



# IMPACT ANALYSIS OF NASA EARTH SCIENCE APPLICATIONS PROJECT

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*NASA VOLCANIC CLOUD DATA FOR AVIATION*

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## Executive Summary

The NASA Applied Sciences Program supports efforts to discover and demonstrate innovative and practical uses of NASA Earth science data and knowledge. The program funds applied science research and applications projects across a range of themes to enable near-term uses of NASA Earth science by public and private organizations.

In 2006, the program initiated a score of projects selected under an open, competitive solicitation.<sup>1</sup> One of the projects — *NASA Volcanic Cloud Data for Aviation Hazards* — focused on developing ash data in near real-time for distribution by the National Oceanic and Atmospheric Administration (NOAA) to decision support systems that, in turn, provide the data to operational aviation management agencies to manage flight operations and ensure safe flights.

NASA's Earth Sciences Division's Applied Sciences Program supplies Earth observations information to NOAA to support the U.S. Volcanic Ash Advisory Centers (VAACs) in Washington, DC, and Anchorage, Alaska. The VAACs, part of a system of nine centers worldwide, were established in the 1990s to detect, measure, and provide near real-time data about volcanic eruptions. Although major eruptions are infrequent, when they do occur, aviation safety officials heavily rely on VAAC data. Typically this information is combined with data from the National Weather Service (NWS) to estimate the extent and concentration of ash plumes. These estimates are used to determine areas where flying conditions may be hazardous. The aviation community uses the results to adjust flight routes and schedules to keep within safe limits. One example of this is the April 2010 eruption of the Eyjafjallajökull volcano in Iceland, which led to the cancellation of more than 100,000 flights. NASA observations were not used at the London VAAC prior to the 2010 eruption; however, on 19 April, seven days after the eruption began, the London VAAC began to use NASA Earth observations for the first time to open up closed airspace more quickly.

After the Iceland event, the Applied Sciences Program reviewed the use of NASA Earth observations by the VAACs to estimate quantitatively the program's benefits with respect to air travel. To assess the quantitative value of the NASA Earth observations, analysts conducted a series of interviews with subject matter experts (SMEs). The SMEs provided descriptions of how the NASA observations could assist authorities in scheduling and routing, and descriptions of the resulting savings: smaller revenue losses from more targeted flight cancellations, and reduced damages to aircraft from better route adjustments. These saving estimates focused on the event following the eruption of Eyjafjallajökull. They were then extrapolated to the world as a whole to develop a global estimate of average annual savings.

Based on the analysis described in this paper, the following estimates of costs avoided (or avoided revenue losses) from use of NASA earth observations were developed:

- ***Eyjafjallajökull Eruption:*** Based on data collected for the eruption at Eyjafjallajökull, the use of NASA Earth observations may have contributed as much as \$72 million in avoided revenue losses and costs. Had the NASA

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<sup>1</sup> NASA Cooperative Agreement Notice NNS06AA05G "Decision Support through Earth Science Research Results"

observations been used by the London VAAC London, an estimated additional \$132 million, for a total of \$204 million, in revenue losses and costs might have been avoided during the incident.

- **Extrapolating to Global Aviation:** Extrapolating the Eyjafjallajökull data to aviation worldwide, use of NASA Earth observations could provide an expected value of up to \$10 million per year in avoided revenue losses.

## 1. Introduction

This report examines the impact on global aviation of NASA's Applied Sciences Program support to the VAACs. Specifically, it examines how using NASA Earth observations provided to the VAACs improves overall information on air conditions after volcanic eruptions and, thus, reduces the number of days which aircraft are grounded. As a result, aircraft are able to fly more, there are fewer delays, and airlines and passengers achieve substantial benefits.

### A. NASA Applied Sciences Program

The NASA Applied Sciences Program supports the Earth Science Division within the NASA Science Mission Directorate. The overarching purpose of the Applied Sciences Program is to discover and demonstrate innovative uses and practical benefits of NASA Earth science data, scientific knowledge, and technology.

The Program funds applied science research and applications projects to promote innovation in the use of NASA Earth science for near-term societal benefits. Overall, the Applied Sciences Program serves as a bridge between the data and knowledge generated by NASA Earth Science Division activities and the information and decision-making needs of public and private organizations. To this end, the Program increases the benefits to society of the Nation's important investments in NASA Earth Science.

