Chapter 6

Seismic Ambient Noise and Its Applicability to Monitor Cryospheric Environment

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1. Introduction

In seismology, most of researches have been investigated by analyzing major seismic 'signals', for instance, body waves and surface waves. Aki [1] first introduced 'coda' waves, which had long been recognized as 'noise', consisting of scattered *S*-waves during propagation through the heterogeneous Earth media. Since then, a number of studies have been conducted to measure medium heterogeneity using coda waves over the world (e.g. [2]). Another revolutionary research dealing with 'noise' in seismology has been reported by [3]. The authors introduced a remarkable method to determine surface wave velocity examining long sequences of seismic ambient noise. It gives us a great opportunity to explore velocity structures underneath by nothing but listening to noise.

An additional interesting feature in terms of 'noise' shown up in the broadband seismic records is microseisms having two predominant peaks in a frequency domain such as primary and secondary microseisms, which have been believed to be originated by long-period ocean waves. The most widely accepted mechanisms for the generation of microseisms are as follows: (1) When ocean waves impact the coast, a part of acoustic energy is transferred into the crust. The directly converted seismic energy (Primary Microseisms, PM) from ocean waves propagates mostly as Rayleigh waves having a predominant period near 8-20 s which is the same period as the ocean waves even *P*-waves have been observed [4]. (2) The most energetic ambient noise is referred to as the secondary microseisms, or Double-Frequency (DF) microseisms, with 4-10 s of predominant period and the generation mechanism is more complex than that of PM. As ocean waves travel toward and strike the coast, reflected waves are generated and nonlinearly interact with incident waves in shallow regions, which results in a frequency doubling of a standard ocean wave [5,6]. The pressure amplitude of propagating incident waves decays exponentially as water depth becomes deeper, whereas the amplitude of standing waves keeps nearly constant with depth. Such powerful DF microseisms could be efficiently excited by significant reflection of wave energy at steep coastlines.

There have been several research efforts (e.g. [7,8]) to identify the source regions of DF microseisms utilizing array analysis, which report that the most DF microseisms are excited near the coastal regions where the swell reaches steep coasts with normal incidence, in good agreement with the Longuet-Higgins model for the generation of DF microseisms [7]. In addition to the determination of source location, scientists have investigated if the DF microseisms vary seasonally in amplitude. According to the spectral analysis for seismic ambient noise by McNamara and Buland [9], the power of DF noise levels in winter is higher than the summer season, which could be observable over the northern hemisphere. Since the DF microseism has been originated by ocean waves, it tends to show seasonal variability, reflecting the vigor of ocean activities [10]. This phenomenon allows us to monitor the Earth's near-surface environment in the ocean using the ambient noise analysis. In Polar Regions, seasonal variation in the DF energy occurs inconsistently compared to the characteristics shown in the lower latitude regions. Recent observations (e.g. [11,12]) suggested that there is a possible relation between the seasonal variability of DF microseisms and sea-ice variability. Tsai and McNamara [13] has theoretically explained that the sea-ice concentration is responsible for the seasonal change of DF microseisms in power with a simple attenuation model.

Even though many literatures have reported fascinating results for seismic ambient noise in both the northern and southern hemispheres, there are only a few studies regarding the DF microseisms in Antarctica [11,12,14,15] due to a dearth of broadband seismic stations. In this chapter, we combine more 3-year data from 2009-2011 with the previous results [11] and present a seismic ambient noise study that could provide more reliable evidence to present strong association between the seasonal change of DF and the variability of sea-ice concentration, in turn we are able to monitor regional cryospheric environment.

2. Data and spectral analysis

Korea Polar Research Institute (KOPRI) has been operating a permanent broadband seismic station (KSJ1, 62.22ºS/58.78ºW; Figure 1) at the King George Island (KGI) in the South Shetland Islands, Antarctica, since 2001. The seismic station is mainly equipped with a three-component broadband Streckeisen seismometer (STS-2) and a 24-bit high-resolution data logger (Q4124). The sensor responses in amplitude and phase guarantee that signals recorded within the frequency range between 120 sec and 20 Hz are reliable to be used without severe distortion. We have collected seismic data with 1 (LHX) and 20 Hz (BHX) sampling rates, and used the BHZ data for the spectral analysis.

