論文の内容の要旨

A numerical study of pyroclastic density currents by a two-layer shallow-water model

(二層浅水波モデルに基づく
火砕流ダイナミクスの数値的研究)

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During an explosive volcanic eruption, a hot mixture of volcanic particles and gas is continuously ejected from the volcanic vent and develops an eruption column. When the density of the mixture remains higher than that of the ambient air, the eruption column collapses to produce pyroclastic density currents (PDCs). PDCs are characterized by strong density stratification, whereby a dilute current (particle concentrations $\lesssim$ 1 vol.%) overrides the dense basal current (particle concentrations $\sim$ 10 vol.%). Each part is controlled by different physical processes due to the difference in the particle volume fraction: the dilute current is affected by air entrainment, thermal expansion of entrained air, frontal resistance of ambient air, and particle settling; the dense current is affected by particle supply from the dilute current, basal friction, and sedimentation. The relative magnitude of the effects of these physical processes depends on source conditions (e.g., mass eruption rate and temperature of erupted materials). As a result of these factors, the deposits of PDCs are extremely variable in distribution and lithofacies. There is a vast amount of field-based works related with the diversity of PDC deposits and experimental-analogue studies related with the physical processes underlying PDC dynamics. We aim to relate the underlying physical processes with the diversity of PDC deposits, by using numerical simulations.

The essential behavior of PDCs can be described by the depth-averaged shallow-water equations. In order to assess the effects of the above physical processes on PDC dynamics and the resulting PDC deposits, we have developed a new two-layer shallow-water model. Because the dilute layer is affected by strong density variation due to thermal expansion of entrained air and particle settling, it is simulated by solving six basic equations: particle mass, entrained air mass, bulk mass, momentum and energy conservation equations, and the equation of state. Because the basal dense layer is affected by the mass and momentum transfer processes due to basal friction, sedimentation and the particle supply from the dilute layer, it is simulated by solving two basic equations: mass and momentum conservation equations. These conservation equations are numerically solved by the finite volume method using the HLL scheme.

We calculated time evolution of two-layer PDCs generated by dilute mixtures from the collapsing column at a constant mass eruption rate. The dilute current, generated from the collapsing column, produces the basal dense current, and a deposit aggrades upward from the base. 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 at the base balance at the frontal region, the front of the dense current does not propagate further. Finally, each layer converges to a steady state. We performed a parametric study by varying the mass eruption rates at source, $\dot{M}_0$, from 10^3 to 10^{11} kg/s, the temperature of erupted material, T_{in}, from 300 to 1200 K, the particle settling velocity at the base of the dilute current, W_{s}, from 0.3 to 3.0 m/s, and the deposition rate at the base of the dense current, D, from 3.0×10^{-5} to 3.0×10^{-2} m/s. As a result, on the basis of the runout disntances of the dilute and dense currents, the steady behaviors of the two-layer PDCs are classified into three flow regimes: Regime 1, Regime 2a, and Regime 2b. In Regime 1, the dense current does not develop, and the dilute current directly forms its deposits. In Regime 2a, the dense current develops, but the steady runout distance of the dilute current is longer than that of the dense current. In Regime 2b, the dense current develops, and the steady runout distance of the dense current is longer than that of the dilute current.

In order to systematically understand mechanisms that make the above classification possible, we have investigated the steady runout distances of the dilute and dense currents by the following three steps. First, we have investigated the basic equations to identify governing dimensionless parameters that control the steady runout distances (Step 1). Secondly, we have derived analytical solutions under the condition where air entrainment is not taken into account (Step 2). Finally, we have evaluated the effects of air entrainment on the steady runout distances on the basis of numerical simulations (Step 3).

In Step 1, as a result of the non-dimensionalization, we have identified four governing dimensionless parameters: $W_{\mathrm{s}}/(\mathcal{U}a_0)$, D/W_{s}, $E|\bar{u}|/W_{\mathrm{s}}$, and $(C_{\mathrm{pa}}T_{\mathrm{a}})/(C_{\mathrm{p0}}T_0)$. The parameter $W_{\mathrm{s}}/\mathcal{U}$ represents the ratio of the particle settling velocity at the base of the dilute current to the horizontal velocity scale of the two-layer PDC. The velocity scale $\mathcal{U}$ depends on the mass eruption rate at source $\dot{M}_0$ (i.e., $\mathcal{U} \propto \dot{M}_0^{1/5}$). The parameter a_0 is the aspect ratio of the height scale of the dilute current to the length (or radius) of the collapsing column, which is imposed on a boundary condition. The parameter D/W_{s} represents the relative magnitude of the effect of deposition from the base of the dense current to that of particle supply from the dilute current. The parameter $E|\bar{u}|/W_{\mathrm{s}}$ represents the relative magnitude of the effect of air entrainment to that of particle settling. Here, $E|\bar{u}|$ is the entrainment velocity, where $\bar{u}$ is the local flow velocity and E is the entrainment coefficient. The parameter $(C_{\mathrm{pa}}T_{\mathrm{a}})/(C_{\mathrm{p0}}T_0)$, defined as the ratio of the enthalpy of the entrained air to the enthalpy scale of the dilute current, represents the degree of thermal expansion of air entrained into the dilute current, where C_{pa} and C_{p0} are the heat capacities at constant pressure of air and the dilute current at the collapsing column edge, respectively, and T_{a} and T_0 is the temperatures of ambient air and the dilute current at the collapsing column edge, respectively.

