Correlation between Ambient Seismic Noises and Economic Growth

Tae-Kyung Hong*[1], Jeongin Lee[1], Giha Lee[1], Junhyung Lee[1], and Seongjun Park[1]

Abstract

Human activity is a major source of high-frequency seismic noise. Long-term ambient seismic noise levels and their influencing factors are investigated. The diurnal seismic noise level in 5–15 Hz display high correlation with human activities including traffic and industrial operations that are related to economic conditions. The temporal noise-level variations are consistent among three components. Analysis with seismic noises in three consecutive months of each year enables us to estimate the noise levels without seasonal effects. The daytime seismic noise-level changes in major cities of 11 countries are assessed using the 3 month records for decades. The annual seismic noise levels present strong correlations with gross domestic product (GDP), particularly with manufacturing and industrial GDP. The seismic noise levels increase quickly with GDP in low-GDP regions but slowly in high-GDP regions. This is because high-GDP regions already have large volumes of existing noise-inducing sources and because added sources contribute weakly. The seismic noise levels increased by 14%–111% for 5–23 yr depending on the economic conditions. The correlation between ambient seismic noise level and economy growth is a global feature. The high-frequency noise level may be a proxy to present the economic condition. Economic growth affects the Earth environment in a wide range of aspects.

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Introduction

The Earth trembles due to various internal and external forces including microseismicity, environmental and meteorological effects (atmospheric pressure, wind speed, temperature, and precipitation), fluvial process, oceanic motions, tidal forces, tectonic forces, and human activity (Burtin *et al.*, 2008; Hsu *et al.*, 2011; De Angelis and Bodin, 2012; Schmandt *et al.*, 2013; Díaz *et al.*, 2014; Barrière *et al.*, 2015; Larose *et al.*, 2015; Amoruso *et al.*, 2017). Here, the human activity is a primary component in the development of daytime high-frequency ambient noises (Bonnefoy-Claudet *et al.*, 2006; Groos and Ritter, 2009; Havskov and Alguacil, 2016).

It is noteworthy that noise-inducing sources have their own effective frequency ranges. The anthropogenic (cultural) sources produce noises at frequencies greater than 1 Hz (Larose *et al.*, 2015; Havskov and Alguacil, 2016). On the other hand, major earthquakes and tectonic forces produce seismic energy dominant at frequencies less than ~3 Hz. Seismic noises from oceanic waves, tidal forces, and large-scale meteorological effects are dominant at lower frequencies of <0.5 Hz (Gutenberg, 1958; Asten, 1978; Bonnefoy-Claudet *et al.*, 2006). River-stream hydrodynamics generate seismic noises at frequencies >1 Hz (Burtin *et al.*, 2008; Gimbert *et al.*, 2014). The seismic noises from bed-load transport in rivers are rich at frequencies of 30–35 Hz (Barrière *et al.*, 2015).

Anthropogenic noise-inducing sources include urbanization (e.g., traffic, construction, and cultural activity), industrial operations, and mining (Groos and Ritter, 2009; Larose *et al.*, 2015; Riahi and Gerstoft, 2015). In particular, vehicle-related (traffic) seismic noises are dominant at 5–40 Hz (Coward *et al.*, 2003; Fuchs *et al.*, 2018). Machinery operation with electrical motors and gearboxes produces narrowband sinusoidal energy at frequencies of 1–50 Hz (Plesinger and Wielandt, 1974; Bokelmann and Baisch, 1999; Kar and Mohanty, 2006; Groos and Ritter, 2009). Anthropogenic noises are typically stronger in daytime and on working days than in nighttime and on weekends (Groos and Ritter, 2009; Díaz, 2016). In addition, the seismic noise level may vary by season and region (McNamara and Buland, 2004; Burtin *et al.*, 2008).

The global economy has grown consistently at a rate of 3%–4% in the last decade, which has accompanied increasing industrial operations. In addition, the global population is increasing. The economic growth and population increase affect the Earth environment in a variety of aspects, including urbanization and environmental pollution. The noise levels may be dependent on the strengths and distances of the

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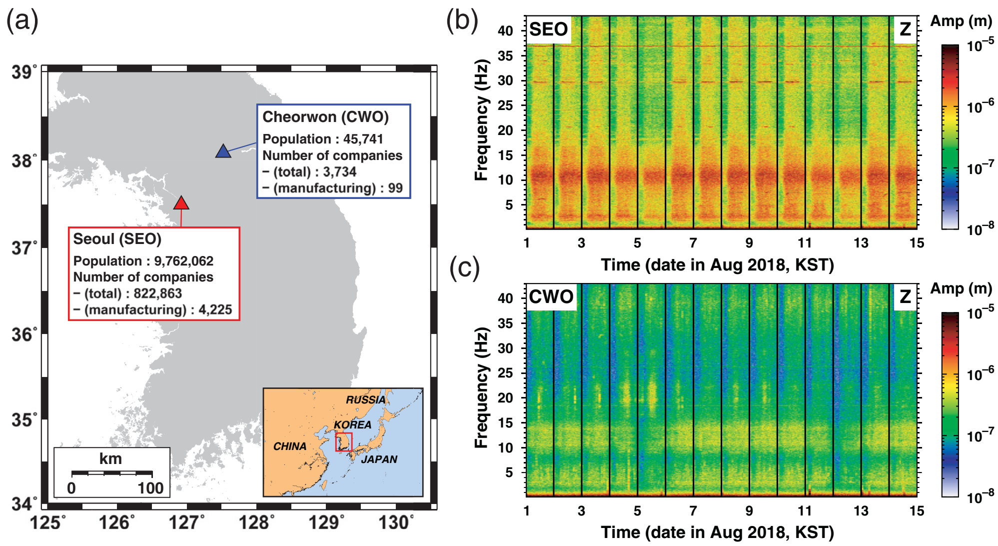

Figure 1. Ambient seismic noises in South Korea. (a) Map of seismic stations in urban (SEO) and rural (CWO) regions. (b) Vertical velocity spectra of seismic noises at stations (b) SEO in Seoul and (c) CWO in Cheorwon for 14 days in August 2018. Seismic noises around 5–15 Hz are dominant. Seismic noises at the SEO station are stronger than those at the CWO station.

noise-inducing sources. The strengths of anthropogenic-noise sources may be dependent on the city size, population, lifestyle, and industrial structure. In addition, the magnitude of human activity is associated with the economic condition. Thus, the high-frequency ambient noises may be related to the economic condition.

The ground vibrations excited by human activities are rich with high-frequency energy that decays fast with distance (Hong *et al.*, 2005; Hong, 2010; Díaz, 2016). The crust in the Earth is heterogeneous, causing multiple scattering of seismic waves during propagation (Aki and Wu, 1988; Sato and Fehler, 1997; Hong and Kennett, 2003, 2004; Hong *et al.*, 2004). The scattered waves may interfere with one another, prevailing in local and regional distances. Thus, the ambient seismic noise level may be influenced by local and regional human activities. We investigate the relationships between ambient seismic noise levels and economic conditions in regions of various economic conditions.

