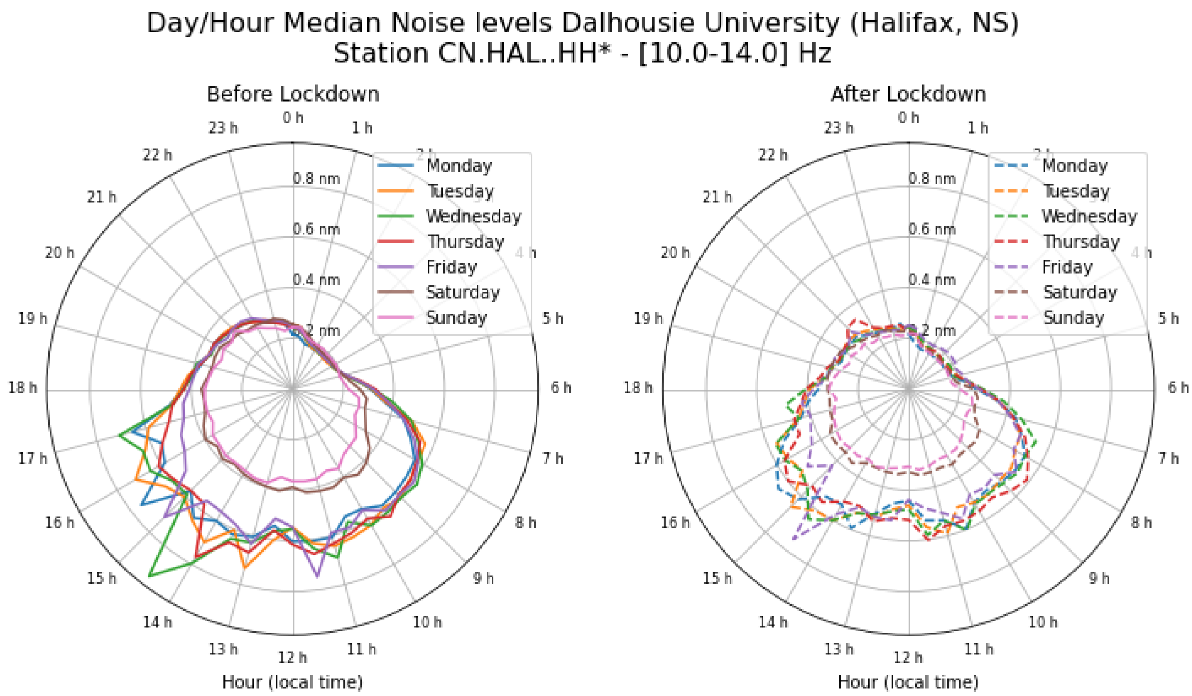

Figure 4.5. Plot of daily seismic noise levels in a frequency range of 10-14 Hz by day (local time) vs. seismic power in amplitude for February 22 to April 22, 2020. Pre-lockdown power levels are shown with a solid line, post-lockdown is displayed in dashed lines.

As with the high rate of fluctuations found in the 4-14 Hz band on certain weekends, weather possibly impacted cultural activity in W_2 due to temperature highs of 10.1°C and 11.1°C on Monday March 28th and Tuesday March 29th respectively, and a heavy rainfall of 45.2 mm on Friday April 2nd.

Daily noise levels by the hour (local time) are plotted against seismic power in amplitude (Figures 4.4 to 4.9). Median values are used to exclude outliers and visualize general daily noise trends in Figure 4.4. A moderate decrease is visible on all days, with patterns in activity continuing into the pandemic. Noise levels steadily increase from 5:00 AM on all days, equalizing around 10:00 AM. On regular business days, moderate to significant peaks are

Table 4.3. Signal variations during weekday versus weekend activity levels for pre- and post-lockdown phases in 2020 with the 10-14 Hz frequency band.

Weekday	Seismic Power	Change	Weekend	Seismic Power	Change
March 16 – 20 (Pre-lockdown)	2.40E-10	N/A	March 21 to 22 (Pre-lockdown)	1.73E-10	N/A
March 23 – 27	2.36E-10	-1.69%	March 28 to 29	1.60E-10	-8.51%
March 30 - April 4	2.17E-10	-10.24%	April 5-6	1.84E-10	5.64%
April 6 – April 10	2.16E-10	-10.74%	April 11-12	1.48E-10	-16.68%
April 13 – April 17	2.15E-10	-11.25%	April 18-19	1.51E-10	-14.54%

