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Propagation of Source Grain-size Distribution Uncertainty by Using a Lagrangian Volcanic Particle Dispersal Model

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1. Motivation and objective

Volcanic ash clouds represent a major hazard for populations living nearby volcanic centers producing a risk for humans and a potential threat to crops, ground infrastructures, and aviation traffic.

Such a phenomenon is affected by numerous uncertainty sources since its dynamics is largely affected by initial and boundary conditions that cannot be predicted in advance.

In this work, we present the results of an uncertainty propagation analysis applied to volcanic ash dispersal from weak plumes with specific focus on the uncertainties related to the grain-size distribution of the mixture.

2. Mt. Etna Case Study

The analysis presented in this work has been performed for dispersal conditions referred to the **event of November 24, 2006 at Mt. Etna**. Plume height was about 4.3 km above sea level[1]. For this event the volcanic cloud showed horizontal stripes oriented perpendicularly to the prevailing wind direction (as observed at other volcanoes, eg. Klyuchevskaya in Kamchatka and Eyjafjallajokull in Iceland). Through field and satellite data it was possible to closely observe the dispersal process. It has been hypothesized that the stripes are produced by Kelvin-Helmoltz instabilities associated to the presence of the volcanic ash itself.

Figure 1 (left) *Cloud ash of 24 November 2006 eruption captured by MOSIS satellite, source NASA.*

Figure 2 (down) *Plume of Mt.Etna eruption of 24 November 2006.*

The wind field used in this study has been generated by the Eulerian fully-compressible non-hydrostatic atmospheric model WRF (The Weather Research and Forcasting Model). Because the wind direction was nearly constant during the event after 12:00PM, we have investigated the phenomenon using a high-resolution two-dimensional simulation. The wind field generated for this simulation covers a domain of about 40 km horizontally and 6 km vertically and Kelvin-Helmoltz instabilities are present in the output in the vertical range between 3300m and 4300m [(2)].

