Windfield stochastic variability integrated in an ash transport and dispersal model

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Outline

Eyjafjallajökull, Iceland

The 2010 eruption of Eyjafjallajökull, Iceland, caused havoc for European aviation with ash emissions from 14 April 2010 into May, peaking during the period 14–18 April.

* http://bowshooter.blogspot.com/2010/05/iceland-volcano-eruption-of.html

- Deal with complex physics.
- Sparse observations - one cannot build a forecast based only on observations.
- To supplement the lack of observations we used mathematical models of advection and dispersion.
- These models require input data on source conditions such as eruption plume height, as well as the windfield.

The question we try to answer

During an eruption

What is the probability of having ash at a certain location above a specified height?

* http://www.guardian.co.uk/world/2010/apr/17/volcano-disruption-flights-grounded-ash

The problem

- The ash clouds extend over large areas and can travel thousands of kilometers from the source volcano, disrupting air traffic and posing a significant hazard to air travel.
- Windfields along with source parameters (vent radius, vent velocity, mean grain size and grain size variance) represent major sources for uncertainties in ash transport and dispersion simulations.
- The volcanic source inputs are usually not well constrained - uncertainty in the inputs is needed to make probabilistic predictions.
- For windfields, ensemble methods are considered to be an effective way to estimate the probability density function of future states of the atmosphere.

Physical models - Bent

The Bent integral eruption column model was used to produce eruption column parameters (mass loading, column height, grain size distribution) given a specific atmospheric sounding and source conditions [1].

The mass eruption rate, M

is estimated as a function of axial jet velocity, U, bent radius, b_0 and bulk density of the erupting mixture, ρ_0:

$$M = \pi b_0^2 \rho_0 U \qquad (1)$$

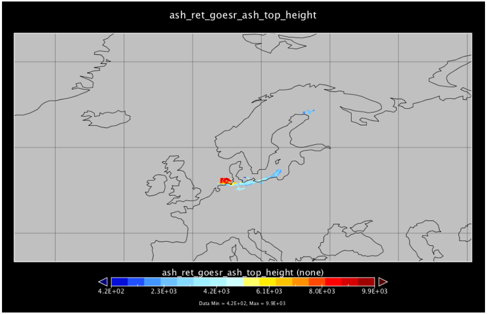
[1] Bursik, M.I. et al. (2009) Volcanic plumes and wind: Jetstream interaction examples and implications for air traffic. J. Volc. and Geo. Res., 186, 60-67

Physicall models - Puff

The Puff Lagrangian model tracks a finite number of Lagrangian point particles of different sizes, whose location R is propagated from timestep k to timestep $k+1$ via an advection/diffusion equation [2].

$$R_i(t_{k+1}) = R_i(t_k) + W(t_k)\Delta t + Z(t_k)\Delta t + S_i(t_k)\Delta t \tag{2}$$

$R_i(t_k)$ is the position vector, $W(t_k)$ is the local wind velocity, $Z(t_k)$ is a turbulent diffusion, and $S_i(t_k)$ is a source term.



[2] Searcy, C. et al. (1998) PUFF: A high-resolution volcanic ash tracking model. J. Volc. and Geo. Res., 80, 1-16

Physical models - `puffin`

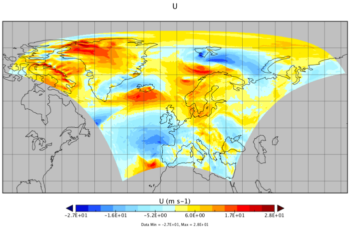
`puffin`

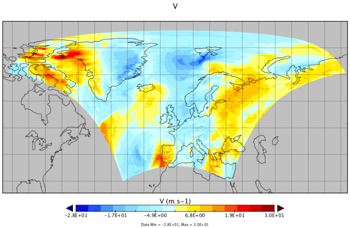
It is a coupled model between `Bent` *and* `Puff`*. This makes the model inputs to be vent velocity and vent diameter that are directly observable and much easier to deal with.*

WRF

Weather Research and Forecast (WRF) model is a numerical weather prediction system, used to forecast the wind speed.

