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Atmospheric resonant oscillations by the 2014 eruption of the Kelud volcano, Indonesia, observed with the ionospheric total electron contents and seismic signals

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ABSTRACT

Acoustic waves from volcanic eruptions are often observed as infrasound in near fields. Part of them propagate upward and disturb the ionosphere, and can be observed with Total Electron Content (TEC) data from Global Navigation Satellite System (GNSS) receivers. Here we report TEC variations after the 13 February 2014 Plinian eruption of the Kelud volcano, East Java, Indonesia, observed with regional GNSS networks. Significant disturbances in TEC were detected with six GNSS satellites, and wavelet analysis showed that harmonic oscillations started at ∼16:25 UT and continued for ∼2.5 h. The amplitude spectrum of the TEC time series showed peaks at 3.7 mHz, 4.8 mHz and 6.8 mHz. Long-wavelength standing waves with a wide range of wavelength trapped in the lower atmosphere are excited by the Plinian eruption. Amplitude spectra of the ground motion recorded by seismometers, however, had frequency components at discrete wave-periods. The condition for the resonant oscillations between the atmosphere and the solid Earth is satisfied only at these discrete wave-period and horizontal wavelength pairs, therefore efficient energy transfer from the atmospheric standing waves to the solid Earth Rayleigh waves occurred at discrete periods and resulted in the harmonic ground motion.

1. Introduction

Large volcanic eruptions often disturb the upper atmosphere including the ionosphere of the earth. Such disturbances can be observed by GNSS receivers as changes in TEC. For example, an N-shaped change in TEC, lasting for ∼100 s, was found after the 2004 September Vulcanian explosion of the Asama volcano, central Japan (Heki, 2006). Such disturbances are caused by compressional pulse in the neutral atmosphere propagating upward as an acoustic wave. A longer-lasting volcanic eruption often show a different type of atmospheric disturbances. For example, Dautermann et al. (2009b) detected ionospheric disturbances excited by the eruption of the Soufriere Hills volcano, the Lesser Antilles, in 2003. They included 1.4 mHz internal gravity wave and ∼4 mHz atmospheric eigenfrequency components. Dautermann et al. (2009a) investigated the strain gauge records after this eruption, and also found the ∼4 mHz oscillation in the solid earth.

Such resonant oscillations of the lower atmosphere are also observed by GNSS-TEC after large earthquakes. Choosakul et al. (2009) reported that the 2004 Sumatra–Andaman earthquake excited ∼4 mHz oscillation in the ionospheric lasting for hours. Rolland et al. (2011) analyzed various types of ionospheric perturbations by the 2011 Tohoku-oki earthquake. It includes an N-shaped wave excited by the Rayleigh wave, and the 3.7 mHz and 4.4 mHz acoustic-trap-modes excited in the lower atmosphere and leaked into the ionosphere. Then, the internal gravity wave appeared ∼45 min later and propagated concentrically outward by ∼225 m/s from the epicenter. Saito et al. (2011) detected 3.7 mHz, 4.5 mHz and 5.3 mHz frequency peaks in the TEC changes. Nishioka et al. (2013) reported internal gravity waves and lower atmospheric trapped waves excited by the 2013 moore EF5 tornado.

Atmospheric resonant oscillations also excite secondary oscillations in the solid Earth, and their frequencies are explained by the

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normal mode theory (Lognonné et al., 1998). The Rayleigh waves in very long period seismograms, after the 1991 Pinatubo eruption, had two peaks, which are interpreted as coupling between the atmospheric oscillations excited by the volcanic eruption and the Rayleigh wave (Kanamori and Mori, 1992). Widmer and Zürn (1992) also reported vertical oscillations of the ground observed by gravimeters around the world. Later, Kanamori et al. (1994) proposed physical mechanisms of such oscillations, but the ground motion period is underestimated about 10%.

Watada and Kanamori (2010) provided an excitation mechanism; the fundamental and overtone of the atmospheric long-wavelength acoustic waves trapped in the low-sound velocity channel in the atmosphere below the thermosphere, and the fundamental mode which propagated as Rayleigh waves in the solid Earth share the same horizontal wavelength along the ground surface and the same wave periods. This acoustic resonance between the atmosphere and the solid Earth resulted in the observed harmonic ground motion composed of Rayleigh waves at two resonance periods. They employed the normal mode method for a combined Earth model with the solid Earth, the ocean and the atmosphere up to 200 km altitude, and succeeded in re-producing as a normal mode summation the harmonic ground motion excited by a point source that models a volcanic eruption in the atmosphere.

In this paper, we report preliminary observation results of harmonic oscillations in ionospheric TEC and seismic records after the 2014 February Plinian eruption of the Kelud volcano, eastern Java, Indonesia. The Kelud volcano is a very explosive volcano, and has erupted 8 times for the last one hundred years. The 2014 February eruption fractured the lava dome made by the 2007 eruption and created a new crater (Sulaksana et al., 2014). Corentin et al. (2015) interpreted the eruption sequence from infrasound and seismic observations. The oscillation in the ionosphere and lithosphere would have been caused by the lower atmospheric trapped waves excited by this eruption. We compare the results from the two kinds of sensors, and discuss how the 13 February 2014 Kelud volcano eruption excited these atmospheric trapped waves, from the oscillations observed in the ionosphere and the solid Earth.

