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EXPRESS LETTER

Aso volcano eruption on October 8, 2016, observed by weather radars

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Abstract

An explosive eruption occurred at the Naka-dake first crater of Aso volcano at 1:46 on October 8, 2016 (JST). According to the field survey conducted by Kumamoto University, Kyoto University, the National Institute of Advanced Industrial Science and Technology, and the Japan Meteorological Agency (JMA), a large amount of ash fell in the northeast direction of Mt. Aso; in addition, ash falls were confirmed in Kumamoto, Oita, Ehime Kagawa and Okayama Prefectures. Although the eruption was not observed using a distant camera, the eruption cloud echoes were captured by five JMA operational weather radars (Fukuoka, Hiroshima, Tanegashima, Muroto-misaki and Matsue). Using these radars, we found that the eruption cloud echo moved in the northeast direction at the lower troposphere, and in the east-northeast direction at the middle troposphere. This result is consistent with the vertical wind shear observed by the JMA wind profiler. After that, the echo of the volcanic ash cloud in the middle troposphere flowed more than 200 km from Mt. Aso and became ambiguous near Tosa Bay in Kochi Prefecture. In this study, we introduce a new probabilistic plume height estimation method. This method probabilistically evaluates errors due to radar beam width and refractivity of the atmosphere. Using this method, the eruption cloud height is estimated at 12,000 ± 687 m (1σ) above sea level (ASL). This height is lower than 13–14 km, the SO_2 cloud altitude estimated by Himawari-8 Ash RGB and the JMA Global Atmospheric Transport Model and is also lower than the radar echo height indicated by JMA (15 km). However, the plume height derived using this method is consistent with 39,000 feet (11.9 km) ASL and the volcanic eruption cloud height analyzed by the Tokyo Volcanic Ash Advisory Center using Himawari-8 infrared bands. Based on the result of the probabilistic estimation method and the duration of the volcanic earthquake due to the eruption (160–220 s), the total emission mass was estimated to be 3.2–7.5 × 10^8 kg, which is almost consistent with the field survey (6.0–6.5 × 10^8 kg).

Keywords: Weather radar, Remote sensing, Volcanic plume, Eruption cloud, Aso volcano

Introduction

Weather radar has captured volcanic plumes or eruption clouds many times (e.g., Sawada 2003; Marzano et al. 2013). In some cases, volcanic plume heights were sequentially estimated (e.g., Mt. St. Helens eruption in 1980 (Harris et al. 1981), Eyjafjallajökull eruption in 2010 (Arason et al. 2011) and Shinmoe-dake eruption in 2011 (Shimbori et al. 2013)). In Japan, volcanic ash column height is an important parameter not only for monitoring volcanic eruption, but also for the Volcanic Ash Fall Forecast (VAFF) issued by the Japan Meteorological Agency (JMA) (Hasegawa et al. 2015). However, in JMA operation, cameras are used to monitor volcanic eruption columns; thus, eruption column heights are sometimes undetermined in cloudy or rainy conditions. Meteorological satellites such as Himawari-8 operated by JMA are available in such cases; however, we cannot detect small eruptions using meteorological satellites when many meteorological clouds exist around the volcano. In such cases, it is expected that weather radar can observe eruption columns.

Weather radar is a useful tool for monitoring volcanic eruptions; however, the observation data contain estimation errors for two main reasons, error due to beam width and refractivity of the atmosphere. Not only

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weather radars, but also all electronic devices that emit radio waves have antenna patterns; and their beam width is defined by "3 dB beam width," which corresponds to the angle between half-power (3 dB lower) points of the main lobe. Weather radar itself cannot recognize where the target is in its beam width area; therefore, its observation data have errors due to beam width. In addition, refractivity of the atmosphere always fluctuates, and it is difficult to monitor this fluctuation. In other words, we must continuously monitor pressure, temperature and humidity of the atmosphere to estimate the refractivity.

As described above, volcanic plume height estimated using weather radar involves some errors; however, weather radar is still useful for monitoring eruptions especially in cloudy conditions.

Aso volcano

Aso volcano is an active volcano in Kumamoto Prefecture, Kyushu Island, and one of the 50 volcanoes that JMA monitors 24 h a day, 365 days a year. A large caldera (17 km × 25 km) of Aso volcano formed due to four gigantic pyroclastic-flow eruptions (JMA 2013). Although several eruptions have occurred at Aso volcano since the beginning of the twenty-first century, only a few were detected by weather radar.

