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# THE IMPACTS ON AIR TRAFFIC FROM VOLCANIC ASH FROM THE 2009 MT. REDOUBT ERUPTIONS

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## 1. ABSTRACT

The March 2009 eruption of Mt. Redoubt created the potential for major problems for aviation due to the dispersion of volcanic ash. Mt. Redoubt, located 110 km west-southwest of Alaska Airlines hub Anchorage, last erupted in 1990 and caused an estimated $101 million cost to the aviation industry (Waythomas, 1998). It is important to assess the impacts on aviation so that valuable information may be obtained and used in developing better warning systems and handling situations associated with these impacts.

A study was performed to (1) determine the altitude of $SO_2$ dispersion through analysis of synoptic meteorological conditions and satellite imagery and (2) investigate the reported impacts on aviation from the volcanic ash dispersion. To assess the altitude of $SO_2$ dispersion, volcanic ash was tracked using OMI $SO_2$ column measurements. The OMI satellite images were assimilated with CALIPSO backscatter profiles, geopotential height plots, and HYSPLIT forward model trajectories. To investigate the impacts on aviation, reports from airports and Volcanic Ash Advisories were also reviewed.

A complex dispersion of volcanic ash resulted from the eruption of Mt. Redoubt. The altitudes of ash dispersion were estimated on 23, 24, and 25 March 2009. On 23 March 2009, the majority of the ash plume remained at approximately 8 km, although reports indicate that the initial plume may have reached 18 km (60,000 ft). On 24 March 2009, most ash was entrained in a passing low pressure system at around 8 km. Some ash was detected by CALIPSO at higher altitudes (10 km and 16 km). Near Hudson Bay, atmospheric patterns suggest dispersion at approximately 3 km. On 25 March 2009, much of the ash plume remaining was detected at higher altitudes three days following the eruption. The stratospheric ash plume was located 14 km above mean sea level, as detected by CALIPSO. By the time the eruptions had subsided in April, Alaska Airlines had cancelled 295 flights and disrupted the flights of over 20,000 passengers.

This project supports Sub Goal 3A of the NASA Strategic Plan, “Study Earth from space to advance scientific understanding and meet societal needs.” Although the aviation industry was well prepared for the 2009 Mt. Redoubt eruption, preparatory measures need to be taken to prevent future volcanic ash encounters and reduce the economic impact from flight delays and cancellations. Improved forecast models and communication with pilots will mitigate the impacts from volcanic ash on aviation.

## 2. INTRODUCTION

Aircraft in flight routes over Alaska are periodically faced with the threat of encountering volcanic ash from any of the major active volcanoes located within the state. Air traffic hundreds or more miles away from volcanic eruptions may be impacted due to the amount of ash in the atmosphere and the rate of its dispersion. When air traffic encounters volcanic ash, a wide range of impacts, including windscreen scouring, catastrophic engine damage and the loss of the aircraft, crew and passengers, is possible.

Volcanic ash may cause serious problems to aviation due to the direct economic effect impacts from damages to the aircraft as well as the need to reroute, delay, or even cancel flights. To date, there have been no reported aircraft crashes due to a volcanic ash encounter. There have been several major close calls involving total engine failure at flight altitudes.

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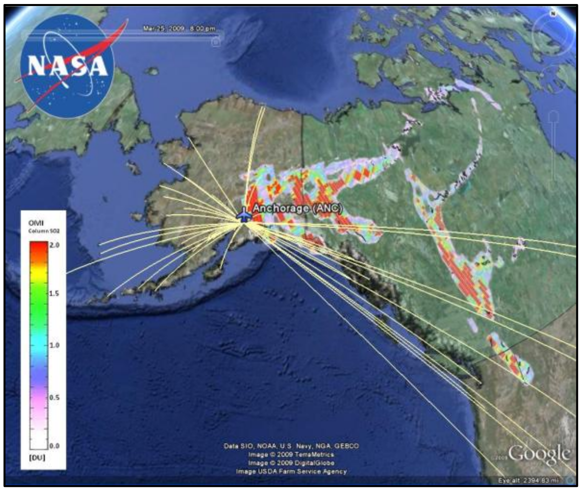


**Figure 1:** OMI $SO_2$ column measurements and flight routes from Anchorage

A series of eruptions from Mt. Redoubt occurred during late March and early April 2009. The first major ash eruption, at 0638Z on 23 March 2009, produced an ash plume exceeding 60,000 feet according to NWS radar observations (AVO, 2009). Much of the dispersion of volcanic ash resulted from the first eruption of Mt. Redoubt. As a result, many commercial flights were either delayed or cancelled, particularly from Anchorage International Airport.