The Applied Sciences Program primarily works through partnerships with public and private organizations that want to improve their internal decision-making activities and/or the products and services they provide their constituents and customers. Where NASA Earth observations and modeling capabilities are evaluated to have potential application, NASA and the partner organizations collaborate to test and integrate the data and modeling capabilities into the decision making and/or products and services. These collaborations involve appropriate academic, business, nonprofit, and other entities to accomplish the project and extend the results.

### B. Decisions Solicitation and the NASA Volcanic Cloud Data for Aviation Hazards Project

In 2006, the program initiated a score of projects selected under an open, competitive solicitation to extend the societal and economic benefits of NASA research in Earth science, information, and technology. One of the projects was *NASA Volcanic Cloud Data for Aviation Hazards*.

The objective of the *NASA Volcanic Cloud Data for Aviation Hazards* project is to develop ash data in near real-time for distribution by NOAA to decision support systems.

The project developed new algorithms and tools to accurately measure sulfur dioxide (SO<sub>2</sub>) and ash in deep volcanic eruption plumes. Operational aviation management agencies used the data during numerous eruptions over the course of the project, including three major eruptions affecting north Pacific air traffic, numerous low latitude eruptions, and an eruption in Iceland that shut down air traffic in Europe for days.

### C. Challenges Addressed by the NASA Volcanic Cloud Data for Aviation Hazards Project

Volcanic ash typically consists of tephra, which consists of bits of pulverized rock and glass less than 2 millimeters (0.1 in) in diameter.<sup>2</sup> In large eruptions, ash can be ejected from the volcano to heights at which commercial aircraft normally cruise. When these high-altitude ejections occur, volcanic ash can cause considerable harm to aircraft in a number of ways:

- **Erosive Effects**: Ash can “blind” pilots by sandblasting the windscreen, taking away the visual cues required for a safe landing. The ash can cause erosive damage to the fuselage, and can form a coating on the plane that affects aerodynamics. In addition, sandblasting can damage the landing lights, causing their beams to diffuse and be ineffective in the forward direction.
- **Blocking or Clogging of Pitot Tubes**: Pitot Tubes are hollow, forward-facing tubes mounted on an aircraft to support flight instruments. Air speed is measured by comparing the pressure in the forward-facing tube to the ambient pressure. Volcanic ash can accumulate in pitot tubes and prevent accurate functioning of the cockpit air speed indicators. Failure of these systems can have catastrophic consequences. For example, in the Birgenair Flight 301 incident an insect created a nest in a pitot tube; the resulting incorrect air speed indications ultimately led to the death of 189 passengers and crew.<sup>3</sup>
- **Electromagnetic Interference**: Volcanic ash particles are charged. As such, they can affect communication by radio and disturb other electrical instruments onboard an aircraft.
- **Engine Failure**: Volcanic ash can severely damage jet aircraft engines. During flight, large volumes of air are sucked into aircraft engines. Very fine volcanic ash particles melt at about 1,100 °C. As ash particles are sucked into a jet engine, they fuse onto the blades and other parts of the turbine (which operates at about 1,400 °C). Substantial quantities of ash can erode and destroy engine parts or cause jams in the rotating machinery. In addition, ash may clog and fuse to engine sensors, leading to erroneous readings, which may result in improper control and unplanned engine shutdowns.

While aircraft-based and ground-based cloud measuring instruments can detect potentially hazardous water-cloud formations, most do not have the ability to differentiate weather clouds from ash clouds. Therefore, aviation regulators around the world, such

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<sup>2</sup> United States Geological Survey (2011).

<sup>3</sup> <http://aviation-safety.net/database/record.php?id=19960206-0>

as the Federal Aviation Administration (FAA) and EUROCONTROL, rely on the data from the VAACs, including NASA observations, to map the location and height of ash plumes. Without the ash plume location information, aircraft must either risk traveling through volcanic ash clouds, or officials must cancel flights to avoid potentially fatal encounters with these ash clouds.

## **2. Background**

### **A. NASA's Applied Sciences Program Support to Volcanic Ash Advisory Centers**

In 1995, nine Volcanic Ash Advisory Centers (VAACs) were established in the following locations<sup>4</sup>:

- Anchorage, AK, USA
- Darwin, Australia
- Tokyo, Japan
- Washington, DC, USA
- London, UK
- Toulouse, France
- Buenos Aires, Argentina
- Montreal, Canada
- Wellington, New Zealand

Established as part of a system under the International Civil Aviation Organization (ICAO), these centers are charged with gathering information on the presence and motion of volcanic clouds and assessing any hazards to aviation.<sup>5</sup> Each location has a geographic area of responsibility for which it reports all information regarding volcanic events.

