Airborne Volcanic Ash—A Global Threat to Aviation

The world's busy air traffic corridors pass over or downwind of hundreds of volcanoes capable of hazardous explosive eruptions. The risk to aviation from volcanic activity is significant—in the United States alone, aircraft carry about 300,000 passengers and hundreds of millions of dollars of cargo near active volcanoes each day. Costly disruption of flight operations in Europe and North America in 2010 in the wake of a moderate-size eruption in Iceland clearly demonstrates how eruptions can have global impacts on the aviation industry. Airborne volcanic ash can be a serious hazard to aviation even hundreds of miles from an eruption. Encounters with high-concentration ash clouds can diminish visibility, damage flight control systems, and cause jet engines to fail. Encounters with low-concentration clouds of volcanic ash and aerosols can accelerate wear on engine and aircraft components, resulting in premature replacement. The U.S. Geological Survey (USGS), in cooperation with national and international partners, is playing a leading role in the international effort to reduce the risk posed to aircraft by volcanic eruptions.

Airborne volcanic ash is a serious hazard to aviation and can cause jet engines to suddenly fail in flight. Explosive volcanic eruptions can send ash to flight levels at speeds of 5,000 to 8,000 feet per minute; given the speed of aircraft and such rapid rise rates for ash clouds, the industry has challenged authorities to notify cockpit crews within 5 minutes of eruption detection worldwide. This image taken from space shows a vertical column of ash and an ash-cloud rising 60,000 feet above Rabaul Volcano, Papua New Guinea, in September 1994 (Space Shuttle STS-064 image). Carried westward by the winds, the ash cloud spread rapidly over busy air routes near Indonesia. The inset photo shows a 1990 eruption cloud from Redoubt Volcano, Alaska (photo courtesy of W. Rose, Michigan Technological University). Taken from an aircraft descending into Anchorage, about 50 miles (80 km) from the volcano, it shows just how similar weather and ash clouds can appear when viewed from the cockpit.

Volcanic eruptions pose a serious hazard to aviation when highly abrasive, pulverized rock debris (ash) and gas are ejected explosively into the atmosphere and dispersed over long distances. Worldwide, more than 100 reported encounters of aircraft with volcanic ash have resulted in hundreds of millions of dollars in damage and, in three dramatic cases, caused the near loss of wide-body passenger jets. For aircraft to avoid encounters with volcanic ash, air traffic controllers, pilots, and dispatchers must be rapidly notified when explosive eruptions occur and ash is in the atmosphere.

In cooperation with national and international partners, the U.S. Geological Survey (USGS) Volcano Hazards Program is playing a leading role in the global effort to reduce the risk of aircraft encounters with ash through timely eruption forecasts and warnings, education about the hazard, and scientific investigation of volcanic processes and ash-cloud properties. Hundreds of active volcanoes around the globe have the potential to severely affect aviation operations, and each year dozens of these volcanoes erupt explosively. On a global basis, volcanic ash is a daily con-

In the United States alone, aircraft carry about 300,000 passengers and hundreds of millions of dollars of cargo near active volcanoes each day. This photo shows a jet on approach into Seattle-Tacoma International Airport in Washington. Mount Rainier, one of more than a dozen potentially active Cascade volcanoes in the Pacific Northwest of the United States, looms in the distance. (Image courtesy Alaska Airlines.)

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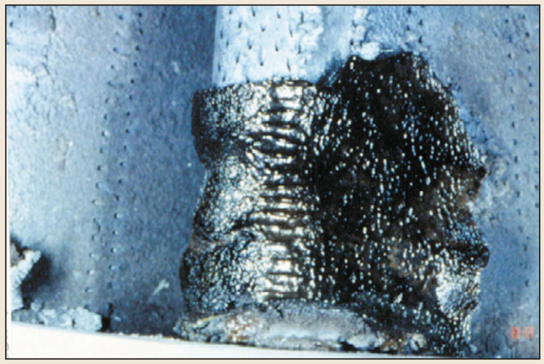
cern to aviation. Volcanic ash clouds are carried by prevailing winds and can drift in different directions at many flight levels for thousands of miles from the erupting volcano. The hazard is complicated by the fact that ash and aerosol clouds from volcanoes can remain aloft at cruise altitudes for days to weeks. These clouds are difficult to distinguish visually from weather clouds and are invisible to air traffic control and aircraft radar. Volcanic activity can also have serious impacts on low-altitude aircraft and on airport operations.



