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Harmonic Ionospheric Oscillation by the 2010 Eruption of the Merapi Volcano, Indonesia, and the Relevance of its Amplitude to the Mass Eruption Rate

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Abstract: Using continuous data from ground-based Global Satellite Navigation System (GNSS) receivers in Java and Sumatra, Indonesia, we studied the response of ionospheric total ionospheric electron content (TEC) to the 2010 Nov.5 eruption of the Merapi volcano in central Java. We then compared the results with the case of the 2014 Feb.13 eruption of the Kelud volcano, eastern Java. The TEC showed a quasi-periodic oscillation of a frequency ~4 mHz with average amplitudes of 0.9 and 1.8 % relative to background values lasting for ~20 and ~120 minutes for the Merapi and Kelud eruptions, respectively. By comparing the two cases, together with the 2015 April eruption of the Calbuco volcano, Chile, we found the relative TEC oscillation amplitude may scale with the mass eruption rate. This suggests that the product of such TEC oscillation amplitude and the duration provides a new measure for the total volume of the volcanic deposits.

Keywords: GNSS-TEC, Ionospheric disturbance, Plinian eruption, Indonesia, Merapi, Kelud, Calbuco

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Introduction

Explosive volcanic eruptions make severe atmospheric perturbations like blast or infrasound. They are often detected by barometers or microphones installed on the ground (e.g. Dabrowa et al., 2011; Matoza et al., 2019). Infrasound monitoring is vital to detect eruptions from the far-field and/or during the nighttime. Such infrasounds are typically monitored with barometers or microphones installed on the ground, enabling us to infer acoustic energy using shock waves and frequency contents. However, it is difficult to detect the acoustic energy propagating to upper atmospheric layers with these conventional instruments.

Such acoustic disturbances are also detected as perturbations in the ionosphere. The ionosphere is the ionized region of the Earth's upper atmosphere and ranges from ~60 to over 1,000 km above ground. It shows diurnal variation governed by solar radiation and is often disturbed by solar and geomagnetic activities. Ionospheric disturbances occur also by activities below, such as earthquakes, tsunamis, and volcanic eruptions. The ionospheric total electron content (TEC) is easily measured with dual-frequency receivers of the Global Satellite Navigation System (GNSS) such as Global Positioning System (GPS) (e.g.

Hofmann-Wellenhof et al., 2008). Continuous observation with dense GNSS networks are useful to study such ionospheric disturbances (Figure 1).

In addition to ionospheric disturbances by large earthquakes (e.g. Heki, 2020) and tsunamis (e.g. Occhipinti et al., 2013), those by volcanic eruptions have been reported (e.g. Astafyeva, 2019). Heki (2006) used the GPS-TEC technique to study the ionospheric response to the Vulcanian explosion of Asama volcano, central Japan, on September 1, 2004. TEC showed transient N-shaped disturbances of a period 1-2 minutes, ~10 minutes after the explosion. Such a TEC change occurs when the acoustic wave excited by the explosion arrives at the ionospheric F region (altitude ~300 km) and make electron density anomalies there (Figure 1 left). The disturbance propagates mainly toward the equator, due to interaction of the ambient geomagnetic fields, with the acoustic wave speed in the F region. For the 2004 Asama eruption, Heki (2006) estimated the explosion energy by comparing the TEC disturbance amplitude with an artificial explosion with known energy (Calais et al., 1998). Nakashima (2018) also studied TEC disturbance signals after the 2015 eruption of the Kuchinoerabujima Volcano, south of Kyushu, Japan.

In contrast to such explosive eruptions, harmonic oscillations of TEC of ~4 mHz often emerge from strong continuous eruptions (Figure 1 right). For example, an oscillation of TEC lasted for ~2 hours associated with the 2003 eruption of the Soufrière Hills volcano, Montserrat, as reported by Dautermann et al. (2009a, b). Nakashima et al. (2016) used GNSS receivers in Indonesia to analyze the TEC response to the 2014 February Plinian eruption of the Kelud volcano eastern Java, Indonesia. They reported resonant oscillations of TEC lasting for ~2 hours. Later, Shults et al. (2016) reported similar TEC oscillations lasting ~1.5 and ~6 hours during the two Plinian eruption episodes on 22 and 23 April 2015, of the Calbuco volcano, Chile.