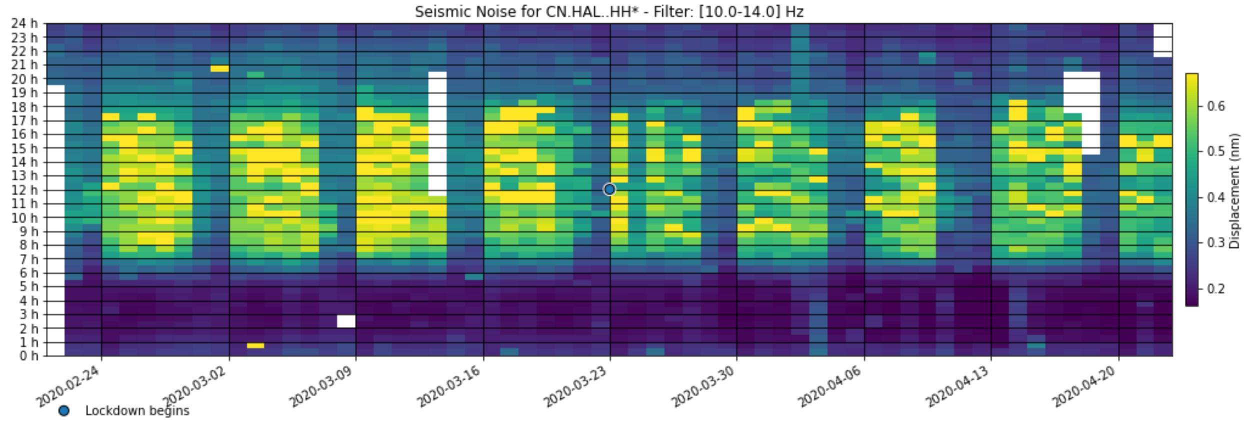

Figure 4.6 Grid map of daily noise levels blocked by day (local time) vs. displacement (nm) seismic noise for February 22 to April 22, 2020. Each block represents a one-hour period on a singular date. Each column is one day. Blue dot indicates the onset of lockdown measures. White bands indicate a loss, or lack, of data.

observed mid-day (12:00 PM to 2:30PM), and between 3:30 PM to 5:00 PM. A distinct change in seismic noise occurs from 6:00 AM to 7:00 AM and from 5:30PM to 6:00 PM (Figure 4.4). A gradual decrease is then observed until midnight. After the lockdown, weekend seismic noise levels mimic those during the week between 7:00 PM to 6:00 AM (Figure 4.4 and 4.5). High noise peaks occur on Monday, Tuesday, Wednesday, and Friday for both pre- and post-lockdown periods (Figure 4.5). A gradual replacement of high displacement values (yellow) by mid-level displacement values (green and blue) from March 22, 2020 onward demonstrate the increasing impact of lockdown measures on the Halifax area.

The most significant characteristic between the pre- and post-lockdown periods is the varying impact to the weekdays versus the weekends. Weekdays experienced a progressive, linear impact to cultural noise with time (Table 4.3). This pattern is visualized by increasingly wide purple bands indicating a normalized displacement of >0.2 µm in Figure 4.3. Rebounded seismic levels in W_2 stem from increased cultural activity on the weekend of April 5^{th} to 6^{th}. Peaks identified on Monday and Friday of W_2 did not impact the overall change enough to offset the steady decline of seismic power week-to-week. The weekend of April 11^{th} to 12^{th} registered a 16.68% reduction is seismic noise, a significant reduction from neighbouring weeks. A block of low normalized displacement is found over a 3-day period on April 10 – 12^{th} (Figure 4.7), possibly resulting from Good Friday/ Easter weekend festivities, holiday store hours, and the onset of additional COVID-19 restrictions (*What's open and closed this Easter weekend 2020 in the Halifax area*, 2020).

