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Rise dynamics of unsteady laboratory jets with implications for volcanic plumes

K.N. Chojnicki [a],*, A.B. Clarke [b], J.C. Phillips [c], R.J. Adrian [b]

[a] Scripps Institution of Oceanography, San Diego, CA, USA
[b] Arizona State University, Tempe, AZ, USA
[c] University of Bristol, Bristol, UK

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ABSTRACT

Geophysical observations of discrete volcanic eruptions suggest their eruption rates vary rapidly in time. To learn how such variations may impact the initial stages of plume rise, we conducted a laboratory study of neutrally-buoyant jets generated by unsteady source conditions analogous to the volcanic case. Turbulent jets were generated by quickly injecting a finite volume of water into a large volume of still water. The mass injection rates evolved over time with a Gaussian-like history, producing jets with peak Reynolds numbers ranging from 10^4 to 10^5, consistent with values estimated for small, discrete eruptions. Except during very early and late times, jet heights show a logarithmic dependence on time; this trend contrasts with the power law dependence for jets produced by steady-state or instantaneous discharge conditions. We show that this logarithmic dependence is the similarity form appropriate for impulsive releases from a time-varying source, and found characteristic length and time scales that consolidate the non-dimensional jet heights, as functions of non-dimensional times, from a range of experimental conditions onto a single trend. The rise of unsteady volcanic plume fronts from short-duration eruptions (Mori and Burton, 2009; Patrick, 2007) show the same trend as that observed in the laboratory. Variations in mass eruption rate strongly influence the initial phases of plume rise and may impact related processes such as mixing, entrainment and eruption column collapse. Consequently, source unsteadiness must be accounted for in physical plume models before they will reliably estimate trajectory, dilution, and stability for volcanic plumes from discrete eruptions.

1. Introduction

Understanding the factors that control ascent of volcanic plumes is essential for accurate reconstruction, interpretation, and prediction of volcanic plume behavior. Volcanic plumes are typically modeled as turbulent flows (Settle, 1976: Wilson, 1976), and a constant discharge rate assumption is a common simplification. However, discharge variability is observed in Vulcanian- (e.g. Clarke et al., 2002) and Strombolian-style (e.g., Taddeucci et al., 2012) eruptions, and rising plumes from these eruptions may be subject to strong and sudden changes in source momentum with potential consequences for plume dynamics, including ascent characteristics. An accurate description of plume rise processes under unsteady discharge conditions is therefore necessary to improve predictions of such quantities as ash-release height and mass flux in these types of eruptions. Since discrete eruptions of volcanoes all over the planet (e.g., Patrick, 2007; Nishimura et al., 2012; Scharff et al., 2008; Lyons et al., 2009; Clarke et al., 2002, Fig. 1) generate volcanic plumes many times per day, this improved understanding is relevant to the global community's response to daily threats from natural hazards.

Due to the great diversity observed in volcanic plume behavior, a variety of theoretical, empirical, and numerical models have been proposed to describe their dynamics (e.g., Valentine et al., 1991; Bursik, 2001; Clarke et al., 2002; Ogden et al., 2008; Tupper et al., 2009). In many cases, the source flux $Q(t)$ [$\mathrm{m^3\,s^{-1}}$] may be continuous in time t, but variable. If the time scale of variation in the source flux is much longer than the time scale of plume rise, then the plume can be modeled as quasi-steady. The time scale of buoyant plume rise is of order $1/B$, where B is the atmospheric buoyancy frequency with a standard atmosphere value of 0.01 $\mathrm{s^{-1}}$ (Sparks et al., 1997). Thus, if the plume source maintains a constant rate for more than about 100–200 s, the plume can be approximated by steady flow, for which steady integral plume models (e.g. Morton et al., 1956; Woods, 1988) can

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* Corresponding author.
E-mail address: kchojnicki@ucsd.edu (K.N. Chojnicki).

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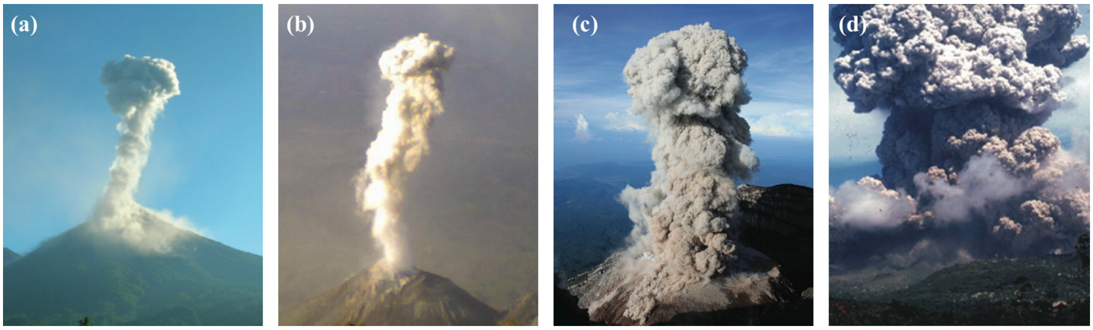

Fig. 1. Photographs showing the variation in short-lived volcanic plumes at (a) Fuego Volcano, Guatemala (Photo by J. Lyons), (b) Santiaguito Volcano, Guatemala (photo by K. Chojnicki), (c) Semeru Volcano, Indonesia (photo by J.-F. Smekens), and (d) Soufrière Hills Volcano, Montserrat (Photo by B. Voight).