NASA's Applied Sciences Program supports the VAACs, specifically through the Langley Research Center's Advanced Satellite Aviation-weather Products (ASAP). ASAP was established in 2002 as a partnership between NASA, the FAA and the NOAA National Weather Service's Aviation Services Branch<sup>6</sup> to develop and improve aviation weather products and information through the infusion of satellite data applications. NASA satellites use Ozone Mapping Instruments (OMI) to detect the UV Aerosol Index and SO<sub>2</sub> clouds. This data is then used to detect volcanic ash and retrieve information regarding ash cloud location, height and mass.<sup>7</sup>

### **B. Potential Benefits**

NASA's support to the VAAC Program is believed to have provided numerous benefits to the aviation community. Figure 1 outlines the flow of benefits from the use of NASA's Earth observations. As a result of having timely and accurate data, aviation regulators are able to direct flights to safe areas around ash clouds, improve flight safety, and reduce overall costs from unnecessary cancellations.

It is important to note that the ability to create real-time data is a key benefit of NASA's involvement when compared to the prior methods of detecting ash. Using VAAC products, regulators assist airlines in avoiding accidents that might result from flying

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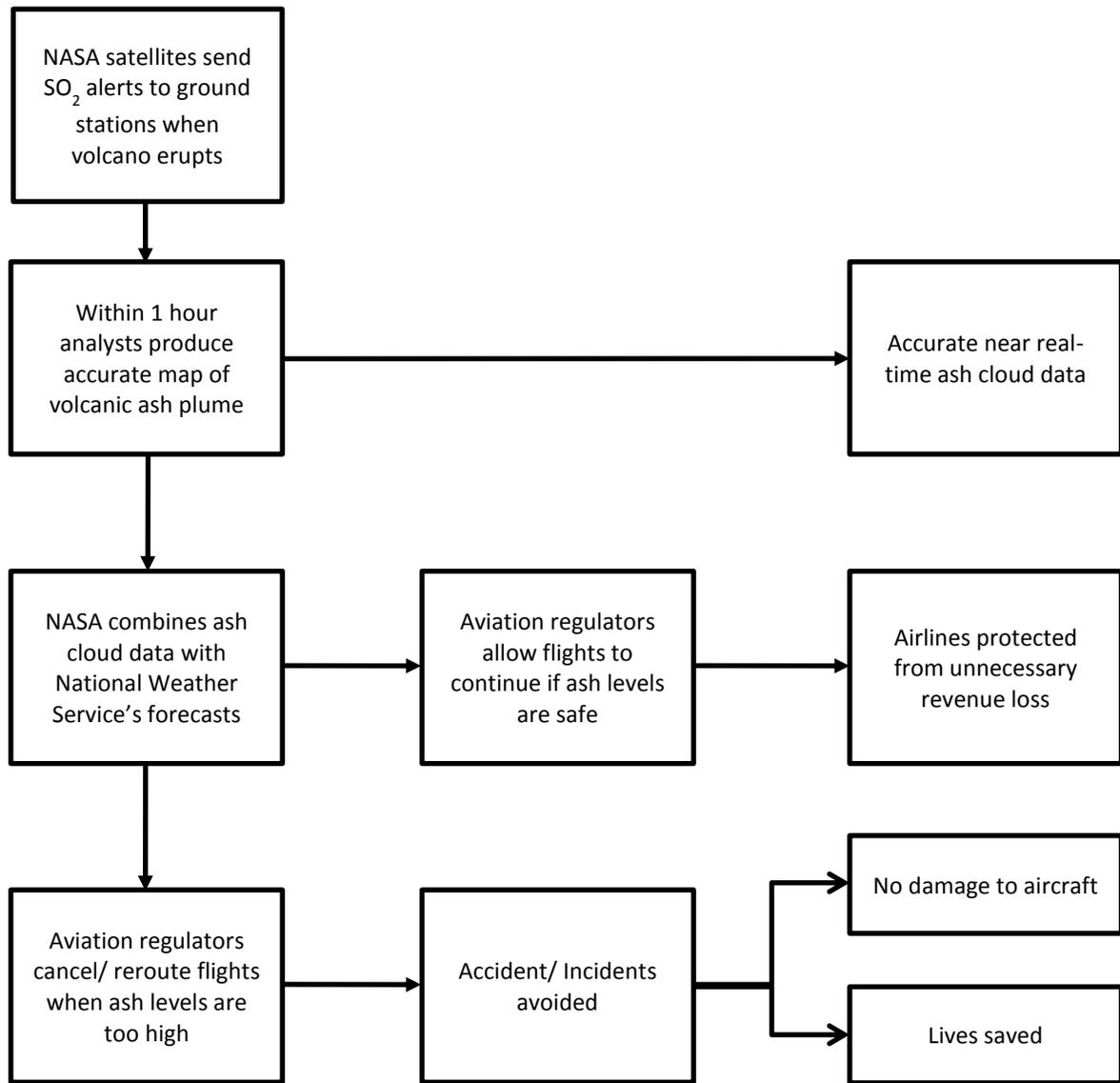
<sup>4</sup> Met Office: Volcanic Ash Advisory Centers (2011)