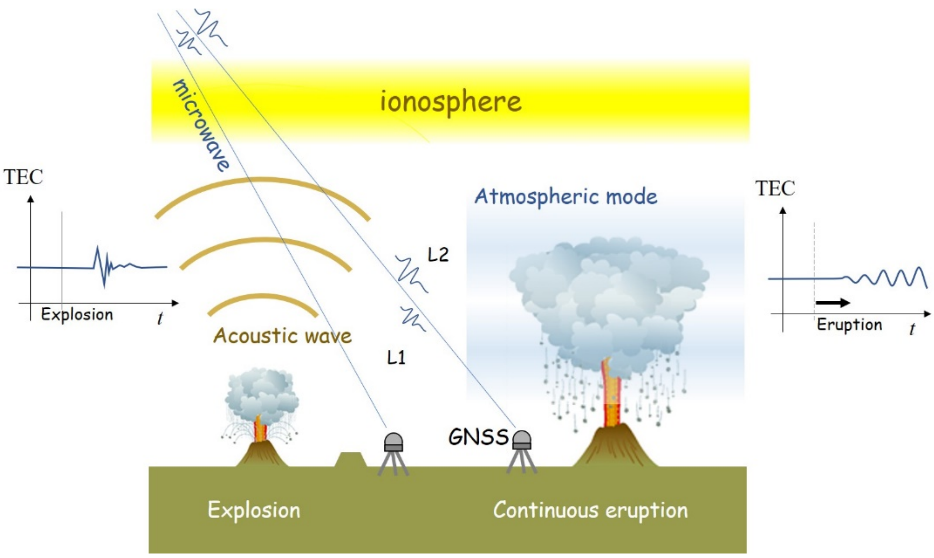

Figure 1. Ionospheric disturbance caused by explosive (left) and continuous (right) volcanic eruptions can be detected by differential ionospheric delays of microwave signals in two carrier frequencies from GNSS satellites. Explosive eruptions often cause transient disturbances in ionosphere while continuous eruptions sometimes excite atmospheric modes and continuous oscillatory disturbances in ionosphere.

GNSS-TEC technique has been applied to study coseismic ionospheric disturbances for tens of cases (Heki, 2020). Like volcanic eruptions, they are characterized by N-shaped disturbances propagating as acoustic waves with magnitude-dependent amplitudes (Cahyadi and Heki, 2015). Acoustic waves propagating upward are bounced back, causing resonant oscillations in distinct frequencies (Tahira 1995). Acoustic resonance in 3.7 and 4.4 mHz was found in background free-oscillations of the solid earth (Nishida et al., 2000), and these frequencies were identified in post-seismic monochromatic TEC oscillations by GPS-TEC after the 2004 Sumatra-Andaman earthquake (Choosakul et al. 2009), the 2011 Tohoku-oki earthquake (Rolland et al. 2011; Saito et al. 2011), and the 2007 Bengkulu earthquake (Cahyadi and Heki 2013).

Harmonic oscillations, often observed during large continuous volcanic eruptions, are also due to such acoustic resonances of the atmosphere. Kanamori et al. (1994) found atmospheric resonance frequency components lasting >5 hours in seismometer records after the 1991 eruption of the Pinatubo volcano, the Philippines, and Watada and Kanamori (2010) considered that harmonic ground oscillation is due to atmospheric resonance excited by continuous eruption of the volcano.

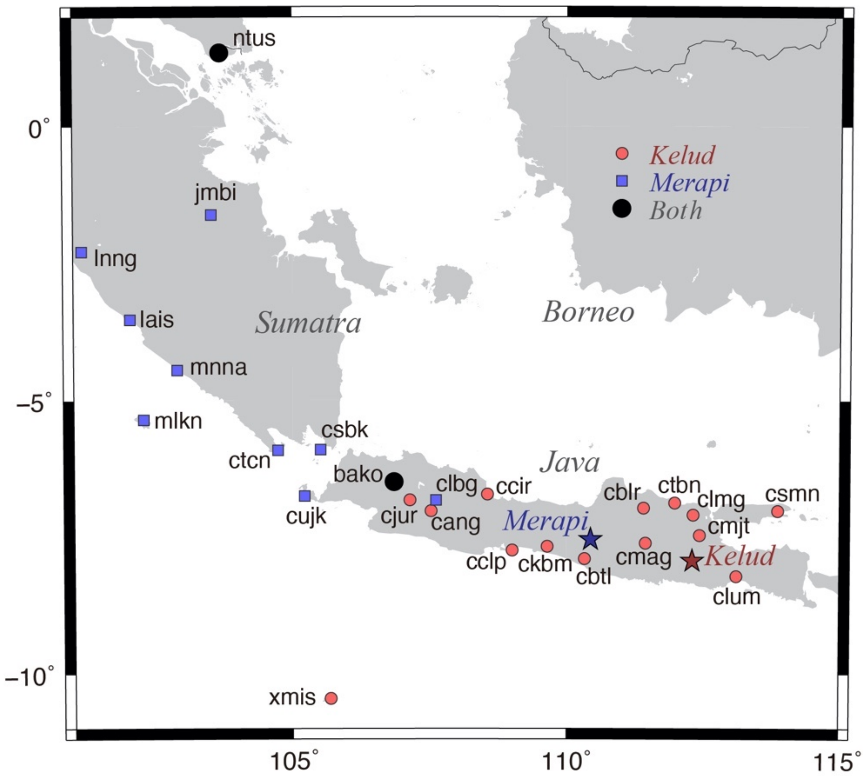

Figure 2. GNSS stations used in this study in Java, Sumatra, and nearby islands. The Kelud volcano, Eastern Java, and the Merapi volcano, Central Java, are marked with the red and blue stars, respectively. Blue and red rectangles show GNSS stations used to study the Merapi and the Kelud eruptions, respectively. The two black circles show stations used for both cases.

