Reducing the risk of volcanic ash to aviation

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What happens in the event of a volcanic eruption?

In the event of an eruption the Volcanic Ash Advisory Centres (VAACs) issue **hazard maps**, showing forecasts of **instantaneous horizontal ash coverage** in three vertically integrated layers of the atmosphere at **6 hourly-intervals** (see Figure 1). The boundaries of the ash show the **maximum expected extent** of the plume.

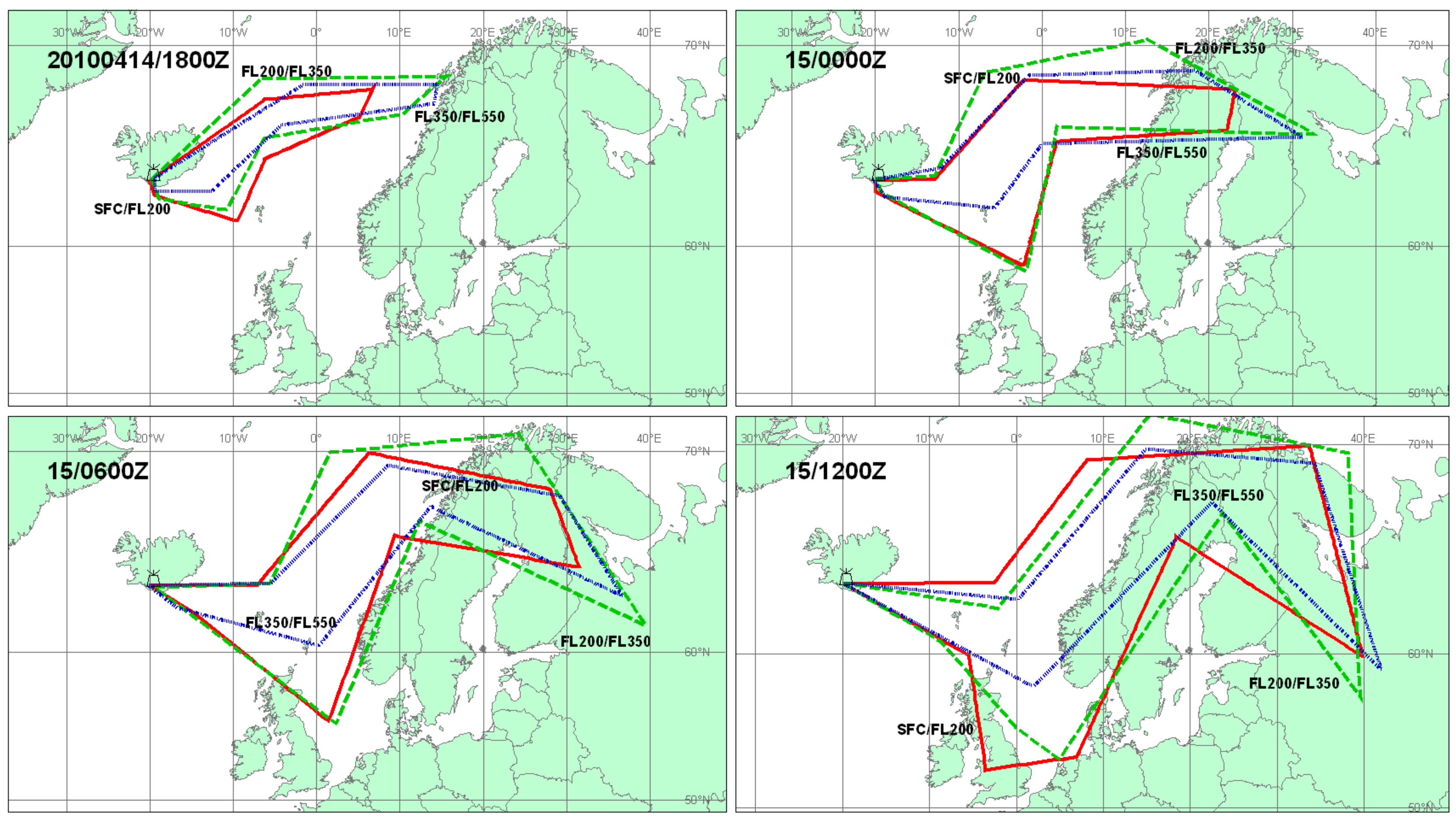

Figure 1: Forecast hazard maps issued by the London VAAC at 1800 on 14/04/2010 during the Eyjafjallajökull eruption. Contours shows the outermost extent of the volcanic ash cloud in 3 layers of the atmosphere.

Hazard maps are created by running **Volcanic Ash Transport and Dispersion (VATD)** models. In the case of the London VAAC the VATD model used is the **Numerical Atmospheric –Dispersion Modelling Environment (NAME)** which is run at the UK Met Office.

After the 2010 Eyjafjallajökull eruption the UK Civil Aviation Authority brought in new guidelines that not only require predictions of ash location but also **ash concentration**.