Ambient Seismic Noise Properties

The seismic noises are composed of natural, anthropogenic, and instrument noises (Byrne, 1961). The seismic noise level may be further modulated by site effects. The magnitude of instrument self-noises varies by the sensor type and installation environment up to an order of several hundred times. The instrument noises may be affected by temperature and atmospheric pressure. The instrument noises may be constant for a given temperature and atmospheric pressure. In addition, the seismic noise level varies seasonally due to different medium responses to temperature and wind at the surface (Hillers and Ben-Zion, 2011). We can assume the natural noises and instrument self-noises to be constant when we analyze seismic data in certain periods.

We calculate the spectral amplitudes of seismic noises in velocity records (Fig. 1). We remove the records with large amplitudes that deviated from the average noise level by more than three times the standard deviation. Ambient seismic noises are strong at frequencies 2–17 Hz and >28 Hz (Fig. 1). Anthropogenic noises are the primary components in the ambient noise field in frequencies of 2–17 Hz. Seismic noises at frequencies >28 Hz are subtle and vary by thermoelastic and meteorological effects (Tsai, 2011; De Angelis and Bodin, 2012).

The seismic noise levels at frequencies of 5–15 Hz rarely vary by thermoelastic effect and may be useful for consistent quantification. The 5–15 Hz frequency band belongs to a frequency channel that animals use for seismic communications (O'Connell-Rodwell, 2007; Hrouzková *et al.*, 2018). We analyze the daytime seismic noises at 5–15 Hz considering the dominant frequencies of anthropogenic noises.

The seismic noise level in 5–15 Hz presents strong diurnal periodicity (Fig. 2). The noise level reaches the daily minimum at ~3 a.m. The noise level increases rapidly with time in the morning, reaching the daily maximum around ~9 a.m. The large noise levels sustain until 4 p.m. local time, with temporal noise-level decrease at lunchtime (~12 p.m.). The noise level decreases mildly with time from ~4 p.m. to nighttime. The daily noise-level variation is on the order of 10 dB for the daily minimum (Fig. 2) (Cara *et al.*, 2003).

The diurnal variations in seismic noise levels are consistently observed in working days and weekends (holidays) (Fig. 2). The noise levels on working days are ~1.5 times larger than those on weekends (holidays) (Fig. 2) (Groos and Ritter, 2009). The noise-level decrease at lunchtime is stronger on working days than on weekends and holidays due to higher human activity on working days. In addition, the seismic noise levels in urban regions are stronger than those in rural regions (Figs. 2, 3). The observation suggests that the daytime noises are controlled primarily by human activities.

We assess the seismic noises in daytime from 10 a.m. to 6 p.m. (8 hr), during which human activities are vigorous (Fig. 3). We calculate the spectral amplitudes based on 2-hr-long time windows that are shifted by 1 hr with 50% overlap.

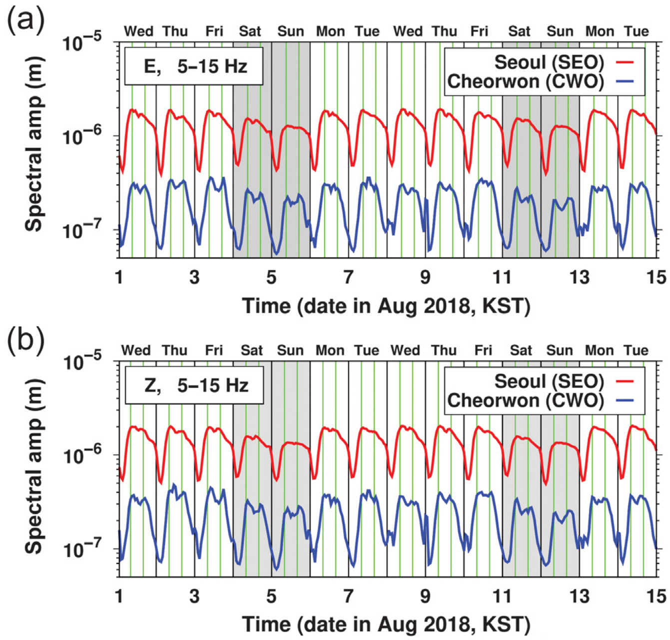

Figure 2. Daily seismic noise variation at frequencies of 5–15 Hz in urban (SEO) and rural (CWO) regions: (a) east–west component and (b) vertical component. The seismic noises exhibit 24 hr periodicity. The seismic noises are stronger on working days than on weekends. The seismic noises in urban regions are larger than those in rural regions.

We thus stack the spectral amplitudes of the daytime seismic noises on weekdays from April to June of each year. The average noise level of three months is representative of the year. The yearly seismic noise levels change consistently in daytime from the 10 a.m. to 6 p.m. levels (Fig. 4). The observation suggests that the daytime noise-level assessment may allow us to stably determine the yearly seismic noise-level changes.

The amplitudes of seismic noises are different among three components (Fig. 5), which may be due to divergent site responses to impulsive sources (Cara *et al.*, 2003). The noise-level variations are, however, consistent among three components (Fig. 5). The analysis of noise levels in a component may enable us to estimate the temporal noise-level variations consistently. We use vertical-component records for analysis. We choose three months of each year in similar weather and climate conditions to minimize the instrument-origin and seasonal effects (Fig. 3). In this study, we analyze the seismic noises in April–June of each year, avoiding summer and winter seasons.

Anthropogenic Noise Sources

We identify the effective anthropogenic noise-inducing sources from a comparison of diurnal variations between noise levels and human activities. We compare the diurnal noise-level variations with various forms of human activities including transportation (traffic), housework, and industrial activity. We analyze the seismic noise levels in Seoul, South Korea. We use the information of traffic volumes for the transportation-related noise source magnitude, and electricity consumptions for the housework and economical activities by business type (Fig. 6). We collect the information of traffic volume and electricity consumption from the Seoul Transport Operation & Information Service (see Data and Resources) and Electric Power Statistics Information System of Korea (see Data and Resources).

The traffic volume increases quickly in the morning. The traffic volume reaches the daily maximum during commute times (7–9 a.m. and 6–8 p.m.). The traffic volume is nearly constant in daytime (10 a.m.–5 p.m.), with a temporal decrease at lunchtime (∼12 p.m.). The traffic volume reaches the daily minimum around 3 a.m. The seismic noise-level variation in commute times generally agrees with the traffic volume variation (Fig. 6). The nighttime noise levels (8 p.m.–6 a.m.) are dominantly affected by the traffic. However, the correlation between the seismic noise-level variation and traffic volume variation is low in daytime (10 a.m.–6 p.m.).

The diurnal electricity consumption presents the level of activity by business type (Fig. 6). The daytime seismic noise level is highly correlated with the electricity consumption of manufacturing industry. The operation of the manufacturing industry decreases at lunchtime, which is consistent with the diurnal noise-level variation. The correlations with other business types, including service businesses, restaurant businesses, and household usage, are relatively weak (Fig. 6). The daytime noise levels from 10 a.m. to 6 p.m. are primarily controlled by industrial operations. The industrial operations with rotating machinery such as electrical motors, gearboxes, and power generators produce long-lasting high-frequency energy at 1–50 Hz (Plesinger and Wielandt, 1974; Coward *et al.*, 2003; Kar and Mohanty, 2006; Groos and Ritter, 2009). This observation suggests that the daytime noise levels may reflect the industrial activities.

