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Reconstructing tephra fall deposits via ensemble-based data assimilation techniques

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Abstract. In recent years, there has been a growing interest in ensemble approaches for modelling the atmospheric transport of volcanic aerosol, ash, and lapilli (tephra). The development of such techniques enables the exploration of novel methods for incorporating real observations into tephra dispersal models. However, traditional data assimilation algorithms, including ensemble Kalman filter (EnKF) methods, can yield suboptimal state estimates for positive-definite variables such as those related to volcanic aerosols and tephra deposits. This study proposes two new ensemble-based data assimilation techniques for semi-positive-definite variables with highly skewed uncertainty distributions, including aerosol concentrations and tephra deposit mass loading: the Gaussian with non-negative constraints (GNC) and gamma inverse-gamma (GIG) methods. The proposed methods are applied to reconstruct the tephra fallout deposit resulting from the 2015 Calbuco eruption using an ensemble of 256 runs performed with the FALL3D dispersal model. An assessment of the methodologies is conducted considering two independent datasets of deposit thickness measurements: an assimilation dataset and a validation dataset. Different evaluation metrics (e.g. RMSE, MBE, and SMAPE) are computed for the validation dataset, and the results are compared to two references: the ensemble prior mean and the EnKF analysis. Results show that the assimilation leads to a significant improvement over the first-guess results obtained from the simple ensemble forecast. The evidence from this study suggests that the GNC method was the most skilful approach and represents a promising alternative for assimilation of volcanic fallout data. The spatial distributions of the tephra fallout deposit thickness and volume according to the GNC analysis are in good agreement with estimations based on field measurements and isopach maps reported in previous studies. On the other hand, although it is an interesting approach, the GIG method failed to improve the EnKF analysis.

1 Introduction

Multiple hazards are associated with volcanic eruptions including lava flows, pyroclastic density currents, lahars, volcanic plumes, and tephra fallout. Specifically, the dispersal of volcanic plumes poses a serious threat to flight safety (e.g. Clarkson et al., 2016), and the subsequent fallout of tephra can cause structural damage to buildings and infrastructure due to excessive loading, as well as disrupting communication networks, airports, power plants, and water and energy distribution networks (Wilson et al., 2014). Additionally, fresh fallout deposits may be resuspended by aeolian processes, affecting the air quality and prolonging the impacts of an eruption many years afterwards (Folch et al., 2014; Dominguez et al., 2020; Mingari et al., 2020).

The characterisation and quantification of past eruptive events are also of paramount importance for volcano hazard and risk assessment studies, which infer the likelihood of future eruption scenarios based on past volcano behaviour. Explosive volcanic eruptions are often characterised and classified by means of tephra deposits (Bonadonna et al., 2015), which provide critical information to infer eruption

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