Numerical simulations of a two-layer shallow-water model for pyroclastic flows by column collapse

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Pyroclastic flow is one of the most hazardous volcanic phenomena. During explosive volcanic eruptions, a mixture of volcanic particles and gas is ejected from the volcanic vent and develops an eruption column. When the eruption column collapses, the mixture falls to the ground and produces pyroclastic flows that propagate as gravity currents. Pyroclastic flows are characterized by strong density stratification, consisting of a dilute flow in the upper region and a dense flow in the lower region. The dynamics of pyroclastic flows is affected by physical processes within each of the dilute and dense parts, such as basal friction and entrainment of ambient air in the interfacial surface. It also depends on the particle transport between the dilute and dense parts. We aim to understand these effects on pyroclastic flow dynamics using numerical simulations.
We have developed a two-layer model to describe the gravity current which has a strong density stratification. In this model, each of dilute and dense parts is assumed to be uniform in any vertical section and is formulated as shallow-water equations. The equations are numerically solved by the finite volume method using the HLL scheme. In the dilute part, the effects of settling of particles, entrainment, and the interfacial drag between the dilute and dense parts are taken into account. In the dense part, the effects of basal friction, sedimentation, and the particle supply from the dilute part are included. In addition, to reproduce the dynamics of gravity current, the balance between the driving force and the resistance of ambient at the flow front should be correctly expressed in the model. In the dilute part, the balance is solved as a boundary condition with the Froude number proposed by Huppert and Simpson (1980). In the dense part, the balance is approximately calculated by setting a thin artificial bed ahead of the front.
We performed numerical simulations for a release of stationary fluid consisting of the dilute part in the rectangular-lock domain on a horizontal ground surface. As a result, the expansion of dilute part, the development of dense part below the dilute part, and the deposition of particles on the ground were reproduced. In addition, the behavior of pyroclastic flows is classified into two regimes: the regime where the dilute part always reaches the head of the flow and governs the total propagation of the flow, and the regime in which the dense part outruns the parent dilute part. The results of our parameter study indicate that which regime can occur mainly depends on particle size. When the currents contain fine-grained particles, the total propagation is dominated by the dilute part. This is because the lower particle-settling velocity of fine particles reduces particle transport from the dilute part to the dense part so that the development of the dense part is limited. When the currents contain coarse-grained particles, owing to a higher particle-settling velocity, particle transport from the dilute part to the dense part becomes substantial, so that the development of the dense part is enhanced. When the dense part becomes thick, it can outruns the parent dilute part. The difference of these regimes determines which one of the two parts forms the lowermost part of the deposits, because the lowermost part of the deposits is formed by the preceding flows. Therefore, the difference may explain the diversity of depositional facies formed by pyroclastic flow.

Keywords: pyroclastic flows, shallow-water model, two-layer model, numerical simulation, volcanic column collapse, pyroclastic flow deposits