Glassy—melted and then resolidified—volcanic ash adheres to the leading edge of a high-pressure-turbine stage-1 nozzle guide vane inside a jet engine that encountered a volcanic ash cloud at 25,000 feet. The patch of dark glass shown here is about 1 inch across. (Photo courtesy of General Electric.)

Hazards and Risks

Volcanic ash consists of small (less than 2 mm or 0.08 inch across) solid, sharp-edged fragments of quickly cooled volcanic glass and minerals blasted at high velocity into the atmosphere during explosive eruptions. This material is abrasive and melts at the high operating temperatures of modern jet engines. When ingested into a jet engine, volcanic ash erodes turbine blades, and the melted ash can adhere to critical parts, causing engine failure (“flameout”). Any forward-facing surface of an airplane engulfed in a volcanic ash cloud is likely to be eroded, including the cockpit and forward cabin windows and landing-light covers. Cockpit windows may become so abraded that pilots have a serious loss of forward visibility. Ash entering sensitive aircraft electronics can interfere with navigation and other onboard systems. As a result of electrical disturbances within the ash cloud, a flight crew may also lose the ability to transmit a distress call.

Sulfur and other gases released in large eruptions also affect aircraft and their occupants. Acidic aerosols formed by the hydration of these volcanic gases produce a corrosive mist that may cause respiratory problems for passengers and flight crews and accelerate deterioration of vulnerable aircraft components. Over a period of many years, such exposure can significantly increase aircraft maintenance costs. Chronic “degassing” of nearby volcanoes upwind of airports can also affect ground operations or even close airfields for years.

Volcanic ash and aerosol clouds above airports and ash falling on and near airports can be hazardous to aircraft on approach and departure, as well as to operations on the ground. Ash on runways reduces braking effectiveness of aircraft, and wet ash is extremely slippery. The fine particles can be resuspended by surface winds and air-

ONE AIRCRAFT’S HARROWING ENCOUNTER WITH VOLCANIC ASH

For more than 4 terrifying minutes on December 15, 1989, a powerless Boeing 747 with 231 passengers aboard plunged in silence towards the rugged, snow-covered mountains 90 miles north of Anchorage, Alaska. Fine ash and a strong odor of sulfur filled the cockpit and cabin as the flight crew donned oxygen masks and initiated emergency procedures to restart all four engines, which had flamed out when the aircraft inadvertently entered an eruption cloud from Redoubt Volcano 150 miles away. Radio transmissions to Anchorage Air Route Traffic Control Center record the severity of the event:

“KLM 867, we have flame out...all engines....and we are descending now.”
“KLM 867 heavy, we are descending now....we are in a fall!”

Although the crippled jet’s engines were restarted, and it ultimately landed safely in Anchorage, it suffered more than $80 million in damage ($140 million in today’s dollars, about half the price of a new Boeing 747). This incident was another “wake-up call” to volcanologists, industry representatives, and aviation officials worldwide. Following this encounter, coordinated efforts to address the hazard of airborne volcanic ash and implement more effective detection tools and warning systems around the globe accelerated.

KLM Flight 867 after landing safely.

port ground operations until removed from the tarmac, an expensive and difficult process. When an airport is closed or operations curtailed because of the presence of ash, significant and costly disruptions result, including the loss of required alternate landing sites for aircraft aloft. This is particularly a concern for twin-engine aircraft operating under ETOPS (Extended-range Twin-engine Operational Performance Standards) flight rules on oceanic flights.

Development of U.S. and International Warning Systems

In response to in-flight engine failure incidents in 1982, the International Civil Aviation Organization (ICAO) created the International Airways Volcano Study Group, which later became the International Airways Volcano Watch program (IAVW). A major goal of the IAVW is to improve global ash detection and warning systems for air traffic controllers, dispatchers, and pilots. Major accomplishments of the IAVW include development of standards for in-flight ash warning messages from the worldwide system of Meteorological Watch Offices and the creation of nine Volcanic Ash Advisory Centers in the mid-1990s. The eruptions of Redoubt (1989–90) and Mount Spurr (1992) volcanoes in Alaska, both of which had a profound impact on regional aviation operations, prompted significant growth of the Alaska Volcano Observatory (AVO), increased monitoring along the Aleutian chain, and development of the first Interagency Operating Plan for Volcanic Ash Episodes. The United States has recently strengthened the ash-cloud warning program for aviation within its airspace by preparing a National Volcanic Ash Operations Plan for Aviation. This plan documents responsibilities, communication protocols, and hazard message formats for the Federal Aviation Administration (FAA), National Oceanic and Atmospheric Administration (NOAA), USGS, and the U.S. Air Force Weather Agency. The plan is available online at http://www.ofcm.gov/p35-nvaopa/pdf/FCM-P35-2007-NVAOPA.pdf.