In order to examine the spectral characteristics of seismic ambient noise, we calculate the Power Spectral Density (PSD) of the seismic noise following the rigorous method by McNamara and Buland [9]. The method requires first parsing continuous time series into 1-hour time series segments, overlapping by 50 % and distributed continuously throughout the day, week, and month. The PSD estimate should be converted into decibels with respect to acceleration

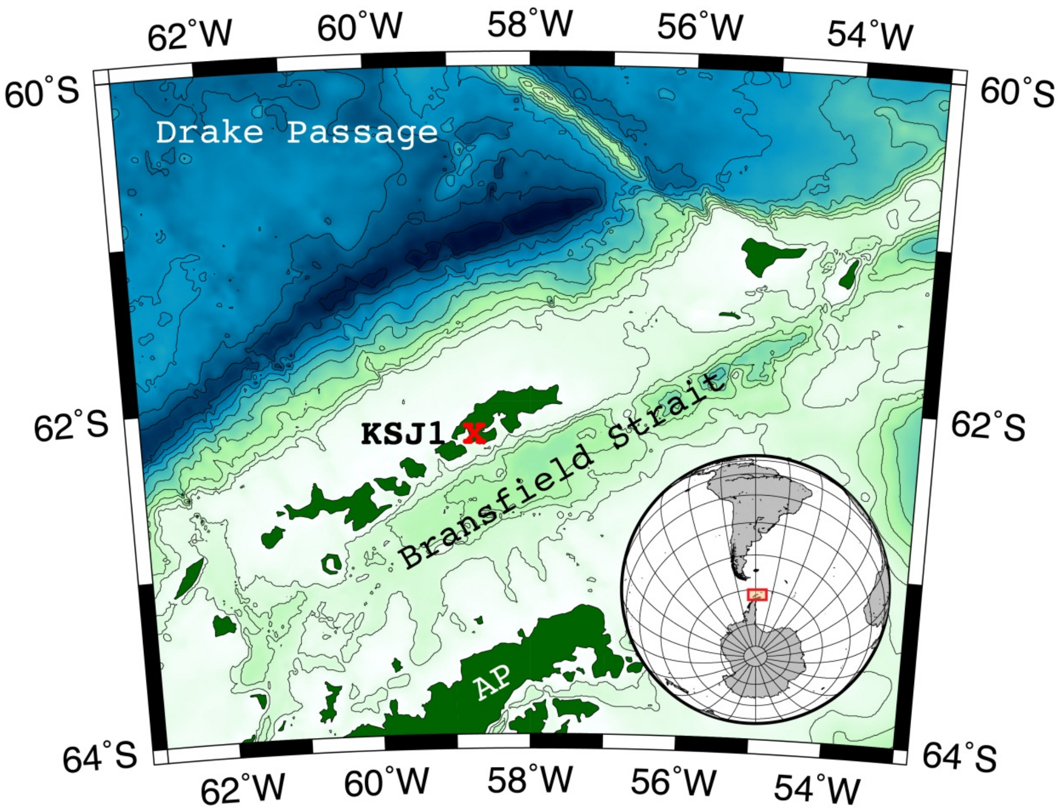

Figure 1. Location of a seismic station (KSJ1) at the King Sejong Korean Antarctic Base in the King George Island (KGI) marked by a red X. The Island is situated in between the Drake Passage and the Bransfield Strait near the Antarctic Peninsula (AP).

(meters/second^2)^2/Hertz for direct comparison to the standard noise model [16] in this study. The PSD technique provides stable spectra estimates over a broad range of periods (0.05–100 sec); however, it suffers from poor time resolution due to the long transforms (3600 sec) and requires many hours of data to compile reliable statistics. For better resolution at shorter periods, a larger number of shorter records should be analyzed [9]. From more than 90,000 PSDs for the period of 2006-2011, we could estimate Probability Density Functions (PDFs) to investigate the highest probability noise level (mode) for each channel as a function of period. As the method utilizes modes rather than higher energy level, we could obtain more reliable information to understand the characteristics of ambient noise, since even damaging earthquakes occurred near the station it is just a small portion out of background noise in terms of occurrence [9]. Moreover, it has a distinctive feature that we do not need to screen continuous quiet time window. At present, it has been known as the most common and robust technique to measure seismic ambient noise and evaluate the performance of seismic stations. More details regarding statistics and spectral analysis should be referred to [9].

