Development of Volcanic Ash Plume Tracking Model PUFF and Estimation of the Airborne Ash Density

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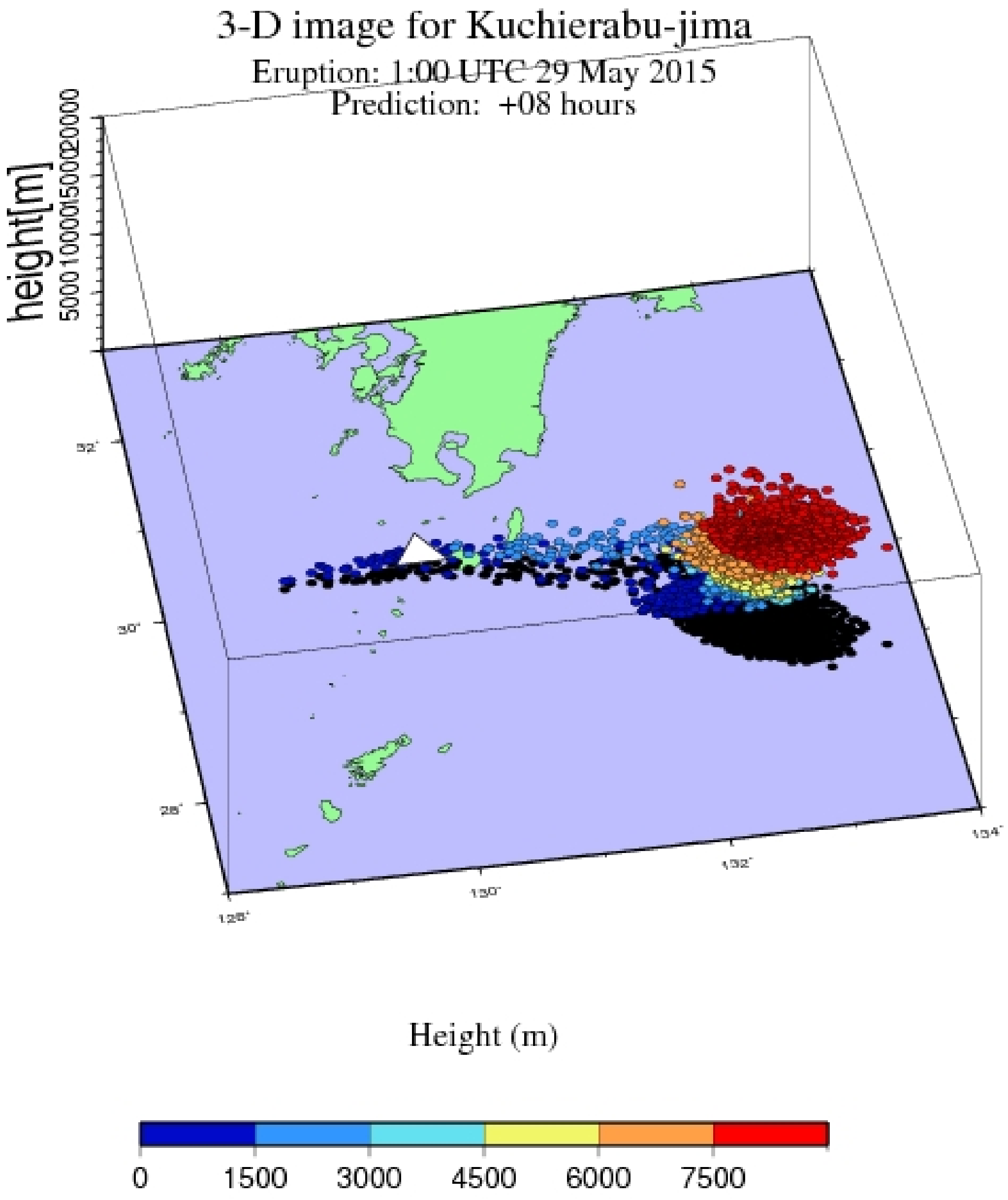
Airborne volcanic ash is a danger object for the aviation safety. Once the jet aircraft encounters the ash cloud and engine failure occurs, the damage is estimated to reach to a billion of US dollar. Hence the real-time monitoring and estimation of the airborne ash density is an important research subject. According to ICAO report, the ash density above 2 mg/m3 is a threshold for the danger zone of the aircraft. A system to predict the airborne ash density is desired based on the real-time observation of the emission rate and plume height.
In this study, we conducted numerical simulations of volcanic ash dispersal from Sakurajima volcano using the real-time volcanic ash plume dispersion model PUFF, combined with the real-time estimation of emission rate and plume height based on seismicity record. The PUFF model is applied to the eruption of Kuchinoerabu-jima in May 2015, and the airborne ash density was estimated based on the fallout data at Yakushima. According to the simulation, the ash plume movement agrees well with the satellite imagery by Himawari-8. The plume is located at 200 km from the volcano 8 hours after the eruption, and has the density more than 100 mg/m3. The simulated result offers important information of airborne ash density which is useful to the aviation safety.

