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An analysis of the infrasound signal from the Miyagi-Oki earthquake in Japan on 16 August 2005

Il-Young Che, Hee-Il Lee, Jeong-Soo Jeon, and Tae-Seob Kang

Earthquake Research Center, Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea

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Following the 16 August 2005 Miyagi-Oki earthquake in Japan, coherent atmospheric infrasonic waves were observed at regional distances (1200–1500 km) using three seismo-acoustic arrays on the Korean Peninsula. A source-location procedure was applied to the distinct long-duration infrasonic signals to construct earthquake-generated infrasound source regions on the Japanese island arc. The results showed that the long-duration infrasonic signal was attributable to extensive seismic ground motions on land areas from the southwestern through to the northeastern part of the island arc as well as regions close to the earthquake epicenter. In many coherent infrasonic signals, an effect of seismic ground motions in sedimentary basins could be identified as a source of infrasound radiation from the large earthquake. These observations and interpretations were confirmed using predictions of possible infrasound arrival azimuth variation by converting real seismological data from the dense Japanese seismic network.

Key words: Infrasound, 2005 Miyagi-Oki earthquake, ground motion, ground-coupled air waves.

1. Introduction

Infrasound monitoring has been selected as a standard technology for detecting possible nuclear explosions in accordance with the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty. Recently, infrasound observation has also been applied in scientific research for monitoring volcanic activities and earthquakes and in the discrimination of anthropogenic seismic events (Bedard and Georges, 2000).

The Korea Institute of Geoscience and Mineral Resources and Southern Methodist University have been operating three permanent seismo-acoustic arrays (CHNAR, KSGAR, and BRDAR) in the Republic of Korea to observe seismic and infrasonic events (Stump *et al.*, 2004). The main purpose of these arrays is to discriminate anthropogenic explosions from natural earthquakes in and near the Korean Peninsula. To fulfill this aim, seismo-acoustic analysis has been applied to the data from these arrays to screen out artificial seismic events followed by distinct infrasonic signals (Che *et al.*, 2002). In addition to detecting anthropogenic infrasonic events, these arrays also provide an opportunity to study infrasound generated by natural phenomena on a global scale, such as large earthquakes, typhoons, and bolide events in Far East Asia.

Generally, earthquakes with magnitudes greater than the detection threshold of m_b-5.5 (Mutschlecner and Whitaker, 1998) generate atmospheric infrasound waves through low frequency oscillation of the Earth's surface near the epicenter and in surrounding regions. Near the epicenter, infrasound is generated by local vertical seismic motion; in surrounding regions farther from the epicenter, infrasound is generated by the interaction of surface waves with topographic features, such as mountains, through a process of diffraction (Le Pichon *et al.*, 2003; Mutschlecner and Whitaker, 2005). A third source of earthquake-associated infrasound is ground oscillation, which occurs when strong seismic surface waves arrive near the infrasound sensor (Kim *et al.*, 2004).

Japan is a typical island arc with various tectonic activities, including volcanism and the occurrence of large earthquakes. Clear barometric variations have been observed in association with large earthquakes in Japan (Watada *et al.*, 2006). The maximum change in atmospheric pressure, recorded using seismograms, has been associated with the arrival of Rayleigh waves (Watada *et al.*, 2006). These observations have verified the relationship between ground motion and the generation of infrasound.

On 16 August 2005, a strong earthquake with a magnitude of 7.2 occurred offshore of the Miyagi-Oki region of Japan, where large interplate earthquakes of $\sim$7.5 in magnitude have occurred repeatedly at intervals of $\sim$37 years (Okada *et al.*, 2005; Nakahara *et al.*, 2006). The epicenter of the 2005 Miyagi-Oki earthquake (38.2°N–142.3°E, 02:46 UT) was located off the east coast of Honshu with a thrust fault mechanism at a depth of 40 km (http://www.bosai.go.jp).

This study reports observations and analysis of the distinct infrasound associated with the 2005 Miyagi-Oki earthquake, especially as observed at regional distances in Korea. To analyze the infrasound data, a Progressive Multi-Channel Correlation (PMCC) method (Cansi, 1995) was used to detect coherent signals and to derive its wave parameters. This method has been proven to be very efficient in analyzing low-amplitude coherent waves within nonco-

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herent noise, including infrasonic signals from earthquakes (Le Pichon *et al.*, 2002). In addition, inverse location procedures applied to earthquakes (Le Pichon *et al.*, 2002, 2003) have been used to localize infrasound source regions. With the interpretation of location procedure results, real seismological data derived from the dense Japanese seismic network were used to predict possible arrival azimuth variations, which were in turn compared to measured variations.

