2nd IUGG-WMO Workshop on Ash Dispersal Forecast and Civil Aviation

Geneva, Switzerland, 18-20 November 2013

Model Definition Document

Introduction

Volcanic Ash Transport and Dispersion Models (VATDM) can be based on different formulations (Eulerian, Lagrangian or Hybrid). In addition, different models might use different parameterizations of different physical processes (e.g., source term, diffusion, sedimentation) and might be designed for specific applications (e.g., local to global coverage). As a result, a critical analysis of individual VATDM is necessary in order to carry out rigorous and robust ash dispersal modelling (reconstruction of past events, forecasting, hazard assessments).

This document updates the model document compiled during the 1st IUGG-WMO workshop on Ash Dispersal Forecast and Civil Aviation (Geneva, 18-20 November 2010) and summarizes main characteristics of most operational and non-operational VATDM currently used (Table 1). Appendices 1 to 14 describe each individual model in detail.

Appendix 1:	ASH3D
Appendix 2:	ATHAM
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Appendix 13:	WRF-Chem
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	ASH3D	ATHAM	FALL3D	FLEXPART	HYSPLIT	JMA-GATM JMA-RATM	MLDP0	MOCAGE	NAME	PUFF	TEPHRA2	VOL-CALPUFF
Operational												
Approach (1)	E/H	E	E	L	H	L	L	E	LH	L	E	H
Method (2)	N	N	N	N	N	N	N	N	N	N	A	S
Coverage (3)	LRG	L	LR	LRG	LRG	RG	LRG	G	LRG	LRG	L	LR
Physics												
Topography												
H wind advection												
V wind advection												
H atm. diffusion								See (5)				
V atm. diffusion												
Particle sed.												
Other dry dep.												
Wet deposition												
Dry part. aggr.												
Wet part. aggr.												
Variable part. shape												
Gas species												
Chemic. processes												
Granulometry												
Variable size class.												
Variable GS distr.												
Variable size limits												
Source term												
Mass distribution(4)	PS/U/ LN	O	ALL	PS/L/U/P /O	PS/L/U/P /LN	PS/L/LN	PS/L/U/ P/O	PS/L	PS/L/U/ BP/O	PS/L/ U/P/O	L/U/LN/O	PS/BP

(1) L=Lagrangian, E=Eulerian, H=Hybrid
(2) A=Analytical, S=Semi-analytical, N=Numerical
(3) L=Local, R=Regional, G=Global
(4) PS=Point Source, L=Linear, U=Umbrella-type, P=Poisson, LN=Log-normal, BP=Buoyant Plume, O= Other (see Appendix).
(5) Neglected. Diffusion of numerical origin appears to be sufficient, with particularly good results at 0.5°.

Table 1. Main characteristics of VATDM

1. Model overview

Model Name	**Ash3d**	
Approach		Tick
	Eulerian	x
	Lagrangian	
	Hybrid	
Method		Tick
	Analytical (e.g. Gaussian)	
	Semi-analytical	
	Numerical	x
Model coverage		Tick
	Local (order of 100s of km)	x
	Regional (order of 1000s of km)	x
	Global (globe coverage, periodicity)	x

	YES	NO
Is the horizontal spatial resolution fixed?		x
Is the vertical spatial resolution fixed?		x
Is it operational for forecast at some Institution/VAAC/VO?		x

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	x	
Horizontal wind advection	x	
Vertical wind advection	x	
Horizontal atmospheric diffusion	x	
Vertical atmospheric diffusion	x	
Particle sedimentation	x	
Other dry deposition mechanisms		
Wet deposition (wet removal)	x	currently only in research mode
Dry particle aggregation		
Wet particle aggregation		
Particle shape	x	
Dispersal of different gas species		
Chemical processes		
Others		

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		x	
Is the granulometric distribution arbitrary?	x		
Is there an upper/lower limit on the particle size?		x	

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling	x	

	YES	NO
Is the model linked to a particular NWP model?		x
Is there some pre-process interface for NWP data interpolation?	x	

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
1) 1-D wind soundings 2) NOAA North American Model Grid 221 3) NOAA North American Models: Grid 216 (Alaska 45 km) 4) NOAA North American Model Grid 105 (polar, 90 km resolution) 5) NOAA North American Model grid 212 (Conus 40 km resolution) 6) NOAA North American Model grid 218 (Conus 12 km resolution) 7) NOAA North American Model grid 242 (Alaska 11 km resolution) 8) NOAA Global Forecast System 0.5 degree model (global) 9) ECMWF model (0.25 degree resolution) 10) NOAA/NCEP 50-year Reanalysis 1 model (2.5 degree resolution) 11) NASA MERRA model (global, 1.25 degree resolution)

Please specify the meteorological variables required:
vx, vy, pressure velocity (vz), geopotential height, temperature

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source	x	
Uniform (linear) vertical distribution	x	
Umbrella-type (top-hat)		
Poisson distribution		
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)	x	
Buoyant plume theory		
Others		

	YES	NO
Can transient columns be described?	x	
Can data (e.g. from satellite retrievals) be assimilated as an “initial” source term condition?		x

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	x	
Tephra deposit thickness	x	
Airborne concentration	x	
Airborne concentration profiles (e.g. at a given height or flight level)		
Vertical concentration profiles	x	
Aerosol optical depth		
Aerosol (gas) concentration		
Cloud mass	x	
Cloud area/volume		
Concentration at ground level		
Others	x	Ash arrival times at airports

Please specify the model output format

	Tick	Comments
ASCII	x	
Binary (exclusive of the model)	x	
netCDF	x	
Grib1		
Grib2		
Graphic format (e.g, eps, gif)	x	
Others	x	Kml format

7. Computational characteristics

Programming language	Fortran 95	
Operating system	Linux	
	YES	NO
Does a parallel version of the code exist?		x
Is it an open source/public code? (eventually, yes)		
External library packages:		
Lapack, NetCDF		

8. Others

References
Denlinger R, Webley P, Mastin LG, Schwaiger H (2013) A Bayesian Method to Rank Different Model Forecasts of the Same Volcanic Ash Cloud. In: Lin J, Brunner D, Gerbig C, Stohl A, Luhar A, Webley P (eds) Lagrangian Modeling of the Atmosphere. Geopress, Washington D.C., pp 299-310
Denlinger RP, Pavolonis M, Sieglaff J (2012) A robust method to forecast volcanic ash clouds. J.

Geophys. Res. 117(D13):D13208
Denlinger RP, Webley P, Mastin LG, Schwaiger H (2013) A Bayesian Method to Rank Different Model Forecasts of the Same Volcanic Ash Cloud. In: Lagrangian Modeling of the Atmosphere. American Geophysical Union, pp 299-310
Mastin LG, Randall M, J., Schwaiger H, Denlinger R (2013) User's Guide and Reference to Ash3d: A Three-Dimensional Model for Atmospheric Tephra Transport and Deposition. U.S. Geological Survey Open-File Report 2013-1122, 48 Pages
Mastin LG, Schwaiger H, Schneider DJ, Wallace KL, Schaefer J, Denlinger RP (2013) Injection, transport, and deposition of tephra during event 5 at Redoubt Volcano, 23 March, 2009. J. Volcanol. Geotherm. Res. 259:201-213
Schwaiger H, Denlinger R, Mastin LG (2012) Ash3d: a finite-volume, conservative numerical model for ash transport and tephra deposition. J. Geophys. Res. 117:B04204

Other comments

1. Model overview

Model Name	**ATHAM**	
Approach		Tick
	Eulerian	✓
	Lagrangian	
	Hybrid	
Method		Tick
	Analytical (e.g. Gaussian)	
	Semi-analytical	
	Numerical	✓
Model coverage		Tick
	Local (order of 100s of km)	✓
	Regional (order of 1000s of km)	
	Global (globe coverage, periodicity)	

	YES	NO
Is the horizontal spatial resolution fixed?		✓
Is the vertical spatial resolution fixed?		✓
Is it operational for forecast at some Institution/VAAC/VO?		✓

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	✓	
Horizontal wind advection	✓	
Vertical wind advection	✓	
Horizontal atmospheric diffusion	✓	
Vertical atmospheric diffusion	✓	
Particle sedimentation	✓	
Other dry deposition mechanisms		
Wet deposition (wet removal)	✓	part of the (currently not supported) wet aggregation scheme
Dry particle aggregation		
Wet particle aggregation	✓	currently not supported in most recent version
Particle shape		
Dispersal of different gas species	✓	
Chemical processes		
Others	✓	Scavenging of volcanic gases by hydrometeors; currently not supported in most recent version

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		✓	
Is the granulometric distribution arbitrary?		✓	
Is there an upper/lower limit on the particle size?		✓	No hard limit, however, the assumptions of a dynamical and thermodynamical equilibrium start to break down for particles larger than a few millimetres.

4. Meteorological data

	Tick	Comments
On-line coupling	✓	Starting from initial conditions the model predicts all meteorological fields.
Off-line coupling		

	YES	NO
Is the model linked to a particular NWP model?		✓
Is there some pre-process interface for NWP data interpolation?		✓

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:

Please specify the meteorological variables required:
Only initial vertical profiles for temperature, humidity and horizontal wind are required. The model is initialised horizontally homogeneously assuming an initial hydrostatic balance.

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source		
Uniform (linear) vertical distribution		
Umbrella-type (top-hat)		
Poisson distribution		
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		
Buoyant plume theory		

Others	✓	Atham simulates the eruption column and plume based on a prescribed volcanic forcing at the lower boundary (vent).

	YES	NO
Can transient columns be described?	✓	
Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition?		✓

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	✓	
Tephra deposit thickness	✓	
Airborne concentration	✓	
Airborne concentration profiles (e.g. at a given height or flight level)	✓	
Vertical concentration profiles	✓	
Aerosol optical depth		
Aerosol (gas) concentration	✓	
Cloud mass	✓	
Cloud area/volume	✓	
Concentration at ground level	✓	
Others		

Please specify the model output format

	Tick	Comments
ASCII		
Binary (exclusive of the model)	✓	optional
netCDF	✓	optional
Grib1		
Grib2		
Graphic format (e.g, eps, gif)		
Others		

7. Computational characteristics

Programming language	Fortran 90		
Operating system	linux		
		YES	NO

Does a parallel version of the code exist?	✓	
Is it an open source/public code? The code is available through collaboration.	✓	✓
External library packages:		