Keywords: Volcanic ash plume prediction, Emission rate of volcanic ash, Aviation safety, Kuchinoerabu-jima, PUFF model, Himawari-8


3-D image for Kuchierabu-jima
Eruption: 1:00 UTC 29 May 2015
Prediction: +08 hours
height[m]
5000 10000 15000 20000
32°
30°
28°
128°
130°
132°
134°
Height (m)
0
1500
3000
4500
6000
7500

Fluid dynamics of very large plumes generated by explosive super-eruptions

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Explosive super-eruptions releasing several hundreds to thousands of km^3 of magma with extremely intense flow rates occurred in the geological past of the Earth. They impacted significantly the climate and global ecosystems. Because of lack of direct observation, plume dynamics of these eruptions are poorly understood. Simple integral models based on the Buoyant Plume Theory (Morton et al., 1956; Woods and Wohletz, 1991) have been commonly used to describe them. The validity of the assumptions behind these models (e.g., self-similarity, constant air entrainment coefficient) should be validated, because the dynamics of super-eruptions can be totally different from a simple buoyant plume. We used a three-dimensional (3D) computational fluid dynamic model (Suzuki et al., 2005) to investigate the main features of these gigantic plumes characterized by Mass Flow Rate (MFR) ranging from 10^9 to 10^{11} kg/s. The lower end of the range corresponds to the most intense Plinian columns such as the 1991 Pinatubo eruption, while the upper end to the most extreme co-ignimbrite plumes such as the Toba eruption occurred 74 ka.

We performed 3D simulations of super-eruptions and compared these results with those of the previous models. At the steady-state for low and intermediate MFR, radii of the umbrella cloud spread as function of time with the same asymptotic behavior predicted by simple box models (Woods and Kienle, 1994) and this dependence can be used to estimate MFR. Simulation results also indicate that the co-ignimbrite plume radius,, growths with MFR with the same scaling for MFR *vs* run-out distance predicted by previous simple models of pyroclastic flows by Bursik and Woods (1996). On the other hand, the maximum heights simulated by the 3D model showed the complex dependency on the MFR, which are significantly different from those of the simple integral model (Woods and Wohletz, 1991). This difference indicates that it is necessary to consider new scaling laws of the effective air entrainment coefficients for using the simple integral models as an extrapolation in order to reproduce the gigantic plumes. Results have large implications on the assessment of the intensity and the impact of these explosive super-eruptions on the Earth climate and past ecosystems.

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Keywords: super-eruption, volcanic plume, fluid dynamics

Numerical simulations of a two-layer shallow-water model for pyroclastic density current

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During an explosive volcanic eruption, a hot mixture of volcanic particles and gas is continuously ejected from the volcanic vent and develops an eruption column. When the density of the mixture remains higher than that of the ambient air, the eruption column collapses to produce pyroclastic density currents (PDCs). PDCs are characterized by strong density stratification, whereby a dilute current (particle suspension flow) overrides the dense basal current (fluidized granular flow). The dynamics of PDCs is affected by physical processes within each of the dilute and dense parts, such as thermal expansion of ambient air entrained into the dilute part and basal resistance in the dense part. It also depends on the particle transport between the dilute and dense parts. We aim to understand these effects on PDC dynamics and the resulting run-out distance, by using numerical simulations.