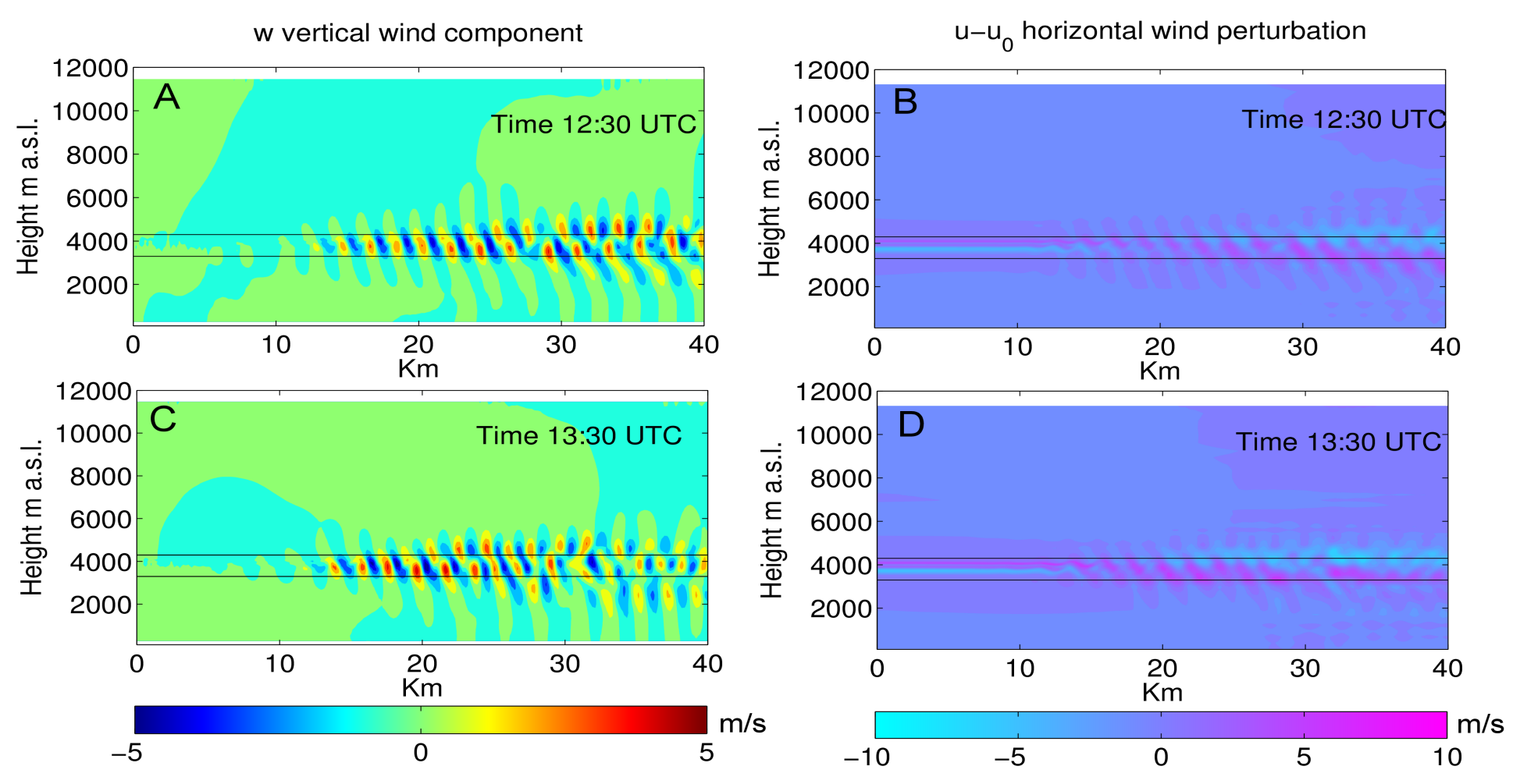


Figure 3. *Background flow field computed by using the 2D High-resolution mesoscale WRF. This model allowed to hypothise the formation of Kelvin-Helmoltz instabilities as responsible for the generation of oscillations in the dispersal process*[2].

3. The Lagrangian particle model LPAC

For this application we used a Lagrangian particle model, named LPAC[3], to simulate the transport of ash under the action of the atmospheric field computed by the mesoscale model WRF. The equations of particle motion are derived expressing the Lagrangian acceleration as the sum of the forces acting along its trajectory. In order to increase the stability of the model, drag forces were calculated implicitly as a function of relative velocity, particle diameter and Reynolds number[4]. No turbulence and aggregation effects were considered. Due to the low concentration of ash in the atmosphere, a one-way coupling between the background flow field and the particles was assumed. In addition, in these simulations, each "particle", or parcel, is assumed representative of the same amount (mass) of pyroclastic material, and not of a single ash particle.

The domain of the simulation has an horizontal extension of about 40 Km and a vertical one of about 6 Km and it was divided into 4 vertical stripes. In each stripe a distinction between the air and the ground was made. The particles are released 2km downwind the left boundary of the domain, with a size sampled from a prescribed distribution.

4. Grain Size Distribution

For volcanic ash particles, the size is generally described as mass fractions in the Krumbein logarithmic scale[5], i.e.:

$$\varphi=\log_2(d/d_0),\ \text{with } d_0 = 1mm.$$

For this work, the uncertainty in the grain-size distribution has been described by assuming a range of values for the main parameters describing the ash particles: mean diameter μ and standar deviation σ of the grain size distribution and the sphericity ψ of the particles.

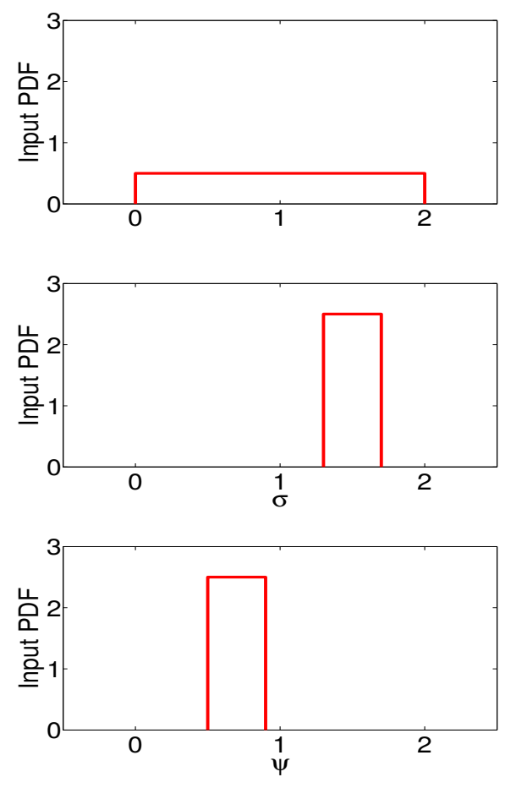


Figure 4. *Range of values representing the uncertainty in the parameters describing the ash particles released in the atmosphere: mean size [0;2], standard deviation [0.5;0.9] of the mean size and sphericity [0.5;0.9] of the particles.*

