

# 3D Numerical Simulation of the Volcanic Eruption Clouds during the 2014 Kelud Eruption

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We present a numerical simulation of the development of volcanic plumes during the 2014 eruption of the Kelud volcano, Indonesia, using a three-dimensional (3D) numerical model. The model is designed to calculate the eruption cloud dynamics and the transport of volcanic pyroclasts in arbitrary wind fields. The simulation results indicate that the plume vertically rises and generates an umbrella cloud at the level where the plume density is equal to the atmospheric density. The umbrella cloud are westwardly drifted and elongated by the strong wind at the tropopause. The volcanic pyroclasts fall from the eruption cloud and their dispersal axis extends leeward. When the magma discharge rate based on the field data is applied to the boundary condition at the volcanic vent, our simulation results successfully reproduce the field observations such as the plume height, the spreading rate of the umbrella cloud, and the fall area of pyroclasts.

**Keywords:** volcanic eruption, eruption column, ash dispersal, turbulent mixing, volcanic hazard

## 1. Introduction

Explosive volcanic eruption is one of the hazardous natural phenomena. During explosive eruptions, a mixture of volcanic pyroclasts (volcanic ash, pumice, etc.) and gases is ejected from a volcanic vent into the atmosphere. The fine volcanic pyroclasts are very abrasive materials, and therefore, they damage computers and electronic devices [1] and pose health risks [2]. The pyroclasts accumulated in the atmosphere are threat to aircraft safety [3]. For the hazard risk assessment, it is important to comprehensively explain various observed data during eruptions and to understand the dynamics of explosive eruptions and the mechanism of pyroclasts dispersal.

The dynamics of eruption cloud is generally divided into two regions: the regions of buoyant plume and the gravity current. The mixture ejected from volcanic vents entrains the ambient air owing to turbulent mixing as it rises. The entrained air expands drastically due to heating from the pyroclasts, which results in the formation of buoyant plume. The eruption cloud (the mixture of the ejected materials and entrained air) stops to rise at the neutral buoyancy level where the mixture density is equal to the atmospheric density. Subsequently, the eruption cloud radially spreads as a gravity current and generates umbrella cloud. The coarse pyroclasts are released from the buoyant plume and deposit in the proximal area of volcano, whereas the fine pyroclasts are transported by the current of umbrella cloud and settle in the distal area [4].

Recent progress in technique for observing eruption clouds

enables us to determine the height of buoyant plumes and the spreading rate of umbrella clouds with a high accuracy. In addition, we can obtain the data of the pyroclasts dispersal area on the basis of field observation. These observed data are considered to reflect the eruption conditions such as the magma discharge rate. In order to reconstruct the dynamics of past eruptions and assess the hazard risk caused by future eruptions, it is required to develop a numerical model that can correctly reproduce the relationship between the eruption conditions and observed data for a wide range of eruption intensity in arbitrary atmospheric conditions. In our project, we have successfully reconstructed the eruption cloud dynamics for the strong eruption of the Pinatubo volcano, Philippines in 1991 [5] and the weak eruption of the Shinmoe-dake volcano, Japan in 2011 [6]. The purpose of this study is to reproduce the eruption cloud dynamics for a moderate eruption that occurred at the Kelud volcano, Indonesia in 2014.

## 2. Numerical model and parameter settings

Our numerical model is designed to simulate the behavior of a mixture of pyroclasts and volcanic gas during explosive volcanic eruption, using a combination of a pseudo-gas model for fluid motion and a Lagrangian model for particle motion [7]. For the calculations of fluid dynamics, we treat an eruption cloud as a single gas with a density calculated using a mixing ratio between the ejected material and the entrained air [8]. A set of partial differential equations for fluid dynamics model

are solved numerically by a general scheme for compressible flow. For the calculations of particle motion, our model employs Lagrangian marker particles of ideal sphere. In this model, the density of particles is assumed to be 2000-2700 kg m<sup>-3</sup>, and 45 marker particles are ejected from the vent every 2 sec at the same velocity as the pseudo-gas. Particle grain sizes are randomly selected within a range of  $3.9 \times 10^{-3}$  to 256 mm. The terminal velocity of the marker particles is added to the vertical velocity of fluid motion at every time step, until the marker particle ceases its motion and settles as sediment when it reaches the ground surface.