Figure 2 demonstrates a statistical view of broadband PDFs of a vertical component for the period of 2006-2011. Two prominent peaks show up around 5 and 10 s in period, which correspond to secondary and primary microseisms, respectively. HNM and LNM indicate (gray curves in Fig. 2) the standard high and low noise model [16], respectively. Although

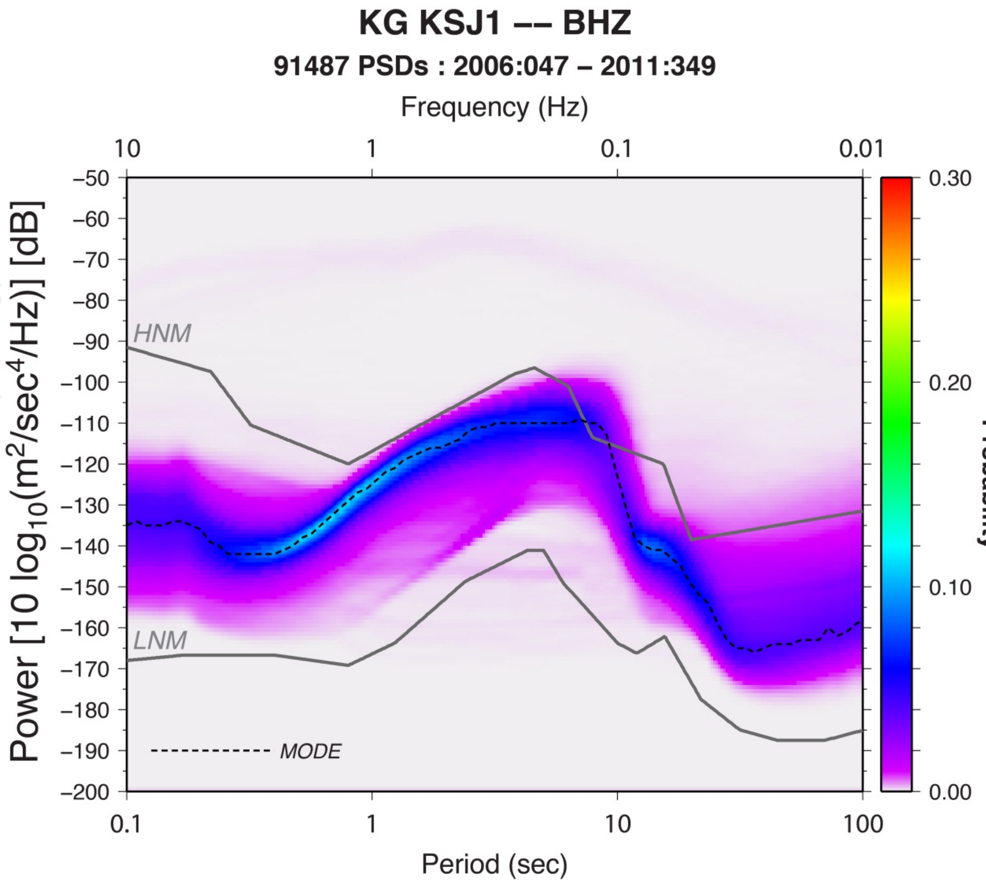

Figure 2. A Probability Density Function (PDF) plot of BHZ for KSJ1 during 2006-2011. Two predominant peaks appear around 5 and 10 s in period, corresponding to secondary (or DF) and primary microseisms, respectively. HNM and LNM indicate (gray curves) the standard high and low noise model (Peterson, 1993), respectively. The most probable energy with respect to frequency is presented by a dashed curve (mode).

several earthquakes occurred near the station during the operation period, they do not affect the overall PDFs as we mentioned earlier.

3. Seasonal variability of DF microseism and its association with sea-ice concentration

We investigated spectral characteristics for KSJ1 through the estimation of PSDs and PDFs of seismic background noise (Fig. 2), and found that the primary and secondary microseisms appear distinctly on the plot. Comparing to the HNM and LNM, we may evaluate that KSJ1 has been well operated in terms of system performance except slightly noisier (or might be higher energy level of DF microseisms) than the HNM around 10 s. In general, a plot of PDFs could provide helpful information on spectral signature of a station; however, temporal patterns of the microseisms are barely identifiable from it. In an attempt to examine temporal variation of the noise level of KSJ1, we obtain the statistical mode for the corresponding periods from daily PSDs so that we could construct a power spectrum with respect to time (Fig. 3). Empty spaces in the figure show data missing due to most likely system malfunctioning. There is nothing noticeable in the period of longer than 10 s throughout the operation time. Having interests in the feature near 4-10 s in period, i.e. DF microseisms, it happens that the DF energy comes to be weaker from July through September (austral winter). The behavior is apparent in 2007, 2009, and 2011, whereas it becomes ephemeral in 2006, 2008, and 2010, but rather weaker in power compared to other seasons in a year. This observation contrasts with the seasonal variability of seismic noises in the northern hemisphere; for instance, the amplitude of the Earth's hum reaches its seasonal maximum in winter season [17,18] revealed from an array analysis. The power of DF microseisms in the northern hemisphere shows a similar pattern (e.g. [19]) as the Earth's hum. Most literatures suggest that these characteristics are attributed to seasonal variation of the intensity of infragravity wave depending on swell amplitudes.

