

<b>Institution:</b> University of Reading
<b>Unit of Assessment:</b> 7 Earth Systems & Environmental Sciences
<b>Title of case study:</b> Limiting the disruption to aviation caused by volcanic eruptions using balloon observations and model testing eruptions
<p><b>1. Summary of the impact:</b></p> <p>The 2010 eruption of Eyjafjallajökull volcano, Iceland caused prolonged closure of European airspace, costing the global airline industry an estimated \$200 million per day and disrupting 10 million passengers. We have developed and tested models that predict the dispersal of volcanic ash and developed instrumentation to monitor ash clouds during flight bans and used it to test the models. Our research played a key role in establishing the need for a flight ban and in the adoption of a more flexible approach to its staged lifting as the emergency continued. It also led to increased levels of readiness and to new emergency procedures being put in place across Europe which have minimised the economic costs and human inconvenience without an unacceptable rise in the risks to passengers and crew. The new procedures safely eliminated unnecessary disruption to flights in the latter days of the crisis and during the subsequent eruption of another Icelandic volcano, Grímsvötn in 2011.</p>
<p><b>2. Underpinning research:</b></p> <p>Over the past 2 decades, the Unit has developed new balloon-based radiosonde instruments,<sup>1</sup> including an aerosol monitoring package which has applications in monitoring volcanic ash clouds. In addition, the Unit has an extensive programme for assessing numerical models. As part of this, since 2007 the Unit has, in close collaboration with the Met Office, made detailed assessments of the capabilities and accuracy of the Met Office's NAME (Numerical Atmospheric-dispersion Modelling Environment) model used for forecasting the dispersion of atmosphere-borne particles originally developed following the Chernobyl radioactivity release in 1986, leading to important enhancements of the model. These tests have used observations by ground-based and airborne lidars (remote sensing devices that illuminate target parts of the atmosphere with a laser and analyse the reflected light) and other numerical models. The Unit was asked by the UK Government's Cabinet Office to apply both techniques urgently, and to give expert guidance during the eruption of Eyjafjallajökull in Iceland in April 2010.</p> <p>Hence the relevant research in the Unit was conducted via two complementary strands. (1) Using technology development funding from NERC,<sup>2</sup> the Unit developed a generic monitoring package for deployment on standard meteorological balloons which measures the size distribution of small atmospheric aerosols such as dust and ash (Nicoll et al., 2011). (2) A parallel on-going research activity has been to test and to contribute to the development of various models used to predict the dispersion of atmospheric pollutants (Dacre, 2010; Davis and Dacre, 2009). The key researchers in the Unit are Prof. R.G. Harrison and Dr H.F. Dacre who were both members of the Unit at the time, Dr A.L.M. Grant, a senior research assistant throughout, and Dr K.A. Nicoll, PhD student in 2008 who subsequently became a PDRA in 2010 and a Leverhulme Fellow in 2011.</p> <p>For both these research strands it is useful to discuss separately the work done (a) before the Eyjafjallajökull eruption on 14 April 2010 and (b) in its immediate aftermath.</p> <p><b>(a) Before the eruption of Eyjafjallajökull</b></p> <p>The radiosonde system has been developed over the past 20 years to carry a range of sensors for atmospheric measurements. Its turbulence measurements have been used as a benchmark for measurements in other planetary atmospheres, notably Titan, when visited by the Cassini/Huygens probe.<sup>3</sup> The system also provides in-situ aerosol observations for calibration and testing of lidar observations and unique data on dust and cloud properties (e.g. Saharan dust distribution<sup>4</sup> and electrification of volcanic ash clouds<sup>5</sup>). We applied the NAME model to Saharan dust clouds<sup>6,7</sup> and the prediction of the structure, amplitude and location of various pollution plumes. We were able to identify and quantify errors in these predictions (Dacre, 2010). In particular, predicted plumes were consistently too small, tended to give excessive concentration at their centre compared to observations and did not have the correct evolution. Comparison with a weather prediction model that employed a convection scheme showed that the dispersion model gave pollutant concentrations that were too low because it transported insufficient pollution vertically out of the turbulent lower atmosphere. Our work led to the Met Office making improvements to their model.</p> <p><b>(b) In the weeks after the ash cloud eruption from Eyjafjallajökull on 14 April 2010</b></p> <p>Met Office was made aware of the Unit's radiosonde technology and ash detection capability at one of the UK radiosonde technology transfer workshops run by the Unit. Consequently, when the</p>

Cabinet Office contacted the Met Office at the start of the Eyjafjallajökull crisis, they were referred to the Unit's balloon flight team (led by Prof R.G. Harrison). At the request of the Cabinet Office, the national standby Chinook helicopter at RAF Odiham was provided to fly the team to sample the ash plume during the early phase of the no-flight ban, enforced on 15 April 2010 (day 1 after the eruption). We used the NAME model in real time to identify Benbecula in northern Scotland as the optimum location at which to test the model predictions. The sounding taken there verified the presence of ash in the region, with concentrations close to the predictions of the (improved) model for that location, thereby providing key new information for decision-making (and the basis of the first peer-reviewed publication on the eruption (Harrison et al., 2010)).