- The model domain is centered on the location of the Eyjafjallajökull vent (63.63 °N and 19.63 °S) with dimensions of 230 × 230 horizontal grids points with spacing of 27 km, 29 pressure levels (1000-100 hPa, excluding the surface) and it comprises most of Europe.





GEFS ensemble

GEFS ensembles account for uncertainty in initial conditions using breeding vectors approach [a]. Breeding method is based on the idea that the analysis that we get out of the data assimilation cycle will accumulate growing errors when it is recycled from one data assimilation cycle to the next.

[a] Toth, Z. and Kalnay, E. (1997) Ensemble forecasting at NCEP and the breeding method. Mon. Wea. Rev., 126, 3292-3302

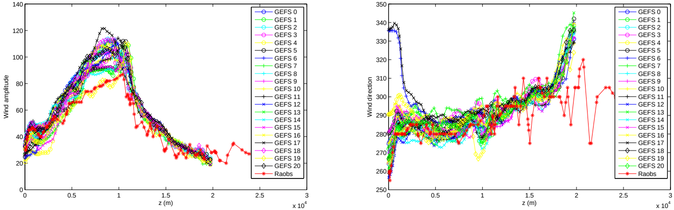
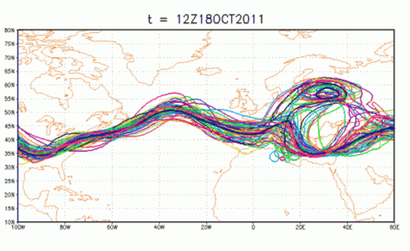


Figure : a) Wind amplitude in knots, lat 60.13 and lon -1.18, April 17 2010 00Z b)Wind direction in deg, lat 60.13 and lon -1.18, April 17 2010 00Z

GEFS ensemble - cont

The NCEP GEFS ensembles consists of 21 members and is run 4 times daily (0000, 0600, 1200, and 1800 UTC) out to 384-h (16 day) lead time. The underlying model for the GEFS is the NCEP Global Forecasting System (GFS), a high-resolution spectral atmospheric model run 4 times daily at the Environmental Modeling Center.



Ensemble spaghetti plot courtesy of http://www.pandowae.de/en/projects/block

We are using the ensemble members produced four times daily, at 0000, 0600, 1200, and 1800 UTC, starting 0000 UTC April 14 to 0000 UTC April 18 at 1°latitude by 1°longitude grid.

Probabilistic forecast

Consider a variable of interest (e.g. ash concentration at a location). We assume this to be a random variable, $\mathbf{x}_k$, whose time evolution is given by the `bent-puff`

$$\dot{\mathbf{x}} = \mathbf{f}(t, \mathbf{x}, \boldsymbol{\Theta}, \mathcal{W}) \tag{3}$$

In Eq 3, $\boldsymbol{\Theta} = \{\vartheta_1, \vartheta_2, \dots\}$ represents uncertain system parameters such as the vent radius, vent velocity, mean grain size and grain size variance and $\mathcal{W}$ is a given windfield from a NWP model.

Parameter	Value range	PDF
Vent radius, b_0, (m)	65-150	Uniform, $+$ definite
Vent velocity, w_0, (m/s)	45-124	Uniform, $+$ definite
Mean grain size, Md_φ, φ	3.5-7	Uniform, $\in R$
σ_φ, φ	$0.5-3$	Uniform, $\in R$

Probabilistic forecast - cont

The probability of having ash at a specific height is given by:

$$P(h) = \int_{\Omega} P(h|W)p(W)dW \approx \frac{1}{N_W}\sum_{i=1}^{N_W} P(h|W_i) \tag{4}$$

Expected value of the height:

$$E[h] = \int hP(h)dh = \int h(\partial, W)\left(\int P(h|W)p(W)dW\right)dh \tag{5}$$

$$= \int\int h(\partial, W)P(h|W)p(W)dWdh = \sum_{i=1}^{N_W} w_i \sum_{q=1}^{N_{CUT}} w_q h(\partial_q, W_i) \tag{6}$$

were w_i are the weights associated with the wind ensemble, while w_q are the obtained from using gPC expansion [3].