8. Others

References
Montopoli M., D. Cimini, M. Lamantea, M. Herzog, H.-F. Graf, and F.S. Marzano (2013): Microwave radiometric remote sensing of volcanic ash clouds from space: model and data analysis, IEEE Transactions on Geoscience and Remote Sensing, 13(9), 4678-4691, doi: 10.1109/TGRS.2013.2260343. Van Eaton A.R., M. Herzog, C.J.N Wilson, and J. McGregor (2012): Dynamics of large-scale 'wet' eruptions: Microphysical controls on ascent of phreatoplinian ash clouds using a case study from the 27 ka Oruanui eruption of Taupo volcano, New Zealand, Journal of Geophysical Research, Solid Earth, 117, B03203, doi:10.1029/2011JB008892. Herzog, M. and H.-F. Graf (2010): Applying the three-dimensional model ATHAM to volcanic plumes: Dynamic of large co-ignimbrite eruptions and associated injection heights for volcanic gases, Geophys. Res. Lett., 37, L19807, doi:10.1029/2010GL044986. Tupper A., C. Textor, M. Herzog, H.-F. Graf, and M. S. Richards (2009): Tall clouds from small eruptions: the sensitivity of eruption height and fine ash content to tropospheric instability, Nat. Hazards, 51, pp. 375-401, doi 10.1007/11069-009-9433-9. Textor C., H. F. Graf, M. Herzog, J. M. Oberhuber, W. I. Rose, G. G. J. Ernst (2006): Volcanic Particle Aggregation in Explosive Eruption Columns. Part I: Parameterization of the Microphysics of Hydrometeors and Ash. J. Volcanl. Geotherm. Res., Vol. 150, pp. 359-377. Textor C., H. F. Graf, M. Herzog, J. M. Oberhuber, W. I. Rose, G. G. J. Ernst (2006): Volcanic Particle Aggregation in Explosive Eruption Columns. Part II: Numerical Experiments. J. Volcanl. Geotherm. Res., Vol. 150, pp. 378-394. Herzog M., J. M. Oberhuber, Hans-F. Graf (2003): A Prognostic Turbulence Scheme for the Non-hydrostatic Plume Model ATHAM. J. Atmos. Sci. 60(22), pp. 2783-2796. Textor C., H.-F. Graf, M. Herzog (2003): Injection of Gases into the Stratosphere by Explosive Volcanic Eruptions. J. Geophys. Res. 108(D19): 4606, doi: 10.1029/2002JD002987. Graf, H.-F., M. Herzog, J. M. Oberhuber (1999): The Effect of Environmental Conditions on Volcanic Plume Rise. J. Geophys. Res., Vol. 104, pp. 24,309-24,320. Herzog M., H.-F. Graf, C. Textor, J. M. Oberhuber (1998): The effect of Phase Changes of Water on the Development of Volcanic Plumes. J. Volcanl. Geotherm. Res., Vol. 87, pp. 29-53. Oberhuber, J. M., M. Herzog, H.-F. Graf, K. Schwanke (1998): Volcanic Plume Simulation on Large Scales. J. Volcanl. Geotherm. Res., Vol. 87, pp. 55-74.
Other comments

1. Model overview

Model Name	**FALL3D**	
Model Approach		Tick
	Analytical (Gaussian)	
	Numerical (Eulerian)	✔
	Numerical (Lagrangian)	
	Numerical (Hybrid)	
	Other	
Model coverage		Tick
	Local (order of 100s of km)	✔
	Regional (order of 1000s of km)	✔
	Global (globe coverage, periodicity)	

	YES	NO
Is the horizontal spatial resolution fixed?		✔
Is the vertical spatial resolution fixed?		✔
Is it operational for forecast at some Institution/VAAC/VO?	✔	

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	✔	
Horizontal wind advection	✔	
Vertical wind advection	✔	
Horizontal atmospheric diffusion	✔	
Vertical atmospheric diffusion	✔	
Particle sedimentation	✔	Different experimental laws available
Other dry deposition mechanisms	✔	Dry deposition mechanism different form sedimentation velocity only for particles smaller than 100 μm (below the limit of the aerosol giant mode) and in the first layer See: J.Feng, A size-resolved model and a four-mode parameterization of dry deposition of atmospheric aerosols, JGR, v113, 2008.
Wet deposition (wet removal)	✔	
Dry particle aggregation		
Wet particle aggregation	✔	(Under test).
Particle shape	✔	
Dispersal of different gas species	✔	Gas species are approached as particles with no settling velocity
Chemical processes		
Others	✔	Volcanic ash resuspension

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		✓	
Is the granulometric distribution arbitrary?	✓		A utility is given to generate Gaussian and bi-Gaussian (bi-modal) distributions
Is there an upper/lower limit on the particle size?		✓	Not recommended above 32-64 mm and below 1 μm

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling	✓	

	YES	NO
Is the model linked to a particular NWP model?		✓
Is there some pre-process interface for NWP data interpolation?	✓	

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
ECMWF re-analyses, NCEP-NCAR re-analyses, ETA, WRF-ARW, GFS (0.5º and 1º), ARPA-SIM, NMM-b, NCEP/NCAR re-analysis (2.5º and 1º), CALMET, vertical profile (e.g. from sounding).

Please specify the meteorological variables required:
2D: Land use (optional), Planetary Boundary Layer height (optional), Friction velocity u* , Monin-Obukhov length, precipitation rate (for wet deposition) 3D: wind velocity, temperature, air density, and potential temperature and specific humidity if wet aggregation is considered.

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source	✓	
Uniform (linear) vertical distribution		
Umbrella-type (top-hat)		
Poisson distribution		
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)	✓	

Buoyant plume theory	✓	
Others		

	YES	NO
Can transient columns be described?	✓	
Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition?		✓

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	✓	
Tephra deposit thickness	✓	
Airborne concentration	✓	
Airborne concentration profiles (e.g. at a given height or flight level)	✓	
Vertical concentration profiles	✓	
Aerosol optical depth	✓	
Aerosol (gas) concentration	✓	
Cloud mass		
Cloud area/volume		
Concentration at ground level	✓	
Others	✓	PMx at surfece

Please specify the model output format

	Tick	Comments
ASCII		
Binary (exclusive of the model)		
netCDF	✓	
Grib1		
Grib2		
Graphic format (e.g, eps, gif)	✓	
Others	✓	GRD format optional

7. Computational characteristics

Programming language	FORTRAN 90	
Operating system	UNIX/LINUX	
	YES	NO
Does a parallel version of the code exist?	✓	
Is it an open source/public code?	✓	
External library packages:		

netCDF

8. Others

References

Costa, A., G. Macedonio, A. Folch (2006). A three-dimensional Eulerian model for transport and deposition of volcanic ashes. Earth Planet. Sci. Lett., 241 (3-4), 634-647.

Folch A., O. Jorba, J. Viramonte (2008). Volcanic ash forecast – application to the May 2008 Chaitén eruption, Nat. Hazards Earth Syst. Sci., 8, 927-940.

Scollo, S., A. Folch, A. Costa (2008). A parametric and comparative study of different tephra fallout models,Journal of Volcanology and Geothermal Research, 176, 199–211.

Folch A., C. Cavazzoni, A. Costa, G. Macedonio (2008). An automatic procedure to forecast tephra fallout, Journal of Volcanology and Geothermal Research 177, 767–777.

Macedonio G., A. Costa, A. Folch (2008). Ash fallout scenarios at Vesuvius: Numerical simulations and implications for hazard assessment, Journal of Volcanology and Geothermal Research, 178, 366–377.

Folch A., A. Costa, G. Macedonio (2009). FALL3D: A Computational Model for Volcanic Ash Transport and Deposition, Computer and Geosciences, doi:10.1016/j.cageo.2008.08.008.

Costa A., A. Folch, G. Macedonio (2010). A Model for Wet Aggregation of Ash Particles in Volcanic Plumes and Clouds: I. Theoretical Formulation, J. Geophys. Res., doi:10.1029/2009JB007175.

Folch A.,A. Costa, A. Durant,G. Macedonio (2010). A Model for Wet Aggregation of Ash Particles in Volcanic Plumes and Clouds: II. Model Application, J. Geophys. Res., doi:10.1029/2009JB007176.

Other comments

See http://bsccase02.bsc.es/projects/fall3d/

1. Model overview

Model Name	**FLEXPART**	
Approach		Tick
	Eulerian	
	Lagrangian	X
	Hybrid	
Method		Tick
	Analytical (e.g. Gaussian)	
	Semi-analytical	
	Numerical	X
Model coverage		Tick
	Local (order of 100s of km)	X
	Regional (order of 1000s of km)	X
	Global (globe coverage, periodicity)	X

	YES	NO
Is the horizontal spatial resolution fixed?		X
Is the vertical spatial resolution fixed?		X
Is it operational for forecast at some Institution/VAAC/VO?	X	

Operational at least at CTBTO and Central Institute for Meteorology, Austria. At the latter also for ash forecasting during Eyjafjallajökull.

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	X	
Horizontal wind advection	X	
Vertical wind advection	X	
Horizontal atmospheric diffusion	X	
Vertical atmospheric diffusion	X	
Particle sedimentation	X	
Other dry deposition mechanisms	X	
Wet deposition (wet removal)	X	
Dry particle aggregation		
Wet particle aggregation		
Particle shape		
Dispersal of different gas species	X	
Chemical processes	X	Only SO2 reaction with OH radical
Others	X	Convection

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		X	
Is the granulometric distribution arbitrary?		X	

Is there an upper/lower limit on the particle size?		X	

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling	X	

	YES	NO
Is the model linked to a particular NWP model?		X
Is there some pre-process interface for NWP data interpolation?		X

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
ECMWF re-analysis (1°×1° horizontal resolution, 91 vertical levels) GFS (0.5°×0.5° horizontal resolution at 26 pressure levels) Different versions exist also for MM5, WRF, etc., but are not used at our institute

Please specify the meteorological variables required:
2D: many 3D: horizontal and vertical wind components, temperature and specific humidity.

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source	X	
Uniform (linear) vertical distribution	X	
Umbrella-type (top-hat)	X	
Poisson distribution	X	
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		
Buoyant plume theory		
Others	X	Detailed vertical ash emission distribution, e.g., from inverse modelling

	YES	NO
Can transient columns be described?	X	

Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition? *Not operational but was done in case studies in the past*	X	

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	X	
Tephra deposit thickness		Should be simple to calculate from the above
Airborne concentration	X	
Airborne concentration profiles (e.g. at a given height or flight level)	X	
Vertical concentration profiles	X	
Aerosol optical depth		
Aerosol (gas) concentration	X	
Cloud mass	X	
Cloud area/volume		Not clear how that would be defined
Concentration at ground level	X	
Others		

Please specify the model output format

	Tick	Comments
ASCII		
Binary (exclusive of the model)	X	
netCDF		
Grib1		
Grib2		
Graphic format (e.g, eps, gif)		
Others		

7. Computational characteristics

Programming language	Fortran	
Operating system	UNIX/LINUX	
	YES	NO
Does a parallel version of the code exist?		X
Is it an open source/public code?	X	
External library packages:		
GRIB decoding library		