Regional Noise-Level Variation

We compare the noise-level variations in five regions (BUS, KWJ, PHA, SEO, and CWO) of South Korea (Fig. 7). The five regions are distributed apart in South Korea. We estimate monthly noise levels for summer (June, July, and August) and winter (December, January, and February) seasons in 2016–2019. The noise levels in summer periods are larger than those in winter periods. The observation suggests that the noise level may vary by season, which is consistent with other studies (McNamara and Buland, 2004; Burtin *et al.*, 2008). In addition, the noise-level variations are consistently observed between horizontal and vertical components (Fig. 7).

The yearly variations of noise levels are similar among the five stations (Fig. 7). This is partly because the levels of human activities change similarly among different regions in a country. Further, seismic waves are multiply scattered in the crust,

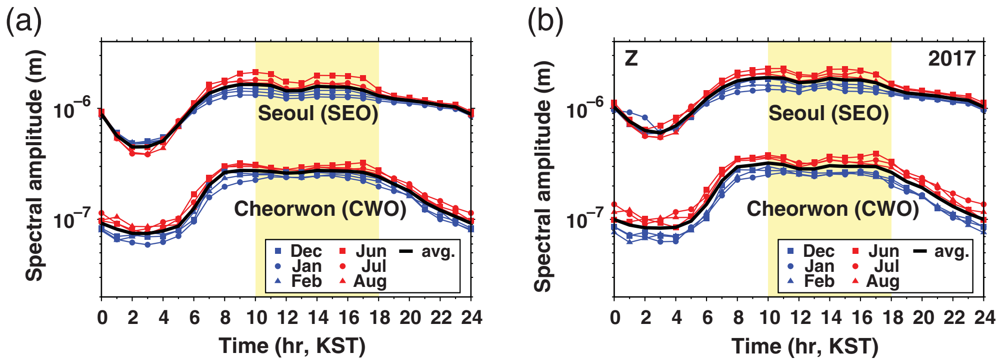

Figure 3. Seasonal variation in diurnal seismic noises at frequencies of 5–15 Hz between summer (June, July, and August) and winter (December, January, and February) periods in 2017: (a) east–west component and (b) vertical component. The seismic noises at two stations (SEO and CWO) are presented. Seismic noises in summer are stronger than those in winter.

being distributed homogeneously in local to regional distances. The scattered waves are well mixed in local and regional distances. The observation suggests that the noise-level change in a region may stand for those in other regions in the country. It may be possible to determine the noise-level variation from a representative site. In addition, because the noise level varies by season, it may be required to analyze noise levels in the same seasons to compare the yearly variations (Fig. 7).

Global Seismic Noise-Level Analysis

We choose 11 countries with different economic conditions (Fig. 8). We select broadband seismic stations of low-seismicity regions that are away from rivers and oceans to avoid the interference of earthquakes and natural forces. Seismic noise-inducing anthropogenic sources are composed of various human activities, the relative influences of which are unknown. The observed seismic noise level at site j, $S_j(f)$, may be expressed by the following:

$$S_j(f) = \sum_{i=1}^{N} \frac{c_i(f)}{a_{ij}(f)} F_i(f), \tag{1}$$

in which f is the frequency, N is the number of anthropogenic sources, F_i is the source spectra of anthropogenic source i, c_i is the source strength, and a_{ij} is the distance-dependent attenuation factor. The source strength c_i may vary by region.

It was reported that human activities are closely related with economic condition (Ranis *et al.*, 2000; Maqin and Sidharta, 2017). Human activity (anthropogenic noise source) generally increases with economic growth. The economic condition can be represented in terms of an economic index. Each anthropogenic source can be expressed in terms of an economic index. Thus, the observed seismic noise level can be rewritten as

$$S_j(f) = \sum_{i=1}^{N} h_{ij}(f)E_j = A_j(f)E_j, \tag{2}$$

in which E_j is the economic index for region containing site j, h_{ij} is the translated strength of anthropogenic source i, and A_j is the composite coefficient that translates the economic index into the seismic noise level. The composite coefficient A_j may be dependent on the industry composition, population, infrastructure, and economic condition of the country and local region.

We may use gross domestic product (GDP) for the economic measure. GDP is an economic index to represent the sociocultural environment and urbanization as well as economic condition. In particular, considering the major components of anthropogenic seismic noises, the manufacturing GDP may be a useful index for the industrial operation and human activity (Fig. 8). We collect the economic information of countries from the World Bank (see Data and Resources). The economic information includes the GDP and industry structure. The GDP indices (total, industry, and manufacturing) are presented in constant $2010 U.S.

We choose seismic stations in 11 countries, including the United States of America (station AAM, first in the 2018 world GDP ranking), China (SSE, second), United Kingdom (EDI, fifth), Canada (OTT, tenth), South Korea (SEO, eleventh), Russia (OBN, twelfth), Australia (thirteenth), Singapore (BESC, thirty-seventh), Portugal (GGNV, forty-fifth), Honduras (TGUH, one hundred ninth), and Mongolia (ULN, one-hundred thirty-first) (Fig. 8). The set of countries is composed of four developing-economy countries and seven advanced-economy countries according to the International Monetary Fund as of 2018. The developing-economy countries are China, Russia, Honduras, and Mongolia. The advanced-economy countries are the United States of America, the United Kingdom, Canada, South Korea, Australia, Singapore, and Portugal.

The annual variations in GDP indices (total, industry, and manufacturing) are similar (Fig. 8). The manufacturing GDP accounts for 11.3% of the GDP in United States, 31.5% in China, 8.2% in United Kingdom, 9.9% in Canada, 28.7% in South Korea, 13.1% in Russia, 6.1% in Australia, 18.8% in Singapore, 12.7% in Portugal, 16.1% in Honduras, and 6.5% in Mongolia. We primarily compare the noise levels with the manufacturing GDP. We use the industry or total GDP alternatively when the manufacturing GDP is not available (China) or when the local economy does not resemble the national economy (Sydney, Australia, and Detroit, United States).