## 3. MT. REDOUBT VOLCANO

Mt. 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. 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, Mt. 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. 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 1989 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).

After a nearly 20-year period of dormancy, Mt. Redoubt began showing signs of activity again in 2008. At 0638Z on 23 March, the AVO reported a large eruption of Mt. Redoubt. Between 0638Z on 23 March and 1300Z on 23 March there were a total of five explosive eruptions. 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)*. 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.

A brief period of calm followed the seventh eruption as seismicity levels returned to normal. However, on the following day, at 1634Z on 26 March, an eighth eruptive event occurred. Local radar confirmed the height of the ash plume at 30,000 feet above mean sea level. At 1724Z on 26 March the AVO reported a “major explosive event” from Mt. 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 to inject volcanic ash into the stratosphere. Several minor steam and ash emissions continued throughout the following days, with the last reported ash emission occurring on 4 April 2009.

## 4. METHODS

The objective of this study is twofold: to assess the altitude of $SO_2$ dispersion and to investigate the reported impacts on aviation from the 2009 Mt. Redoubt eruption. The altitude of $SO_2$ dispersion was determined through analysis of synoptic meteorological conditions and satellite imagery. Volcanic ash was tracked using AURA/OMI $SO_2$ column measurements on 23, 24, and 25 March 2009. Corresponding times were matched with CALIPSO backscatter profiles, geopotential height plots, and HYSPLIT forward model trajectories.

The CALIPSO backscatter profiles show the vertical cross section of the atmosphere along an orbital path. The geopotential height plots were reviewed to assess the geostrophic wind flow at various pressure levels in the atmosphere. Finally, HYSPLIT forward model trajectories initialized at Mt. Redoubt show the expected dispersion of particles in the atmosphere at a given altitude and time period. For this study we initialized the 72-hour model run at 06Z on 23 March 2009, with a new trajectory created every 8 hours. The purpose of generating multiple trajectories was to simulate the continued volcanic activity of Redoubt during the hours and days following the initial eruption. Through analysis of these data we estimated the level in the atmosphere in which $SO_2$ dispersion, and by extension ash dispersion, likely occurred on 23, 24, and 25 March 2009.

The reported impacts on aviation from volcanic ash dispersion were also investigated. We performed this study by evaluating the impacts incurred by airports due to ash dispersion and comparing actual ash dispersion with issued volcanic ash advisories. Newspaper articles also provided valuable information regarding the travel impacts from the volcanic eruption. Based on the reported impacts, we evaluated the actions taken various airlines in response to the 2009 Redoubt eruption.

## 5. RESULTS / DISCUSSION

Results indicate that a complex dispersion of volcanic ash resulted from the eruption of Mt. Redoubt. The altitudes of ash dispersion were estimated on 23, 24, and 25 March 2009 using CALIPSO backscatter profiles, geopotential height plots, HYSPLIT forward model trajectories, and $SO_2$ column measurements. Figure 2 displays a Google Earth visualization of CALIPSO profiles for 23, 24, and 25 March overlaid with OMI $SO_2$ column measurements over the corresponding time periods.

On 23 March 2009, CALIPSO detected a cloud/aerosol feature at or below 10 km, geopotential heights showed ash dispersion supported by atmospheric pattern between 400 and 200 mb (see Figure 3), and HYSPLIT forward trajectories supported ash dispersion at or below 11 km. The majority of the ash plume likely remained at approximately 8 km, although reports from the National Weather Service indicate that the initial plume may have reached 18 km (60,000 ft).

