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DEPARTMENT OF METEOROLOGY

A STUDY OF THE VUNERABILITY OF AIRLINE FLIGHTS TO VOLCANIC ERUPTIONS

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ABSTRACT

Exposure to volcanic ash puts aircraft in flight at a heightened risk for an emergency situation. Case studies of the 2008 Okmok and Kasatochi eruptions, as well as the 2009 Redoubt eruption, were performed to examine the vulnerability posed to aircraft by volcanic ash clouds. Synoptic meteorological conditions and satellite imagery for each eruptive event were analyzed to better understand the volcanic ash dispersion from each eruption. Through comparison with HYSPLIT model forward trajectories, an assessment of the performance of ash dispersion models was conducted. The HYSPLIT model run predicting ash dispersion from the Kasatochi eruption performed better than the model run for ash dispersion from the Okmok eruption. The HYSPLIT forward trajectories for the Redoubt eruption correctly predicted the extent of the volcanic ash cloud 27 hours following the eruption. Extensive monitoring and accurate ash dispersion modeling for the Redoubt eruption aided aircraft pilots in avoiding ash encounters. Yet after the Kasatochi eruption, atmospheric flow heavily influenced the increased occurrence of aircraft ash encounters, despite accurate ash dispersion modeling for the eruptive event.

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Acknowledgments

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Introduction: Aircraft Encounters with Volcanic Ash

Ash released from volcanic eruptions poses a significant hazard to aircraft in flight. Volcanic activity is not infrequent, as a volcanic eruption typically occurs somewhere on earth at any given time. Although a large majority of eruptions pose an inconsequential risk to the aviation industry, every so often particularly explosive eruptions propel volcanic ash to levels of the atmosphere which threaten the safety of aircraft in flight. The eruptive columns from a volcano can rise from a source region at vertical velocities of 5 to 180 ms^{-1} and can reach altitudes of 45 km, well above the maximum flight altitudes of commercial aircraft (Self and Walker, 1994).

In recent years, increased air traffic near volcanically active regions has put aircraft at a heightened risk for encountering ash from erupting volcanoes. Areas such as the North Atlantic and North Pacific are at particularly high risks due to the rapid expansion of flight routes over these regions. In most cases of volcanic ash encounters, the pilot inadvertently steered the aircraft into an ash cloud at night (Grindle and Burcham, 2003). The duration of the ash encounter often is quite short, as much of the damage incurred to the aircraft occurs during the initial few seconds of contact.

Flight routes are planned and issued by air traffic control centers to ensure that aircraft reach their destinations safely and timely. Volcanic ash poses a critical threat to aircraft, because an ash encounter can cause costly, and sometimes catastrophic, damage to both aircraft and crew. According to the United States Geological Survey (USGS), all ash encounters with aircraft since 1973 are attributed to 30 volcanic sources, as indicated by Figure 1. Between 1973 and 2000, there were 97 documented reports of aircraft encountering airborne volcanic ash (Figure 2). One particularly active year in 1991 is attributed in large part to the 15 June eruption of Mount Pinatubo, which resulted in 20 ash encounters with aircraft. Several encounters with volcanic ash have resulted in major damage to the aircraft. A few of the most serious ash encounters have even resulted in complete engine failure while in flight, in which the aircraft glided to lower altitudes before the engine(s) could be restarted.

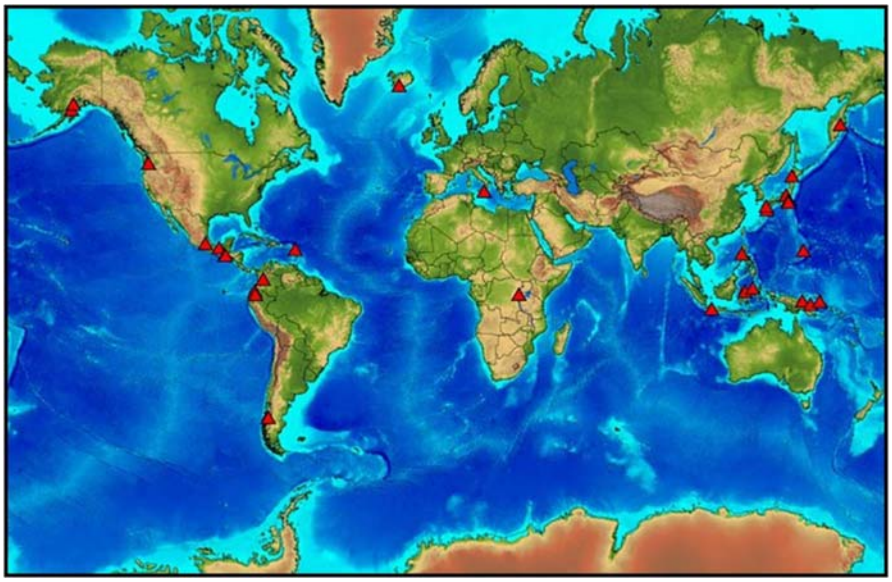

Figure 1: Sources of ash encounters with aircraft since 1973 (Guffanti, 2004)

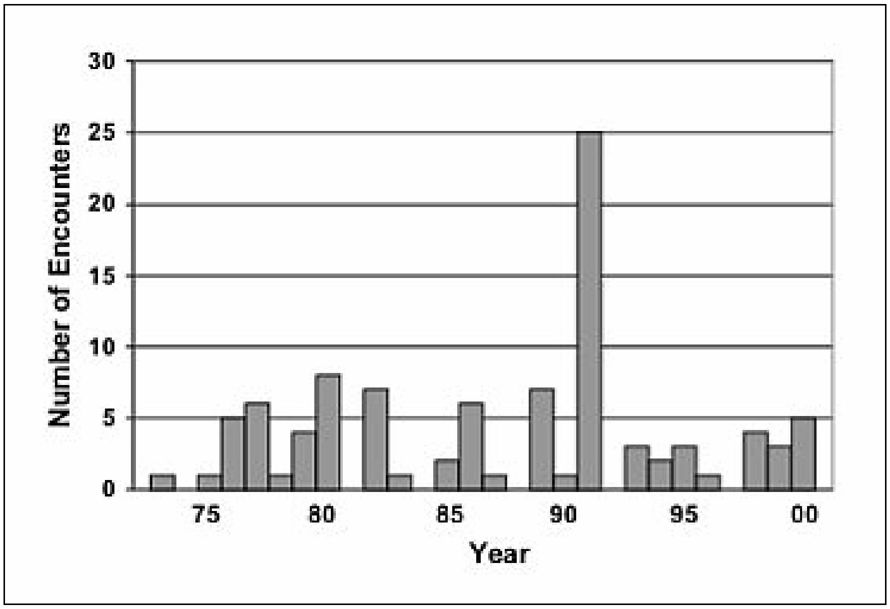

Figure 2: Reported aircraft encounters with volcanic ash (ICAO, 2001)

Ash particles are composed of glass shards and fine-grained rock and can cause abrasion to exposed areas of aircraft including the windshields, compressor fan blades, and fuselage surfaces. Abrasion to the windshield can result in complete frosting of the surface which severely reduces visibility, whereas abrasion to compressor fan blades can lead to malfunction of an engine's mechanical parts. Even a brief encounter with an ash plume likely requires an aircraft to receive a new coating of paint, which costs hundreds of thousands of dollars (EOV, 2000). The abrasive characteristic of volcanic ash contributes to significant erosion of exposed surfaces of aircraft which can lead to substantial costs to repair damages.

The exterior damage from one particular ash encounter is shown in Figure 3, in which a 747-400 jumbo jet inadvertently flew through an ash cloud from the 1991 Pinatubo eruption. The 1991 eruption of volcano Pinatubo was one of the largest eruptions in the twentieth century and resulted in 20 volcanic ash encounters with aircraft in flight. A vast majority of these encounters occurred with an ash cloud at least 12 hours old and hundreds of kilometers from its source. The aging of ash clouds reduces the threat posed to aircraft, as larger (>30 μm diameter) particles have already settled from the cloud.

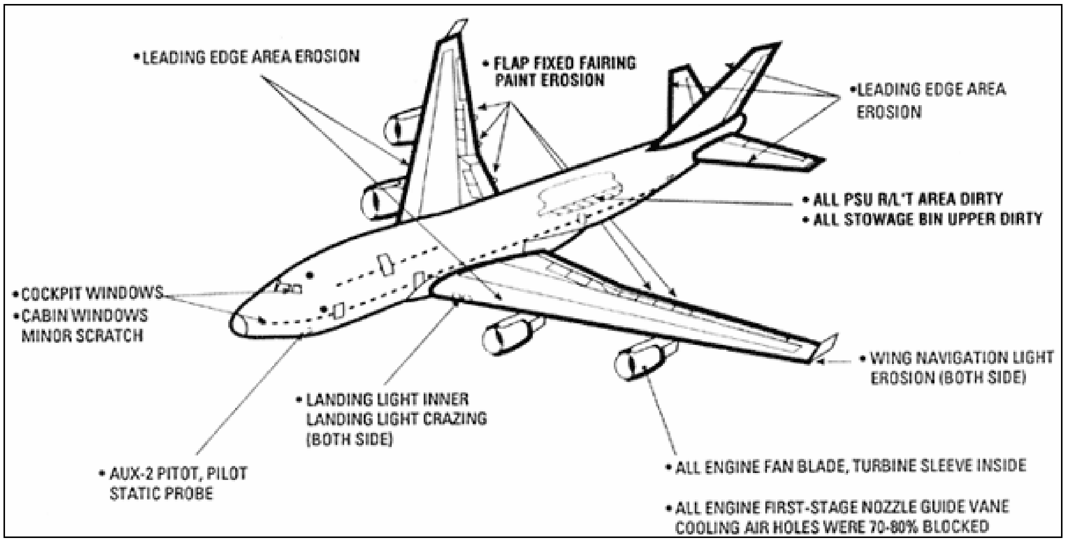

Figure 3: Aircraft Damage from a 1991 Pinatubo ash encounter (Casadevall, 1999)

Nevertheless, particles from an ash cloud often cause significant complications for the engines of aircraft. Increasingly, commercial airlines use large twin-engine aircraft for transoceanic flights. The turbine engines of these aircraft have operating temperatures exceeding 1000°C, which is high enough to melt volcanic ash in the 1 to 10 micron diameter range (Grindle and Burcham, 2003). Melted ash deposited in the engine leads to an immediate degradation of engine performance. The continued buildup of melted ash in the hot sections of the engine can cause a rapid increase in burner static pressure and discharge pressure, resulting in a dangerous surge in the engine known as a flameout.