Calculations were performed in a 3D domain with a non-uniform grid. A computational domain extends 37 km vertically (*Z*-direction) and 120 km × 80 km horizontally (*X*- and *Y*-directions, respectively). From a circular vent on the ground, the mixture of solid pyroclasts and volcanic gas is ejected with a constant flow rate. A free-slip condition is applied at the

ground boundary and a continuous condition is applied at the other boundaries of the computational domain. Grid sizes were set to be smaller than  $D_0/16$  near the vent, where  $D_0$  is the vent diameter, and to increase at a constant rate (by a factor of 1.02) with distance from the vent up to  $D_0/2$ .

Kelud volcano, located in Java Island, Indonesia, erupted on February 13, 2014. The explosive eruption continued for about 2 hours from 22:45 local time [9]. The atmospheric conditions at the volcano during the eruption were calculated using the Global Spectral Model of Japan Meteorological Agency. This model provides vertical profiles of the atmospheric density, pressure, temperature, and wind velocity (Fig. 1); the prevailing wind direction is southwesterly at the low altitude and easterly winds at the near-tropopause heights (~16 km asl.). In the simulations presented here, initial atmospheric conditions are given as a function of height (*Z*) using these vertical profiles, and are assumed to be horizontally uniform at each height, with vertical wind velocity assumed to be zero.

The volatile content and magma temperature are tentatively set to be 5 wt% and 1273 K, respectively. We assume that the pressure at the vent is equal to the atmospheric pressure. From these values, the initial density of the ejected material is estimated to be 2.89 kg m<sup>-3</sup>. In this study, the exit velocity is assumed to be the sound velocity of the mixture (173 m s<sup>-1</sup>). Dividing the total mass of pyroclastic deposits by the duration of the eruption, magma discharge rate is estimated to be  $3.7\text{-}7.0 \times 10^7$  kg s<sup>-1</sup> [10]. Here, we assume that the magma discharge rate is  $3.7 \times 10^7$  kg s<sup>-1</sup>.

### 3. Simulation results

Our simulation has reproduced the formation of volcanic plume and umbrella cloud (Fig. 2). At 30 min. after the eruption, the plume reaches to 25-30 km asl. The eruption cloud rises buoyantly below 20 km (Fig. 2c). The cloud keeps to rise above this level owing to its excess momentum. The top of plume has a higher density and a lower temperature than those of the ambient atmosphere (Fig. 2c,d). Such a lower temperature, called as “cloud top overcooling”, was observed during the Pinatubo 1991 eruption and explained by the adiabatic decompression of the cloud in the stratified atmosphere [11]. The eruption cloud spreads horizontally at 15-20 km and generates a large umbrella cloud. The maximum height of the plume ( $H_T = 25\text{-}30$  km) and the altitude of the umbrella cloud ( $H_U = 15\text{-}20$  km) are consistent with those estimated from the satellite images ( $H_T^{\text{OBS}} = 22\text{-}30$  km and  $H_U^{\text{OBS}} = 17\text{-}18$  km [9]).

The time evolution of the umbrella cloud area is derived from the time series of the numerical simulation results (Fig. 3). At the first stage of the eruption (< 1000 s), the umbrella cloud expands rapidly. Subsequently, the expansion rate of the umbrella cloud decreases with time. After 1000 s, the evolution of the area approaches the line of constant  $A^3/t^4$ , where *A* is the area of umbrella cloud. This means that the lateral evolution of

