Institution: University of Exeter		
Unit of Assessment: UoA 7 Earth Systems and Environmental Sciences		
Title of case study: Developing the Resilience to Icelandic Volcanic Eruptions (DRIVE)		
Period when the underpinning research was undertaken: 2010-2019		
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:**
James Haywood Florent Malavelle	Professor of Atmospheric Science Research Fellow	2010 – present 2011 – 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 (indicative maximum 100 words)

The closure of UK and European airspace for the first week after the Eyjafjallajökull volcanic eruption in Iceland in 2010 cost airlines around $1.7bn, with knock-on impacts on the global economy estimated at $4.7bn (~£500m per day). This study details work by Prof Jim Haywood in developing resilience to volcanic aerosols. Specifically:

- Development of new technology, instrumentation and retrievals used to determine aerosol types and concentrations including development and deployment of a fully instrumented civil contingency aircraft and patented volcanic ash sensors on commercial aircraft.
- Changes to practice that kept UK airspace open during intrusions of volcanic ash (July 2019) and detection and attribution of smoke detected on aircraft to wild-fires that averted widespread aviation disruption (October 2017) saving at least £500M.
- Policy briefings to the government Cabinet Office Briefing Room (COBRA) and United Nations Office for Disaster Risk Reduction.

2. Underpinning research (indicative maximum 500 words)

Haywood has been employed at the University of Exeter since 2016 and has 20 years of experience observing and modelling atmospheric aerosols including volcanic sulphate **[3.1]** and ash **[3.2-3.4]** and smoke from deforestation and wildfires [**3.4-3.6**]. Haywood was a key player in the UK's response to the Eyjafjallajökull eruption, having coordinated research from missions of NERC's Facility for Airborne Atmospheric Research (FAAM) aircraft into the resulting ash plume. These missions made unique observations of volcanic ash mass concentrations through in-situ observations [**3.2**], passive remote sensing measurements and active Light Detection and Ranging (lidar) instrumentation [**3.3**]. These measurements proved invaluable for the UK's Volcanic Ash Advisory Centre (VAAC) and contributed to the Civil Aviation Authority (CAA) opening airspace at the earliest possible opportunity. Haywood has also been one of the world's leading aerosol scientists in measuring the physical and optical properties of smoke from agricultural practices, deforestation and wildfires, having led many airborne measurements worldwide over a period of around 20 years [**3.5-3.6**]. Most recently, he has been the overall Principal Investigator of a NERC large grant (£3.7m, CLARIFY, NE/L013797/1) that examined the microphysical and optical properties of smoke and its climatic impact over Ascension Island after transport from the African mainland [**3.5**]. Haywood won an open competition Natural Environment Research Council PhD CASE studentship (Developing the Resilience to Icelandic Volcanic Eruptions, DRIVE; NE/M009416/1) supported by the CAA and recruited Martin Osborne as a PhD student.

Haywood's underpinning research [**3.2-3.3**] contributed to the procurement of a fully-instrumented civil-contingency aircraft (MOCCA) that operated until the Covid-19-induced reduction of commercial flights. Analysis by Haywood's group showed that MOCCA was able to accurately monitor non-spherical particles such as volcanic ash [**3.4**]. Informed by Haywood's underpinning research [**3.2-3.6**], a series of 10 lidar instruments funded by the CAA have been deployed by the Met Office across the UK to provide additional volcanic ash retrievals [**3.4**]. The algorithms developed by Osborne and Haywood for these lidars can discriminate non-spherical ash particles and absorbing smoke from other atmospheric aerosols using a combination of Raman lidar, sun-photometer-derived aerosol size distributions, and depolarisation capabilities.

The development and deployment costs for the MOCCA and the lidar network are commercial in confidence but are likely several million GBP, with significant ongoing running costs. Recognising the need for low-cost systems for detecting volcanic ash, Haywood developed a cheap, lightweight prototype "Zeus" sensor and developed the mathematical model based on ash-induced charging and discharging of the aircraft frame. The Zeus sensor has multiple international patents (Haywood as one of three named inventors **[5.5]**) and has been successfully trialled by FlyBe Dash-8 and British Airways Boeing 747 aircraft.