Role of the Aviation Community

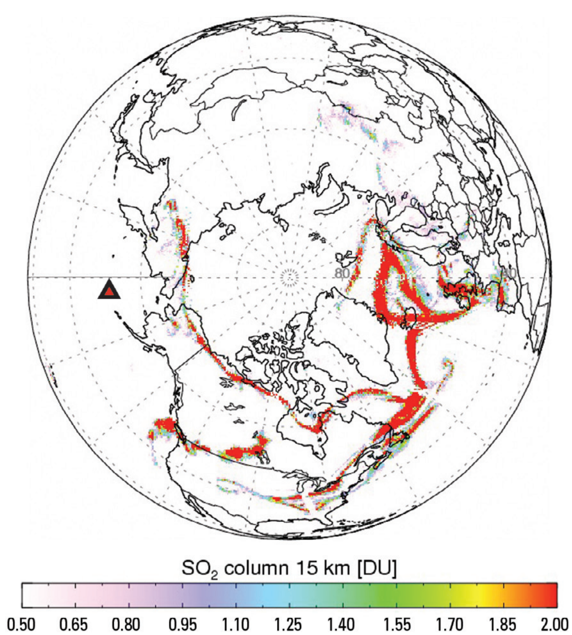
Pilot education is a key factor in mitigating the hazard from aircraft encounters with volcanic ash. **(continued on page 5)**

VOLCANIC ASH CAN IMPACT AIRPORT OPERATIONS

Volcanic ash falling on and near airports is a hazard to aircraft on approach and departure, as well as to operations on the ground. Ash accumulation of more than a trace amount (~1 mm or the thickness of a dime) requires complete removal for airports to resume full operations. Ash does not simply blow away and disappear; it must be disposed of in a manner that minimizes remobilization by wind and aircraft. Case studies of cleanup methods are online at http://www.avo.alaska.edu/pdfs/cit2773.pdf. Recommended procedures for the protection and cleanup of ash-contaminated airports are given by the International Civil Aviation Organization (ICAO) in the Manual on Volcanic Ash, Radioactive Material, and Toxic Chemical Clouds (Document 9691-AN/954, 2002), available online at http://www2.icao.int/en/anb/met-aim/met/iavwopsg/Documents/Forms/AllItems.aspx.

The weight of rain-soaked ash fall from the 1991 eruption at Pinatubo Volcano in the Philippines caused this DC-10 to fall back on its tail at Cubi Point Naval Air Station (photo courtesy of R.L. Rieger/U.S. Navy). An inch of wet ash can weigh as much as 10 pounds per square foot.

Workers clean ash at Mariscal Sucre International Airport in Quito, Ecuador. (Photo courtesy of El Commercio, Quito, Ecuador.)



The sulfur dioxide (SO_2) cloud produced by the August 7, 2008, eruption of Kasatochi Volcano (red triangle) in the central Aleutian Islands of Alaska remained fairly coherent for a few days, drifting south and east across North America and the Atlantic Ocean. Eventually it split into multiple streams and circled the northern hemisphere between 35,000 to 45,000 feet above sea level, as shown in this composite satellite image from August 16. Colors represent the relative amount of gas, with red being the highest and blue the lowest. There may or may not be detectable ash associated with such sulfur dioxide clouds. Data are from NASA's EOS-Aura satellite and its Ozone Monitoring Instrument (OMI), courtesy of Dr. Simon Carn, Michigan Technological University. (DU represents Dobson Units, a measure of the mass of SO_2 per unit area of atmosphere.)

Aviation Color Code Used by U.S. Geological Survey Volcano Observatories

Color codes, which are in accordance with recommended International Civil Aviation Organization (ICAO) procedures, are intended to inform the aviation sector about a volcano's status and are issued in conjunction with an Alert Level. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption, especially in regard to ash-plume information and likely outcomes.