At 21:52 JST (=UTC+9) on October 7, 2016, a small eruption occurred (Fukuoka Regional Volcanic Observation and Warning Center (VOWC) 2017). The first eruption was not detected by a distant camera but detected by weather radar. The maximum echo height of this eruption by JMA was 4.6 km above sea level (ASL). At 1:46 JST on October 8, 2016, about 4 h after the first eruption, a second (larger) eruption occurred. The duration of this eruption is estimated to be 160–220 s based on seismic records (Shimbori 2017). The Tokyo Volcanic Ash Advisory Center (VAAC) issued volcanic ash advisories (VAAs) after the eruption and reported that the volcanic cloud height was estimated at 39,000 feet (11.9 km) using Himawari-8 infrared bands (Tokyo VAAC 2016). JMA issued a volcanic alert level 3 at 1:55 JST, which corresponds to a volcanic warning to the nonresidential area near the crater (Fukuoka Regional VOWC 2017).

According to the field survey by Kumamoto University, Kyoto University, the National Institute of Advanced Industrial Science and Technology (AIST) and JMA, a large amount of ash fell in the northeast direction of Mt. Aso. In addition, surveys by JMA Local Met Offices confirmed ash falls in Kumamoto, Oita, Ehime, Kagawa and Okayama Prefectures. Miyabuchi et al. (2017) concluded that the total eruption mass was $6.0–6.5 \times 10^8$ kg.

The eruption on October 8, 2016, was captured not by cameras, but by weather radar.

JMA weather radar network

In this study, JMA operational weather radar network (JMA-RDN) data are used. There are 20 radars in JMA-RDN in Japan. Figure 1 presents a location map around Aso volcano and their main specifications. JMA operates scan sequences that aim to make a 3D dataset in 10 min.

We adopt a 4/3 earth-radius model that assumes the standard state of the atmosphere. Here, we briefly explain this model in accordance with Doviak and Zrnic (1993). In this model, the effective earth-radius factor is defined by

$$k_e = \frac{1}{1 + a(dn/dh)}, \tag{1}$$

where a is the earth's radius, n is the refractivity of the atmosphere, and h is the altitude, respectively. Past researchers found that dn/dh is almost constant, and k_e can be empirically approximated by 4/3. With this parameter, a radar beam height can be deduced by

$$h = k_e a \left[\frac{\cos\theta_e}{\cos\left\{\theta_e + s/(k_e a)\right\}} - 1 \right], \tag{2}$$

where s is the horizontal distance between the radar and the target, and θ_e is the elevation angle. In this study, we first determined the distance s; then, radar echo heights were estimated. However, Eq. (2) does not include the radar antenna height h_0; therefore, we modified it as follows:

$$h = (k_e a + h_0) \left[\frac{\cos\theta_e}{\cos\left\{\theta_e + s/(k_e a)\right\}} - 1 \right] + h_0. \tag{3}$$

Although we can constantly estimate beam height using this model, the beam height determined by this method involves errors due to refractivity of the atmosphere.

Probability estimation method

We developed a new probability estimation method that estimates not deterministic height but probability density of the radar echo height. In the first step, we assumed that probability density follows normal distribution. In mathematical form, the probability density is

$$f_i(h_j) = \frac{1}{\sqrt{2\pi}\sigma_i} \exp\left\{ -\frac{(h_j - \mu_i)^2}{2\sigma_i^2} \right\}, \tag{4}$$