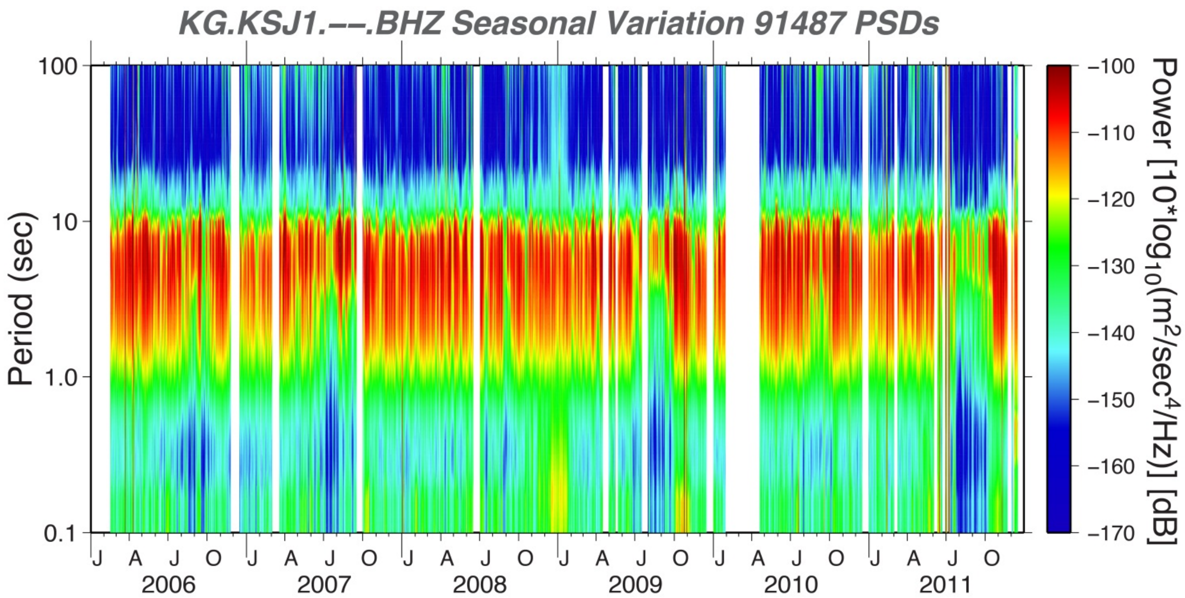

Figure 3. Spectral amplitude variation in seismic noise for BHZ (broadband vertical component) during the period of 2006-2011. Note that the seismic energy at the frequency range of DF microseisms (4-8 s) becomes weaker during July to September annually, which is a different behavior from that of the northern hemisphere except the Arctic region. Empty spaces in the plot indicate data missing or a period of malfunctioning.

Ringdal and Bungum [20] reported a pure sinusoidal pattern in long period noise level, i.e. seasonal maximum in winter and minimum in summer, from a spectral analysis of NORSAR data for three years. It does not, however, necessarily occur in the Polar Regions, especially Antarctica, and might be due to a regional difference between the northern and southern hemispheres. More specifically, [15] similarly observed weaker energy of DF microseisms in austral winter at the station DRV, Antarctica, and explained that the acoustic energy from ocean swell tends to be severely attenuated by sea ice and reflecting waves along the coast suffers as well causing fewer DF microseisms generated by sources. We refer to it as 'sea-ice damping effect' in this study. Recently, numerical modeling approach to figure out this phenomena has been made by Tsai and McNamara [13], which shows that 75-90 % of the variability in microseism power in the Bering Sea can be predicted using a simple model of microseism damping by sea ice. Moreover, they argued that we could use the microseism as a good indicator to monitor the strength of sea ice that is not easily measured by through other means.

In order to carefully study the direct relation between the energy of DF microseisms and the sea ice condition, we extract and integrate the DF power ranging 4-10 s in period out of the power spectrum and collect Sea-Ice Concentration (SIC) information. To create time series of SIC, we used data based on brightness temperature observations at 89 GHz obtained from the AMSR-E (Advanced Microwave Scanning Radiometer for EOS Aqua) on board NASA's Aqua satellite. The brightness of each image pixel is converted to the SIC using the ASI (ARTIST Sea Ice) algorithm [21]. The data offer SICs on a grid with 6.25 km resolution with a complete daily coverage of the Polar Regions. A domain for calculating SIC covers a part of the Drake Passage allowing us to compare to the DF energy in this study. The calculated percentage of SIC is the percentage of grid cells containing more than 15 % sea ice. This is mainly attributed to the fact that the accuracy of the SIC is ±15 % in regions of first-year ice [22].