We have developed an unsteady two-layer model to describe density currents with strong density stratification. In this model, each of dilute and dense parts is assumed to be uniform in any vertical section and is formulated by shallow-water equations. In the dilute part, the effects of particle settling, entrainment of ambient air, thermal expansion, interfacial drag between the dilute and dense parts, and resistance of ambient at the flow front are taken into account. In the dense part, the effects of basal resistance, sedimentation, and the particle supply from the dilute part are included. The equations are numerically solved by the finite volume method using the HLL scheme. A stationary dilute mixture with its higher density than that of the ambient air is initially (i.e., $t = 0$) set in the rectangular reservoir with a solid backwall, and an additional mixture with the same composition as the initial mixture is supplied to the reservoir at a constant rate at $t > 0$. A density current is produced on a horizontal ground surface by an instantaneous release of the mixture at $t = 0$ and the subsequent steady supply of the mixture in the reservoir.

We calculated time evolution of a PDC (e.g., thicknesses and velocities of dilute and dense parts, and thickness of deposit). The result is divided into two stages. In the first stage (Figure 1a), the dilute part propagates, and the dense part develops. Because the dense part propagates slowly owing to basal resistance, the maximum run-out distance in this stage is determined by the front position of the dilute part (L_1). In the second stage (Figure 1b), the density of the frontal region of the dilute part falls to that of the ambient air owing to particle settling and thermal expansion of entrained air. The mass of this frontal region ascends from the current into a co-PDC plume (i.e., co-ignimbrite ash cloud), whereas the dilute part around the source forms a steady dilute density current. The run-out distance of the steady current (L_S) is much shorter than L_1. Subsequently, the dense part extends beyond L_1, and the run-out distance of the PDC is determined by the front position of the dense part (L_D).

Previously, the run-out distance of PDC was estimated on the basis of a steady one-layer dilute PDC model (Bursik & Woods, 1996). This run-out distance corresponds to L_S, and does not represent L_1 or L_D. Therefore, the run-out distance proposed by the previous study may be underestimated.

Keywords: pyroclastic density current, shallow-water equation, two-layer model, run-out distance, particle suspension flow, granular flow