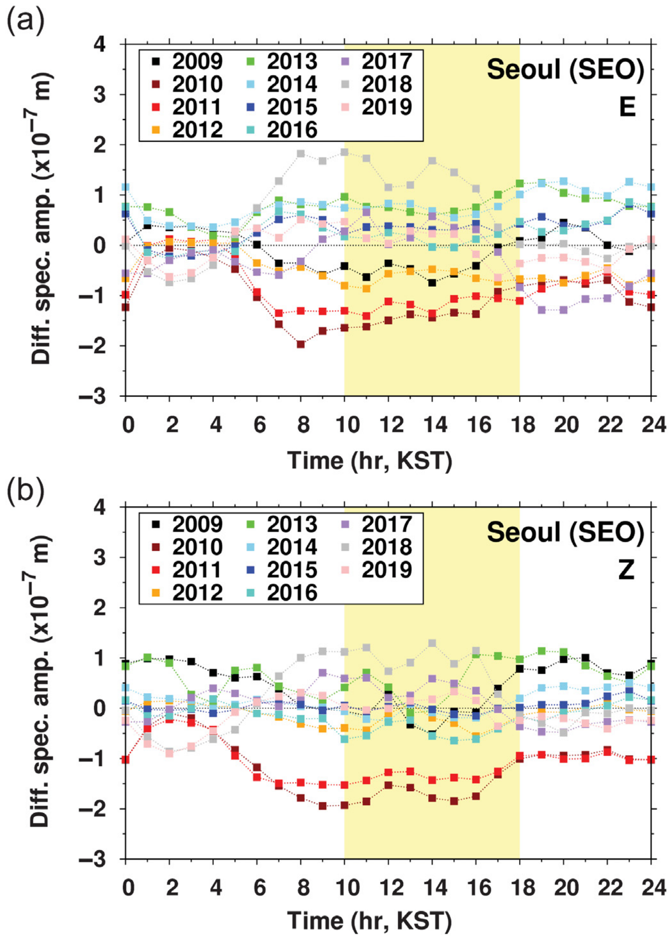

Figure 4. Differences between yearly seismic noises and average seismic noises from 2009 to 2019: (a) east–west component and (b) vertical component. Seismic noise levels are different among years. The differential noise levels are consistent in the time period from 10 a.m. to 6 p.m. The differential noise levels are similar between the east–west and vertical components.

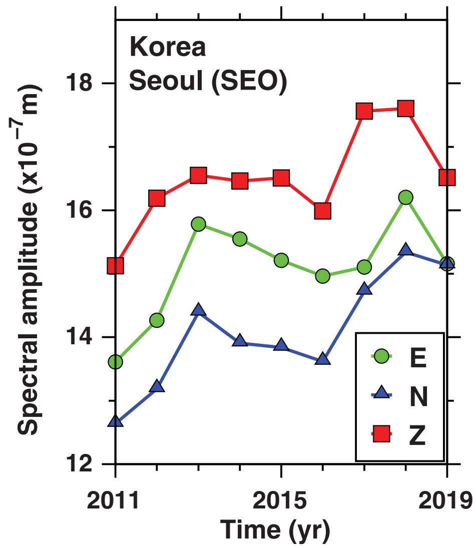

Figure 5. Comparison of yearly seismic noises among three components at station SEO. The seismic noise levels change consistently among the three components.

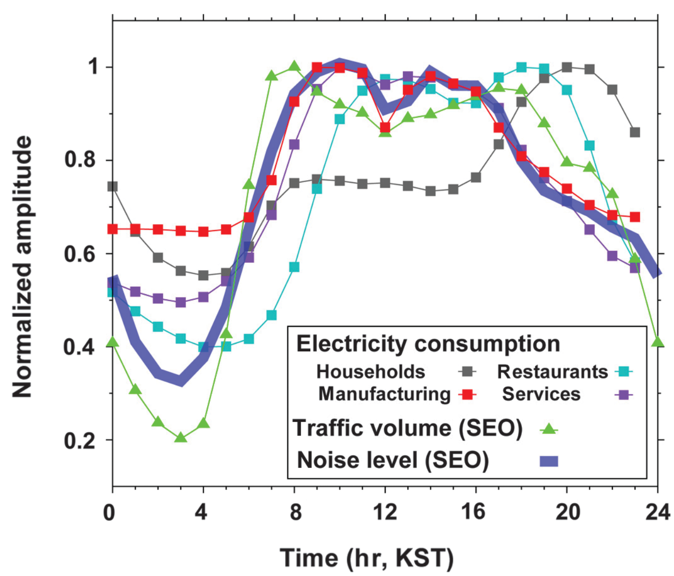

Figure 6. Comparison of seismic noises at 5–15 Hz with electricity consumption by business type and traffic volume. The diurnal seismic noise variation is highly correlated with the diurnal electricity consumption change of the manufacturing industry. Daily peak times of traffic volumes are not consistent with those of seismic noises.

Global Variation in Seismic Noise Levels

We analyze the seismic noise levels in major cities of the selected countries. We collect vertical broadband seismic records from stations in low-seismicity regions to avoid contamination by seismic activity. The stations are AAM (United States of America), SSE (China), EDI (United Kingdom), OTT (Canada), SEO (South Korea), OBN (Russia), RIV (Australia), BESC (Singapore), GGNV (Portugal), TGUH (Honduras), and ULN (Mongolia). The seismic data are available since 1996. We assess the spectral amplitudes of daytime seismic noises from April to June, which allows us to assess the major human activities with minimization of the seasonal-variation effect on seismic noises (Hillers and Ben-Zion, 2011) (Fig. 3).

The manufacturing GDP of the United States of America increased linearly during 2002–2007, decreased during 2007–2009, and has increased since 2009. In 2018, the manufacturing industry composed 11.7% of the GDP; the construction industry, 4.3%; the mining industry, 1.7%; and the service industry, 80%. The car manufacturing industry composes 3.5% of GDP. Seismic records are available from the AAM station near Detroit since 2002. Detroit belongs to an industry belt that experienced large economical fluctuations