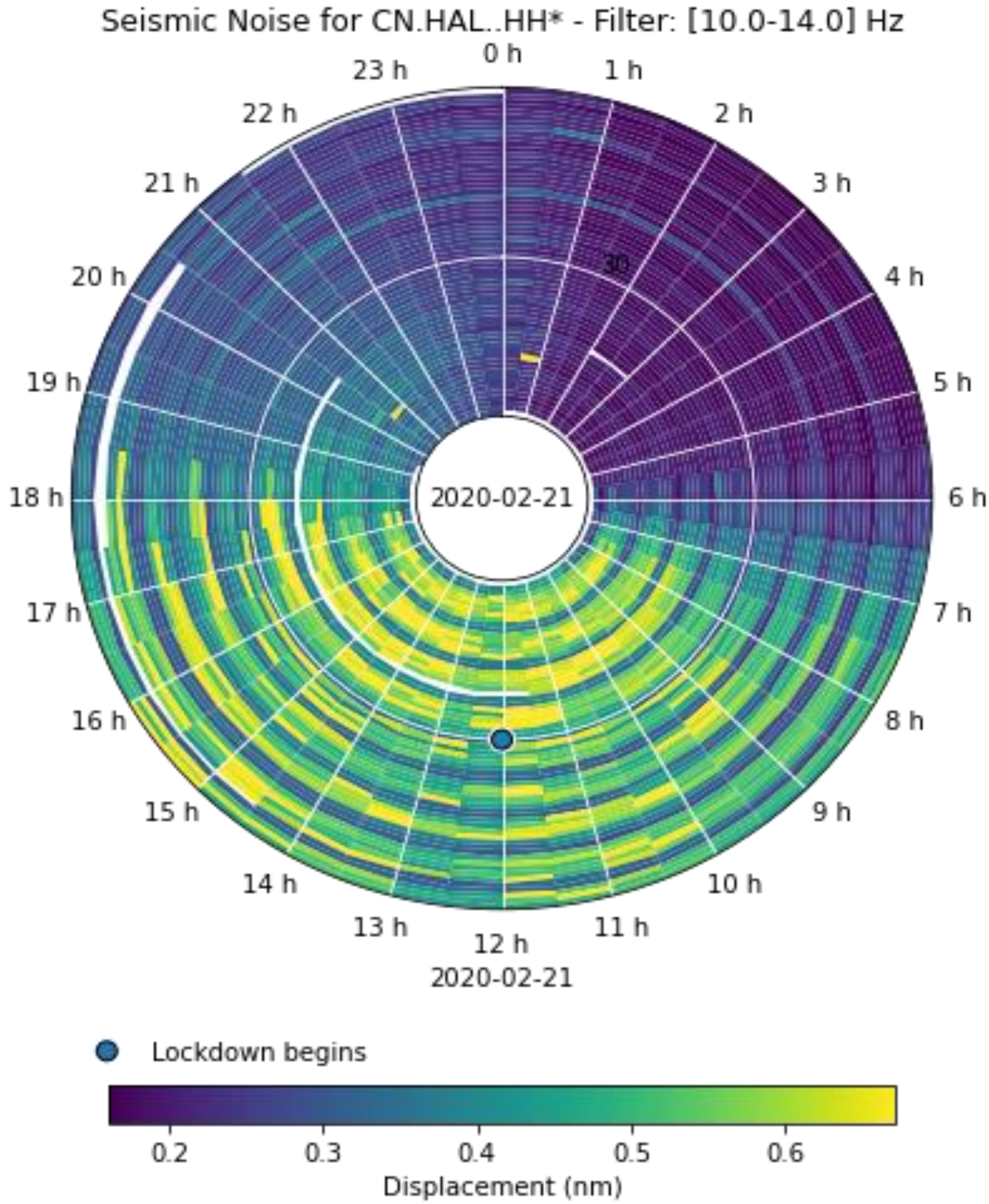

Figure 4.7. Colourmapped clock plot of daily noise levels from February 22, 2020 (center) to April 22, 2020 (outer rim). Each record of the disk represents one day. Blue dot indicates the onset of lockdown measures. White bands indicate a loss, or lack, of data.

4.2 Comparison of 2019 to the 2020 Time Series

A second time series is constructed for the period of February 22 to April 22, 2019, to produce a baseline for comparison of trends identified in the 2020 data. A time series plot visualizing displacement values (nm) over the baseline exhibits an increase in seismic activity from March to mid-April (Figure 4.8) which may correlate with the transition into spring weather. At warmer temperatures, the likelihood of outdoor activities increases. The Halifax Windsor Park weather station, located 2.25 kilometers from the CN.HAL station (direct line measurement produced in Google Earth Pro), reported a temperature increase from below freezing to >10°C by March 16th. Above zero temperatures continued through the month. A drop in seismic noise on April 3rd correlates with a spring storm where total precipitation reached 46.2 mm, suggesting less human activity in the region. A decrease occurs on April 17th, which may align with a cooler temperature of 3.9 degrees (~3°C difference from the surrounding dates).

Unlike the 2020 period, isolated peaks are not present, reducing the y-axis by 1.2 nm (to approximately half the displacement of many peaks in the 2020 signals). Instead, normal business days (Monday to Friday) register steady, repetitive signals. Therefore, the peaks are not seasonal and are unique to 2020. They potentially originate from intense anthropogenic activities such as the increased construction transpiring on the Halifax Peninsula at the time. However additional analyses would need to be conducted to restrict the frequency of the peaks and to

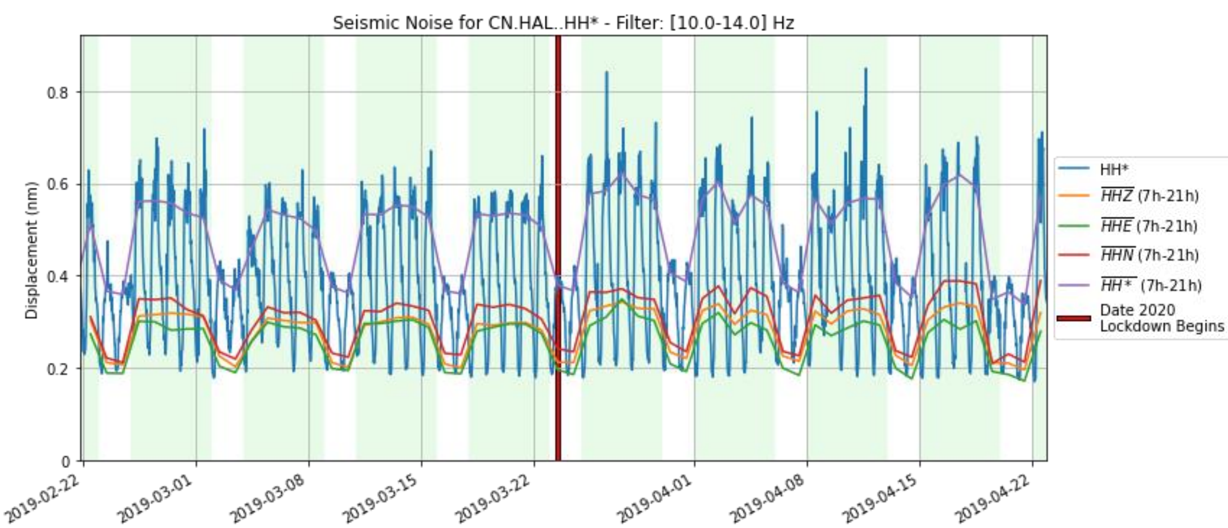

Figure 4.8. Temporal variations of PSD for the 2019 baseline period. The date of the initial lockdown order in 2020 is shown with a red band. Normal business days are shown in green. Mean displacement values (nm) from HHZ, HHE, and HHN traces are in blue (HH*). Mean horizontal and vertical traces are shown in orange, green, and red thin lines. Purple line (mean HH*) provides a smoothened trend line from median HH* values.

produce a polarization analysis to isolate the directionality of the signals (see Section 6.2). Additionally, a higher displacement (surges between 0.1 to 0.5 nm) occurs on Fridays in three out of the four weeks in March, which is not repeated in 2020. This suggests the human activity/activities producing these signals did not continue into the following year, and the impact is a direct result of lockdown measures.

