# 論文内容の要旨

## 論文題目　A numerical and experimental study on the dynamics of volcanic eruption cloud

## (火山噴煙のダイナミックスに関する数値的及び実験的研究)

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### Introduction

During explosive volcanic eruptions, a mixture of hot volcanic gases and pyroclasts is released from the volcanic vent into the atmosphere. The mixture of volcanic gases and pyroclasts entrains ambient air and becomes buoyant because of expanding entrained air. The eruption clouds rise and form the eruption columns. After the eruption columns reach the neutral buoyancy level, the eruption clouds flow horizontally as gravity currents, and form umbrella clouds. The dynamics of eruption clouds such as the expansion rate can be observed in satellite remote sensing images. In addition, during explosive volcanic eruptions, pyroclasts are released from the volcanic vent into the atmosphere as ash and lapilli. Such erupted pyroclasts fall out from the eruption clouds to ground surface as tephra. The tephra deposits can be observed as geological data.

The aim of this study is to correlate the dynamics of explosive eruption cloud with geological data of tephra deposits. In previous studies, vertical 1-dimensional (1-D) models are used to describe the dynamics of eruption clouds. It is also assumed that the pyroclastic particles are homogeneously mixed in eruption clouds in considering the process of tephra-falls from the umbrella clouds. However, it is not clear whether the models can adequately reproduce the dynamics of eruption clouds including the umbrella clouds that are direct supply sources of tephra. Accordingly, we focus on the following three problems in this study. First, in order to investigate the dynamics of eruption clouds, 3-dimensional (3-D) numerical simulations including the vast area of umbrella cloud are performed. Second, in order to investigate the settling behavior of particles from umbrella clouds, laboratory experiments of solid particles settling in turbulent flow are performed. In these experiments, the effect of inhomogeneous particle distribution and that of particle settling through the density stratified free boundary are taken into consideration. Finally, we combined the dynamics of eruption clouds and the behavior of particle settling in turbulent flow using the concept of turbulent intensity.

## 3-dimensional eruption cloud simulation

The simulation model is designed to reproduce the fluid dynamical features of the eruption cloud, such as column height and laterally spreading umbrella cloud as a function of the conditions at volcanic vent such as vent size and exit velocity and magma properties. Because the dynamics of eruption cloud is determined by the buoyancy in the atmosphere, the most essential physics is that the density of eruption clouds varies non-linearly with the mixing ratio between ejected material and air. Therefore, the present simulation model is carefully designed to reproduce the non-linear relationship between the density of the mixture and the mixing ratio as well as the mixing ratio due to turbulent mixing. Suzuki et al., [2005] have suggested that, in order to reproduce the features of turbulent mixing, it is essential to apply (1) 3-D coordinates, (2) high order accuracy calculation scheme, and (3) sufficiently small grid size. In accordance with this suggestion, we develop a numerical code to calculate the dynamics of eruption cloud using the CIP method for the high order accuracy scheme, 3-D coordinates and a sufficiently small grid size. In this study, the computational method is improved in several ways. For example, preliminary calculation have shown that the simple CIP method largely modifies the relationship between the density of mixture and the mixing ratio of the magmatic component and air, which may cause a fatal numerical error affecting the quantitative features of the dynamics of eruption clouds. In this study, this problem has been resolved by employing a new method to correct the value of the temperature of the mixture in each step. The all improvements of computational method are listed in Table 1. A series of simulations of turbulent jet were performed using the improved simulation code, and the numerical code has been validated by comparison with the experimental results of turbulent jets. The simulation results of turbulent jets successfully and quantitatively reproduced the feature of turbulent mixing observed in the laboratory experiments (e.g., self-similarity and power spectrum of turbulence).

Table 1: The list of improvement of computational method.

| | |
|---|---|
| Turbulent mixing | The CIP method, high spatial resolution, 3-D model |
| Consistency of equation of state | Correction of temperature |
| Stability of calculation | Interpolation check |
| Mass conservation | The CIP-CSL2 method |
| Stability when artificial viscosity is removed | The C-CUP method |
| Decrease of computational effort | Variable grid size |
| Boundary condition | Radiation boundary condition, sponge layer |

Using the numerical model developed in this study, simulations of eruption cloud were performed. The simulation of the present 3-D model successfully reproduces the basic features of the dynamics of eruption clouds including a stable eruption column and umbrella cloud [Figure 1]. The calculation results of the 3-D model indicates that the maximum plume height and volume expansion rate of eruption cloud are consistent with the results of previous 1-D models. Representative results of the 3D-model are as follows: (1) the height of umbrella cloud coincides with the altitude of the neutral buoyancy level (N. B. L in Figure 1) calculated by the 1-D model [e.g., Woods, 1988] , (2) substantial amounts of air is entrained during the lateral spread of umbrella clouds, and (3) the value of the empirical constant which describes the dynamics of gravity current during the lateral spread of an umbrella cloud is estimated to be 0.055.