8. Others

References
Stohl, A., M. Hittenberger, and G. Wotawa (1998): Validation of the Lagrangian particle dispersion model FLEXPART against large scale tracer experiments. Atmos. Environ. 32, 4245-4264. Stohl, A., and D. J. Thomson (1999): A density correction for Lagrangian particle dispersion models. Bound.-Layer Met. 90, 155-167. Stohl, A., C. Forster, A. Frank, P. Seibert, and G. Wotawa (2005): Technical Note : The Lagrangian particle dispersion model FLEXPART version 6.2. Atmos. Chem. Phys. 5, 2461-2474. Eckhardt, S., A. J. Prata, P. Seibert, K. Stebel, and A. Stohl (2008): Estimation of the vertical profile of sulfur dioxide injection into the atmosphere by a volcanic eruption using satellite column measurements and inverse transport modeling. Atmos. Chem. Phys. 8, 3881-3897. Stohl, A., A. J. Prata, S. Eckhardt, L. Clarisse, A. Durant, S. Henne, N. I. Kristiansen, A. Minikin, U. Schumann, P. Seibert, K. Stebel, H. E. Thomas, T. Thorsteinsson, K. Tørseth, and B. Weinzierl (2011) Determination of time- and height-resolved volcanic ash emissions for quantitative ash dispersion modeling: The 2010 Eyjafjallajokull eruption, Atmos. Chem. Phys., 11, 4333-4351, doi:10.5194/acp-11-4333-2011. Kristiansen, N. I., A. Stohl, F. Prata, N. Bukowiecki, H. Dacre, S. Eckhardt, S. Henne, M. Hort, B. Johnson, F. Marenco, B.Neininger, O. Reitebuch, P. Seibert, D. Thomson, H. Webster, B. Weinzierl (2012) Performance assessment of a volcanic ash transport model mini-ensemble used for inverse modelling of the 2010 Eyjafjallajökull eruption, J. Geophys. Res., 117, D00U11, doi:10.1029/2011JD016844
Other comments
See http://transport.nilu.no/flexpart/

1. Model overview

Model Name	**HYSPLIT**	
Approach		Tick
	Eulerian	
	Lagrangian	
	Hybrid	x
Method		Tick
	Analytical (e.g. Gaussian)	
	Semi-analytical	
	Numerical	x
Model coverage		Tick
	Local (order of 100s of km)	x
	Regional (order of 1000s of km)	x
	Global (globe coverage, periodicity)	x

	YES	NO
Is the horizontal spatial resolution fixed?		X
Is the vertical spatial resolution fixed?		X
Is it operational for forecast at some Institution/VAAC/VO?	X	

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	X	Resolution of meteorology model
Horizontal wind advection	X	
Vertical wind advection	X	
Horizontal atmospheric diffusion	X	
Vertical atmospheric diffusion	X	
Particle sedimentation	X	
Other dry deposition mechanisms	X	
Wet deposition (wet removal)	X	
Dry particle aggregation		
Wet particle aggregation		
Particle shape	X	Fixed for VAAC simulation
Dispersal of different gas species	X	VAAC simulation only with particles
Chemical processes	X	VAAC assumes no transformation
Others		

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		X	Fixed for VAAC simulation
Is the granulometric distribution arbitrary?		X	Fixed for VAAC simulation
Is there an upper/lower limit on the particle size?	X		~ 100 μm

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling	x	

	YES	NO
Is the model linked to a particular NWP model?		X
Is there some pre-process interface for NWP data interpolation?	X	

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
(assume input rather than assimilate) NCEP GFS, NAM, RAP, Regional Re-analysis, NOAA/GSD HRRR, ECMWF, NCEP/NCAR Reanalysis, and others if they can be formatted to the HYSPLIT/ARL-meteorology-format (basic grib-to-hysplit-format converter program included in HYSPLIT system)

Please specify the meteorological variables required:
Minimum requirement: 3-dimensional winds, temperature, humidity either on pressure, sigma, or hybrid surfaces; surface pressure, 10-m winds, 2-m temperature, precipitation

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source	X	
Uniform (linear) vertical distribution	X	Only this at VAAC
Umbrella-type (top-hat)	X	
Poisson distribution	X	Approximated
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)	X	Approximated
Buoyant plume theory		
Others	X	User-specified

	YES	NO
Can transient columns be described?	x	
Can data (e.g. from satellite retrievals) be assimilated as an “initial” source term condition?	X, qualitatively	X, quantitatively

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	X	given appropriate GSD, VAAC does not output this
Tephra deposit thickness	X	given appropriate GSD, VAAC does not output this
Airborne concentration	X	with respect to unit source at VAAC
Airborne concentration profiles (e.g. at a given height or flight level)	X	Concentration in layers (fixed layers at VAAC)
Vertical concentration profiles		
Aerosol optical depth		
Aerosol (gas) concentration		
Cloud mass		
Cloud area/volume		
Concentration at ground level	X	not at VAAC
Others	X X	Particle positions Mass loading (not at VAAC)

Please specify the model output format

	Tick	Comments
ASCII	X	
Binary (exclusive of the model)	X	
netCDF		
Grib1	X	
Grib2		
Graphic format (e.g, eps, gif)	X	ps, gif at VAAC ; GIS shapefile, Google Earth not at VAAC
Others		

7. Computational characteristics

Programming language	FORTRAN90	
Operating system	UNIX/Linux, PC, Apple,	
	YES	NO
Does a parallel version of the code exist?	X	
Is it an open source/public code?	X	
External library packages:		
only to convert output to grib1 (NCEP w3 lib)		

8. Others

References
Draxler, R.R., and G.D. Hess, 1997: Description of the HYSPLIT_4 modeling system. NOAA Tech. Memo. ERL ARL-224, NOAA Air Resources Laboratory, Silver Spring, MD, 24 pp. Draxler, R.R., and G.D. Hess, 1998: An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition. Aust. Meteor. Mag., 47, 295-308. Draxler, R.R., 1999: HYSPLIT4 user's guide. NOAA Tech. Memo. ERL ARL-230, NOAA Air Resources Laboratory, Silver Spring, MD. Barbara J.B. Stunder, Jerome L. Heffter, Roland R. Draxler, 2007, Airborne Volcanic Ash Forecast Area Reliability, Weather and Forecasting, 22:1132-1139
Other comments
The model is designed to support a wide range of simulations related to the atmospheric transport and dispersion of pollutants and hazardous materials, as well as the deposition of these materials (such as mercury) to the Earth's surface. Some of the applications include tracking and forecasting the release of radioactive material, volcanic ash, wildfire smoke, dust, and pollutants from various stationary and mobile emission sources. HYSPLIT can be run interactively on ARL's READY (Real-time Environmental Applications and Display sYstem, http://ready.arl.noaa.gov/) web site, or it can be installed on a PC and run using a graphical user interface. Meteorological offset ensemble and associated post-processing programs are included with the HYSPLIT system.

1. Model overview

Model Name	**JMA Global Atmospheric Transport Model (JMA-GATM)**		
Model Approach		Tick	
	Analytical (Gaussian)		
	Numerical (Eulerian)		
	Numerical (Lagrangian)		
	Numerical (Hybrid)		
	Other		
Model coverage		Tick	
	Local (order of 100s of km)		
	Regional (order of 1000s of km)		
	Global (globe coverage, periodicity)		
		YES	NO
Is the horizontal spatial resolution fixed?			
Is the vertical spatial resolution fixed?			
Is it operational for forecast at some Institution/VAAC/VO?			

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography		depend on NWP model
Horizontal wind advection		
Vertical wind advection		
Horizontal atmospheric diffusion		
Vertical atmospheric diffusion		
Particle sedimentation		as dry deposition
Other dry deposition mechanisms		
Wet deposition (wet removal)		only washout, not rainout
Dry particle aggregation		
Wet particle aggregation		
Particle shape		considered in the settling velocity
Dispersal of different gas species		
Chemical processes		
Others		radioactive decay

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?	✓		under development, tracer mass allocation with 80 classes
Is the granulometric distribution arbitrary?	✓		using log-normal distribution for grain size
Is there an upper/lower limit			about 0.1 mm upper limit and

on the particle size?			0.01mm lower limit

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling		JMA Global Spectral Model (JMA-GSM)

	YES	NO
Is the model linked to a particular NWP model?		✓
Is there some pre-process interface for NWP data interpolation?		

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
(i) JMA-GSM (0.1875° ×0.1875° L60, operationally) (ii) Japanese Reanalysis (JRA-25, 1.25° ×1.25° L23)

Please specify the meteorological variables required:
wind vector, temperature, specific humidity, pressure, precipitation

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source		option
Uniform (linear) vertical distribution		default, reverse cone shape and uniform vertical and horizontal distribution
Umbrella-type (top-hat)		
Poisson distribution		
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		Suzuki 1983
Buoyant plume theory		
Others		

	YES	NO
Can transient columns be described?		
Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition?	✓*	

* only volcanic-ash cloud area on satellite imagery

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load		not operational
Tephra deposit thickness		
Airborne concentration		only dispersion area in operation
Airborne concentration profiles (e.g. at a given height or flight level)		
Vertical concentration profiles		
Aerosol optical depth		
Aerosol (gas) concentration		
Cloud mass		
Cloud area/volume		
Concentration at ground level		
Others		trajectory of specific tracers

Please specify the model output format

	Tick	Comments
ASCII		
Binary (exclusive of the model)		
netCDF		
Grib1		
Grib2		
Graphic format (e.g, eps, gif)		
Others		

7. Computational characteristics

Programming language	Fortran90		
Operating system	AIX		
		YES	NO
Does a parallel version of the code exist?			
Is it an open source/public code?			
External library packages:			
JMA 'NWPLIB', 'NuSDaS', HITACHI 'MATRIX/MPP'			

8. Others

References
Iwasaki, T., T. Maki and K. Katayama, 1998: Tracer transport model at Japan Meteorological Agency and its application to the ETEX data. Atmos. Environ., 32, 4285–4295. Sakamoto, M., 2013: Atmospheric transport model. Outline of the Operational Numerical Weather Prediction at the Japan Meteorological Agency, 95-98.
Other comments
Tokyo VAAC replaced its old model with JMA-GATM in December, 2013.

1. Model overview

Model Name	**JMA Regional Atmospheric Transport Model (JMA-RATM)**	
Model Approach		Tick
	Analytical (Gaussian)	
	Numerical (Eulerian)	
	Numerical (Lagrangian)	
	Numerical (Hybrid)	
	Other	
Model coverage		Tick
	Local (order of 100s of km)	
	Regional (order of 1000s of km)	
	Global (globe coverage, periodicity)	

	YES	NO
Is the horizontal spatial resolution fixed?		
Is the vertical spatial resolution fixed?		
Is it operational for forecast at some Institution/VAAC/VO?		

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography		depend on NWP model
Horizontal wind advection		
Vertical wind advection		
Horizontal atmospheric diffusion		
Vertical atmospheric diffusion		
Particle sedimentation		as dry deposition
Other dry deposition mechanisms		
Wet deposition (wet removal)		only washout, not rainout
Dry particle aggregation		
Wet particle aggregation		
Particle shape		considered in the settling velocity
Dispersal of different gas species		
Chemical processes		
Others		radioactive decay

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?	✓		tracer mass allocation with 80 classes
Is the granulometric distribution arbitrary?	✓		using log-normal distribution for grain size

Is there an upper/lower limit on the particle size?			96 mm upper limit

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling		JMA Nonhydrostatic Model (JMA-NHM)

	YES	NO
Is the model linked to a particular NWP model?		✓
Is there some pre-process interface for NWP data interpolation?		

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
(i) JMA-LFM (Local Forecast Model, 2km×2km L60, operationally) (ii) JMA-MSM (Meso-Scale Model, 5km×5km L50, operationally) (iii) R/A (Radar/Rain gauge-Analyzed Precipitation (45″ ×30″ Surf.)