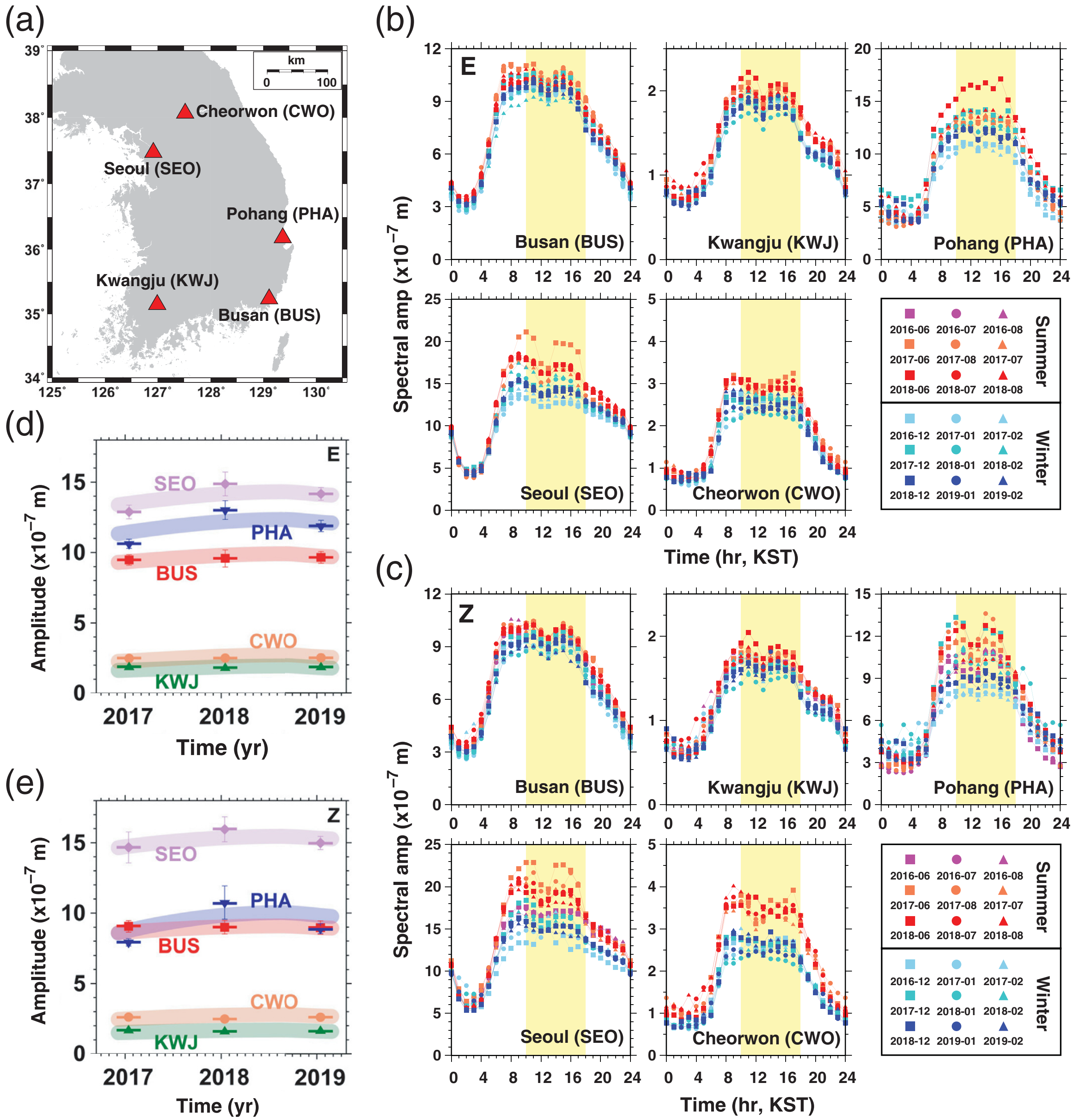

Figure 7. Seismic noise-level variations in summer and winter periods for three years. (a) Map of five stations, monthly averaged diurnal seismic noise levels in (b) east–west and (c) vertical components, and the daytime noise levels in (d) east–west and (e) vertical components for winter periods. The seismic noise levels in summer are generally larger than those in winter. The yearly noise-level changes are similar among stations.

over the last decades. The local economic condition was different from the national economic situation. We thus compare the noise levels with the GDP of the local region. The noise levels follow the GDP of the local region well. The noise level in Detroit increased by 22% for 15 yr when the local GDP increased by 7% (Fig. 9).

China presented rapid economic growth over recent decades. The GDP growth rates were 6.6%–14.2% during 2000–2018. The industry structure was composed of 7.9% primary

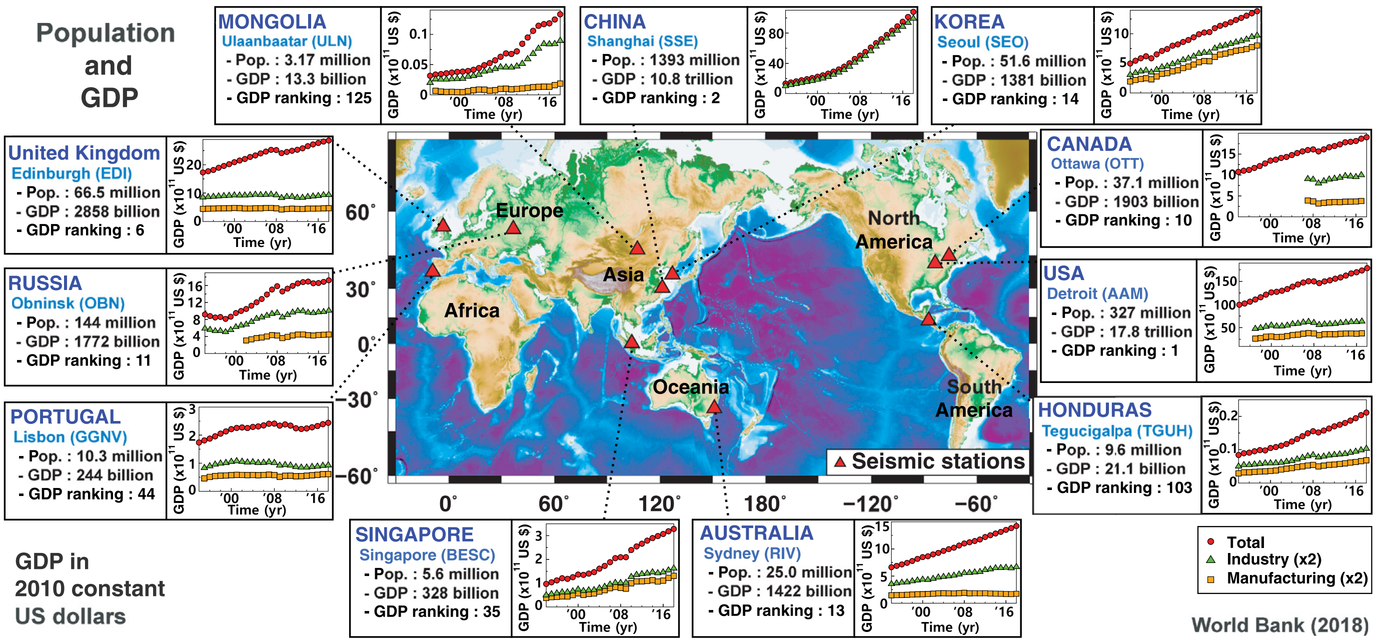

Figure 8. Economic growth history and economic conditions of 11 countries and regions. The total, industry, and manufacturing gross domestic product (GDP) in constant $2010 U.S. are presented. The locations of stations (triangles) are marked on the map.

industry, 40.5% of secondary industry, and 51.6% of tertiary industry as of 2017. The manufacturing industry of China composed 31.5% of the GDP as of 2010. The GDP has increased consistently since 2003. Seismic records are available from the SSE station in Shanghai since 2003. The total and industry GDPs are available for China. The noise levels generally follow the industry GDP (Fig. 9). The noise level increased by 64% for 17 yr when the industry GDP increased by 271%.

The manufacturing GDP of the United Kingdom presented multiple ups and downs since 2008. The secondary industry composes 20.2% of the industry structure. The tertiary industry composes 79.2%. The manufacturing industry of the United Kingdom composes 8.2% of the GDP. The seismic noise levels at the EDI station in Edinburgh generally follow the manufacturing GDP variation with a 1 yr delay in the noise-level trend. The noise level increased by 18% for 10 yr when the manufacturing GDP increased by 11% (Fig. 9).