Here we present a new example of ionospheric disturbances by the 2010 Merapi eruption and compare the results with past examples, i.e. the 2014 Kelud eruption (Nakashima et al., 2015) and the 2015 Calbuco eruption (Shults et al., 2016), to better understand ionospheric disturbances by continuous volcanic eruptions. We also explore the possibility of ionospheric disturbances as new information to complement classical indices like Volcanic Explosivity Index (VEI).

Volcanic eruptions and GNSS data in Indonesia

Merapi volcano, central Java, Indonesia, erupted repeatedly with average intervals of 4-6 years. The 2010 eruption sequence of the Merapi volcano started after 4 years of quiescence with a phreatomagmatic blast on October 26. The activity peaked at midnight on November 4 (November 5 in local time) and lasted until July 15, 2012. This eruption sequence changed the summit morphology drastically (Surono et al., 2012) and is regarded as one of the most violent events of this volcano in its observation history. The details of this eruption sequence are available in articles included in the special issue of this journal (Jousset et al., 2013).

According to the eruptive timeline of the 2010 eruption compiled by Komorowski et al. (2013), the activity started as the non-eruptive stage 1 characterized by various kinds of unrest. Then, the phreatomagmatic blast on October 26 occurred as stage 2, and it is followed by stage 3 characterized by recurrent rapid dome growth and destruction explosion and collapse. The ionospheric signals discussed in this study are found around ~17:30 UT, November 4 (00:30 LT, November 5), shortly after the most intensive phase (stage 4). The stage 4 started at 17:02 UT, November 4 (00:02 LT, November 5), followed by a paroxysmal eruption lasting for ~10 minutes. The plume height reached 17 km during this stage (Carr et al, 2020). Then subsequent sub-Plinian eruption lasted for ~3 hours (stages 5 and 6). VEI of the whole eruption sequence is recorded as 4.

We used data from 11 permanent tracking dual-frequency GNSS stations in the InaCORS (Indonesian Continuously Operating Reference Stations) network and IGS (International GNSS Service) network around the volcano (Figure 2). The details of the methods to extract TEC from raw GNSS data are explained in Heki (2020). We converted the ionospheric linear combination, i.e. the phase differences of the two microwave carriers (L1: ~1.5 GHz and L2: ~1.2 GHz), into TEC. Figure 3 shows examples of the TEC changes during 16-18 UT observed using ~10 different GPS satellites at two GNSS stations.

For the February 13, 2015, VEI 4 Plinian eruption of the Kelud volcano, eastern Java, Nakashima et al. (2016) performed GNSS-TEC studies using InaCORS and IGS stations around the volcano (Figure 2). The climactic phase of this eruption started around 16:10–16:15 on that day, and the eruption column reached ~26 km above sea level, and the umbrella cloud laterally spread at a height of 18–20 km (Suzuki and Iguchi, 2019). The period of the TEC oscillation reported in Nakashima et al. (2016) occurred during this phase.

For comparison, we discuss ionospheric disturbances after the April 22-23, 2015, Calbuco volcano eruption reported in Shults et al. (2016). There we downloaded GNSS data from the Argentine GNSS network RAMSAC (Red Argentina de Monitoreo Satelital Continuo) (http://www.ign.gob.ar) and processed the data in the same way as the two other eruptions. The two Plinian eruption episodes on April 22 and 23 with TEC oscillations correspond to stages 3 and 4, respectively, of the eruption sequence compiled by Romero et al. (2016). The plume of these eruptions had the maximum height of 23 km above sea level

(Van Eaton et al, 2016), and the VEI was recorded as 4.

Original TEC is the slant-TEC (STEC), number of electrons integrated along the line-of-sight (LoS) connecting satellites and receivers. They are usually expressed using TECU (TEC unit, 1 TECU = 10^{16} el/m^2). After removing the inter-frequency bias using differential code bias (DCB) in the header information of Global Ionospheric Maps obtained from University of Berne, Switzerland (www.aiub.unibe.ch/download/) (satellite bias) and the receiver bias determined by minimum scalloping (Rideout and Coster, 2006), we convert STEC to vertical TEC (VTEC) by multiplying them with the cosine of the incidence angle of LoS at the ionospheric piercing point (IPP) with a hypothetical thin layer at the altitude of maximum ionization (300 km in this study). Propagation of ionospheric disturbances is represented by using the ground projection of IPP called sub-ionospheric points (SIP).