<sup>5</sup> US House of Representatives (2011), p. 3

<sup>6</sup> The National Weather Service is a part of NOAA.

<sup>7</sup> Krotkov et al., (2011), p. 4

through dangerous ash clouds, potentially saving lives and avoiding damage to aircraft. These mapping and tracking products allow air safety officials to better estimate when flying conditions are safe, thus preventing additional revenue losses from keeping operations closed due to uncertainty of ash levels.



**Figure 1: Potential Benefits of Volcanic Ash Advisories**

*Source: Booz Allen Hamilton analysis*

### **3. Methodology for Estimating Program Impacts**

#### **A. Analysis Overview**

NASA's Applied Sciences Program conducted an evaluation of the impact of the use of NASA Earth observations by the VAAC program. Although the program has been in existence for many years, its impact became most apparent during a major volcanic eruption of 2010. The eruption of Eyjafjallajökull in Iceland provided a test case of the benefits of the program.

To estimate benefits, the analytic team obtained data on flight cancellations and revenue losses due to the eruption of Eyjafjallajökull, as well as a range of estimates for the cost of repairing or replacing aircraft systems damaged by interactions with volcanic ash. The team interviewed project and NASA program staff to understand the decision processes that the observations supported, and then used a Bayesian-inspired approach based on historical data to develop an estimate of how much the NASA Earth observations would reduce the uncertainty about the level of ash threat. The team applied this risk reduction to the estimates of potential costs to estimate the risk-adjusted value of the observations. These risk-adjusted results were then extrapolated to the world as a whole to develop an overall estimate of the potential impact of the use of NASA Earth observations in the VAAC program.

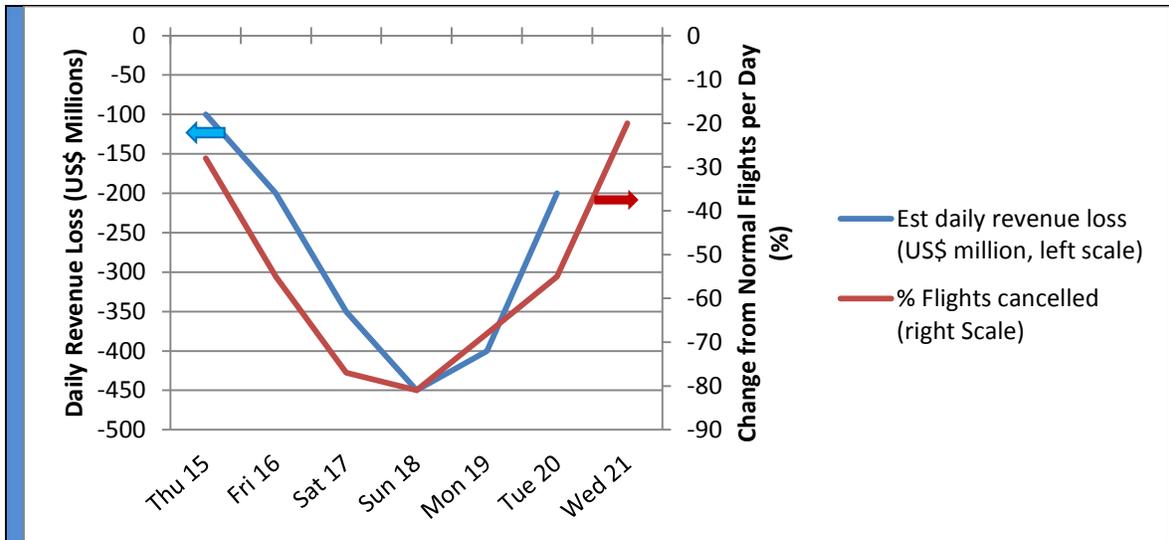
#### **B. Potential Revenue Loss Impact from Flight Cancellations**