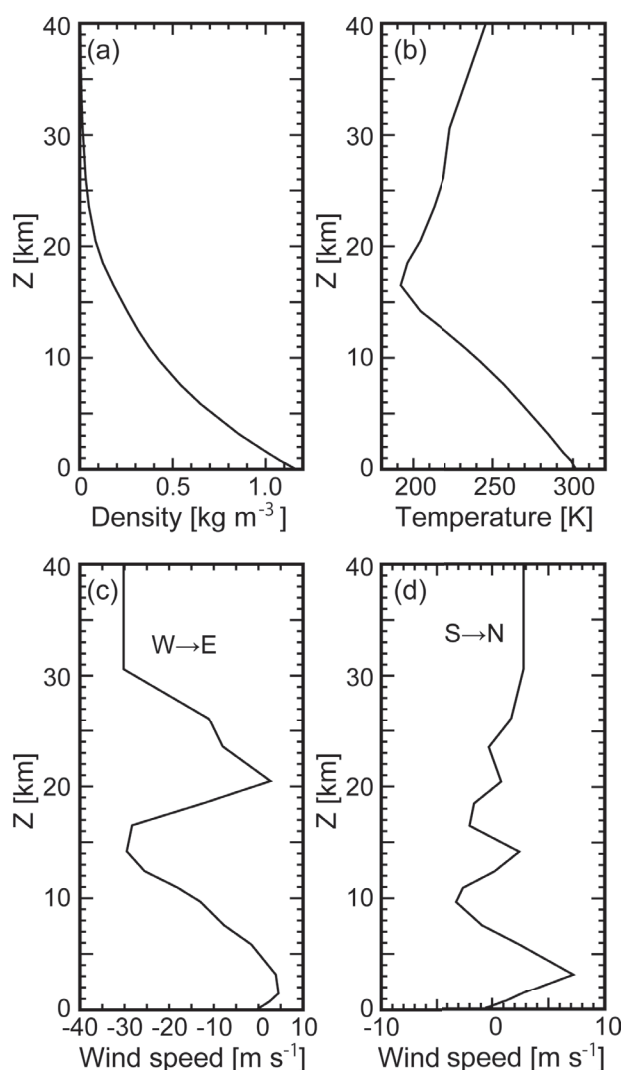


Fig. 1 Initial atmospheric conditions used in the simulations: (a) density, (b) temperature, (c) wind speed from west to east, and (d) wind speed from south to north. These profiles were provided by the Global Spectrum Model of Japan Meteorological Agency.

