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Dynamics of volcanic umbrella clouds

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Atmospheric injection of volcanic ash and aerosols during explosive eruptions is controlled by the dynamics of a volcanic column and associated umbrella cloud, which are connected by a turbulent fountain which initiates horizontal spreading at the neutral buoyancy level. Column and cloud are usually also subject to a wind field. Physical models of these phenomena provide a useful framework to interpret satellite observations, constraining gas and aerosol fluxes, for example. We present a new theoretical and experimental study of an axisymmetric turbulent umbrella cloud intruding horizontally at its neutral buoyancy level into a static environment linearly stratified in density. The intrusion is fed from by a constant horizontal volume flux (Q0) at a finite radius (R0), where it has a constant thickness (2H0). The characteristics of the fountain (R0, H0, Q0) derive from a vertical forced plume (source momentum and buoyancy fluxes Mi , Fi) and environmental stratification N. Our theory highlights the importance of the vertical profiles of density and velocity within the umbrella cloud of which we present experimental measurements. We also emphasize the importance of turbulent drag as the intrusion advances through the ambient fluid, and demonstrate the existence of two dynamical regimes. Initially, the volume flux from the fountain is mainly opposed by turbulent drag, and umbrella cloud radius (RN(t)) grows linearly in time. The intrusion thickens and a some entrainment occurs in this regime. Subsequently, the intrusion breaks down into two parts: i) between the source and a transition radius (R0<r<RT(t)), a steady region in which buoyancy and turbulent drag are exactly balanced, and intrusion thickness (2H) and mean velocity (U) are time-independent and decreasing functions of r ; ii), a contiguous unsteady « frontal » region, between the transition radius and the front (RT<r< RN). The theory predicts intrusion shape and an asymptotic spreading behaviour (RN∼t5/9) which agree well with experimental data. We apply our analysis to satellite observations of several sustained plinian events including the Pinatubo 1991 climactic eruption, and show that both the initial and asymptotic spreading regimes predicted by the model are present. The solution that we present is analytic and therefore can in principle be developed to obtain a rapid interpretation of satellite observations of spreading umbrella clouds.