Seismic power levels in 2019 and 2020 were quantified and compared on a weekly and monthly basis (Table 4.4). A marginal increase was observed in for the month following March 22nd, of 0.32%, with a higher, steady seismic noise level of 5.26 – 6.84% in three out of the four weeks (a reduction of -1.23% was observed in W_4). A grid map produced of noise levels per date and time in 2019 displays a clear trend of increasing seismic levels from early March to late April (Figure 4.9), which provides a stark contrast to the patterns exhibited in 2020 (Figure 4.6). Week 4 saw high displacement (0.50-0.60 nm) during the week, but those values were averaged and minimized by the extended weekend and the loss of data between 11:00 AM to 8:30 PM on April 17, 2019. In a comparison of the same dates in 2019 to 2020, the weeks following the

TABLE 4.4. Comparison of 2019 to 2020 power levels in the band 10-14 Hz. Power levels in weeks 1-4 (W_1 – W_4) for 2019 and 2020 are compared with seismic power from March 15th to 21st of the same year (representing the week prior to lockdown in 2020) to quantify the change in seismic power before and after the initial lockdown mandate.

Year	Period	Mean Displacement (nm)	Change (%)
2019	W_1	2.35E-10	6.84%
	W_2	2.31E-10	5.26%
	W_3	2.32E-10	5.65%
	W_4	2.16E-10	-1.23%
	Change in Month Following Lockdown	1.00E-12	0.32%
2020	W_1	2.02E-10	-10.35%
	W_2	2.08E-10	-6.82%
	W_3	1.99E-10	-11.92%
	W_4	2.05E-10	-9.09%
	Change in Month Following Lockdown	2.60E-11	-11.85%
Difference Between Years	W_1	3.26E-11	**17.19%**
	W_2	2.27E-11	**12.08%**
	W_3	3.26E-11	**17.57%**
	W_4	1.09E-11	**7.86%**
	Change in Month Following Lockdown	-2.50E-11	**12.17%**

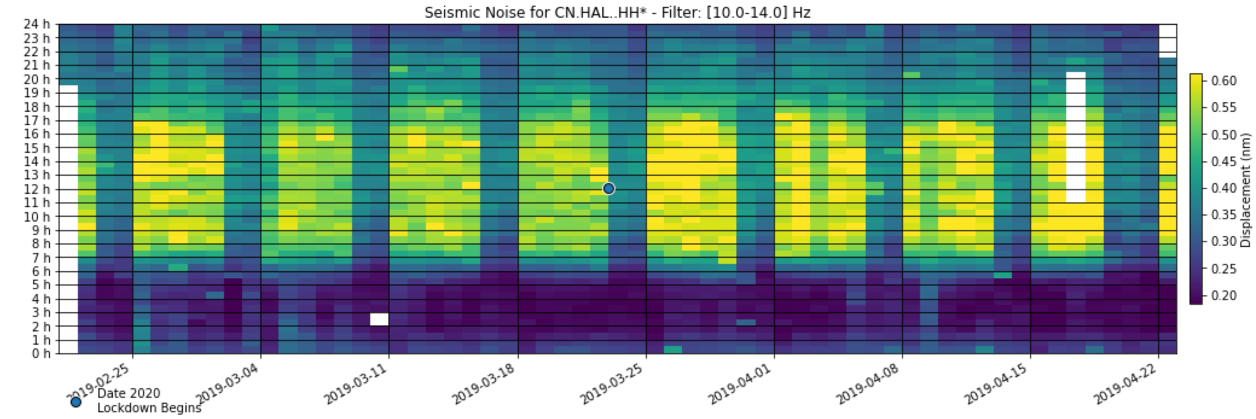

Figure 4.9 Grid map of daily noise levels in 2019 by day (local time) vs. displacement (nm). Seismic noise reflects variations in the frequency band 10-14 Hz registered at the CN.HAL station between February 22, to April 22, 2019.Each block represents a one-hour period on a singular date. Each column is one day. Blue dot indicates the onset of lockdown measures. White bands indicate a loss, or lack, of data.

lockdown date in 2019 were significantly higher by 7.86% to 17.57%. In the month following March 22nd, a reduction of 12.17% was found over 2019 noise levels.

A lower-than-normal reduction in noise occurs on the weekend preceding April 22nd in both 2019 and 2020 (Figure 4.8 and 4.9), suggesting the change in seismic power is unrelated to lockdown measures. However, the source of change in human activities may not be constant between the years. Easter weekend, including Good Friday, span the dates of April 17-19th in 2019 producing a ~20% decrease in cultural noise over the 3-day period from the prior weekend (Figure 4.8). This decrease is substantial in comparison to the overall impact of the COVID-19 restrictions (Table 4.4), although the value produced is likely much greater due to already diminished seismic levels in April. These finding align with research from Lecocq et al. (2020a) and Xiao et al. (2020) where they found significant impacts to noise levels during the annual cycles of holidays. In contrast, Good Friday and Easter fell on an earlier weekend in 2020 (April 10-12) and therefore the holiday did not impact the 2020 seismic record on these dates. Additionally, no entertainment events (due to increasing public health measures in the province) or impactful weather events were found to occur on the weekend of April 18-19, 2020. However, these dates signify the extent of a two-day deadly rampage (referred to as the Nova Scotia Massacre) which resulted in 22 deaths and fires set to 16 locations from a singular mass shooter. The gunman was reported to be travelling towards Halifax and residents were instructed to stay indoors. The evening of April 18, 2020 suffered a data loss in the seismic record around 8:00PM (Figure 4.6), when the rampage began. The reduction in seismic noise outside of this window still produced a visible impact on the seismic record of 14.54% - only a 2.14% difference from

Easter weekend. The influence of external factors, especially when they are not singular events and easily defined such as concerts, fireworks, or rush-hour, can be challenging to quantify in a meaningful way. Isolating the footprints of wide-spread cultural impacts, such as a mass shooting or pandemic, cannot be exact. Although efforts have been made to constrain the frequencies studied to cultural noise generated on the Halifax Peninsula, contamination of signals from outside the study extent is possible. However, characterizing the seismic patterns and the external factors impacting the cultural noise record allows for a reference point to be established.