References to the research (indicative maximum of six references)

3.1 Malavelle, F., **J.M. Haywood**, et al., Strong constraints on aerosol-cloud interactions from volcanic eruptions, *Nature*, 546, 485–491, 2017 doi.org/10.1038/nature22974
3.2 Johnson, B., Turnbull, K., Brown, P, Burgess, R., Dorsey, J., Baran, AJ, Webster, H., **J.M. Haywood**, J, Cotton, R., Ulanowski, Z., Hesse, E., Woolley, A and Rosenberg, P , In situ observations of volcanic ash clouds from the FAAM aircraft during the eruption of Eyjafjallajökull in 2010, *J. Geophys. Res*., 117, D00U24, 2012 doi.org/10.1029/2011JD016760
3.3 Marenco, F., B. Johnson, K. Turnbull, S. Newman, **J.M. Haywood**, H. Webster, and H. Ricketts, Airborne lidar observations of the 2010 Eyjafjallajökull volcanic ash plume, *J. Geophys. Res.*, 116, D00U05, 2011 doi.org/10.1029/2011JD016396
3.4 Osborne, M., **F. Malavelle**, M.Adam, J. Buxmann, J.Sugier, F. Marenco, and **J. Haywood**, Saharan dust and biomass burning aerosols during ex-hurricane Ophelia: observations from the new UK lidar and sun-photometer network, *Atmos. Chem. Phys*., 19, 3557–3578,2019 doi.org/10.5194/acp-19-3557-2019
3.5 Haywood, J.M., et al., Overview: The CLoud-Aerosol-Radiation Interaction and Forcing: Year-2017 (CLARIFY-2017) measurement campaign, *ACPD*, 2020-729, 2020 doi.org/10.5194/acp-2020-729
3.6 Haywood, J.M., et al., The mean physical and optical properties of regional haze dominated by biomass burning aerosol measured from the C-130 aircraft during SAFARI 2000, *J. Geophys. Res.,* 108(D13), 8473, 2003 doi.org/10.1029/2002JD002226

4. Details of the impact (indicative maximum 750 words)

Volcanic ash is an aviation hazard and costly to the industry [**5.1**]. The closure of UK and European airspace for the first week after the Eyjafjallajökull volcanic eruption in Iceland in 2010 cost airlines around $1.7bn [**5.1**] with knock-on impacts on the global economy estimated at $4.7bn [**5.1**]. Current international aviation safety regulations are based on qualitative 'visible or 'discernible ash' [**5.2**] detection limits that suffer from obvious operational and technical limitations. Prior to October 2017, there was no aviation requirement for reporting the presence of large quantities of smoke. However, atmospheric smoke can cause severe disruption to flights as it can frequently be misidentified as originating from the aircraft, causing activation of emergency procedures. Haywood's expertise has been called upon by the VAAC in critical situations such as the unrest of Katla Volcano, Iceland, in 2016, the smoke associated with Portuguese wild-fires in October 2017, and the eruption of Raikoke, Kamchatka Peninsula, in 2019.

4.1 Development of new technology, instrumentation and retrievals used to determine aerosol types and concentrations including development and deployment of a fully instrumented civil contingency aircraft and patented volcanic ash sensors on commercial aircraft.

a) Lidar instrumentation
Osborne and Haywood showed that the alignment of the depolarising filter blocks used in each of the 10 lidars was inaccurate leading to high uncertainties and biases in derived

volcanic ash mass concentrations. Therefore, they designed, manufactured and installed bolt-on external hardware and developed integrated software algorithms that correct these fundamental issues leading to a significant improvement of the minimum sensitivity of the instruments [**5.3**]. Subsequent to the corrections, these instruments can estimate volcanic ash concentrations at an unrivalled sensitivity for a stand-alone network. The minimum detection threshold for volcanic ash is around 10 $\mu g \cdot m^{-3}$, which can be compared to the quantitative 'no-fly' limits of 4000 $\mu g \cdot m^{-3}$ adopted by the VAAC and CAA. These algorithms are now used routinely by VAAC forecasters to determine aerosol types and concentrations during aerosol intrusion events over the UK [**5.4**].

b) Development and deployment of MOCCA aircraft and electrostatic volcanic ash sensor for use on civil airlines

Haywood helped in successfully making the case for a new aircraft for monitoring volcanic ash (MOCCA). The equipment on MOCCA was based on Haywood's analysis of data from the Eyjafjallajökull eruption [**3.2, 3.3, 5.10**]. MOCCA operated 2015-2020 on a 24/7, 365 days per year basis. To service this requirement, Haywood was one of five rostered MOCCA coordinators having been on-call on 88 separate occasions for a total of over 500 days and is the most experienced of all the MOCCA coordinators.

As one of three named inventors, Haywood filed 12 joint patents for the Zeus electrostatic sensor, six of which have been already been granted or published [**5.5**]. The patents cover a wide range of geographic areas and countries including Europe and the USA. These sensors rely on triboelectric charging from volcanic ash particles being transferred to the airframe when a plane encounters concentrations of volcanic ash. The rate of charge build-up and dissipation can be measured and modelled using a relatively simple conceptual model (developed by Haywood) and can be converted to a volcanic ash concentration. The Zeus sensor has routinely been flown routinely on FAAM, MOCCA and BA Boeing 747 and FlyBe Dash-8 aircraft [**5.6**]. Commercialization is currently being investigated in collaboration with BA and avionics companies.

