Numerical Simulations of Volcanic Ash Plume Dispersal for Sakura-jima using a Real-time Emission Rate Estimation

Hiroshi L. TANAKA¹ and Masato IGUCHI²

1: Center for Computational Sciences

University of Tsukuba

Tsukuba 305-8577 JAPAN

2: Sakurajima Volcano Research Center

Disaster Prevention Research Institute, Kyoto University

Kyoto 305-8571 JAPAN

Submitted to Journal of Disaster Research (JDR)

Submitted: July 31, 2018

Abstract

In this study, a real-time volcanic ash dispersion model called PUFF is applied to Sakura-jima volcano erupted on 16 June 2018. The emission rate of the ash mass from the vent is estimated based on the empirical formulae developed for Sakura-jima volcano using seismic monitoring and ground deformation data. According to the time series of the estimated emission rate, a major eruption occurred at 7:20 JST indicating the emission rate of 1000 ton per min and continued for 15 min showing the plume height of 4500 m, which appears to be consistent with ground observations by video cameras. The volcanic plume dispersion model PUFF is then applied to this event using the emission rate and the plume height estimated in a real time base. It is found that we need to introduce an adjusting constant to fit the model prediction of the ash fallout with the ground observation. Once the particle mass is calibrated, the distributions of ash fallout are compared with other eruption event to confirm the model performance. Finally, the airborne ash density is computed for the 3D space. According to the PUFF model simulations, the ash concentration of 100 mg/m³ extends to wide area around the volcano within one hour after the eruption. The simulation result quantitatively indicates the location of the danger zone for the commercial airliners. The PUFF model system combined with the real-time emission rate estimation is useful for aviation safety purpose as well as ground transportation and human health around the active volcanos.

Key word: PUFF model, ash dispersion, Sakura-jima volcano, Aviation safety, airborne ash density

1. Introduction

Sakura-jima volcano in Japan has been erupting frequently for years, and people living around the volcano, especially in Kagoshima city, have been suffering from the falling ashes. For this reason, the most advanced observational network has been established around the volcano, monitoring the eruption 24 hours a day. Volcanic ash falling on the ground as well as floating and traveling in the air is a great concern to aviation agencies, including the Kagoshima Regional Airport. When a commercial airliner encounters an airborne ash plume, the damage is estimated as 1 million US dollars for the replacement of the jet engines, and 1 billion US dollars if the aircraft crashes, the worst case scenario. After the first major incident of commercial airliner encountering into airborne ash at Redoubt volcano eruption in 1989, the International Civil Aviation Organization (ICAO) established Volcanic Ash Advisory Centers (VAAC) in 9 sectors around the world. The Tokyo VAAC, established in 1997, is one of the 9 VAACs (see Onodera, 1997). However, similar incidents involving commercial airliners encountering volcanic ash have occurred many times in the world. The Tokyo VAAC started to operate Lagrangian and Eulerian models to forecast the position of volcanic ash clouds (Tokyo Aviation Weather Service Center, 2001). According to the assessment of aviation safety by ICAO, an ash density of 2 mg/m^3 and above is considered to be the danger level for commercial airliners (Kelleher, 2010). Such an information of airborne ash density is not available because the source data of ash emission rate is unknown. The unknown airborne ash density was the major problem for the eruption event of the Eyjafjallajokull eruption in April 2010 to close airports in Europe for more than a week as documented by Leadbetter et al. (2010)

A volcanic ash plume tracking model called PUFF was developed along with the eruption of Redoubt volcano in 1989 at the Alaska Volcano Observatory (AVO) in the Geophysical Institute, University of Alaska Fairbanks (Tanaka, 1991; Kienle et al., 1991;

Dean et al., 1993). In their Lagrangian model, forecasted wind data were provided by UNIDATA, and transport, diffusion, and gravitational fallout were considered in the model (Tanaka 1994). The performance of the volcanic ash tracking model PUFF has been examined for Alaskan volcanos (Tanaka et al., 1993; Akasofu and Tanaka, 1993), for Usu volcano (Tanaka and Yamamoto, 2002), and further demonstrated by actual eruptions occurring in the world, including Sakura-jima volcano in Japan. The PUFF model has been operational at AVO (Searcy et al. 1998), and transplanted to many other agencies, including National Weather Service in NOAA, U.S. Geological Survey, University of Tsukuba, University of Messina, Sicily, Japan Weather Association, and Japan Airlines.

Recently, the PUFF model was applied to the eruption of Kelud volcano in Indonesia with a major Plinian eruption at 15:50 UTC on 13 February 2014. The umbrella-shaped ash plume reached well into the stratosphere with the plume top at 17 km in height. The circular anvil cloud reached a radius of about 100 km during the first hour. The circular shape of the plume top started to drift westward across the island of Java holding the same radius, and it continued moving westward with a gradual spread due to diffusive mixing. Nine hours after the eruption, the center of the plume top had drifted about 600 km westward over the Indian Ocean. By that time, the plume top had a radius of 300 km. The airports closed and 150 domestic flights were canceled on 14 February. The 3D structure of the drifting ash plume was clearly simulated by the PUFF model (Tanaka et al. 2016).