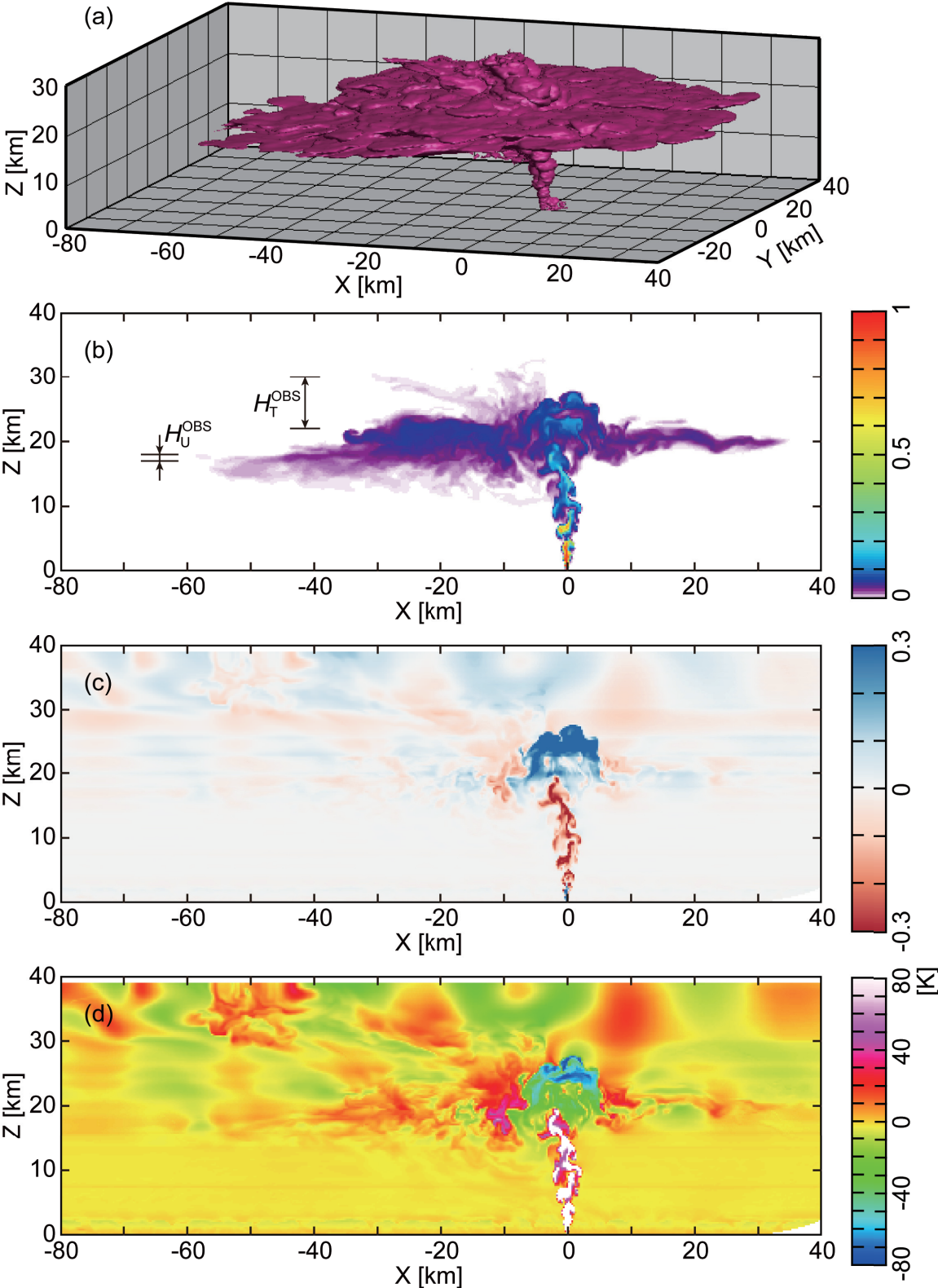


Fig. 2 Results of 3D numerical simulation of a plume during the Kelud 2014 eruptions at 30 min after the eruption. (a) Isosurface of  $\zeta = 0.02$ , where  $\zeta$  is the mass fraction of the ejected material. Cross-sectional distribution of (b) the mass fraction of the ejected material, (c) the density difference relative to stratified atmospheric density at the same vertical height,  $\Delta\rho = \rho/\rho_a - 1$ , where  $\rho$  is the cloud density and  $\rho_a$  is the atmospheric density, and (d) the temperature difference,  $\Delta T = T - T_a$ , where  $T_a$  is the atmospheric temperature.

the umbrella cloud can be described by the simple model for the gravity current intruding into the stratified environment [12]. When the magma discharge rate is  $3.7 \times 10^7 \text{ kg s}^{-1}$ , the evolution of the umbrella cloud is in quantitative agreement with those observed by the satellite images.

Our simulation has also reproduced the dispersal of particles in the atmosphere and their settlement on the ground (Fig. 4). The fine particles (shown by red or green points in Fig. 4a) are transported by the current of the umbrella cloud. The horizontal distribution of the fine particles in the atmosphere is elongated leeward (i.e., westward); it extends to 45 km east and 85 km west at 45 min. after the eruption. In contrast, the coarse particles (blue points) leave from the volcanic plume and fall to the ground near the vent (Fig. 4b). The size of particle deposited on the ground decreases with the distance from the vent. The dispersal axis of the fall deposit is elongated westward. Although the simulated duration (45 min.) is substantially shorter than the actual time of fallout, our model can capture the general features of dispersal axis obtained by the field observations [10].