As shown in Figure 4, there is clear seasonal variation found in both the power of DF microseisms (red curve) and the SIC (black curve) from 2006-2011. To quantify how they are closely related, we apply cross correlation that is a standard method of estimating the degree to which two series are correlated. The bin size of each time series is chosen to be 1-day. The resultant cross-correlation coefficient is given by -0.70 that is a strong negative correlation. The result implies that as the SIC becomes higher, i.e. more sea-ice in the ocean, the DF power decreases, which is coincident with the hypothesis of 'sea-ice damping effect'. We also determined the lag time as almost zero from the cross correlation, which indicates that the DF energy responses immediately to the sea-ice condition nearby. When one may take a closer look at the period of May through September in a year, it becomes more prominent.

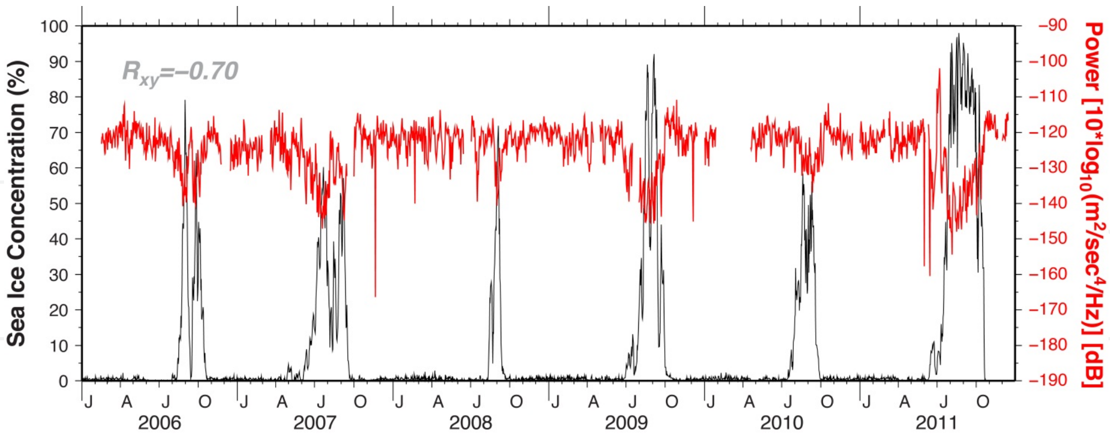

Figure 4. A comparative plot of Sea Ice Concentration (SIC, black curve) sampled near the KGI toward the Drake Passage vs. seismic energy of DF microseisms (red curve) observed at KSJ1 during 2006-2011. When either the SIC increases or decreases, the DF power responses immediately (negatively correlated), suggesting the DF energy is a relevant seismic proxy to monitor cryospheric environment especially the sea ice condition nearby. The strong correlation (-0.70) between them supports the hypothesis.

Remote sensing using satellites allows us to extensively improve our knowledge over various scientific issues, especially in Polar Regions. For instance, we can measure surface melt extent on ice, moving speed of glaciers, ice mass balance by means of AMSR-E, InSAR satellites, and GRACE, respectively. Even though all these methods give us great opportunities to monitor dramatic changes in the cryospheric environment, we should still conduct in-situ measurements to obtain physical and mechanical properties of ice such as stiffness. From the recent development on theoretical approach to predict the variability in DF microseisms [13] and the obvious evidence linking the variation of the DF energy to the SIC in this study, we anticipate that a long-term observation of the DF microseisms could be a good tool to monitor local climate change in Polar Regions. Most of literatures in seismology have dealt with several major issues such as determination of velocity and attenuation structures in the Earth, precise locating techniques, and investigation of earthquake sources. In this study, beyond that horizon, we find out that a seismological method could play a key role in understanding physical interaction between climate change and the cryosphere.

4. Conclusions

Substantial advances in seismograph technology allow us to consistently observe the Earth's continuous oscillation everywhere in the world. The DF microseism has been known that it is excited by ocean waves, thus it is likely to show seasonal variations [11]. Examining the ambient seismic noise level at KSJ1 during the period of from 2006-2011, we found a distinct seasonal pattern in the period of 4-10 s; the DF energy comes to be weaker from July through September (austral winter) in every year. Cross correlation results tell us that as the SIC becomes higher, the DF power decreases, and confirm that the DF energy responses immediately to the sea-ice condition. Consequently, we propose that a long-term observation of the DF microseisms should be necessary to monitor local climate change in Polar Regions, which contributes extra benefits to the satellite remote sensing.

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