Please specify the meteorological variables required:
momentum, potential temperature, pressure, density, precipitation

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source		Option
Uniform (linear) vertical distribution		Option
Umbrella-type (top-hat)		under development
Poisson distribution		
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		Default, Suzuki 1983
Buoyant plume theory		
Others		

	YES	NO
Can transient columns be described?		
Can data (e.g. from satellite retrievals) be assimilated as an “initial” source term condition?	✓*	

* under development, only volcanic-ash cloud top of radar echo

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load		
Tephra deposit thickness		not operational
Airborne concentration		not operational
Airborne concentration profiles (e.g. at a given height or flight level)		
Vertical concentration profiles		
Aerosol optical depth		
Aerosol (gas) concentration		
Cloud mass		
Cloud area/volume		
Concentration at ground level		
Others		Lapilli-fall area (area of maximum grain size) trajectory of specific tracers, not operational

Please specify the model output format

	Tick	Comments
ASCII		
Binary (exclusive of the model)		
netCDF		
Grib1		
Grib2		
Graphic format (e.g, eps, gif)		
Others		

7. Computational characteristics

Programming language	Fortran90		
Operating system	AIX		
		YES	NO
Does a parallel version of the code exist?			
Is it an open source/public code?			
External library packages:			
JMA ‘NWPLIB’, ‘NuSDaS’, HITACHI ‘MATRIX/MPP’			

8. Others

References
Saito, K, T. Shimbori and R. Draxler, 2014: JMA's Regional ATM calculations for the WMO Technical Task Team on meteorological analyses for Fukushima Daiichi Nuclear Power Plant accident. J. Env. Rad. (submitted).
Other comments
The model is now under development and will be operational at JMA in 2015, therefore there is a possibility of changing the above specifications.

1. Model overview

Model Name	**MLDP0 (Modèle Lagrangien de Dispersion de Particules d'ordre zéro)**	
Approach		Tick
	Eulerian	
	Lagrangian	×
	Hybrid	
Method		Tick
	Analytical (e.g. Gaussian)	
	Semi-analytical	
	Numerical	×
Model coverage		Tick
	Local (order of 100s of km)	×
	Regional (order of 1000s of km)	×
	Global (globe coverage, periodicity)	×

	YES	NO
Is the horizontal spatial resolution fixed? * The horizontal and vertical spatial resolutions are fixed for a specific run, but can be changed from one run to another.		×*
Is the vertical spatial resolution fixed?		×*
Is it operational for forecast at some Institution/VAAC/VO?	×	

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	×	Works in sigma/eta/hybrid terrain following vertical coordinate
Horizontal wind advection	×	
Vertical wind advection	×	
Horizontal atmospheric diffusion	×	Lateral mixing is simulated with a first order Langevin equation to account for the effects of unresolved horizontal fluctuations of the mean wind (mesoscale fluctuations or meandering). Ref.: Maryon, 1998, *Atmospheric Environment*, **32** (2), 115–121, doi:10.1016/S1352-2310(97)00325-7.
Vertical atmospheric diffusion	×	Vertical mixing is handled through a random displacement equation (diffusion limit of the first order Langevin equation for stationary, inhomogeneous, Gaussian turbulence, i.e. zeroth order model). Vertical diffusion modelled through a diffusion coefficient according to: • Y. Delage formula for surface layer • J. J. O'Brien profile for above layers Ref.: • Delage, Y., 1997, *Boundary-Layer Meteorology*, **82** (1), 23–48, doi:10.1023/A:1000132524077. • O'Brien, J. J., 1970, *Journal of the Atmospheric Sciences*, **27** (8), 1213–1215, doi:10.1175/1520-0469(1970)027<1213:ANOTVS>2.0.CO;2.
Particle sedimentation	×	Gravitational settling modelled according to Stokes' law through a particle/grain size distribution.
Other dry deposition mechanisms	×	Trajectory reflection probability formalism near the surface (modelled in term of a deposition velocity and an absorption probability). Ref.: Wilson *et al.*, 1989,

		Agricultural Forest and Meteorology, **47** (2–4), 139–154, doi:10.1016/0168-1923(89)90092-0.
Wet deposition (wet removal)	×	Wet scavenging modelled when a particle is presumed to be in a cloud.
Dry particle aggregation		
Wet particle aggregation		
Particle shape		
Dispersal of different gas species		No, except for inert tracer mode.
Chemical processes		
Others	×	Radioactive decay, survival rate of Footh-and-Mouth Disease virus, Avian Influenza

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		×	The particle (grain) size distribution can be defined by the user.
Is the granulometric distribution arbitrary?		×	
Is there an upper/lower limit on the particle size?		×	However, the density of a particle is fixed for all size classes.

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling	×	Linked to Environment Canada's NWP GEM Global/Regional Model.

	YES	NO
Is the model linked to a particular NWP model?	×	
Is there some pre-process interface for NWP data interpolation?	×	

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
Yes. ECMWF, NCEP/NCAR re-analysis

Please specify the meteorological variables required:
Geopotential height, surface pressure, temperature, 3D wind speeds/directions (horizontal and vertical motion), humidity (specific humidity or relative humidity or dew point spread).

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source	×	
Uniform (linear) vertical distribution	×	
Umbrella-type (top-hat)	×	

Poisson distribution	×	
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		Could be added.
Buoyant plume theory		
Others	×	The eruptive vertical column distribution can be defined by the user.

	YES	NO
Can transient columns be described? * We can modulate the release as a function of time and height, including lulls.	×*	
Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition? * Indirectly. The data are used by the modeller to define the input parameters. However, they are not inputted directly in the model parameters (i.e. without human intervention).	×*	

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	×	Mass per unit surface.
Tephra deposit thickness		
Airborne concentration	×	
Airborne concentration profiles (e.g. at a given height or flight level)	×	Given height and in layers.
Vertical concentration profiles	×	
Aerosol optical depth		
Aerosol (gas) concentration	×	Indirectly, in tracer mode.
Cloud mass		Not done in our operational response because it is not required, but could easily be done.
Cloud area/volume		Not done (highly dependant on how one defines "the cloud").
Concentration at ground level	×	
Others	×	Mass loading (total column concentrations), 4D geospatial coordinates of Lagrangian particles, age of particles, etc.

Please specify the model output format

	Tick	Comments
ASCII		
Binary (exclusive of the model)	×	Exclusive to EC/CMC
netCDF		
Grib1	×	Output can easily be converted to binary GRIB format
Grib2	×	Output can easily be converted to binary GRIB format
Graphic format (e.g, eps, gif)	×	
Others	×	PS, JPEG, PNG, TIF, SHP (shapefile), etc.

7. Computational characteristics

Programming language	Fortran 90	
Operating system	Linux/AIX	
	YES	NO
Does a parallel version of the code exist?	×	
Is it an open source/public code?		×
External library packages:		

8. Others

References

Main references:

Draxler, R., Arnold, D., Chino, M., Galmarini, S., Hort, M., Jones, A., Leadbetter, S., **Malo, A.**, Maurer, C., Rolph, G., Saito, K., **Servranckx, R.**, Shimbori, T., Solazzo, E., Wotawa, G., 2013, "World Meteorological Organization's Model Simulations of the Radionuclide Dispersion and Deposition from the Fukushima Daiichi Nuclear Power Plant Accident", *Journal of Environmental Radioactivity*, in press (accepted 26 September 2013).

Draxler, R., Arnold, D., Galmarini, S., Hort, M., Jones, A., Leadbetter, S., **Malo, A.**, Maurer, C., Rolph, G., Saito, K., **Servranckx, R.**, Shimbori, T., Solazzo, E., Wotawa, G., 4 February 2013, "Annex III: The World Meteorological Organization's Evaluation of Meteorological Analyses for the Radionuclide Dispersion and Deposition from the Fukushima Daiichi Nuclear Power Plant Accident", *WMO Publication*, Third Meeting of WMO Task Team on Meteorological Analyses for Fukushima-Daiichi Nuclear Power Plant Accident, Vienna, Austria, 67 pp.

D'Amours, R., Malo, A., Servranckx, R., Bensimon, D., Trudel, S., Gauthier, J.-P., 2010, "Application of the atmospheric Lagrangian particle dispersion model MLDP0 to the 2008 eruptions of Okmok and Kasatochi volcanoes", *Journal of Geophysical Research*, **115** (D00L11), 1–11, doi:10.1029/2009JD013602.

Servranckx, R., Malo, A., February 2012, "Technical Document no. 778, Annex 4: RSMC Montréal Users' Interpretation Guidelines Atmospheric Transport Model Outputs, Version 11", Document distributed to World Meteorological Organization (WMO), Canadian Meteorological Centre, RSMC Montréal, Environmental Emergency Response Section, Dorval, QC, Canada, 16 pp.

D'Amours, R., Malo, A., 2004, "A Zeroth Order Lagrangian Particle Dispersion Model MLDP0", *Internal Publication*, Canadian Meteorological Centre, Environmental Emergency Response Section, Dorval, QC, Canada, 19 pp.

Other references:

Becker A., Wotawa, G., De Geer, L.-E., Seibert, P., Draxler, R. R., Sloan, C., **D'Amours, R.**, Hort, M., Glaab, H., Heinrich, P., Grillon, Y., Shershakov, V., Katayama, K., Zhang, Y., Stewart, P., Hirtl, M., **Jean, M.**, Chen, P., 2007, "Global backtracking of anthropogenic radionuclides by means of a receptor oriented ensemble dispersion modelling system in support of Nuclear-Test-Ban Treaty verification", *Atmospheric Environment*, **41** (21), 4520–4534, doi:10.1016/j.atmosenv.2006.12.048.

D'Amours, R., Mintz, R., Mooney, C., Wiens, B. J., 2013, "A modeling assessment of the origin of Beryllium-7 and Ozone in the Canadian Rocky Mountains", *Journal of Geophysical Research: Atmospheres*, **118**, 1–11, doi:10.1002/jgrd.50761.

Durant, A. J., Rose, W. I., 2009, "Sedimentological constraints on hydrometeor-enhanced particle deposition: 1992 Eruptions of Crater Peak, Alaska", *Journal of Volcanology and Geothermal Research*, **186** (1-2), 40–59, doi:10.1016/j.jvolgeores.2009.02.004.

Potempski, S., Galmarini, S., Addis, R., Astrup, P., Bader, S., Bellasio, R., Bianconi, R., Bonnardot, F., Buckley, R., **D'Amours, R.**, van Dijk, A., Geertsema, G., Jones, A., Kaufmann, P., Pechinger, U., Persson, C., Polreich, E., Prodanova, M., Robertson, L., Sørensen, J., Syrakov, D., 2008, "Multi-model ensemble analysis of the ETEX-2 experiment", *Atmospheric Environment*, **42** (31), 7250–7265, doi:10.1016/j.atmosenv.2008.07.027.

Stocki, T. J., Ungar, R. K., **D'Amours, R.**, Bean, M., Bock, K., Hoffman, I., Korpach, E., **Malo, A.**, 2011, "North Korean nuclear test of October 9th, 2006: The utilization of health Canada's radionuclide monitoring network and environment Canada's atmospheric transport and dispersion modelling", *Radioprotection*, **46** (6), S529–S534, doi:10.1051/radiopro/20116803s.

Stocki, T. J., Armand, P., Heinrich, P., Ungar, R. K., **D'Amours, R.**, Korpach, E. P., Bellivier, A., Taffary, T., **Malo, A.**, Bean, M., Hoffman, I., **Jean, M.**, 2008, "Measurement and modelling of radioxenon plumes in the Ottawa Valley", *Journal of Environmental Radioactivity*, **99** (11), 1775–1788, doi:10.1016/j.jenvrad.2008.07.009.