The PUFF model was also applied to the eruption of Kuchinoerabu-jima volcano in Japan on 29 May 2015 (Tanaka and Iguchi 2016). A major eruption occurred at 0:59 UTC, and the ash plume reached 9 km above the ground. According to Himawari-8 satellite monitoring, the ash plume drifted in the east-southeast direction. The observed ash fallout over Yakushima island is in the order of 100 g/m². Using this observational

fact, the total emissions are estimated to be 600,000 tons for this event. Since the ash mass is represented by particles in PUFF model, a comparison of the particle distribution with the fallout observation in Yakushima enables us to estimate the airborne ash density by this method. The PUFF model simulation showed that the core region of the plume at 9 km in height indicated 100 mg/m³ of airborne ash density even for the plume 250 km away from the erupting volcano. The satellite images show the exact location of the ash plume. The PUFF model simulation can estimate the airborne ash density over a much wider diffused area to identify the danger zone for aircrafts.

It has been argued that the quantitative estimation of ash mass emission rate from the vent is essential for the quantitative assessment of ash fallout on the ground or airborne ash density for the aviation safety purpose. Responding to this demand, Iguchi (2012; 2016) proposed a method for real-time evaluation of discharge rate of volcanic ash from the vent based on the historical records of rich observational network around Sakura-jima volcano. According to the analysis of seismic record and ground deformation signals associated with vulcanian eruptions at Sakura-jima, it was found that the seismic amplitude at a specific frequency band is highly correlated with the ejected volcanic ash amount. In reference to this relation the volcanic ash discharge rate was expressed by a linear combinations of ground deformation, seismic amplitude and a correction factor. Specifically, the ash emission rate is represented by kinetic energy associated with continuous volcanic tremors and the ground deformation data for vulcanian eruptions. The proposed method provides the volcanic ash discharge rate in quasi-real time. By combining the PUFF model with the quasi-real time discharge rate, we can predict the total amount of ash fallout distributed over a wide area immediately after a volcanic eruption. Moreover, we can predict the airborne ash density and 3D structure of ash plume dispersal in a real-time base.

The purpose of this study is to simulate the volcanic ash plume dispersal from Sakura-

jima volcano using the PUFF model, based on a real-time volcanic ash emission rate estimated by the nearby seismic records and ground deformation data proposed by Iguchi (2012; 2016). The combined new system is applied first to the Sakura-jima eruption event at 22:20 UCT on 15 June 2018. The vulcanian eruption continued about 15 min, and the ash plume reached 4500 m a.s.l. A dense ash fallout of 662 g/m² was reported at Kagoshima Meteorological Observatory. In this study, the distribution of ash fallout by the model is calibrated with the ground observation introducing an adjusting parameter. The calibrated PUFF model system is applied to an independent eruption event on 13 November 2017 in order to quantitatively assess the performance of the PUFF model system. Furthermore, the 3D distributions and temporal variation of airborne ash density is estimated quantitatively. Newly developed PUFF model system is expected to identify the location and spread of the danger zone for commercial airliners in a real-time base.

2. Description of the PUFF model

The PUFF model for real-time volcanic ash plume prediction was constructed by Tanaka (1994) and reported in detail by Searcy et al. (1998) as an application of pollutant dispersion models. Some modifications on diffusion and the initial plume shape were documented by Tanaka et al. (2016). Therefore, only a brief description is presented here. The model is based on a three-dimensional (3D) Lagrangian form of the fluid mechanics. In the Lagrangian form, material transport is conducted by the fluid motion, and diffusion is represented by a stochastic process of random walk (e.g., Chatfield, 1984). Here, the plume dispersion model is constructed by a sufficiently large number of random variables $r_i(t)$, $i = 1 \sim M$, representing position vectors of M particles from the origin of the volcanic vent. With a discrete time increment Δt , the governing equation may be

written as

$$\begin{cases} r_i(0) = S, & i = 1 \sim M, & \text{for } t = 0, \\ r_i(t + \Delta t) = r_i(t) + V\Delta t + Z\Delta t + G\Delta t, & i = 1 \sim M, & \text{for } t > 0, \end{cases} \quad (1)$$

where $r_i = (x, y, z)$ is a position vector of the i -th particle at time t . S designates the initial locations of the particles as a source term. $V = (u, v, w)$ is the local wind velocity to transport the particle, $Z = (c_h, c_h, c_v)$ is the diffusion velocity containing diffusion speeds generated by Gaussian random numbers, and $G = (0, 0, -w_t)$ is the gravitational fallout velocity approximated by extended Stokes Law. Note that the diffusion Z depends on the direction, and the gravity settling G depends on the particle size.

For the computation of the transport, the wind velocity V is obtained from the real-time Grid Point Values (GPV) data provided by the global spectral model (GSM) of the Japan Meteorological Agency (JMA). The diffusion speed c of the random walk process may be related to the diffusion coefficient K as $c = \sqrt{2K/\Delta t}$, where Δt is set to 5 min in the model. The appropriate horizontal diffusion coefficient is $K_h=150$ (m²/s). Since the vertical diffusion is considerably smaller than the horizontal diffusion, we set $K_v=1.5$ (m²/s) in this study. These default values are used for the numerical experiment in this study.

Gravitational settling is based on an extended Stokes Law for the settling of particles of various grain sizes. For the volcanic ash, the size may vary widely from fine ash to boulders. Large particles settle out within a short time, and the particle size spectrum of the ash plume tends to decrease in scale. We have assumed an initial particle size of logarithmic Gaussian distribution with its standard deviation 2.0 centered at -3.0. Namely, a mean particle size is 1.0 mm on a log scale.