4.3 Patterns in Mobility and Traffic Data

The final stage presents mobility and traffic data significant to noise generation within the Halifax region. Google Mobility Reports are used to obtain data on the movement of people in Halifax through various location categories. Reports are compiled from tracked location data

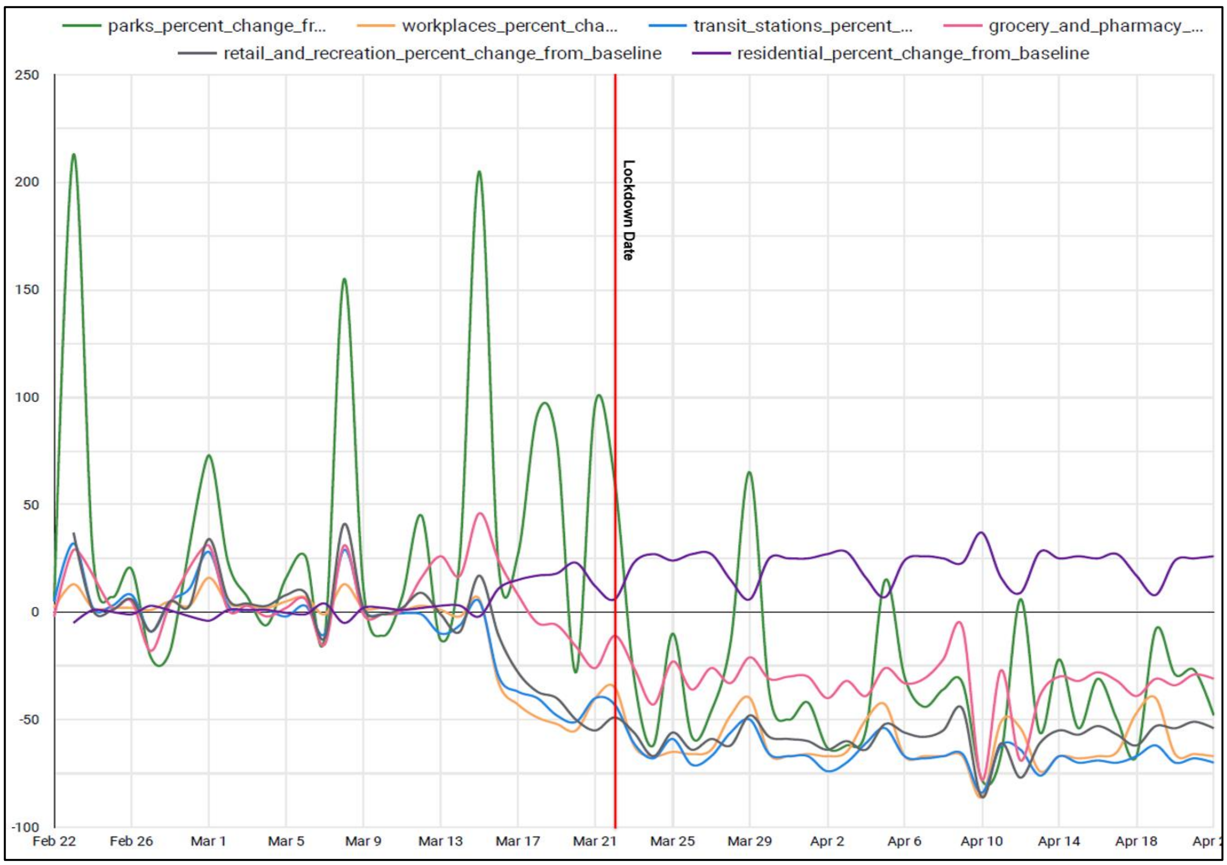

Figure 4.10. Google Mobility Report of human activity in the Halifax region between February 22 to April 22, 2020. Categories tracked include parks (urban and provincial), workplaces, transit stations, grocery and pharmacy, retail and recreation, and residential. Percent change is plotted over time. Percent change is calculated from a baseline compiled from the 5-week period January 3-February 6, 2020 for the Halifax Regional Municipality sub-region. Data were obtained on March 2, 2022.