In Step 2, we have derived the analytical solution of the steady runout distances from the mass conservation equations of the two-layer PDCs for the case without air entrainment to understand the theoretical framework of the regime transition. The analytical solution shows that the steady runout distances of the dilute and dense currents primarily depend on the parameter $W_{\mathrm{s}}/(\mathcal{U}a_0)$, which in turn depends on the mass eruption rate at source $\dot{M}_0$. The analytical solution also suggests that the boundaries of regimes (i.e., Regimes 1, 2a and 2b) are mainly determined by the parameter D/W_{s}, which is independent of the mass eruption rate at source $\dot{M}_0$.

In Step 3, we have compared the analytical solution derived in Step 2 with numerical results of the two-layer model where the effects of air entrainment are taken into consideration. The numerical results show that the parameter $E|\bar{u}|/W_\mathrm{s}$ is mainly determined by the parameter $W_\mathrm{s}/\mathcal{U}$. Thus, the runout distance of the two-layer PDCs is strongly affected by air entrainment in the case of small $W_\mathrm{s}/(\mathcal{U}a_0)$ (i.e., large $\dot{M}_0$), whereas the effect of air entrainment is limited in the case of large $W_\mathrm{s}/(\mathcal{U}a_0)$ (i.e., small $\dot{M}_0$).

The numerical results show that the effects of thermal expansion of entrained air on the steady runout distances strongly depend on the parameter $(C_\mathrm{pa}T_\mathrm{a})/(C_\mathrm{p0}T_0)$. When the temperature of erupted material is high (i.e., small $(C_\mathrm{pa}T_\mathrm{a})/(C_\mathrm{p0}T_0)$), a large degree of thermal expansion of entrained air significantly enhance the liftoff; as a result, the steady runout distance of the dilute current decreases as the degree of air entrainment increases. In this case, the steady runout distance of the dense current also decreases because thermal expansion of entrained air leads to decreasing of the particle supply from the dilute current to the dense current. When the temperature of erupted material is low (i.e., large $(C_\mathrm{pa}T_\mathrm{a})/(C_\mathrm{p0}T_0)$), on the other hand, the entrainment of air results in thickening of the dilute current without enhancing liftoff; as a result, the steady runout distance does not decrease or can even increase as the degree of entrainment increases. Because thickening of the dilute current also leads to decreasing the particle settling from the dilute current to the dense current, the steady runout distance of the dense current decreases as the degree of entrainment increases for the large $(C_\mathrm{pa}T_\mathrm{a})/(C_\mathrm{p0}T_0)$ case, too.

The present results account for diverse features of PDC deposits (e.g., distributions and sedimentary structures). A wide range of distributions of PDC deposits can be accounted for by variable runout distances of PDCs, depending on the mass eruption rate at source, $\dot{M}_0$. Generally, a wide variety of sedimentary structures of PDC deposits (e.g., massive and/or stratified lithofacies) result from the flow-particle interaction inside the boundary layer at the bottom of PDCs. It is considered that some of the diversities of PDC deposits are explained by the difference in the flow-particle interaction in the bottom boundary layer between the dilute and dense currents. When stratified lithofacies are dominantly observed from proximal to distal areas, the PDC deposits are interpreted to be emplaced by PDCs of Regime 1. When massive lithofacies are dominantly observed from proximal to distal areas, the PDC deposits are interpreted to be emplaced by PDCs of Regime 2b. When distal lithofacies change from massive to stratified, the PDC deposits are interpreted to be emplaced by PDCs of Regime 2a. Our results that the region of Regime 2a expands in the regime diagram as the temperature of erupted material decreases are consistent with the observation that stratified surge deposits are commonly observed in the deposits of phreatomagmatic eruptions.