2. Data analysis and results

2.1. GNSS-TEC data

Ionospheric delays of microwave signals from GNSS satellites are frequency dependent, and phase differences between the L1 and L2 carriers provide information on the ionosphere between the satellite and the ground station. TEC is the number of electrons integrated along the line-of-sight, and can be calculated from the L1 and L2 phase differences. We extracted the TEC information before and after the 2014 February eruption of the Kelud volcano from the raw data of 37 GNSS stations in and around Indonesia. The observation data are from three networks, (1) the GNSS network in Java run by the Badan Informasi Geospasial (BIG), (2) Sumatra GPS Array (SuGAr) operated in Sumatra by Indonesian Institute of Science and California Institute of Technology, and (3) International GNSS Service (IGS) stations (Fig. 1). The SuGAr stations observed only Global Positioning System (GPS), the American GNSS, every 15 s. Other stations received signals from both GPS and GLONASS (GLObal'naya NAvigatsionnaya Sputnikovaya Sistema), the Russian GNSS, every 30 s, except for COCO where only GPS data are recorded.

We extracted the components with periods around 270 s from slant TEC time series using the Mexican-hat wavelet. In order to make it possible to compare amplitudes between different station–satellite pairs, we converted the amplitudes into those in vertical

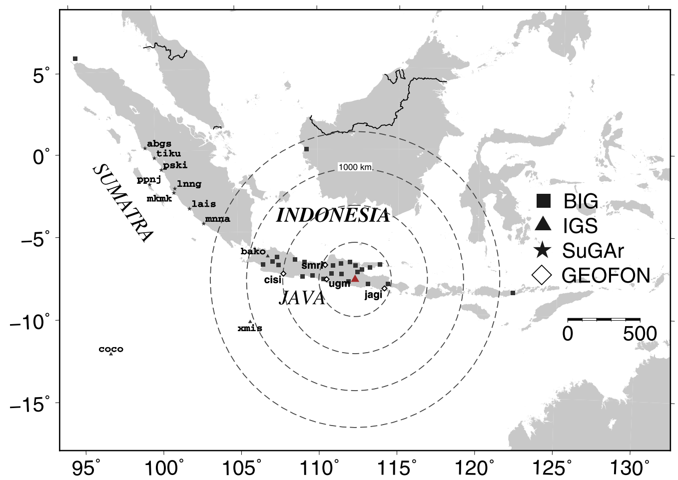

Fig. 1. Map of the Java Island and nearby islands, and the GNSS stations and broadband seismometers used in this study. The Kelud volcano is marked with the red triangle in Eastern Java Island. Black triangles and stars indicate IGS and SuGAR stations, respectively. We use also 26 stations which are run by BIG. White diamonds show GEOFON stations whose waveforms are shown in Figs. 3 and 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

TEC by multiplying with the cosine of the incidence angle of the line-of-sight with a thin layer at 250 km height. This height is also used to calculate the coordinates of sub-ionospheric points (SIPs).

After extracting the 270 s components, we estimated their propagation velocity by plotting the time and distance from the volcano of the TEC disturbances following Rolland et al. (2011). The estimated propagation velocity was ∼0.8 km/s, close to the acoustic wave speed in the F region of the ionosphere, and the oscillation in this period continued from 16:25 UT to 19:00 UT (Fig. 2). The SIPs of the disturbance in this frequency show clear concentric wavefronts propagating outward from the volcano (Fig. 2(c), Animation S1).

We obtained the frequency spectrum of the TEC oscillations. First, we extracted components with frequencies 2.0–8.0 mHz with a band-pass filter for the stations within 1000 km from the volcano. At first, for individual satellites, we adjusted the time axes of the time series of different stations assuming 0.8 km/s as the propagation velocity. The TEC data obtained with the same satellite results have similar geometry, and geometry plays an important role in TEC observations. We confirmed that these waveforms have similar structure, and then we further stacked them again (Fig. 3(a)), and then converted the doubly-stacked time series into the frequency domain. The spectrum showed two clear peaks at 3.7 mHz and 4.8 mHz (Fig. 3(a)).

2.2. Seismic data

The 2014 eruption of the Kelud volcano was a very explosive one and it caused many solid Earth and atmospheric events which destroyed observation instruments near the volcano. Corentin et al. (2015) investigated the eruption sequence with remote (>200 km) low-frequency-seismic (<0.2 Hz) and infrasound data. They found three types of seismic signal (S_LL: long lasting wave, S_P1: only visible nearby sites and S_P2: short-duration energetic signal) and two types of infrasound signal (I_1: first event and I_LL: long lasting second event) and constructed the eruption sequence from difference of these signals. Here we also look into the eruption time-line from the seismometer records of periods 17–33 s observed at three stations with the STS-2 broadband sensors of GEOFON ∼200 km from the volcano, and another GEOFON station ∼500 km from the volcano (Fig. 4). The signal first appears at