2. Seismo-Acoustic Arrays

Three permanent seismo-acoustic arrays, CHNAR, KSGAR, and BRDAR, were in operation in the Republic of Korea at the time of the Miyagi-Oki earthquake infrasound observations. The CHNAR array, a triangular 1-km aperture seismo-acoustic array located in the northern part of the country, was originally installed in August 1999 with four pairs of collocated GS-13 short-period vertical seismometers and Validyne DP250 acoustic gauges. In November 2003, the KSGAR seismo-acoustic array was installed on the northeastern coast of the country. The design of the KSGAR array is similar to that of CHNAR, but with Chaparral Physics Model II sensors, flat to within 3 dB from 0.1 to 200 Hz, used in place of the Validyne gauges. To record highly correlated acoustic signals, four auxiliary acoustic gauges were placed several tens of meters distant from each main gauge. Three additional acoustic gauges were added at one station to make a small acoustic array with an aperture of about 100 m. When KSGAR was installed, the acoustic array in CHNAR was reconfigured by adding seven acoustic gauges and by replacing existing gauges with Chaparral Physics Model II sensors to make the two arrays similar. In October 2004, the third seismo-acoustic array, BRDAR, was installed on Baekryeong Island, located in the remote northwestern part of the country. The BRDAR array configuration is similar to the previous arrays, but with one more station consisting of a seismometer and two acoustic sensors to increase detection resolution. All acoustic sensors in these arrays are connected to wind noise reducers consisting of ten porous hoses in a radial pattern with a diameter of 16 m. Seismic and infrasound signals from the arrays are digitized at 40 samples per second and linked in real time.

3. Infrasound Observations and Source Locations

The Miyagi-Oki earthquake on 16 August was a major earthquake in 2005. Following the earthquake, ground-coupled air waves were recorded at an infrasound monitoring station (IS30) in Japan (Honma *et al.*, 2006). The coupled airwaves propagated in all directions, and some of their energy was clearly observed at the three distant seismo-acoustic arrays in Korea (KSGAR, CHNAR, and BRDAR, in order of arrival); the horizontal distance from the epicenter to the arrays was ∼1200, ∼1300, and ∼1500 km, respectively, great circle azimuths from each array to the epicenter are 87.7°, 85.6°, and 83.6°, respectively. The relative distances from the epicenter to the arrays in time delay of the sequential arrivals were ∼7 (CHNAR) and 17 min (BRDAR) after arrival at KSGAR.

Figure 1 shows the long-duration infrasonic signals recorded at KSGAR and the azimuth variations of the source directions and apparent velocities of the coherent signals. The infrasonic signal showed a lens shape in the dominant frequency band of 0.2–2.0 Hz and a pressure change of about 0.4 Pascal (for KSGAR), and lasted up to 40 min at all arrays. This characteristic long signal duration, compared to the short duration of seismic source time, implies that the infrasound source is not restricted to ground motions in a limited area, such as near the epicenter; rather, many parts of the signals may be attributable to additional sources.

The azimuth variations were the result of array processing using cross-correlation among 11 elements of infrasonic signals recorded at KSGAR (realized by WinPMCC v 2.1). For KSGAR, the estimated arrival azimuths started at 124° (measured clockwise from the north) in the front part of the long-duration signals and decreased over time, ending at about 62°. The results for BRDAR and CHNAR had similar azimuth variations, about 118°–53° and 113°–55°, respectively.

Distant source locations generating infrasonic waves were constructed based on the inverse location procedure using a celerity model (propagation range from the source divided by travel time; Le Pichon *et al.* (2002)). The known earthquake origin time and epicenter coordinates made it possible to localize the source regions with the measured azimuth and slowness variation from the infrasound signals. We used a constant velocity of 3.3 km/s for seismic surface waves propagating out from the epicenter. Local meteorological observations (ground to ∼30 km in altitude) in Japan and the empirical atmospheric models MSISE90 and HWM-93 were used to model the atmospheric infrasound propagation using a reformulated tau-p method (Garcés *et al.*, 1998). The propagation modeling showed that infrasonic waves were mainly refracted from stratospheric regions in addition to weak signals from thermospheric regions. Figure 2 shows a result from the location procedure: infrasound source locations in terms of arrival times of infrasound at KSGAR. A celerity of 0.29 to 0.31 km/s determined by ray tracing was used in determining the locations. In addition, ray path deflections caused by winds normal to the propagation direction were corrected as a function of latitude, $-1.0°$ in the south and $+1.5°$ in the north, values also calculated from ray path modeling using the atmosphere model. In Fig. 2, infrasound coupled by the ground motion of the Miyagi-Oki earthquake was excited extensively on the Japanese island arc, including regions near the epicenter. The colors of arrival times indicate that the source regions passed from the southwest to the northeast along the island arc. In terms propagation of seismic surface waves, peak ground motions for the regions far from the epicenter would be excited within ∼4 min (∼800 km) of initiation of the earthquake. Thus, direct atmospheric coupling from ground motion would be made during that time. However, geographically different horizontal distances from each source region to KSGAR indicate that the arrivals extend for a period of up to 40 min. Regions closer to an array than the epicenter (the southern part of Honshu) generated a signal prior to the peak signal, and regions farther from the arrays than the epicenter (Hokkaido) generated the latter part of the long-duration signal. However, the peak infrasonic signal was nearly coincident with the