Other comments

The model MLDP0 is tightly coupled with the 4D visualization & analysis software toolkit SPI developed for the needs of Environmental Emergency Response Section (EERS) of the Canadian Meteorological Centre (CMC).

1. Model overview

Model Name	**MOCAGE-accident**	
Approach		Tick
	Eulerian	x
	Lagrangian	
	Hybrid	
Method		Tick
	Analytical (e.g. Gaussian)	
	Semi-analytical	
	Numerical	x
Model coverage		Tick
	Local (order of 100s of km)	
	Regional (order of 1000s of km)	
	Global (globe coverage, periodicity)	x

	YES	NO
Is the horizontal spatial resolution fixed?	x (see comment)	
Is the vertical spatial resolution fixed?	x (see comment)	
Is it operational for forecast at some Institution/VAAC/VO?	x	

Comment : In operations, MOCAGE-accident is currently used with 0.5° resolution and 47 vertical levels (up to 25km of altitude ; Planetary Boundary Layer has ~7 levels, and resolution in the free troposphere ranges from 500m to 800m approximately at the tropopause). In "study mode", finer resolution can be used over limited area domains, in particular on the horizontal (e.g. 0.1°). Vertical resolution can be increased also, but this requires specific validation.

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	x	From the ARPEGE operational Numerical Weather Prediction Model of Météo-France, averaged at 0.5° resolution.
Horizontal wind advection	x	Semi-lagrangian advection scheme (Williamson and Rasch, 1989) using a cubic polynomial interpolation in all three directions.
Vertical wind advection	x	See above.
Horizontal atmospheric diffusion		Neglected. Diffusion of numerical origin appears to be sufficient, with particularly good results at 0.5° (Pisso et al., 2009)
Vertical atmospheric diffusion	x	K-scheme from (Louis, 1979); the

		vertical diffusion coefficient K depends on height, wind shear and atmospheric stability.
Particle sedimentation	x	Settling velocity depends on the size and density of particles.
Other dry deposition mechanisms	x	Simple treatment of dry deposition, using fixed deposition velocities. The “study mode” version offers a more detailed aerosol dry deposition scheme (Nho et al., 2004).
Wet deposition (wet removal)	x	Use of a detailed scheme which takes into account the convective part following (Mari et al., 2000) and the stratiform part following (Liu et al., 2001).
Dry particle aggregation		No representation yet.
Wet particle aggregation		No representation yet.
Particle shape		No representation yet.
Dispersal of different gas species	x	Any gas that can be considered as a tracer can be treated, if basic characteristics (such as molar weight and Henry’s Law constants) are defined by the user.
Chemical processes		Chemical processes are not implemented in MOCAGE-accident, but are part of MOCAGE. MOCAGE is the 3D CTM of Météo-France used both in operations and research, for applications from air quality forecasting to the study of interactions between climate and chemistry. MOCAGE-accident is a sub- version of MOCAGE, dedicated to accidental release without chemistry (only possibly radioactive decay). Point source release of reactive gases is a possible option with MOCAGE, but not in an operational context.
Others	x	Convection is accounted for: transport by convection is based on the mass flux scheme of (Bechtold et al., 2001), with embedded representation of scavenging (Mari et al., 2000).

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?	x		In the current operational version for VAAC, only one size of particles is considered (10µm). In "study mode", several classes can be used to represent the size spectrum, with a full flexibility on the number of classes.
Is the granulometric distribution arbitrary?	x		It is planned to implement shortly an arbitrary distribution; number of classes used is not definitely fixed yet and should be of the order of 5 to 8 classes, which is fully tractable within the strong time constraints.
Is there an upper/lower limit on the particle size?	x		In the future version, there will be an upper limit (e.g. 65 or 100µm) and a lower limit (e.g. 0.2µm).

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling	x	

	YES	NO
Is the model linked to a particular NWP model?		x
Is there some pre-process interface for NWP data interpolation?	x	

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
In the operational version for VAAC Toulouse, choice is given to the forecaster on duty between operational global NWP models from Météo-France (ARPEGE) and ECMWF (IFS). In "study mode", MOCAGE-accident can be fed (in principle, but requiring validation) with any meteorological datasets if available in grid points, after pre-processing (formatting for MOCAGE read-in routine, but also computation of vertical velocity, see below). MOCAGE has been already successfully run with a range of met. forcings : HIRLAM, ARPEGE-Climate, ECHAM, AROME.

Please specify the meteorological variables required:
Hydrostatic winds (vertical velocity is re-computed systematically to ensure rigorous non-divergence on the model grid), temperature, pressure, humidity and rainfall at the surface.

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source	x	
Uniform (linear) vertical distribution	x	Base of the column is the volcano altitude. Top of the column is prescribed by the operator.
Umbrella-type (top-hat)		
Poisson distribution		
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		
Buoyant plume theory		
Others		

Comment : Work is planned to provide more options for the forecaster on duty in the operational configuration of MOCAGE-accident.

	YES	NO
Can transient columns be described?		x (see comment)
Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition?		X

Comment : In operations currently, the source term is prescribed simply; characteristics -base and top of the column, as well as emission rate and particle size and density- remain constant over the whole duration of an individual forecast (persistency is assumed, with no hypothesis on future source term evolution) , but can indeed change from one forecast to the next one. In study mode, characteristics of the release can change arbitrarily in time.

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	x	
Tephra deposit thickness		
Airborne concentration	x	
Airborne concentration profiles (e.g. at a given height or flight level)	x	In study mode only
Vertical concentration profiles	x	In study mode only
Aerosol optical depth	x	In study mode only
Aerosol (gas) concentration		Airborne concentrations?

Cloud mass	x	In study mode only
Cloud area/volume		
Concentration at ground level	x	
Others		

Please specify the model output format

	Tick	Comments
ASCII		
Binary (exclusive of the model)	x	
netCDF	x	In study mode only
Grib1	x	
Grib2		
Graphic format (e.g, eps, gif)	x	png
Others		

7. Computational characteristics

Programming language	Fortran 77/90	
Operating system	UNIX	
	YES	NO
Does a parallel version of the code exist?	x	
Is it an open source/public code?		x
External library packages:		
libemos		

8. Others

References
Other comments

1. Model overview

Model Name	**NAME (Numerical Atmospheric dispersion Modelling Environment)**	
Approach		Tick
	Eulerian	
	Lagrangian	✓ [1]
	Hybrid	✓ [2]
Method		Tick
	Analytical (e.g. Gaussian)	
	Semi-analytical	
	Numerical	✓
Model coverage		Tick
	Local (order of 100s of km)	✓
	Regional (order of 1000s of km)	✓
	Global (globe coverage, periodicity)	✓

	YES	NO
Is the horizontal spatial resolution fixed?		✓
Is the vertical spatial resolution fixed?		✓
Is it operational for forecast at some Institution/VAAC/VO?	✓ [3]	

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	✓	Uses topography from the driving NWP meteorological model
Horizontal wind advection	✓	
Vertical wind advection	✓	
Horizontal atmospheric diffusion	✓ [4]	
Vertical atmospheric diffusion	✓ [4]	
Particle sedimentation	✓	Based on Stokes flow with the Cunningham correction applied for small particle sizes
Other dry deposition mechanisms	✓	a) Land-surface dependent dry deposition scheme (based on surface resistance concept) – not used for volcanic ash applications b) Simple surface resistance scheme
Wet deposition (wet removal)	✓	Rain out (in-cloud removal) and wash out (below-cloud removal by rain impaction).
Dry particle aggregation		
Wet particle aggregation		
Particle shape		NAME currently assumes spherical particles, but research has been conducted with the model

		examining the impact of particle shape on volcanic ash transport
Dispersal of different gas species	✓	Species can have different chemical and radiological properties and different deposition characteristics.
Chemical processes	✓	Comprehensive sulphur/nitrogen/hydrocarbon chemistry scheme used for air quality modelling applications. Sulphate chemistry has also been used for volcanic gas research studies.
Others		Radiological decay (half-life decay and decay chains), cloud gamma and dose assessments; decay of biological and vector species; deep convective mixing; resuspension.

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		✓	User-specified
Is the granulometric distribution arbitrary?	✓		User-specified particle size distribution (cumulative fraction)
Is there an upper/lower limit on the particle size?		✓	Normally applied for particle size range 0.1 μm – 100.0 μm for volcanic ash applications

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling	✓	NAME reads 3-d fields output from an NWP model at a specified frequency (operational data is currently 3-hourly for global NWP forecasts; hourly for higher resolution NWP models). NAME supports the nesting of different met data sets within the same run (e.g. high resolution forecast data nested within a global forecast).

	YES	NO
Is the model linked to a particular NWP model?		✓
Is there some pre-process interface for NWP data interpolation?		✓

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
a) UK Met Office Unified Model (MetUM)

   a. global (~25km)
   b. regional (North Atlantic/Europe at ~12km)
   c. high resolution (UK at 1.5 km)
b) ECMWF IFS (real-time forecasts)
   a. operational deterministic
   b. Ensemble Prediction System
c) ECMWF ERA (reanalysis products)
   a. ERA-40
   b. ERA-Interim
d) Single-site met observations typical of a surface weather observation station (for short-range applications)
e) Rainfall radar data

Please specify the meteorological variables required:
The full set of meteorological variables is listed here, but NAME can be run on a subset of these if not all the variables are available. **Model-level fields (3-dimensional):** u,v,w wind components temperature specific humidity dynamic cloud water/ice pressure **Single-level or surface fields (2-dimensional):** u,v surface stress components surface sensible heat flux surface pressure/mean sea level pressure near-surface temperature (e.g. at 2 metres) convective cloud amount/base/top dynamic low/medium/high cloud amounts dynamic/convective rain rates dynamic/convective snow rates roughness length boundary layer depth soil moisture* canopy height* canopy water* stomatal conductance* *optional (not used for volcanic ash modelling)

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source	✓	
Uniform (linear) vertical distribution	✓	
Umbrella-type (top-hat)	✓	But NAME can model most types of source configurations as composite sources (based on point, line, area and volume components).
Poisson distribution		
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		
Buoyant plume theory	✓	NAME has a plume-rise scheme for buoyancy and momentum driven releases developed for modelling industrial plumes. The scheme solves an integral model for the governing conservation equations of mass, momentum and heat. It is an advancement on the Briggs formulae. The NAME plume rise code is not used for volcanic ash applications (the effective eruption height is always specified directly).
Others		

	YES	NO
Can transient columns be described?	✓	
Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition?	✓[6]	

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	✓	NAME was not specifically designed to compute tephra deposits (esp. short-range fallout of very large particles). However there is no physical reason why the existing sedimentation scheme should not be valid for this regime. The fact that aggregation is not treated by

		NAME may be an issue however.
Tephra deposit thickness		Can be calculated from the above
Airborne concentration	✓	
Airborne concentration profiles (e.g. at a given height or flight level)	✓	
Vertical concentration profiles	✓	
Aerosol optical depth	✓	Total column mass loading is a direct output, AOD can be produced as a post-processed quantity
Aerosol (gas) concentration	✓	
Cloud mass	✓	
Cloud area/volume	✓	In principle these quantities could be computed in a post-processing step, although these variables are not ordinarily calculated.
Concentration at ground level	✓	
Others	✓	A wide range of NAME outputs are possible, including individual particle trajectories, particle travel times, meteorological variables, etc. Statistical processing of output fields (calculation of means, percentiles, etc.) is also available directly in the model.