Volcanic ash that melts within the engine turns into a semi-liquid molten glass which poses a hazard to internal mechanical parts. The molten ash may form a coating on the surfaces of fuel nozzles, combustors, and turbines. The clogging of essential channels reduces the efficiency of fuel mixing and limits the intake of air passing through the engine. The reduction in engine efficiency from molten ash deposition leads to possible loss of thrust, surge, and flameout (Grindle and Burcham, 2003). Internal damage to an aircraft's engine due to an ash encounter puts the safety of pilots, crew, and passengers at a higher risk for an emergency situation.

Ash Encounters in International Airspace

Although no fatalities have resulted from volcanic ash encounters with aircraft, the economic impact of such encounters is substantially large. Between 1980 and 1998, aircraft encounters with volcanic ash have caused more than U.S. $250 million in damage to engines, avionics, and airframes (EOV, 2000). In a 2000 eruption of volcano Miyake-jima in Japan, five aircraft encountered volcanic ash while in flight. This incident caused a reported 12 million dollars in damage due to aircraft repairs, diversions, and lost operating time (Tupper et al., 2004).

In the same year (2000), a DC-8 NASA research aircraft encountered ash from the Hekla volcano in Iceland. The aircraft was en route from Edwards Air Force Base in Edwards, CA to Kiruna, Sweden and was commissioned for the SAGE III Ozone Loss and Validation Experiment (SOLVE). At the time of the ash encounter during the early morning of February 28, 2000, the visibility of any particulates was severely limited by total darkness with no moon at night. Although there was no apparent damage to the aircraft during the encounter, which lasted only seconds, the cost of dismantling and repairing the four damaged engines was estimated at U.S. $3.2 million. (Grindle and Burcham, 2003)

The 2000 Hekla ash encounter is the only known aircraft ash encounter over the North Atlantic. Despite the fact that only one incident has been reported in the North Atlantic region, Icelandic volcanoes such as Hekla pose an increasingly high risk to transatlantic flights. In recent years there has been a volcanic eruption in Iceland, on average, every four to five years. The subarctic North Atlantic region is one of the most heavily trafficked air corridors in the world (Lacasse 2001). On average, approximately

250 flights pass through the Icelandic Oceanic Control Area (IOCA) per day (Sveinbjörnsson 2001). Current trends indicate that air traffic over this region is expected to increase steadily in the near future.

Volcanic Ash Detection using Radar

Once a volcano has erupted, accurate real-time information is essential for tracking a potentially hazardous ash plume. Depending on atmospheric wind conditions, volcanic ash may disperse several kilometers from its source in only one hour. Real-time data are crucial because a slight change in wind direction may put new locations at increased risk for ash exposure. Radar is often used to track volcanic ash in the critical hours following an eruption. In the case studies explored in this paper, the two regions studied are the U.S. Pacific Northwest (Alaskan volcanoes) and the North Atlantic (Icelandic volcanoes).

The Next Generation Radar (NEXRAD) system is a network of permanent radars in the United States operated and maintained by the National Weather Service. The type of Doppler radar used as part of the NEXRAD system is the WSR-88D, which can detect precipitation and wind velocities. WSR-88D radars are located at various sites across the United States, including one in Nikiski, Alaska. The radar at Nikiski is the one closest in proximity to the Mount Redoubt volcano, which has recently erupted.

The elevated levels of seismic activity at the Mount Redoubt volcano on the Kenai Peninsula made it practical to install a secondary radar to monitor activity at the volcano. In early March 2009 geophysicists from the Alaska Volcano Observatory constructed the radar and on March 12, 2009 it was installed at Kenai Municipal Airport, about 52 miles from the volcano. The radar allows scientists to more accurately measure ash fall amounts and velocities of an ash plume following an eruption. The new radar allows better location for ash detection near Mount Redoubt. Whereas the Nikiski radar is obstructed by nearby mountains, the new radar provides a clearer view of the airspace around Mount Redoubt.

Air traffic over the North Atlantic is particularly difficult to monitor because aircraft flying over oceanic regions are often out of range of radar. Radar is frequently used in commercial aviation to accurately pinpoint the position of aircraft in flight. Because radar has a range of up to 250 kilometers, it is effectively useless in tracking flights over most oceanic regions. Detailed information about flight position is critical for rerouting aircraft in the event of a volcanic eruption. Since there is a relatively sparse network of radar observations over the North Atlantic, the ability to accurately track the location of aircraft in flight is severely limited.

The only radar system in place in Iceland is a C-band radar located near Keflavik International Airport in the southwestern part of the island. Approximately 140 kilometers from Hekla, the Keflavik radar is within sufficient range to detect the onset of an eruption of the volcano. However, specifications of the radar limit its ability to detect larger features in the atmosphere such as a dispersed volcanic ash cloud. The Keflavik radar has a vertical detection limit between 2 and 12 kilometers, which means it can only detect features in the atmosphere between 2 and 12 kilometers above sea level at Hekla’s location (Figure 4). Because the elevation of Hekla is 1491 meters, radar can only detect ash particles from Hekla that have ascended to an altitude of 2000 meters.

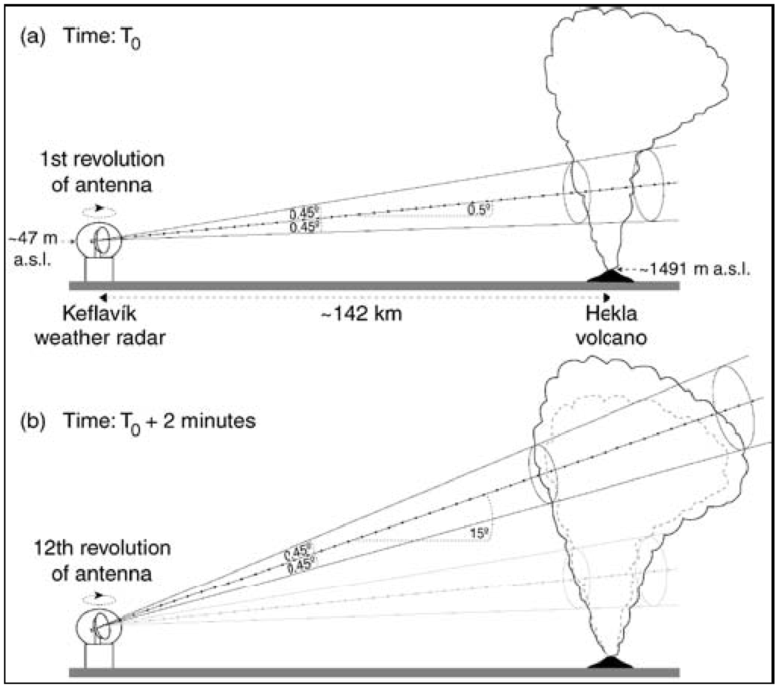

Figure 4: Hekla eruptive plume as detected by Keflavik radar (Guffanti, 2004)

The 26-27 February 2000 Hekla eruption was the first eruption to be continuously monitored in Iceland by real-time radar observations. During this period, the rising eruptive column was advected downwind to the north-northeast under the prevailing meteorological conditions. As the ash cloud rose to 12 kilometers above sea level and beyond 250 kilometers from the radar, it was no longer within detectable range of the Keflavik radar. Other volcanoes in Iceland, such as Grimsvotn, Askja, and Katla, are located further than 250 kilometers from the radar and are therefore completely beyond detectable range of the Keflavik radar. The limitations of the current radar system in Iceland prevent the tracking of volcanic ash clouds. In turn, these limitations severely jeopardize aviation safety in the event of a volcanic eruption (Lacasse 2001).

The detection of volcanic ash clouds by radar is not always available when needed. A method of identifying ash clouds on a larger spatial scale is through use of satellite imagery. One of the methods used to distinguish the volcanic ash signature in satellite imagery is the “split window” technique. This technique takes the difference between thermal infrared channels 4 and 5 of the AVHRR instrument. Using the thermal infrared image-based ash plume detection algorithm, volcanic ash can be determined based on a positive “split window” thermal anomaly in AVHRR data. This technique is often used by the Volcanic Ash Advisory Centers (VAAC) as a method to identify an ash plume. However, a disadvantage of using satellite imagery for ash detection is that resolution is not always adequate for observational purposes. After an ash cloud has dispersed and become thinner over time, it becomes increasingly more difficult to detect the volcanic ash through satellite imagery.