5. Lagrangian simulations results

Before carrying out the full uncertainty quantification analysis, it is interesting for look at the results of LPAC obtained for a particular set of the input parameters, and then varying only one of the input parameters at a time. In Figure 5 the results of a simulation with μ=1, σ=1.5 and the sphericity ψ=0.7 are presented, with the different colors representing parcels of particles with different sizes (red for the smallest particles). In addition, in the bottom panels, the histograms of the size of the particles in the four stripes in the atmosphere (upper row) and on the ground (lower row) are plotted. In addition, in each panel the mean diameter and the standard deviation of the grain size distribution are reported. We can see how only the distribution in the portion of the domain closer to the release is representative of the original one.

In Figs. 6-8 the effects of varying ony one parameter at a time on the grain size distributions after 3 hours of simulation are presented (when an almost steady-state is reached).

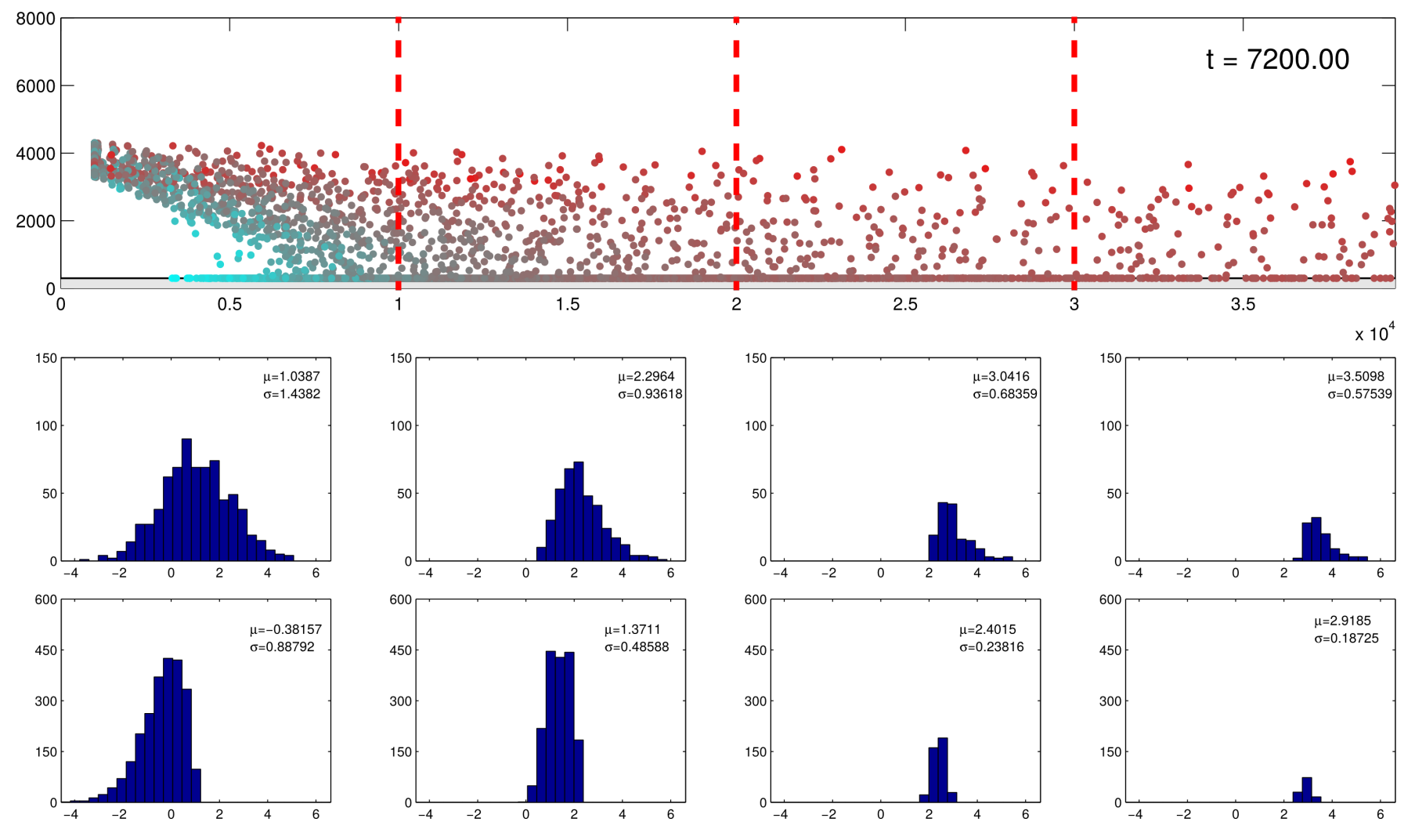
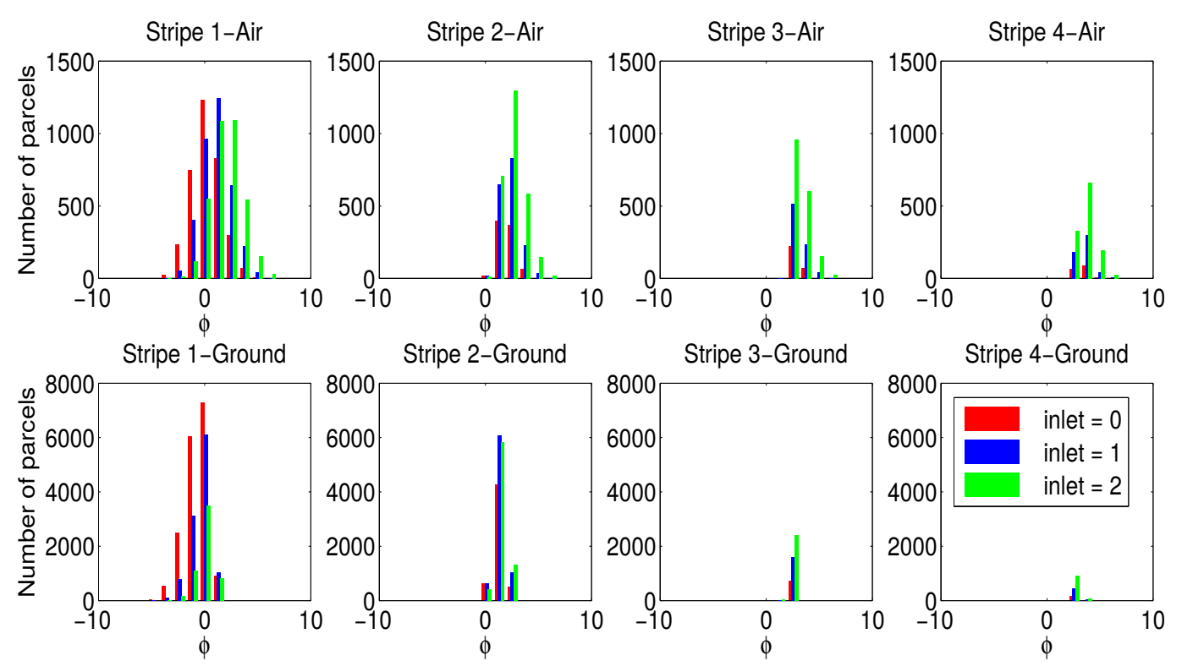
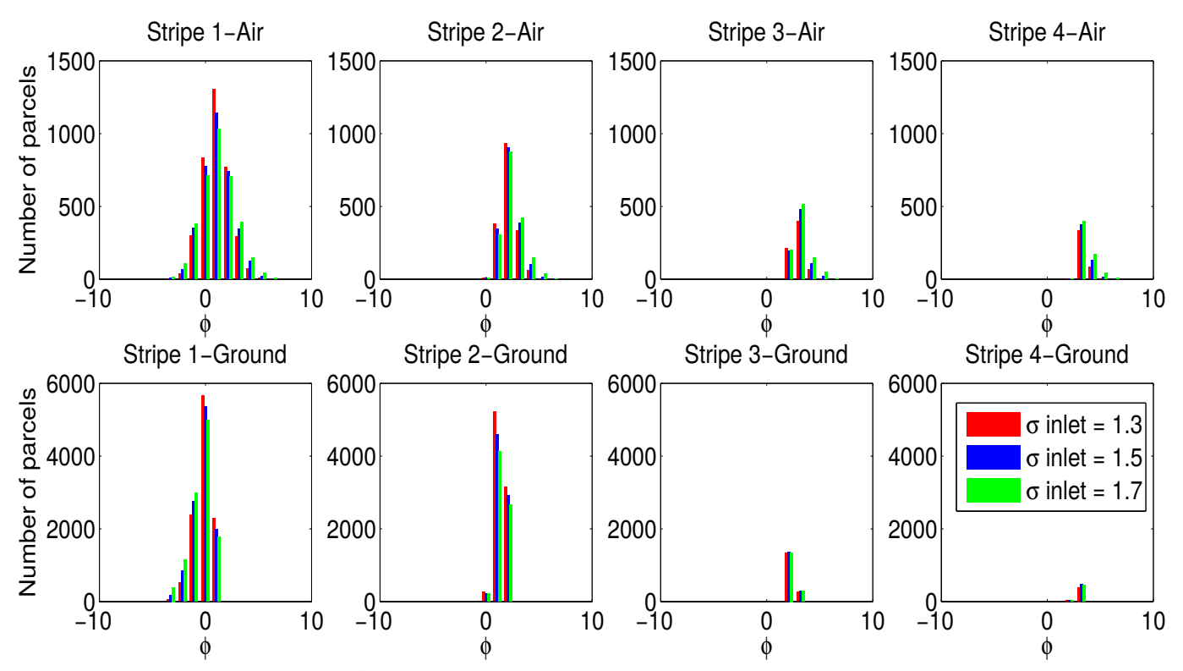