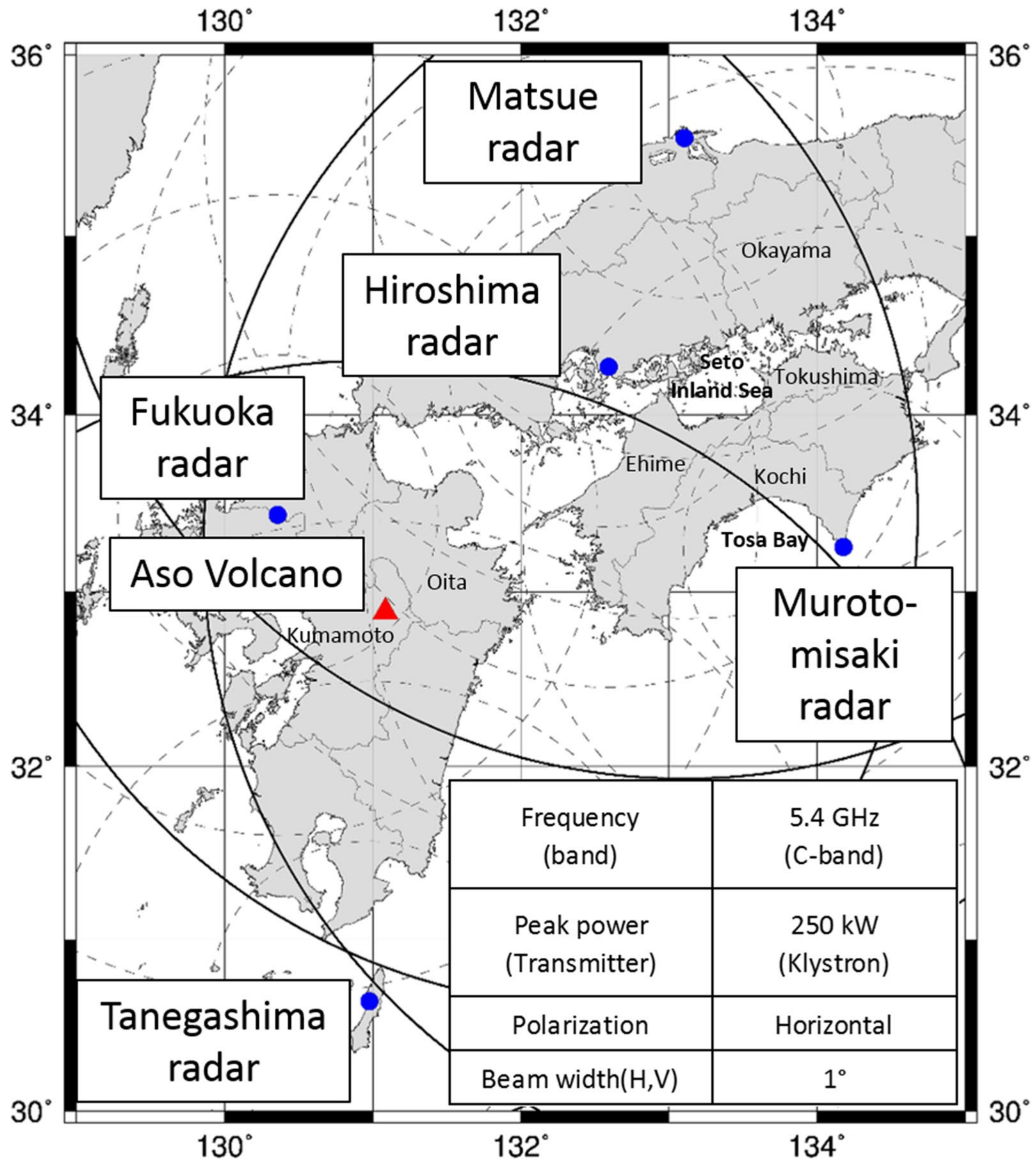

Fig. 1 Map of radars (●) around Aso volcano (▲) and main specifications of JMA-RDN. Dashed concentric circles show 100, 200 and 300 km from each radar. Solid concentric circles show 400 km, which correspond to the maximum ranges

where σ_i is the standard deviation and μ_i is the median value of the probability density of an i-th radar ($i=1,2,\ldots$). Here, the values of $h_j\left(=j\Delta h\right)$ are discretized sea-level altitudes ($j=0,1,\ldots\infty$). In addition, we assume that $\mu_i = H_c$ and $\sigma_i = \beta(H_u - H_l)/2$, where H_c is the center of the beam height, H_u is the upper limit of the beam width, and H_l is the lower limit. H_c can be derived using Eq. (3). Substituting $\theta_e \pm \theta_B/2$ into θ_e, H_u and H_l are also derived using Eq. (3). Here, θ_B is a 3 dB beam width, and β is a coefficient considering the difference between the actual antenna pattern and the probability distribution based on normal distribution. This coefficient varies depending on specifications of radars or characteristics of eruption cases; however, for simplification, $\beta = 1$ is assumed in this study.