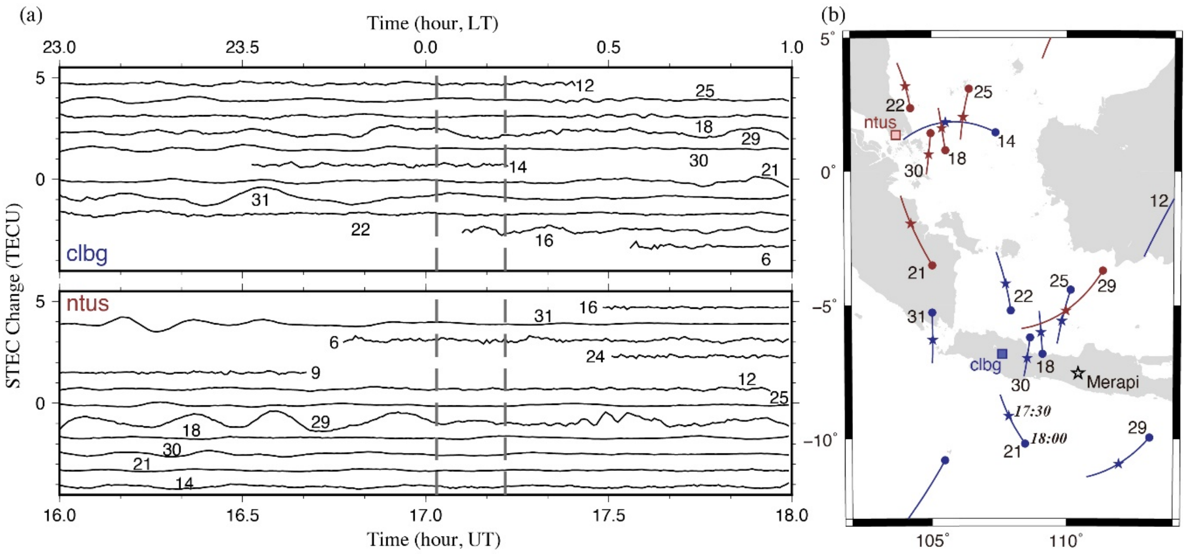

Figure 3. (a) Time series 16.00–18.00 UT (23:00 to 01:00 in LT), Nov.5, 2010, of STEC changes observed at the two GNSS stations, clbg and ntus. The period within the two dashed vertical lines corresponds to the stage 4 of the 2010 Merapi eruption (17:02-17:13 UT) (Komorowski et al., 2013). Ionospheric TEC oscillations are seen 20 minutes after the eruption with satellites 25 and18 from clbg and with satellite 29 from ntus. (b) Trajectories of SIP for GPS satellites in 17.1-18.0 UT as seen from clbg (blue) and ntus (red) stations. On the trajectories, small stars indicate SIP at 17.5 UT, and filled circles indicate those at 18.0 UT.

TEC oscillation and its propagation after the 2010 Merapi eruption

Figure 3a shows TEC time series high-pass filtered by subtracting the best-fit polynomials with degrees 8 (Heki, 2020). The period within the two dashed vertical lines indicates the stage 4 of the 2010 Merapi eruption (17:02-17:13 UT) (Komorowski et al., 2013). Ionospheric TEC oscillations started shortly after the end of stage 4 (~17:20 UT) with GPS satellites 18 and 25 from the clbg station (Figure 3a top) and with GPS satellite 29 from ntus (Figure 3a bottom). The TEC oscillation has periods of 4-5 minute. N-shaped disturbances are often seen after explosive volcanic eruptions (e.g. Heki, 2006), but these types of signals were not observed. Figure 3b shows that SIP tracks of these satellites are located near the volcano. Figure 4 shows that the observed peak frequency of the oscillation shown in Figure

3 is consistent with the two atmospheric mode frequencies, 3.7 and 4.4 mHz, although the duration is not long enough to enable separation of the two peaks. Peaks seen for lower frequencies (1-2 mHz) would reflect the misfit of the polynomial reference curves to the observed STEC curves.