Figure 5. *Lagrangian simulation of the particles dispersion in the atmosphere (top). The color is representative of the size of the particles. On the bottom the grain size distributions in four stripes of the domain are plotted for the particles in the atmopshere and on the gorund.*

LINK TO THE VIDEO





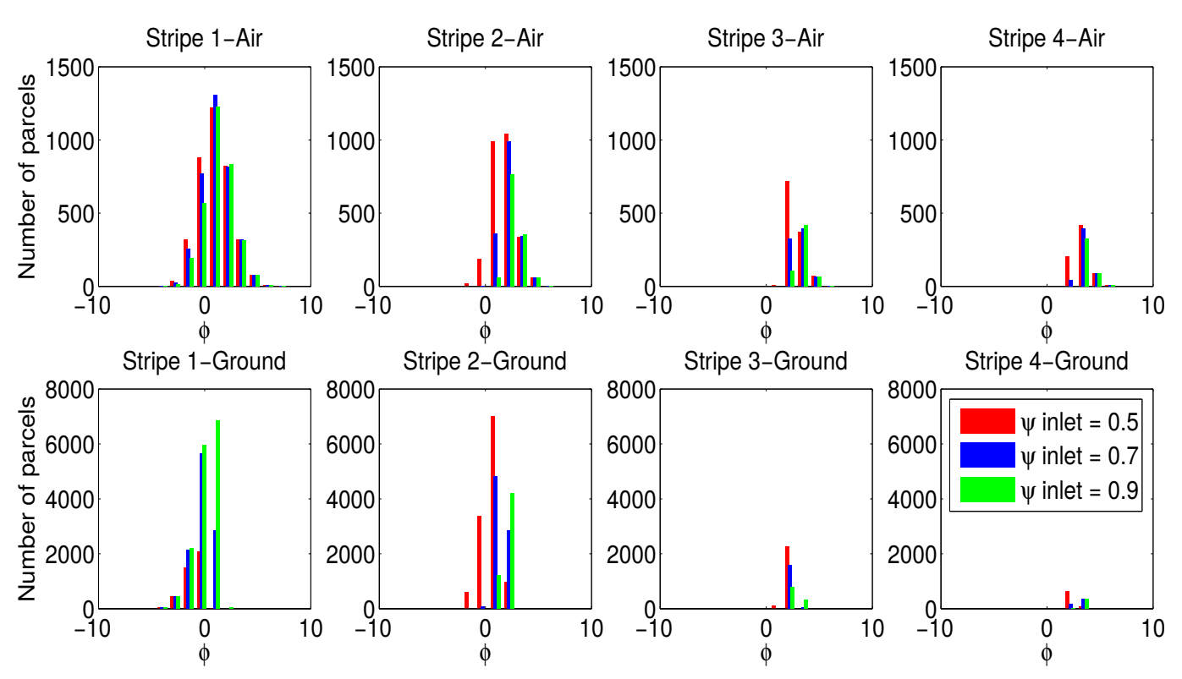


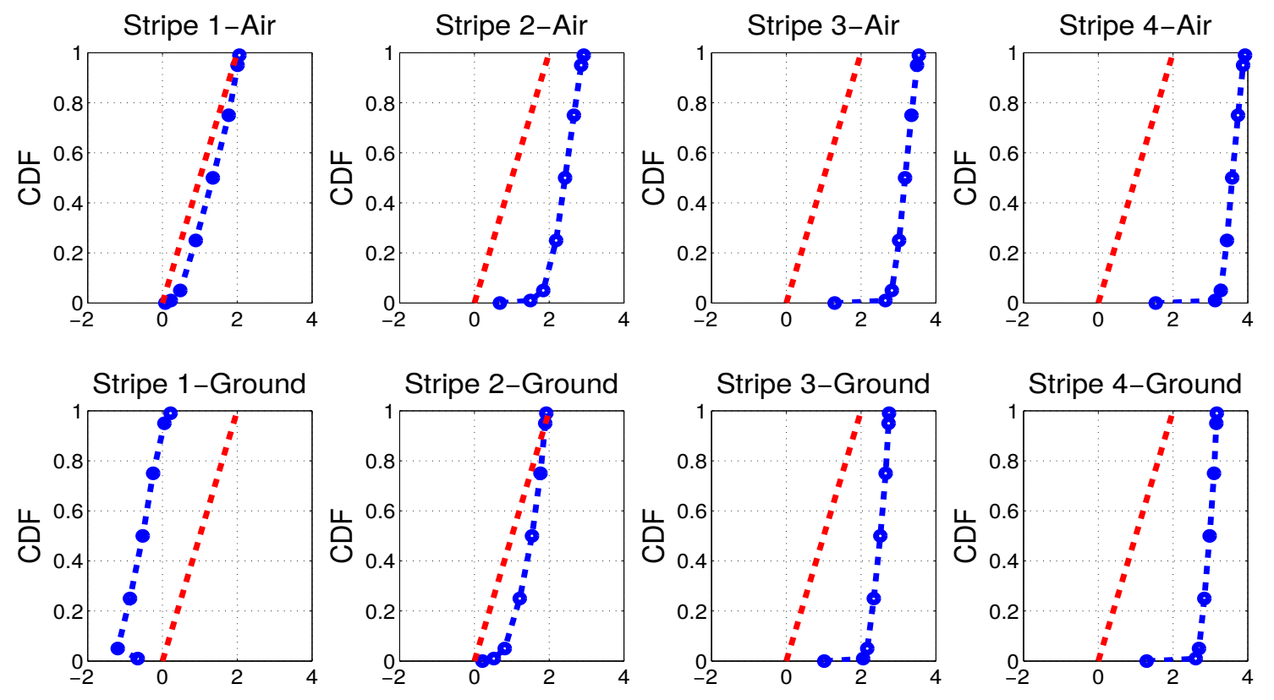
