Earth and Planetary Science Letters 467 (2017) 138–148

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Experiments on mixing in pyroclastic density currents generated from short-lived volcanic explosions

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A R T I C L E I N F O

Article history:
Received 1 September 2016
Received in revised form 3 March 2017
Accepted 4 March 2017
Available online xxxx
Editor: T.A. Mather

Keywords:
pyroclastic density current
mixing
sedimentation

A B S T R A C T

During short lived volcanic eruptions, dilute, turbulent pyroclastic density currents are often observed to spread laterally from a collapsing fountain. These flows entrain and heat air while also sedimenting particles. Both processes lead to a reduction in the bulk density and since these flows often become vertically stratified, the upper part of the flow may then exhibit a reversal in buoyancy and lift off. The relative importance of entrainment and sedimentation in controlling the lift-off and the associated run-out distance of short-lived flows is not well-understood. We report a series of novel analogue laboratory experiments in which a suspension of dense particles and salt powder is released into a flume filled with CO_2-laden water. A strong circulation develops in the head of the current: as current fluid reaches the front of the flow, it rises and mixes with ambient fluid which is displaced upwards over the advancing head. As the salt powder in the current mixes with the ambient fluid, small CO_2 bubbles are released, decreasing the bulk density below the ambient and the mixture then rises off the current. As it advances, progressively more of the material in the flow circulates through the head, becomes buoyant and rises from the flow. Within a distance of order 9–12 times the initial size of the flow, all the original fluid has cycled through the head of the flow, mixed with ambient and lifted off. This suggests that dilute turbulent pyroclastic density currents produced by short-lived explosions, of initial length-scale L, will only propagate distances of order 9–12L. Currents with larger particles sediment more of their particles before the flow has fully mixed with the ambient, and this leads to a reduction in the mass which lifts off from the flow.

1. Introduction

Pyroclastic density currents are one of the most dangerous type of volcanic phenomena known to humankind. They involve highly complex fluid dynamic processes which remain poorly understood and which are closely related to the dynamics of submarine turbidity currents. Indeed, the research challenges they pose overlap with scientists working in a number of fields including wider volcanology, hazard sciences, decision making, geophysics, fluid mechanics, engineering, sedimentology and the hydrocarbon industry.

During many short-lived volcanic explosions, pyroclastic density currents composed of fragmented magma and fine ash form, either following collapse of a fountain or following partial failure and fragmentation of a dome. There is a spectrum of such flows, ranging from fully dilute and fully turbulent surge-type flows to granular–fluid pyroclastic density currents, which involve a range of gas–particle transport processes ranging from concentrated and non-turbulent transport to fully dilute turbulent flow. The evolution of the flows is complex, and often the flows become segregated into a dilute and highly turbulent surge-type flow together with a dense basal flow which behaves more as an avalanche (Fisher, 1979; Calder et al., 1999; Dade and Huppert, 1996; Ogburn et al., 2014). This study explores the dynamics of pyroclastic density currents produced by a short-lived eruption, in which, following eruption, a dense particle laden suspension feeds the flow.

One of the earliest recorded examples of a devastating pyroclastic density current developed during the eruption of Mt Pelee, Martinique, 1902. Important examples have also been described during the eruption of Soufriere Hills Volcano, Montserrat (Druitt et al., 2002; Ogburn et al., 2014), Lascar volcano, Chile (Calder et al., 2000), Colima volcano (Sulpizio et al., 2014), Galeras Volcano, Columbia (Stix et al., 1997), as well as Merapi volcano in Indonesia (Gertisser et al., 2012). Dilute pyroclastic density currents represent an important hazard in terms of their propagation distance and speed, with flows travelling distances in the range of a few km from the volcano with speeds of several tens of metres per second while pyroclastic density currents produced from directed blasts may travel larger distances in the range

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http://dx.doi.org/10.1016/j.epsl.2017.03.009

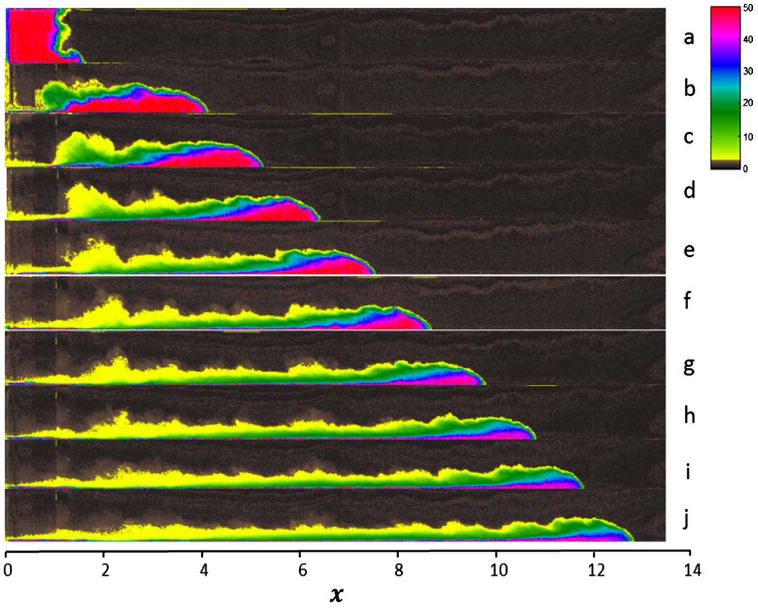

Fig. 1. Evolution of the concentration of a saline gravity current as it advances along a flume. The colour scale indicates the mass of salt in the fluid per unit mass of liquid (g/kg) as a function of position in the current, with the initial saline fluid behind the lock gate having a value 50 g/kg.