As previously stated, the cancellation of flights due to the Iceland volcanic eruption caused major revenue losses for airlines. The International Air Transport Association (IATA)<sup>8</sup> estimated that airlines lost \$1.7B in revenues over one week, 15-21 April 2010. Figure 2 displays the reduction in flights per day (red line), and the resulting estimated revenue loss (blue line), for this period.

The IATA data indicate that, on the day of greatest impact, approximately 80 percent of European flights were cancelled, resulting in approximately \$450 million in lost revenue. The next day, 19 April, was the day that the London VAAC began to use the NASA observations to verify and validate their ash modeling and predictions. On the 20<sup>th</sup> and 21<sup>st</sup> flight operations were gradually restored to normal. Based on this information, the analytic team assumed that the maximum potential revenue loss in the absence of the NASA observations was approximately \$450 million per day; or, stated differently, \$450 million was the maximum possible revenue loss that could be avoided if decision makers had perfect information about the location of dangerous volcanic ash clouds in April 2010.

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<sup>8</sup> IATA Economics (2010), p. 3.



**Figure 2: Estimated Revenue Loss and Percentage of European Flights Cancelled 15-21 April 2010**

Source: IATA Economics (2010)

### C. Damage Avoidance Impacts

As previously mentioned, volcanic ash can cause severe damage to an aircraft, and existing meteorological instruments do not have the ability to measure the ash levels in clouds. Table 1 describes some significant incidents involving aircraft interacting with volcanic ash over the past four decades.

**Table 1: Examples of Aircraft Encounters with Volcanic Ash**

Eruption	Damage caused to aircraft
Mt. St. Helens, US – 1980	A 727 and a DC-8 experienced damage to their windshields and to several aircraft systems.
Galunggung, Indonesia – 1982	A 747 lost thrust from all four engines and descended from 36,000 ft. to 12,500 ft. before all four engines were restarted. All four engines were replaced before the aircraft returned to service.
Mt. Redoubt, US – 1989	A 747 ingested ash in all four engines which required replacement. Many other systems were also repaired or replaced.
Mt. Pinatubo, Philippines – 1991	Flights grounded for several days.
Mt. Popocatepetl, Mexico – 1997	Significantly reduced visibility for landing.

Source: Casadevall and Murray (2000)

There were no reports of damaged aircraft during the Iceland event—a potentially huge avoided cost to commercial airlines. Engine repairs alone can cost millions of dollars. Based on data retrieved from Boeing, a major aircraft manufacturer, repairing an engine due to foreign object damage can cost up to \$1.6 million per engine, and replacing an engine can cost up to \$10 million. Table 3 outlines the cost to repair an aircraft engine due to foreign object damage for two types of engines.

**Table 2: Estimated Repair Costs to Two Types of McDonnell Douglas Engines**

Repair Action	Low Estimate	High Estimate
Replace engine	\$3,000,000	\$8,000,000
Repair damage	\$250,000	\$500,000
Replace fan blades (per set)	\$7,000	\$25,000

*Source: Bechtel (1998)*

These estimated engine repair costs do not include the possibility of additional potential losses that have not/may not be quantifiable including:

- Fines imposed by air regulators;
- Increase in insurance premiums;
- Restoration of environmental or physical property damage at crash site;
- Additional litigation judgments, court costs, legal fees, etc.; and
- Loss of consumer confidence.

The use of NASA Earth observations might enable the avoidance of such potential losses during volcanic events by reducing the uncertainty of the location of dangerous volcanic ash clouds, and hence reducing the probability of encountering damaging ash.