Volcanic Ash Dispersion Modeling

To better understand how volcanic ash is transported in the atmosphere, dispersion modeling has been developed extensively in recent years. Dispersion modeling has been particularly effective as a complement to observational data as well as satellite imagery. By modifying eruptive parameters such as plume height, eruption duration, and particle concentration, a modeler has the ability to adjust the initial settings of the model to produce a more accurate simulation of an eruption. Dispersion models specifically designed for volcanic ash are known as volcanic ash transport and dispersion (VATD) models (Peterson 2007).

The Puff dispersion model is a type of VATD model developed at the University of Alaska, Fairbanks. The model was created "to forecast the relative exposure of aircraft and ground facilities to ash from a volcanic eruption" (Peterson 2007). Utilizing a Lagrangian framework of an adjustable number of tracer particles, the Puff model couples numerical weather prediction (NWP) data with customizable initialization settings. Adjustable parameters for Puff 2.0 include simulation hours, eruption hours, wind model, number of particles, plume height, plume bottom, and plume shape. The online version of the Puff model, known as WebPuff, is made freely available by the University of Alaska, Fairbanks Alaska Volcano Observatory. As example of model output from volcanic ash dispersion model WebPuff is shown in Figure 5 (http://puff.images.alaska.edu). For this example, the model was initialized at volcano Hekla at 1000Z on 3 September 2008 using the AVN-GFS wind model and Poisson plume shape input parameters.

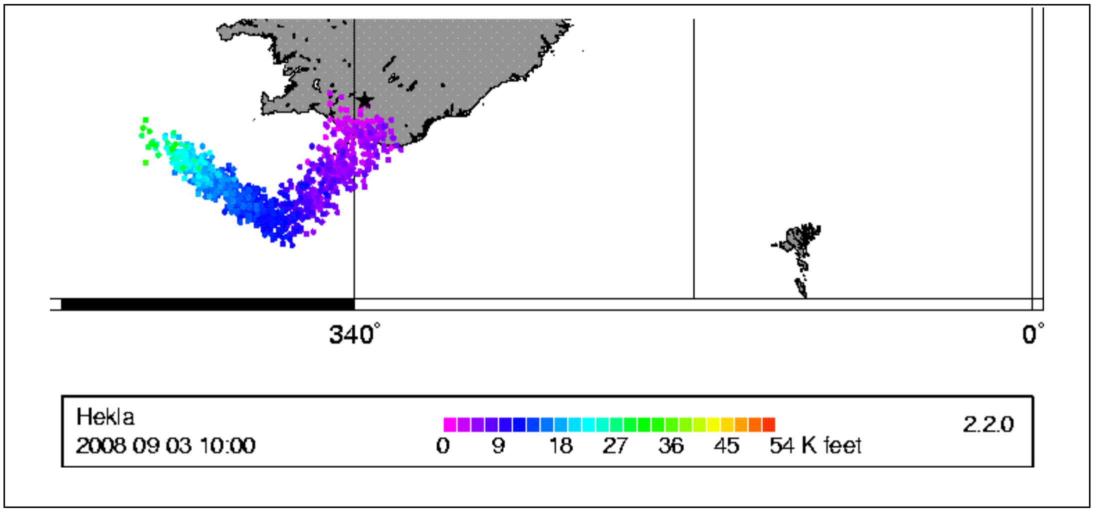

Figure 5: WebPuff 2.2 ash dispersion model initialized at volcano Hekla (AVO)

The Puff model, unlike most other dispersion models, has been designed with a focus on ash exposure from an aircraft encounter with an ash plume. Potential exposure to volcanic ash is calculated based on the total amount of airborne ash that a hypothetical linear aircraft trajectory would encounter. The wind field is computed through interpolation of three simultaneous meteorological soundings from three nearby weather station locations. By integrating the concentration of ash, *c*, along the trajectory path with aircraft velocity, *V*, and time, *t*, the exposure, *E*, is computed as follows:

$$E = \int cVdt \qquad (1)$$

The units of exposure are in grams per meter squared. Figure 6 is a diagram showing the hypothetical trajectory of an aircraft with cross-sectional area, *A*, and velocity, *V*, flying through an ash cloud of ash concentration, *c*.

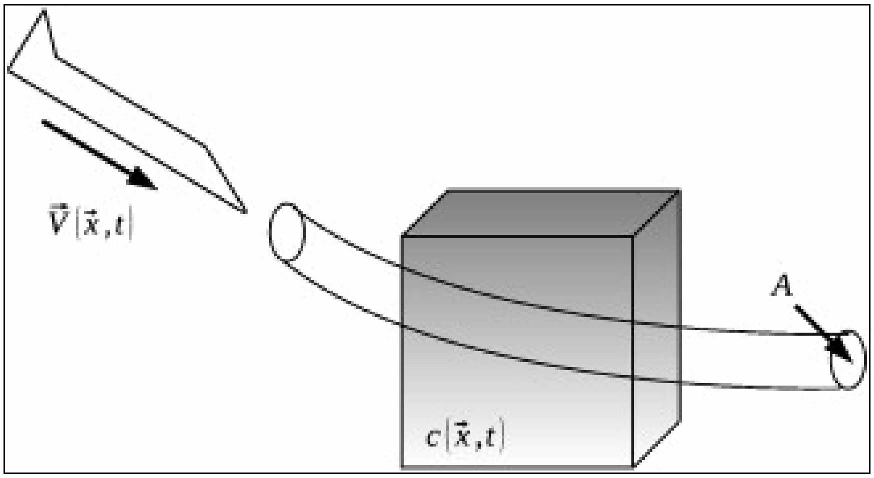

Fig. 6: Potential exposure through an ash cloud (VanLooy et al., 2007)

The resolution of the grid size is an important consideration for the accuracy of the model conditions. A finer resolution grid size leads to more intensive computing for running the dispersion model; therefore, advances in computing speed and efficiency would lead to more highly resolved model outputs. Numerically, the integral from Equation 1 is solved through a series of summations at discrete time steps (Peterson, 2007). Through use of ash dispersion models such as Puff, the impact of aircraft encounters with volcanic ash may be more fully understood.

Case Study: Okmok and Kasatochi Eruptions

I performed a meteorological case study to identify the potential vulnerabilities to commercial aviation from volcanic ash. Eruptions from two separate Alaskan volcanoes, Okmok and Kasatochi, were analyzed. Although volcanic eruptions in the Aleutians Islands are not uncommon, the fact that both eruptions occurred within a period of one month makes this particular situation especially rare. For this reason, the eruptions of Okmok and Kasatochi were chosen to assess the impact of a large volcanic eruption on commercial flight paths.

Volcanic eruptions in the Aleutian Islands often pose a greater threat to aviation than eruptions in Iceland. Geologically, volcanoes in Alaska and Iceland are quite different. Icelandic volcanoes are produced in rift zones caused by spreading of the North American and Eurasian tectonic plates, whereas Alaska volcanoes were formed as a result of subduction of the Pacific Plate underneath the North American Plate. As a result of the mechanism in which Alaskan volcanoes are formed, Alaskan volcanoes tend to produce more explosive eruptions than volcanoes in Iceland.

Volcanic activity is more frequent in the North Pacific than in the North Atlantic, historically speaking. Moreover, increased frequency of transpacific commercial flights puts aircraft at heightened risks. Due to prevailing westerly winds, the dispersion of volcanic ash from the Aleutian Islands typically affects airspace in southern Alaska southward to the U.S. Pacific Northwest region. Many of the volcanoes of the Aleutian Islands pose a heightened threat of impact on Anchorage, Alaska, the largest city located downwind of the volcanoes and a major airline hub for transpacific and cross-polar commercial flights.

A widely used index to assess the relative explosivity of a volcanic eruption is the volcanic explosivity index (VEI). The VEI was first introduced in a 1982 paper by Newall et al. published in the Journal of Geophysical Research. The VEI is based on qualitative observations of eruption criteria of the volcano, including plume height, ejecta volume, and eruptive duration. The scale ranges from 0 to 8, with each increment in scaling equivalent to a ten-fold increase in the magnitude of power (Newall et al., 1982).

The eruption of Okmok occurred at 1143Z on 12 July 2008 after a prolonged period of seismic activity. Ash released from the initial eruption reached altitudes of 15 kilometers and drifted to the south and east over the North Pacific Ocean. The VEI of the eruption was determined to be 4, corresponding to a plume height between 10 and 25 km, an ejective column greater than 0.1 km^2, and a total eruptive duration greater than 12 hours. The eruption of 2008 eruption of Kasatochi also registered a VEI of 4. Unlike Okmok, however, which is a stratovolcano, Kasatochi is a shield volcano. Kasatochi erupted on 7 August 2008. Shortly before the eruption a magnitude 5.6 earthquake was recorded during a period of seismic activity lasting between five and ten minutes. The ash plume released from the volcano reached an altitude of 10.7 kilometers and drifted to the south. The VEI of the eruption was determined at 4. Kasatochi had three major eruptions on 7 August, with the ash emissions becoming more continuous during the penultimate eruptive event.

In this particular case study, the eruptions of Okmok and Kasatochi produced volcanic ash that was injected into the stratosphere. Once the ash had reached this level of the atmosphere, it dispersed over a much larger area. Two topics are explored in this case study to address the potential for ash encounters, as follows: archived synoptic meteorological conditions and Significant Meteorological Advisories (SIGMETs).

a) Archived Synoptic Conditions

To assess the impact of ash dispersion resulting from these two eruptions, the synoptic meteorological conditions were analyzed over the time period during which the eruptions occurred. The synoptic patterns of geopotential heights at multiple pressure levels were compared to determine the altitudes at which the majority of ash dispersed for each eruption. Geostrophic winds were estimated based on height fields at pressures levels of 850 hPa, 700 hPa, 500 hPa, 300 hPa, and 200 hPa and assuming the geostrophic approximation. The altitude over which the winds most closely fit the flow of ash dispersion for each eruption was determined based on estimates of observed wind vectors.

