

# **The detection, characterization and tracking of recent Aleutian Island volcanic ash plumes and the assessment of their impact on aviation**

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**The Aleutian Islands of Alaska are home to a number of major volcanoes which periodically present a significant hazard to aviation. During summer of 2008, the Okmok and Kasatochi volcanoes experienced moderate eruptive events. These were followed a dramatic, major eruption of Mount Redoubt in late March 2009. The Redoubt case is extensively covered in this paper. Volcanic ash and SO<sub>2</sub> from each of these eruptions dispersed throughout the atmosphere. This created the potential for major problems for air traffic near the ash dispersions and at significant distances downwind. The NASA Applied Sciences Weather Program implements a wide variety of research projects to develop volcanic ash detection, characterization and tracking applications for NASA Earth Observing System and NOAA GOES and POES satellites. Chemistry applications using NASA AURA satellite Ozone Monitoring System (OMI) retrievals produced SO<sub>2</sub> measurements to trace the dispersion of volcanic aerosol. This work was complimented by advanced multi-channel imager applications for the discrimination and height assignment of volcanic ash using NASA MODIS and NOAA GOES and POES imager data. Instruments similar to MODIS and OMI are scheduled for operational deployment on NPOESS. In addition, the NASA Calipso satellite provided highly accurate measurements of aerosol height and dispersion for the calibration and validation of these algorithms and for corroborative research studies. All of this work shortens the lead time for transition to operations and ensures that research satellite data and applications are operationally relevant and utilized quickly after the deployment of operational satellite systems.**