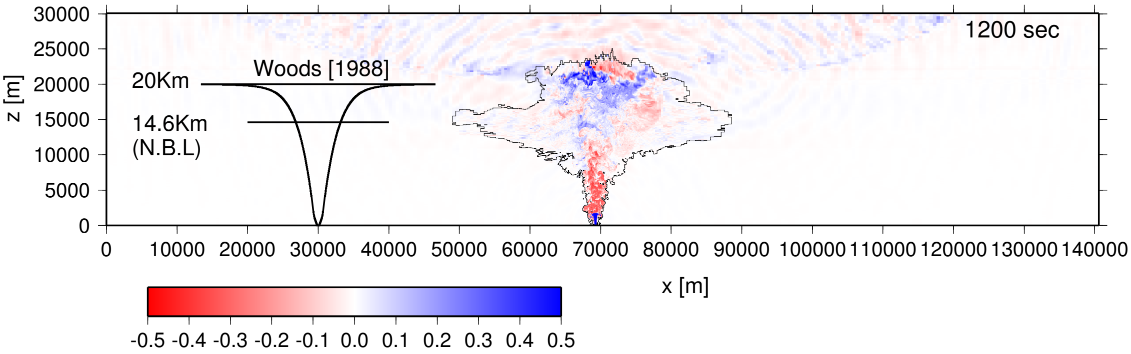

Figure 1: Distribution of the difference between the bulk density and the stratified atmospheric density at the same vertical position calculated by the 3D-model at 1200 sec. Calculated result of 1D-model of Woods [1988] is also superimposed.

## Experiments of particle settling in turbulent flow

In previous tephra dispersal models, it is assumed that particles are homogeneously distributed because of turbulence in umbrella clouds. Such an assumption is appropriate only when turbulence is sufficiently large relative to the terminal velocity of particles [Martin and Nokes, 1988]. The previous tephra dispersal models are based on the experimental results of particle settling in turbulent flow with a rigid bottom boundary, whereas particles fall out through a free boundary at the base of umbrella clouds. In this study, laboratory experiments of particle settling in turbulent flow are performed focusing on the following points. First, in order to investigate the effects of free boundary condition at the bottom of umbrella clouds, experiments of particle settling in stratified fluids were performed. In these experiments, two fluids with different densities are stratified, and only the upper layer is turbulently stirred. After supplying particles into the well mixed upper layer, evolution of particle concentration is measured. The results of the 2-layer experiments are compared with the single layer experiments. Second, the experiments are performed by systematically changing turbulent intensity, particle diameter and fluid viscosity. Through these experiments, the relationship between the turbulent intensity and the eddy diffusion coefficient for particle concentration are established.

The experimental results suggest that, when turbulent intensity is large relative to the particle terminal velocity, the eddy diffusion coefficient is sufficiently large so that the assumption of homogeneous particle distribution is appropriate. However, when turbulent intensity is small relative to the particle terminal velocity, such an assumption is not appropriate. We propose a generalized model which describes the evolution of particle concentration in the fluid where the turbulent intensity is small relative to the particle terminal velocity as follows:

$$c_{mean} = c_0 \exp\left(\kappa \frac{-v_s t}{h}\right) \qquad (1)$$

where $c_{mean}$ is the mean particle concentration of the entire fluid, $c_0$ is the initial particle concentration, $v_s$ is the terminal velocity of particles, $h$ is the fluid depth, and $t$ is the time. In the generalized model, the fall out rate of particle from the base of umbrella cloud is corrected by taking into consideration the effect that the particle concentration increases from the top to the base using a parameter $\kappa$. The parameter $\kappa$ is defined as $\kappa \equiv c_{base}/c_{mean} = (S/C)/(1 - \exp(-S/C))$, where $c_{base}$ is the particle concentration at the base of fluid, $S$ is the ratio of terminal velocity of particle $v_s$ to turbulent intensity $W_{rms}$, and $C$ is an empirical constant determined by experimental results. From the present experimental results, $C$ is obtained to be 0.8 when the particles fall out through the free boundary.

When turbulent intensity is small relative to the particle terminal velocity ($S = v_s/W_{rms} > 0.1$), the value of $\kappa$ is larger than 1 in Eq. (1) (inhomogeneous distribution model). When turbulent intensity is sufficiently large relative to the particle terminal velocity ($S \leq 0.1$), the value of $\kappa$ becomes close to 1 in Eq. (1) (homogeneous distribution model). The experimental results shows that whether particle distribution follows the homogeneous or inhomogeneous distribution model can be judged from the value of $S$ which is calculated from the particle terminal velocity $v_s$ and the turbulent intensity $W_{rms}$.