After we derive n probability density functions using Eq. (4), we compose them using the following formula:

$$f_{\text{composite}}\left(h_j\right) = \frac{\prod_{i=1}^{n} f_i\left(h_j\right)}{\sum_{j=0}^{\infty}\left\{\prod_{i=1}^{n} f_i\left(h_j\right)\right\}\Delta h}. \quad (5)$$

The numerator represents the product of the probability densities, and the denominator normalizes the total probability density. Using this method, we can estimate a composite density function of the echo height. If there is an inversion layer in the lower troposphere, abnormal propagation may occur. However, this method can mitigate the impact of such outliers if only a few of the radars are affected by the inversion layer.

Results of JMA-RDN

Figure 2 indicates the time series of radar reflectivity plan position indicator (PPI) images of the eruption cloud echo near the vent. The echo was captured by five weather radars (Fukuoka, Hiroshima, Tanegashima, Muroto-misaki and Matsue radars) in JMA-RDN. Observation data of the elevation angle where the eruption cloud echo is clearly caught are extracted from each

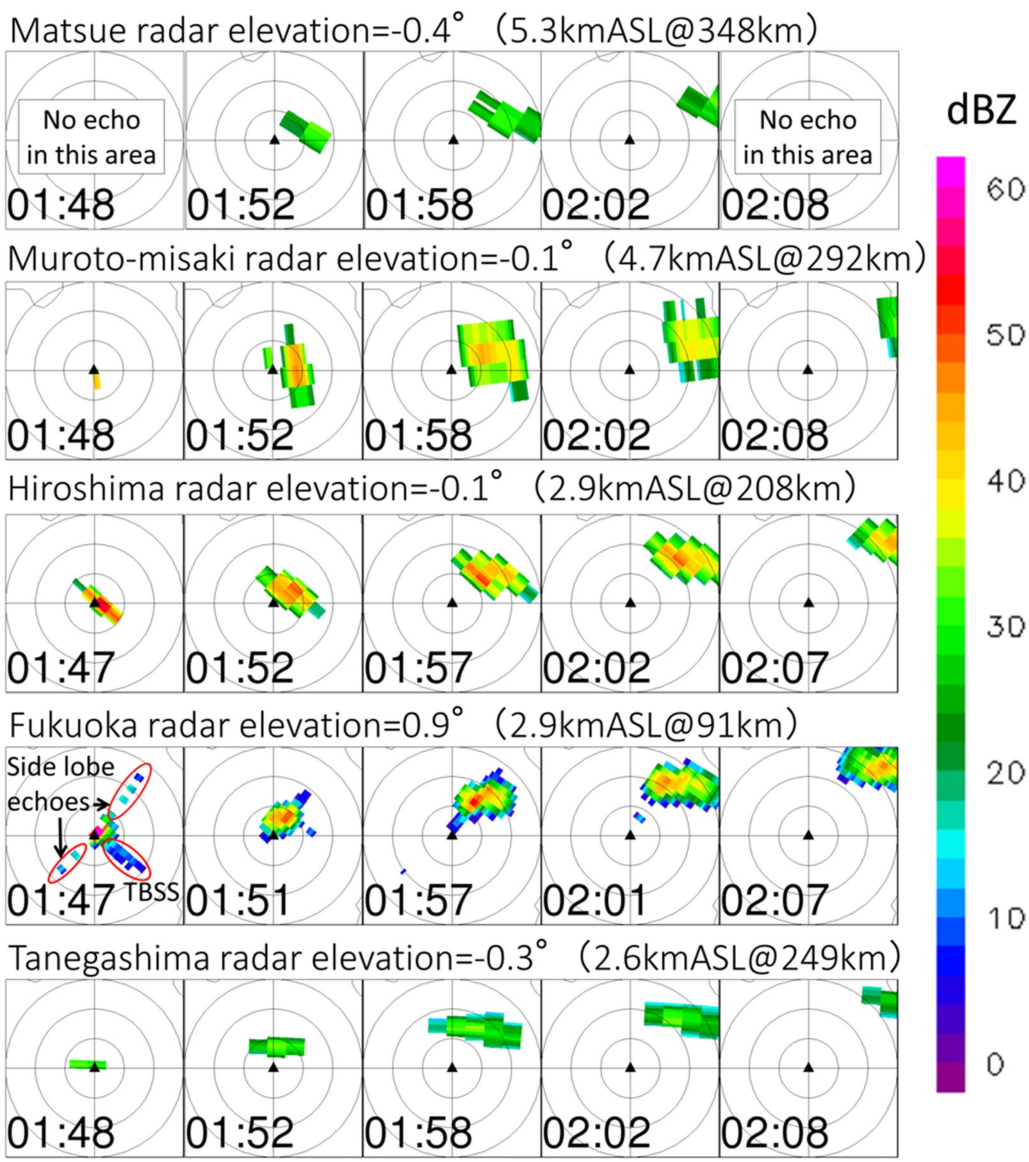

Fig. 2 Eruption cloud echoes observed by JMA-RDN from eruption time (1:46 JST) to 2:10 JST, October 8, 2016. Concentric circles represent 5, 10 and 15 km from the crater of Mt. Aso (▲)

radar. Results indicated that the eruption was not continuous, and the subsequent echo was no longer generated 5 min after the eruption. In addition, the volcanic ash in the atmosphere flowed in the northeast direction in the lower troposphere (below 3 km ASL), and in the east-northeast direction in the middle troposphere (5–10 km ASL). The arcuate echoes in the first image by Fukuoka radar are pseudo-echoes, known as side lobe echoes, and the radial echo is a Three-Body Scatter Signature/Spike (TBSS) (e.g., Bringi and Chandrasekar 2001; Doviak and Zrnic 1993).

