Numerical Simulations of Spreading Umbrella Clouds in Explosive Volcanic Eruptions

Project Representative
Takehiro Koyaguchi Earthquake Research Institute, University of Tokyo

Authors
Yujiro Suzuki Institute for Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology
Takehiro Koyaguchi Earthquake Research Institute, University of Tokyo

Volcanic activity is one of the observable "dynamic phenomena" at the boundary between the atmosphere and the solid Earth. In order to predict the volcanic eruptions on the basis of geophysical observations and reconstruct the historic volcanic eruptions on the basis of the volcanic sediments, we are developing a numerical model for eruption cloud dynamics. The present 3-D model has successfully reproduced the qualitative features of large scale eruption columns and umbrella clouds. The quantitative agreement between the observations in the Pinatubo 1991 eruptions and the results of the present 3-D simulations (e.g., eruption column height, altitude and spreading rate of umbrella cloud as a function of mass discharge rate) validates the present numerical model. We have also successfully visualized the face structures of eruption clouds on the basis of the 3-D simulation results.

Keywords: volcanic eruption cloud, pseudo-gas model, turbulent mixing, volcanic hazard

1. Introduction

During explosive volcanic eruptions, a mixture of hot ash (solid pyroclasts) and volcanic gas is released from the volcanic vent into the atmosphere. The ejected material has an initial density of several times as large as the atmospheric density since it contains more than 90 wt. % solid pyroclasts at the vent. As the ejected material entrains ambient air, the density of the mixture drastically decreases and becomes less than the atmospheric density because the entrained air expands by heating from the hot solid pyroclasts. As a result, an eruption column buoyantly rises up to a height of several tens of kilometers. The eruption column exhausts its thermal energy and loses its buoyancy within the stratified atmosphere. At the neutral buoyancy level (NBL) where the cloud density is equal to that of the atmosphere, the eruption cloud spreads laterally and an umbrella cloud grows [1].

The height of eruption column and the spreading rate of umbrella cloud are key observable quantities for understanding of the dynamics of eruption clouds. They are obtained from satellite images [2, 3] and from other field observations, and they reflect the source conditions at the vent such as mass discharge rate of magma. The relationship between the observable quantities and the source conditions has been the central issue of the dynamics of eruption clouds.

The aim of this study is to establish the relationship between the observable quantities of the eruption clouds and the eruption conditions at the vent using a 3-D time-dependent fluid dynamics model for eruption cloud. The simulation results are tested by comparison with the field observations of the Pinatubo 1991 eruption.

2. Model Description

The numerical model of eruption cloud is based on the model of Suzuki et al. [4]. The model is designed to describe the injection of a mixture of solid pyroclasts and volcanic gas from a circular vent above a flat surface of the earth in a stationary atmosphere. We apply a pseudo-gas model; we ignore the separation of solid pyroclasts from the eruption cloud and treat an eruption cloud as a single gas.

The fluid dynamics model solves a set of partial differential equations describing the conservation of mass, momentum, and energy, and a set of constitutive equations describing the thermodynamic state of the mixture of solid pyroclasts, volcanic gas, and air. These equations are solved numerically by the Roe scheme [5]. The MUSCL method is applied to interpolate the fluxes between grid points [6]. The calculations are performed on 3-D domain.

One of the most essential physics which governs the dynamics of eruption clouds is that the density of eruption clouds varies nonlinearly with the mixing ratio between the ejected material and air. We reproduce this nonlinear feature of mixture density by changing the effective gas constant and the effective specific heat of the mixture as

$$R_m = n_a R_a + n_g R_g, \quad (1)$$

$$C_{vm} = n_a C_{va} + n_g C_{vg} + n_s C_{vs}, \quad (2)$$

where R is the gas constant, n is the mass fraction, and C_v is the specific heat at constant volume. The subscripts m, a, g, and s refer to the mixture, air, volcanic gas, and solid pyroclasts, respectively. The mass fraction of air (n_a), volcanic gas (n_g), and solid pyroclasts (n_s) satisfy the condition of $n_a + n_g + n_s = 1$. Using these procedures, the equation of state for the mixture of the ejected material and air can be approximated by the equation of state for an ideal gas;

$$p = \rho R_m T, \quad (3)$$

where p is the pressure, ρ is the density of the mixture, and T is the temperature.