#### **4. Estimate of Impacts**

The analytic team used the approach and findings in Section 3 to estimate the benefits from VAAC operations, as supported by the NASA observations, during the Eyjafjallajökull eruption. The team then expanded these results to estimate the average expected annual benefit globally.

##### **A. Estimate of Impacts During Eyjafjallajökull Eruption**

The eruption of Eyjafjallajökull began on 12 April 2010. However, it was not until 15 April that airspace began to close. Eruptions continued until 23 April, but after 19 April the London VAAC's data and models showed that flights could safely resume operations in some areas. On that same day, the London VAAC used NASA observations for the first time to refine and validate the findings and predictions of their existing systems and models.

As a result of the findings at the London VAAC, in the afternoon of 19 April, German carriers Lufthansa and Air Berlin obtained permission for some flights from and to German airports under Visual (non-instrument) Flight Rules. Lufthansa was permitted to send planes to long-haul destinations to return stranded passengers later that day.

Late on 19 April and early on 20 April, some flights were permitted to take off in northern Europe, including flights from Scotland and northern England, but Manchester Airport, which had planned to open on 20 April, remained closed because of a new ash cloud. The UK Civil Aviation Authority announced that all UK airports would be permitted to open at 10 PM on 20 April. Twenty-six British Airways long-haul flights were already in the air and requesting permission to land. By 20–21 April several airlines confirmed that air service would resume in stages and started publishing lists of selected flights, with most airlines resuming service shortly after.<sup>9</sup>

Based upon this chronology, it is not possible to definitively identify the counter-factual case of what would have happened in the absence of the NASA observations. Presumably, flight operations would not have resumed as rapidly, as the level of uncertainty about safe flight regions would have remained above the acceptable threshold of the policy makers. Decisions would have been made based on existing data sources, such as:

- On-site volcano monitoring and eruption reporting (including volcanological, seismological, and geological monitoring and analysis);
- Remote monitoring (including ground station monitoring, Doppler radar, airborne monitoring, and other, non-NASA satellite monitoring);
- Modeling and forecasting the expected path of the cloud; and
- Directly observing and communicating the extent of the plumes.

For the counterfactual case, the analytic team considered two sets of decisions by regulators: either to slow the reopening of flight routes to take into account the increased uncertainty about the danger, or to reopen routes at the same rate, assuming more risk of aircraft damage due to uncertainty about which routes were safe.

To estimate the impact of the NASA Earth observations in these cases, the analytic team used historical data to estimate the probability of any given passenger aircraft flight being damaged by volcanic ash before and after the integration of NASA Earth observations into the U.S. VAAC system in 2007. While this approach abstracts some detail—for example, it considers global rather than U.S. eruptions and incidents, and it does not address other significant control measures since 2007—it allows for a data-driven estimate of the relative impact of integrating NASA Earth observations into the VAAC system.

Table 3 shows the data used for performing this counterfactual analysis. For each year 1996-2010, the table shows the number of significant passenger aircraft incidents involving volcanic ash, as recorded by Guffanti et al. (2007); the number of volcanic eruptions above Volcanic Explosivity Index 3, for which columns can extend into the commercial flight levels, as reported by the Smithsonian's Global Volcanism Program (2011); an eruption index, consisting of the annual eruptions divided by the average eruptions (22.2) for 1996-2010; a "weighted incidents" count, equaling the raw number of incidents divided by the eruption index; the number of passenger flight departures, from

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<sup>9</sup> All restrictions removed on the 23rd of June but air flight had resumed in most places gradually from the 19th.

IATA; and a “weighted incidences per flight”, representing the weighted probability of a given flight encountering a volcanic ash incident; this weighted probability is the weighted incident count divided by the number of passenger flight departures. For clarity, this last column is multiplied by  $10^{-7}$  to produce a number between 0 and 10.