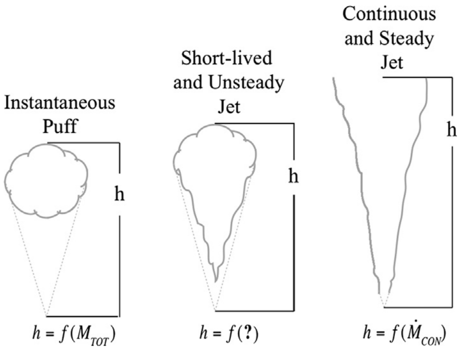

Fig. 2. While the controls on height in a still ambient environment are known for instantaneous puffs (the time-integrated momentum, M_{TOT}) and continuous and steady jets (the constant, time-averaged momentum, $\dot{M}_{CON}$), we focus here on the controls on height for short-lived and unsteady jets, as they are not well understood.

provide a good description. For very short duration eruptions, integral approaches based on impulsive release of pure buoyancy, i.e. 'thermals' (Morton et al., 1956; Woods, 1995), or impulsive momentum, i.e. 'puffs' (Richards, 1965), can reasonably be applied. However, the common volcanic eruptions discussed here appear to be fed by unsteady and short-lived but non-instantaneous sources, whose time scales are intermediate to those of quasi-steady or instantaneous sources. As we show here, treating these eruptions as instantaneous events neglects the contribution of variable discharge rate to plume motion and underestimates the rise rate and final height, while treating them as steady and continuous neglects the limited source duration and overestimates their rise rate and final height (Fig. 2).

Findings from previous analogue studies suggest that the responses of laboratory jets to variability in source flux may be complex. Kieffer and Sturtevant (1984) found that, when the discharge was suddenly initiated and then maintained at a constant rate for a long duration, the effects of time-varying discharge were limited to the jet front, formed while the source momentum varied. Once the source momentum reached a constant state, so did the flow-front propagation speed. While different from the problem studied here (sudden initiation and continued variation over a short duration), the results of Kieffer and Sturtevant (1984) suggest that jet front propagation is sensitive to variability in source conditions.

Many volcanic plumes are ejected into the atmosphere at velocities that significantly exceed those in the surrounding atmosphere. Momentum discharge therefore dominates initial rise processes near the vent. Buoyancy forces are expected to control the motion far from the vent once the initial momentum has sufficiently dissipated. Thus, variable discharge rates may alter near-vent rise dynamics and the transition to buoyancy-driven rise in volcanic plumes.

Here we shall neglect buoyancy in order to focus on understanding momentum dissipation in the purely momentum-driven limit. We thus restrict our investigation to the end-member case of laboratory jets driven only by initial momentum in order to understand the dynamics of early rise phases in the near-vent region in natural volcanic events. Specifically, we investigate the potential effects of discharge variability on volcanic-plume rise by examining the dynamics of turbulent laboratory jets with a time-varying discharge history. We find that discharge variability alters the laboratory jet rise process when the variations are large and occur on the same time scale as the source duration. From these laboratory data, we develop an empirical formulation for estimating jet rise under these highly unsteady discharge conditions. Its form compares favorably with observations of analogous volcanic plumes.

2. Experimental methods

Following Clarke et al. (2009), we conducted a series of analogue laboratory experiments to examine the rise behavior of turbulent jets resulting from a time-varying discharge of a neutrally-buoyant fluid into a still ambient fluid. In this problem the injected momentum is the only agent driving the rise. Successful application of the experimental results is based on extrapolation to the much larger scales of volcanic plumes using non-dimensional analysis and the assumptions of geometric and dynamic similarity.

A sketch of the experimental apparatus is shown in Fig. 3. Analogue jets were generated by injecting water into a tank of still water through a vertically oriented pipe. The tank had dimensions of $0.6 \times 0.6 \times 1.2$ m deep, and it was filled with water to a depth of 0.95 ± 0.01 m. Both the ambient and the source reservoirs were filled from the lab water supply and brought to room temperature to eliminate air dissolved in the water. A ball valve (DynaQuip) separated the source fluid from the ambient fluid reservoir. The source fluid was pressurized with a pump (Graco Ultra 395) and then released into the ambient reservoir by rapidly opening the valve using an actuator (DynaQuip). Both the form of the discharge history and the discharge duration were outcomes of the source decompression, not set *a priori*.

Injection characteristics and the resultant jet rise were measured as functions of time for various source Reynolds number ($Re_0 = 10^4$–10^5, based on the vent diameter and peak jet velocity at the vent). The Re_0 range was achieved by varying the diameter of the circular orifice, $d_0 = 3, 9$ or 15 mm, from which the jet entered the tank and the pressure in the system prior to valve opening, 3.4 and 6.9 MPa (gauge pressure). The experimental conditions are summarized in Table 1.

The mass flow rate of water that entered the tank $\dot{m}(t)$ [$\text{kg}\,\text{s}^{-1}$] was measured by a Coriolis mass flow meter (Kueppers KCM3000) sampling at 100 Hz. The volume flux $Q(t)$ [$\text{m}^3\,\text{s}^{-1}$] and vertical velocity of the source, averaged across the plane of the vent at $y = 0$, $V_0(t)$ [$\text{m}\,\text{s}^{-1}$] were determined according to