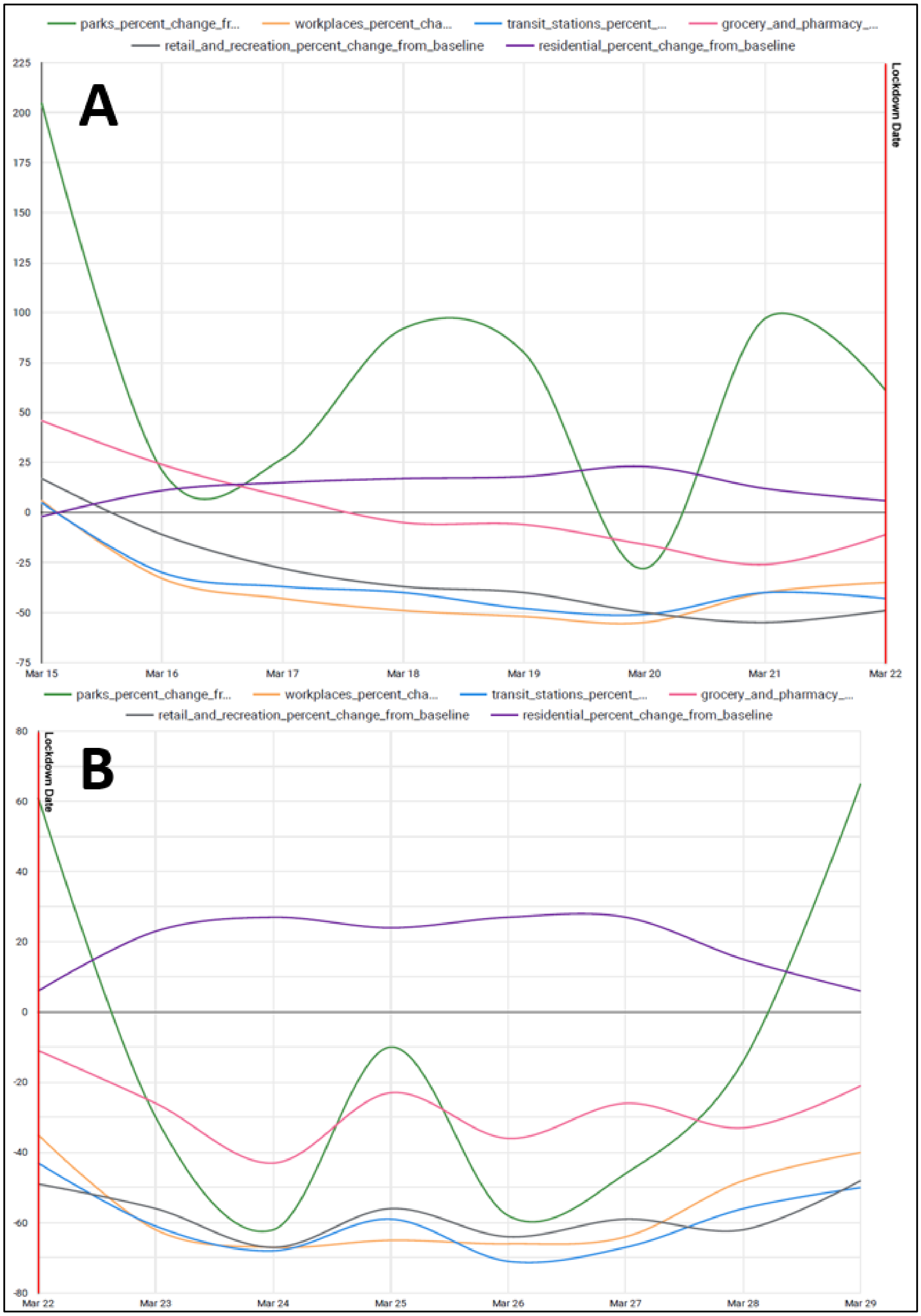

Figure 4.11. Google Mobility Report of human activity in Halifax for the week before and week after the lockdown. A (top): Pre-lockdown week March 15-March 22, 2020; B (bottom): post-lockdown week March 22-March 29, 2020. Note change in y-limit of each graph, , which has been auto-sized to the data range of each temporal period. Categories tracked include parks (urban and provincial), workplaces, transit stations, grocery and pharmacy, retail and recreation, and residential. Percent change is calculated from a baseline compiled from the 5-week period January 3-February 6, 2020 for Canada. Data were obtained on March 2, 2022.

on any mobile devices in the zone with Google Location History activated between February 22 to April 22, 2020 (Figure 4.10) and narrowed into the week prior and the week following lockdown measures (Figure 4.11). A stark decline in all non-residential categories follows the lockdown date. An average reduction of 70-80% from baseline data (compiled from the 5-week period January 3-February 6, 2020) is observed. Peaks in activity at park locations are common before and after the lockdown, however, the peaks in post-lockdown are 20-50% of the pre-lockdown surges. Activity in residential zones increased an average of 20-25% from pre-lockdown data beginning March 14th. Human activity at transit stations, workplaces, and retail/recreation location categories ebb and flows in sync with each other in both pre- and post-lockdown periods. Distinct drops in human activity occur on April 10th and April 18-19th in all categories except residential; these reductions are also found within the seismic data (Figure 4.2, 4.3, 4.6). A notable reduction in human activity on February 28th is not reflected within the 4-18 Hz range. A report was compiled of aggregated data for all of Canada between the same dates

