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A numerical study of pyroclastic flow dynamics: A shallow-water model for gravity currents with wide ranges of density differences

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During explosive volcanic eruptions, gravity currents of mixtures of volcanic particles and gas flowing on the ground surface (pyroclastic flows) are commonly generated. The pyroclastic flows are characterized by strong density stratification with wide ranges of density ratio $\rho_c/\rho_a = 10^{0-3}$, where ρ_c and ρ_a are the densities of the currents and ambient, respectively. We aim to understand the dynamics of pyroclastic flows, such as flow velocity and run-out distance. For this purpose, we have developed a new numerical model based on shallow-water equations for gravity currents with a wide range of ρ_c/ρ_a.

In order to calculate gravity currents with a wide range of ρ_c/ρ_a, the balance between the driving force and the resistance of ambient at the flow front (i.e., front condition) needs to be correctly taken into account. In previous works, two types of numerical models have been proposed to solve the front condition: Boundary-Condition (BC) model and Artificial-Bed (AB) model. In BC model, the front condition is calculated directly as a boundary condition at each time step. In AB model, on the other hand, the front condition is calculated by setting a thin artificial bed ahead of the front. We have verified these numerical models by comparing their results with exact analytical solutions which are available for a simple case of homogeneous currents. The results show that AB model provides good approximations of the exact solutions for $\rho_c/\rho_a \gtrsim 10^2$, given a sufficiently small artificial bed thickness, whereas it fails to reproduce the exact solutions when $\rho_c/\rho_a \lesssim 10^2$. On the other hand, the results of BC model agree well with the exact solutions when $\rho_c/\rho_a \lesssim 10^2$, whereas it tends to overestimate the speed of the front position when $\rho_c/\rho_a \gtrsim 10^2$. It is, therefore, suggested that AB model is applicable to the currents of $\rho_c/\rho_a \gtrsim 10^2$, whereas BC model should be used for the currents of $\rho_c/\rho_a \lesssim 10^2$.

On the basis of the present results, we have developed a two-layer model for a pyroclastic flow with a strong density stratification, where a dilute overriding part with $\rho_c/\rho_a = 10^{0-1}$ is calculated by BC model, and a dense basal part with $\rho_c/\rho_a = 10^{2-3}$ is calculated by AB model. Our preliminary results show that the choice of appropriate models for the calculation of the front condition is essential in order to reproduce the dynamics of pyroclastic flows and the resultant sediments from the pyroclastic flows.