Institution: University of Bristol		
Unit of Assessment: 7 – Earth Systems and Environmental Sciences		
Title of case study: Mitigating the risk volcanic ash poses to civil and military aviation through advances in ash modelling and measurement		
Period when the underpinning research was undertaken: 2000-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Watson, Matthew	Lecturer/Reader	2004-present
Phillips, Jeremy	Lecturer/Reader	1997-present
Brooker, Richard	Laboratory Manager	2010-present
Woodhouse, Mark	Researcher	2011-present
Cashman, Katharine	Professor	2011-present
Rust, Alison	Lecturer/Reader	2006-present
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Substantial changes in global airspace management were necessary after the Eyjafjallajökull volcanic ash crisis of 2010. Research at the University of Bristol (UoB) has played a central role in these changes by:

- Enabling Rolls-Royce to develop plane engines that can be safely flown through volcanic ash clouds
- Building new methods and tools to improve ash forecasting and monitoring, now used by Volcanic Ash Advisory Centres around the world
- Advising NATO on safe military operations, not only in ash clouds but also in other dusty environments, reducing risk to personnel
- Avoiding airport closure during volcanic eruptions by advising the Guatemalan Civil Aviation Directorate and Geological Survey

These impacts have resulted in socio-economic benefits for the aviation industry, including minimising exposure to liabilities of over GBP2 billion, and safer flight for passengers and aviation personnel all over the world.

2. Underpinning research

Volcanic eruptions can inject huge quantities of ash high into the atmosphere, where it presents significant risk to civil and military aircraft. Mitigation strategies are costly, requiring cancelled flights, rerouting and more intense maintenance regimes. Research across the School of Earth Sciences at UoB has made a significant contribution towards the global understanding of volcanic ash cloud composition, dynamics and hazard, particularly in the reduction of uncertainty in modelling and observation.

Volcanic ash effects on aircraft engines

Work by the experimental petrology group, in conjunction with Rolls Royce, tested the behaviour of a range of volcanic materials with engine components at high temperatures. This research demonstrated that the nature of volcanic ash (median grain size and composition) strongly affects its transport and deposition and its deleterious effects, such as accretion, erosion and corrosion, on the engine [**3.1**]. The results, using UoB's experimental design, indicated that ash with lower silica content and finer ash particles are more likely to stick to engine parts. Silicic ash, on the other hand, tends to form cindery deposits, which are more likely to self-clean [**3.2**]. At the request of Rolls-Royce, UoB researchers performed experiments with desert dust, which is chemically similar to volcanic ash and can also cause problems with engine function and, thus, flight safety. These experiments demonstrated that desert dust with lower quartz content can behave similarly to volcanic ash, and presents greater damage to engines than volcanic ash as it is usually present at lower altitudes.

Volcanic ash modelling

Volcanic ash dispersion models are crucial in forecasting ash clouds for aviation hazard management. They are used by all nine Volcanic Ash Advisory Centres (VAACs) worldwide, who issue warnings to pilots. These models had typically ignored the relationship between the rise height of volcanic plumes and the rate that particles are injected into the atmosphere. UoB research showed that neglecting wind effects, as was operational practice, can lead to underestimates of the amount of ash released by as much as a factor of 100, as was the case at Eyjafjallajökull **[3.3]**. The UoB modelling group developed a free web tool, PlumeRise, which gives more accurate estimates of the amount of ash injected into the atmosphere during a volcanic eruption because, uniquely, it properly accounts for the effect of the atmospheric state and wind. This reduces the risk of underestimating the amount of ash released and the extent of airspace containing ash, which would otherwise compromise the management of airspace during volcanic crises.

Characterisation of volcanic ash

The UoB group have made significant developments in methods for observing and characterising volcanic ash from satellites. As more satellite observations of an ash cloud become available, the observed location of the cloud at a particular time can be used to reinitiate the dispersion model in a process known as data insertion. This method was first applied by UoB academics, supported by researchers at the Met Office, to two recent eruptions which affected European airspace (Eyjafjallajökull and Grímsvötn). UoB demonstrated, for the first time, large reductions of up to 50% in the uncertainty of forecasts **[3.4]**. In addition, uncertainty in well-established observational methods was delimited, improving confidence in satellite measurements **[3.5]**. Further improvements have been made by taking the shape of ash particles on the distance travelled into consideration. The traditional assumption that particles are spherical can lead to underestimation by up to 400km of the distance they will travel **[3.6]**.

