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Effects of vertical diffusivity and plume shape on the inversion analysis of tephra fallout deposits

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Estimation of volcanic plume condition from fallout deposits is an important volcanological subject; such estimations are indispensable for reconstruction of the dynamics of volcanic plumes in the past as well as forecast of tephra fallout distribution during ongoing eruptions. The goal of this study is to develop an accurate inversion method to estimate tephra source parameters (location, height, amount and grain size of tephra) from distribution of tephra fallout deposits. In previous studies on the inversion analyses using tephra fall deposits (e.g., Klawonn et al., 2012; Mannen 2014), vertical diffusivity of particles and bending of volcanic plume due to wind are sometimes assumed to be negligible. In this study, we investigated the applicability of these assumptions through systematic advection-diffusion simulations of single-sized tephra particles released from point sources above a vent.

In the advection-diffusion simulation of single-sized particles from a point source, the released particles diffuse and form a "particle cloud". If the vertical diffusivity of particles is ignored, particle clouds diffuse only horizontally and the distribution of particles is described by a bivariate Gaussian distribution (BGD). On the other hand, when the vertical diffusion exists, the particle cloud has an oblate spheroid shape. Because of the presence of wind, the vertically extending particle cloud keeps its horizontal movement after the landing of its bottom until the settlement of its top. As a result, the distribution of deposits deviates from a BGD in three ways: (1) increase of the kurtosis in the cross wind direction, (2) increase of the skewness and (3) increase of the variance along the wind direction. Among these deviations, (1) and (2) are caused by vertical diffusion of particles during deposition of the particle cloud and become significant when $(D_z/v_t z)^{1/2} \geq 0.2$ where D_z is the vertical diffusion coefficient, v_t is the terminal velocity, z is the source height. The deviation (3) is caused by horizontal movement of the particle cloud in the wind direction during the deposition and becomes significant when $D_z{}^{1/2} D_h{}^{-1/2} W v_t{}^{-1} \geq 3$ where W is the wind velocity, D_h is the horizontal diffusion coefficient.

Volcanic plumes generally bent to leeward when wind is present. The effect of bending plumes on the distribution of tephra fallout deposits is evaluated through comparison between the bending distance of the plumes and the advection distance of settling particles. Dimension analysis and wind-affected volcanic plume models (e.g., BENT; Bursik 2001) suggest that the trajectory (bending distance x and height z) of a bending weak plume is approximated by $z=CB^{1/3}W^{-1}x^{2/3}$ (Wright 1971), where C is a constant, B is the effective buoyancy flux (Sparks et al., 1997). On the other hand, the advection distance of particles can be calculated as $b=zW/v_t$. If the bending distance x is as large as the particle advection distance b (i.e., $x/b \geq n$; n is a constant of order 10^{-1}), the effect of bending plumes cannot be ignored; on the basis of the equations of bending distance and advection distance, this condition can be rewritten as $C^{-3}B^{-1}zWv_t{}^2 \geq n^2$.

The above results show that the effect of vertical diffusivity is significant when finer particles are released from lower altitudes. In contrast, the effect of bending plume is significant when coarser particles are released from higher altitudes. The results also suggest that both the effects can be insignificant for particles with intermediate grain size. From the above equations, it is inferred that the terminal velocity of such particles with intermediate grain size ranges $D_z/0.04z \leq v_t \leq nC^{3/2}B^{1/2}z^{-1/2}W^{-1/2}$ when $Wz(D_zD_h)^{-1/2}<75$ and $WD_z{}^{1/2}/3D_h{}^{1/2} \leq v_t \leq nC^{3/2}B^{1/2}z^{-1/2}W^{-1/2}$ when $Wz(D_zD_h)^{-1/2}>75$. These relationships between grain size and particle distribution must be taken into consideration in the inversion analysis.

Keywords: volcanic plume, tephra fallout deposits, advection-diffusion model, inversion analysis