Please specify the model output format

	Tick	Comments
ASCII	✓	Output files conform to a generic plain text format, but the structure of specific output files is highly configurable through a range of model options (e.g. for fields output, time series at a location, etc).
Binary (exclusive of the model)		
netCDF	✓[7]	
Grib1	✓[7]	
Grib2	✓[7]	
Graphic format (e.g, eps, gif)	✓	IDL or Python used to create output graphics in .ps, .gif, and .png formats
Others		G.I.S. products created via downstream systems (ArcView)

7. Computational characteristics

Programming language	Fortran 95 (using IDL/Python for graphics)		
Operating system	Linux, Windows [8]		
		YES	NO

Does a parallel version of the code exist?	✓[9]	
Is it an open source/public code?		✓
External library packages:		
ECMWF 'GRIBAPI' package required for running on ECMWF GRIB met files.		

8. Others

References

Jones, A.R., Thomson, D.J., Hort, M. and Devenish, B., "The U.K. Met Office's next-generation atmospheric dispersion model, NAME III", in Borrego, C. and Norman, A.-L. (Eds) Air Pollution Modeling and its Application XVII (Proceedings of the 27th NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application), Springer, pp. 580-589, 2007.

Leadbetter. S.J. and Hort, M.C., "Volcanic ash hazard climatology for an eruption of Hekla volcano, Iceland", Journal of Volcanology and Geothermal Research, 199, 230-241, 2011.

Webster, H.W. et al., "Operational prediction of ash concentrations in the distal volcanic cloud from the 2010 Eyjafjallajokull eruption", Journal of Geophysical Research, 117, D00U08, doi:10.1029/2011JD016790, 2012.

Witham, C.S., Hort, M.C., Potts, R., Servranckx, R., Husson, P. and Bonnardot, F., "Comparison of VAAC atmospheric dispersion models using the 1 November 2004 Grimsvötn eruption", Meteorological Applications 14, 27-38, 2007.

Other comments

Notes:

[1] NAME also uses non-Lagrangian techniques for modelling certain processes (e.g. chemistry). Chemistry is not used in volcanic ash applications, although has been used for modelling volcanic SO_2 plumes.

[2] An Eulerian modelling scheme to support a fully hybrid approach is in development.

[3] Operational atmospheric dispersion model at the UK Met Office (WMO RSMC for radiological emergency response; VAAC for Volcanic Ash; UK civil emergency response).

[4] NAME uses random-walk techniques of varying levels of sophistication to treat plume diffusion. Within the boundary layer, the default (fast) scheme assumes vertically homogeneous turbulence with a diffusive scheme damped for the slower plume growth rate at small travel times. 'Turbulence' and 'meander' scales are treated independently. A more comprehensive (but slower) treatment is provided by 'near-source' schemes that includes inhomogeneous turbulence profiles and the velocity memory of particles. A constant-magnitude 'free tropospheric' turbulence is applied above the boundary layer. For volcanic ash applications only the most simple turbulence scheme is used.

[5] NAME supports point, line, area and volume sources using either a uniform distribution or Gaussian distribution. For volcanic ash applications, a uniform vertical distribution is adopted: column_min $\leq$ z $\leq$ column_max.

[6] An inversion scheme (InTEM) has been developed that allows a source term derived from satellite data to be utilised at any point during an eruption.

[7] Currently available via downstream post-processing.

[8] Primary operating systems used are Linux and Windows, but NAME has also been compiled for SUN Solaris and Mac systems.

[9] Parallelisation uses OpenMP architecture to run on shared-memory systems.

1. Model overview

Model Name	**Puff VATD Model**	
Approach		Tick
	Eulerian	
	Lagrangian	√
	Hybrid	
Method		Tick
	Analytical (e.g. Gaussian)	
	Semi-analytical	
	Numerical	√
Model coverage		Tick
	Local (order of 100s of km)	√
	Regional (order of 1000s of km)	√
	Global (globe coverage, periodicity)	√

	YES	NO
Is the horizontal spatial resolution fixed?		√
Is the vertical spatial resolution fixed?		√
Is it operational for forecast at some Institution/VAAC/VO?	√	

2. Model physics

	Tick	Comments
Topography	√	Using gtopo30 DEM
Horizontal wind advection	√	
Vertical wind advection	√	
Horizontal atmospheric diffusion	√	Defined value or 'turbulent' from wind field
Vertical atmospheric diffusion	√	
Particle sedimentation		
Other dry deposition mechanisms	√	Settling can be defined as stokes, Reynolds or constant
Wet deposition (wet removal)		
Dry particle aggregation		
Wet particle aggregation		
Particle shape	√	Considered to be spherical
Dispersal of different gas species		
Chemical processes		
Others	√	Puff is a simple advection/dispersion model

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		√	Defined by a mean size and s.d or using phi size bins.
Is the granulometric distribution arbitrary?		√	
Is there an upper/lower limit on the particle size?		√	

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling	√	Numerical Weather Prediction wind data is used to drive the Puff model ash dispersion and transport

	YES	NO
Is the model linked to a particular NWP model?		√
Is there some pre-process interface for NWP data interpolation?		√

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
GFS, NAM 216 ,NOGAPS, NCEP Reanalysis, ECMWF, WRF Can use any wind field model as long as 3D and Puff source file (puffrc) has defined model and the parameters representing U, V, T and geo_potential_height

Please specify the meteorological variables required:
U, V, T, Geo Pot Height

5. Eruptive column (source term)

	Tick	Comments
Point source	√	Can specify any location globally
Uniform (linear) vertical distribution	√	
Umbrella-type (top-hat)	√	Defined by thickness of umbrella region, uniform shape below
Poisson distribution	√	
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		
Buoyant plume theory		
Others	√	Define plume height, can vary with time or fixed for eruptive event

	YES	NO
Can transient columns be described?	√ (if one means varying heights with time)	
Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition?	√ (can be adapted to)	

6. Model outputs

	Tick	Comments
Tephra deposit load	√	With defined erupted ash mass and particle size distribution
Tephra deposit thickness	√	With defined erupted ash mass
Airborne concentration	√	Can be done with accurate input

		source information
Airborne concentration profiles (e.g. at a given height or flight level)	√	
Vertical concentration profiles	√	Puff is 3D so requires analysis of model outputs but it is possible
Aerosol optical depth		
Aerosol (gas) concentration		
Cloud mass	√	With defined erupted ash mass and particle size distribution
Cloud area/volume	√	
Concentration at ground level	√	With accurate input source terms and scaling can determine load as mg/m^2
Others		

Please specify the model output format

	Tick	Comments
ASCII	√	Requires using netcdf reader and then can output to ascii
Binary (exclusive of the model)		
netCDF	√	Output files for concentrations are '.nc' and for airborne particles are 'cdf'
Grib1		
Grib2		
Graphic format (e.g, eps, gif)	√	Images as png, jpeg, gif. Animations as mpeg and gif.
Others	√	Web based outputs as html, php and also Google Earth KML and KMZ.

7. Computational characteristics

Programming language	C and C++ with additional libraries, with shell and perl scripts for automated forecasts	
Operating system	Unix/Linux	
	YES	NO
Does a parallel version of the code exist?	√	
Is it an open source/public code?	√	
External library packages:		
Requires netcdf, udunits library, GMT for plotting		

8. Others

References
Searcy, C., Dean, K. G., Stringer, W., 1998. PUFF: A volcanic ash tracking and prediction model, *Journal of Volcanology and. Geothermal Research,* **80**, 1-16.
Peterson, R. A., Dean, K. G., 2008. "Forecasting exposure to airborne volcanic ash based on ash dispersion modeling", *J. Volcanology and Geothermal*

Res. **170**, 230-246 doi:10.1016/j.jvolgeores.2007.10.003.

Webley, P.W., 2010. Four Dimensional Volcanic Ash Cloud Predictions in Google Earth, with a special case of an ash-aviation encounter. *Computer and Geosciences Special Issue: Virtual Globes*.doi:10.1016/j.cageo.2010.02.005.

Webley, P.W., Dean, K.G., Dehn, J., Bailey, J.E., and Peterson, R., 2010, Volcanic-ash dispersion modeling of the 2006 eruption of Augustine Volcano Using the Puff Model, chapter 21 of Power, J.A., Coombs, M.L., and Freymueller, J.T., eds., The 2006 eruption of Augustine Volcano, Alaska: USGS Professional Paper 1769, 507 - 526 [http://pubs.usgs.gov/pp/1769/chapters/p1769_chapter21.pdf].

Other comments

The Puff Volcanic Ash Dispersion and Transport model has been developed at the University of Alaska Fairbanks – Geophysical Institute. The model runs quickly and has been used extensively in the Alaska and North Pacific Region by the Alaska Volcano Observatory, U. S. National Weather Service (VAAC, AAWU and CSWU) and AirForce Weather Agency.

Recently, as of May 2013, the Puff website has become password protected, due to change in funding sources.

The Puff model website, http://puff.images.alaska.edu see Figure 1, provides an online interface to the model. As of October 1, 2010, automated forecasts are provided for 37 volcanoes globally, every 3 – 6 hrs, for initial plume altitudes from 4 – 16 km above sea level. These are 24 hour forecasts, with model outputs every 1 hr. Additionally, model outputs are provided in GIF and Google Earth KML/KMZ format to allow automated viewing of forecasts without forecasters having to be sure they are using the most recent model run. Outside Alaska and North Pacific, the model has been used routinely by the Darwin VAAC as a tool to provide a validation tool to their own forecasts as with Darwin and as a new and novel visualization and forecasting tool for OVSICORI, Costa Rica.

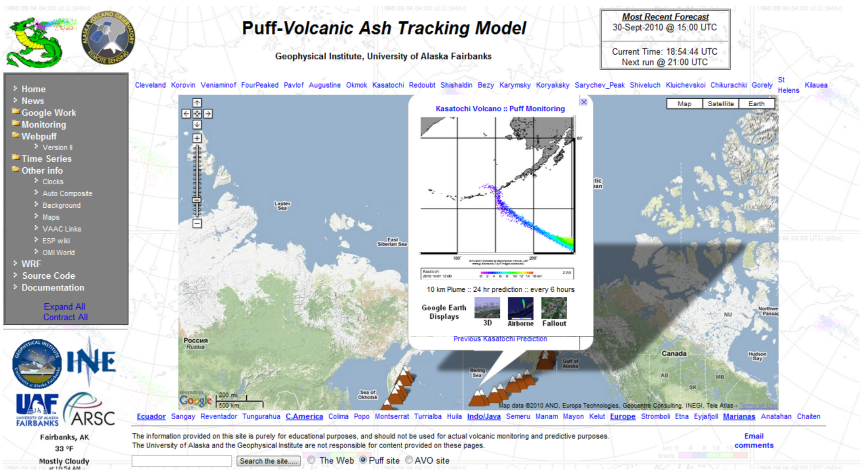

Figure 1 Puff Volcanic Ash Transport and Dispersion model website

We provide an interactive page, http://puff.images.alaska.edu/auto_forecasts_new.php see Figure 2, where one can view the entire model runs for each volcano and start height. This is useful to be able to choose the volcano and plume initial height. The user can then view the animation of ash cloud movement and a set time period in the forecast.