Color	Description
GREEN	Volcano is in typical background, noneruptive state or, *after a change from a higher level,* volcanic activity has ceased and volcano has returned to noneruptive background state.
YELLOW	Volcano is exhibiting signs of elevated unrest above known background level or, *after a change from a higher level,* volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, **OR** eruption is underway with no or minor volcanic-ash emissions [ash-plume height specified, if possible].
RED	Eruption is imminent with significant emission of volcanic ash into the atmosphere likely **OR** eruption is underway or suspected with significant emission of volcanic ash into the atmosphere [ash-plume height specified, if possible].

Volcano observatories are a source of important hazard information for aviation users. Airlines can use warnings of impending or ongoing volcanic activity to select safe and efficient routes that avoid ash-contaminated airspace. Aviation Color Codes are used by all U.S. Volcano Observatories to indicate the status of volcanoes and are recommended for use worldwide by the International Civil Aviation Organization (ICAO).

EDUCATION AND COORDINATION

To inform the aviation industry and flight crews about the hazards of volcanic ash, the International Civil Aviation Organization (ICAO) has produced a variety of educational and resource materials, including the poster below. In addition, professional aviation organizations, such as the Air Line Pilots Association, have also made a sustained effort to promote understanding of the hazard and of methods of ash avoidance—http://www.alpa.org/Portals/Alpa/VolcanicAsh/VolcanicAsh.htm. Scientists with the USGS Volcano Hazards Program also give briefings to pilots, dispatchers, controllers, and others in order to familiarize the aviation community with volcano monitoring, hazards, and warning systems. In addition to the education of aviation personnel, effective coordination among volcano observatories, air traffic control authorities, and aviation meteorology services is essential to reduce aircraft encounters with ash clouds.

(continued from page 3) To address this, a consortium of pilot organizations, the FAA, aircraft manufacturers, and other aviation interests have developed and promoted operating procedures for flight crews whose planes inadvertently enter a volcanic ash cloud. This guidance is now part of flight crew training and emergency checklists for many airlines.

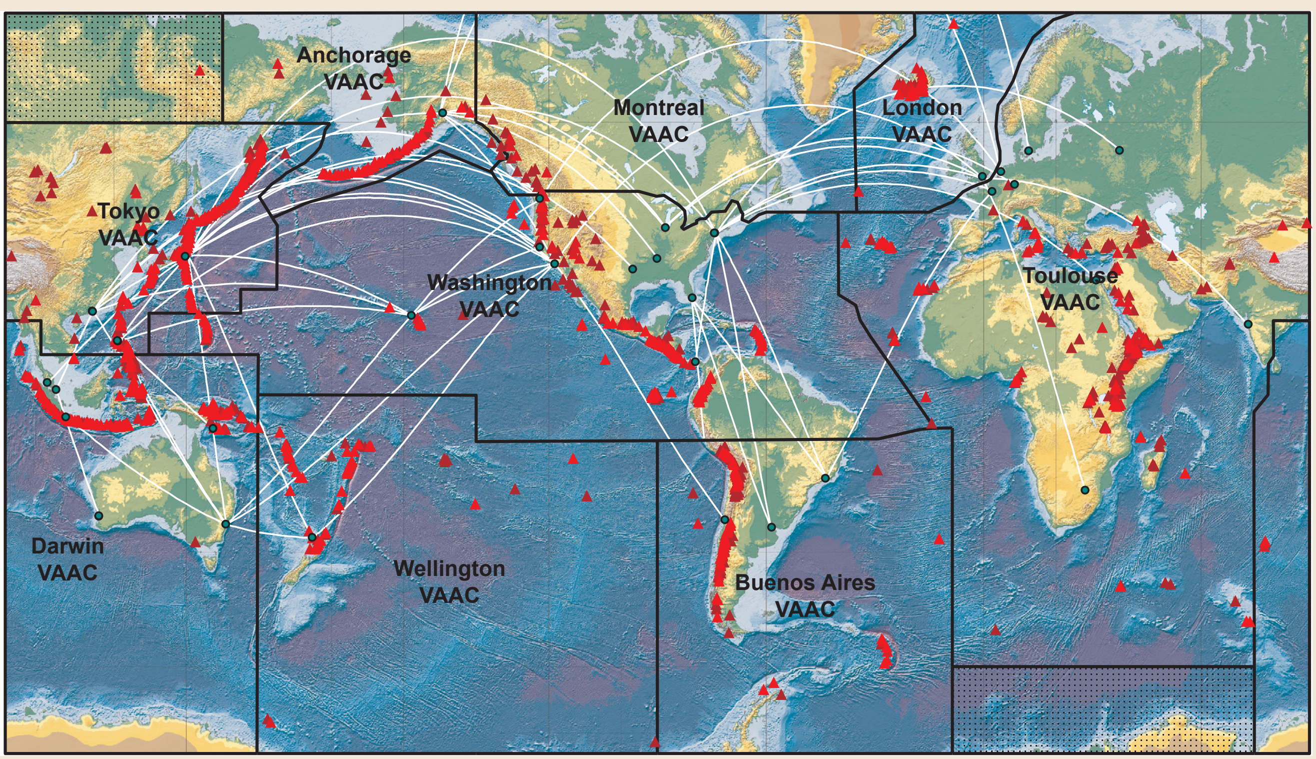
During a volcanic eruption, flight crews are important partners in disseminating warning information to keep aircraft safe. Often pilot reports are the first direct observations of a volcanic event. Details of such observations are of great help to volcanologists trying to interpret data from distant eruptions and to meteorologists and aviation managers who issue warnings and may have to restrict air space. Flight crews can greatly assist in these efforts by relaying key descriptive information contained in the Volcanic Activity Report Form (VAR) to air traffic control (ATC) centers.