1–10 km (Coombs et al., 2010; Cole et al., 2014; Lube et al., 2015; Komorowski et al., 2013; Cronin et al., 2013). The topography can have a dominant impact on the flow evolution causing the dilute part of the flow to decouple from the denser basal part of the flow (Ogburn et al., 2014), and the dilute component may then advance independently from the basal flow. As air is mixed into the pyroclastic density current, the air heats up and its density decreases, thereby lowering the bulk density of the overall mixture (Wilson and Walker, 1982; Woods and Bursik, 1994). When operating in combination with sedimentation, the upper parts of the flow may become buoyant and lift off, forming an ash plume (cf. Woods and Wohletz, 1991; Woods and Kienle, 1994; Clarke et al., 2002).

Owing to the importance of these flows, and the complexity of the interaction between the dense lower part of the flow and the overlying dilute flow, numerous models have been developed to account for the dynamics, using numerical and experimental modelling approaches. Reviews of both experimental and theoretical models of pyroclastic density currents (Sulpizio et al., 2014; Dufek, 2016) summarise the range of behaviour from dense avalanching flows to more dilute suspension flows. Of particular importance is the vertical stratification which often emerges in numerical models which suggest that there is a basal zone of high particle concentration overlain by a more dilute ash flow (Todesco et al., 2002; Takahashi and Tsujimoto, 2000; Clarke et al., 2002; Ishimine, 2005; Calder et al., 1997; Valentine and Wohletz, 1989). However, the detailed dynamics is complex and many of the models rely on detailed parameterisations of turbulence and particle transport in a multi-phase flow.

Andrews and Manga (2012) carried out experiments using heated fine powder in an air based flume measuring the sedimentation pattern to estimate the fraction of the particle load which lifts off. Larger scale experiments have also been carried out in which particle suspensions in air have been released from a central source (Dellino et al., 2007, 2008) or a large flume (Lube et al., 2015) and spread over 10's metres. Some different, but complementary small-scale analogue laboratory experiments have been carried out to examine the evolution of the density of pyroclastic density currents using particle laden currents of fresh water migrating through a flume filled with saline solution. As the particles sediment, the residual fluid becomes buoyant and lifts off (cf. Sparks et al., 1993; Woods and Bursik, 1994; Bonnecaze et al., 1993). In another class of experiments, currents composed of methanol and ethylene glycol (MEG) mixed with water have been released into a water filled flume to examine the role of mixing on the dynamics of pyroclastic density currents. The density of a MEG–water mixture may initially be smaller than water, but on mixing with water, it becomes relatively dense, and so by running such an experimental system upside down, the generation of buoyancy through mixing can be modelled. Huppert et al. (1986) and Woods and Bursik (1994) carried out such MEG–water experiments, with the current propagating along a sloping boundary, demonstrating the importance of mixing in the head and the increase in the rate of entrainment as the angle of slope increases.

Since these water-bath studies, there has been considerable progress in understanding the entrainment of ambient fluid into gravity currents (Sher and Woods, 2015; Samasiri and Woods, 2015). A strong circulation within the head means that all the current fluid eventually reaches the front of the flow where it rises up over the continuing head. Here it mixes with a fraction of the ambient fluid, originally ahead of the current, and which is displaced up over the head. The mixed fluid is then left behind the continuing head of the flow, forming a dilute wake. In Fig. 1, we present a series of images to illustrate the evolving width-averaged buoyancy within a saline gravity current as it migrates along a 3 m long flume. The buoyancy, shown in false colour, is obtained by using a uniform light source on the rear face of the tank, and calibrating the light intensity as a function of the salinity of the current, so that the width-averaged concentration of salt can be measured at each point along the flume using a high resolution digital image (Sher and Woods, 2015). The figure illustrates that after travelling about 10 lock lengths, all the original fluid in the current has mixed with ambient fluid and, subsequently, the concentration of salt everywhere in the flow is less than 0.4 of the original concentration. The speed of the current, u, in this initial phase of the flow is approximately constant and given by

$$u = 0.9(g'_o h)^{1/2} \tag{1}$$

where g'_o is the reduced gravity defined in terms of the density difference between the ambient fluid, ρ_a, and the original lock gate fluid, ρ_c, $g'_o = g(\rho_c - \rho_a)/\rho_a$, and h is the depth of the head. By comparison of the rate of change of volume of the current based