The manufacturing industry of Canada composes 9.9% of the total GDP. The manufacturing industry composes 10.4% of the industry structure. The manufacturing GDP has increased consistently in Canada since 2009. The secondary industry composes 19.7%. The tertiary industry takes 70.1%. Economic growth rates in 2013–2017 were 1.0%–3.0%. Seismic records are available from the OTT station in Ottawa since 2011. The noise levels reasonably follow the manufacturing GDP. The noise level increased by 27% for 7 yr when the manufacturing GDP increased 13%.

South Korea is a representative country of high-manufacturing industry. The manufacturing industry is the fifth largest in the world. The manufacturing industry composed 30% of the GDP in 2018. The service industry composed 59.1% of GDP. South Korea has presented economic growth rates of 2.3%–8.9% since 2000 with low-temporal growth of 0.7% in 2009. The GDP has linearly increased in South Korea with a growth rate of 2%–4% since 2010. Seismic data in the SEO station in Seoul are available since 2008. We compare the noise amplitudes with the manufacturing GDP. The yearly noise levels generally follow the manufacturing GDP (Fig. 9).

Russia presents large variations in the manufacturing GDP around 2009 and 2015. The industry structure of Russia was composed of 3.9% of primary industry, 36.1% of secondary industry, and 60% of tertiary industry in 2012. The manufacturing industry of Russia accounts for 13.1% of the GDP. Seismic data since 2004 were collected from the OBN station near Moscow. The yearly variation in seismic noise resembles the manufacturing GDP variation (Fig. 9). The noise level increased by 89% for 16 yr when the manufacturing GDP increased by 20%.

Australia has presented mild decreases in manufacturing GDP since 2012. On the other hand, the total GDP increased each year. In 2017, the manufacturing industry composed 6.3% of the GDP; the mining industry composed 6.3% of the GDP; the construction industry composed 7.9% of the GDP; and the service industry composed 76.5% of the GDP. The total GDP generally increases each year, whereas the manufacturing GDP decreases each year. Seismic records are available from the RIV

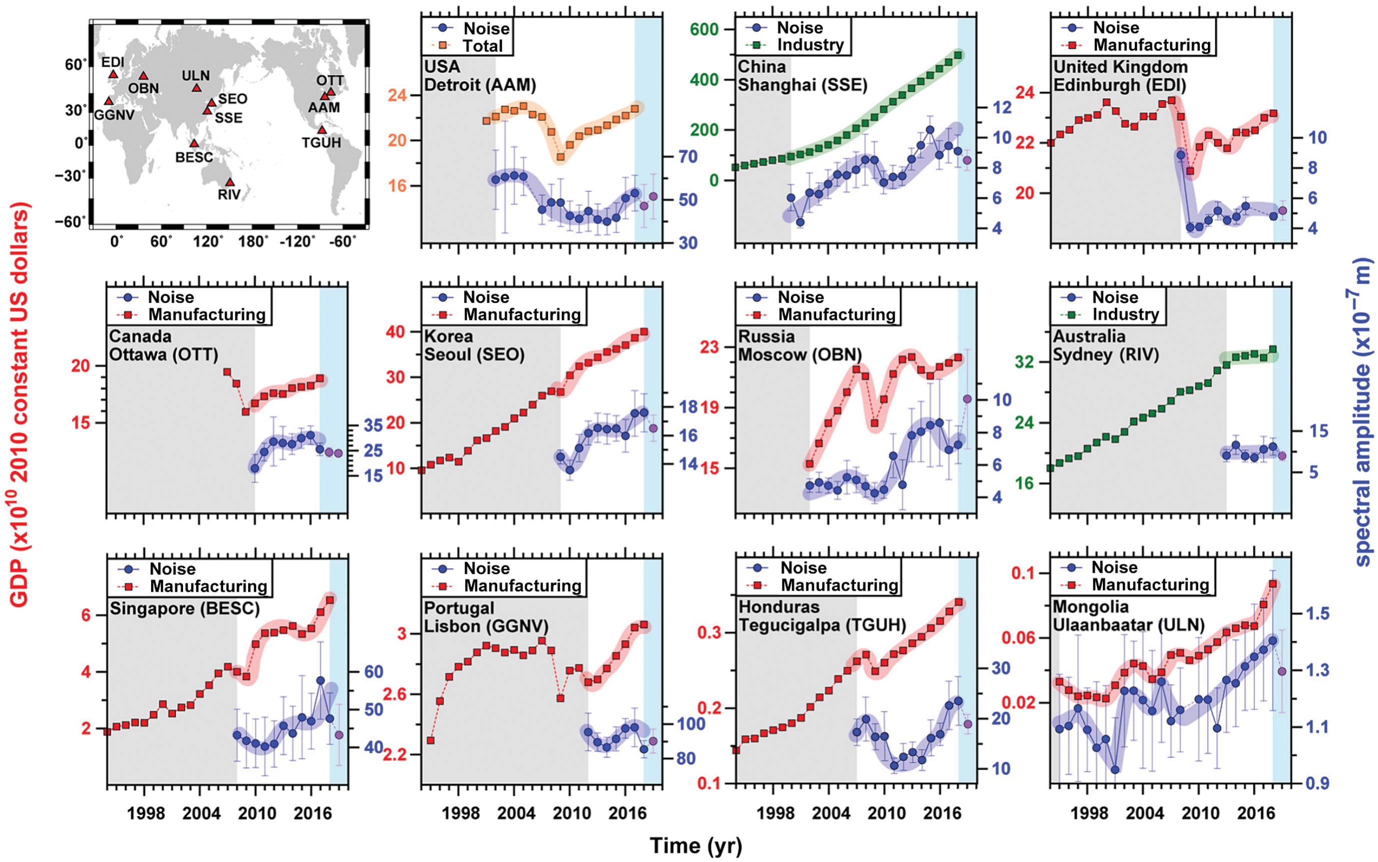

Figure 9. Seismic noise changes with year. The yearly seismic noise levels are compared with GDP. The manufacturing GDP for eight countries (United Kingdom, Canada, Korea, Russia, Singapore, Portugal, Honduras, and Mongolia), industry GDP for two countries (China and Australia), and total GDP of the local government for one region (Detroit, United States) are presented. The seismic noise-level changes are similar to the GDP changes.

station in Sydney since 2013. The noise levels were stationary with weak fluctuations. The trend in noise levels poorly match with the trend in manufacturing GDP, which may be due to the low proportion of the manufacturing industry. The noise levels resemble the industry GDP (Fig. 9). The noise level increased by 36% for 5 yr when the industrial GDP increased by 4%.

Singapore presented an increasing manufacturing GDP trend with temporal decreases in 2009 and 2015. The service industry composed 71.3% of the total GDP in 2017. Manufacturing GDP accounts for 19.2%. The primary industry is low. The manufacturing industry of Singapore composes 18.8% of GDP. Seismic records are available from the BESC station in Singapore since 2011. The noise-level trend generally agrees with the manufacturing GDP trend. The noise level increased by 43% for 10 yr when the manufacturing GDP increased by 52%.