[3] Bursik, M.I. et al. (2012) Estimation and propagation of volcanic source parameter uncertainty in an ash transport and dispersal model: application to the Eyjafjallajökull plume of 14 - 16 April 2010, Bull. Volc.

CUT (Conjugate Unscented Transform)

The output moments are approximated as a weighted sum of the output of simulations run at carefully selected values of uncertain input parameters (quadrature points)

Conjugate Unscented Transform selects points that will integrate polynomials of total degree $2N$ -1 in n-dimensional space. To find the 8^{th} order moment in 4 dimensions, we need:

- 9^4 Clenshaw-Curtis points
- 5^4 Gauss-Legendre points
- 161 CUT points

Results

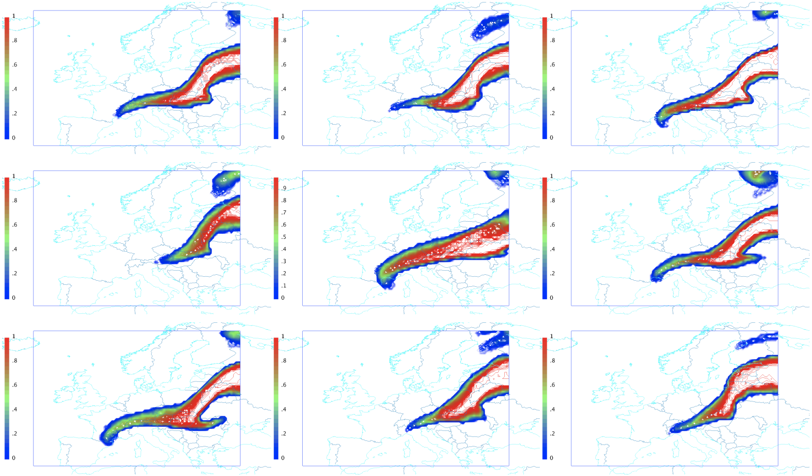


Figure : Probability of having ash at height greater than 1000m for a each wind field (first 9)

Results

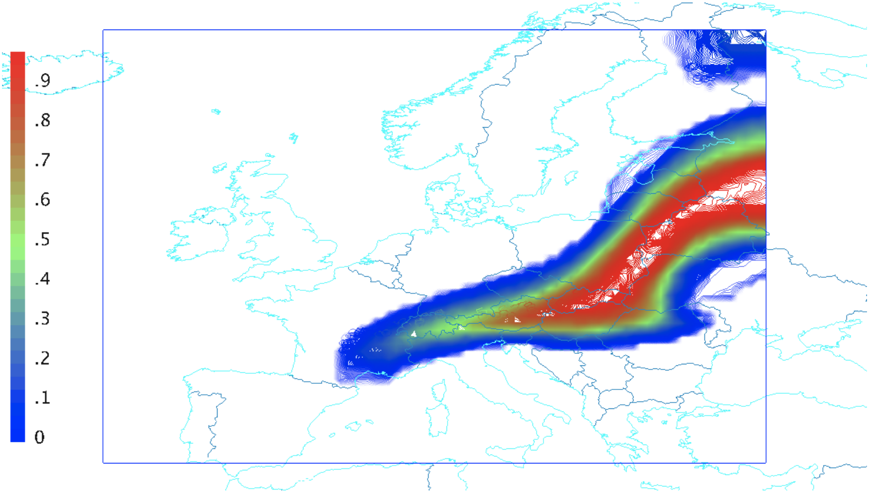


Figure : Mean probability of having ash at height greater than 1000m

Conclusions

- We account for the variability of the windfields in a volcanic ash cloud transport and dispersion model.
- Using WRF wind ensemble we are trying to capture the dependency on initial conditions that can lead to large differences in the forecasts.
- Output uncertainty due to uncertain input parameters is determined with a polynomial chaos quadrature-based sampling of the multidimensional puff input vector space.
- This work was supported by AFOSR grant number FA9550-11-1-0336 and NSF-IDR CMMI grant number 1131074.