3. Results

Using the 3-D pseudo-gas model, we carried out simulations of explosive eruptions that generate large-scale umbrella clouds in the atmosphere. The conditions of simulations were set to cover those of the Pinatubo 1991 eruption ($m_0 = 10^{8.5-9}$ kg/s [3, 7]). The tropical atmosphere is applied to the atmospheric condition and the magmatic properties of the Pinatubo 1991 ejecta are applied to the vent conditions; initial temperature of T_0 = 1053 K and initial mass fraction of volcanic gas of n_{g0} = 0.06 [8] and specific heat for constant volume of the solid pyroclasts (C_{vs}) of 1100 J/(K kg) are assumed.

Our simulations have successfully reproduced the global features of eruption clouds (Fig. 1). Eruption clouds rise as eruption columns or co-ignimbrite ash clouds, and then, they generate laterally spreading umbrella clouds at high altitudes (Fig. 2). We compare these results of the 3-D simulations with the satellite images of the climactic phase of the Pinatubo 1991 eruption and also with the dynamics of the umbrella clouds reconstructed by the granulometric data of the tephra fall deposits.

The climactic phase of the Pinatubo 1991 eruption started

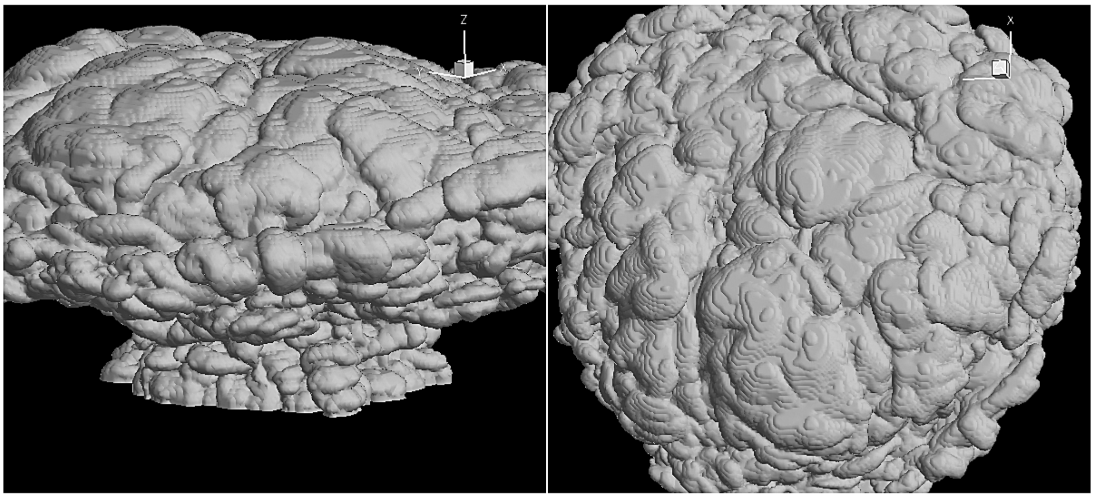

Fig. 1 A representative numerical result of large-scale volcanic eruption clouds at 500 s from the beginning of eruption. Lateral view (left) and top view (right) of the iso-surface of the mass fraction (10^{-2}) of the ejected material (volcanic gas plus solid pyroclasts) from the volcanic vent.