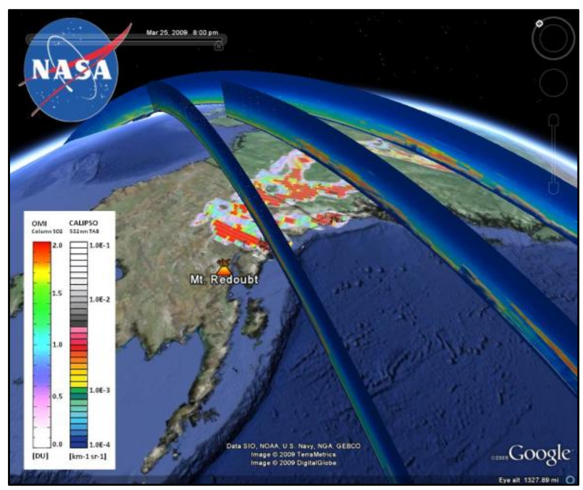


**Figure 2:** CALIPSO backscatter profiles with OMI $SO_2$ column measurements

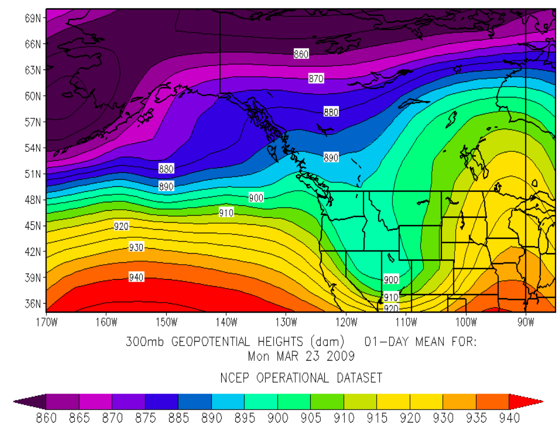


**Figure 3:** Geopotential height field plot at 300mb for 23 March 2009 (NCEP)

On 24 March 2009, CALIPSO detected a cloud/aerosol feature at or below 9 km with additional features detected at 10 km and 16 km, and geopotential heights showed most of the ash dispersion supported by atmospheric pattern between 500 and 300 mb and ash dispersion near Hudson Bay supported by atmospheric pattern at 700 mb. HYSPLIT forward trajectories supported ash dispersion at or below 11 km. Most ash was entrained in a passing low pressure system at around 8 km. It is possible that some ash was detected by CALIPSO at higher altitudes (10 km and 16 km). Near Hudson Bay, however, atmospheric patterns suggest ash dispersion at approximately 3 km.

On 25 March 2009, CALIPSO detected a cloud/aerosol feature at or below 8km with additional features detected at 14 km, geopotential heights showed most of the ash dispersion supported by atmospheric pattern between 500 and 150 mb, and HYSPLIT forward trajectories supported ash dispersion between 11 km and 15 km. Much of the ash plume remaining was detected at higher altitudes three days following the eruption. The stratospheric ash plume was likely located 14 km above mean sea level, as detected by CALIPSO.

According to the Alaska Volcano Observatory, there were 26 reported volcanic eruptions from Mt. Redoubt during 2009. Steam emission commenced at 2100Z on 15 March. The released steam was a precursor to the first major ash eruption, which occurred at 0638Z on 23 March. The eruptive period of Redoubt lasted for nearly two weeks. Most eruptions during this period produced minor ash and steam plumes; a few eruptions posed more serious problems, especially for aviation. The most recent ash emission occurred at 1358Z on 4 April 2009.

Commercial aviation was most notably disrupted by two major explosive events from Mt. Redoubt: at 0638Z on 23 March and at 1724Z on 26 March. The first five eruptions, occurring over a period of 6 hours on 23 March, caused 35 flight cancellations from Anchorage International Airport. The eruptions took place at night between 10:38 pm and 4:31 am local time, visibility of the ash plume would have been increasingly difficult for pilots. Four minor eruptions ensued, with considerably less impact on aviation. An eruption at 1724Z on 26 March, with an ash plume exceeding 65,000 feet above mean sea level, resulted in an additional 10 flight cancellations. By the time the eruptions had subsided in April, Alaska Airlines had cancelled 295 flights and disrupted the flights of over 20,000 passengers (The News Tribune, 2009).

The Anchorage Volcanic Ash Advisory issued on 23 March 2009 is displayed in Figure 4. The gray polygons reveal areas of greatest risk for encountering volcanic ash for the given time period. The four panels correspond to forecast times of 1609Z on 23 March, 2325Z on 23 March, 0525Z on 24 March, and 1125Z on 24 March. The extent of the ash advisory is determined by a variety of observational criteria including GOES satellite imagery, AVO reports, pilot reports, radar, and forecast models. Volcanic Ash Advisories are used by airlines to assess the risk in flying certain flight routes after a volcanic eruption. The issued ash advisory may influence the decision by airlines to delay or cancel flights.