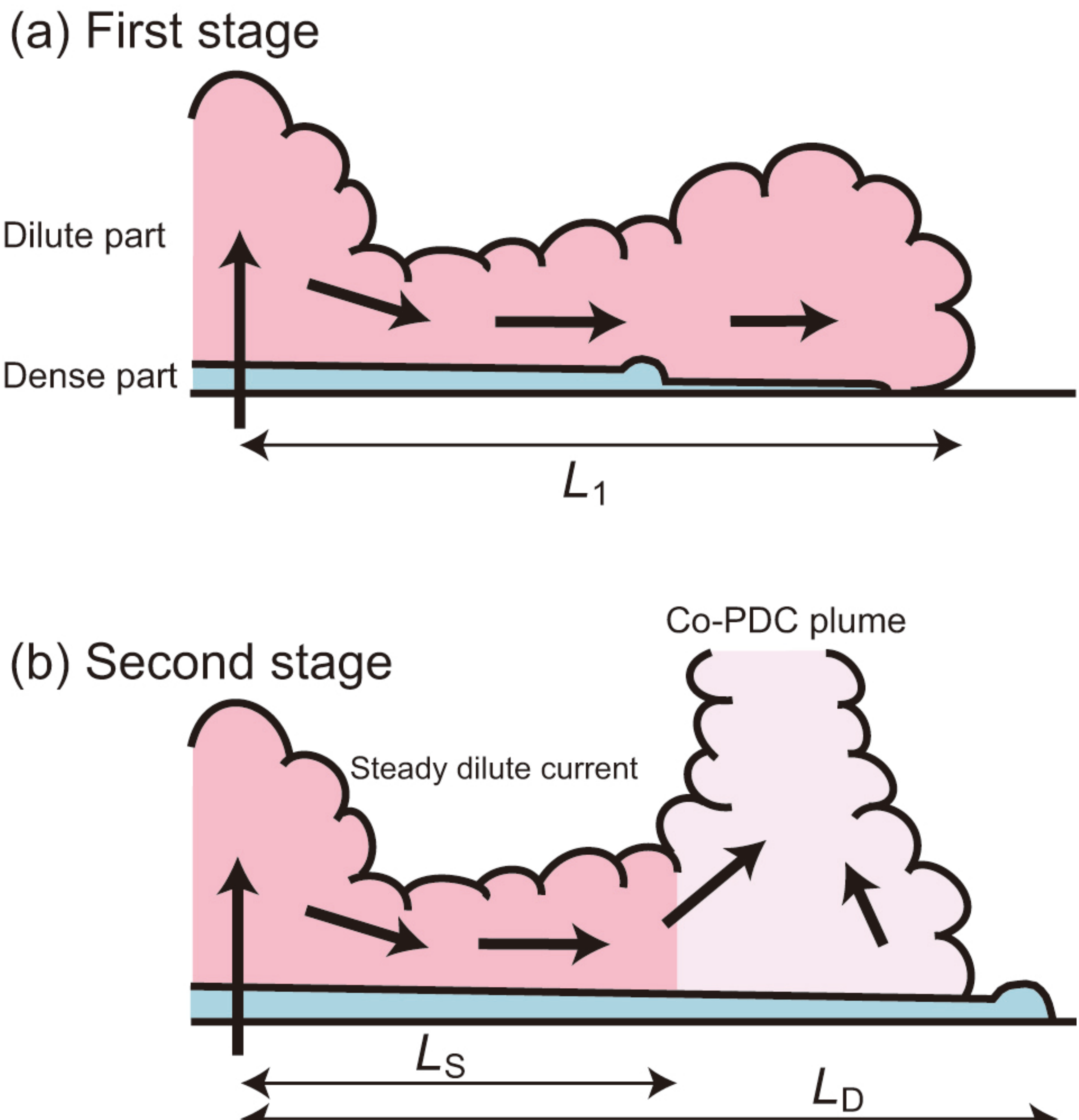

Figure 1 Schematic illustrations showing time evolution of a PDC.

A refractive index model of volcanic ash derived from satellite infrared sounder measurements for applications of HIMAWARI-8 retrieval algorithm

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Japan Meteorological Agency (JMA) has been developing a retrieval system to provide volcanic ash products from HIMAWARI-8 infrared measurements through a volcanic ash detection/evaluation algorithm. For the estimation of ash cloud parameters, i.e. cloud top height, optical depth, particle size, and associated mass loading, accurate radiative transfer calculations in the modeled atmosphere are important. Because optical properties of the ash clouds strongly depend on the ash refractive index, a dataset of spectral refractive index in the infrared region for various types of volcanic ash materials is desirable. The current models of refractive index for volcanic ash, which were published more than thirty years ago, are insufficient in spectral resolution as well as in the number of alternatives for the use of multi-channel satellite remote sensing.

As reported in the literatures, refractive index of volcanic rocks and/or ash materials at infrared wavelengths had been estimated in laboratory from the spectral reflectance for the applied infrared light. The situation of satellite infrared sounder measurements for volcanic ash clouds in the atmosphere over land/ocean is essentially similar to the laboratory measurements. It suggests that the ash refractive index can be estimated from the infrared spectroscopy by satellites in condition of no ice/water clouds contamination and if the other unknown parameters, i.e. the ash cloud parameters, the atmospheric profile, and surface temperature/emissivity, are determined in advance or derived simultaneously. The estimated refractive index of the ash material by satellite infrared sounder has a potential to improve volcanic ash retrieval by HIMAWARI-8 for the same ash clouds and also for the ash clouds erupted from the same type of volcanos. In this work, a refractive index model, which derived from the measurements of infrared sounders, AIRS and IASI, for some volcanic events is proposed.