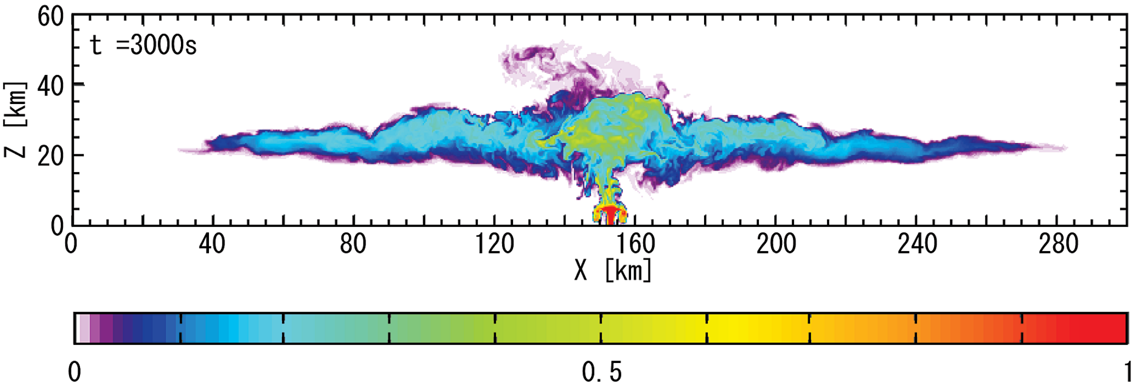

Fig. 2 A representative numerical result of eruption cloud for the case of $m_0 = 10^9$ kg/s at 3000 s from the beginning of eruption. The color illustrates the cross-sectional distribution of the mass fraction of the ejected material.

at 1340 LT (local Philippine time) on 15 June and lasted approximately 9 hours. A large eruption cloud was observed from the satellite images and its dimensions were estimated from the shadow of the cloud; the total column height was up to 40 km at the first stage of eruption and the altitude of top surface of the umbrella cloud was 25 km at its edge [2, 3]. The cloud expanded up to 280 km in diameter (60,000 km^2) at 1440 LT and 40 km in diameter (120,000 km^2) at 1540 LT. It expanded up to 250 km upwind until 1940 LT, covering an area of 300,000 km^2, and subsequently the east end of the cloud moved westward, at which time the cloud reached a stagnation points upwind but continued to grow downwind and crosswind.

The evolution of the radius of the umbrella cloud in the 3-D simulation is consistent with those observed from the satellite images [2, 3] (Fig. 3). On the basis of dimensional analysis, if the volumetric flow rate of the umbrella cloud is constant, the increase rate of radius of umbrella cloud is constant: L^3/t^2 = const., where L is the radius and t is the time. The value of L^3/t^2 with $m_0 = 10^9$ kg/s ($L^3/t^2 = 2.2 \times 10^8$ m^3/s^2) agrees with the observed increase rate of the radius of the umbrella cloud in the Pinatubo 1991 eruption (L^3/t^2 = 1.7–1.8 × 10^8 m^3/s^2). The total height of the eruption column (37.4 km) and the altitude of umbrella cloud (23.3 km) with $m_0 = 10^9$ kg/s are also consistent with the observations (34–40 km and 21–25 km; Fig. 4).

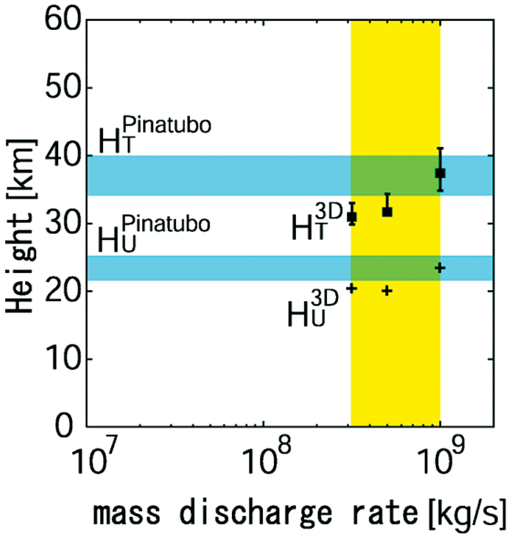

Fig. 4 Characteristic heights of eruption clouds as a function of the mass discharge rate m_0. Square represent the total heights of eruption column (H_T^{3D}) based on the time-averaged levels of $n_g + n_s = 10^{-2}$. The error bars are based on the levels of $n_g + n_s = 10^{-1}$ and 10^{-3}. Pluses represent the altitude of the spreading umbrella clouds (H_U^{3D}). Horizontal blue zone are the range of the total height and the altitude of the spreading umbrella cloud observed in the Pinatubo 1991 eruption. Vertical yellow zone is the range of the estimated mass discharge rate in the Pinatubo 1991 eruption ($m_0 = 10^{8.5\text{–}9}$ kg/s).

