3-D numerical simulation of umbrella clouds (2): Validation of the observable data

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The heights of eruption column and the volumetric expansion 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 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 spread radially and an umbrella cloud grows.

Woods (1988) proposed a steady vertical 1-D model of eruption column in which it is assumed that the pressure of eruption column is equal to the atmospheric pressure and that the column is well-mixed horizontally, and predicted that heights of eruption column and umbrella cloud increase as the mass-discharge rate increases. Sparks et al. (1997) proposed a horizontal 1-D model and predicted the relationship between the volumetric expansion rate and radius of umbrella cloud. However, the assumptions in those vertical and horizontal 1-D models are not always valid. We aim to develop a 3-D numerical model of an eruption column and umbrella cloud, and compare our results with those of 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. The partial differential equations are solved numerically by the Roe scheme. We apply the MUSCL method to attain a high-order accuracy, and also 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 pyroclastic flows, co-ignimbrite ash clouds and umbrella clouds. The eruption column fully collapses to spread radially as a pyroclastic flow. After donwflow of the collapsing column develops, the upper part of the downflow entrains ambient air and forms co-ignimbrite ash clouds. Subsequently, the umbrella cloud begins to spread radially at the height of 30 km.

We have compared some characteristic heights and volume fluxes between our 3-D model and the previous 1-D models. As a result, (1) the total height of the 3-D model is greater than that of the vertical 1-D model. (2) The height of umbrella cloud in the 3-D model is consistent with that of NBL estimated by the vertical 1-D model. (3) The NBL in the 3-D model is lower than that of the vertical 1-D model. (4) The horizontal volume flux in the umbrella cloud in the 3-D model is consistent with the vertical volume flux at the NBL estimated by the vertical 1-D model. (5) For a given volume flux, the radial expansion rate of umbrella cloud in the 3-D model is smaller than that of the horizontal 1-D model. The differences in (1) and (3) are attributed to the fact that the pressure of eruption cloud is generally higher than the ambient air at the same altitude while the umbrella cloud is growing. On the other hand, (2) and (4) indicate that the pressure in the umbrella cloud is almost equal to the atmospheric pressure. The difference in (5) implies that the volumetric expansion rate and the mass-discharge rate at the vent based on the field data and the 1-D models may be underestimated.