3-D numerical simulation of umbrella clouds (3): Application to the Pinatubo 1991 eruption

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The heights of eruption column and the spreading rate of umbrella cloud are key observable data for understanding of the eruption cloud dynamics. During explosive volcanic eruptions, a mixture of solid pyroclasts and volcanic gas is released from the volcanic vent into the atmosphere. As the ejected material entrains ambient air, an eruption column buoyantly rises as a turbulent plume. When the eruption column exhausts its thermal energy and loses its buoyancy within the stratified atmosphere, the eruption cloud spreads radially as a gravity current and an umbrella cloud grows. Woods [1988] proposed a steady vertical 1-D model of eruption column in which the column is assumed to be well-mixed horizontally, and predicted the heights of eruption column and umbrella cloud and the volume flux rate when the mass-discharge rate at the vent is given. Sparks et al. [1997] proposed a horizontal 1-D model in which the umbrella cloud is assumed to be well-mixed vertically, and predicted the spreading rate of umbrella cloud when the volume flux rate is given. However, these 1-D models contain empirical constants (entrainment coefficient of turbulent plume, k, and Froude number of gravity current, Fr). We aim to develop a 3-D numerical model of an eruption column and umbrella cloud, and determine the values of these empirical constants in the 1-D models.

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 [Suzuki et al., JGR, 2005]. We apply a pseudo-gas model because the relative velocity of gas and ash particles is sufficiently small, and employ the Euler equations of a compressible gas. The nonlinear density change of the ejected material and air with the mixing ratio is reproduced by changing the effective gas constant of the mixture in the equation of state for ideal gases. We apply a third-order accuracy scheme, and have carefully performed sensitivity tests with different grid sizes to find the condition where the efficiency of turbulent mixing no longer depends on the grid size.

Our simulations have successfully reproduced the behavior of eruption clouds including eruption columns, pyroclastic flows, co-ignimbrite ash clouds and umbrella clouds. Simulations for the mass-discharge rate of 10^8-10^9 kg/s indicate (1) the height of umbrella cloud based on the 3-D model is consistent with those based on the vertical 1-D model with k=0.1, (2) the spreading rate of umbrella cloud based on the 3-D model is consistent with those based on the horizontal 1-D model with Fr=0.1.

We apply the 1-D models with the above values of empirical constants to the observations of the Pinatubo 1991 eruption. Applying the horizontal 1-D model with Fr=0.1 to the observed spreading rate of umbrella cloud, the volume flux rate is estimated to be 1.6×10^{11} m3/s. The vertical 1-D model with k=0.1 predicts that the mass-discharge rate is 1.8×10^9 kg/s for the estimated volume flux rate. On the other hand, applying the vertical 1-D model with k=0.1 to the observed height of umbrella cloud (25 km), the mass-discharge rate is estimated to be 1.7×10^9 kg/s, which is consistent with that estimated from the spreading rate of umbrella cloud. These mass-discharge rates estimated by the 1-D models are consistent with that independently estimated by the granulometric methods of Koyaguchi and Ohno [2001] (0.6-1.1×10^9 kg/s).