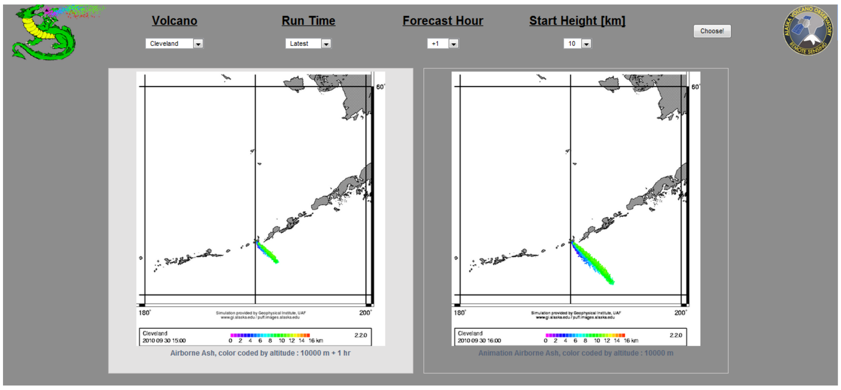

Figure 2 Interface to Puff model forecasts, where user can choose volcano and start height from drop down menus

When a given volcanic event is detected, the Puff model can be run through an interface for the time of the start of the event, http://puff.images.alaska.edu/cgi-bin/login_agu.pl, see Figure 3. The user can define plume height, eruption length, simulation length, output timing, wind field model, number of ash particles and plume shape. The user can return later to view any previous model run, they can edit the plotted ash cloud maps and generate a Google Earth KML/KMZ file of their model run simulation.

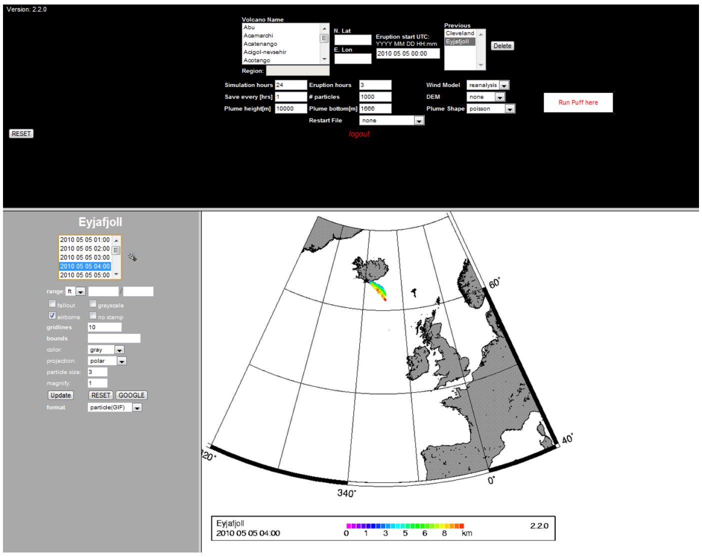

Figure 3 Webpuff interface to allow users to run their own Puff model simulations

Recently, the Puff model has been developed to allow an ash exposure tool to be adapted. This allows the users to provide an aircraft route and from airborne concentrations determine the exposure over time of the aircraft, see Peterson and Dean (2008). Finally, the Puff VATD model has the capabilities to forecast multiple eruptive events. If a volcano, such as Augustine in 2006 has multiple events over a short period of time, then multiple airborne ash clouds will need to be forecasted. Puff allows the user to run a 'restart' from a previous model run.

1. Model overview

Model Name	TEPHRA2	
Approach		Tick
	Eulerian	X
	Lagrangian	
	Hybrid	
Method		Tick
	Analytical (e.g. Gaussian)	X
	Semi-analytical	
	Numerical	
Model coverage		Tick
	Local (order of 100s of km)	X
	Regional (order of 1000s of km)	
	Global (globe coverage, periodicity)	

	YES	NO
Is the horizontal spatial resolution fixed? ➔ Defined by the calculation grid adopted		X
Is the vertical spatial resolution fixed?		X
Is it operational for forecast at some Institution/VAAC/VO? ➔ INGV Catania	X	

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	X	
Horizontal wind advection	X	
Vertical wind advection		
Horizontal atmospheric diffusion	X	Accounts for plume diffusion (i.e. plume radius increase with height) and for two diffusion laws: -> linear (Fickian) diffusion for large particles -> power-law diffusion for small particles (Suzuki 1983)
Vertical atmospheric diffusion		
Particle sedimentation	X	
Other dry deposition mechanisms		
Wet deposition (wet removal)		
Dry particle aggregation		
Wet particle aggregation		
Particle shape		
Dispersal of different gas species		
Chemical processes		
Others	X	Variable particle velocity with height and Reynold’s number

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		X	
Is the granulometric distribution arbitrary?	X		
Is there an upper/lower limit on the particle size?		X	

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling		

	YES	NO
Is the model linked to a particular NWP model?		X
Is there some pre-process interface for NWP data interpolation?		X

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
NCEP/NCAR, ECMWF Re-analysis

Please specify the meteorological variables required:
Geopotential height, U-wind, V-wind

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source		
Uniform (linear) vertical distribution	X	It is possible to define the plume ratio from which particles start falling.
Umbrella-type (top-hat)	X	
Poisson distribution		
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)	X	
Buoyant plume theory		
Others	X	Beta with best-fit parameters inferred from inversion techniques

	YES	NO
Can transient columns be described?		X
Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition?		X

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	X	
Tephra deposit thickness	X	
Airborne concentration		
Airborne concentration profiles (e.g. at a given height or flight level)		
Vertical concentration profiles		
Aerosol optical depth		
Aerosol (gas) concentration		
Cloud mass		
Cloud area/volume		
Concentration at ground level		
Others	X	Grainsize distribution at each grid point

Please specify the model output format

	Tick	Comments
ASCII	X	
Binary (exclusive of the model)		
netCDF		
Grib1		
Grib2		
Graphic format (e.g, eps, gif)	X	
Others	X	Working on shapefiles (ArcGIS) and Google Earth

7. Computational characteristics

Programming language	C		
Operating system	Unix		
		YES	NO
Does a parallel version of the code exist?		X*	
Is it an open source/public code? ➔ http://www.cas.usf.edu/~cconnor/vg@usf/tephra.html ➔ https://vhub.org/resources/tephra2		X	
External library packages:			
* TEPHRA1 (no topography)			

8. Others

References
Bonadonna, C., C. B. Connor, B. F. Houghton, L. Connor, M. Byrne, A. Laing, and T. K. Hincks (2005), Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at Tarawera, New Zealand, J. Geophys. Res., 110, B03203, doi:10.1029/2003JB002896. Connor, L.J. and C.B. Connor. 2006. Inversion is the key to dispersion: understanding eruption dynamics by inverting tephra fallout. In Mader, Coles, Connor, and Connor 2006, 231–242. http://www.cas.usf.edu/~cconnor/vg@usf/tephra.html

Other comments
A graphical interface has been developed to (i) collect, process and perform statistical analysis of input parameters, (ii) run the model using different deterministic and probabilistic scenarios and (iii) process output data to produce comprehensive hazard assessments.

1. Model overview

Model Name		
Approach		Tick
	Eulerian	
	Lagrangian	
	Hybrid	✔
Method		Tick
	Analytical (e.g. Gaussian)	
	Semi-analytical	✔
	Numerical	
Model coverage		Tick
	Local (order of 100s of km)	✔
	Regional (order of 1000s of km)	✔
	Global (globe coverage, periodicity)	

	YES	NO
Is the horizontal spatial resolution fixed?		✔
Is the vertical spatial resolution fixed?		✔
Is it operational for forecast at some Institution/VAAC/VO?	✔ It is routinely used at INGV – Catania for volcanic ash dispersal forecast at Mt. Etna ✔ It will be used for operational purposes at Icelandic Meteorological Office	

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	✔	
Horizontal wind advection	✔	
Vertical wind advection	✔	
Horizontal atmospheric diffusion	✔	
Vertical atmospheric diffusion	✔	
Particle sedimentation	✔	
Other dry deposition mechanisms		
Wet deposition (wet removal)	✔	
Dry particle aggregation		
Wet particle aggregation		
Particle shape	✔	
Dispersal of different gas species	✔	
Chemical processes	✔	Not yet tested for volcanic gases, but already implemented in original CALPUFF code
Others		

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		✔	
Is the granulometric distribution arbitrary?	✔		
Is there an upper/lower limit on the particle size?		✔	

4. Meteorological data

	Tick	Comments
On-line coupling		
Off-line coupling	✔	

	YES	NO
Is the model linked to a particular NWP model?		✔
Is there some pre-process interface for NWP data interpolation?	✔	

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
ECMWF Re-analysis, GFS (0.5° and 1°), COSMO/Lami, NCEP/NCAR Re-analysis, NAM, NCEP/NARR archive

Please specify the meteorological variables required:
2D: Land use, sea level pressure, precipitation accumulation (for wet deposition) 3D: Wind speed, wind direction, temperature, humidity, vertical velocity (Pa/s)

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source	✔	
Uniform (linear) vertical distribution		Not yet implemented but feasible if required
Umbrella-type (top-hat)		Not yet implemented but feasible if required
Poisson distribution		Not yet implemented but feasible if required
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		Not yet implemented but feasible if required
Buoyant plume theory	✔	
Others		

	YES	NO
Can transient columns be described?	✔	
Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition? It is not routinely done, but it is possible to invert the plume theory model in order to define the volcanological input data at the vent able to produce "observed" column heights taking into account the current meteorological condition.		

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	✔	This is the standard output
Tephra deposit thickness	✔	It is not the standard output, but could be computed with a simple post-processing
Airborne concentration	✔	
Airborne concentration profiles (e.g. at a given height or flight level)	✔	
Vertical concentration profiles	✔	
Aerosol optical depth		
Aerosol (gas) concentration	✔	
Cloud mass	✔	
Cloud area/volume	✔	The same as for Tdt
Concentration at ground level	✔	
Others	✔	PMx concentration at surface

Please specify the model output format

	Tick	Comments
ASCII	✔	In order to be read with NCL libraries
Binary (exclusive of the model)		
netCDF		
Grib1		
Grib2		
Graphic format (e.g, eps, gif)	✔	png
Others	✔	VTK file format (to be read by Paraview)

7. Computational characteristics

Programming language	Fortran 77/90	
Operating system	UNIX/LINUX	
	YES	NO
Does a parallel version of the code exist?	✔	
Is it an open source/public code?		✔
External library packages:		

8. Others

References

Spinetti, C., Barsotti, S., Neri, A. , Buongiorno, M. F., Doumaz, F., and Nannipieri L. (2013) Investigation of the complex dynamics and structure of the 2010 Eyjafjallajökull volcanic ash cloud using multispectral images and numerical simulations. *J Geophys Res: Atmospheres*, 118, 4729–4747, doi:10.1002/jgrd.50328

Barsotti, S., D. Andronico, A. Neri, P. Del Carlo, P.J. Baxter, W.P. Aspinall, T. Hincks (2010), Quantitative assessment of volcanic ash hazards for health and infrastructure at Mt. Etna (Italy) by numerical simulation, *Journal of Volcanology and Geothermal Research*, Volume 192, Issues 1-2, 20 April 2010, Pages 85-96.

