Acoustic VLP signals accompanying the continuous ash emission following Vulcanian eruptions

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Acoustic observation of active volcanoes has been provided the considerable information to understand the source process of volcano explosions (e.g., Fee and Matoza, 2013). However, Very Long Period (VLP) signals of acoustic wave accompanying volcanic explosions are poorly understood.In 2012-2013, we have conducted broadband seismic and infrasound observations of Vulcanian eruptions at Lokon-Empung volcano in Indonesia. The temporal observation network consists of 4 broadband seismometers (Trillium 40, Nanometrics Inc., 0.025-50 Hz) and an infrasound microphone (SI 102, Hakusan Co., 0.05-1500 Hz). About 80 % of observed vulcanian explosions are followed by the continuous ash emissions, which is recognized as the vibration in the seismic and infrasound waveforms. We find a VLP phase at the onset of the vibration in the band pass (0.03-0.1 Hz) vertical displacement waveforms and 0.1 Hz low pass pressure waveform. The apparent propagation velocity of the VLP phase at each station can be explained by the sound velocity near the ground from the vent. Hence, it is regarded that the VLP phase is induced by the acoustic wave accompanying the continuous ash emission. We analyze the broadband seismic data because the signals that have the period longer than 20 s (out of range of the flat pressure response of the microphone) dominate the band pass ground displacement waveforms.Similar VLP signals accompanying the continuous emission following the Vulcanian eruption can be seen in the broadband seismic records at Shinmoedake volcano in Japan in 2011. National research Institute for Earth science and Disaster prevention (NIED) has operated two broadband seismometers (Trillium 240, Nanometrics Inc., 0.004-200 Hz) and two barometers (AP270, Koshin Co.) near the active vent during the period of the activity of Shinmoedake in 2011. Seismic waveforms of Vulcanian eruptions on Jan. 27, 2011 show the explosive signals accompanying theexplosion and subsequent tremor induced by the continuous ash emission. Two infrasound microphones operated by Japan Meteorological Association (JMA) also recorded the signals associated with continuous ash emission after the explosion. We see the VLP phase propagating from the vent with the sound velocity accompanying the ash emission in the band pass (0.01-0.05 Hz) vertical displacement waveforms. The pressure change similar to the VLP phase is seen from the filtered (0.01-0.05 Hz) pressure waveforms recorded by the barometers.The maximum amplitude of vertical velocity of the VLP phase at both Lokon-Empung and Shinmoedake is in order of 10^{-7} m/s at 2-5000 m from the vent. The vertical velocity of the ground induced by the pressure change in the atmosphere is given by Ben-Menahem and Singh (1981). If we set the P-wave velocity and density of the ground as 2700 m/s and 2500 kg/m^3 as tentative values, we obtain the pressure change inducing the VLP phase at each station is in order of the 10^1 Pa. Since the signals having the wavelength about 10^3 m constitutes of the VLP phase, we can assume that the VLP phase can be excited by the point source at the vent and propagates as a linear sound wave. Based on this assumption, we can estimate the rate of mass outflow of the atmosphere (Lighthill, 2001) at the source. With the dry-air density in the atmosphere (1 kg/m^3), we estimate the mass flow rate of atmosphere in order of the 10^5 m^3/s. Although this estimation includes the effects of the amplification factor of the stations and wind noise, it is consistent to the mass flow rate of Vulcanian eruptions reported by the previous works (e.g., Koyaguchi, 2008). Therefore, the excitation of the VLP phase can be explained by the pressure change accompanying the formation of the ash column. Further investigation of the VLP phase can contribute to understand the dynamics of

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the ash column and source process of Vulcanian eruptions.

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