To track how the volcanic ash was dispersed after the eruptions of Okmok and Kasatochi, SO_2 dispersion columns were examined, as measured by Aura/Ozone Monitoring Instrument (OMI) satellite images. The SO_2 columns are recorded in units of DU, or Dobson Units. One Dobson Unit is equivalent to a layer of sulfur dioxide in the atmospheric that is 10 μm thick under standard temperature and pressure. The time of the satellite overpass, as indicated on the Aura/OMI satellite images, provides a reference of time over which the ash had dispersed after the eruption had occurred. Figure 7 shows the dispersed spread of SO_2 approximately 120 hours after the eruption of Okmok.

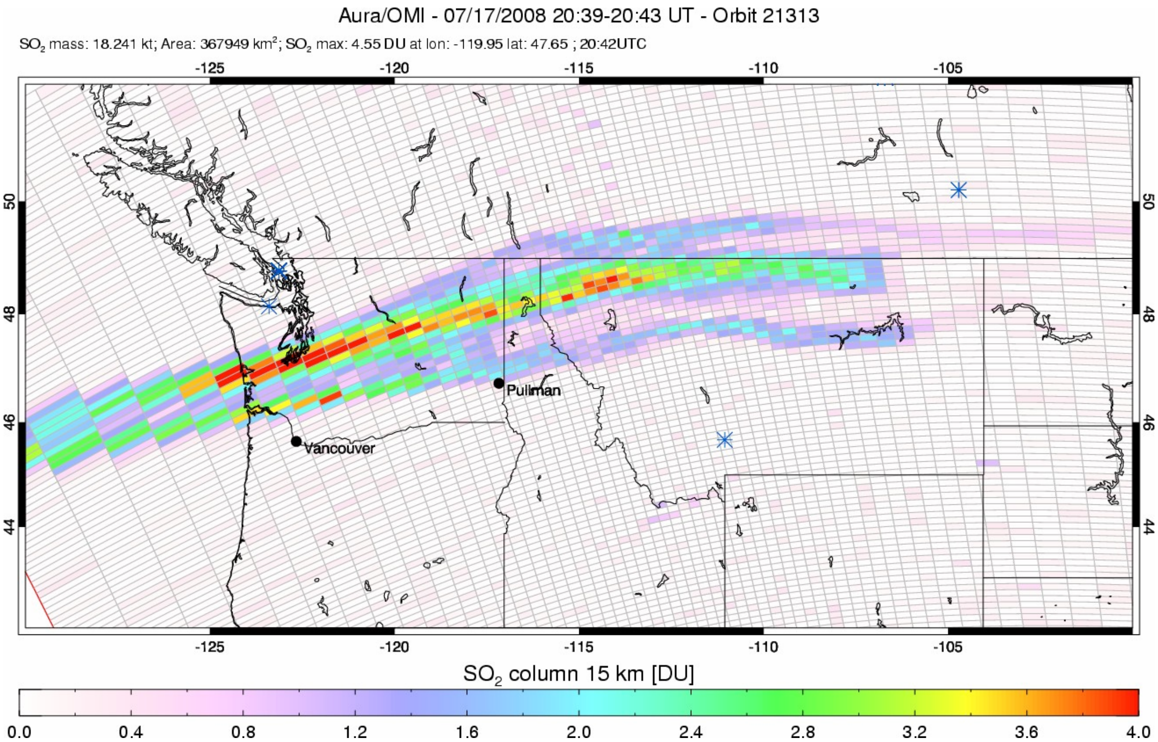

Figure 7. SO_2 as detected by Aura/OMI in the northwestern United States five days after the initial eruption of Okmok (UMBC Sulfur Dioxide Group)

The synoptic patterns for both volcanic eruptions were quite different. An archive of meteorological data courtesy of the NOAA Air Resources Laboratory (ARL) shows the conditions at the time of each eruption. The eruption of Okmok began at 1143Z on 12 July 2008 and the volcano continued eruption sporadically over a period of five and a half weeks. The eruption which produced a 50,000-foot ash plume was observed around 2000Z on 12 July 2008. An archive of geopotential heights and wind vectors at 300 hPa shows the synoptic conditions at flight level for most commercial aircraft. Figure 8a shows the pattern of geopotential heights over Alaska at this time. A large area of low heights is situated over the Chukchi Peninsula with a ridge of high heights located further east along south-central Alaska. The pattern of wind vectors reveals westerly flow along the Alaska Islands with stronger, more northerly winds south of Anchorage (Figure 8b).

The synoptic pattern at the time of the eruption suggested ash dispersion tracking eastward initially, then taking a more southward direction into the North Pacific.

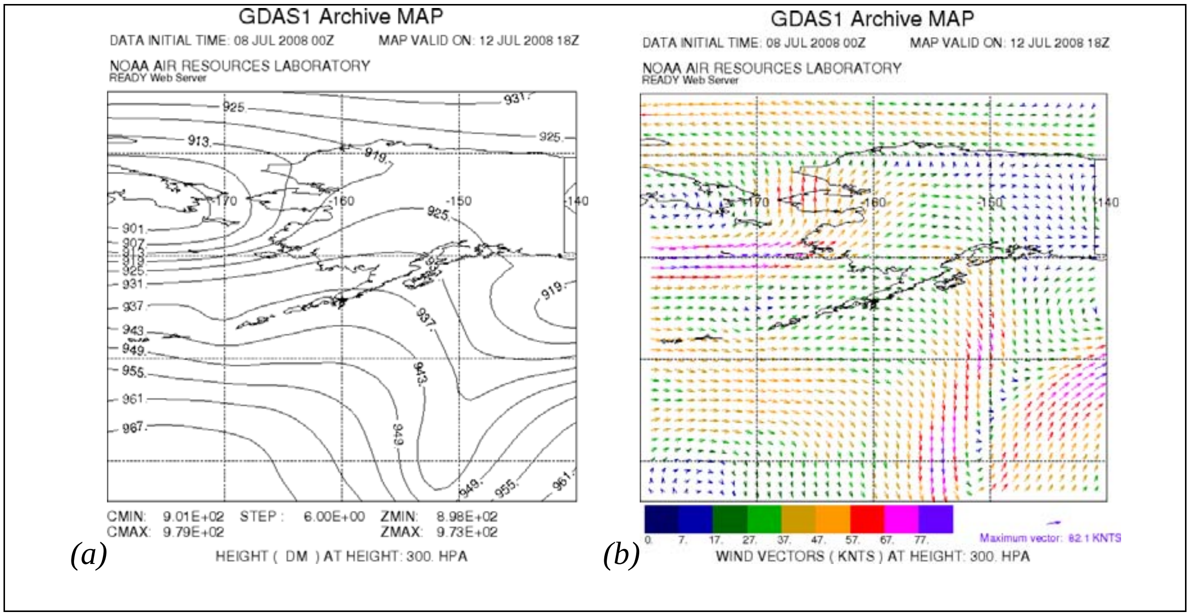

Figure 8. Archived synoptic conditions on 12 July 2008 at 18Z, showing the geopotential heights (**a**) and wind vectors (**b**) at 300 hPa (NOAA ARL)

Model forward trajectories from HYSPLIT were generated to assess the effectiveness of dispersion modeling for forecasting ash after a volcanic eruption. The HYSPLIT model runs were initialized through the READY HYSPLIT tool from the NOAA Air Resources Laboratory. AURA/OMI SO_2 column measurements during simultaneous time periods were compared.

Figure 9 shows a comparison of the HYSPLIT model run with the measured SO_2 column data. The HYPSLIT model was initialized at 2000Z on 12 July 2008 and the current run shown is at 1400Z on 13 July. Also featured in Figure 9 is a SO_2 column measurement from the AURA/OMI instrument from 0018Z on 13 July. The HYSPLIT model is a trajectory model of ash dispersion, whereas the AURA/OMI plot is a measurement of column SO_2 in the atmosphere, which is a tracer for ash dispersion (Figure 9).

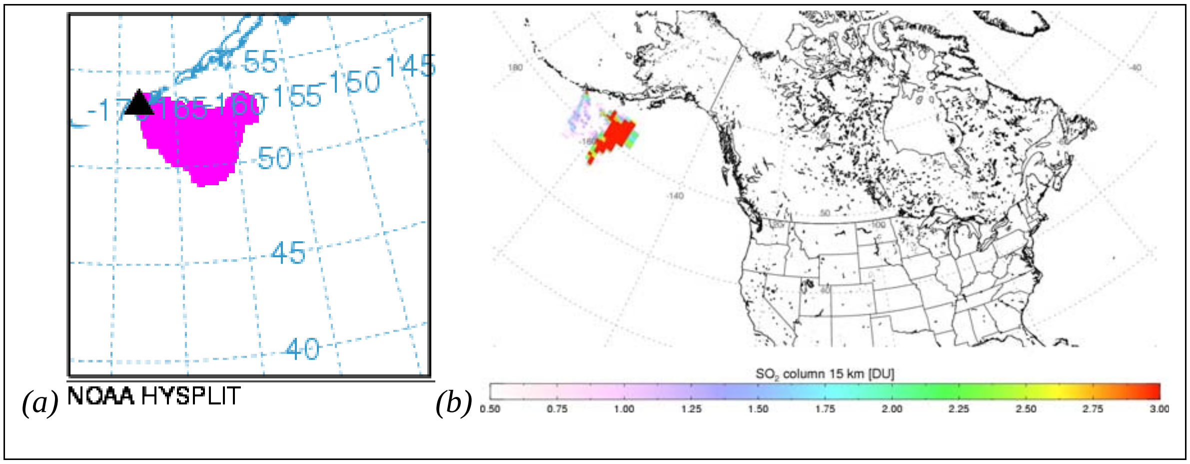

Figure 9. HYSPLIT forward trajectory (**a**) and column SO_2 as detected by AURA/OMI (**b**) from volcano Okmok (NOAA ARL, UMBC Sulfur Dioxide Group)

Analysis of the HYSPLIT model run reveals notable discrepancies with the actual measured satellite detection. The HYSPLIT model run at 1400Z on 13 July shows an ash cloud situated mainly between 50ºN and 55ºN and west of 160ºW. Conversely, the actual measured SO_2 column at 0018Z on 13 July shows that the ash cloud mainly between 50ºN and 55ºN but east of 160ºW. Therefore, since the ash cloud actually was detected further east more quickly than the forecast model, the HYPSLIT model underestimated the dispersion rate of the volcanic ash through the atmosphere. The HYSPLIT model run captured the trailing end of the ash cloud from the volcano as detected by column SO_2 measurements (Figure 9b), however overestimated the extent of the ash cloud near the volcano. Although the HYSPLIT model run is based on archived GDAS1 meteorological data, this case illustrates that the forecasted ash dispersion is not very accurate even 24 hours after the initial eruption.