Figure 6 (top-left). *Effect of varying the mean of the distribution only in the interval [0;2]. The standard deviation and the sphericity of particles are kept constant.*

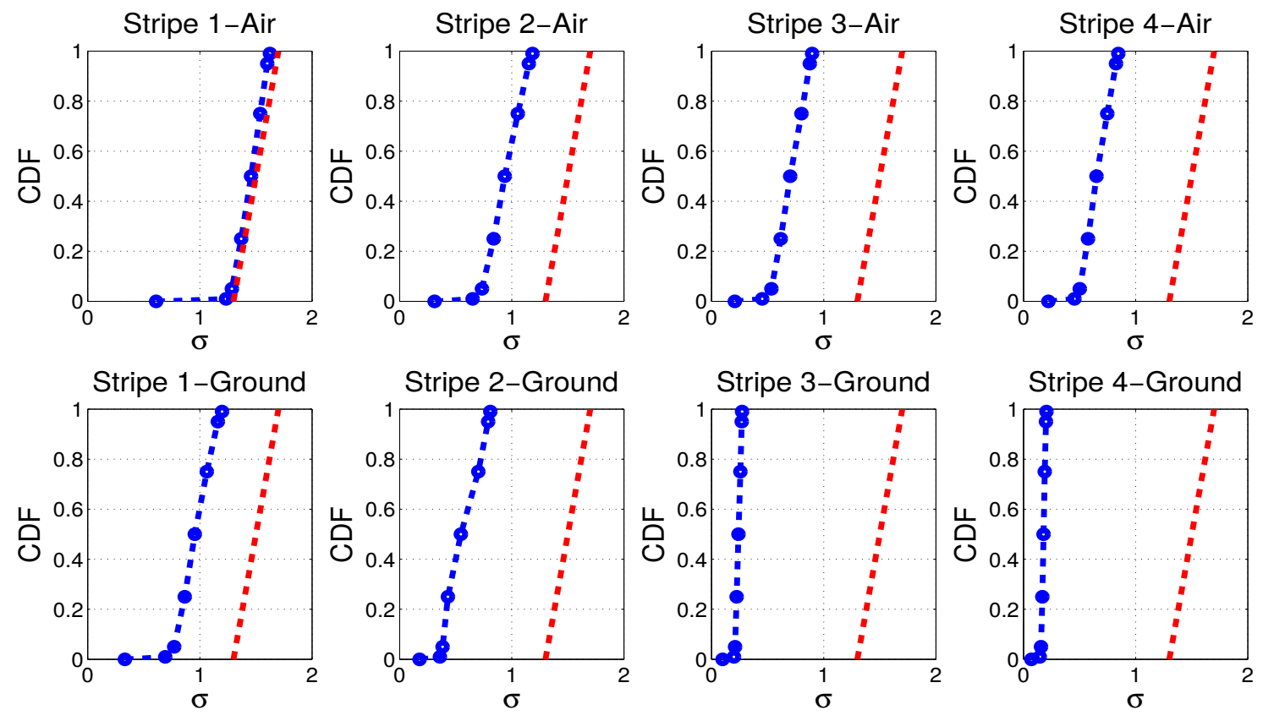
Figure 7 (top-right). *Effect of varying the standard deviation of the distribution in the interval [1.3;1.7]. The mean and standard deviation of the initial distribution are kept constant.*