Figure 3 presents the 3-km-height and vertical cross-sectional images of reflectivity constant altitude PPI (CAPPI) images synthesized from weather radars of JMA-RDN. Radar data from 1:50 to 2:00 JST were used to compose the data. Radar echo heights are determined with a threshold $Z_t = 12$ dBZ by JMA (Shimbori et al. 2013); however, the echo heights in this case reached 15 km ASL (Fig. 5b), which is the maximum height in the JMA's method.

Figure 4 presents snapshots of the volcanic ash cloud echo moving over a wide area observed using Muroto-misaki radar. The elevation angles were selected in order to confirm the echo at the middle troposphere, whose altitude was 5–10 km ASL. The eruption cloud echo existed at 1.2 degrees (9 km ASL) at 2:31 JST, at 1.2 degrees (5 km ASL) and 1.9 degrees (7 km ASL) at 3:31 JST and at 3.8 degrees (7 km ASL) at 4:36 JST. This figure confirms that the eruption cloud echo at the middle troposphere flowed in the east-northeast direction and reached Tosa Bay in Kochi Prefecture, which is 200 km from Mt. Aso. Figure 5b presents sequential echo heights observed by JMA. At the initial phase (at 2:00 and 2:10 JST), the echo reached 15 km, which is the maximum height of the JMA method, and then gradually became lower, finally reaching 7 km ASL (Fig. 5b). As discussed later, echo heights, especially at the initial phase, may have been overestimated.

Results of probabilistic analysis

Figure 5a presents the results of probabilistic estimation. In Fig. 5a, the colored curves denote probabilistic estimation results by single radar. The final (composite) result is denoted by a bold black curve. Using the probabilistic method, the eruption altitude of Mt. Aso volcano on October 8, 2016, was estimated at 12,000 m ASL (10,700 m above the crater edge) $\pm$687 m (1σ), using the radar data from 1:50 to 2:10 JST. The blue broken line denotes the result of satellite observation by Tokyo VAAC (Tokyo VAAC 2016), and the orange broken line denotes the maximum echo height determined by JMA. Figure 5b compares the probabilistic estimation (red dot and error bar corresponding to 1σ) and the JMA echo heights (blue dots).