The eruption of Kasatochi occurred on 7 August 2008 after an intense period of seismic activity. A magnitude 5.6 earthquake occurred a few kilometers from Kasatochi in the minutes preceding the initial eruption. The exact timing of the initial eruption is unknown at present since no seismic equipment is installed at Kasatochi Island and the volcano is not extensively monitored by the AVO. Based on satellite imagery from GOES, the eruptive plume from Kasatochi was first viewed at 00Z on 08 August 2008.

On 07-08 August 2008, three distinct explosions were detected by seismic instruments installed on nearby Great Sitkin Volcano: 2201Z on 07 August and 0150Z and 0435Z on 08 August. The first two eruptions of Kasatochi produced hot gas with little or no ash plume. The third eruption, however, caused a thick ash plume which rose to 45,000 feet above mean sea level. This ash plume is responsible for much of the ash dispersion which eventually drifted over the Pacific Northwest several days later.

The synoptic conditions during the eruption of Kasatochi differed from those observed at the onset of the Okmok eruption. Figure 10 shows archived meteorological data from 08 August 2008. The plot of geopotential heights over Alaska shows several distinctive features at this time. A large area of low pressure was situated north of Anchorage with generally meridional flow over much of the region. A northwesterly atmospheric flow is found over Kasatochi, influenced in part by a secondary occluded low to the south and west. The synoptic pattern on 08 August suggests ash dispersion tracking towards the southeast into the North Pacific.

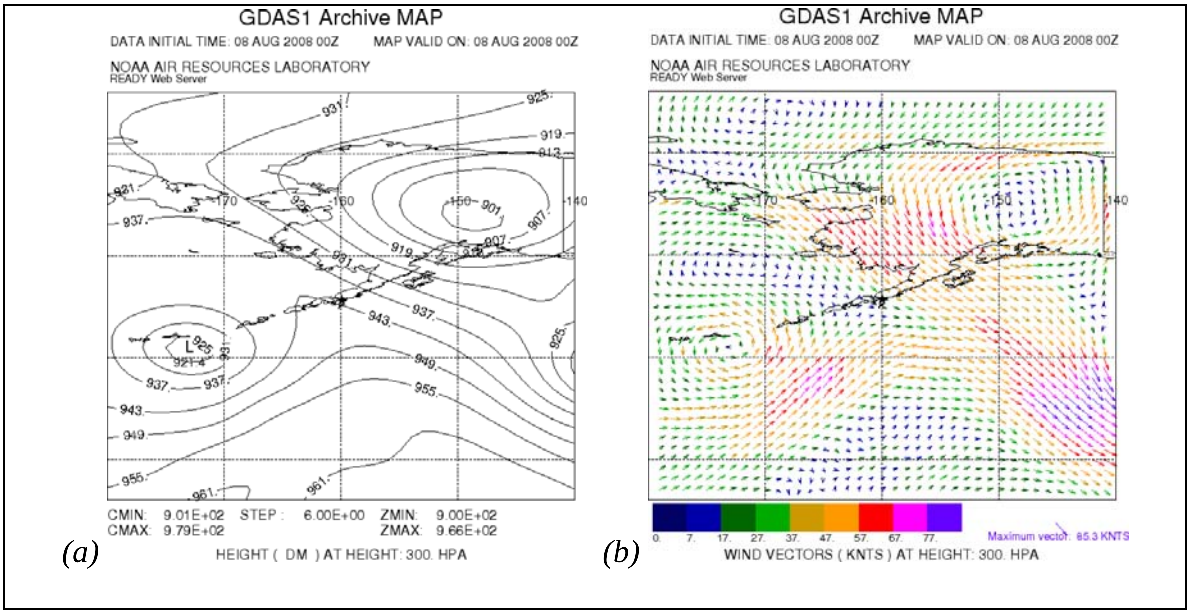

Figure 10. Archived synoptic conditions on 08 August 2008 at 00Z, showing the geopotential heights (**a**) and wind vectors (**b**) at 300 hPa (NOAA ARL)

Similar to the Okmok case study, HYSPLIT model forward trajectories were generated to compare with actual measured satellite data after the eruption of Kasatochi. Figure 11 shows the comparison of the HYSPLIT model run with the measured SO_2 column data. The HYPSLIT model was initialized at 2200Z on 07 August 2008 and the current run shown is at 0400Z on 09 August. The top of the ash plume was parameterized at 45,000 feet, as reported by the AVO at the time of the eruption. Also featured in Figure 11 is a SO_2 column measurement from the AURA/OMI instrument from 0056Z on 09 August.

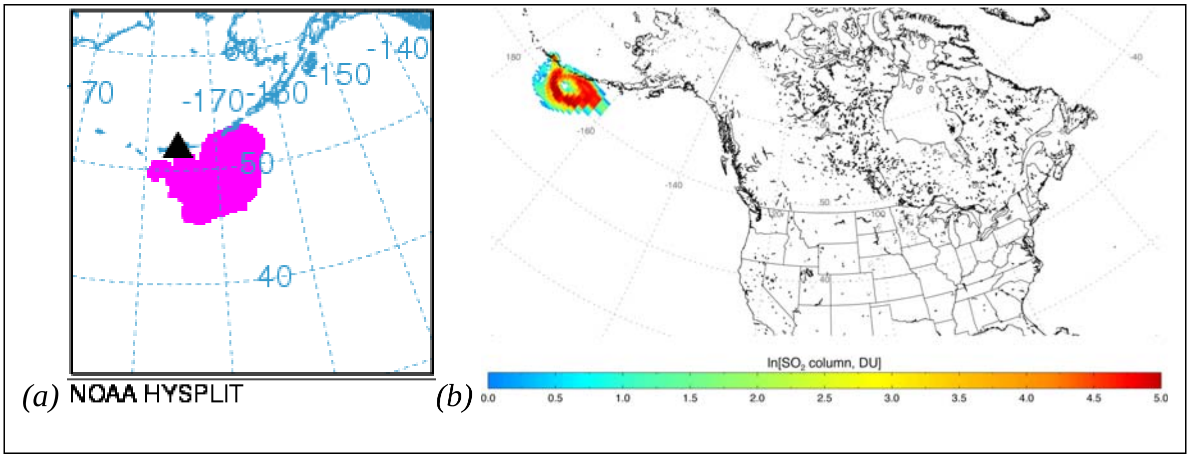

Figure 11. HYSPLIT forward trajectory (**a**) and column SO_2 as detected by AURA/OMI (**b**) from volcano Kasatochi (NOAA ARL, UMBC Sulfur Dioxide Group)

Through comparison of the HYSPLIT model run with actual satellite measurements, it can be shown that there is relatively good agreement for both images. The HYSPLIT model run detects an ash cloud situated between 160ºW and 180ºW centered at approximately 50ºN. The shape of the ash cloud is horizontally oblique with the ash cloud extending over volcano Kasatochi. The measured SO_2 column at 0056Z on 09 August also shows an ash cloud detected between 160ºW and 180ºW centered at 50ºN. The HYSPLIT model run closely matches the spatial extent of the volcanic ash dispersion as illustrated in Figure 11b from the measured SO_2 column.

The SO_2 column measurements reveal a circular hole of lower SO_2 values in the middle of the ash cloud which is not evident in the run output of the HYPSLIT model forward trajectory. However, other accompanying runs of HYSPLIT did detect a hole feature in the ash cloud. It should be noted that the extent of the ash dispersion from the Kasatochi eruption was much closer in proximity to the source volcano than in the case of the Okmok eruption. Therefore, the model performed better in the Kasatochi case because the volcanic ash was not as widely dispersed in the atmosphere. Although the model run from the Okmok eruption had noticeable flaws in the output, the model run for the Kasatochi eruption proved to be quite effective in forecasting the extent of the volcanic ash cloud 24 hours after the eruption.

b) SIGMETs Data

The Significant Meteorological Advisories (SIGMETs), issued by the Volcanic Aviation Weather Center (AWC) in Kansas and the Alaskan Aviation Weather Unit (AAWU) in Alaska, were examined to determine the information available to the aviation community at the time of each eruption. SIGMETs are advisories issued to alert air traffic that volcanic ash may pose a threat at a particular location and altitude. By understanding where in the atmosphere threats of volcanic ash were determined, there is increased confidence in the direction and speed of airflow accompanying volcanic ash dispersal. The SIGMETs are analyzed in conjunction with synoptic maps to provide additional information about the locations of heightened risk of volcanic ash. An example of an actual SIGMET issued by the AWC is provided in Figure 12, courtesy of the Naval Research Laboratory (NRL). This SIGMET was generated on 10 August 2008 shortly after the onset of the Kasatochi eruption.

