Atmospheric Environment 143 (2016) 190–201

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Modelling wet deposition in simulations of volcanic ash dispersion from hypothetical eruptions of Merapi, Indonesia

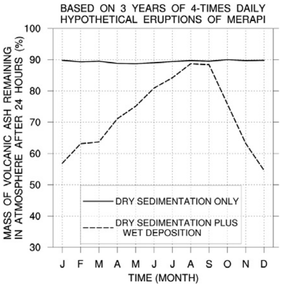
Richard A. Dare*, Rodney J. Potts, Alan G. Wain

Australian Bureau of Meteorology, Australia

HIGHLIGHTS

- Dispersion model simulations based on hypothetical eruptions of Merapi, Indonesia.
- Four 24-h simulations per day over a period of three years.
- Dry sedimentation removes a mean of 10% of the total released volcanic ash mass.
- Wet deposition removes an addition 30% of the total mass during the wet season.
- Results are most sensitive to the coefficient in the bulk wet deposition formulation.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form
29 July 2016
Accepted 8 August 2016
Available online 10 August 2016

Keywords:
Volcanic ash
Wet deposition
Dispersion modelling
HYSPLIT
Merapi
Indonesia

ABSTRACT

The statistical impact of including the process of wet deposition in dispersion model predictions of the movement of volcanic ash is assessed. Based on hypothetical eruptions of Merapi, Indonesia, sets of dispersion model simulations were generated, each containing four simulations per day over a period of three years, to provide results based on a wide range of atmospheric conditions. While on average dry sedimentation removes approximately 10% of the volcanic ash from the atmosphere during the first 24 h, wet deposition removes an additional 30% during seasons with highest rainfall (December and January) but only an additional 1% during August and September. The majority of the wet removal is due to in-cloud rather than below-cloud collection of volcanic ash particles. The largest uncertainties in the amount of volcanic ash removed by the process of wet deposition result from the choice of user-defined parameters used to compute the scavenging coefficient, and from the definition of the cloud top height. Errors in the precipitation field provided by the numerical weather prediction model utilised here have relatively less impact.

1. Introduction

Volcanic ash particles that are injected into the atmosphere by volcanic eruptions are a hazard to aircraft (Pieri et al., 2002). Once present in the atmosphere, these particles are moved by winds and atmospheric turbulent motions (Draxler and Hess, 1998). Volcanic ash particles also descend towards the Earth's surface due to gravity (Heffter and Stunder, 1993). The speed of descent depends on the size, density and shape of the particle (Ganser, 1993). Under moist atmospheric conditions, the removal of particles from the

---

* Corresponding author. Australian Bureau of Meteorology, 700 Collins Street, Melbourne, 3001, Australia.
E-mail address: R.Dare@bom.gov.au (R.A. Dare).

http://dx.doi.org/10.1016/j.atmosenv.2016.08.022

atmosphere may be enhanced (Langmann et al., 2010). Water may condense, or ice may sublimate, onto a particle, or there may be a collision between an ash particle and a cloud droplet (Textor et al., 2006a). The hydrometeor that results from these processes may then grow to the size of a rain drop due to condensation, autoconversion and accretion (Rutledge and Hobbs, 1983). Alternatively, an ash particle may collide with a rain drop inside a cloud or below the base of a cloud (Hertel et al., 1995). Once attached to a falling rain drop, the volcanic ash particle may fall at a speed that is greater than that of an equivalent non-accreted particle in a dry atmosphere (Slinn, 1984). In addition to these interactions between a volcanic ash particle and a water drop, the process of wet aggregation may occur in which the presence of magmatic or atmospheric water allows formation of aggregates of multiple volcanic ash particles (Textor et al., 2006b). As these aggregates are larger than individual particles, they fall with a greater speed (Devenish et al., 2012). Consequently, wet processes have the ability to remove volcanic ash particles from the atmosphere that would, under dry atmospheric conditions, have remained suspended in the atmosphere for a longer period (Langmann et al., 2010). Therefore, when considering the evolution of volcanic ash in an atmosphere that is moist, it is important to consider wet processes. This point is particularly relevant to tropical environments where volcanoes are located, such as Indonesia and surroundings, where a moist tropical atmosphere overlies an area containing many volcanoes (Tupper and Kinoshita, 2003; Bear-Crozier et al., 2012).

