A numerical study of pyroclastic density currents by a two-layer shallow-water model: Flow regimes and lateral lithofacies variations

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During explosive volcanic eruptions, a hot mixture of volcanic particles and gas is continuously ejected from the volcanic vent and occasionally flows on the ground to produce pyroclastic density currents (PDCs). PDCs are characterized by strong density stratification, whereby a dilute current (particle concentrations < 1 vol.%) overrides a dense basal current (~ 10 vol.%). The difference in the particle concentration leads to differences in the dynamics and resulting runout distance between the dilute and dense currents, which causes diverse features of PDC deposits. We aim to numerically investigate PDC dynamics to account for the diversity of PDC deposits.

To reproduce density currents with strong density stratification, we have developed a new two-layer shallow-water model. In the calculation of the dilute layer, the effects of particle settling, entrainment of ambient air, thermal expansion of entrained air, and frontal resistance of ambient air are taken into account. In the calculation of the dense layer, the effects of particle supply from the dilute layer, basal friction, and deposition are included. We assumed that the dilute mixture (< 1 vol.%) radially spreads from the vent over a horizontal ground surface at a constant mass discharge rate. We performed a parametric study for various mass discharge rates at source, particle settling speeds at the base of the dilute current, W_s, and deposition speeds at the base of the dense current, D.

Numerical results show that the dilute current, generated from the source, produces the dense basal current. When the frontal region of the dilute current becomes lighter than ambient air to reverse buoyancy and liftoff, the front of the dilute current does not propagate further. When the mass flux of the dense current and the deposition rate balance at the frontal region, the front of the dense current stops propagating. Finally, each layer reaches to a steady state. The results of the parametric study show that the dynamics of the two-layer PDCs depends on the non-dimensional parameter D/W_s, which represents [the deposition rate at the base of the dense current] / [the mass supply rate from the dilute current to the dense current]. As D/W_s decreases, the runout distance of the dense current increases whereas that of the dilute current does not change. When D/W_s is large, the dense current does not develop, and the dilute current directly forms its deposits. When D/W_s is small, the steady runout distance of the dense current is longer than that of the dilute current. When D/W_s has an intermediate value, the steady runout distance of the dilute current is longer than that of the dense current.

The above difference in the flow regimes results in a wide variety of sedimentary structures of PDC deposits (e.g., massive and/or stratified lithofacies), because the flow-particle interaction inside the boundary layer at the bottom of PDCs is significantly different between the dilute and dense currents. When D/W_s is large, stratified lithofacies may be predominant from proximal to distal areas because of the deposition from the dilute current. When D/W_s is small, massive lithofacies may be predominant because of the deposition from the dense current. When D/W_s has an intermediate value, the deposition mainly occurs from the dense current in proximal area and directly from the dilute current in distal area, so that the lithofacies of the deposits change from massive to stratified one with distance from the source.

Keywords: Pyroclastic density current, Shallow-water equation, Numerical simulation, Explosive volcanic eruption, Runout distance, Sedimentary structure