4.2 Changes to practice that kept UK airspace open during intrusions of volcanic ash (July 2019) and detection and attribution of smoke detected on aircraft to wild-fires that averted widespread aviation disruption (October 2017).

In October 2017, 32 emergency procedure and MAYDAY calls from aircraft owing to reports of smoke within aircraft were received in UK airspace [**5.7**] leading to emergency descents, emergency landings and emergency evacuations, that caused much passenger distress, displacement of passengers and damage to aircraft [**5.8**]. Real-time analysis of operational data from the lidar algorithms developed by Osborne and Haywood revealed that there were unusually high concentrations of atmospheric smoke transported from fires on the Iberian Peninsula to UK airspace by the synoptic meteorology associated with Hurricane Ophelia. This external smoke entered through the aircraft air-vents causing the strong smell of burning reported by air-crews. These results were communicated via the VAAC to the National Air Traffic Service (NATS) and CAA, and via the World Meteorological Organisation (WMO) Commission for Aeronautical Meteorology (CAeM) to the International Civil Aviation Organization (ICAO). Utilising Osborne and Haywood's algorithms together with dispersion simulations allowed the NATS to prevent more widespread disruption to the aviation fleet. Given that closure of UK airspace during the shutdown caused by Eyjafjallajökull volcanic eruption caused an estimate £500m/day cost to the economy **[5.1]**, avoidance of disruption to even just 1 in 100 flights equates to a cost saving to the economy of ~£5m. In a presentation to the WMO and Met Office, Ian Lisk, President, CAeM of WMO stated

> "*Lovely to be able to see the lidars being used* […] *to actually see world leading research [being put to use] is exciting. In terms of the MAYDAYs* […] *being able to provide advice that says you're smelling smoke because there's a lot of it up there* […] *is a big deal"* [**5.4**].

In July 2019, the UK VAAC used Haywood and Osborne's lidar algorithms to detect volcanic ash from the Raikoke eruption in UK airspace at aircraft cruise altitudes. Concentrations of volcanic ash reached a maximum of ~0.1 mg m^3 (100 μg m^{-3}) which frequently exceeded those detected during the period when airspace was closed due to the Eyjafjallajökull eruption (see Table 4 of Johnson et al., (2012) [**3.2**]). Volcanic ash continued to be detected for a period of around 3 weeks albeit at lesser concentrations. These results were communicated via the VAAC to the CAA, CAeM and ICAO. As the ash was 'discernible', if ICAO regulations [**5.2**] were adopted then UK airspace would have been closed. The fact that airspace was NOT closed shows the confidence that the VAAC, the CAA, CAeM and ultimately ICAO place on Osborne and Haywood's retrieval methods. It also shows the levels of trust that have been developed between the scientists, the aviation industry and policy makers. Ian Lisk, President of CAeM of the WMO stated of Haywood's work,

> "*The eruption of Raikoke in June 2019 and the resultant plume of ash of very low concentrations of ash and sulphates into UK airspace have provided an excellent case study to demonstrate the success and benefits of the work undertaken by you* […] *your work has helped to support the pull through of this world leading science* [quantitative assessment of volcanic ash] *into operations*." [**5.9**].

Even one day of airspace closure proved to have an impact on the global economy estimated at around £500m/day **[5.1]**. Without the pioneering work of Haywood and his group, under ICAO regulations, UK airspace should have been closed. A conservative estimate of the costs avoided by not closing airspace is £500m.

4.3 Science and policy briefings to the UK Government
Haywood has been at the forefront of science to policy communications. In 2014, Haywood produced a policy briefing to the United Nations Office for Disaster Risk Reduction [**5.10**] highlighting the development of the MOCCA and lidar/sun-photometer network. In 2016, Haywood acted as the MOCCA coordinator during the unrest at Katla (Iceland) where the aviation alert was raised from green to amber. Haywood acted as part of the Met Office Incident Management Team providing scientific capability advice to the Met Office VAAC and to the government COBRA [**5.11**].