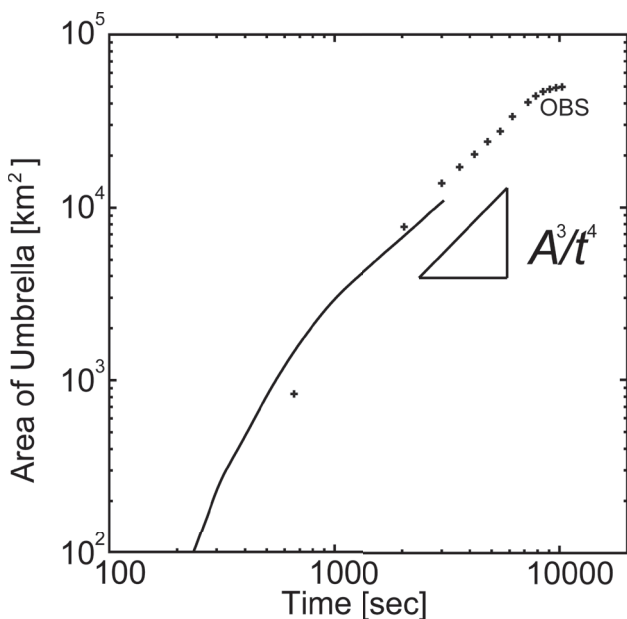


Fig. 3 Area of the spreading umbrella cloud as a function of time for the simulations of the Kelud 2014 eruption. The observed data are also plotted by pluses in the figure.

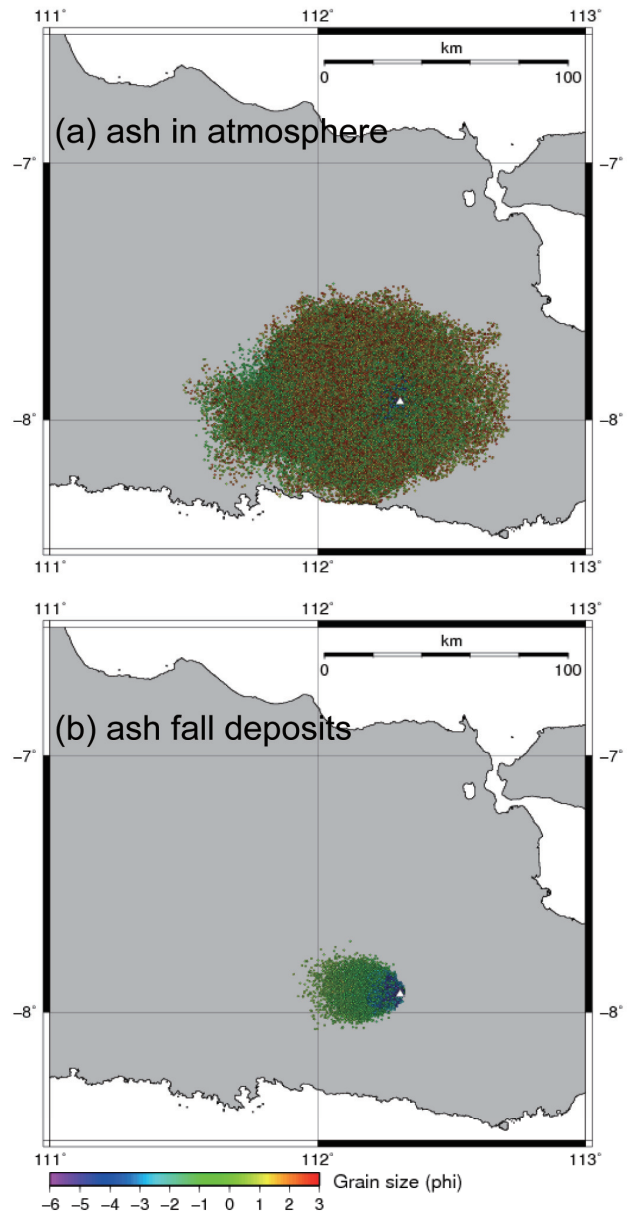


Fig. 4 The simulation results of tephra dispersal during the 2014 Kelud eruption. The distributions of (a) marker particles accumulated in the atmosphere and (b) those deposited on the ground at 45 min. after the eruption are shown. Particle colors represent particle sizes.