Modeling the source S of an eruption, the number of particles released at every time step may be adjusted in order to draw optimal statistical information from the model

products. In this study, we generate a maximum of $M_0=5000$ particles uniformly in time using a uniform random number generator over the time step Δt , which scales the emission rate. The number of source particles M_0 for one time step changes with time scaled linearly with the emission rate ϵ which is provided in a quasi-real time.

Given an initial vertical velocity of the emission with a specified damping (e-folding) time τ_0 , the particles generated by a uniform random number in time are redistributed in the vertical from the vent z_1 to the plume top level z_2 . Using time integration for the vertical velocity, the final form is given as $z(t) = z_2 - (z_2 - z_1)\exp(-t/\tau_0)$ during the time step Δt . Since z_1 and z_2 are given, we can put a large number of particles near the plume top by adjusting the damping time τ_0 , which is set to 30 s in this study. The initial plume height varies in time as a function of the estimated emission rate.

The diffusion coefficient is amplified in the vertical z by a linear scaling above the volcano. The amplified diffusion coefficient is reduced in the horizontal direction by the Gaussian function scaled by a radius r from the vent as

$$c'_h = c_h \times [1 + \frac{z}{z_0}\exp\{-(\frac{r}{r_0})^2\}]. \quad (2)$$

We set $z_0 = 1000$ m and $r_0 = 1000$ m in this study considering the feature of vulcanian eruptions. In this study, these default values are used for the numerical experiment.

The governing model equation is integrated in time, and the distribution of the particles in the atmosphere is presented in various mapping projections. The total number of the plume particles M in the atmosphere increases with each time step. When the particles drop to the ground, the fallout locations are recorded. Likewise, when the particles have moved out from the prescribed computing domain, they are removed from the computation. The distribution of ash fallout is computed by counting the total number of the ash particles in a unit area on the ground. Likewise, the distribution of the airborne

ash density is computed by counting the total number of the ash particles in a unit volume in the atmosphere. The output products of the map projections are drafted using the Generic Mapping Tools software (Wessel et al. 2013) and are open to the public through the internet.

3. Description of the emission rate estimation

The most unique attempt in this study is to couple the PUFF model with the real-time estimation of the emission rate ϵ using tilt and strain record and seismic data provided by the observational network for Sakura-jima volcano (see Iguchi 2012; 2016). According to Iguchi (2016), the volcanic ash emission for a monthly sum W_e (ton) is expressed by a linear combinations of the following two terms and a correction factor:

$$W_e = \alpha A + \beta V + \gamma, \quad (3)$$

where A is a monthly sum of seismogram spectrum in the seismic record at 2-3 Hz (unit in m/s) for continuous volcanic tremors, and V is a monthly sum of pressure source volume change (unit in m³) for vulcanian eruptions. The coefficients and intercept are statistically determined using past observation records as $\alpha=3.8\times10^{-5}$, $\beta=2.6$, and $\gamma=-1.03\times10^5$. The estimating formulae is validated using monthly data, and the error for individual eruptions is estimated as 10 percent at 2.5×10^4 tons. The proposed method provides the volcanic ash discharge rate in quasi-real time by converting W_e (ton) to the emission rate (ton/min). In this study, we adjust the emission rate as $\epsilon = aW_e$, where a is an adjusting constant to be determined by ground observation of ash fallout. It is noted that the formulae tends to underestimate the emission rate for small eruption events by the negative value of the intercept. The adjusting constant a is determined by fallout observations so that the model predictions fit with the observations.

The thermal energy of eruption is known to be proportional to the fourth power of the plume height. Thus the plume height z_2 is estimated from the emission rate ϵ as

$$z_2 = z_1 + b \epsilon^{1/4}, \quad (4)$$

where z_1 is the height of the vent and the coefficient is empirically given as $b=400.0$ in this study.

4. Result of the model simulation for 16 June 2018

The PUFF model simulation is conducted using the real-time emission rate estimation for the eruption event on 16 June 2018. Figure 1 shows the time series of the emission rate (ton/min) without the adjusting term for local time on 16 June 2018 estimated by Eq. (3) with one min interval. There is an explosive eruption at 7:20 JST (22:20 UTC) showing the emission rate of 1000 ton/min. Some minor emission follows the major emission for several hours. Figure 2 shows the time series of the emission rate converted to 5 min (ton/5min) and the corresponding plume height (m) estimated by Eq. (4) as the input for the PUFF model. The simulation started at 7:10 JST (22:10 UTC) and ended at 13:10 JST (4:10 UTC). The simulation interval is noted from 0 to 6 hours in the abscissa. The emission rate indicates a peak value of 5000 ton/5min and lasted for 15 min. Since $M_0=5000$ particles are generated for $\Delta t = 5$ min for the peak emission rate of 5000 ton/5min, we find that one particle indicates 1.0 ton (1000 kg) of ash mass in this event. The corresponding plume height indicates 4500 m, which agrees quite well with the visual observation record by the monitoring camera. The estimated specific numbers are 549, 4911 and 1662 ton/5min, respectively, for the emission rate, and 3053, 4466 and 3671 m, respectively, for the plume top for the consecutive three model time steps.

Figure 3 illustrates the wind vectors at 925 hPa and 500 hPa at 0:00 UTC on 16

June 2018. The real-time GPV data are provided by the Japan Meteorological Agency through the portal site at the Center for Computational Sciences of the University of Tsukuba. There is a northwesterly wind about 10 m/s at 500 hPa over Sakura-jima volcano. The wind at 925 hPa is easterly with about 10 m/s, indicating a large vertical shear. The performance of the PUFF model simulation of the ash dispersal relies totally on the accuracy of the wind data.