In response to an urgent request from the Met Office, and supported by emergency funding from NERC via NCAS,<sup>8</sup> the Unit also tested the performance of NAME in monitoring the dispersion of the ash during the initial phase of the eruption (14-16 April 2010) and later (4-18 May 2010) (Dacre et al. 2013, Grant et al. 2012). It was shown that NAME model captured the timing and structure of the ash layer at its centre. However, there were important caveats. The main qualitative finding was that the accuracy of model forecasts was largely dependent on accurate information about the volcano source characteristics. Quantitatively, the main finding was that it was necessary to parameterise the fall out of large particles and aggregation and subsequent fall out of small particles in order to capture the observed volcanic ash concentrations over the whole of Europe. With these findings it was possible to define prediction uncertainties as a function of position and so develop a more flexible approach to air space closures.

1. [http://www.met.reading.ac.uk/~jq902220/curr\\_res/Met\\_tech\\_published.pdf](http://www.met.reading.ac.uk/~jq902220/curr_res/Met_tech_published.pdf)

2. for example, NERC Directed (Research Programme: Technology) Grant NE/H002081/1 £135k

3. R.D. Lorenz et al. (2007) *Planet. Space Sci.* 55, 13, 1936. doi:10.1016/j.pss.2007.04.007

4. <http://www.guardian.co.uk/news/2011/apr/01/weatherwatch-desert-dust>

5. T.A. Mather and R.G. Harrison (2006) *Surveys in Geophys.*, 27 (4) 387-432.

6. for example, NERC SOLAS Grant NE/C517276/1 £147k

7. C.L. McConnell et al. (2008), *J. Geophys. Res.*, 113, D14S05, doi: 10.1029/2007JD009606.

8. National Centre for Atmospheric Science emergency funding. Documents Available upon request

### 3. References to the research:

A WoS search (October 2013) shows that following peer-reviewed publications have averaged 5.2 citations each per year since publication. Because there are two strands to the work, and both involved building up the Unit's capabilities before the eruption and employing them after it, we cite a large number (9) papers. A subset of 3 publications for assessing research quality is marked with an asterisk. Research before the eruption was funded by a number of grants, mainly from NERC<sup>2,6</sup> and a Leverhulme Fellowship (Nicoll). Work after the eruption was funded by the Cabinet Office and NCAS emergency funding from NERC.<sup>8</sup>

\*H. F. Dacre, A. L. M. Grant, R. J. Hogan, S. E. Belcher, et al. (2011), [Evaluating the structure and magnitude of the ash plume during the initial phase of the 2010 Eyjafjallajökull eruption using lidar observations and NAME simulations](#), *J. Geophys. Res.*, 116, D00U03, doi:10.1029/2011JD015608 (41 cites)

\*K.A. Nicoll, R.G. Harrison, Z. Ulanowski, [Observations of Saharan dust layer electrification](#) *Environ. Res. Lett.*, 6, 1 (2011) 014001., doi:10.1088/1748-9326/6/1/014001 (23 cites)

\*N.I. Kristiansen et al. (incl. H.F. Dacre) (2012), [Performance assessment of a volcanic ash transport model mini-ensemble used for inverse modeling of the 2010 Eyjafjallajökull eruption](#), *J. Geophys. Res.*, doi:10.1029/2011JD016844 (13 cites)

R.G. Harrison, K.A. Nicoll, Z. Ulanowski, T.A. Mather, [Self-charging of the Eyjafjallajökull volcanic ash plume](#), *Env. Res. Lett.*, 5, 024004 (2010), doi:10.1088/1748-9326/5/2/024004 (30 cites)

H.F.Dacre (2010), A new method for evaluating regional air quality forecasts, *Atmos. Env.*, doi: 10.1016/j.atmosenv.2010.10.048 (1 cite)

L.S.Davis and H.F.Dacre (2009), [Can dispersion model predictions be improved by increasing the temporal and spatial resolution of the meteorological input data?](#), *Weather*, 64, 232-237, doi: 10.1002/wea.421 (4 cites)

A.L.M.Grant, H.F.Dacre, et al. (2012), [Horizontal and vertical structure of the Eyjafjallajökull ash cloud over the UK: A comparison of airborne lidar observations and simulations](#), *Atmos. Chem. Phys.*, 12, 10145-10159. doi:10.5194/acpd-12-9125-2012 (1 cite)