The enhanced removal of volcanic ash particles from the atmosphere due to aggregation has been discussed extensively (Carey and Sigurdsson, 1982; Pieri et al., 2002; Bonadonna and Phillips, 2003; Durant et al., 2009; Bonadonna et al., 2011; Devenish et al., 2012). There has also been a large amount of work on the removal of materials in the atmosphere due to hydrometeor scavenging (Jylha, 1991; Hertel et al., 1995; Draxler and Hess, 1998; Seinfeld and Pandis, 1998; Laakso et al., 2003; Loosmore and Cederwall, 2004; Sportisse, 2007; Folch et al., 2013; Leadbetter et al., 2015). This process is also known as wet deposition because the process results in a particle being deposited on the Earth's surface following collection by a hydrometeor. There have been relatively fewer discussions concerning the wet deposition of volcanic ash particles. McCormick et al. (1995) mentioned wet removal of volcanic ash following the eruption of Pinatubo, but did not consider this point in detail. Langmann et al. (2010) modelled wet deposition of volcanic ash from the Kasatochi volcano in the Aleutin Islands. Stevenson et al. (2012) noted observations of rain water in Norway that contained volcanic ash particles. Webster and Thomson (2014) modelled the wet deposition of volcanic ash particles produced by an eruption in Iceland. Many models used for simulating the dispersion of volcanic ash particles include representations of wet deposition, including, for example, HYSPLIT (Draxler and Hess, 1998), FLEXPART (Stohl et al., 2005), COSMO-MUSCAT (Heinold et al., 2012) and NAME (Webster and Thomson, 2014). The aim of the current work is to, first, assess the magnitude of the effect of wet deposition in numerical dispersion model forecasts of the movement of volcanic ash in a tropical atmosphere, and second, investigate sources of uncertainties in the wet deposition formulation. In the bulk wet deposition process used here, the physics of interactions between cloud droplets, rain drops, and volcanic ash particles are not explicitly simulated. This process removes volcanic ash particles from the atmosphere without considering accretion, aggregation, changes in particle fall speeds, or other microphysical processes.

Details of the dispersion model, the numerical weather prediction (NWP) model that provides meteorological fields to the dispersion model, and the wet deposition formulation are discussed in the next section. The basic configuration of the model experiments conducted in this investigation is discussed in Section 3. Results from the model experiments are presented in Section 4. These include assessment of the impact of wet deposition relative to dry simulations, evaluation of the relative contribution of in-cloud and below-cloud wet depositions, sensitivity to changes in defining the heights of the cloud base, cloud top, and scavenging parameters, the relative impact of errors in NWP model precipitation fields, and impact of wet deposition on the area of the volcanic ash cloud. Findings are discussed in Section 5, followed by a summary in Section 6.

2. Dispersion model and wet deposition formulation

2.1. Dispersion model

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) dispersion model (Draxler and Hess, 1997, 1998; Stein et al., 2015) has been applied to a wide variety of atmospheric pollutant modelling tasks, with a large number of users, as documented by Stein et al. (2015). Relevant to the current work, the HYSPLIT model has been used widely for predicting the movement of volcanic ash particles in the atmosphere (Draxler and Hess, 1998; Tupper et al., 2006; Witham et al., 2007; Schumann et al., 2011).

The version of HYSPLIT used here (733) is modified to use the scheme of Ganser (1993) to predict the sedimentation of volcanic ash particles, as discussed by Dare (2015), in place of the Stokes formula. All particles at all heights within the model atmosphere are subject to sedimentation. The density of volcanic ash particles is defined as 2500 kg m^{-3} and the particle sphericity (Wadell, 1932) is set equal to 0.8. The particle size distribution used here (Fig. 1) is based on the observations of Hobbs et al. (1991) and the modelling experiments of Heffter and Stunder (1993), Dacre et al. (2011) and Devenish et al. (2012).

2.2. NWP model

Meteorological fields are provided to the dispersion model by the global NWP model operated at the Australian Bureau of Meteorology (ABOM). This model is named the Australian Community Climate and Earth System Simulator (ACCESS) and is based closely on the United Kingdom Meteorological Office's Unified Model (Cullen, 1993; Davies et al., 2005; Rawlins et al., 2007).

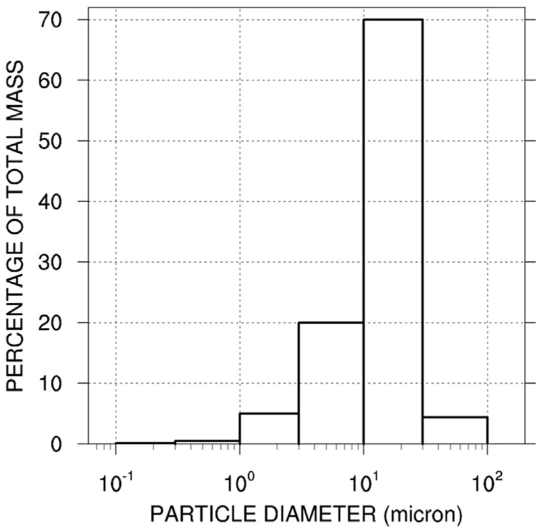


Fig. 1. Particle size distribution used in all model simulations.