Figure 4 illustrates the results of the PUFF model simulation of the ash plume dispersal for (a) 7:30, (b) 8:00, (c) 8:30, and (d) 9:00 JST, respectively. The colors indicate different plume heights. The result for 7:30 shows a point source of the ash plume indicating some spread due to the imposed diffusion. At 8:00, 40 min after the eruption, the ash plume at the altitude of 4 km (red) started to drift southward, while the lower level ash clouds were moving to the west to Kagoshima city area. The result for 8:30, 70 min after the eruption shows further southward drift indicating the plume top (red) over Tarumizu city. Plume height decreases at the source region. Interestingly, the lower part of the plume (blue) moves west, reaching the coast of the East China Sea. The result for 9:00, 100 min after the eruption shows the plume top (red) reaching near Ibusuki. The movement of the ash plume is very different for the lower and upper part of the ash clouds.

Figure 5 depicts zonal-height (X-Z) and meridional-height (Y-Z) cross sections of ash plume dispersal for every 5 min starting from 7:10 JST. The plume shape for the first 5 min after the eruption shows the plume top at 3000 m indicating a simple vertical column over the vent. The result of the X-Z section shows a westward movement of airborne ash transported by the low level winds while the plume top near 5000 m drifts eastward. The plume shape of high concentration tilts eastward with respect to height. The result of the Y-Z section shows that the high concentration of ash plume moves southward with

no vertical tilt. It is clear that the initial plume has no umbrella shape for the vulcanian eruptions.

Figure 6 plots zonal-height (X-Z) and meridional-height (Y-Z) cross sections of ash plume dispersal for (a) 7:30, (b) 8:00, (c) 8:30, and (d) 9:00 JST, respectively. The colors of particles indicate a different plume height. At 7:30, the ash particles tilts eastward with respect to height in the X-Z plot as shown in Fig. 5. Particles above 3000 m move eastward and those below 3000 m moves westward in the X-Z plot. In the Y-Z plot, the particles above 3000 m drift southward, and the low level particles are continuously supplied by the weak but steady eruption. By analyzing the series of the plots, it is clear that the ash fallout is in the western side and southern side of the volcano.

Figure 7 illustrates the results of the PUFF model simulation of the 3D perspective image of the volcanic ash plume dispersal at 8:30 JST on 16 June 2018. The figure is for 70 min after the beginning of the eruption. The colors of particles indicate a different plume height, and the projection onto the ground is marked by black dots. Since the high level ash plume drifted southward indicating eastward stretch, the ash cloud lines up on east-west direction. In contrast, the low level ash clouds are transported to west direction covering Kagoshima city due to the large vertical wind shear. The low level wind is much stronger than the high level wind.

Figure 8 plots the particle distribution for ash fallout accumulated during the 6 hours following the eruption. The fallout covers the southwest slope of the Sakura-jima volcano extending to the west direction for Kagoshima city and to East China Sea. As was calculated by the peak emission rate, one particle represents 1.0 ton (1000 kg) of ash mass when the adjusting parameter is not considered. According to the in-situ observations of ash fallout over Kagoshima city (JMA 2018), ash fallout of 662 g/m^2 was reported at the Kagoshima Meteorological Observatory in Kagoshima city.

Figure 9 plots the ash fallout distribution evaluated from Fig. 8 in the units of g/m^2 with a common log-scale, i.e., 1.0 denotes 10 g/m^2 . The contours are calculated by counting the number of fallout particles using 1 km grid meshes. In the calculation, we take a common log-scale of mass for each grid, and applied a spatial smoothing for the mapping purpose. Note that the adjusting constant of $a = 30$ is introduced to fit the contour of 662 g/m^2 at Kagoshima city. According to the result, the ash fallout of 10 g/m^2 appears over the coast line of the East China Sea, and the contour of 1000 g/m^2 touches the Kagoshima city. Figure 10 plots the same ash fallout contours as Fig. 9 but using 100 m grid meshes to analyze the ash fallout along the west side of mountain slope of Sakura-jima volcano. According to the result, a contour of 1000 g/m^2 is analyzed along the west side slope, as consistent with Fig. 9. According to the observation, ash fallout of 2150 g/m^2 was recorded at Sabo Center at the west side coast of Sakura-jima. The simulation result is consistent with the ground observation for this case. By applying an appropriate spatial average after taking a common log-scale for the total mass of each grid, we can present the horizontal distribution of ash fallout as in the case of Eulerian model based on a grid system.

Since every particle in the PUFF model is given a known amount of mass by the adjusted emission rate in Eq. (3), we can analyze even for the airborne ash density as a function of time. Figure 11 plots the horizontal distribution of the airborne ash density (mg/m^3) for (a) 7:30, (b) 8:00, (c) 8:30, and (d) 9:00 JST, respectively. The contours represent the ash density with a common log-scale, i.e., 1.0 denotes 10 mg/m^3 . The values in the figures are the maximum in the vertical column at each grid point. According to the result, ash plume is seen over Sakura-jima at 7:30 as a point source over the vent. At 8:00, the ash cloud extends in east-west direction covering from Kagoshima city to Tarumizu city showing an overall southward drift. At 8:30, the ash cloud extends from the vent to westward over Kagoshima city and Hinoki city, then it bends back to Kagoshima

Bay and Tarumizu city. The ash density is more than 10 mg/m^3 over Tarumizu city. At 9:00, the ash cloud extend from the vent to westward over East China Sea, then it bends back to Minami-Satsuma city and Kagoshima Bay and Tarumizu city, showing a further southward drift. There is a wide zone of ash density above 2 mg/m^3 in the figure, indicating a danger zone for commercial airliners. The airborne ash density simulated by the PUFF model provides quantitative information about the possible extension of the danger zone for aviation safety for the eruption events of Sakura-jima volcano.