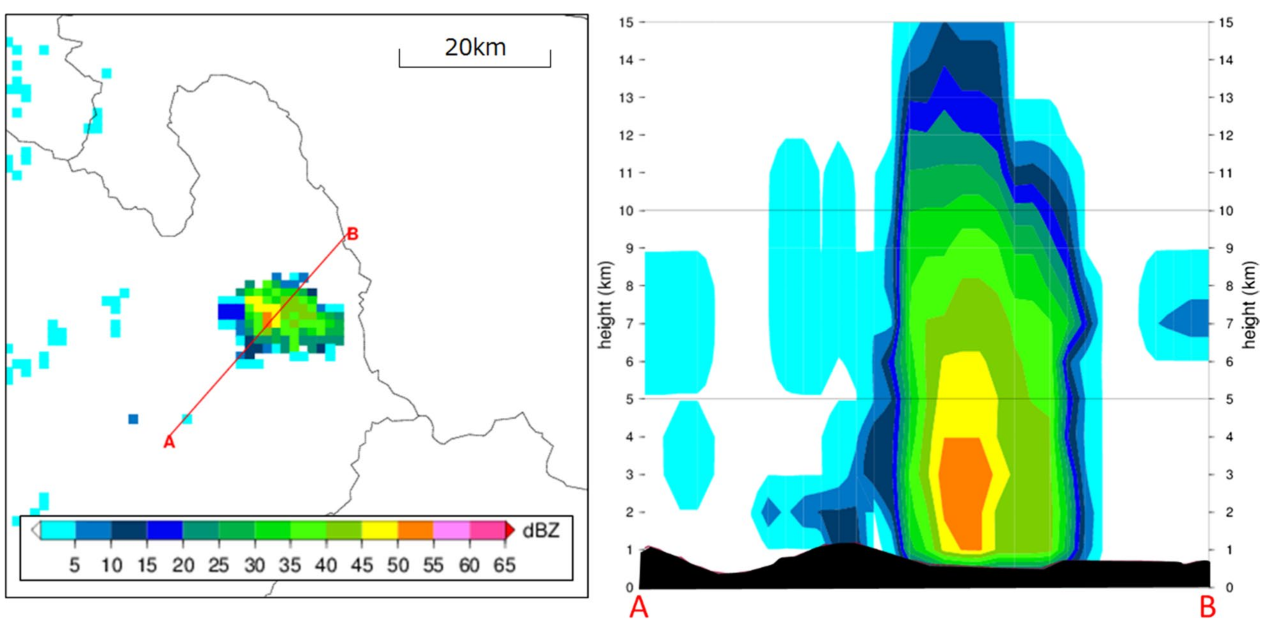

Fig. 3 3 km CAPPI of reflectivity (2:00 JST, October 8, 2016) (left) and vertical cross section (right) along line A–B. The echo height may be overestimated

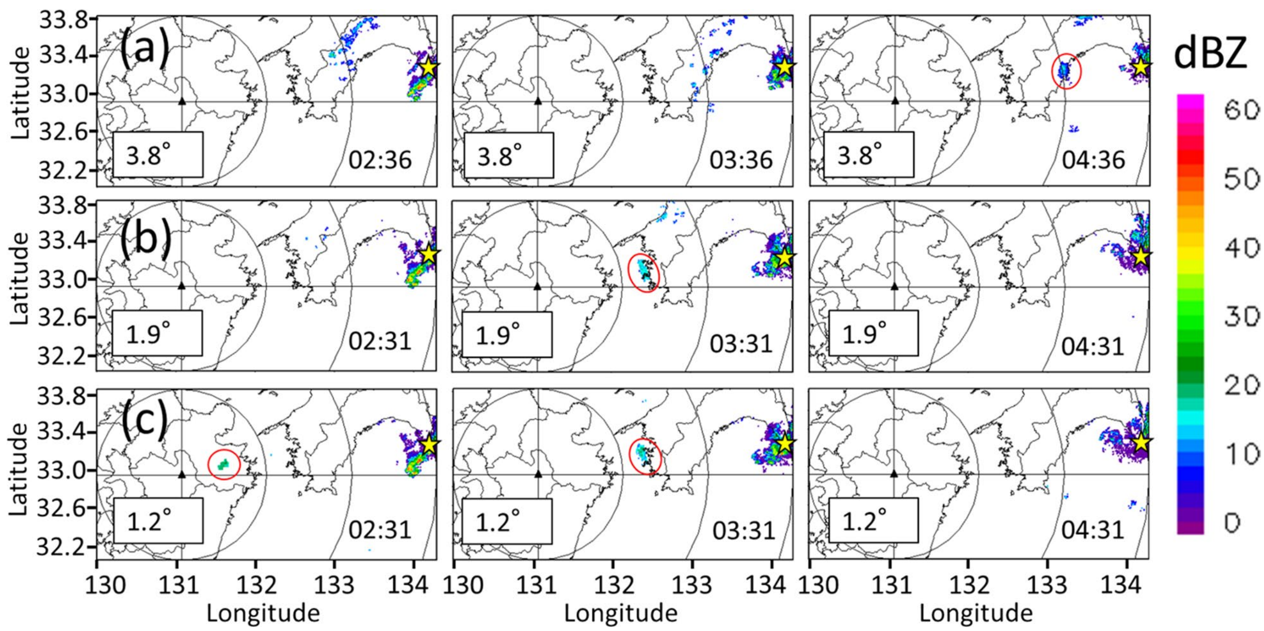

Fig. 4 Eruption cloud echo (red ellipse) observed by Muroto-misaki radar (yellow star) (from 2:31 to 4:36 JST, October 8, 2016). Elevation angles are **a** 3.8 (upper row), **b** 1.9 (middle row) and **c** 1.2 degrees (bottom row). Concentric circles represent 100, 200 and 300 km from Mt. Aso (▲)