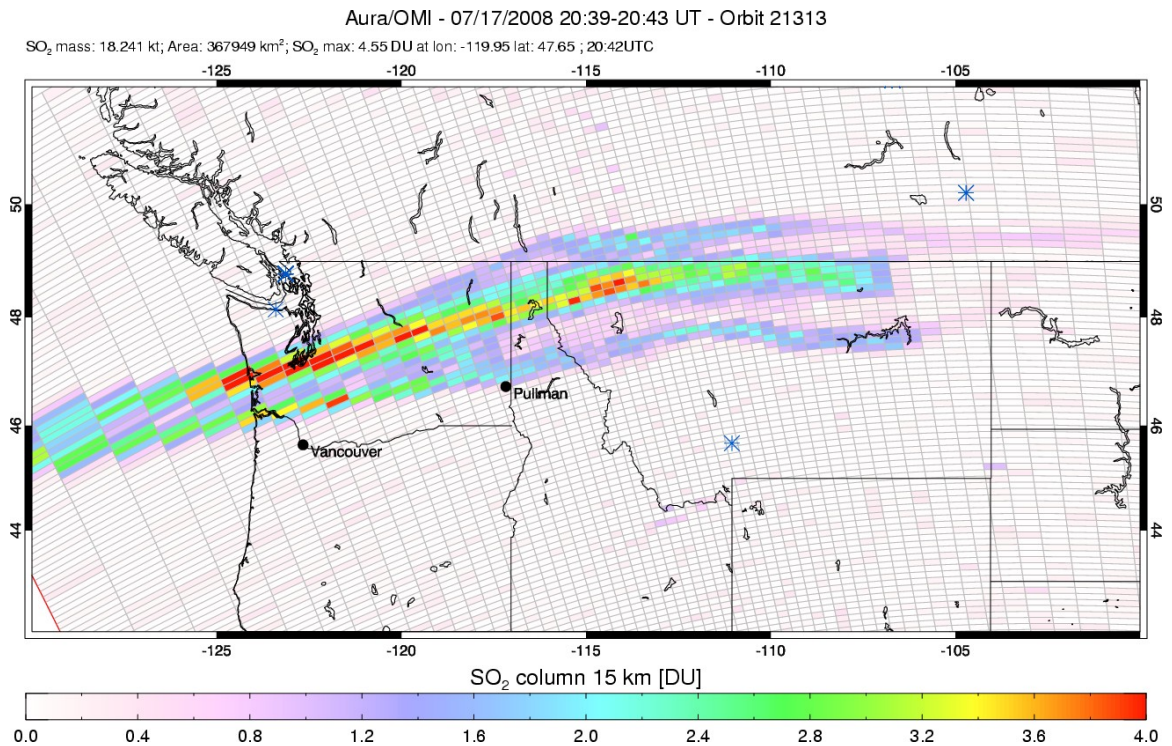
## **Introduction**

This paper provides an overview of research results using NASA Earth Observing System and NOAA GOES and POES satellites to detect, characterize and track volcanic

ash in the atmosphere. It examines several case studies to highlight how data taken during recent eruptions of the Okmok, Kasatochi and Redoubt volcanoes in the Aleutian Islands of Alaska were used by the Alaska, Washington and Montreal Volcanic Ash Advisory Centers (VAAC) to assist in developing and issuing Volcanic Ash Advisories (VAA) and by the FAA, USGS and others to assess their impact on the National Airspace System.

### Case I: Okmok Volcano

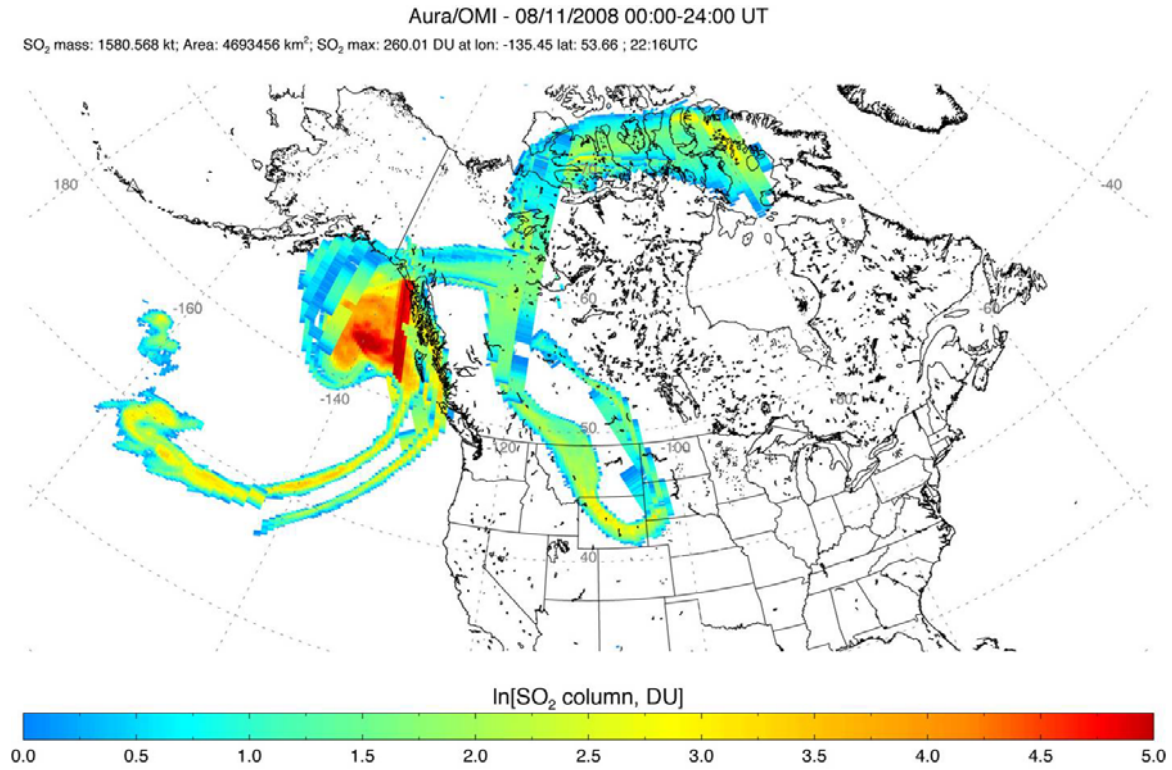
Okmok erupted on July 12, 2008. Figure 1 shows the dispersion of SO<sub>2</sub> which is routinely used as a proxy for volcanic ash. The dispersion of volcanic ash from Okmok occurred over the northwestern United States five days after the volcano's initial eruption. Figure 1 exhibits a zonal flow pattern in consonance with the prevailing westerlies.