Portugal displayed a large decrease in manufacturing GDP in 2012. In 2017, tertiary (service) industry composed 75.7% of the total GDP, primary industry accounted for 2.4%, and secondary industry composed 21.9%. The manufacturing industry of Portugal composes 12.7% of the GDP. Seismic records are available from the GGNV station in Geofisico near Lisbon since 2010. The general trend in seismic noises agrees with the manufacturing GDP trend with a one year delay. The noise level increased by 14% for 8 yr when the manufacturing GDP increased by 13%.

Approximately 45% of the population in Honduras live in rural regions. The agricultural sector composes 12.5%–13.8% of the GDP. The GDP comprised of 13.9% of agriculture, 27.7% of industry, and 58.4% of services as of 2012. The manufacturing industry of Honduras composes 16.1% of GDP. Honduras presented increasing manufacturing GDP each year except 2009. The seismic noise levels at the TGUH station in Tegucigalpa have followed the manufacturing GDP since 2007. The noise level increased by 111% for 11 yr when the manufacturing GDP increased by 31%.

The GDP of Mongolia has increased consistently since 1994. Mongolia had a GDP growth rate of 17.3% in 2011, which was the largest growth rate. The GDP growth rate has decreased since 2011, reaching 1% in 2016 and 5.1% in 2017. The mining industry composed 14.9%–21.5% of the GDP in 2010–2016. The agriculture and farming industry composed 12% of GDP in 2017. The manufacturing industry

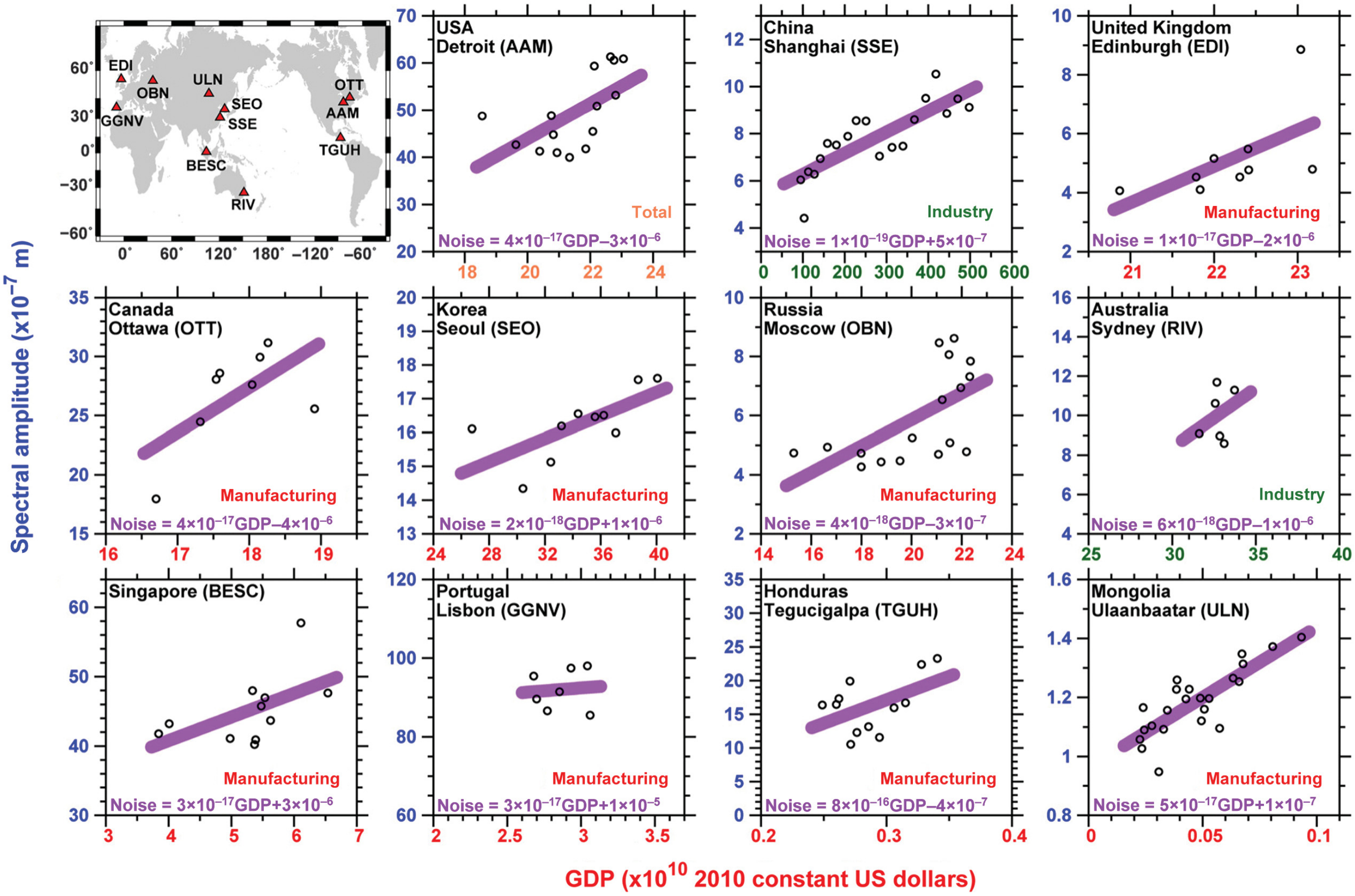

Figure 10. Seismic noise-level changes as a function of manufacturing or industry GDP. The seismic noises are proportional to the manufacturing or industry GDP. The linear relationships are presented.

of Mongolia composes ~6.5% of the GDP. The manufacturing GDP presented multiple ups and downs in 2000, 2003, 2005, 2008, and 2009. The seismic data are available from the ULN station in Ulaanbaatar since 1995. The noise-level trend agrees with the manufacturing GDP trend. The noise level increased by 54% for 23 yr when the manufacturing GDP increased by 244%.

The seismic noise levels display strong linear relationships with the total GDP as well as the manufacturing or industry GDP (Figs. 10 and 11). The linear relationships between noise level and GDP are different by region. The noise-level increase rates are relatively low in Shanghai (China), Edinburgh (United Kingdom), Moscow (Russia), Sydney (Australia), and Seoul (Korea) where the GDP is generally large. On the other hand, we observe high noise-level increase rates in low-GDP regions, including Tegucigalpa (Honduras) and Lisbon (Portugal). Seismic noises in Detroit, United States, display a high increase rate for local GDP. Seismic noises in Singapore and Ottawa (Canada) present mild increase rates (Fig. 12).

The noise level is dependent on the industrial structure, source strengths, distances, and site effects. Industrial operation and related human activity are effective sources to induce the anthropogenic noises. Anthropogenic noise sources at a wide range of distances contribute to developing stable seismic noises. The site effects may also modulate the noise level. The correlation between noise level and GDP may enable us to utilize the seismic noises for in situ assessment of economic condition. Thus, the seismic noises may function as a precursor for economic trends. The noise levels suggest some regions, including Detroit (United States), Shanghai (China), Ottawa (Canada), Seoul (Korea), Singapore, Tegucigalpa (Honduras), and Ulaanbaatar (Mongolia), appear to have low economic growth in 2019 (Figs. 9 and 12).