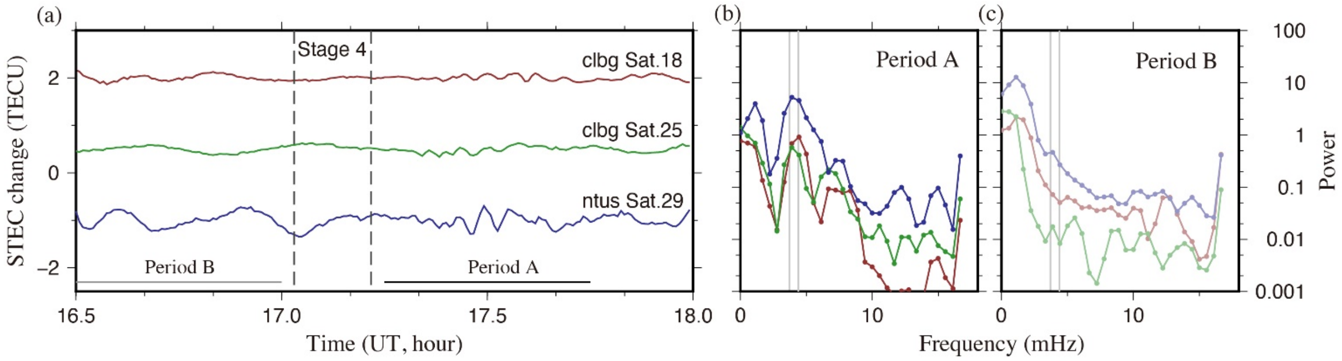

Figure 4 (a) The high-pass filtered STEC time-series at clbg (GPS Sat. 18 and 25) and ntus (GPS Sat. 29) show monochromatic oscillation lasting ~20 minutes shortly after the stage 4 of the Merapi eruption. Two gray horizontal lines show time windows (Period A 17:15-17:45 UT, Period B 16:30-17:00) used for the spectral analyses of the two periods. (b) Period A shows peaks around 4 mHz, close to the two atmospheric resonance frequencies 3.7 and 4.4 mHz (two vertical lines in light gray), but (c) Period B does not show such peaks.

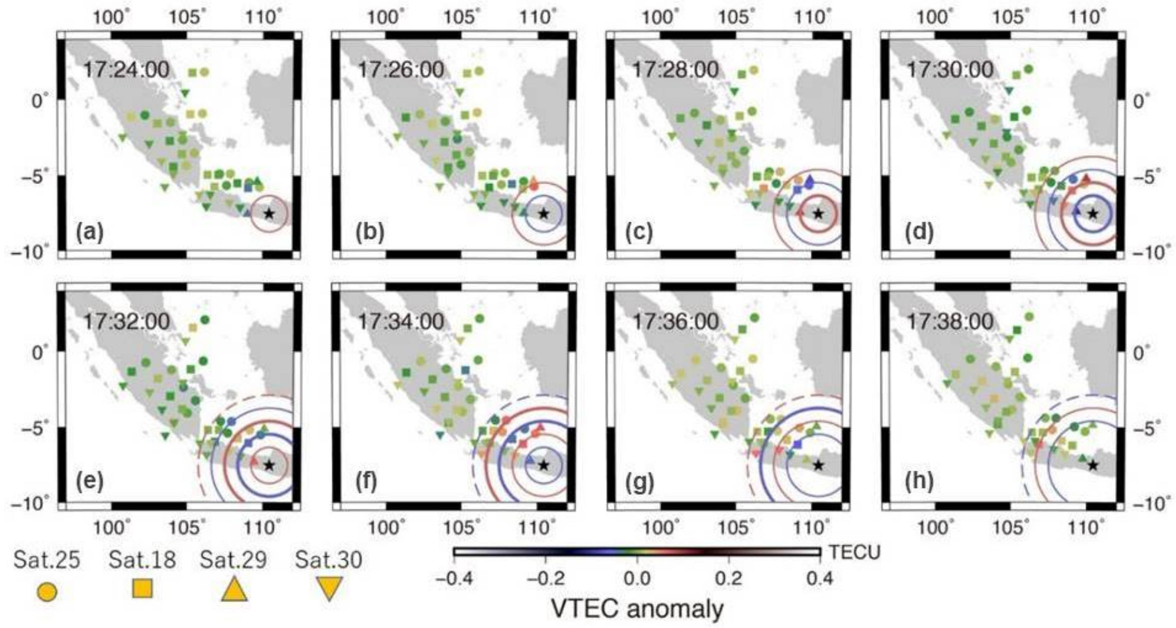

Figure 5 Spatial distributions of the VTEC anomalies by the 2010 Merapi eruption at 8 epochs with 2-minutes time separation (epoch times given in UT). Red and blue circles correspond to positive and negative anomalies (values in Figure 3 converted to VTEC), respectively. Circular wave crests are drawn assuming their expansion from the Merapi volcano by a velocity of ~0.8 km s^{-1}.

Figure 5 shows snapshots of distribution of VTEC anomalies at 8 epochs during a 14-minutes period. Ionospheric anomalies emerged ~20 minutes after the start of the stage 4 eruption and alternating positive and negative wave crests propagate outward from the volcano. The stage 4 activity consists of laterally directed dome explosions over a period of 11 minutes which destroyed the rapidly emplaced lava dome (Komorowski et al. 2013). This would have excited acoustic waves propagating upward, and let standing waves in lower atmosphere grow large enough to make detectable harmonic oscillations in the ionosphere in 20 minutes. After this stage, stage 5 (dome collapse) and stage 6 (sub-Plinian eruption) lasted for ~3 hours (Komorowski et al., 2013), but we do not find significant ionospheric disturbances during this period.