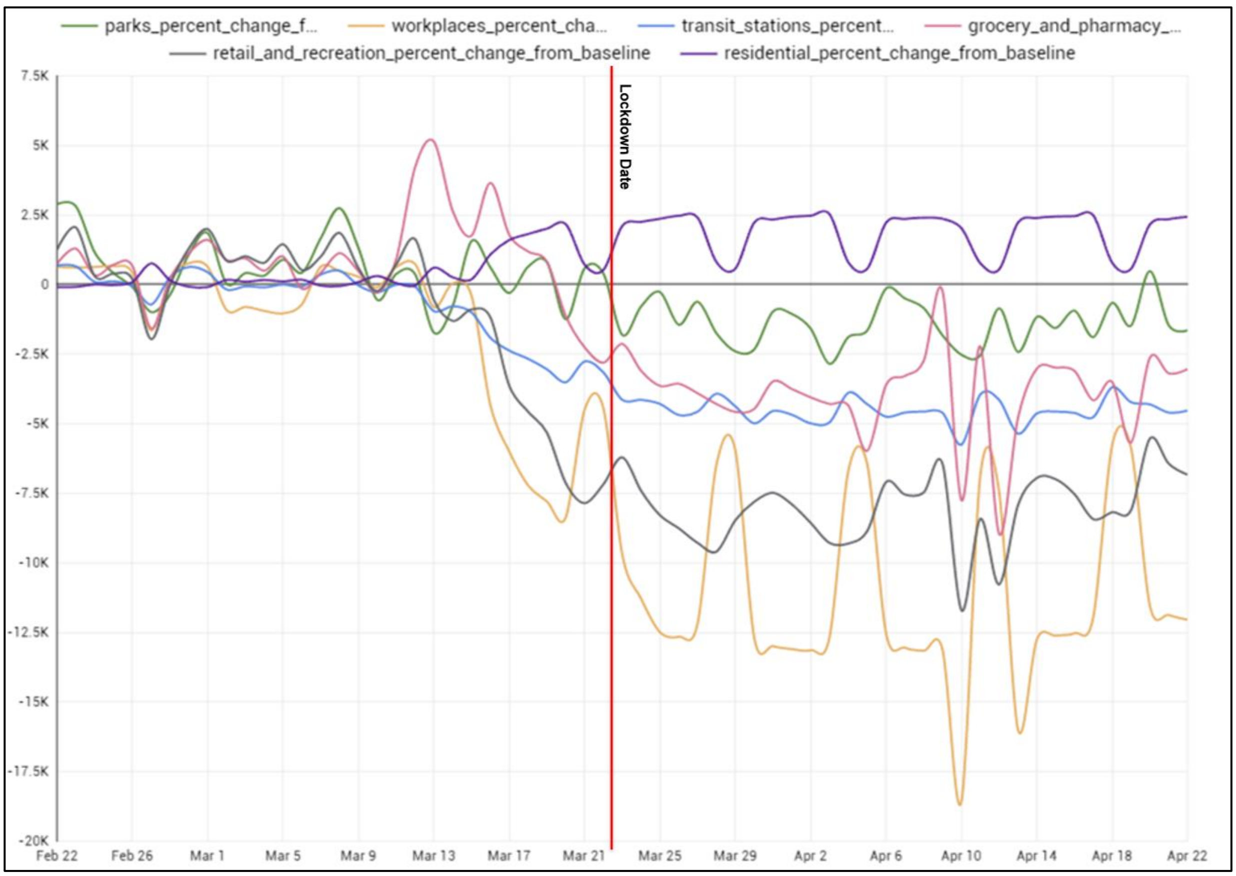

Figure 4.12. Google Mobility Report of human activity across Canada between February 22 to April 22, 2020. Categories tracked include parks (urban and provincial), workplaces, transit stations, grocery and pharmacy, retail and recreation, and residential. Percent change is calculated from a baseline compiled from the 5-week period January 3-February 6, 2020 for Canada. Data were obtained on March 2, 2022.

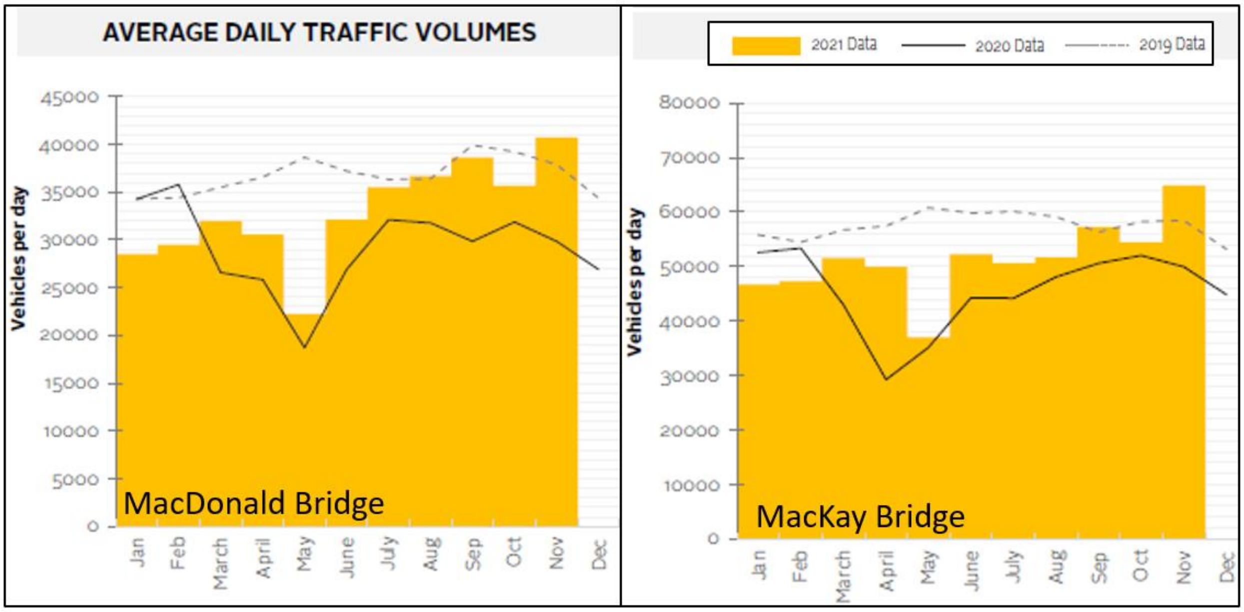

Figure 4.13. Average daily traffic volumes for MacDonald and MacKay bridges in Halifax. Graphs modified from COVID-19 Mobility Indicators, 2022.