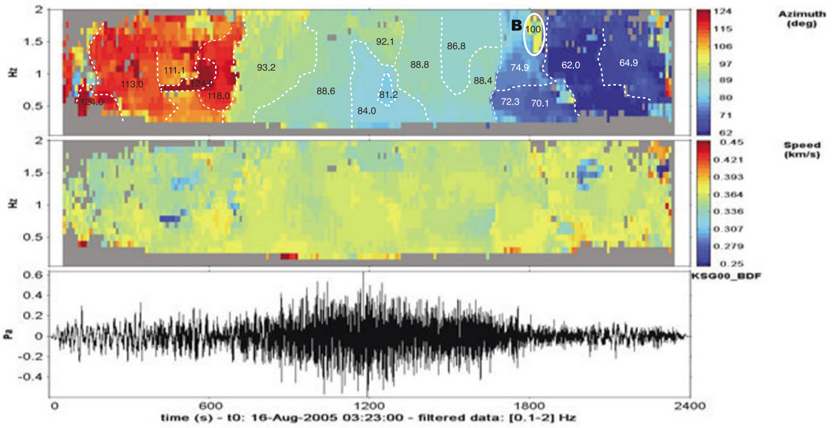

Fig. 1. Results of Progressive Multi-Channel Correlation (PMCC) calculations on infrasonic recordings at the KSGAR array in terms of the azimuth (upper), apparent velocities (middle), and waveforms (lower) in the 0.1–2.0 Hz frequency band. Numeric values in the azimuth panel indicate local azimuth values separated by dotted lines. The mark "B" indicates the azimuth due to infrasonic sources from ground motion in the Kanto Basin.

regions close to the epicenter and its travel velocity was estimated to be about 0.3 km/s.

Although the source regions, based on arrival times, gradually changed along the arc from the southwest to the northeast, some complexities exist in the arrival azimuths (Figs. 1 and 2). Local variations in the azimuths may be explained by differences in coupling rates among regions. Destructive and constructive interference among infrasonic waves generated from different regions could also explain these complexities. Some of the signals related to seismic ground motions in the Kanto Basin, a large sedimentary basin, and its surroundings were particularly remarkable. Strong ground motion data (discussed later) estimated a longer duration in the basin relative to other regions, when duration is defined as the time interval between the points at which 5% and 95% of the total energy is recorded (Trifunac and Brady, 1975). The duration of strong motion in the basin is estimated to be up to 150 s, two- or threefold longer than in other non-basin regions, indicating that longer infrasound generation is possible in the basin. Because the distance from KSGAR to the basin is similar to the distance to regions generating strong infrasound near the epicenter, the initial motions are almost hidden by the overwhelming signals from regions near the epicenter. However, the longer ground motion in the basin occurred in the latter part of the signal (denoted as "B" in Fig. 1). This basin-associated signal could appear when only slight infrasound was produced in other regions. The occurrence coincided with the arrival of infrasound from rare land regions in the Tsugaru Strait, separating Honshu and Hokkaido in northern Japan. Because the distances to the basin and the strait are nearly equal, while no or weak generation of infrasound occurred in the strait, infrasound from the basin could be observed at KSGAR.

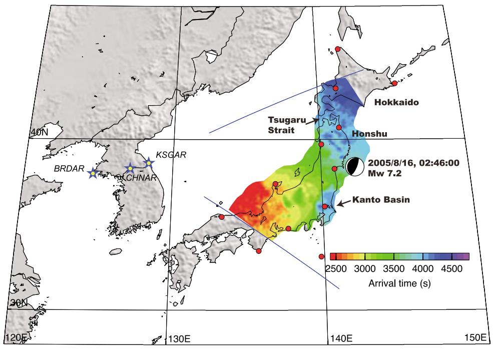

Fig. 2. Distribution of infrasound source locations based on arrival times determined from infrasonic recordings at the KSGAR array. The beach ball indicates the fault mechanism and location of the 2005 Miyagi-Oki earthquake. Solid red circles indicate locations of local meteorological observations in Japan.