Communicating the Hazard—The Aviation Color Code and the VONA

Volcano observatories provide important volcano hazard information for meteorological and aviation authorities who are responsible for issuing SIGMETs (advisories of Significant Meteorological information), NOTAMs (Notices To Airmen), and other warning products. Airlines can use warnings of impending or ongoing volcanic activity to select safe and efficient routes that avoid ash-contaminated airspace. In 1990, USGS scientists at AVO developed a four-color alert system for volcanic activity. This system was used to quickly inform the aviation community about the severity of hazard and level of activity at a volcano. ICAO has adopted a modified version of this color code system as the recommended guideline for volcano observatories worldwide. A change in the color code (either up or down) or a significant change within a color code prompts USGS volcano observatories to issue a specialized message for aviation users called a VONA—Volcano Observatory Notice for Aviation—that summarizes hazard information for pilots, aviation managers, controllers, and dispatchers in concise text.

VOLCANIC ASH ADVISORY CENTERS (VAAC)

Because volcanic ash clouds travel long distances, official response to an ash-cloud threat must be coordinated internationally. Under the auspices of the World Meteorological Organization (WMO) and the International Civil Aviation Organization (ICAO), nine regional Volcanic Ash Advisory Centers (VAACs) provide advisories to international Meteorological Watch Offices (MWOs) about the location and movement of ash clouds. The VAACs are located in Anchorage, Buenos Aires, Darwin, London, Montreal, Toulouse, Tokyo, Washington, D.C., and Wellington. VAACs use volcano-observatory reports, pilot reports, geostationary and polar-orbiting satellite data, and ash-dispersion models as the bases for their advisories. As an ashcloud drifts downwind, responsibility for issuing advisories generally passes from one VAAC to the next. The map shows volcanoes of the world (red triangles), areas of responsibilities for VAACs, and simplified major global air routes (white lines). Dotted regions are not covered by any VAAC because of satellite or other infrastructure limitations.