(Figure 4.12). Nationally, the overall pattern of human activity found in the Halifax region from pre-lockdown to post-lockdown is mirrored. At both scales, a decline in activity reduces in the first few days to a low on February 28th. A moderate rise occurs on March 1st, March 8th, and March 12th, with a stronger peak occurring on March 14th in all non-residential categories. A surge in grocery and pharmacy is present at both scales on April 11th. The trend in residential activity across Canada parallels that of the Halifax region. Workplace and transit activity see a greater divergence Canada-wide, that suggests a less dependent relationship exists nationally between the two activities than in the Halifax region. Park activity sees fluctuations in activity across Canada but does not experience the same isolated peaks as Halifax, likely resulting from the averaging of aggregated data smoothening out individual peaks.

Bridge vehicle and public transit reports were obtained from the Halifax Harbour Bridge authority's Transportation Planning division (Figure 4.13). Both bridges link to the city of Dartmouth over a body of water; signal attenuation is expected to dampen the effect of sound from traffic directly on the bridge and its influence is not quantified. Instead, bridge traffic flow is used as indicator of human activities. MacDonald and MacKay bridges averaged ~35,000-40,000 and 50,000- 60,000 vehicles, respectively, per day in 2019. Daily traffic volumes lessened by ~15,000 vehicles per day for the February to April period in 2020. Increased traffic in May 2019 at both bridges was inverted in 2020 with a down surge of traffic. Ridership on public transit reduced by ~80% on weekdays from February to April on all three types of transit offered by the city: conventional buses, ferries, and Access-A-Bus paratransit services. Saturday ridership on conventional buses decreased by ~72.7%, ferry boardings by >90%, and Access-A-Bus by ~46.7%. Sunday ridership experienced similar effects of the pandemic, losing 75% of ridership on conventional buses, 87.5% on ferries, and 78.5% for Access-A-Bus services.

4.4 Study Potential

The characterization of cultural noise in response to lockdown measures is a new application of seismology to monitor human activities. To utilize this research in new ways, methods in the characterization of cultural noise, discussion of data and results, and the allocation of activities to specific frequencies, need to be established. This research provides a reference of cultural noise in the Halifax region (and Nova Scotia, at large) during the onset of the COVID-19 pandemic. The results of this study can be used to determine the efficacy of lockdown measures, especially if compared to seismic trends stemming from various public health measures and lockdown phases, and as a tool for establishing future mandated restrictions in the region. Additionally, it can be used as a reference for future studies to determine how well the province's largest city recovered over time from the impact of the pandemic. Broadly, seismic noise can be used to monitor changes in human activities, and to track gradual or sharp changes in the functioning of a city.

CHAPTER 5: CONCLUSIONS AND FURTHER WORK

5.1 Summary and Main Conclusions

Following the background study (Chapter 1) and a review of literature (Chapter 2), two main research questions were identified.

1. Did seismic noise levels in the Halifax Peninsula change during the first COVID-19 lockdown?
2. Is there a correlation between seismic trends and human activity?

This study provides a reference of the impact of the initial lockdown on cultural noise in the Halifax region, using the Halifax Peninsula as a study. A probability spectrum density narrowed the anthropogenic component of the seismic spectra to around 10 Hz. A seismic analysis found a reduction in mean seismic power was observed in the frequency bands 4-14 Hz, 10-14 Hz, and 8-18 Hz for a period of at least 4 weeks. The band 10-14 Hz displayed a progressive and distinct impact to the initial lockdown measures and was used to represent cultural noise within this study. In response to lockdown measures, cultural noise dampened by 11.85% from the month prior. In comparison to 2019, seismic power had dropped 17.19%. Rebounds in seismic power were correlated, but not linked, to improved weather conditions and major constructions projects. Anonymous mobility data narrowed to the subregion of Halifax showed an average reduction of 70-80% in all non-residential categories following the beginning of the lockdown. Park activity continued to show sharp fluctuations like in pre-lockdown trends, but at 80-50% of the original levels. Local public transit maintained service during the lockdown and a distinct pattern was identified between workplace, transit station, retail and recreation categories suggesting a shared impact on the seismic record, and possibly a reliance on public transit for work and shopping needs during the lockdown. Easter weekend and the Nova Scotia Massacre led to a reduction in seismic power comparative to the impact of initial lockdown measures in Halifax and produced a visible reduction in Google Mobility data. The noise data indicates that human activity did not decrease as much as reported in major cities, which displays how differently a municipality can react to lockdown conditions.

5.2 Recommendations for Further Work

As research was conducted for this study, several topics were identified which would be beneficial for future work. Firstly, the methods of this study can be extended to determine the effect of each phase of lockdowns in 2020 and 2021 during the heaviest impact of provincial health regulations. The established noise patterns could be used to determine if the trends coincide with government mandated restrictions to determine the lockdown efficacy of the study area. Additionally, these studies can be used as a reference point over time; for instance, how did Halifax rebound after the pandemic? Secondly, cultural noise patterns can also be compared with the number of active COVID-19 infections as reported from Nova Scotia's public health information system, Panorama (COVID-19: Data visualization, 2021). This type of analysis could be used to quantify the correlation between human mobility and fluctuations in COVID-19 infections. Thirdly, to more effectively correlate individual peaks and changes in cultural noise, a polarization analysis should be implemented to determine the directionality of the signals. Conducting a polarization analysis would add an ancillary layer to the results by narrowing the directionality of specific signals in specific bands to determine the direction of wave arrival. Used in combination with knowledge of specific noise sources, it could be used to isolate frequencies related to concerts, transportation, construction (if the source location was known and restricted to a time range), etc. Implementing this ancillary layer to cultural noise analysis will benefit the research field by allowing various noise sources to be better understood and identified in the seismic record.

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