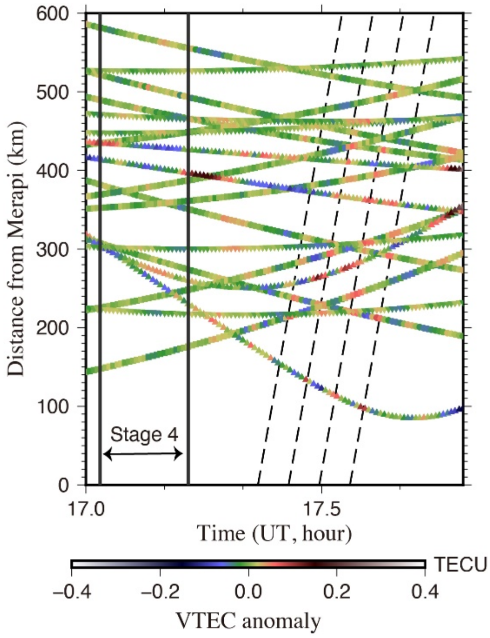

Figure 6 Distance-time diagram of the ionospheric disturbance after the stage 4 of the 2010 Merapi eruption based on the GPS satellite 18, 25, 29 and 30 and stations located to the west or northwest of the volcano. The positive peak of ionospheric variation (shown in red) as shown in Figure 5 propagates with the apparent velocity of ~0.8 km s^{-1} (dashed lines).

We estimated propagation velocity by plotting the time and distance from the volcano of the TEC disturbances as ~0.8 km/s (Figure 6). This is consistent with that Nakashima et al. (2016) found for the 2014 Kelud eruption and corresponds to the acoustic wave speed in the F region of the ionosphere. Figures 5 and 6 suggest that the TEC oscillation can be traced as far as 500-600 km from the volcano.

Comparison between the 2010 Merapi, 2014 Kelud, and 2015 Calbuco eruptions

Oscillation amplitudes

Next, we discuss the amplitudes of the observed resonant oscillation in VTEC anticipating that such amplitudes reflect the intensity of the continuous eruption. The observed amplitudes would, however, depend also on other factors such as distance from the volcano, the LoS incidence angles with the wave fronts, and the angle between the wave fronts and geomagnetic fields. The largest amplitudes of the electron density changes are expected to occur when the wave front of the neutral atmosphere is perpendicular to the geomagnetic field (Rolland et al. 2013). Also, a large amplitude occurs when LoS penetrates the wave front with a shallow angle.