**Figure 1.** SO<sub>2</sub> as detected by Aura/OMI in the northwestern United States five days after the initial eruption of Okmok.

### Case 2: Kasatochi Volcano

Kasatochi erupted on August 7, 2008. Figure 2, below shows the complex dispersive pattern of SO<sub>2</sub> four days later which evolved from a very complex, dynamic, mid-latitude synoptic pattern.



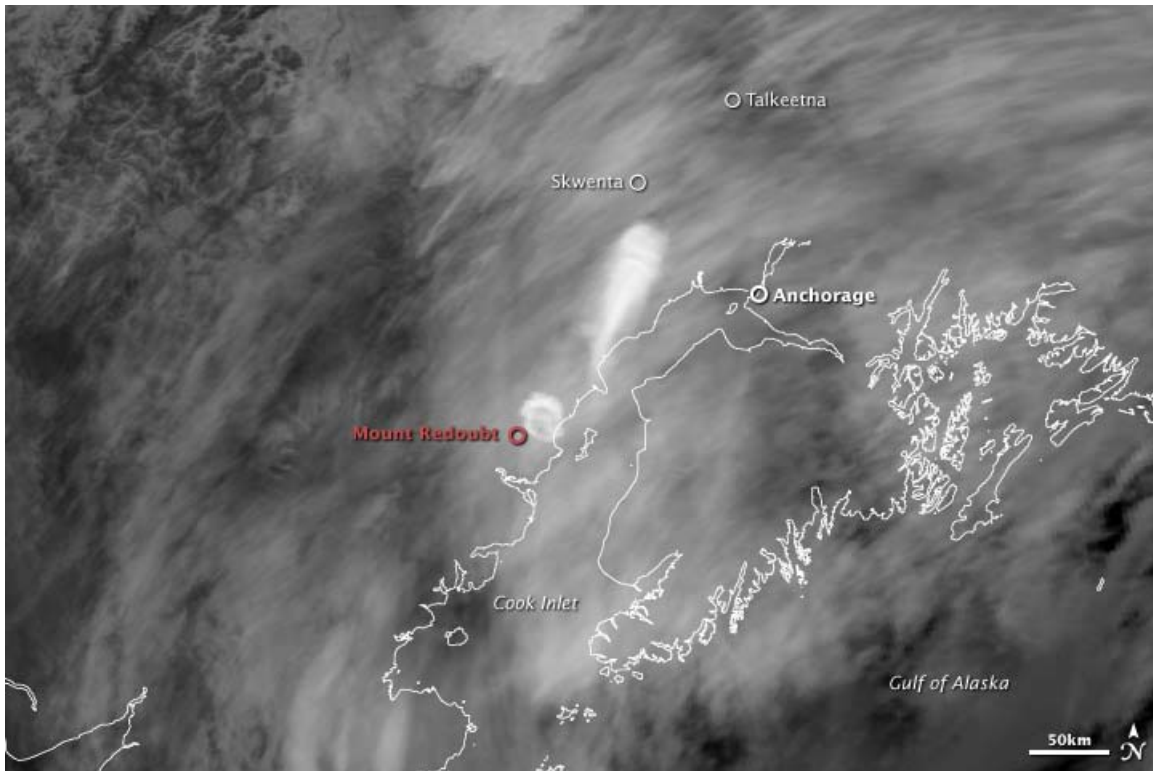
**Figure 2.** SO<sub>2</sub> as detected by Aura/OMI in North America four days after the initial eruption of Kasatochi.