H.F. Dacre, A. L. M. Grant, and B. T. Johnson (2013) [Aircraft observations and model simulations of concentration and particle size distribution in the Eyjafjallajökull volcanic ash cloud.](#)

*Atmos. Chem. Phys.*, 13, 1277-1291. (1 cite)

B.J. Devenish et al. (incl. H.F. Dacre) (2012), [A study of the arrival over the United Kingdom in April 2010 of the Eyjafjallajökull ash cloud using ground-based lidar and numerical simulations](#), *Atmos. Env.*, 48, 152–164. doi:10.1016/j.atmosenv.2011.06.033 (14 cites)

#### 4. Details of the impact:

The Unit's research was key to the implementation of flexible emergency procedures that minimise disruption to air traffic without compromising safety, during volcanic ash emergencies.

##### **Contribution of the Unit's radiosonde measurements**

Flight bans were brought into effect during the crisis by nations across Europe because volcanic ash can seriously damage jet aircraft engines. The aviation industry's standing instructions for dealing safely with volcanic ash, published by the UN's International Civil Aviation Organization (ICAO), are to avoid all encounters with ash. During the initial phase of the Eyjafjallajökull eruption, the UK government adopted this "zero risk" approach and the Civil Aviation Authority (CAA) published a (non-zero) safety limit for volcanic ash particle concentration. The no-flight ban that had been imposed was quickly confirmed as appropriate by the Unit's radiosonde measurements. Our balloon flights were crucial because remote sensing observations cannot give the necessary detailed information on particle concentrations, size spectrum and composition that are essential to assessing the hazard (see Annex 1a of Zehner (2010)<sup>9</sup>) and the ban prevented manned research aircraft flights. Furthermore, because NAME could be run back-wards to define the ash source characteristics, the early use of balloons was useful in defining the source characteristics. After the eruption, as part of ensuring national readiness for future such emergencies, the Met Office contracted the Unit to produce more instruments (to date 20) to train Met Office staff to use them and the associated analysis software developed at the Unit.<sup>10</sup> The success of this is evident in the Met Office deployment of the equipment during the May 2011 Grímsvötn eruption in Iceland. They successfully measured ash above Fort William on 24 May 2011.<sup>11</sup>

##### **Contribution of the NAME model testing and analysis**

The Met Office has international commitments to provide dispersion modelling in emergencies caused by the releases of hazardous gases and materials into the atmosphere. It has been designated a VAAC (Volcanic Ash Advisory Centre) to provide forecasts and guidance to the CAA, National Air Traffic Services (NATS), airports and airlines in order to support their decisions on whether aircraft can fly safely. The London VAAC is particularly important for European aviation as it is responsible for monitoring and forecasting the movement of volcanic ash from Iceland.<sup>12</sup> The decisions for European nations were based on scientific advice provided by the London VAAC, relayed by the European Organization for the Safety of Air Navigation (EuroControl). However, national authorities soon came under pressure from European airlines, several of whom claimed that test flights in the supposed danger zone "showed that the models were wrong"<sup>17</sup>. After the bans had been in place for three days all major airlines claimed that authorities had been excessively cautious in their approach. In particular, the airlines disputed the validity of the NAME model in use by the VAAC and dismissed the estimates it gave on the ash cloud extent as "based on theoretical models, not on facts".<sup>17</sup> The UK authorities defended their "zero risk" regulatory response, pointing out that it was consistent with the guidelines by ICAO in their 2007 Manual on Volcanic Ash, as well as with the Volcanic Ash Contingency Plan (EUR Region).<sup>16,18</sup> Thus the validity of NAME became one of the two central issues (the other being the safe ash concentration limits for a jet engine) and its testing became an urgent requirement.

Consequently, the Met Office requested urgent additional testing of the model be done, and in particular its performance during the Eyjafjallajökull event. This was organised by the Met Office Chair at Reading (at that time, Prof. S.E. Belcher) as part of the newly-formed research partnership between the University and the Met Office. Emergency funding for the work was negotiated from NERC's NCAS.<sup>8</sup> Quoting VAAC staff:<sup>13</sup> "...to achieve maximum benefit the data needed to be analysed, compared with the model predictions, and appropriate lessons learnt regarding how much material was actually being emitted from the volcano and how much material survived the near-source fall-out processes (sedimentation of large particles, aggregation and sedimentation of fine ash, wash out, etc.) to reach the far field. Dacre et al (2011) was the first example of such an analysis and hence played a key role in the development of our ash modelling approach, both during the event itself using preliminary results which were made available to us, as well as after the event when our approach was revised further. The revised approach was deployed to good effect during the eruption of Grímsvötn in 2011." The key element of the revised model which was

used during the Grimsvotn eruption was a parameterisation quantifying fall out of large particles and aggregation and subsequent fall out of small particles. This parameterisation allowed quantitative predictions of volcanic ash to be made.