5. Result of the model simulation for 13 November 2017

In this section, the same PUFF model simulation is further conducted using the real-time emission rate with the same adjusting constant for the eruption event on 13 November 2017 in order to compare the performances of the PUFF model system. The magnitude of the eruption was as large as the case for 16 June 2018. However, the visual observation was not available due the cloud cover at that time. It is found in the previous section that the estimated emission rate is 30 times smaller when the predicted fallout is compared with the observed fallout. In this section, we confirm whether this calibration is appropriate for other case.

Figure 12 shows the time series of the emission rate estimated by Eq. (3) and the corresponding plume height (m) evaluated by Eq. (4) as the input for the PUFF model converted to 5 min interval. The simulation started at 22:00 JST (13:00 UTC) and ended at 04:00 JST (19:00 UTC). The simulation time is noted from 0 to 6 hours in the abscissa. The emission rate indicates a peak value of 5000 ton/5min and lasted for 15 min. The corresponding plume height indicates 4500 m, which agrees quite well with the MP (multi-parameter) radar observation recently installed at Tarumizu station even though the visual observation was absent. At that time, the upper air wind was southwesterly

with the speed about 15 m/s at 500 hPa level.

Figure 13 illustrates the results of the PUFF model simulation of the ash plume dispersal for (a) 22:30, (b) 23:00, (c) 23:30, and (d) 24:00 JST, respectively. The colors indicate different plume heights as in Fig. 4. The result for 22:30 shows a point source of the ash plume indicating some drift to the northeast direction. At 23:00, 40 min after the eruption, the ash plume at the altitude of 4 km (red) drifted to northeast over Miyakonojo city, but the lower level ash clouds moved to the north for Kirishima city. The result for 23:30, 70 min after the eruption shows further northeastward drift. Plume height decreases at the source region. Interestingly, the lower part of the plume (blue) moves north to the Kagoshima Regional Airport, bending to eastward as height increased. The result for 24:00, 100 min after the eruption shows the plume top (red) reaching the Pacific coast over Miyazaki city. The movement of the ash plume is very different for the lower and upper part of the ash clouds.

Figure 14 depicts zonal-height (X-Z) and meridional-height (Y-Z) cross sections of ash plume dispersal for every 5 min as in Fig. 5 starting from 22:00 JST. The plume shape for the first 5 min after the eruption shows the plume top at 3000 m indicating a eastward drift from the vent. The plume top reaches 4000 m in the next 5 min showing a flat plume top. The result of the X-Z section shows a eastward movement of airborne ash transported by the upper level winds. The plume shape of high concentration tilts eastward with respect to height. The result of the Y-Z section shows that the high concentration of ash plume moves northward with no vertical tilt. It is clear that the initial plume has no umbrella shape for the vulcanian eruptions.

Figure 15 illustrates the results of the PUFF model simulation of the 3D perspective image of the volcanic ash plume dispersal at 23:30 JST on 13 Nov. 2017. The figure is for 70 min after the beginning of the eruption. The colors of particles indicate a different

plume height as in Fig. 7. Since the high level ash plume (red) drifted northeastward indicating a gradual northward drift for low level plume (blue), the plume is elongated from north to east as the distance increases.

Figure 16 plots the particle distribution for ash fallout accumulated during the 6 hours following the eruption. The fallout covers the northeast slope of the Sakura-jima extending to the northeast direction for Miyakonojo city. As was calculated by the peak emission rate, one particle indicates 30.0 ton of ash mass after the calibration.

Figure 17 plots the ash fallout distribution evaluated from Fig. 16 in the units of g/m^2 with a common log-scale as in Fig. 9. The contours are calculated by counting the number of fallout particles using 1 km grid meshes. According to the result, the ash fallout of 100 g/m^2 contour appears over Kirishima city, and 10 g/m^2 contour appears over Miyakonojo city. According to the in-situ observations of ash fallout around Kirishima city (JMA 2018), ash fallout of 63 g/m^2 was reported at Fukuyama station, which agrees with the prediction.

Figure 18 plots the same ash fallout contours as Fig. 17 but using 100 m grid meshes to analyze the ash fallout along the northeast side of mountain slope of Sakura-jima volcano. According to the result, a contour of 1000 g/m^2 is analyzed along the north side slope, while the contour of 10000 g/m^2 appears near the vent. According to the in-situ observations of ash fallout within Sakura-jima, ash fallout of 2417 g/m^2 was reported at KOM and 2584 g/m^2 at FUT stations, which agrees well with the prediction.

Figure 19 plots the horizontal distribution of the airborne ash density (mg/m^3) for (a) 22:30, (b) 23:00, (c) 23:30, and (d) 24:00 JST, respectively. The values in the figures are the maximum in the vertical column at each grid as in Fig. 11. According to the result, the ash plume is seen at the northeast side of Sakura-jima at 22:30. At 23:00,

the ash cloud extends in east-west direction reaching to Miyakonojo city. At 23:30, the ash cloud drifts northward over Kagoshima Regional Airport. The ash density is 100 mg/m³ over Miyakonojo city. At 24:00, the ash cloud extend from the vent to the Pacific coast over Miyazaki city. There is a wide zone of ash density above 2 mg/m³ in the figure, indicating a danger zone for commercial airliners. The PUFF model can provides quantitative information about the danger zone for aviation safety, and the same system is applicable to other volcanoes in Japan.