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 (a) https://en.wikipedia.org/wiki/British_Airways_Flight_9: "*At approximately 13:42 UTC (20:42 Jakarta time), the number four Rolls-Royce RB211 engine began surging and soon flamed out. The flight crew immediately performed the engine shutdown drill, quickly cutting off fuel supply and arming the fire extinguishers. Less than a minute later, at 13:43 UTC (20:43 Jakarta time), engine two surged and flamed out. Within seconds, and almost simultaneously, engines one and three flamed out, prompting the flight engineer to exclaim, "I don't believe it—all four engines have failed!",* **(b)** Press Release http://news.bbc.co.uk/1/hi/business/8634147.stm : On 21 April 2010 after ~1 weeks of airspace closure, the BBC reported, "*Global airlines have lost about $1.7bn (£1.1bn) of revenue as a result of the disruptions caused by the Icelandic volcanic eruption, a body [International Air Transport Association (IATA)] has said*." **(c)** Oxford Economics Report: The Economic Impacts of Air Travel Restrictions Due to Volcanic Ash, PDF Document. Page 2 "*The total impact on global GDP caused by the first week's disruption amounts to approximately US$4.7 billion*."

5.2 Flight Safety and Volcanic Ash. Risk Management of Flight Operations with Known or Forecast Volcanic Ash Contamination, ICAO Document 9974, 2012. PDF Document
"*Current avoidance guidance refers to visible or discernible ash. There is a need to define these terms in a manner that facilitates their use both at dispatch and in the en route phase of flight (such as quantitative descriptors).*"

5.3 Conference proceedings from the 29th International Lidar Radar Conference, China, 2019.

5.4 Video demonstration by Osborne and Haywood to Ian Lisk (President of World Meteorological Organisation (WMO) Commission for Aeronautical Meteorology (CaeM)) and

Jonathan Dutton, Head Aviation, Met Office, of the capabilities of the operational lidar system. 28 Sept 2020.

5.5 Granted and published patents (of 12 filed):
(i) Europe, #11775818.5 (Aerosol detection, granted 02/03/2016)
https://patents.google.com/patent/EP2622387B8/en?oq=13821873).
(ii) USA, #13821873 (Aerosol detection, granted 07/14/2015)
https://patents.google.com/patent/US20130193978A1/en?oq=13821873
(iii) Canada, #2812752 (Aerosol detection, granted 23/01/2018)
https://patents.google.com/patent/CA2812752C/en?oq=13821873
(iv) China, #201180046658.0 (Gasoloid detection, granted 20/04/2016)
https://patents.google.com/patent/CN103282798B/en?oq=201180046658
(v) Brazil, #BR112013007332-1 Aerosol detection, published 03/11/2020)
https://patents.google.com/patent/BR112013007332B1/en?oq=BR112013007332
(vi) Russia, #2013109016 (Aerosol detection, granted 10/11/2015)
https://patents.google.com/patent/RU2013109016A/en?oq=2013109016

5.6 Press Release http://aviationtribune.com/airlines/europe/british-airways-experimenting-ash-detecting-zeus-device/ : *"An early prototype of ZEUS has been flying on the NERC/Met Office dedicated research aircraft and a Flybe Dash-8 Q400 passenger aircraft since 2012, gathering background data from around Europe. This data was used to demonstrate that the ZEUS sensor can distinguish between the levels of electrostatic charge on the aircraft when flying in normal conditions and when volcanic ash is present."*

5.7 ICAO Incident Report, PDF Document. Page 6: "*The UK AAIB informed the Investigation that they were notified of about 32 events [….]. Most crews declared either a PAN-PAN or a MAYDAY and the majority of crews went on oxygen […]. There were clusters of affected aircraft in the following locations; Channel Islands, Liverpool, Manchester, and later in the day at Heathrow."*

5.8 Air Accident Investigation Branch (AAIB) Bulletin, PDF Document. Page 66: *"The following safety action was recommended: Met Office systems allow a SIGMET to be issued that contains smoke related information and, although it is not compliant with the ICAO format or existing templates, a test showed that it was compatible with NATS's systems. In future a SIGMET will be issued"*

5.9 Letter from Ian Lisk, President of World Meteorological Organisation (WMO) Commission for Aeronautical Meteorology (CAeM) who work closely with ICAO to provides guidance on hazards such as volcanic ash.

5.10 United Nations, Office for Disaster Risk Reduction Case Study: Developing an aviation warning system for Icelandic Volcanic Eruptions, United Nations Office for Disaster Risk Reduction: UNISDR Scientific and Technical Advisory Group. PDF Document

5.11 Letter from Clare Lee, Head of Observational Based Research, Met Office. "*Also, thank you for standing in for me at the Met Office Incident Management Team (IMT) meeting that took place during the afternoon. The IMT provide policy advice direct to the government through Cabinet Office Briefings (COBRA) and more informal channels. The advice that you were able to give the IMT was very much appreciated and the IMT were very happy with the level of support that you gave them."*