3. References to the research (maximum of six references)

[3.1] Gielhl, C., **Brooker**, R.A., Marxer, H., Nowak, M. (2017). An experimental simulation of volcanic ash deposition in gas turbines and implications for jet engine safety, Chemical Geology 461, 160-170. DOI: 10.1016/j.chemgeo.2016.11.024

[3.2] Pearson, D. and **Brooker**, R. (2020). The accumulation of molten volcanic ash in jet engines; simulating the role of magma composition, ash particle size and thermal barrier coatings. Journal of Volcanology and Geothermal Research, 389, p.106707. DOI: 10.1016/j.jvolgeores.2019.106707

[3.3] **Woodhouse**, M.J., Hogg, A.J., **Phillips**, J.C. (2016). A global sensitivity analysis of the PlumeRise model of volcanic plumes, Journal of Volcanology and Geothermal Research 326, 54-76. DOI: 10.1016/j.jvolgeores.2016.02.019

[3.4] Wilkins, K.L., Mackie, S., **Watson**, M., Webster, H.N., Thomson, D.J., Dacre, H.F. (2015). Data insertion in volcanic ash cloud forecasting, Annals of Geophysics 57. DOI: 10.4401/ag-6624

[3.5] Western, L.M., **Watson**, I.M., Francis, P.N. (2015). Uncertainty in two-channel infrared remote sensing retrievals of a well-characterised volcanic ash cloud, Bulletin of Volcanology 77 (8), 67. DOI: 10.1007/s00445-015-0950-y

[3.6] Saxby, J., Beckett, F., **Cashman**, K., **Rust**, A., Tennant E. (2018) The impact of particle shape on fall velocity: Implications for volcanic ash dispersion modelling Journal of Volcanology and Geothermal Research 362, 32-48. DOI: 10.1016/j.jvolgeores.2018.08.006

GRANTS ·

I. **Wagner, T**. *Consortium on Risk in the Environment: Diagnostic, Integration, Benchmarking, Learning and Elicitation*, (CREDIBLE), NERC October 2012 - September 2017, GBP1,100,000.
II. **Thomas, H**. *Reducing the economic impact of volcanic activity to aviation*. NERC KE FELLOWSHIP. January 2016 - November 2018, GBP90,973.

III. **Woodhouse, M**. *VolcTools - enhancing ease of use and uptake of tools to improve prediction and preparedness of volcanic hazards*. NERC KE FELLOWSHIP. January 2018 – November 2020, GBP154,208
IV. **Watson, M**. *Characterisation of the Near-Field Eyjafjallajökull Volcanic Plume and its Long-range Influence* NERC June 2011 – May 2015, GBP547,998.
V. Various NERC-CASE Studentship with the Met Office (Saxby, Wilkins, Western) 2014-2019
VI. **Watson, M**. *Environment Particulate Characterisation*, DSTL contract #DSTL/AGR/000616/01 for NATO AVT-250, June 2018 – December 2018, GBP49,049.

4. Details of the impact

The transport of ash by the wind can result in dispersion over vast areas at heights where aircraft fly. The ash poses a severe hazard to airframes and engines, requiring mitigating restrictions on flight operations. A notable example affecting the UK was the 2010 eruption of Eyjafjallajökull (Iceland) which resulted in extended closure of airspace, the cancellation of more than 100,000 flights and an estimated economic loss across all sectors of USD5 billion. The research conducted by UoB has led to safer air travel and demonstrable impacts which benefit the aerospace industry, airlines, airspace management and the military. These impacts continue to mitigate the level of disruption by ash in the UK airspace seen in 2010.

1. Ash-tolerant engines for Rolls-Royce

Triggered by the 2010 crisis, Rolls-Royce approached the UoB researchers in 2011 and instigated a collaborative project (running 2011-2017) aimed at minimising aviation disruption caused by volcanic clouds whist maintaining high safety requirements [**5.1**]. In March 2017, Rolls-Royce published a technical note [**5.1**] which established, for the first time for any engine manufacturer, a dosage up to which their engines can tolerate ash and led to a 2018 UK Civil Aviation Authority Flight Safety Award. In developing this dosage, Rolls-Royce relied on underpinning research carried out by UoB, drawing on the new understanding of how ash affects engines [**3.1**, **3.2**, noting publication of **3.1** was delayed at the funder's request] and observations and modelling of volcanic ash clouds [**3.3-3.6**]. The translation of this UoB research into practice represents a wholly new and very valuable approach that is "*ultimately based around engine exposure dose rather than simply ash concentration.* [This] *will save the aviation industry, and the wider economy, multiple 10s of £millions annually*" through reduced disruption and better maintenance regimes (Engine Environmental Protection, Rolls-Royce) [**5.1**].