6. Concluding Summary

In this study, a real-time volcanic ash dispersion model called PUFF is applied to the Sakura-jima volcano erupted on 16 June 2018. In this new system, the discharge rate of the ash mass from the vent is estimated based on the empirical formulae developed for Sakura-jima volcano using seismic monitoring and ground deformation data. According to the time series of the estimated discharge rate, a major eruption occurred at 7:20 JST indicating the emission rate of 1000 ton per min and continued for 15 min. The major eruption was followed by minor eruptions for several hours. The emission rate is converted to the plume height by an empirical formulae, indicating the plume height reaching 4500 m, which appears to be consistent with ground observations by video cameras. The volcanic plume dispersion model PUFF is applied to this event using the emission rate and the plume height estimated in a real time base.

According to the result of the PUFF model simulation, the ash plume at high altitude beyond 3000 m moved southward showing a stretch in east-west direction, while the ash clouds at low level moved westward overcasting Kagoshima city. The ash fallout is represented by a number of particles in the Lagrangian form of PUFF model. The particle distribution is then converted to the fallout ash density in units of g/m², and compared

with the ground observation. It is found that we need to introduce the adjusting constant of $a=30$ to fit the model prediction with the observation of 662 g/m^2 at Kagoshima Meteorological Observatory in Kagoshima city. The ash fallout indicates the distribution of 10 g/m^2 contour extending westward direction more than 100 km to the East China Sea. The finer grid analysis shows the fallout of 1000 g/m^2 along the mountain slope of Sakura-jima volcano at the west side. According to the ground observation, ash fallout of 2150 g/m^2 was recorded at Sabo Center at the west side coast of Sakura-jima, which agrees well with the model prediction.

Since the emission rate is calibrated in the present model, the airborne ash density can be computed for the 3D space. According to the PUFF model simulation, the ash concentration of 100 mg/m^3 extends to Kagoshima city in the west as well as Tarumizu city in the southeast within one hour after the eruption. According to ICAO, an ash density of 2 mg/m^3 and above is considered dangerous for commercial airliners. The simulation results quantitatively indicate the location of the danger zone for the commercial airliners.

In this study, the same PUFF model simulation is further conducted using the real-time emission rate with the same adjusting constant for the eruption event on 13 November 2017 in order to compare the performances of the PUFF model system. According to the in-situ observations, ash fallout of 63 g/m^2 was reported at Fukuyama station. The ash fallout increases more along the mountain slope within Sakura-jima, showing 2417 g/m^2 at KOM and 2584 g/m^2 at FUT stations. These amounts agree well with the model prediction, supporting that the calibration by the adjusting constant is appropriate.

The PUFF model system combined with the real-time discharge rate estimation is useful for aviation safety purpose as well as ground transportation and human health around the active volcanos. Further improvement of the system is needed for both the PUFF model and emission rate estimation. It is expected to apply this new PUFF model

system to many other volcanoes in Japan and in other countries.

Acknowledgments

The authors are grateful for the support of Dr. H. Nakamichi of DPRI, Kyoto University and Mr. Mamoru Izumi of SATREPS for their technical assistance. This research was supported by the SATREPS research project and by Grant-in-Aids (15H05794) of the Japan Society for the Promotion of Science (JSPS).

References

- [1] S.-I. Akasofu, and H. L. Tanaka, “Urgent issue of developing volcanic ash tracking model,” *Kagaku Asahi*, No.5, 121-124 (in Japanese), 1993.
- [2] C. Chatfield, “The analysis of time series: An introduction,” Chapman and Hall, 286 pp, 1984.
- [3] K. G. Dean, S. I. Akasofu, and H. L. Tanaka, “Volcanic hazards and aviation safety: Developing techniques in Alaska,” *FAA Aviation Safety Journal*, Vol. 3, No. 1, 11-15, 1993.
- [4] M. Iguchi, “Prediction of volume of volcanic ash ejected from Showa crater of Sakurajima volcano, Japan,” *Disaster Prevention Research Institute, Annual Report B, University of Kyoto*, 55, 169-175, 2012.
- [5] M. Iguchi, “Method for real-time evaluation of discharge rate of volcanic ash: Case study on intermittent eruptions at the Sakurajima volcano, Japan,” *J. Disaster Res.*, 11, 4-14, 2016.
- [6] Japan Meteorological Agency (JMA), Home Page:
<http://www.data.jma.go.jp/svd/vois/data/kouhai/>, 2018.
- [7] R. Kelleher, “Atlantic conference on Eyjafjallajokull and aviation,” *UK volcanic ash safety regulation, Keflavic Airport, Iceland*, 2010.
- [8] J. Kienle, A. W. Woods, S. A. Estes, K. Ahlnaes, K. G. Dean, and H. L. Tanaka, “Satellite and slow-scan television observations of the rise and dispersion of ash-rich eruption clouds from Redoubt volcano, Alaska,” *EOS*, Vol. 72, 2, 748-750, 1991.
- [9] S. Leadbetter, P. Agnew, L. Burgin, et al., “Overview of the NAME model and its role as a VAAC atmospheric dispersion model during the Eyjafjallajokull eruption

April 2010,” Proc. EGU General Assembly, Vienna, Austria, p 15765, 2010.