Figure 8 (bottom-left). *Effect of varying the sphericity of the particles only in the interval [0.5;0.9]. The mean value and standard deviation of the particles size distribution are kept constant.*

6. Uncertainty quantification analysis

The DAKOTA toolkit from Sandia National Labs has been adopted to perform uncertainty quantification (UQ) and sensitivty analysis. In the present work we have chosen to adopt as UQ technique the so-called Generalized Polynomial Chaos Expansion, which is included within the class of Stochastic Expansion Method. The term "Chaos" simply refers to the uncertainty in the input, while the term "Polynomial" is used because propagation of uncertainties in the outputs is described by reconstructing the output of the model as polynomials. The first step is to model the input variables through appropriate probability distributions: here we assumed a uniform distribution of the uncertain input parameters (see Figure 4). The choice of these distributions affects the basis used for the polynomial reconstruction of the ouput of the model (response functions). In this case Legendre polynomials have been used as the basis for the expansion and an order 7 for the polynomials reconstructed has provided a good compromize between accuracy and computational cost. The coefficients of the elements of the basis have been computed through appropriate quadrature formulas, requiring 343 simulations and 1.5 hours on 46 CPUs. Once the expansion coefficients have been calculated, the polynomials have been used as emulators of the reponse functions and several statistics were evaluated numerically. In particular 10000 samples have been evaluated on the expansion to compute the cumulative distribution functions of the probabilities of the parameters describing the grain size distributions in the four stripes, in the atmosphere and on the ground. 7 cumulative probability levels (0.01, 0.05, 0.25, 0.5, 0.75, 0.95, 0.99) have been fixed and mapped into the corresponding response levels and the results are plotted in Figure 9. In addition, in Table 1 other statistical parameters related to the uncertainty in the grain size distributions in the atmosphere and on the gorund are reported.





Response function t=10800s: μ				
	Stripe 1 air	**Stripe 2 air**	**Stripe 3 air**	**Stripe 4 air**
Mean	1.12	2.27	3.08	3.51
Mode	0.89	2.42	3.17	3.58
	Stripe 1 ground	**Stripe 2 ground**	**Stripe 3 ground**	**Stripe 4 ground**
Mean	-0.39	1.33	2.41	2.90
Mode	-0.25	1.76	2.65	3.09
Response function t=10800s: σ				
	Stripe 1 air	**Stripe 2 air**	**Stripe 3 air**	**Stripe 4 air**
Mean	1.41	0.89	0.66	0.61
Mode	1.45	0.83	0.61	0.57
	Stripe 1 ground	**Stripe 2 ground**	**Stripe 3 ground**	**Stripe 4 ground**
Mean	0.91	0.51	0.23	0.17
Mode	0.86	0.70	0.22	0.16
Response function t=10800s: Number of parcels				
	Stripe 1 air	**Stripe 2 air**	**Stripe 3 air**	**Stripe 4 air**
Mean	3517	1843	907	593
Mode	3613	1554	380	229
	Stripe 1 ground	**Stripe 2 ground**	**Stripe 3 ground**	**Stripe 4 ground**
Mean	10693	7693	1689	525
Mode	8606	6831	1396	237

Figure 9 (left-top). *Cumulative distribution functions of the mean of the grain size distributions computed in every stripe. The red curve of each plot represents the initial distribution of the released particles.*

Figure 10 (left-bottom). *Cumulative distribution functions of the standard deviation of the grain size distibution. The red curve of each plot represents the initial distribution of the released particles.*