Keywords: volcanic ash, refractive index, Himawari-8

Temporal variation of the 2011 Shinmoe-dake subplinian eruption inferred from the stratigraphic GSD variation

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Spatial variations of grain-size distributions (GSDs) in pyroclastic fall deposits reflect the effects of the temporal variations of the volcanic activity and of the transportation under the atmospheric condition. To reconstruct the temporal variation of GSD at the source position during the eruption, we have carried out theoretical studies in which we construct the relationship of GSD variations between at the source position and at a certain observation locality in the vertical and horizontal two-dimensional space (here after we call as two-dimensional model). We apply this relationship to the pyroclastic fall deposit produced by the 2011 Shinmoe-dake subplinian eruption and estimate the temporal variation of GSD at the source position.
Shinmoe-dake is an andesitic stratovolcano which belongs to the Kirishima volcano complex, south of Kyushu, southwest of Japan (the elevation is 1,421m asl). Three subplinian eruptions occurred on January 26 to 27, 2011. During the subplinian eruptions, temporal variations of the volcanic activity such as eruption column height (Shimbori et al., 2013) and geodetic rate of volumetric change (Ueda et al., 2013) were observed. The stratigraphic variations of GSDs in the pyroclastic fall deposits show a coarsening in the lower part and a fining in the upper part of the sediment produced by the first subplinian eruption on January 26 at locality Mk, 7.9 km SE from the vent (Iriyama and Toramaru, 2015). By using the observed stratigraphic GSD variations and the two-dimensional model, we estimated the temporal variation of GSD at the source position. We characterized GSDs as power-law distributions, then we obtained the temporal variation of the power-law exponent of the source GSD, which suggests coarsening in the early stage and fining in the late stage.
Applying the relationship among the source GSD, mass eruption rate, and the maximum plume height reported by steady-state calculation of the plume dynamics (Girault et al., 2014) to the 2011 Shinmoe-dake subplinian eruption together with the estimated source GSD and the observed eruption column height, we have the estimated temporal variation of the mass eruption rate consistent with the geodetic data of the volumetric change.

Keywords: grain-size distribution, pyroclasts, temporal variation, mass eruption rate

Pyrrhotite oxidation as a tool for reconstructing thermal structure of eruption columns

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Entrainment of ambient air is a key process in eruption cloud dynamics as it thermally expands and produces buoyancy. Because magma fragments (pyroclasts) are cooled and oxidized by air entrainment, petrological analysis may evaluate independently the entrainment process. To quantify the degree of interaction between fragmented magma and entrained air, we focused on oxidation of pyrrhotite (Po, $Fe_{1-x}S$) in the pyroclasts. In this study, we simulated cooling of pyroclasts to examine the coupling between degree of oxidation and eruption dynamics. Cooling of pyroclasts was simulated using a newly-developed routine for a three-dimensional (3-D) eruption column model, while oxidation kinetics of Po are already relatively well understood. By testing the parameter sensitivity of the degree of oxidation and comparing simulated and natural oxidation degrees for a Plinian eruption, we examined the usefulness of Po oxidation as a marker for magma-air interaction and an indicator of eruption-column thermal structure in the 3-D model.

Three simulations with different mass discharge rates and magma temperatures were performed based on the 3-D eruption column model. In the simulations, two types of thermal structures corresponding to jet flow and fountain flow (Suzuki and Koyaguchi 2012) were observed with magma discharge rates of 10^6–10^7 kg/s and ~10^9 kg/s, respectively. Both of the flow types included an "unmixed core" (or high mass fraction zone) in the column. The fountain-type maintained high temperature longer than the jet-type because the fountain-type unmixed core was not eroded until extensive air entrainment occurred at the top of the fountain.

The oxidation degree of pyroclasts was then calculated on the basis of predicted temperature change of particles in the eruption column. Po in volcanic rocks is often oxidized to form magnetite (Mt, Fe_3O_4) and then hematite (Hm, Fe_2O_3) (Matsumoto and Nakamura 2012). The growth rate of Hm from Mt can be applied to measure the oxidation degree of pyroclasts as it has been determined experimentally (Païdassi 1958). Calculations of Hm width were made for approximately 300 to 1000 oxidation markers in the eruption column for each simulation condition, and expressed as frequency distributions of oxidation degree. Our calculations showed that Hm-width distribution varied according to the mass discharge rate (i.e., flow type) and initial magma temperature. The distribution of oxidation degree was broad in the case of fountain-type, whereas it was narrow in the case of jet-type. In addition, an eruption column which has a high initial magma temperature and jet-like structure was characterized by a long-tailed distribution, which results from a presence of high oxidation degree markers. These results indicate that Po oxidation can be potentially used for characterizing the thermal structure of eruption columns.