Rolls-Royce are the first engine manufacturer in the world to do this and, as a result, they are currently the only engine supplier certified to operate in volcanic ash. Rolls-Royce lease their engines to airlines who can now operate in volcanic ash conditions. Rolls-Royce's engines are thus a more desirable option: "[which] *gives Rolls-Royce a competitive advantage when selling aircraft engines to airlines that operate in regions prone to frequent volcanic eruptions, because no other engine manufacturer has the knowledge and capability to allow their customers to use the approach*" (Engine Environmental Protection, Rolls-Royce) [**5.1**]. Improvement in understanding of engine exposure and damage mechanisms enables clear boundaries to be defined in terms of responsibility for ash-related damage, reducing Rolls-Royce's exposure to the costs of ownership. Rolls-Royce estimate the cost of liabilities to be "*over GBP 2billion*", a cost which "*the Bristol group's knowledge is being used to help reduce*" [**5.1**].

2. Better ash forecasting with PlumeRise and robust ash characterisation

Dispersion forecasts for volcanic ash are reliant on inputs to characterise the eruption conditions and ash properties. The British Geological Survey state "*The fundamental research on volcanic plume dynamics at the University of Bristol has contributed greatly to the international effort to better understand and respond to volcanic ash emergencies*" [**5.3**]. The London Volcanic Ash Advisory Centre (VAAC) is responsible for managing airspace in N. Europe and the N. Atlantic. Underpinning research using the PlumeRise model [**3.6**] resulted in their decision to invest in developing their own operational plume model. This model has increased the capability of the London VAAC to better initialise volcanic ash cloud dispersion models and uses non-spherical particles and two new particle size distributions as a direct result of research carried out at UoB

[**3.3**]. This has enabled improved forecasting of the early stages of ash dispersion when there is incomplete knowledge of the ash particle size distribution [**5.2, 5.3**].

The PlumeRise model has an online interface which is available to users globally and, as of March 2020, 500 unique users have requested over 95,000 model runs. Users, who in total represent eight of the nine VAAC regions, include the London, Darwin and Buenos Aires VAACs and the Icelandic Met Office [**5.4**]. The Darwin VAAC now runs a local version which it uses for monitoring Indonesian airspace, one of the world's busiest for flights, combined with a high density of active, ash-producing volcanoes and have stated "*The PlumeRise model, web-interface and under-pinning research have contributed significantly to the work of VAAC Darwin and the Bureau of Meteorology, and therefore to the management of the ash hazard to aviation within our area of responsibility and more widely through our connections with the global VAAC network. The PlumeRise model supports our operational responsibilities, helping us to provide informative and science-based advice to the aviation industry*" [**5.4**]. The model is used operationally many times each year, including for activity from Krakatau in Indonesia and Ulawun in Papua New Guinea in 2020.

The Icelandic Met Office have used PlumeRise in their eruption scenario planning exercises and incorporated it into their forecast and response system. During the Bardarbunga eruption in 2014-2015 the model provided daily, high-quality outputs that allowed for rapid assessment of the risks [**5.5**]. The Icelandic Met Office describe PlumeRise as "*an invaluable tool for assessing potential eruption scenarios and initializing ash dispersion models …. At the time of the recent Holuhraun eruption (2014-15), the PlumeRise model was the only accessible plume model that could run with the real atmosphere*" and further "*These outputs were shared in the regular meetings between IMO and the Department for Civil Protection, and would have allowed for rapid assessment and dispersion model initiation had an explosive eruption occurred*" [**5.5**]. Through formal communications between the Icelandic Met Office and the UK Met Office, these benefits were passed on to the London VAAC. PlumeRise training has been included in the annual International Training Schools on Convective and Volcanic Clouds Detection Monitoring and Modelling since 2015, reaching over 100 early career practitioner professionals from over 20 countries, as well as established research scientists.

3. Safer military operations for NATO

Watson, Phillips and Brooker of UoB were invited by NATO to co-author a technical report, completed in 2018, for NATO and the UK Ministry of Defence that defines NATO's position on safe military operations in hostile environments (including desert dusts and sea salt, as well as volcanic ash) [**5.6**]. The UoB team led Chapter 3 of the report, which detailed the current state of the art in satellite remote sensing observations (specifically uncertainties), dispersion modelling and data assimilation, based upon previous research [**3.3-3.6**]. At ~400 pages and ~200,000 words the full report is available to over 2,000,000 NATO personnel as a guide for best practice. The report defines research and development priorities on safe operations in contaminated environments for the 28 countries within NATO. The UK's Defence Science and Technology Laboratory (DSTL) state "*The University of Bristol were responsible for one of the key chapters of the AVT-250 final report that set the context for the EP [Environmental Particulate] problem in aviation. This chapter included: a summary of EP characterisation methods, tools and equipment; the impact of meteorology on EP endurance and its dispersion; and guidance on the likelihood of encounter of EP at critical locations of interest to the NATO Nations when operating in other parts of the world and during different times of the year*" [**5.7**].