### Case 3: Mount Redoubt Volcano



**Figure 3.** The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on NASA's Terra satellite obtained this image of Mount Redoubt and its environs on May 5, 2009, just two days before it erupted explosively. There was little visible activity other than the vapor plume near the center of the image.

Mt. Redoubt erupted explosively at 10:38 P.M. the night of Sunday, March 22, 2009. Figure 4, below captured the eruptive plume which was estimated to reach a height of 50,000 feet above MSL.



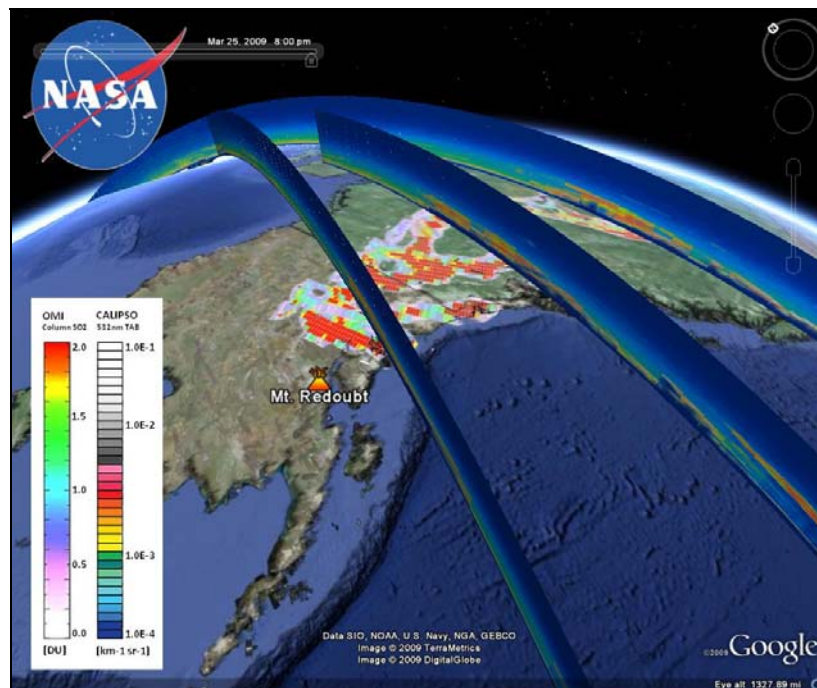
**Figure 4.** Volcanic ash detected on March 22, 2009 in thermal infrared imagery by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite.

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).

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

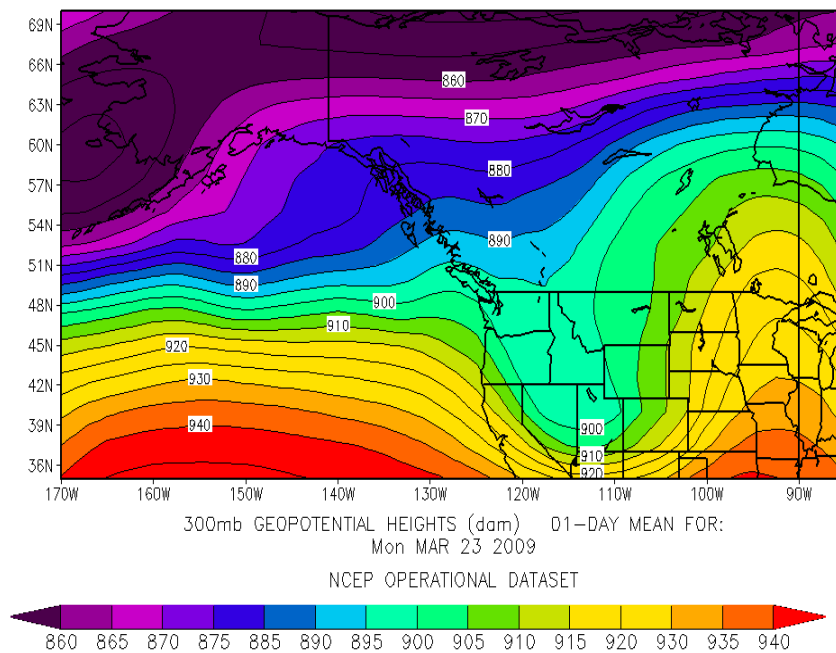
observed, although the eruptive event was much less intense than previous eruptions. The ash plume did not exceed 12,000 feet above mean sea level. A brief period of calm followed the seventh eruption as seismicity levels returned to normal. However, on the following day, at 1634Z on 26 March, an eighth 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.