VATD models can predict ash concentrations, however, currently there is **no formal framework** for determining the uncertainties on these forecasts.

How can uncertainty in ash forecasts be quantified?

VATD models are **complex** and as such there are many sources of uncertainty in the resulting forecast. These include:

- **Source uncertainty:** eruption source parameters (including plume height, particle size distribution and mass eruption rate) and driving meteorology.
- **Parameter uncertainty:** parameters used in the representation of advection, dispersion and loss processes such as sedimentation, wet and dry deposition.
- **Structural uncertainty:** Missing processes such as aggregation of particles and gravity current spreading.

VATD models run **too slowly** to evaluate at very many parameter choices. We can however build an **emulator** to **predict** the model's output at any parameter choices given a collection of runs at other parameter choices.

What is an emulator?

An **emulator** is a **simple approximation** of the complicated model that can be evaluated almost instantly. Rather than trying to approximate the entire output, we intend to concentrate on **interesting summaries** of the output, for instance maxima, minima, or averages in particular areas at particular times.

Here emulators for a given quantity, y, consist of **two parts**: a linear combination of simple functions $g_i(x)$ of the parameters x, corresponding to the **mean trend**, and a **variance term** u(x) chosen so that the covariance between two parameter choices depends on the **distance** between them.

$$y(x) = \sum_i \beta_i g_i(x) + u(x)$$

This leads to an emulator that estimates the **expected value** and the **variance** for the summary y should we run NAME at parameter choice x, such that:

- For any x that we actually ran NAME for, the expected value of y(x) is the **value we observed** from the model run, and the variance is **zero**.
- When x is **near** a choice at which we ran NAME, the expected value will be **close** to this observed value and the variance will be **low**.
- When x is **far** from any model run, the expected value will be close to the **mean trend** and the variance will be **high**.

With an emulator, we can explore parameter space much faster, and find out which **parameters contribute the most to the forecast uncertainty**. It is possible to identify plausible and implausible regions of parameter space through **history matching**.

Case Study: Eyjafjallajökull eruption 14 May 2010

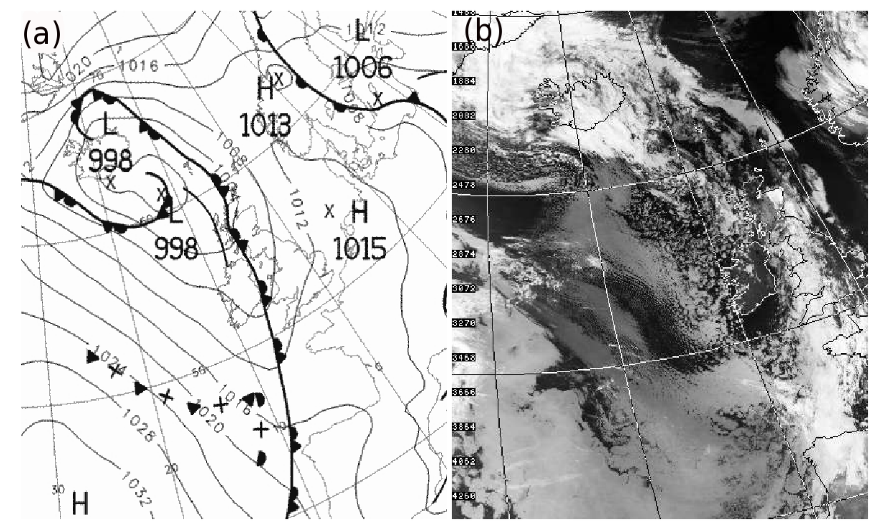

Figure 2: (a) UK Met Office surface analysis chart at 0000 on 14 May 2010. (b) AVHRR infrared satellite image at 0613 on 14 May 2010 (provided by the Dundee satellite receiving station).

Between 12 and 14 May a low pressure system moved across Iceland transporting ash cyclonically to the North and West of Iceland on 12 May, towards Europe on 13 May and to the West of Iceland on 14 May. Figure 2 shows the synoptic situation and satellite detected clouds at 0000 on 14 May.

In this case study

- **15 parameters** were varied **simultaneously** using parameter ranges determined by an **expert elicitation** exercise.
- **500 simulations** using the **NAME model** were used as inputs to the emulation.

Figure 3 shows the "worst" and "best" case scenarios of ash column loading for 1200 on 14 May 2010 produced using plausible parameter values determined by the experts in the elicitation exercise.