Table 1. *Mean and the most probable values of μ and σ and number of parcels present in the four stripes (in air and on the ground) three hours after the beginning of the release in the atmosphere.*

7. Sensitivity Analysis

A variance-based sensitivity analysis was also performed to quantify the global sensitivity indices of the response functions to the uncertain input parameters. 10,000 samples have been evaluated using the polynomial expansions to compute the Sobol indices, representing how much of the variability of an output can be apportioned to the variability prescribed to the input parameters. The sensitivity analysis shows that the variability of the sphericity of particles, controlling the drag and consequently the settling velocity of the particles, exerts a major role in determining the range of grain-size distribution parameters of the particles deposited on the ground in the four stripes, whereas the variability of the parameters of the grain-size distributions in the atmosphere are mainly controlled by variability of the the mean value and sphericity of the initial distribution.

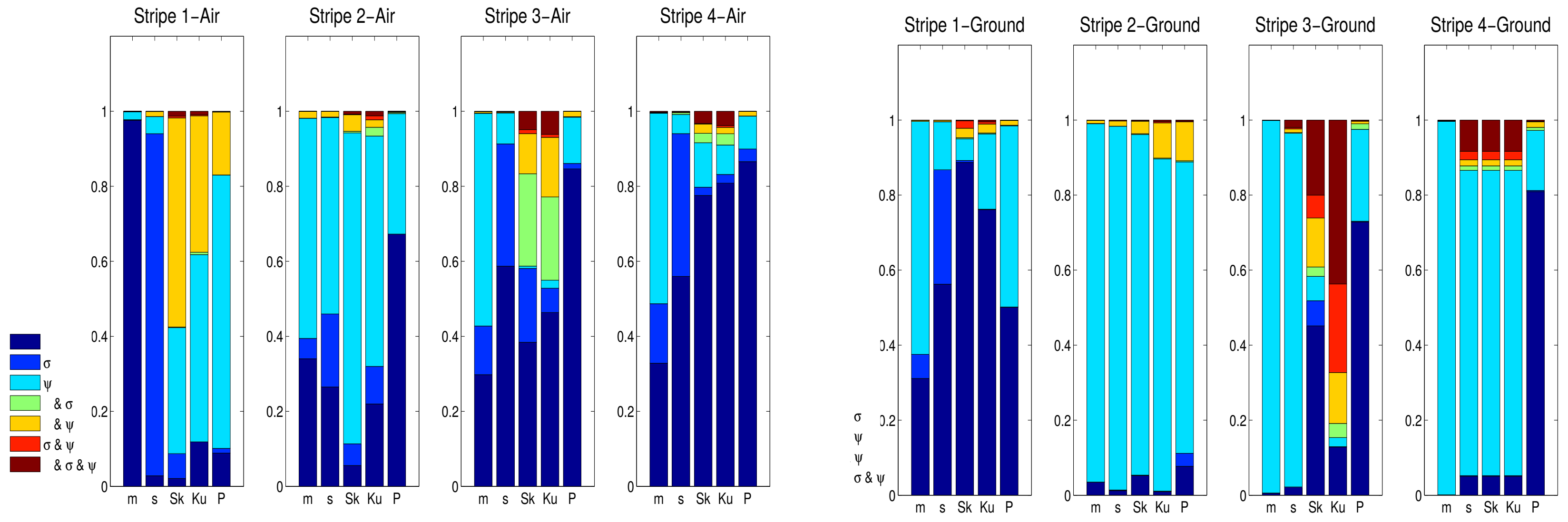


Figure 11. *Sobol Indices for the parameters characterizing the grain size distribution of the particles in the four stripes in the air (left) and on the ground (rigth).*

8. Conclusions

An uncertainty quantification and a sensitivity analysis were performed for the dispersion of ash particles in the atmosphere by using a Lagrangian particle model coupled with a mesoscale non-hydrostatic model and adopting a PCE technique. The analysis shows that, for the weak plume event considered, the grain-size distribution, on the ground and in the atmosphere, strongly depend on the distance from the source. Furthermore, grain-size distributions in the atmosphere and deposited on the ground significantly differ even at the same distance from source. Uncertainty ranges of the mean and standard deviation of the grain-size distribution strongly reduce with distance from source and the values can be significantly different from those at the release. Based on sensitivity analysis, the sphericity of particles largely controls the mean and standard deviation of the deposited particles and significantly affects the grain-size distribution in the atmosphere, at given distance from source.

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