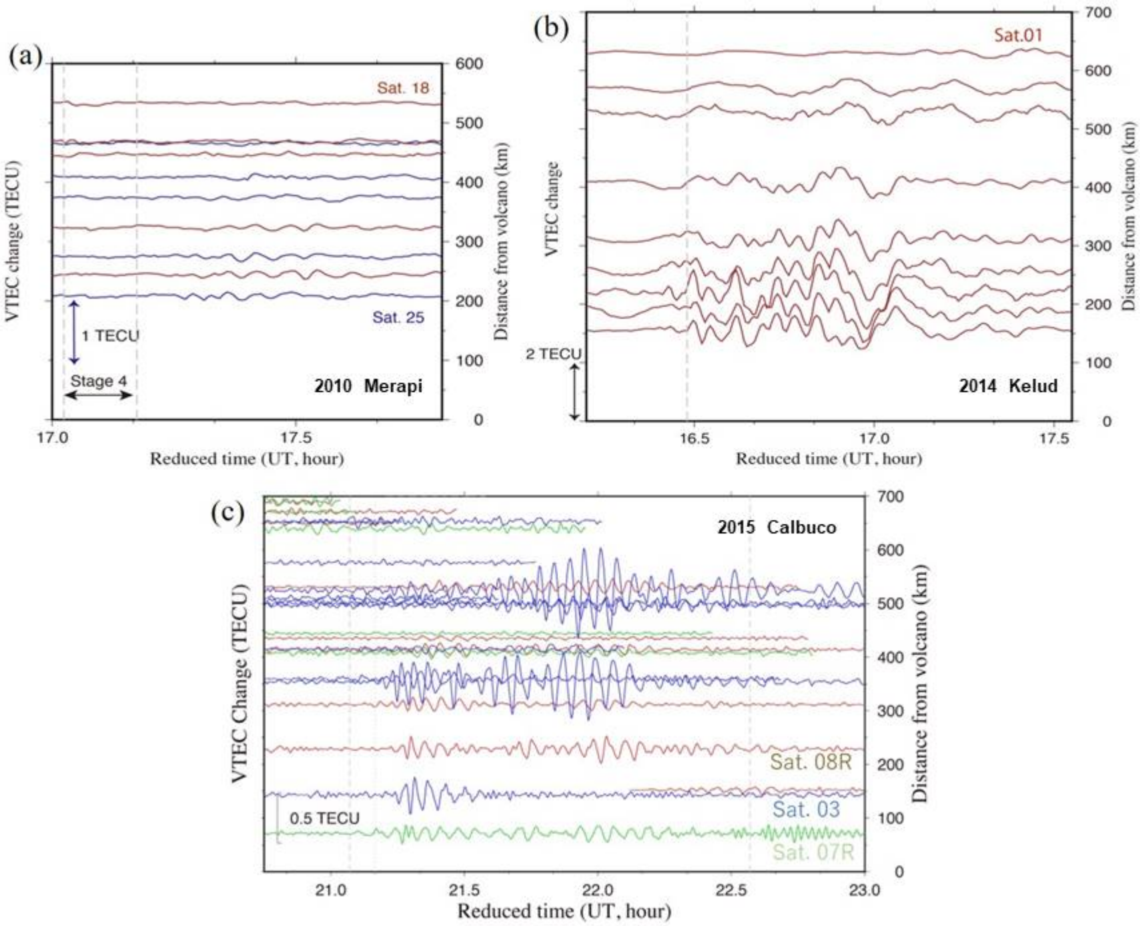

Figure 7. Comparison of the ionospheric disturbance amplitudes of the two Indonesian cases, (a) 2010 Merapi, (b) the 2014 Kelud, and (c) the 2015 Calbuco (first eruption episode on 22 April) eruptions. Time axes are shifted backward to the volcanoes assuming 0.8 km s^{-1} propagating speed so that the TECs for different satellite-station pairs oscillate in phase. The vertical dashed line in (b) indicate the onset of the TEC oscillation, and the two vertical dashed lines in (c) indicate the period of the continuous eruption. In (c), we used the RAMSAC stations with SIPs located to the north of the volcano, and the distance from the volcano (right axis) is calculated at 21:10 (vertical dashed line). Average peak-to-peak amplitudes and their uncertainties are derived using the first 20 minutes of the oscillation using the satellite-station pair with the distance from the volcano around 200 km.

Considering these points, we compared the VTEC oscillation amplitudes of the two Indonesian volcanoes using the satellite-station pairs with similar geometric conditions. For the 2015 Calbuco eruption, we used data with one GPS satellite (Sat.03) and two GLONASS (Russian GNSS) satellites (Sat.07R and 08R) during the first eruptive episode. We compare them in Figure 7. For the Calbuco case, the observing time window is longer than the other cases and we see change in the oscillation amplitudes in time reflecting the changing distance between the volcano and the SIP. Also, between-satellite amplitude differences are caused by differences in geometry as explained above.

Index for total volume of deposit

From Figure 7, stations with distance 200-300 km from the Merapi volcano after its 2014 eruption is shown to have an average peak-to-peak VTEC fluctuation of 0.10 ± 0.01 TECU. On the other hand, stations with similar distances from the Kelud volcano show the VTEC oscillations with amplitude of 0.73 ± 0.09 TECU (average over the first 20 minutes). The background VTEC in each eruption was ~11 and ~40 TECU for the 2010 Merapi and the 2015 Kelud eruptions, respectively. Then their amplitudes relative to background VTEC values are 0.91 ± 0.12% and 1.83 ± 0.23%, respectively. For the 2015 Calbuco case, the amplitude of oscillation was 0.23 ± 0.02 TECU and the background VTEC was ~26.0 TECU, and so the relative amplitude is 0.89 ± 0.09%.

Here we assume that relative amplitude of TEC oscillation is proportional to the volume ejected in a unit time, often called mass eruption rate (MER). To test its validity, we compare the TEC amplitudes with the published values of MER for the three eruptions (Figure 8a). The TEC oscillation amplitudes for the 2014 Kelud eruption is nearly twice as large as the other two, and this is consistent with the higher MER values of the Kelud eruption (3-4 $\times 10^7$ kg s^{-1}) inferred with numerical simulations for its Plinian eruption on 13 February by Suzuki and Iguchi (2019) than the other two. The average MERs are estimated as $\sim 10^7$ kg s^{-1} for the stage 4 of the 2010 Merapi (Komorowski et al., 2013) and as 0.08-2.4 $\times 10^7$ kg s^{-1} for the stages 3 and 4 of the 2015 Calbuco (Van Eaton et al., 2016) eruptions from the amount of the deposits.

This idea can be further confirmed by comparing the products of the relative oscillation intensity and the oscillation duration with the total volume of the deposit by the eruption. The duration is ~20 minutes for the 2010 Merapi eruption. The oscillation continued over an interval of ~120 minutes for the 2014 Kelud eruption (see Figure2 of Nakashima et al., 2016). The 2015 Calbuco eruption occurred as two episodes, and we assumed the total duration 450 minutes.