We also compared calculated Hm widths with petrographic data from the Sakurajima 1914 Plinian eruption. The Hm widths based on the simulation were approximately one-third the thickness of those observed in natural pumices. Three potential explanations for this discrepancy are: (1) thermal conduction of the pumice clasts, which is neglected in the present 3-D model, affects the Po reaction degree; (2) Po reaction rate was underestimated; and/or (3) Po oxidation started in the volcanic conduit before magma fragmentation, possibly accompanying open-system outgassing of the magma.

Keywords: eruption column, oxidation, pyrrhotite

Volcanic ash plume observation by weather radars

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In spite of the existence of many eruption cases observed by weather radars (e.g. Sawada (2003), Marzano et al. (2013)), the quantitative ash estimation (QAE) technique is not established yet. One of the reason is an uncertainty of reflectivity. Roughly speaking, the parameter represents both size and number of clutters, however, we can't separate it into the components. In other words, only with reflectivity, we can’t determine the particle size distribution (PSD) of targets.
In such a circumstance, it is expected that polarimetric weather radar can obtain information about the PSD inside volcanic ash plume. Generally, polarimetric radars transmit horizontal and vertical radio waves at the same time, and receive the backscattered waves, thus, we can get the ratio and the correlation coefficient of two components. We think these parameters are effective for QAE.
Another way we think effective for observing volcanic ash plume is a fast-scan radar. As fast-scan radars can get a 3D image of a volcanic ash plume in a moment, we believe that this kind of radars can contribute to better understanding of dynamics of volcanic ash plume.
Meteorological Research Institute (MRI) installed an X-band multi-parameter (polarimetric) radar (MRI-XMP) and a Ku-band fast-scan radar (MRI-Ku) near Sakurajima volcano, and started observation from March, 2016. In this presentation, we will present some cases of volcanic ash plume observed by these radars, and discuss the problems and the prospects of the future.

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Keywords: volcanic ash plume, weather radar, polarimetric radar, fast-scan radar, Sakurajima volcano

Development of a Volcanic Ash Data Assimilation System for Atmospheric Transport Model

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In the Japan Meteorological Agency (JMA), there are two major operations related to volcanic ash forecasting: the Volcanic Ash Fall Forecast (VAFF) and the Volcanic Ash Advisory (VAA). The VAFF provides information for local governments and residents who may be affected by ash fall from volcanoes (Hasegawa et al., 2015). The VAA is issued to airline companies and aviation authorities for safe aviation services.

In these operations, the forecasts are calculated by atmospheric transport models including advection process, gravitational fall process and deposition process (wet/dry). The most important and uncertain factor of the models is the initial condition of volcanic ash. In operations, the initial condition is based on the empirical model of Suzuki (1983). Since it includes many assumptions and empirical research, it often fails to reproduce actual plumes of volcanic eruptions.

On the other hand, in recent years, research of observation techniques of volcanic ash by weather radar and satellites have advanced. The Meteorological Research Institute (MRI), one of the facilities of JMA, has started observation using two different types of weather radar. Besides, in 2015, the Himawari-8 geostationary meteorological satellite was put into operation. Himawari-8 has sixteen observation bands as against five in its predecessor, MTSAT-2. Using this abundant observation data of new-generation satellite, physical quantities of volcanic ash clouds (including top height, mass loading and particle radius) can be retrieved (Hayashi et al., JpGU2016).

In the present study, using both radar and satellite observation, we are developing a volcanic ash data assimilation system to improve initial conditions of the atmospheric transport models.

We have adopted the three-dimensional variational data assimilation scheme (3D-Var), which has low computational cost and is suitable for creating initial conditions immediately after an eruption occurs. Analysis variables are concentration of ash and size distribution parameters (median particle size and dispersion) which are mutually independent. It is assumed that observation error covariance matrix is diagonal, and background error covariance matrix has the relationship between correlation and distance and has the Gaussian form (Ishii et al., JpGU2016).