#### 4. Concluding remarks

We have performed a numerical simulation of eruption cloud for the 2014 eruption of the Kelud volcano. The simulation results agree well with the maximum height and spreading rate of eruption cloud observed in the satellite images and the dispersal axis of fall deposits based on the field observations. Our model is considered to be a useful tool that links eruption conditions (i.e., magma discharge rate) and field observations.

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## 火山噴煙の3次元数値シミュレーション： インドネシア・ケルト火山 2014 年噴火の再現

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本プロジェクトでは、地球内部のマグマ発生から地表におけるマグマ噴出に至る火山現象について、相変化・相分離・熱輸送・乱流を伴う流体力学的問題として数値モデル化し、大規模数値シミュレーションを用いた火山現象の物理過程に関する理解と、計算結果の防災への応用を目指している。当面の課題として、特に、火山噴煙の到達高度や火山灰の降灰分布を定量的に正しく再現できる数値モデルを開発し、噴煙ダイナミクス・降灰メカニズムを支配する乱流混合などの素過程の理解を進めている。

爆発的火山噴火の噴煙は、浮力によって上昇する噴煙柱と、水平に拡大する傘型噴煙で特徴付けられる。火口から噴出した火山灰と火山ガスの混合物は、上昇にしたがって周囲の大気と混合する。混合大気は噴出物の熱によって膨張し、噴出物と混合大気からなる噴煙が浮力で大気中を上昇して噴煙柱を形成する。噴煙密度が成層大気の密度と釣り合う高度に達すると、重力流として水平方向に拡大し、傘型噴煙を形成する。これらの噴煙形成の過程で火山灰粒子も上空へと運ばれる。大きな終端速度を持つ比較的粗い粒子は、噴煙柱から分離して火口付近に堆積する。一方、細かい粒子は傘型噴煙や上空の風によって運ばれ、火口から遠方に堆積する。これら噴煙柱の最高高度や、傘型噴煙の高度・拡大速度、堆積物分布は直接的な観測可能量であり、噴火メカニズムや噴火強度を推定する上で貴重な情報源となる。

本プロジェクトでは、実際の気象場における観測可能量と火口での噴出条件の関係を定量的に再現する数値モデルの開発を進め、これまでに、大規模噴火事例（フィリピン・ピナツボ 1991 年噴火）、および、小規模噴火事例（新燃岳 2011 年噴火）の噴煙ダイナミクスと火山灰の輸送過程のシミュレーションを行い、観測データを総合的に説明することに成功している。また、これらの成果の中で、大規模噴火では傘型噴煙の重力流が、小規模噴火では風が噴煙挙動や火山灰輸送を主に支配することを明らかにした。中規模噴火では重力流と風の両方が支配要因となるため、噴煙挙動と火山灰輸送はより複雑になると推定される。そこで、本研究では中規模噴火事例の再現を目指し、インドネシア・ケルト火山 2014 年噴火のシミュレーションを行った。

インドネシア・ケルト火山では、2014 年 2 月 13 日の深夜に爆発的噴火が発生した。この噴火について、人工衛星画像から推定される噴火継続時間と地質調査から得られた噴出物の総量から平均的な噴出率を求め、それを火口における境界条件として与え、さらに、気象の再解析モデルから得られた火山付近の大気状態を初期条件として与えて、数値シミュレーションを行った。数値モデルとしては、これまでに本プロジェクトで開発した流体-粒子系の 3 次元数値モデルを用いた。数値シミュレーションの結果は、噴煙柱の最高高度、傘型噴煙の高度・拡大方向・拡大率、堆積物分布等の複数の野外観測データを総合的に説明した。この結果は、本プロジェクトで開発した数値モデルが、幅広い噴火規模の噴煙のダイナミクスに対して適用可能であることを示している。

キーワード: 火山噴煙, 火砕流, 降灰分布, 乱流混合, 火山災害