Discussion

The results of JMA-RDN confirmed that the plume flowed in the northeast direction in the lower troposphere and in the east-northeast direction in the middle troposphere. This result is consistent with the vertical shear of the wind observed by the JMA wind profiler at the Oita Local Met Office (Shimbori 2017). It is also consistent with the fact that ash fall was widespread around the coastal area of the Seto Inland Sea.

The echo top height estimated by JMA reached about 15 km ASL; however, the median value of the probabilistic estimation result (12 km) was 3 km lower than that (Fig. 5). This result implies that the radar echo top altitude by JMA may be overestimated. In addition, the median value is lower than 13–14 km ASL, the top altitude of SO_2 cloud estimated by Himawari-8 Ash RGB and the JMA Global Atmospheric Transport Model by Ishii et al. (2018). However, the result of our method is almost equal to 39,000 feet (11.9 km) ASL, which was derived by Himawari-8 infrared bands (Tokyo VAAC 2016).

We assume that there is little chance that volcanic ash particles whose sizes are mm order, which are mainly targeted by weather radars, could have reached 200 km or more away from the crater. Therefore, in this study, the echo detected near Tosa Bay is assumed to contain many precipitation particles produced by volcanic ash particles acting as nuclei.

Based on the probabilistic estimation result and the duration (160–220 s) of the volcanic earthquake associated with the eruption (Shimbori 2017), the total amount of ejecta is estimated to be $3.2–7.5 \times 10^8$ kg, using $\mathrm{H} = 2.00 \times \dot{V}^{0.241}$ (Mastin et al. 2009). Here, H is the height above crater (km), and $\dot{V}$ is the volumetric flow rate (m^3 dense-rock equivalent (DRE) per second), where the magma density is assumed to be 2500 kg/m^3. The total mass is almost consistent with the field survey ($6.0–6.5 \times 10^8$ kg) by Miyabuchi et al. (2017).

Summary and conclusion

Aso volcanic eruption on October 8, 2016 was detected by weather radars. The volcanic ash in the lower troposphere flowed northeastward; as a result, it is assumed that ash falls occurred in the coastal area of the Seto Inland Sea. The volcanic ash cloud echo in the middle troposphere flowed in the east-northeast; then it was confirmed near Tosa Bay, which was more than 200 km away from the crater. We had not previously confirmed that an echo due to a single and discontinuous eruption traveled 200 km or more. We assume that the echo confirmed near Tosa Bay consisted of many precipitation particles generated with volcanic ash particles acting as nuclei.

The eruption altitude was estimated to be 12,000 m ASL $\pm$ 687 m (1σ). Using this result and the duration of the earthquake (160–220 s) due to the eruption, the total mass of the ejecta was estimated to be $3.2–7.5 \times 10^8$ kg, which is consistent with the value of the field survey.