- [10] S. Onodera, “Volcanic activity and flight operations,” Aviation Meteorological Notes, 45, 13-30, 1997.
- [11] C. Searcy, K. Dean, and B. Stringer, “PUFF: A volcanic ash tracking and prediction model,” J. Volc. and Geophys. Res., 80(1-2), 1-16, 1998.
- [12] H. L. Tanaka, “Development of a prediction scheme for the volcanic ash fall from Redoubt volcano,” First Int’l. Symp. on Volcanic Ash and Aviation Safety, Seattle, Washington. U.S. Geological Survey, Circular 1065, 58, 1991.
- [13] H. L. Tanaka, K. G. Dean, and S. I. Akasofu, “Predicting the movement of volcanic ash clouds,” EOS, Vol. 74, No .20, 231-231, 1993.
- [14] H. L. Tanaka, “Development of a prediction scheme for volcanic ash fall from Redoubt volcano, Alaska,” Proc. First International Symposium on Volcanic Ash and Aviation Safety, U.S. Geological Survey, Bulletin 2047, 283-291, 1994.
- [15] H.L. Tanaka, and K. Yamamoto, “Numerical simulations of volcanic plume dispersal from Usu volcano in Japan on 31 March 2000,” Earth, Planets and Space, 54, 743-752, 2002.
- [16] H.L. Tanaka, M. Iguchi, and S. Nakata, “Numerical simulations of volcanic ash plume dispersal from Kelud volcano in Indonesia on February 13, 2014,” J. Disaster Res., 11, 31-42, 2016.
- [17] H.L. Tanaka, and M. Iguchi, “Numerical simulations of volcanic ash plume dispersal from Kuchinoerabu-jima volcano on 29 May 2015,” J. Natural Disaster Sci., 37, 79-90, 2016.

- [18] Tokyo Aviation Weather Service Center, “Volcanic ash advisory service, Japan Meteorological Agency,” *Geophys. Maga. Ser. 2*, Vol. 4, Nos. 1-4, 2001.
- [19] P. Wessel, W. H. F. Smith, R. Scharroo, J. F. Luis, and F. Wobbe, “Generic Mapping Tools: Improved version released,” *EOS Trans, AGU*, 94, 409-410, 2013.

Figure legends

- Fig. 1** Time series of the emission rate (ton/min) for local time on 16 June 2018 estimated by Eq. (3). There is an explosive eruption at 7:20 JST showing the emission rate of 1000 ton/min.
- Fig. 2** Time series of the emission rate converted to 5 min (ton/5min) and the corresponding plume height (m) estimated by Eq. (4) as the input for the PUFF model. The simulation started at 7:10 JST (22:10 UTC) and ended at 13:10 JST (4:10 UTC). The simulation interval is noted from 0 to 6 hours in the abscissa.
- Fig. 3** Distribution of wind vectors at 925 hPa and 500 hPa levels at 00:00 UTC on 16 June 2018 (9:00 JST). The real-time GPV data is provided by Japan Meteorological Agency through the Center for Computational Science, University of Tsukuba.
- Fig. 4** PUFF model simulation of the ash plume dispersal for (a) 7:30, (b) 8:00, (c) 8:30, and (d) 9:00 JST, respectively. The particle colors indicate different plume heights.
- Fig. 5** Ash plume dispersal in zonal-height (X-Z) and meridional-height (Y-Z) cross sections for every 5 min starting from 7:10 JST.
- Fig. 6** Zonal-height (X-Z) and meridional-height (Y-Z) cross sections of ash plume dispersal for (a) 7:30, (b) 8:00, (c) 8:30, and (d) 9:00 JST, respectively. The colors of particles indicate different plume heights.
- Fig. 7** PUFF model simulation of the 3D perspective image of the volcanic ash plume dispersal at 8:30 JST on 16 June 2018. The figure is for 70 min after the beginning of the eruption. The colors of particles indicate a different plume height, and the projection onto the ground is marked by black dots.

Fig. 8 Particle distribution of ash fallout over 6 hours from the onset of the eruption on 16 June 2018.

Fig. 9 The estimated concentration of ash fallout (g/m^2) in common log-scale, i.e., 1.0 denotes $10 \text{ g}/\text{m}^2$. The contours are calculated by counting the number of fallout particles in Fig. 8 using 1 km grid meshes.

Fig. 10 As in Fig. 9, but the contours are calculated using 100 m grid meshes. The contour 2.0 denotes $100 \text{ g}/\text{m}^2$.

Fig. 11 Distribution of airborne ash density (mg/m^3) for (a) 7:30, (b) 8:00, (c) 8:30, and (d) 9:00 JST, respectively. The values are in common log-scale, i.e., 1.0 denotes $10 \text{ mg}/\text{m}^3$.

Fig. 12 Time series of the emission rate converted to 5 min ($\text{ton}/5\text{min}$) and the corresponding plume height (m) as in Fig. 2. The simulation started at 22:00 JST (13:00 UTC) and ended at 04:00 JST (19:00 UTC).

Fig. 13 PUFF model simulation of the ash plume dispersal on 13 November 2017 for (a) 22:30, (b) 23:00, (c) 23:30, and (d) 24:00 JST, respectively, as in Fig. 4. The particle colors indicate different plume heights.

Fig. 14 Ash plume dispersal in zonal-height (X-Z) and meridional-height (Y-Z) cross sections for every 5 min as in Fig. 5, starting from 22:00 JST.