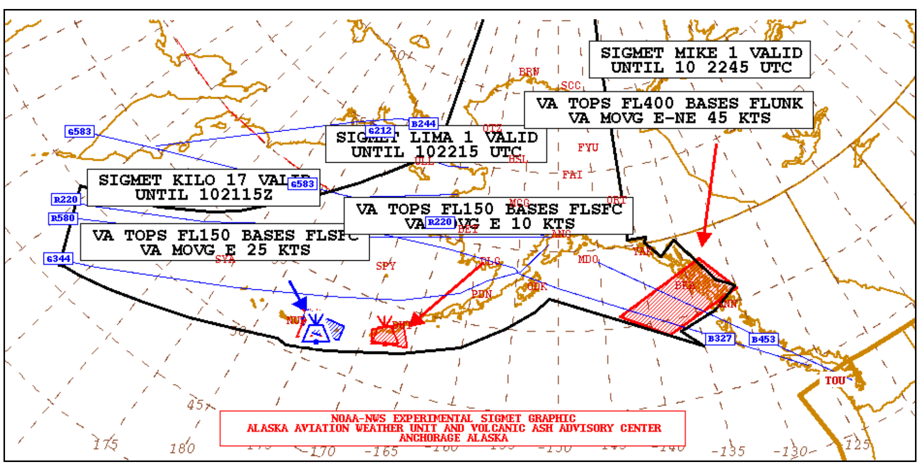

Figure 12. SIGMET issued on 10 August 2008 for volcano Kasatochi (NRL)

Ash avoidance is recognized by the FAA as pilots' first option when confronted with volcanic ash. Consequently, air traffic may be required to alter its prescribed route in the event of a volcanic eruption, as a means of avoiding a potential ash encounter. In the cases of the Okmok and Kasatochi eruptions, ash dispersion was spread over relatively large geographic areas which forced many commercial flights to change course. Often, a flight is forced to alter its route while already in flight. Rerouting increases costs to the airline industry resulting from additional fuel consumption and lost revenue due to flight delays and cancellations.

Volcanic Activity at Mount Redoubt

Mount Redoubt is a 3,108-meter (10,197 ft) stratovolcano located at 60.4852°N and 152.7438°W in the Chigmit Mountains of Alaska. According to the Alaska Volcano Observatory, the volcano is nearly 10 kilometers in diameter at its base with a volume of 30 to 35 cubic kilometers. An eruption of Redoubt has major implications for the city of Anchorage, Alaska, which is situated 110 kilometers to the east-northeast. A volcanic eruption poses an especially large threat to aircraft flying to and from the airport at Anchorage. Anchorage International Airport is the cargo hub for Alaska Airlines and is the third largest air-cargo hub in the world. (AVO, 2009)

In the last century, Mount Redoubt erupted three times: 1902, 1966, and 1989. The last eruption (1989-1990) produced a 45,000-foot ash plume which disrupted air traffic in southern Alaska. Two major eruptive events in December 1989 and January 1990 caused a massive emission of tephra, ash, and gas which spread throughout the atmosphere. On 15 December 1989, the eruption of Redoubt created serious complications for 231 passengers of KLM flight 867, which was forced to make a dramatic emergency landing after a brief encounter with volcanic ash. Within 60 seconds of the ash encounter, all four engines of the Boeing 747-400 aircraft shut down during flight. The aircraft began a powerless descent of 13,000 feet over mountainous terrain during a 4-minute period. Once the engines could be restarted, the aircraft made a safe emergency landing at Anchorage International Airport.

The aviation industry incurred large economic costs as result of the volcanic eruption. The Boeing 747 aircraft involved in the ash encounter on 15 December 1989 sustained structural and mechanical damages exceeding $80 million. During the time period following the eruption, many other flights were grounded to prevent the possibility of an ash encounter. Anchorage International Airport was forced to cancel hundreds of flights, contributing to a $2.6 million downfall in revenue for the airport. The total economic cost to the aviation industry from the 1989-1990 was estimated at $101 million, according to a 1998 economic impacts study. (Waythomas, 1998)

2009 Eruption of Mount Redoubt

After a nearly 20-year period of dormancy, Mount Redoubt began showing signs of activity again in 2008. On 5 November 2008, a large discharge of melt water was observed draining from the base of the Drift Glacier located near the summit crater. A volcano alert level of YELLOW/ADVISORY was put in effect from 5 November 2008 until 25 January 2009, at which time it was elevated to ORANGE/WATCH. During the period lasting from 25 January to 26 February, observations and measurements revealed seismic unrest at Redoubt. Measurements detected strong tremors, elevated levels of volcanic gases (CO_2, SO_2, and H_2S), and occasional steam plumes, according to the Alaska Volcano Observatory (AVO, 2009).

Seismic activity decreased substantially beginning on 26 February, although volcanic emissions continued near the summit. On 10 March 2009 the volcano alert level was lowered to YELLOW/ADVISORY. After an episode of intense seismic activity on 13 March 2009, the volcano alert level was again elevated to ORANGE/WATCH. An observational flight from the AVO reported an ash and steam plume reaching 15,000 feet above mean sea level on the south flank of Redoubt. Minimal activity ensued in the following days, prompting the AVO to lower the alert level to YELLOW/ADVISORY.

At the time the alert level was lowered, the AVO staff reported that despite anomalously high volcanic emissions at the summit, the reported low levels of activity could persist for months or even years. On 21 March at 1809Z, the alert code was raised to ORANGE/WATCH after a rapid increase in seismic activity. The seismic activity reflected the upward motion of magma as it neared the surface. The violent tremors continued periodically throughout the day on 21 March into 22 March.

At 0638Z on 23 March, the AVO reported a large eruption of Mount Redoubt. Between 0638Z on 23 March and 1300Z on 23 March there were a total of five explosive eruptions, each lasting between four and thirty minutes in duration. The eruptions occurred at 0638Z, 0702Z, 0814Z, 0939Z, 1231Z on 23 March. According to the Anchorage Volcanic Ash Advisory Center, issued at 1725Z on 23 March, the highest ash plume may have reached 60,000 feet above mean sea level, based on analysis of satellite imagery (http://www.avo.alaska.edu/activity/Redoubt.php). Most of the ash cloud following the eruption was suspended in the atmosphere between 25,000 and 30,000 feet above mean sea level.

At 0341Z on 24 March, the AVO recorded a sixth eruption, in which the National Weather Service posted a new ashfall advisory for areas north of the volcano. At 1312Z on 25 March, a seventh eruption of Redoubt was observed, although the eruptive event was much less intense than previous eruptions. The ash plume did not exceed 12,000 feet above mean sea level. The National Weather Service did not issue an ashfall advisory following the seventh eruption. (AVO, 2009)

A brief period of calm followed the seventh eruption as seimicity levels returned to normal. The AVO lowered the volcano alert level from RED/WARNING to ORANGE/WATCH at 2135Z on 25 March. On the following day, however, an eighth eruptive event occurred at 1634Z on 26 March. At the onset of the eruption, the AVO once again raised the volcano alert level to RED/WARNING. Local radar confirmed the height of the ash plume at 30,000 feet above mean sea level. Seismic tremors continued afterwards during a period of violent unrest. At 1724Z on 26 March the AVO reported a “major explosive event” from Mount Redoubt. According to the National Weather

Service, the ash plume had reached a peak height of 65,000 feet above mean sea level, high enough in the atmosphere to inject volcanic ash into the stratosphere.

The last eruption, which occurred at 9:24 am Alaska local time, further complicated air traffic to and from Anchorage International Airport. At the time of the eruption, low level winds from the northwest carried volcanic ash across the Cook Inlet toward the Homer region, whereas upper level stratospheric winds were directed from the southwest toward Anchorage. The National Weather Service issued an ash advisory warning with a geographic extent given by the image in Figure 13b. In response to the airborne volcanic ash threat, the Anchorage International Airport was forced to cancel many of its flights. The first five eruptions of Mount Redoubt caused 35 flight cancellations from Anchorage International Airport. The 26 March eruption resulted in an additional 10 flight cancellations. Since the onset of the first eruption on 23 March 2009, an estimated 4,000 airline passengers were affected by flight cancellations, according to Alaska Airline officials (http://www.alaskaair.com).