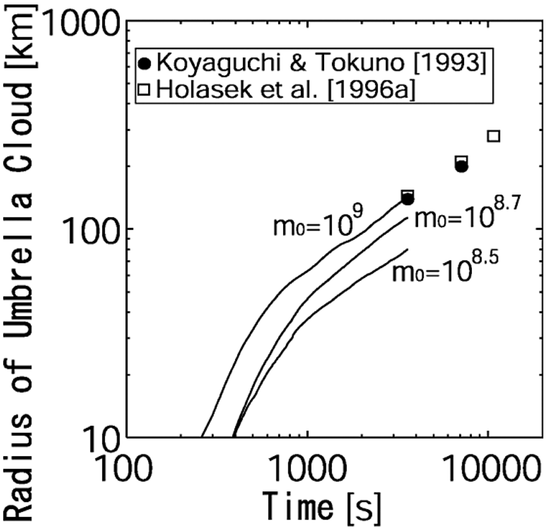

Fig. 3 Radii of the spreading umbrella clouds as a function of the time in the case of $m_0 = 10^{8.5}$, $10^{8.7}$, and 10^9 kg/s. The data observed in the Pinatubo 1991 eruption [2, 3] are also plotted.

The volumetric flow rate of the umbrella cloud can be estimated from the granulometric data of the tephra fall deposits on the basis of the tephra-dispersal model [7]. Applying this method to the Pinatubo 1991 tephra fall deposits, the volumetric flow rates of the first and second half of the climactic phase are estimated to be 5–9 × 10^{10} m^3/s and 2–4 × 10^{10} m^3/s, respectively. The range of the volumetric flow rate estimated from the 3-Dsimualtions with $10^{8.5\text{–}9}$ kg/s (2.4 – 8.8 × 10^{10} m^3/s) is consistent with those estimated from the granulometric data (Fig. 5).

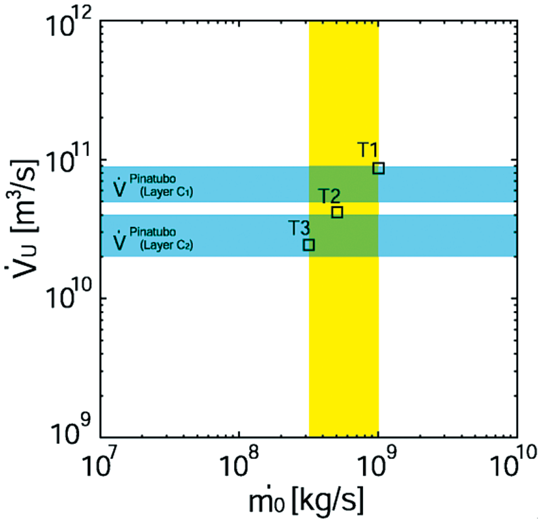

Fig. 5 Horizontal volumetric flow rates in the umbrella cloud (V_U) as a function of the mass discharge rate m_0 for the results of the 3-D simulations. Horizontal blue zones are the ranges of the volumetric flow rate of umbrella clouds for the first (Layer C_1) and second (Layer C_2) halves of the climactic phase of the Pinatubo 1991 eruption estimated from the granulometric method [7]. Vertical yellow zone is the range of the estimated mass discharge rate in the Pinatubo 1991 eruption ($m_0 = 10^{8.5\text{–}9}$ kg/s).

4. Summary

We have presented numerical 3-D simulations of the dynamics of eruption columns and umbrella clouds emplaced into the stratified atmosphere by explosive volcanic eruptions. Our numerical model successfully reproduces the quantitative features of large-scale eruption clouds such as that of the Pinatubo 1991 eruption. This quantitative agreement between the observations and the results of the 3-D simulations (e.g., column height, altitude and spreading rate of umbrella cloud as a function of mass discharge rate) validates the present numerical model.

5. References

[1] A. W. Woods, "The dynamics of explosive volcanic eruptions", Rev. Geophys., 33(4), 495–530, 1995.

[2] T. Koyaguchi and M. Tokuno, "Origin of the giant eruption cloud of Pinatubo, June 15, 1991", J. Volcanol. Geotherm. Res., 55(1–2), 85–96, 1993.