Volcanic ash was tracked using AURA/OMI SO<sub>2</sub> 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 the 72-hour model run was initialized 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 the level in the atmosphere was estimated in which SO<sub>2</sub> dispersion, and by extension ash dispersion, likely occurred on 23, 24, and 25 March 2009 (Matus and Hudnall, 2009).



**Figure 5:** CALIPSO backscatter profiles with OMI SO<sub>2</sub> column measurements

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<sub>2</sub> column measurements. Figure 5 displays a Google Earth visualization of CALIPSO profiles for 23, 24, and 25 March overlaid with OMI SO<sub>2</sub> 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 6), 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).



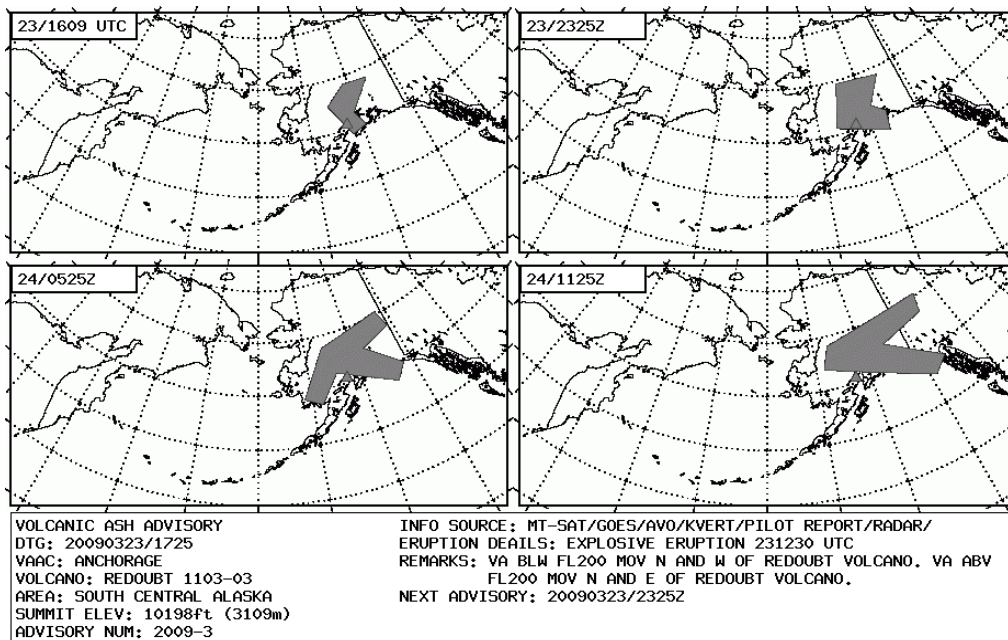
**Figure 6:** Geopotential height field plot at 300mb for 23 March 2009 (NCEP)

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).



**Figure 7:** Volcanic ash advisory issued on 23 March 2009 (VAAC Anchorage)

The Anchorage Volcanic Ash Advisory issued on 23 March 2009 is displayed in Figure 7. 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.

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<sub>2</sub> 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.

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 7) shows an extensive region of threatened airspace surrounding Mt. Redoubt. Although OMI SO<sub>2</sub> 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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