To confirm the interpretation of infrasound arrivals, we predicted possible arrival azimuth variations from real ground motions. For this purpose, we used strong ground motion records obtained by the K-NET, National Research Institute for Earth Science and Disaster Prevention (NIED; Kinoshita (1998)). The K-NET, with about a 25-km average distance between stations, provided a total of 456 recordings at different stations in Japan for the Miyagi-Oki earthquake. This quantity of observations enabled us to re-create consecutive spatial distributions of the ground motion after source initiation. We first converted accelerograms to velocity seismograms, considering the direct relationship between ground velocity and atmospheric pressure change, and cut the seismograms to include the dominant surface wave part with a speed of 2.7–4.3 km/s. Next, to determine the azimuth variation with respect to frequency, we applied a 10-band Gaussian filter between 0.2 and 2.0 Hz. Interpolation was performed to produce maps of ground velocity amplitude at equally spaced grids on land. The grid size (wavelength) was set at 6 km, considering the general propagation speed of surface waves and period, i.e., ∼1.5 s, of surface waves. Every grid in each interpolated ground motion map had its own location, ground velocity of the vertical ground motion, and estimated arrival time at KSGAR. These maps provided the progression of surface wave energy across the arc. All points in the maps were projected into arrival time and frequency plane. Amplitude (ground velocity) was then used for weighting values to find the maximum value to select an azimuth at each window in time and frequency. The predicted azimuth variation esti-

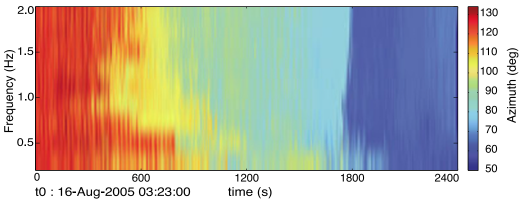

Fig. 3. Prediction of possible infrasound azimuth variations using real ground motion data.

mated from the real seismograms is shown in Fig. 3. This result agreed reasonably well with the measured arrival azimuth variation; both indicated that arrivals shifted from the southwest to the northeast, although the details (Fig. 1) were not exactly coincident. Sustained seismic waves in the Kanto basin from the short-period K-NET data are falling outside the frequency band (0.2–2.0 Hz) used in the prediction. Thus, the effects of ground motions in the Kanto basin are not shown in the result (Fig. 3). The prediction identified a sudden change in azimuth variations when skipping infrasound generation at Tsugaru Strait with an arrival time of about 1800 s. Furthermore, the prediction also confirmed the interpretation of infrasound arrivals and generation and the detection of ground motions from a large earthquake.

4. Conclusions

Earthquake-generated infrasound observed at a regional distance was used to image remote ground motions as sources of infrasound. Characteristics of the long-duration infrasonic signal from the submarine Miyagi-Oki earthquake were attributable to ground-to-air coupling of extensive on-land areas in the Japanese island arc. The increasing horizontal distance to the arrays, with the southwest to northeast distribution of ground motions, resulted in the expanded signal duration of up to 40 min in the present observations.

Although the ground-coupled air waves were observed at a regional distance, different ground-to-air coupling patterns were identified. One location identified in this study was particularly interesting because of seismic motions trapped in a sedimentary basin. In addition to violent earthquake ground motions near the epicenter and the radiation in mountain regions caused by interacting with surface waves, the comparatively long duration of ground motion in the sedimentary basin could be defined as one source of infrasound related to the large earthquake.

Direct conversion of real seismic ground motion based on the relationship between pressure change in air and ground velocity allowed the prediction of possible arrival azimuth variation from sources. The predicted variations generally coincided with observed variations and confirm the interpretations of this study and earthquake-associated infrasound generation mechanisms.

Based on these infrasound observations from Korea, not all large earthquakes in the Japanese island arc have been accompanied by detectable infrasonic signals. About 160 earthquakes larger than magnitude 5.5 occurred in the Japanese island arc since August 1999. However, infrasonic signals from only 11 large earthquakes were observed at the arrays although all earthquakes have not yet been investigated. The occurrence of infrasound may be related to characteristics of ground motion in the source region. Another important factor in determining the possibility of infrasound may be related to seasonally dependent dynamic atmospheric conditions. Therefore, future studies aiming to comprehensively understand earthquake-generated infrasound should consider characteristics of ground motions and examine detailed atmospheric conditions.

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I.-Y. Che (e-mail: che10@kigam.re.kr), H.-I. Lee, J.-S. Jeon, and T.-S. Kang