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Estimation of dispersion coefficient in the troposphere from satellite images of volcanic plumes: Application to Mt. Etna, Italy

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Abstract

The lateral dispersion of volcanic plumes in the troposphere is investigated using satellite images. Two plume images have been selected from the Mount Etna eruption that occurred in October/November 2002.

To reproduce the satellite images two modelling approaches are presented. The first one uses deterministic trajectories released from a line source extending over a range of altitudes chosen from direct observations. The second uses stochastic trajectories from an area source located at a fixed height, where the source size and the effective diffusion coefficient are determined by data analysis. The meteorological model BOLAM (Bologna Limited Area Model) supplies the atmospheric dynamics. Both approaches reproduce the main features of the observed plumes, with differences in the cross section distribution of the density.

Keywords: Transport; Turbulent dispersion; Lagrangian stochastic model; Volcanic eruptions

1. Introduction

The visual inspection of satellite images of volcanic plumes travelling in the troposphere for distances of the order of 10^3 km reveals a certain amount of lateral dispersion as well as the mean transport. However, since images of this kind give information integrated along the vertical, the apparent dispersion can be the result of a superposition of different effects.

It should be noted that the satellite image is a Eulerian "snapshot" taken at a given instant, thus representing the superposition of different air parcels starting from the source at different times.

Considering transport above the boundary layer (as occurs for the volcanic plume), lateral dispersion may appear because the vertical thickness of the plume is large enough to involve atmospheric layers with different mean velocities. Moreover, the time variability of velocity allows trajectories starting at

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different times to reach different points, even when the vertical thickness is negligible (in the absence of vertical fluctuations of velocity, i.e. of turbulence, shear dispersion cannot occur).

To evaluate the lateral dispersion affecting transport Gifford (1982, 1984) and Barr and Gifford (1987) fitted sets of large scale dispersion observations using as a model the Orstein–Uhlenbeck process, which is a Markov model for the tracer velocity. The fit permits the estimation of the characteristic velocity variance and time scales, leading to the determination of the horizontal dispersion coefficient K_h (strictly speaking, the dispersion coefficient for the direction normal to the mean flow) in the range of values between 5×10^3 and $6.0 \times 10^4\,\mathrm{m^2\,s^{-1}}$.

Coefficient diffusion estimates are used in transport models for various meteorological applications. Although the main emphasis is placed on wind advection, it is interesting to observe that different authors have needed to introduce some dispersion effects.

The model FLEXPART (Stohl et al., 1998), originally designed for emergency response and research applications, utilises the mean wind derived from meteorological analyses (ECMWF) with a superimposed noise, determined from the variance of the wind averaged over a number of points surrounding the particle position in space and time. The corresponding time scale is taken as half of the time interval for which the wind fields are available.

The model VAFTAD (Volcanic Ash Forecast Transport and Dispersion), developed to forecast volcanic plumes (Heffter and Stunder, 1993; Heffter, 1996), advects the centre of independent Gaussian puffs with the mean horizontal wind, released at different levels from the volcano top up to a fixed maximum height (default 16 km a.s.l.). The puff variance σ^2 grows according to the empirical law $\sigma = 0.5t$, where σ is in m and t in s (see Heffter, 1965), which is not consistent with a diffusive approach.

CANERM (CANadian Emergency Response Model) is a Eulerian model, originally developed in response to the Chernobyl nuclear accident (Pudykiewicz, 1988, 1989), and later adapted to predict transport and dispersion of volcanic ash. Advection is calculated using a semi-Lagrangian scheme. The diffusivities are dependent on the boundary layer conditions at the lower levels according to Businger et al. (1971), and are taken to be constant above. Note that D'Isidoro et al. (2005) showed that the numerical scheme in itself produces a dispersion effect.

The model PUFF (Searcy et al., 1998) uses a Langevin equation to introduce some stochastic effects on the position of particles released as in VAFTAD. The resulting horizontal diffusion coefficients are in the range $(0.8-8.0) \times 10^4\,\mathrm{m^2\,s^{-1}}$, whereas a fixed value of the vertical diffusion coefficient $K_z = 100\,\mathrm{m^2\,s^{-1}}$ is adopted. However, applications of this model with high resolutions lead to the use of $K_h = 10^2\,\mathrm{m^2\,s^{-1}}$ (see Tanaka and Yamamoto, 2002).

In all of these models, the spread of trajectories is useful to account for unresolved motions, rather than to simulate a true dispersion process, regardless of the unpredictability of the motion. With respect to a "perfect model" this assumption produces a wider coverage of areas affected by the transported particles. The aim of this work is to provide two different descriptions of the observed spread. The paper proceeds as follows. In Section 2 data treatment is described; in Section 3 the effective diffusion coefficient is estimated; in Section 4 deterministic and stochastic trajectories are used and compared with observations, in order to assess the applicability of the different methods, and in Section 5 some conclusions are drawn.

2. Treatment of satellite images to discriminate volcanic ash

MODIS images (from both the Terra and Aqua platforms) were acquired during the October/November 2002 eruptions of Mount Etna with the purpose of locating the position of the ash plume. During the daytime ash clouds and plumes can be relatively easy to locate, because they are often darker than meteorological clouds (ice/water clouds) under the same solar illumination and viewing conditions. At night, ash clouds and meteorological clouds are more difficult to distinguish from each other so that only infrared imagery can be used and the thermal signals depend on the temperature of the cloud tops. Prata (1989a) developed a technique for discriminating ash clouds/plumes from meteorological clouds using two infrared channels in the 10–12 μm spectral window. The technique relies on the observation that ash clouds, composed mostly of silicate, scatter and absorb infrared radiation in a different manner to clouds composed mostly of water vapour, water droplets or ice habitats. This phenomenon, termed