From the 3-D simulation results, the turbulent intensity $W_{rms}$ in an eruption cloud is obtained. For several different diameters of pyroclasts ($d$), the terminal velocity of particles $v_s$ and the value of $S$ are calculated. Figure 2 shows the distributions of the $S$ for $d$=16, 1 and 0.125 mm. For $d$=16 mm, the value of $S$ is close to 1 or more than 1 except for the central part of eruption cloud. For $d$=1 mm, the value of $S$ is as low as 0.2 around the center of eruption cloud, and it becomes close to 1 in the umbrella cloud away from its central axis. For $d$=0.125 mm, the values of $S$ is almost close to 0.1 in the whole eruption cloud. The distribution of $S$ in the eruption cloud which calculated numerically by the 3-D model indicates that pyroclasts with large diameters (e.g., $d > 16$ mm) are not homogeneously distributed in the vertical direction in the eruption cloud; it is considered that pyroclasts are concentrated at the base of umbrella cloud. On the other hand, pyroclasts with small diameters (e.g., $d < 0.125$ mm) are considered to be distributed homogeneously in the cloud. It is suggested that the generalized model [Eq. (1)] is more appropriate than the homogeneous distribution model which is used in the previous tephra dispersal models.

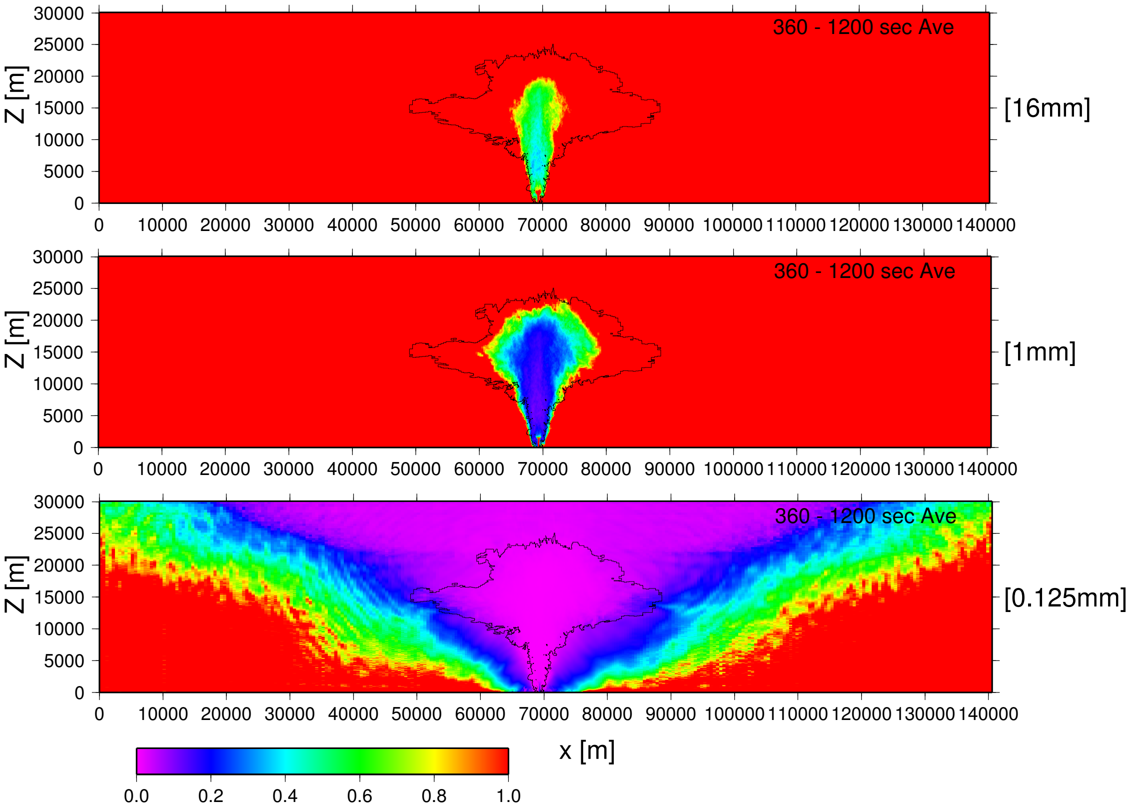

Figure 2: The distributions of the $S$ ($v_s/W_{rms}$). Results for three different particle diameters ($d$=16, 1 and 0.125 mm) are shown. The terminal velocity is calculated using physical properties of typical pumice grains. The turbulent intensity is calculated by the present 3D-model.