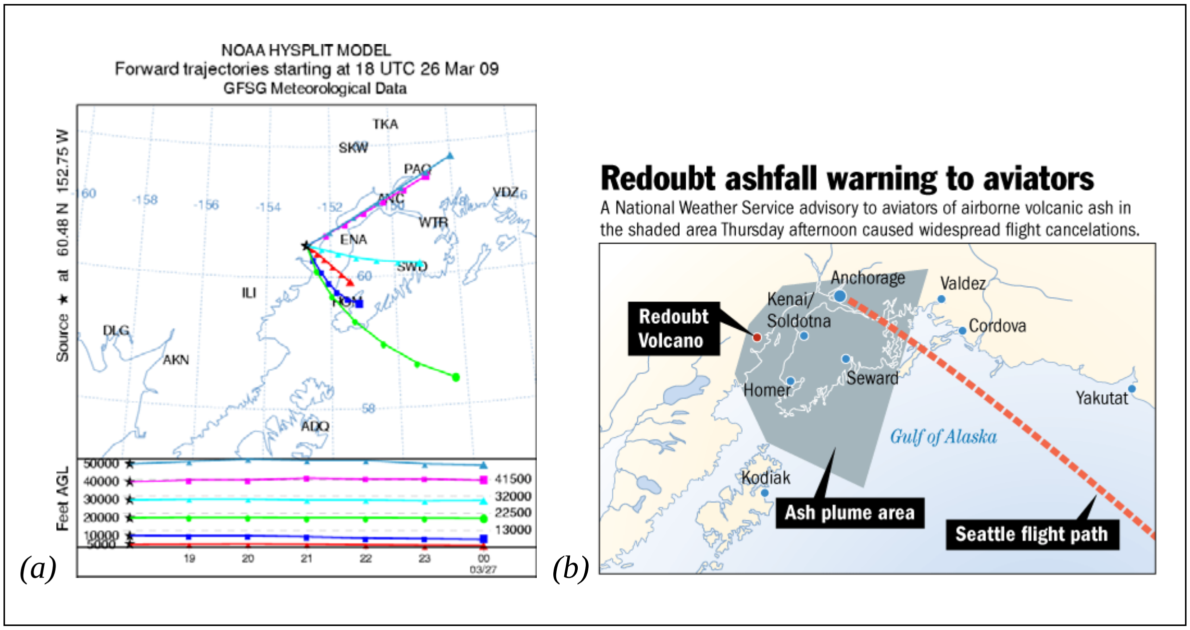

Figure 13. Hysplit forward model trajectory initialized at 1800Z on 26 March 2009 (**a**) and the extent of the NWS-issued ash advisory in gray (**b**) following a 1724Z eruption on 26 March 2009 (AVO, NWS)

A consequence of the ninth eruption of Mount Redoubt was a powerful lahar produced along the Drift River. A lahar is a mudflow of pyroclastic material and water resulting from a volcanic eruption. The National Weather Service issued a Flash Flood Warning for the Drift River, which serves as a runoff channel from the Drift Glacier. A large concern for local residents was that the lahar would damage nearby Drift River Oil Terminal where over six million gallons of crude oil is reserved. The Drift River Oil Terminal is managed by Chevron Oil Company. Following the lahar, it was determined that the oil terminal was not damaged. In preparation for another eruption, about 60 percent of the oil was removed from the terminal on 6 April 2009.

A tenth eruption of Mount Redoubt occurred at 1640Z on 27 March. The height of the ash plume has been estimated at 50,000 feet by the National Weather Service based on radar imagery. A series of small tremors ensued in the hours following the ninth eruption. Several minor ash plumes were reported by the AVO. At 1358Z on 4 April, another significant eruption occurred at Redoubt with the height of the ash plume estimated at 50,000 feet based on radar from the National Weather Service. Seismicity levels dropped considerably after the eruption. The AVO lowered the volcano alert level to ORANGE/WATCH at 1455Z on 6 April. Figure 9 shows the 10-minute averaged time series of seismic readings at seismic station REF, located approximately 3 miles from the summit on the south face of the volcano.

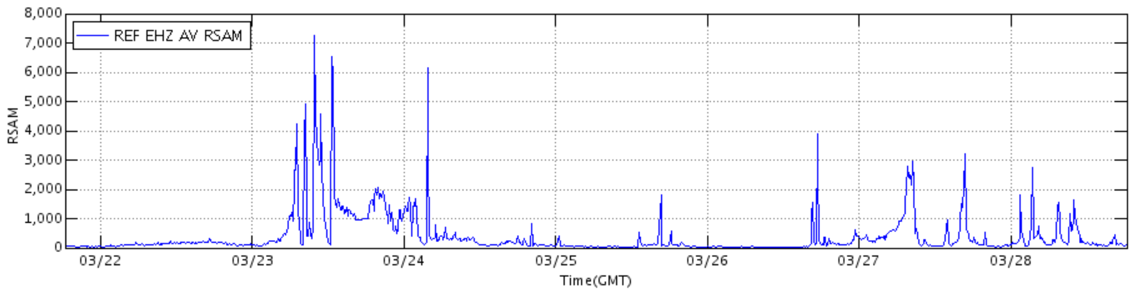

Figure 14. REF seismic time series at 1800Z on 28 March 2009 (AVO)

The AVO had mounted a fully-automated web camera approximately 7.5 kilometers from the summit crater to monitor activity at Mount Redoubt. Prior to the initial volcanic eruption on 23 March, intense seismic tremors severely damaged the AVO's web camera. Therefore, no images of the first eruption were captured. The web camera was replaced several hours later in time to capture the sixth eruption at 0341Z on 24 March. Figure 11 shows an image captured at 0355Z on 24 March, just 14 minutes after the onset of the eruption.

Figure 15. Eruption of Mount Redoubt at 0355Z on March 24, 2009 (AVO)

Analysis of Ash Dispersion

The weeks and months leading up to the eruption of Mount Redoubt were heavily monitored by the AVO. Sufficient lead time, coupled with a fortuitous wind pattern, allowed the aviation industry to prepare itself well in advance for the initial eruption. The synoptic conditions during the initial eruption are displayed in Figure 12. A strong low pressure system was situated over the Bering Sea. The tightest height gradient is located due south of the Aleutian Islands. Based on geostrophy in the height field, we expect southerly flow at 500mb over Mount Redoubt. As supported by subsequent satellite imagery, winds carrying the volcanic ash clouds generally were southerly at this level of the atmosphere.

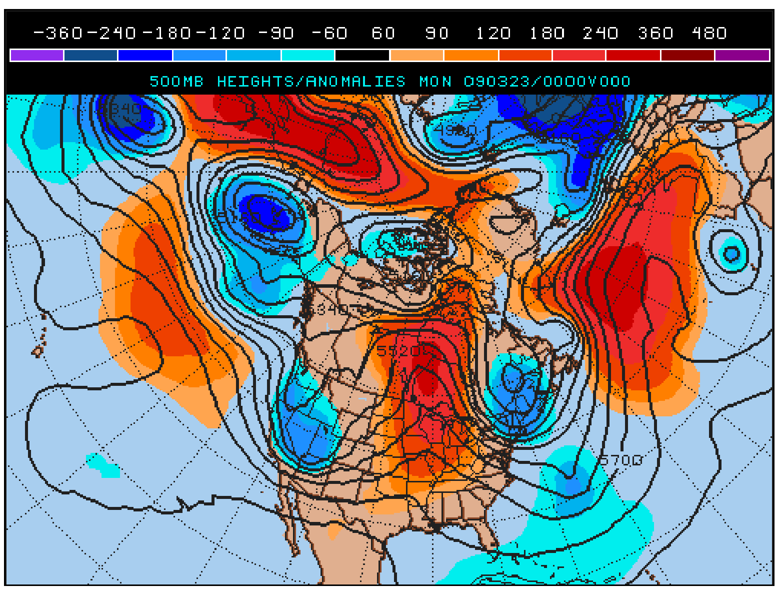

Figure 16. 500mb synoptic pattern at 0000Z on March 23, 2009 (PSU E-wall)

The wind pattern proved to be quite fortuitous for Anchorage. Precautionary measures for an eruption of Mount Redoubt had been in effect since January 2009. Safety goggles and safety masks had been made available to all employees and customers of the airport. Furthermore, all aircraft at Anchorage International Airport had been wrapped in a sealant to protect against volcanic ash. Alaska Airlines services over 50 flights a day to Anchorage and 2 flights a day to Kodiak, Alaska, according to Alaska Airlines (http://www.alaskaair.com).

SO_2 column measurements from Aura/OMI reveal the atmospheric transport of volcanic ash occurring since the 23 March eruption of Mount Redoubt (Figure 13). The SO_2 column is an effective tracer for volcanic plumes. The eruption occurred at 1725Z on 22 March and the ash plume ascended to a height of 60,000 feet according to National Weather Service radar. According to the archived upper-air sounding from Anchorage International Airport at 00Z on 24 March, the height of the tropopause was at approximately 300 mb, or 8680 meters (24478 feet). Figure 13a shows SO_2 column at 2043Z on 23 March 2009. Figure 13b shows SO_2 column at 1807Z on 24 March 2009. Figure 13c shows SO_2 column at 1711Z on 25 March 2009. As is shown from Figures 13 a, b, and c, the ash plume drifted eastward following the eruption with the center of the eruptive plume approximately over Anchorage. The plume continued to drift to the east and south based on upper-level atmospheric flow. By 25 March, the SO_2 column measurements suggest that the plume had reached a northern extent near Great Bear Lake in the Canadian Northwest Territories and a southern extent in eastern Washington.