**Table 3: Data for Estimating the Relative Impact of NASA Earth observations**

Year	Incidents	Eruptions >=VEI 3	Eruption Index (Eruptions/Avg)	Weighted Incidents (Incidents / Index)	Flights	Weighted Incidents/Flight (x $10^{-7}$ )
1996	1	20	0.90	1.11	19,900,000	0.56
1997	2	19	0.86	2.34	19,900,000	1.17
1998	4	21	0.95	4.23	20,000,000	2.11
1999	5	22	0.99	5.05	21,000,000	2.40
2000	4	25	1.13	3.55	20,000,000	1.78
2001	3	22	0.99	3.03	22,500,000	1.35
2002	1	20	0.90	1.11	22,500,000	0.49
2003	0	23	1.04	0.00	21,500,000	0.00
2004	0	20	0.90	0.00	22,500,000	0.00
2005	1	23	1.04	0.97	24,000,000	0.40
2006	0	19	0.86	0.00	24,000,000	0.00
2007	8	22	0.99	8.07	26,000,000	3.10
2008	0	27	1.22	0.00	26,000,000	0.00
2009	0	23	1.04	0.00	25,000,000	0.00
2010	0	27	1.22	0.00	25,000,000	0.00

Sources: Guffanti et al. (2010), Smithsonian Institution (2011), IATA, Booz Allen analysis

The analytic team analyzed the weighted probabilities of an incident before and after 2007, when the NASA Earth observations were first introduced into the VAAC system. The team chose 1996 as the first year for analysis to ensure that a full decade of data was analyzed prior to the VAACs using the NASA Earth observations.

The weighted incidents for each set of years (1996-2006, 2007-2010) were summed and divided by the total number of flights for each period to get an average weighted probability of an incident. For the earlier period, this ratio is  $0.889 \times 10^{-7}$ , and for the later period the ratio is  $0.791 \times 10^{-7}$ , suggesting that the use of the NASA Earth observations reduces the probability of an aircraft experiencing a volcanic ash incident by a factor of  $1 - (0.791 \times 10^{-7}) / (0.889 \times 10^{-7})$ , or about **12 percent**.<sup>10</sup>

This estimated reduction can be interpreted to represent the increase in certainty resulting from the integration of NASA sources into decision making. Thus, without the NASA information regulators would either be 12 percent more likely to allow an aircraft to fly such that it would encounter damaging ash, or would slow the relaxation of the flight ban to take into account the 12 percent additional uncertainty of each flight path’s safety.

While no actual damage was reported, suggesting that regulators took the latter approach, it is possible that without the NASA observations the regulators would have

<sup>10</sup> Note that these estimates did not control for factors other than those listed.

taken the more risky approach. The president of the German airline Air Berlin, in an interview with the newspaper *Bild am Sonntag*, stated that the risks for flights due to this volcanic haze were nonexistent, because the regulator's assessment was based only on a computer simulation produced by the VAAC.<sup>11</sup> Such statements suggest that, in the absence of evidence based on stronger, NASA-supported VAAC simulations, regulators might have been pressured to allow at least some aircraft on or after 19 April to fly into areas that the NASA observations would have identified as high risk. Assuming these flights would have occurred on 19 April, and would have resulted in two engines that would require repair for as much as \$500,000 (from Section 3.C), then the total savings from using NASA observations would be ~\$1 M in avoided aircraft damage, plus the revenue loss on 20 and 21 April that would have resulted from the re-tightened control likely after the incident. As will be shown below, these tighter flight controls would correspond to about \$24 million in revenue loss.

The other counterfactual scenario assumes that, given their uncertainty without NASA information, regulators would have slowed the reopening of the airspace by some fraction. While one percentage point of uncertainty does not necessarily correspond to one percentage point of additionally cancelled flights, this relationship can serve as an approximation to the reaction of regulators.

Under these conditions, the team assumed that 12 percent more flights were likely to be cancelled each day on 19 April and later—or, more precisely, that 12 percent additional revenue was lost each day.<sup>12</sup> Based on the IATA Economics (2010) data shown in Figure 2, this yields impacts of \$48 million on 19 April and \$24 million on 20 April, for a total of \$72 million. (Per the discussion in the IATA document, revenue losses for 21 April were not recorded, but were probably compensated for by additional flights on 22 April to remove backlog.)

Using these data we can create two credible estimates for impacts:

- assuming a risk-adverse regulator and greater limitations on flights without NASA observations, NASA observations could have saved up to \$72 million in unnecessary delays; and
- assuming a less risk-adverse regulator and fewer limitations on flights, NASA observations could have saved \$1 million in damages to aircraft on 19 April, with \$24 million in unnecessary delays on 20 April, for a total of \$25 million.