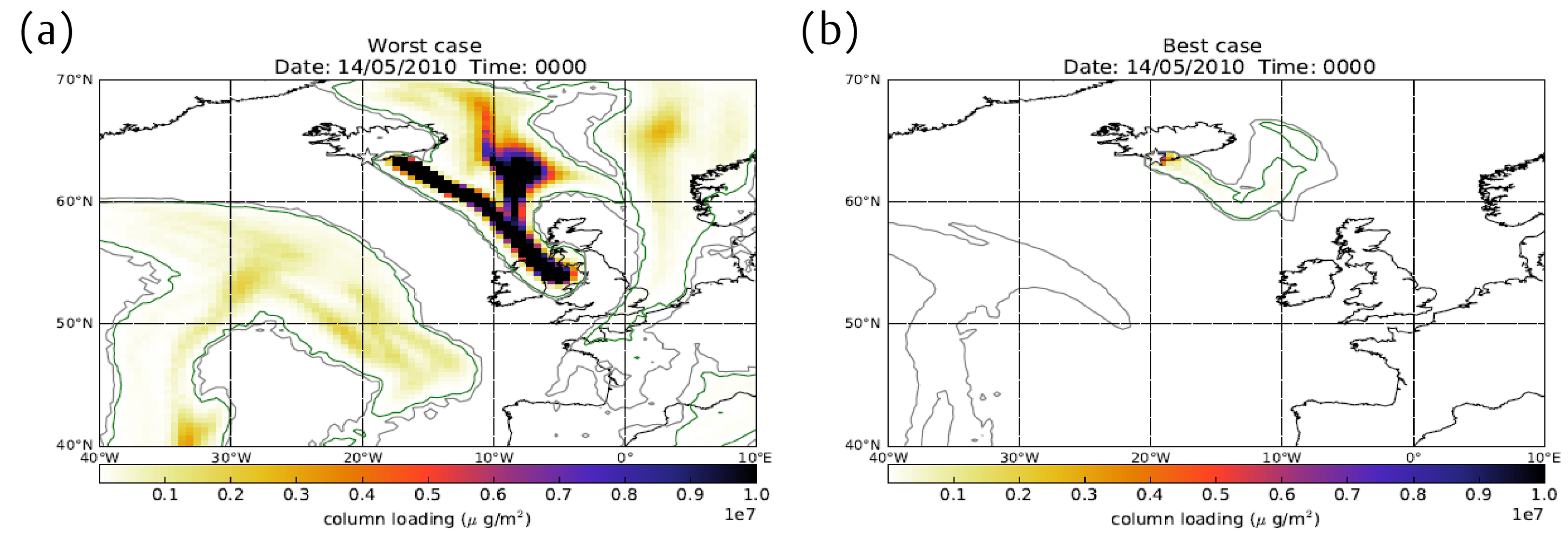

Figure 3: (a) Worst case and (b) best case scenario ash column loading distributions for 0000 on 14 May 2010. Filled contours show linear scale and solid contours show log scale.

In this study the **average ash column loading** in **81** pre-determined regions (2/3 per hour) was emulated. The regions for 0000 14 May 2010 are shown in Figure 4 and are based on the location of ash determined by SEVIRI brightness temperatures.

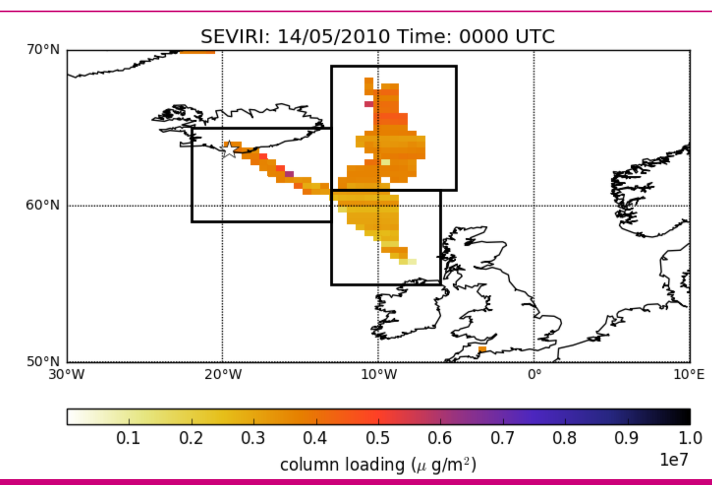

Figure 4: SEVIRI satellite retrieved ash column loading 0000 14 May 2010 with emulation regions indicated.

In practice only a small number of parameters contribute to the uncertainty in each region. The four *most active* parameters are (see Table 1):

- **plume height**
- **mass eruption rate**
- **standard deviation of the velocity for free tropospheric turbulence**
- **precipitation rate required for wet deposition**

This information will be used

- to inform future **research priorities** and measurement campaigns.
- to prioritise variables to perturb in a small **operational ensemble.**

Parameter	Number of regions where parameter is active
Plume height	81
Mass eruption rate	81
Standard deviation of velocity for free tropospheric turbulence	66
Precipitation rate required for wet deposition	65
Particle size distribution scale parameter	20
Lagrangian timescale for free tropospheric turbulence	18

Table 1: The six most active parameters and the number of regions that they are used in emulation.

Future work

- **History matching**: using observations in conjunction with the emulator to find plausible parts of parameter space. This can be used to inform parameter values in an operational ensemble.
- Develop **novel** methods to **communicate the uncertainty** for the end-users of volcanic ash forecasts, such as a **probabilistic** volcanic ash forecast product.