The former Chief Scientist of US Air Mobility Command, who led two research task group (RTG) efforts in which Watson played a pivotal role, states "*The most significant impact has been the creation of a new research effort, with direct lineage to AVT-RTG-250, in The Technical Cooperation Program (TTCP) collaboration. TTCP is a collaborative S&T forum among Australia, New Zealand, Canada, the United States of America, and the United Kingdom. A recent major program start is "Owning the Extreme Environment", with the audacious goal of safe operations in conditions previously denied to or avoided by operators. The [NATO AVT-]250 study …helped focus and inform the TTCP. I ... can attest that the structure and methodology Dr. Watson and his* *team originated to characterize, analyze, and forecast environmental threats will provide a foundation for our study*" [**5.8**].

4. Minimising airport closure in Guatemala during volcanic eruptions

UoB research is also informing national responses to volcanic eruptions, helping to minimise economic and societal disruption, continuing the work undertaken for the Icelandic ash crisis. Guatemala has some of the world's most persistently active explosive volcanoes, two of which lie within 40km of the main airport, La Aurora. The UoB researchers ran a workshop in 2017 to disseminate research on managing airspace in proximity to a volcanic ash source with the Guatemalan Civil Aviation Directorate, DGAC. At this workshop, training in the tools developed by UoB [**3.1-3.6**] was given to over 40 air traffic control staff. As a result, DGAC could ensure that La Aurora airport stayed open during the major eruption of Fuego in 2018, except for a period of about 24 hours on the 3rd and 4th of June: "*You* [UoB] *have run several workshops in the last five years, including with SENACYT (the executive secretariat for STEM in Guatemala), INSIVUMEH and DGAC (the Guatemalan civil aviation authority). They cite you as the key leader advising them in policy making around volcanic ash and aviation safety, and because of this INSIVUMEH were able to pass better information about the eruption to the DGAC more quickly during the eruption*" [**5.9**] and "*As a result, DGAC was able to manage the eruptions of February, June and November 2018 with greater certainty and that better understanding enabled us to keep the airport open when otherwise we might have closed it*" [**5.10**]. As Guatemala's only international airport, La Aurora airport is an absolutely vital transport hub serving the entire country and was a critical entry point for overseas aid after the disaster.

5. Queens Anniversary Prize 2015

Testament to the UoB research team's achievements, they were awarded the Queen's Anniversary Prize in 2015. The award recognised the "*outstanding research into the risks posed by volcanoes to aviation, developing an innovative computer model for predicting ash plume movement and helping to make airspace safer for the public"*.
https://www.queensanniversaryprizes.org.uk/winners-archive/
http://www.bristol.ac.uk/news/2015/november/queens-anniversary-prize-2015.html
https://www.express.co.uk/news/royal/620661/University-awarded-Queen-Anniversary-Prizes-dementia

5. Sources to corroborate the impact

[5.1] Rolls-Royce (2020) Factual Statement - Associate Fellow – Engine Environmental Protection
Rolls-Royce (2017) Volcanic Ash and Aviation – Rolls-Royce Position, May 2017
[5.2] London VAAC/Met Office (2020) Factual Statement - Strategic Head of Atmospheric Dispersion and Air Quality
[5.3] British Geological Survey (2019) Factual Statement – Head of Volcanology
[5.4] Darwin VAAC (2020) Factual Statement – VAAC Darwin Manager
[5.5] IMO Icelandic Meteorological Office (2020) Factual Statement - Group Leader of Atmospheric Research
[5.6] NATO (2018) AVT-250 'Environmental Particulate Foreign Object Damage' Report (see Chapter 3)
[5.7] DSTL (2019) Factual statement - Principal Engineer Air Propulsion and Energy Systems Team
[5.8] Erbschloe Technical Consulting (2020) Factual statement – former Chief Scientist of US Air Mobility Command (2006-2015)
[5.9] INSIVUMEH (2020) Factual statement – Sub-director of INSIVUMEH
[5.10] DGAC (2020) Factual statement – Head of Air Traffic Control at Guatemala City airport.