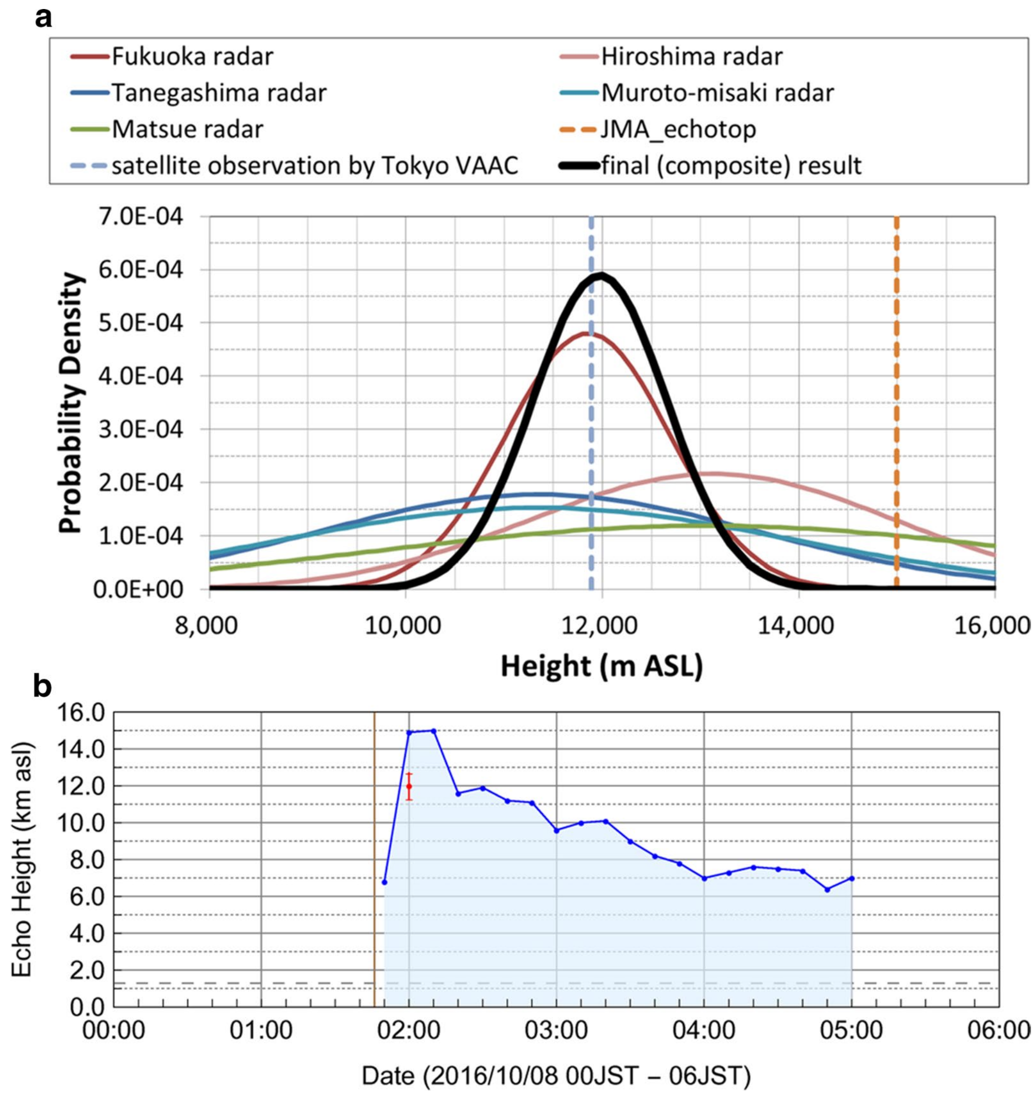

Fig. 5 **a** Result of probabilistic echo height estimation and **b** sequential radar echo heights by JMA. In **a**, the x-axis plots height (m ASL) and y-axis plots probability density. Black solid line represents the composite probability density, estimated by the data from 1:50 to 2:10 JST, October 8, 2016. In **b**, the *x*-axis shows the date (JST) and the *y*-axis shows echo height (km ASL). The red dot and error bar indicate the result of the probability estimation and its 1σ (68.3%) range. The blue dots show JMA radar echo heights

Although the effectiveness of cloud height estimation using weather radars is confirmed in this study, it is difficult to obtain further information on the constituents of volcanic ash cloud echo using single polarization radars such as JMA-RDN. To obtain more detailed information, high estimation of the internal state of the plume using an advanced instruments such as polarimetric (dual-pol) radar will be necessary.

Abbreviations
JST: Japan Standard Time; VAFF: Volcanic Ash Fall Forecast; JMA: Japan Meteorological Agency; VOWC: Volcanic Observation and Warning Center; VAAC: Volcanic Ash Advisory Center; VAA: Volcanic Ash Advisory; AIST: National Institute of Advanced Industrial Science and Technology; JMA-RDN: JMA Operational Weather Radar Network; PPI: plan position indicator; TBSS: Three-Body Scatter Signature/Spike; CAPPI: constant altitude PPI; DRE: dense-rock equivalent.

Authors' contributions
ES gathered radar data, analyzed them and performed the probabilistic estimation. KF performed the total mass estimation. TS summarized the echo top heights by JMA weather radars. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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