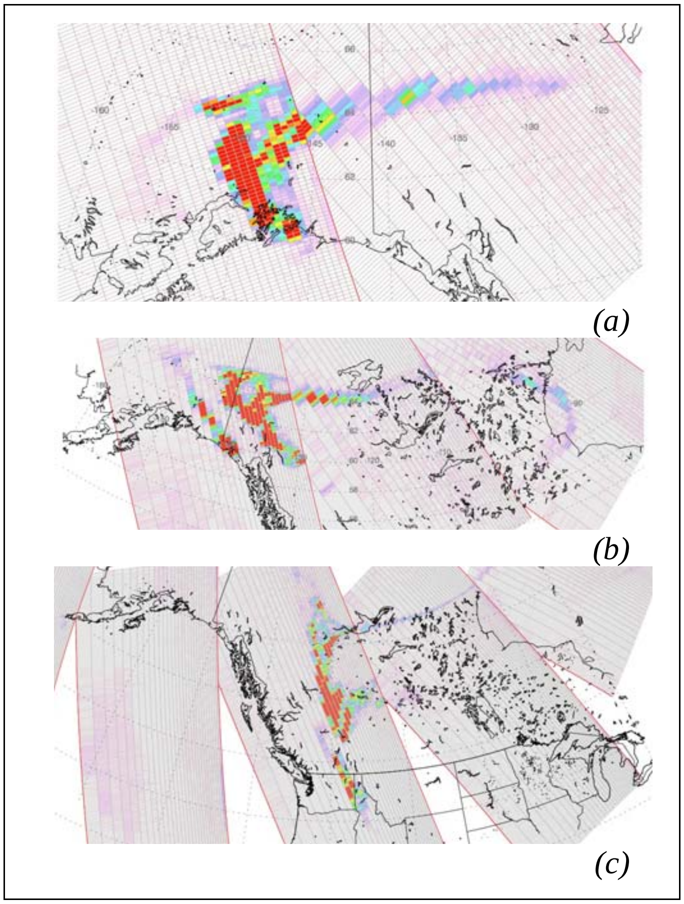

Figure 17. OMI SO_2 column measurements at 2043Z on 23 March (**a**), 1807Z on 24 March (**b**) and 1711Z on 25 March (**c**) (UMBC Sulfur Dioxide Group)

The NOAA's Air Resources Laboratory provides model HYSPLIT forward trajectories specifically designed for volcanic ash transport. The HYSPLIT model is widely used for trajectory modeling. I attempt to compare how well the HYSPLIT model performed in predicting volcanic ash dispersion after the eruption of Mount Redoubt as compared to OMI SO_2 column measurements. It should be noted that SO_2 column measurements do not detect volcanic ash itself but rather SO_2 column measurements are an effective tracer of volcanic ash transport.

The forward trajectory product, known as READY HYSPLIT volcanic ash dispersion model, is available from the NOAA Air Resources Laboratory website http://www.ready.noaa.gov. To create a forward trajectory for the Okmok eruption, the following parameters were used, initialized at 23Z on 22 March 2008: 12-hour total run time, 50000-foot ash column height, and 6-hour eruption. Based on these parameters, the following output of the HYSPLIT model was generated (Figure 18a) and compared with AURA/OMI satellite imagery of SO_2 column measurements (Figure 18b).

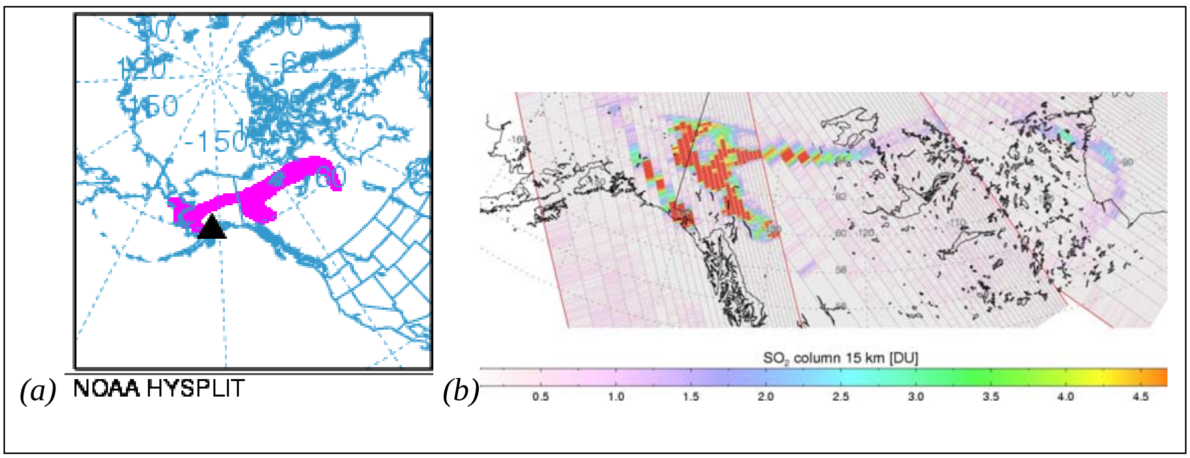

Figure 18. HYSPLIT forward trajectory (**a**) and column SO_2 as detected by AURA/OMI (**b**) from volcano Redoubt (NOAA ARL, UMBC Sulfur Dioxide Group)

The HYSPLIT volcanic ash dispersion model performed well in predicting the extent of the ash cloud approximately 27 hours after the eruption. The easternmost extent of the volcanic ash as indicated by the HYSPLIT model run is located west of the western coast of Hudson Bay. Conversely, the easternmost extent of the volcanic ash as indicated by the AURA/OMI instrument is east of the western coast of Hudson Bay. The HYSPLIT model run is valid at 0500Z on 24 March whereas the satellite imagery is valid at 1807Z on 24 March. The HYSPLIT model correctly identified features of the volcanic ash cloud, including the extended region of volcanic ash along the Pacific coast of British Columbia. The hook-like shape of the cloud is also captured by the HYSPLIT model run. The model suggests a trailing end to the ash cloud which extends to volcano Redoubt; however, the column SO_2 measurements do not detect any such feature in the ash cloud.

Summary and Conclusions

The airline industry is exposed to a considerable threat from volcanic eruptions not only in the U.S. Pacific Northwest, but across the North Atlantic and many other locations where volcanic activity and a high frequency of airline flights co-occur. The recent activity of Mount Redoubt showed how critically important the weather is in ash dispersion following an eruption. Although the city of Anchorage was spared from the brunt of the ashfall following the 23 March 2009 eruption, a slight shift in winds may have proved disastrous to the aviation industry in Alaska and the U.S. Pacific Northwest. Trajectory modeling reveals that wind patterns are not always as favorable as they were when Mount Redoubt initially erupted at 0638Z on 23 March 2009.

The results from the Okmok and Kasatochi studies show two examples of how volcanic ash can disrupt commercial aviation. Although the bulk of volcanic ash fallout occurs within the initial few hours after an eruption, the fine-grained ash that caused significant difficulty to aircraft can linger in the atmosphere for several days after an eruption and disperse over hundreds of kilometers. The case studies of volcanoes Okmok, Kasatochi, and Redoubt focused primarily on areas near or around the U.S. Pacific Northwest. However, the results of this paper can be applied broadly to any volcanic eruption in any region. The airline industry has much to gain from understanding the need to prepare and prevent the occurrence of in-flight ash encounters. Because the issue of ash avoidance is primarily one of economic implications, an investment in preparing for volcanic encounters would yield high returns for the airline industry over the long term.

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Bachelor of Science in Meteorology, Minor in Geographic Information Systems
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Professional Experience

NASA DEVELOP National Program, Langley Research Center, Hampton, VA, May-Aug. 2008
Evaluated aspects of data processing associated with the CALIPSO mission and presented results live on NASA TV at NASA Headquarters in Washington, D.C.

Peter R. Gould Center for Geography Outreach and Education, PSU, Sept. 2007-May 2008
Completed GIS and cartographic projects for various local clients, including the National Park Service, Penn State University, and National Geographic.

Leadership Experience

NCAR Undergraduate Leadership Workshop, NCAR, Boulder, CO, June 2008
Participated in a 5-day workshop to learn key professional leadership skills while gaining valuable insight on the atmospheric research community in Boulder.

Penn State Campus Weather Service, PSU, Sept. 2005-May 2009
Lead weekly shifts to produce weather forecasts for campus newspaper, *The Daily Collegian*. Volunteered as a shift member to forecast for local radio and video clients.

Research Experience

CAUSE 2008: Volcanoes, Glaciers, and their Societal Impacts, College of EMS, Iceland
May 11- 23, 2008
Conducted field work on aspects of geology, glaciology, and meteorology using lidar, GPS, and seismometers during a 12-day expedition across southern Iceland.

GEOG 497C: Environmental Issues Across the Americas, College of EMS, Peru, December 2008
Conducted interdisciplinary study at research stations in Amazonia to investigate the effects of local climate change on communities in the Madre de Dios Region of Peru.

Publications and Contributions

Matus, A., B. Scarino, D. Henderson, B. Lee, and C. Trepte, The evaluation and application of CALIPSO products with focus on expedited data retrievals, temperature dataset comparisons, and trajectory modeling, *Fourth Symposium on Lidar Atmospheric Applications*, American Meteorological Society, Phoenix, AZ, January 2009

L. Hudnall, A. Krueger, **A. Matus**, J. Murray, and M. Pippin, The impacts on air traffic of volcanic ash from the Okmok and Kasatochi eruptions during the summer of 2008, *Aviation Weather Information*, 39th AIAA Fluid Dynamics Conference, San Antonio, TX, June 2009

Activities

Secretary, Penn State University Branch of the AMS (PSUBAMS), 2006-2009
Member, American Meteorological Society, 2006-2009
Member, Chi Epsilon Pi Meteorology Honors Society, 2007-2009
Member, Penn State Campus Weather Service, 2005-2009
Volunteer, THON Dance Marathon against Pediatric Cancer, 2005-2009
Volunteer, Earth and Mineral Sciences Open House (EMEX), 2009
Team Manager, Nittany Lion Mens Basketball Team, 2006-2009

Awards and Achievements

EMSAGE Laureate, May 2009
Kruhoeffer Endowed Scholarship in Meteorology, August 2008
Schreyer Summer 2008 Research Scholarship, May 2008
Schreyer Ambassador Travel Grant, March 2008
Matthew J Wilson Honors Scholarship, 2007/2008
Dean's List, Penn State University, 2005-2009

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Working knowledge of ArcGIS.
Working knowledge of HTML and CSS.
Experience with MATLAB, Perl, C++, and Visual Basic.

References available upon request.