From the radar observation, it is expected that we can obtain three-dimensional ash concentration in the atmosphere and parameters of ash particle size distribution in the atmosphere. On the other hand, the satellite observation is expected to provide only two-dimensional parameters of ash clouds such as mass loading, top height and particle radius. Currently, we are trying to estimate the thickness of ash clouds using vertical wind shear.

Here, we show two case studies of data assimilation system. One is the February 14th, 2014 eruption case of Kelut in Indonesia for an experiment of data assimilation with virtual radar observation, and the other is the May 29th, 2015 eruption case of Kuchinoerabujima in Japan for an experiment of data assimilation with actual satellite observations.

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Keywords: data assimilation, atmospheric transport model, volcanic ash

Observations of volcanic eruption columns using Himawari-8 Super-Rapid Scan 30-sec imagery

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Japan Meteorological Agency (JMA) began operation of the new-generation geostationary meteorological satellite, Himawari-8, on 7 July 2015. The imager on board is called Advanced Himawari Imager (AHI), whose observation performance is highly improved compared to that of the predecessor geostationary meteorological satellites MTSAT-series. For example, the number of observation bands is increased from 5 (1 visible band and 4 infrared bands) to 16 (3 visible bands, 3 near-infrared bands, and 10 infrared bands), the spatial resolution is almost doubled (1 km to 0.5-1 km for visible and near-infrared bands and 4 km to 2 km for infrared bands), and the full-disk observation frequency is improved from hourly to every 10 minutes. Furthermore, for the small regions including Japan (two areas coverage of the 2000 km (E/W) and 1000 km (N/S) rectangle over the North-Eastern and South-Western Japan) and a target area (1000× 1000 km), high-frequency observation as much as every 2.5 minutes is carried out. These high-resolution and high-frequency data enable us to observe relatively small-scale and quickly changing phenomena, such as volcanic eruption clouds. The increase in number of the observation bands improves the capability of volcanic ash clouds detection and estimation of various parameters, such as amount and particle size of ash (Hayashi *et al*. 2016), and can be expected to estimate an amount of sulfur dioxide in volcanic clouds. Furthermore, the imagery at two Landmark areas of the 1000 km (E/W) and 500 km (N/S) rectangle can be obtained at every 30 seconds (Super-Rapid Scan observation). The main purposes of this observation are the navigation of satellite, image registration, and moon observation for calibration of AHI (Bessho *et al*. 2016). In recent times, the landmark areas are used experimentally for observation of phenomena such as rapidly developing cumulonimbus clouds and volcanic eruptions, and these set at the areas which contains the active volcanoes such as Sakurajima, Aso, and Asama volcano.
We start the study on the dynamics of eruption columns just after the start of eruption by using the Super-Rapid Scan data. In this paper we talk about the comparative studies of Himawari-8 band 3 (0.64 μm, spatial resolution 0.5 km) Super-Rapid Scan imagery of the eruption column of Sakurajima volcano with the observational data obtained by weather radars (Sato *et al*. 2017) and video data captured by volcano monitoring cameras of JMA.

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Keywords: Himawari-8, Super-Rapid Scan, eruption column, volcanic eruption, geostationary meteorological satellite, Sakurajima volcano

A sequence of plinian eruption preceded by dome destruction at Kelud volcano, Indonesia, on February 13, 2014: insights from tephra fallout and pyroclastic density current deposits