### ***New procedures and the lifting of the flight ban***

Based on the results from, and the additional tests of the NAME model and on the national risk management procedure, EU Member States, national air safety authorities, national air traffic controllers, and EuroControl realised that a more differentiated assessment of the risk posed by the ash cloud was needed than the “zero risk” blanket response. Using the work done by the Unit, the VAAC were able to divide NAME-predicted maps into three zone types (depending on the degree of contamination) such that flight bans could be restricted to smaller regions. On 20 April 2010 (day 6 of crisis) new procedures were defined, which led to a partial reopening of European airspace. By 22 April 2010 (day 8) regular flight schedules resumed.<sup>14</sup> This experience allowed more precise risk assessment procedures to subsequently be put in place in Europe “allowing for a much more graduated response and minimising closure of European airspace”.<sup>15</sup> Specifically, these procedures are credited as ensuring the subsequent eruption of Grímsvötn, which began on 21 May 2011, caused proportionally much less disruption. (The Grímsvötn event actually produced more ash than the Eyjafjallajökull event, but direct comparisons are difficult because weather conditions, and hence dispersion, was different). Europa.eu (the official website of the EU) states: “This is partially due to the different nature of the Grímsvötn volcano as well as different weather conditions. But to a much greater extent it is due to the more precise risk assessment procedures that have been put in place in Europe – allowing for a much more graduated response and minimising closure of European airspace”.<sup>15</sup>

The Eyjafjallajökull eruption caused prolonged closure of European airspace. The International Air Transport Association (IATA) estimated the airline industry worldwide lost £130 million per day as a result. The more flexible flight restrictions made possible by our research allowed these losses to be cut during the latter days of the crisis and during the Grímsvötn eruption. In addition to the economic impact on passengers, airlines and cargo there is saved human cost, as flight bans cause disruption to the schedules and plans of individuals from all walks of life and nationalities. 100,000 flights were cancelled, with over 10 million people affected. 42,600 flights were cancelled on the first three days of the crisis whereas only 900 were cancelled in the corresponding interval for the Grímsvötn eruption.

### **5. Sources to corroborate the impact:**

<sup>9</sup>. Zehner, C. Ed. (2010). Monitoring Volcanic Ash from Space. *Proceedings of the ESA-EUMETSAT workshop* on the 14 April to 23 May 2010 eruption at the Eyjafjoll volcano, South

Iceland. Frascati, Italy, 26-27 May 2010. ESA-Publication STM-280. doi:10.5270/atmch-10-01

<sup>10</sup>. 5 UoR contracts (£26k in total) to provide radiosonde technology, training and software licences: “Radiosonde Dust Charge Sensor”; “Sonde DCS Licence”; “Radiosonde Digital Acquisition System”, “Sonde DAS Licence”; and “Training for Met Office employees” (Available upon request).

<sup>11</sup>. Met Office Chief Scientist’s evidence to House of Commons (HoC) Science and Technology select committee. Scientific advice and evidence in emergencies. Transcript of oral evidence (to be published as hc 498-ii) “Scientific advice and evidence in emergencies: volcanic ash” 3 Nov 2010.

<http://www.publications.parliament.uk/pa/cm201011/cmselect/cmsctech/498/498.pdf>

The three radiosondes requisitioned from UoR in Q148 from G.Stringer to Prof Slingo (page Ev38)

<sup>12</sup>. C. Witham, et al., The current volcanic ash modelling setup at the London VAAC, Technical Summary (v1.1), Met Office Report, April 2012 – Available upon request or Met Office

<sup>13</sup>. Testimonial letter from VAAC Met Office Science Fellow – Available upon request

<sup>14</sup>. Volcanic Ash Cloud Timeline - April Events, Eurocontrol - Eur. Org. For the safety of air navigation, <http://www.eurocontrol.int/articles/volcanic-ash-cloud-timeline-2010-events>

<sup>15</sup>. European Commission, 2011, Volcano Grimsvotn: how is the European response different to the Eyjafjallajokull eruption last year? Frequently asked questions, MEMO/11/346 Brussels, 26 May 2011 [http://europa.eu/rapid/press-release MEMO-11-346\\_en.htm](http://europa.eu/rapid/press-release_MEMO-11-346_en.htm)

<sup>16</sup>. Alemanno, A (2010) The European Volcanic Ash Crisis: Between International and European Law, ASIL Insight, 14, Issue 21, <http://www.asil.org/sites/default/files/insight100712pdf.pdf>

<sup>17</sup>. Statement by Giovanni Bisignani, Director, General, & C.E. of the International Air Transport Association, IATA, April 19, 2010. <http://www.iata.org/pressroom/speeches/Pages/2010-04-21.aspx>

<sup>18</sup>. <http://www.eubusiness.com/news-eu/iceland-volcano.478>