Fig. 15 PUFF model simulation of the 3D perspective image of the volcanic ash plume dispersal at 23:30 JST on 13 November 2017, as in Fig. 7. The figure is for 70 min after the beginning of the eruption.

Fig. 16 Particle distribution of ash fallout over 6 hours from the onset of the eruption as in Fig. 8, but on 13 November 2017.

Fig. 17 The estimated concentration of ash fallout (g/m^2) in common log-scale, as in Fig. 9 but on 13 November 2017. The contours are calculated using 1 km grid meshes.

Fig. 18 As in Fig.17, but the contours are calculated using 100 m grid meshes.

Fig. 19 Distribution of airborne ash density (mg/m^3) for (a) 22:30, (b) 23:00, (c) 23:30, and (d) 24:00 JST, respectively, as in Fig. 11 but on 13 November 2017.

Figure 1 Time series of the emission rate (ton/min) for local time on 16 June 2018 estimated by Eq. (3). There is an explosive eruption at 7:20 JST showing the emission rate of 1000 ton/min.

Figure 2 Time series of the emission rate converted to 5 min (ton/5min) and the corresponding plume height (m) estimated by Eq. (4) as the input for the PUFF model. The simulation started at 7:10 JST (22:10 UTC) and ended at 13:10 JST (4:10 UTC). The simulation interval is noted from 0 to 6 hours in the abscissa.

Figure 3 Distribution of wind vectors at 925 hPa and 500 hPa levels at 00:00 UTC on 16 June 2018 (9:00 JST). The real-time GPV data is provided by Japan Meteorological Agency.

Figure 4 PUFF model simulation of the ash plume dispersal on 16 June 2018 for (a) 7:30, (b) 8:00, (c) 8:30, and (d) 9:00 JST, respectively. The particle colors indicate different plume heights.

Figure 5 Ash plume dispersal in zonal-height (X-Z) and meridional-height (Y-Z) cross sections for for every 5 min starting from 7:10 JST.

Figure 6 Zonal-height (X-Z) and meridional-height (Y-Z) cross sections of ash plume dispersal for (a) 7:30, (b) 8:00, (c) 8:30, and (d) 9:00 JST, respectively. The colors of particles indicate different plume heights.

Figure 7 PUFF model simulation of the 3D perspective image of the volcanic ash plume dispersal at 8:30 JST on 16 June 2018. The figure is for 70 min after the beginning of the eruption. The colors of particles indicate a different plume height, and the projection onto the ground is marked by black dots.

Sakura-jima

Start Time: 18/06/16 07:10 JST

Duration: + 6 hours

Ash Fallout

Figure 8 Particle distribution of ash fallout over 6 hours from the onset of the eruption on 16 June 2018.

Sakura-jima

Eruption: 18/06/16 07:10 JST

Duration: + 6 hours

Ash Fallout $\log_{10}$ (g/m²)

Figure 9 The estimated concentration of ash fallout (g/m²) in common log-scale, i.e., 1.0 denotes 10 g/m². The contours are calculated by counting the number of fallout particles in Fig. 8 using 1 km grid meshes.

Sakura-jima

Eruption: 18/06/16 07:10 JST

Duration: + 6 hours

Ash Fallout $\log_{10}$ (g/m²)

Figure 10 As in Fig. 9, but the contours are calculated using 100 m grid meshes. The contour 2.0 denotes 100 g/m².

Figure 11 Distribution of airborne ash density (mg/m³) for (a) 7:30, (b) 8:00, (c) 8:30, and (d) 9:00 JST, respectively. The values are in common log-scale, i.e., 1.0 denotes 10 mg/m³.

Figure 12 Time series of the emission rate converted to 5 min (ton/5min) and the corresponding plume height (m) as in Fig. 2. The simulation started at 22:00 JST (13:00 UTC) and ended at 04:00 JST (19:00 UTC).

Figure 13 PUFF model simulation of the ash plume dispersal on 13 November 2017 for (a) 22:30, (b) 23:00, (c) 23:30, and (d) 24:00 JST, respectively, as in Fig. 4. The particle colors indicate different plume heights.

Figure 14 Ash plume dispersal in zonal-height (X-Z) and meridional-height (Y-Z) cross sections for every 5 min as in Fig. 5, starting from 22:00 JST.

Figure 15 PUFF model simulation of the 3D perspective image of the volcanic ash plume dispersal at 23:30 JST on 13 November 2017, as in Fig. 7. The figure is for 70 min after the beginning of the eruption.

Sakura-jima

Start Time: 17/11/13 22:00 JST

Duration: + 6 hours

Ash Fallout

Figure 16 Particle distribution of ash fallout over 6 hours from the onset of the eruption as in Fig. 8, but on 13 November 2017.

Sakura-jima

Eruption: 17/11/13 22:00 JST

Duration: + 6 hours

Ash Fallout $\log_{10}$ (g/m²)

Figure 17 The estimated concentration of ash fallout (g/m²) in common log-scale, as in Fig 9 but on 13 November 2017. The contours are calculated using 1 km grid meshes.

Sakura-jima

Eruption: 17/11/13 22:00 JST

Duration: + 6 hours

Ash Fallout log10 (g/m²)

Figure 18 As in Fig.17, but the contours are calculated using 100 m grid meshes.

Figure 19 Distribution of airborne ash density (mg/m3) for (a) 7:30, (b) 8:00, (c) 8:30, and (d) 9:00 JST, respectively, as in Fig. 11 but on 13 November 2017.