Barsotti, S., L.G. Mastin, L. Nannipieri, A. Neri, J.R. Schaefer, K.L. Wallace, D.J. Schneider, (2009), Ash dispersal forecasts and event reconstruction of the Redoubt Volcano's 2009 explosive activity using the VOL-CALPUFF model, *AGU Fall meeting 2009*, San Francisco.

Barsotti, S., and A. Neri (2008), The VOL-CALPUFF model for atmospheric ash dispersal: 2. Application to the weak Mount Etna plume of July 2001, *Journal of Geophysical Research,* 113, B03209, doi:10.1029/2006JB004624.

Barsotti, S., A. Neri, and J. S. Scire (2008a), The VOL-CALPUFF model for atmospheric ash dispersal: 1. Approach and physical formulation, *Journal of Geophysical Research*, 113, B03208, doi:10.1029/2006JB004623.

Barsotti S., L. Nannipieri and A. Neri (2008b), MAFALDA: An early warning modeling tool to forecast volcanic ash dispersal and deposition, *G-cube*, doi: 10.1029/2008GC002133.

Other comments

I filled the present module keeping in mind the current version of the VOL-CALPUFF code. It is still true that with more or less simple pre and post-processing it would be possible to modify the type of output information, output format, or input source description.

1. Model overview

Model Name	**WRF-Chem VATD Model**	
Approach		Tick
	Eulerian	√
	Lagrangian	
	Hybrid	
Method		Tick
	Analytical (e.g. Gaussian)	
	Semi-analytical	
	Numerical	√
Model coverage		Tick
	Local (order of 100s of km)	√
	Regional (order of 1000s of km)	√
	Global (globe coverage, periodicity)	√

	YES	NO
Is the horizontal spatial resolution fixed?		√
Is the vertical spatial resolution fixed?		√
Is it operational for forecast at some Institution/VAAC/VO?		√

2. Model physics

	Tick	Comments
Topography	√	
Horizontal wind advection	√	
Vertical wind advection	√	
Horizontal atmospheric diffusion	√	
Vertical atmospheric diffusion	√	
Particle sedimentation	√	
Other dry deposition mechanisms		
Wet deposition (wet removal)	√	
Dry particle aggregation		
Wet particle aggregation		
Particle shape		
Dispersal of different gas species	√	
Chemical processes	√	
Others		

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?	√		10 bins have been introduced
Is the granulometric distribution arbitrary?		√	
Is there an upper/lower limit on the particle size?		√	

4. Meteorological data

	Tick	Comments
On-line coupling	√	Chemistry online in WRF
Off-line coupling		

	YES	NO
Is the model linked to a particular NWP model?	√	
Is there some pre-process interface for NWP data interpolation?	√	

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
A Weather Research and Forecasting (WRF) model data assimilation system (WRFDA) is freely available allowing assimilating observational data. Typically WRF is initialized with other (global or mesoscale) NWP data.

Please specify the meteorological variables required:

5. Eruptive column (source term)

	Tick	Comments
Point source		
Uniform (linear) vertical distribution		
Umbrella-type (top-hat)	√	The top of the umbrella needs to be specified as emission height source
Poisson distribution		
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		
Buoyant plume theory		
Others		

	YES	NO
Can transient columns be described?		√
Can data (e.g. from satellite retrievals) be assimilated as an "initial" source term condition?	√	

6. Model outputs

	Tick	Comments
Tephra deposit load	√	
Tephra deposit thickness	√	
Airborne concentration	√	3-d fields of mass concentrations for each particle bin
Airborne concentration profiles (e.g. at a given height or flight level)	√	from netCDF processing
Vertical concentration profiles	√	from netCDF processing
Aerosol optical depth	√	
Aerosol (gas) concentration	√	

Cloud mass	√	
Cloud area/volume	√	
Concentration at ground level	√	every sigma (terrain following) level available
Others	√	Ash arrival times at airports

Please specify the model output format

	Tick	Comments
ASCII		
Binary (exclusive of the model)		
netCDF	√	netCDF format is standard for WRF
Grib1		
Grib2		
Graphic format (e.g, eps, gif)	√	PDF/JPEG/PNG using plotting in NCL
Others		

7. Computational characteristics

Programming language	Fortran 90	
Operating system	Unix/Linux	
	YES	NO
Does a parallel version of the code exist?	√	
Is it an open source/public code?	√	
External library packages:		
NetCDF		

8. Others

References

Stuefer M., Freitas, S. R., Grell, G., Webley, P., Peckham, S., McKeen, S. A., 2013: Inclusion of Ash and SO2 emissions from volcanic eruptions in WRF-Chem: development and some applications. Geoscientific Model Development, Volume 6, 457-468, doi:10.5194/gmd-6-457-2013, 2013.
Webley P., T.S. Steensen, M. Stuefer, G. Grell, S. Freitas, and M. Pavolonis, 2012: WRF/CHEM volcanic ash dispersion and tracking model analysis of the Eyjafjallajokull 2010 eruption. Journal of Geophysical Research, Vol. 117, D00U26, 21 pp.
Grell, G. A., S. E. Peckham, R. Schmitz, S. A. McKeen, G. Frost, W. C. Skamarock and B. Eder, 2005: Fully coupled online chemistry within the WRF model, Atmos. Environ., 39, 6957-6975.

Other comments

The Weather Research and Forecasting (WRF) model coupled with Chemistry (Grell et al. 2005) has been modified for volcanic emission applications (Stuefer et al. 2013, Webley et al. 2012). The model simulates the emission, transport, mixing, and chemical transformation of volcanic ash and SO2 simultaneously with the meteorology.

1. Model overview

Model Name	**REMOTE** (Regional Model with Tracer Extension)		
Model Approach			Tick
	Analytical (Gaussian)		
	Numerical (Eulerian)		✔
	Numerical (Lagrangian)		
	Numerical (Hybrid)		
	Other		
Model coverage			Tick
	Local (order of 100s of km)		✔
	Regional (order of 1000s of km)		✔
	Global (globe coverage, periodicity)		
		YES	NO
Is the horizontal spatial resolution fixed?			✔
Is the vertical spatial resolution fixed?			✔
Is it operational for forecast at some Institution/VAAC/VO?			✔

2. Model physics

Please, specify if the model accounts for the following parameters/processes:

	Tick	Comments
Topography	✔	
Horizontal wind advection	✔	
Vertical wind advection	✔	
Horizontal atmospheric diffusion	✔	numerical diffusion
Vertical atmospheric diffusion	✔	
Particle sedimentation	✔	
Other dry deposition mechanisms	✔	dry deposition of particles out of the first model layer
Wet deposition (wet removal)	✔	
Dry particle aggregation		
Wet particle aggregation	✔	first preliminary parameterisations
Particle shape	✔	spherical
Dispersal of different gas species	✔	photochemical species, SO_2 and various primary and secondary aerosols, e.g. sulphate
Chemical processes		photochemistry
Others	✔	- volcanic ash re-mobilisation as a source term - aerosol microphysical processes: nucleation, condensation, coagulation - coupled volcanic ash – sulphate microphysical evolution

3. Particle granulometry

	YES	NO	Comments
Is the number of classes (bins) fixed?		✔	
Is the granulometric distribution arbitrary?		✔	log-normal size distribution functions
Is there an upper/lower limit on the particle size?	✔		~1000 μm

4. Meteorological data

	Tick	Comments
On-line coupling	✔	
Off-line coupling		

	YES	NO
Is the model linked to a particular NWP model?		✔
Is there some pre-process interface for NWP data interpolation?	✔	

If the model can assimilate meteorological data from different NWP models or meteorological datasets, please specify which ones:
ECMWF analysis, NCEP analysis

Please specify the meteorological variables required:
2D: surface pressure, surface temperature, soil temperature, soil wetness 3D: horizontal wind vectors, geopotential height, temperature, specific humidity

5. Eruptive column (source term)

Please specify which of the following options are possible for describing the mass (concentration) distribution along the eruptive column

	Tick	Comments
Point source	✔	With flexible vertical distribution above the vent
Uniform (linear) vertical distribution	✔	
Umbrella-type (top-hat)	✔	
Poisson distribution		
Log-normal (Suzuki) distribution (e.g. Suzuki 1983; Armienti et al. 1988)		
Buoyant plume theory		
Others		

	YES	NO
Can transient columns be described?	✔	
Can data (e.g. from satellite retrievals) be assimilated as an “initial” source term condition?		✔

6. Model outputs

Please specify if the model outputs the following variables (or, in case it just outputs a primary variable – mass, concentration, puff or particle location, etc – if it exists a postprocess utility to compute them):

	Tick	Comments
Tephra deposit load	✔	
Tephra deposit thickness	✔	
Airborne concentration	✔	
Airborne concentration profiles (e.g. at a given height or flight level)	✔	
Vertical concentration profiles	✔	
Aerosol optical depth	✔	as post-processing option
Aerosol (gas) concentration	✔	SO_2 concentrations, sulphate particle number and mass concentration, precipitation
Cloud mass	✔	
Cloud area/volume	✔	
Concentration at ground level	✔	
Others		

Please specify the model output format

	Tick	Comments
ASCII		
Binary (exclusive of the model)	✔	IEEE
netCDF		
Grib1		
Grib2		
Graphic format (e.g, eps, gif)		
Others		

7. Computational characteristics

Programming language	FORTRAN 77/95		
Operating system	UNIX/LINUX		
		YES	NO
Does a parallel version of the code exist?			✔
Is it an open source/public code? Code available on request / in collaboration – personal introduction recommended		✔	✔
External library packages:			

8. Others

References
O'Dowd, C., S. Varghese, D. Martin, R. Flanagan, D. Ceburnis, J. Ovadnevaite, G. Martucci, J. Bialek, C. Monahan, H. Berresheim, A. Vaishya, T. Grigas, G. Jennings, B. Langmann, T. Semmler and R. McGrath, The Eyjafjallajökull Ash Plume – Part 2: Forecasting ash cloud dispersion, Atmos. Environ. 48, 143–151, doi:10.1016/j.atmosenv.2011.10.037, 2012. Langmann, B., K. Zakšek and M. Hort, Atmospheric distribution and removal of volcanic ash after the eruption of Kasatochi volcano: A regional model study, J. Geophys. Res., 115, D00L06, doi:10.1029/2009JD013298, 2010. Langmann, B., M. Hort and T. Hansteen, Meteorological influence on seasonal and diurnal variability of Nicaraguan volcanic emission dispersion: A numerical model study, J. Volc. Geotherm. Res. 182, 34–44, 2009. Langmann, B., S. Varghese, E. Marmer, E. Vignati, J. Wilson, P. Stier and C. O'Dowd, Aerosol distribution over Europe: A model evaluation study with detailed aerosol microphysics, Atmos. Chem. Phys. 8, 1591–1607, 2008.
Other comments