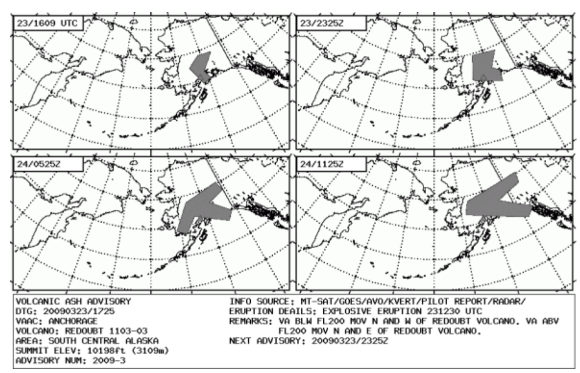


**Figure 4:** Volcanic ash advisory issued on 23 March 2009 (VAAC Anchorage)

This graphical Volcanic Ash Advisory was the only one publically available during the eruption of Mt. Redoubt. The ash advisory suggests that most of the ash dispersion occurred to the east of the volcano with some ash dispersion occurring to the west of the volcano. Actual $SO_2$ column measurements reveal nearly all ash dispersion occurred to the east of the volcano. As a result, the issued ash advisory covered a much larger extent than necessary. It is possible that flights may have been rerouted, delayed, or cancelled as a result of the larger ash advisory.

Several factors may have led the Anchorage Volcanic Ash Advisory Center to issue a Volcanic Ash Advisory extending to the west of the volcano. At the time of the issuance at 1725Z on 23 March, volcanic ash below FL200 was detected moving north and west of the volcano whereas volcanic ash above FL200 was detected moving north and east of the volcano. In addition to observational reports, model runs may also influence the volcanic ash advisory extent. A particular model run from the HYSPLIT forward trajectory model supports a larger extent of the Volcanic Ash Advisory. Initialized at the time of the initial eruption, the model indicates that air parcels above 5 kilometers AMSL will disperse eastward and air parcels below 5 kilometers AMSL will disperse westward. Since the majority of actual ash dispersion occurred east of Mt. Redoubt, perhaps the ash plume reached a higher altitude than expected. This would potentially account for model output of ash dispersion west of Mt. Redoubt and, ultimately, a larger extent of the ash advisory.

The inability to fly not only creates complications for travelers, but also disrupts air transport of food and prescription drugs into the state of Alaska. The economic impact of the delayed transport of goods is substantially significant. Following an ash-rich eruption at 2329Z on 28 March, tephra was reported falling out at Valdez and Anchorage. Precautionary measures forced airlines to ground flights at Anchorage for extended hours. Due to the long-term dispersion of volcanic ash, Mt. Redoubt's eruptions caused problems for Anchorage International Airport which lasted for several weeks following the eruption.

## 6. CONCLUSION

Results indicate the impact on aviation due to volcanic ash dispersion of the 2009 Mt. Redoubt eruption. 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. Several flights were rerouted or canceled as a result of ash dispersion from the eruption. Measures should be taken to improve forecasts of volcanic ash and communication to pilots to minimize impacts from volcanic ash on aviation.

The aviation industry was well prepared for the eruption of Mt. Redoubt. Communication with the Alaska Volcano Observatory allowed Alaska Airlines to take preparatory measures weeks prior to the initial eruption. No ash encounters with aircraft resulted from the 2009 Mt. Redoubt eruption. Despite having adequate knowledge of ash dispersion, many airlines incurred significant economic costs as a result of the 2009 Redoubt eruption. Hundreds of flights had been delayed or cancelled following the eruption, particularly after the 23 March eruption. OMI satellite measurements reveal the pattern of ash dispersion and areas where airspace was most at risk. Much of the ash cloud had drifted north and east of Anchorage before turning southward through British Columbia. Considering that quite often the upper level winds over Anchorage are steered downwind of Mt. Redoubt, conditions were relatively favorable for pilots in Anchorage.

Volcanic Ash Advisories are frequently used by airlines to assess the risk of using certain commercial flight routes. Pilots may be advised not to fly in regions as indicated by Volcanic Ash Advisories. The Volcanic Ash Advisory issued on 23 March (Figure 4) shows an extensive region of threatened airspace surrounding Mt. Redoubt. Although OMI $SO_2$ column measurements reveal upper level winds transported the ash plume to the north and east, the issued Volcanic Ash Advisory indicates areas to the south and west of Redoubt at risk for volcanic ash. Aircraft may have avoided flying through regions south and west of Redoubt due to the ash advisory issued by the Anchorage Volcanic Ash Advisory Center. However, there was a minimal risk for ash in these regions and therefore flight delays or cancellations in these areas would have resulted in unnecessary economic costs. Improved communication between Volcanic Ash Advisory Centers and ash detection agencies will improve the quality of information ultimately disseminated to pilots. Since the issue of ash avoidance is primarily an issue 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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