The noise levels in Lisbon, Portugal (station GGNV), are ~2–5 times larger than those in the other regions, which may be associated with the site condition of the station. The shear-wave velocity of the top 30 m from the surface V_{S30} is as low as ~300 m/s (see Data and Resources, Wald and Allen, 2007; Allen and Wald, 2009). In addition, the station GGNV is placed in the city center of Portugal where high seismic noises are expected. Thus, the high seismic noise level in station GGNV may be due to the combined effect of local source strengths and site amplification.

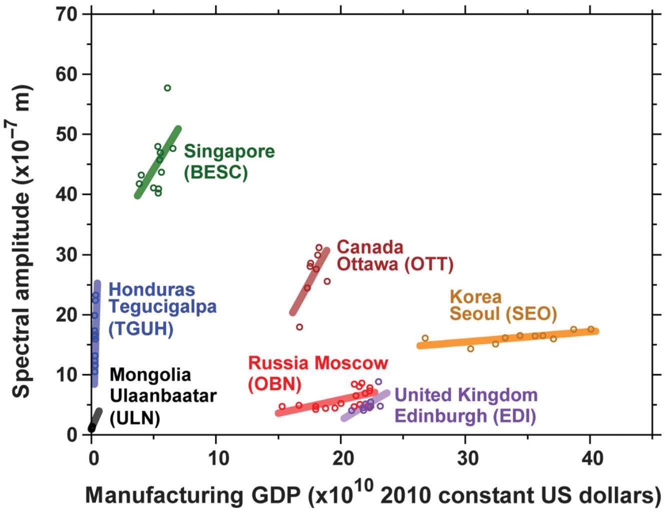

Figure 11. A composite view of seismic noise-level changes as a function of manufacturing GDP for seven stations (countries) for which manufacturing GDP values are available. Strong linear relationships are observed between the seismic noise level and manufacturing GDP.

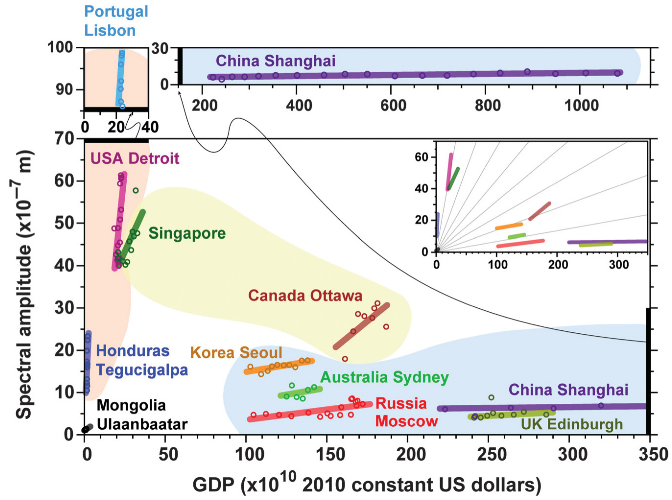

Figure 12. Seismic noise-level changes as a function of total GDP. The seismic noise levels are proportional to the GDP. A local government GDP is presented for Detroit, United States. The noise increase rates are large in low-GDP regions (Tegucigalpa, Honduras; Detroit, United States; and Lisbon, Portugal), whereas they are small in high-GDP regions (Seoul, Korea; Sydney, Australia; Moscow, Russia; Edinburgh, United Kingdom; and Shanghai, China). The seismic noise levels are proportional to the total GDP. A composite view of the fitted lines is presented (inset).

The seismic noise levels generally increase fast in low-GDP regions. On the other hand, the seismic noises grow slowly in high-GDP regions. The observation suggests that the global seismic noise level keeps increasing with economic growth. Because the noise-inducing sources may affect the noise levels in adjacent regions, seismic noise reduction may not be feasible with the effort of single regions.

Discussion and Conclusions

We investigated the properties of high-frequency ambient seismic noises. The ambient seismic noises are collected from urban and rural regions in South Korea. The diurnal noise-level variation at frequencies greater than 2 Hz is primarily associated with human activity. The noise levels of urban regions are higher than those in rural regions. In addition, the noise levels on working days are 1.5 times larger than those on weekends. The daytime noise levels are higher than the nighttime noise levels. The diurnal noise-level variations resemble the diurnal cycles of human activities. In particular, the daytime noise levels in 5–15 Hz are well represented by the magnitudes of regional industrial operations. The observation suggests that the daytime noise level in 5–15 Hz varies with the economic condition.

Seismic waves induced by human activities are scattered in the crust where small-scale heterogeneities are present abundantly. The scattered waves are distributed homogeneously in local and regional distances (Aki and Wu, 1988; Sato and Fehler, 1997; Hong and Kennett, 2003; Hong *et al.*, 2005). Further, the local economic condition is controlled by the national economic situation. Thus, local noise-level variations may present the national economic condition unless the local regions have independent or closed economic environments. The similar trends of noise-level variations between urban and rural regions support that local noise-level variations may be used for the inference of regional or national economic conditions.

We assessed the diurnal noise levels of decades in major cities of 11 countries in diverse economic conditions. The daytime noise levels in 5–15 Hz display high correlations with economic growth. The annual noise levels in the cities increased by 14%–111% for 5–23 yr depending on the economic conditions. The noise-level increase rates in low-GDP regions were larger than those in high-GDP regions.

We observed linear relationships between GDPs and noise levels. The slopes of linear relationships are different by region, which may be partly associated with the difference in base noise levels. The observation suggests that every region has its own relationship between GDP and noise level. The base noise level may be dependent on various factors including medium properties (e.g., V_{S30}), industry composition, city size, transportation system, and population density. However, it is possible to estimate the GDPs based on observed noise levels when the relationships are determined.

The seismic noises are ground responses to the composite effects of microseismic sources. It is generally difficult to distinguish the energy excited from a particular microseismic source. However, the noise level may increase with increasing microseismic sources. The GDP represents the products and activities of people (i.e., noise-inducing sources). Thus, the noise level may be naturally correlated with the GDP.

The current daytime noise levels in major cities are equivalent to the ground-motion levels caused by earthquakes magnitudes less than ~M_w 1.0 in tens of kilometers. In addition, the consistent noise levels during daytime in major cities compose environments similar to a situation for which global major cities suffer from the continuous occurrence of microearthquakes at local distances in daytime. Further, the ambient noise levels may keep increasing with global economy growth. The high correlation between noise level and GDP may enable us to infer the regional and national economic conditions from ambient noise levels.

Data and Resources

The seismic records are collected from Korea Meteorological Administration (http://www.weather.go.kr/weather/earthquake_volcano/domesticlist.jsp) and Data Management Center of Incorporated Research Institutions for Seismology (http://ds.iris.edu/ds/nodes/dmc). We obtain the information of traffic volume and electricity consumption from the Seoul Transport Operation & Information Service (http://topis.seoul.go.kr/) and Electric Power Statistics Information System of Korea (http://epsis.kpx.or.kr). The economic information of countries in the World Bank is available at https://data.worldbank.org/. V_{S30} models and data are available at http://earthquake.usgs.gov/data/vs30. All websites were last accessed in April 2020.

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