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A plinian-style eruption with a radially spreading umbrella cloud occurred on February 13, 2014, at Kelud volcano, Indonesia. We present the sequence of this plinian event based on a geological study of the eruptive products, analysis of satellite images of the eruption plume, and surface features of the volcanic edifice before and after the eruption. The eruptive deposits were divided into four major depositional units (Units A, B, C, and D) and used to determine the sequence of events. The plinian phase was preceded by partial destruction of the existing lava dome and generation of high-energy pyroclastic density currents (PDCs) with a maximum runout distance of ˜6.8 km mainly towards the NE. The PDCs produced a series of depositional subunits (Units A_{0-2}) and caused surface damage (blown-down trees and vegetation) over an area of 12 km^2 (stage 1). The main phase of the eruption was characterized by a strong eruption plume that produced widespread fallout tephra (Unit B) over East and Central Java (stage 2). The winds above the volcano significantly affected the tephra dispersal process. In stage 3, the plinian column collapsed, generating dense PDCs that flowed down the volcano valleys, producing pumiceous lobate deposits (Unit C). The declining phase of the eruption produced fine-rich fallout tephra layers (Unit D_{1-2}) from low-level eruption plumes and/or ash lofted from PDCs. The eruption sequence constructed from field observations is supported by geophysical observations, including remote seismic and infrasound signals, total electron content variation, lightning strokes, and satellite observations. The initial high-energy PDCs and fallout tephra contained juvenile pumice and dome-derived lithic clasts, and isolated crystals originated from the fragmentation of porphyritic magma. The deposit features and componentry suggest that newly ascended magma triggered the destruction of the lava dome and the generation of high-energy PDCs, and during the subsequent climactic phase the dome was completely destroyed. Thus, the pre-existing lava dome significantly affected the course of the eruption. This type of eruption sequence has not been previously documented in the historical records of Kelud volcano activity. The total volume of erupted material was estimated as 0.25–0.50 km^3 (bulk deposit volume), corresponding to 0.14–0.28 km^3 in DRE, and the mean eruption rate as $6.5 \pm 2.8 \times 10^7$ kg/s. The scale of the 2014 eruption had a VEI of 4, and was one of the largest eruptions at Kelud volcano over the past century. The eruption sequence and estimated physical parameters of the 2014 eruption will help assess future volcanic activity and potential hazards at Kelud volcano.

Keywords: Plinian, pyroclastic density current, blown-down tree, lava dome, Kelud

A One-dimensional Steady State Model of a Buoyancy-generating Turbulent Plume and its Application to Volcanic Eruption Columns

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I will talk about a one-dimensional steady state model of turbulent plumes in which the buoyancy flux significantly increases with height. This model clearly suggests the importance of the formulation of the increase in buoyancy flux due to thermal expansion of entrained air to appropriately describe the fundamental features of volcanic eruption columns. An analytical solution of a simple form is specifically derived for an idealized axisymmetric turbulent plume of a linearly increasing buoyancy flux in a uniform environment. The solution predicts that the upward velocity of the plume is constant along the height, in contrast to the upward velocity of a common incompressible plume, the velocity of which decreases inversely proportional to the third root of the height. More realistic plumes in both uniform and density-stratified environments are also investigated by modifying the one-dimensional model. The model yields several scaling parameters, some of which are used to estimate the terminal height of an eruption column. Numerical investigations using the parameters indicate that the thermal energy in an eruption column is exhausted for heating and expanding entrained air before reaching the terminal height. Numerical investigations also imply that the buoyancy flux in an eruption column may be less than half of that predicted by the conventional theory of an incompressible plume. The discussion based on the present model also sheds new light on the physical background of the superbuoyant behavior of an eruption column.

Keywords: Eruption column, Turbulent plume, One-dimensional model, Buoyancy flux, Thermal expansion

Backscattering characteristic of volcanic eruptions based on LIDAR observation around Sakurajima Volcano

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Increases in aerosol due to eruptions have been detected by lidars distant from erupting volcanoes. Backscattering coefficient and depolarization ratio are examined related with volcanic ash particles (eg. Sassen et al.,2007). A lidar is installed on the flank of Sakurajima volcano and lidar observation is conducted for volcanic ash plume above the craters of the volcano to obtain spacio-temporal distribution of backscattering intensity and depolarization ratio. Sakurajima volcano is the most active volcano and has continued eruptions at the Showa crater since 2006 and white plume is emitted from the Minamidake crater continuously.

Depolarization ratio of white plume is almost the same as water cloud (0.05-0.1). On the other hand, depolarization ratio of volcanic ash cloud is much higher (0.40-0.45) than the white plume and water cloud. The highest value of depolarization ratio (0.72) was obtained only just above the crater immediately after eruptions for short-term. The high depolarization ratio is caused by larger density of volcanic ash particle with non-spherical shape.

Keywords: Volcanic smoke colored white, Volcanic smoke include volcanic ash, LIDAR, Backscattering intensity, Depolarization ratio, Sakurajima Volcano