Figure 8b compares the total amount of the volume of ejecta by the three eruptions studied here. For the 2010 Merapi eruption, it is reported as $\sim 36.3 \times 10^6$ m^3, with >70 % of this volume deposited during the stage 4 (Charbonnier et al., 2013). In the figure, we attached an error bar assuming the true volume is between 70 and 100 % of this value. For the 2014 Kelud eruption, the total bulk deposit volume is estimated as 220 $\times 10^6$ m^3 (Hidayati et al., 2018) or 250-500 $\times 10^6$ m^3 (Maeno et al., 2019). For the 2015 Calbuco eruption, we used the value 560±280 $\times 10^6$ m^3 by Van Eaton et al. (2016). Figure 8 suggests that total volume of the deposits is roughly proportional to the index defined as the product of relative TEC osillation amplitude and the oscillation duration.

The GNSS-TEC technique has several drawbacks. First of all, we need continuous GNSS stations around volcanoes and the technique can be used only for recent eruptions. The June 1991 Pinatubo eruption is considered to have MER as large as 10^9 kg s^{-1} (Suzuki and Koyaguchi, 2009). Figure 8a suggests that there were ultra-strong TEC oscillation signals if GNSS receivers were available at that time. Unfortunately, near-field observation data of the harmonic TEC oscillation are not available, although a longer period (~20 minutes) TEC oscillations, possibly due to internal gravity waves, were observed during 12-15 June by receiving microwave signals from a geostationary satellite in Taiwan (Cheng and Huang, 1992).

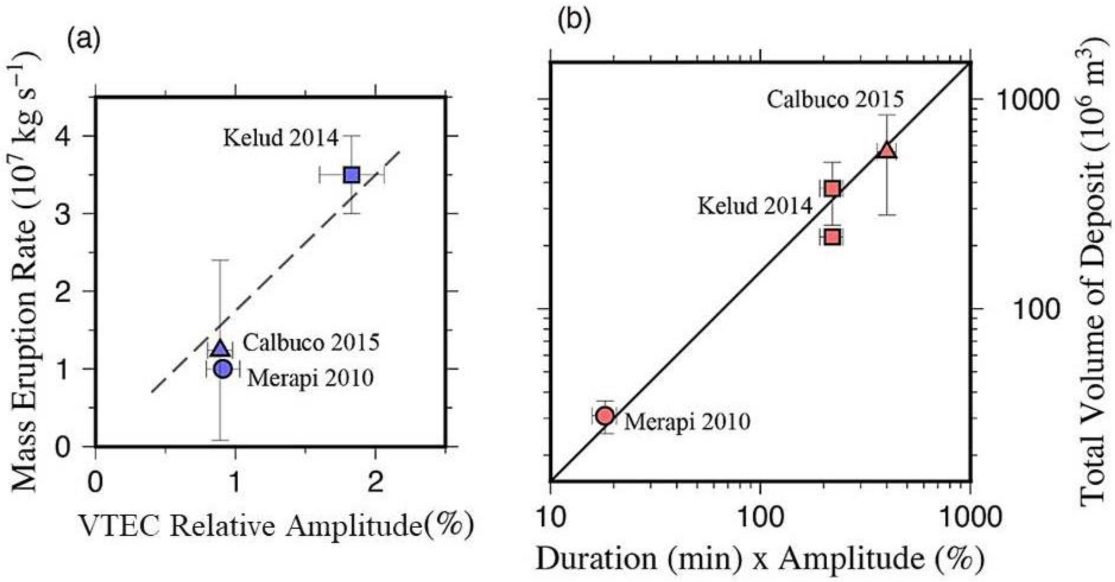

Figure 8 (a) Comparison of the relative VTEC oscillation amplitudes and MERs of the 2010 Merapi (Komorowski et al., 2013), 2015 Calbuco (Van Eaton et al., 2016), and the 2014 Kelud (Suzuki and Iguchi, 2019) eruptions. (b) Comparison of the products of the ionospheric disturbance amplitudes and the durations, with the total volume of the deposits of the 2010 eruption of the Merapi volcano (Charbonnier et al., 2013), 2014 eruption of the Kelud volcano (Hidayati et al., 2018; Maeno et al., 2019), and the 2015 eruption of the Calbuco volcano (Van Eaton et al., 2016).

Another drawback is that the amplitudes of TEC oscillation are sensitive to the geometry of LoS, wave front, and the geomagnetic field, and it is difficult to compare the TEC oscillations for different eruptions with exactly the same condition. Nevertheless, ionospheric disturbances provide useful information on intensive volcanic eruptions. In real time, TEC can be monitored from GNSS stations hundeds of kilometers away from the volcano (Figure 7). Amplitudes of the harmonic oscillation of TEC would offer a rough estimate of MER of the ongoing eruption in minutes. After the eruptions, the products of the oscillation amplitudes and the durations would offer a new scale, independent from conventional VEI, for estimating the total volume of deposits by Plinian eruptions. This would be useful especially when geological approaches are difficult.

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