[3] R. E. Holasek, S. Self, and A. W. Woods, "Satellite observations and interpretation of the 1991 Mount Pinatubo eruption plumes", J. Geophys. Res., 101(B12), 27, 635–27, 655, 1996.

[4] Y. J. Suzuki, T. Koyaguchi, M. Ogawa, and I. Hachisu, "A numerical study of turbulent mixing in eruption clouds using a three-dimensional fluid dynamics model", J. Geophys. Res., 110, B08201, 2005.

[5] P. L. Roe, "Approximate Riemann solvers, parameter vectors, and difference schemes", J. Comput. Phys., 43, 357–372, 1981.

[6] B. van Leer, "Towards the ultimate conservative difference scheme III. Upstream-centered finite-difference scheme for ideal compressible flow", J. Comput. Phys., 23, 263–275, 1977.

[7] T. Koyaguchi and M. Ohno, "Reconstruction of eruption column dynamics on the basis of grain size of tephra fall deposits. 2. Application to the Pinatubo 1991 eruption", J. Geophys. Res., 106(B4), 6513–6533, 2001.

[8] M. J. Rutherford and J. D. Devine, "Preeruption pressure-temperature conditions and volatiles in the 1991 Mount Pinatubo", in Fire and Mud, edited by C. G. Newhall and R. S. Punongbayan, pp.751–765, Univ. of Wash. Press and Philippine Inst. Of Volcanology and Seismology, Seattle and Quezon City, 1996.

爆発的火山噴火における傘型噴煙拡大の数値シミュレーション

プロジェクト責任者
小屋口剛博　東京大学　地震研究所

著者
鈴木雄治郎　海洋研究開発機構　地球内部変動研究センター
小屋口剛博　東京大学　地震研究所

本プロジェクトでは、大規模数値シミュレーションによって固体地球と地球表層・大気にまたがる火山現象の理解を目指している。特に、防災上重大な問題となる火山噴煙の拡大を定量的に再現・予測する数値モデルの開発に取り組んでいる。

火山噴煙のダイナミクスは、噴出物（火山灰＋火山ガス）と大気からなる混合物の密度変化、乱流による混合過程、大気の成層構造、などの影響によって広いスケール階層性と強い非線形性を持つ。爆発的火山噴火では、火口から火山灰と火山ガスの混合物が高温・高速で噴出する。噴出物は90wt.%以上の火山灰（固体）を含んでいるため、噴出直後は周囲の大気よりも重く、火砕流として地面を流れ下ることが予想される。しかし、乱流混合で周囲の大気を取り込むと、取り込んだ大気を火山灰の熱によって急激に膨張させ、周囲の大気よりも軽くなる。この場合、噴出物と大気の混合物（噴煙）は上昇し噴煙柱となる。成層構造を持つ大気は上空に行くほど密度が低くなるため、相対的に噴煙が重くなり上昇を止め傘型噴煙として水平方向へと拡大する。本プロジェクトではこのような噴煙現象を再現するための3次元流体数値モデルを開発した。本モデルでは、混合比によって理想気体の状態方程式における気体定数を変化させることによって噴煙の変則的な密度変化を再現した。また、空間3次精度の計算スキームを適用することで十分に発達した乱流状態を再現した。

数値シミュレーションの結果、火口から出た重い噴出物が大気と混合することで軽くなり高度数十kmまで上昇し、その後水平方向数百kmまで傘型噴煙が拡大する様子を再現することができた。これらの計算結果をピナツボ火山の1991年大規模噴火で得られた観測データと比較することでモデルの妥当性を評価した。噴火後のフィールド調査で得られた火山灰の総量および観測された噴火の継続時間から火口での噴出率が見積もられているので、それを囲うにおける噴火条件として数値シミュレーションを行った。この条件では、噴煙柱が火山体の直上で高度40kmまで上昇し、傘型噴煙が高度25kmで噴火開始後1時間後に水平距離140kmまで達するという計算結果が得られ、人工衛星写真からの観測データと定量的に一致した。

キーワード：火山噴煙，擬似ガスモデル，乱流混合，火山災害