## **B. Extrapolating Impacts Globally**

Extrapolating these data to the world as a whole, the analytic team used the weighted probability of a damaging ash encounter without the use of NASA Earth observations of  $0.889 \times 10^{-7}$ , and with the NASA Earth observations of  $0.771 \times 10^{-7}$ , for a difference of  $0.118 \times 10^{-7}$ . Assuming 25 million departures (as was reported in 2010), and the lower bound for an engine repair at \$250,000, and assuming two engines would require repair,

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<sup>11</sup> Quandt (2010).

<sup>12</sup> This assumes for each flight regulators would have a “fly/no-fly” decision. Assuming that they would be wrong 12 percent of the time without NASA data and that they would be conservative in their decisions, they would make the “wrong” decision (i.e., no-fly when flight would actually be safe) 12 percent of the time.

the annual expected savings of using NASA Earth observations is approximately \$147,500 in avoided aircraft damages.

To estimate the potential savings due to reduced revenue losses, the analytic team noted that, from the Jenkins (2007) data, 90 percent of explosive eruptions last 10 days or fewer. They used the 5-day duration of the Eyjafjallajökull incident as a conservative assumption for an “average” disruption and noted that the NASA observations were only used for three days in Eyjafjallajökull case. Thus, the potential savings for the repeat of such an incident would include the 12 percent savings to the revenue losses that *could* have been realized in 15-18 April if the NASA observations were used. Accounting for this savings yields an estimate of an additional \$132 million, for a total potential savings of \$204 million for the incident.

Incidents with the magnitude of Eyjafjallajökull are not common, but still tend to occur at least every decade (e.g., Mount Saint Helens in 1982, and Mount Pinatubo in 1991). Smaller, but significant, disruptions occur even more often. For example, in June 2011, just 14 months after Eyjafjallajökull, Chile's Puyehue volcano caused major disruptions to South American air traffic, and later forced a flight shutdown in Melbourne, Australia and major flight cancellations in New Zealand. Until the Eyjafjallajökull incident, NASA Earth observations support was limited to the Washington and Anchorage VAACs, rather than in all nine worldwide VAACs. However, these two VAACs do address large areas of the Earth's surface, covering much of the central Pacific and Arctic Oceans. The analytic team had insufficient data to perform a full geographically specific analysis of the historical costs and event frequencies using the U.S.-based VAACs. In the absence of comprehensive data, the team used a conservative estimate of one smaller event, approximately 1/10 as disruptive as Eyjafjallajökull, occurring every other year within the regions currently using NASA Earth observations, leading to an order-of-magnitude estimate of \$10 million in avoided revenue losses.

Based on this analysis, the analytic team estimated that the annual cost avoided by use of NASA Earth observations is on the order of \$150,000 for avoided equipment damage and \$10 million for revenue-loss avoidance. These estimates should be interpreted as an expected value of cost avoided, in the statistical sense. The expected value may be understood in the context of the law of large numbers. Specifically, the expected value can be interpreted as the long-run average of the results of many independent repetitions. The value may not be “expected” in the general sense. In fact it may be unlikely or even impossible (e.g., an expected value for family size might be 2.5 children). However, the expected value provides an indicator (similar to the mean or average) that expresses the likely value of an event given a particular probability distribution.

Given this mean-value interpretation and the assumptions the team made in this calculation, the expected value of using NASA observations may be reasonably estimated to be as large as \$10 million annually.

## **5. Conclusions**

Using Earth observations provided by NASA through NOAA, the U.S.-based VAACs provide near real-time information about ash plumes. The satellite data allows for the development of precise images and maps of the size, location and height of ash clouds.

The London VAAC also used this data in the latter part of the Eyjafjallajökull volcanic eruption of 2010, which may have resulted in millions of dollars of savings for the European civilian air transportation industry.

Based on the analysis described in this paper, the analytic team developed the following impact estimates of costs avoided (or avoided revenue losses) from use of NASA Earth observations:

- ***Eyjafjallajökull Eruption:*** Based on data collected for the eruption at Eyjafjallajökull, the use of NASA Earth observations may have resulted in as much as \$72 million in avoided revenue losses and costs. Had the NASA observations been used by the London VAAC earlier, an estimated additional \$132 million, for a total of \$204 million, in revenue losses and costs might have been avoided during the incident.
- ***Extrapolating to Global Aviation:*** Extrapolating the Eyjafjallajökull data to aviation worldwide, use of NASA Earth observations could provide an expected value of up to \$10 million per year in avoided revenue losses.

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