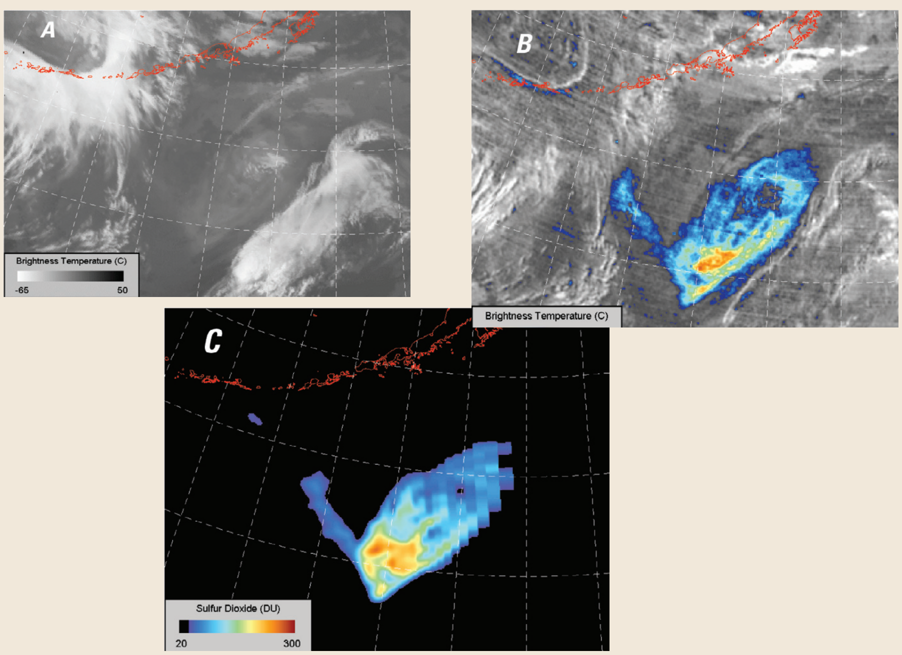
The Future

The worldwide growth of air traffic, especially in volcanically active regions such as the Pacific Rim, means that volcanic ash will remain a serious hazard to aviation. Furthermore, the expected introduction of "free-flight" air traffic operations by the FAA and increased use of twin-engine aircraft across remote areas of the planet (areas having few alternate landing sites) make timely detection and reporting of eruptions, ash-cloud movement, and anticipated ash fall essential to flight safety. The 2010 Icelandic eruption highlighted this and many other remaining challenges facing safe and efficient aviation operations during an explosive volcanic event.

Keys to reducing the risk to aviation are (1) increased ground-based volcano monitoring (only a very small percentage of volcanoes that threaten aviation are currently considered well-monitored with modern instrumentation) and improved eruption forecasts; (2) development of new and improved tools and techniques to detect, track, and characterize volcanic clouds that are a hazard to aviation; (3) improved forecasting of ash-cloud movement and expected ash fall; (4) research and education to better quantify and build awareness of the hazard; and (5) refinement of protocols to ensure rapid communication of ash-hazard warnings to flight crews. Scientists in the USGS Volcano Hazards Program are continuing to work with national and international partners to accomplish these goals and improve flight safety and efficiency around the world.

REMOTE SENSING OF VOLCANIC ASH CLOUDS

Remote sensing by satellite is a powerful tool used to detect and quantify volcanic clouds, especially in remote areas of the globe. Volcanic clouds containing ash (mineral and glass fragments) and gases such as sulfur dioxide (SO_2) absorb energy from different wavelengths of the electromagnetic spectrum in different amounts than weather clouds—this allows satellite sensors to differentiate the various cloud constituents. Volcanic ash is detected by comparing the intensity of radiation at two thermal infrared wavelengths, creating images of "brightness temperature difference," while SO_2 is typically detected using several wavelengths of ultraviolet energy. Limitations of these techniques are frequency of image acquisition (geostationary satellites provide images approximately every 15 minutes, but others may provide data only a few times a day), the amount of water vapor in the atmosphere, daylight (for ultraviolet satellite data), and masking effects of weather clouds for some sensors. New sensors developed in the past decade hold great promise for better real-time tracking and characterization of volcanic clouds.



Satellite images showing the usefulness of the thermal infrared brightness temperature-difference technique and the ultraviolet absorption technique for discriminating volcanic ash and SO_2, respectively, in volcanic clouds that are physically mixed and visually indistinguishable from weather clouds. These images from August 2008 show an ash cloud from Alaska's Kasatochi Volcano over the northern Pacific, about 2 days after the eruption. Shorelines (red) are enhanced for reference. A *shows a thermal infrared brightness-temperature image.* B *is an enhanced image showing volcanic ash detected using a two-wavelength thermal infrared brightness temperature difference.* C *shows the corresponding SO_2 cloud as indicated by the ultraviolet wavelength absorption technique. (Images processed by D. Schneider, USGS.)*

Christina A. Neal and Marianne C. Guffanti

Edited by James W. Hendley II
and Peter H. Stauffer
Graphic design by Judy Weathers

COOPERATING ORGANIZATIONS
Airline Pilots Association
Alaska Division of Geological and Geophysical Surveys
Environment Canada, Canadian Meteorological Center, Montreal Volcanic Ash Advisory Center
Federal Aviation Administration
International Air Transport Association
International Civil Aviation Organization
National Oceanic and Atmospheric Administration/ National Environmental Satellite Data and Information Service/ Satellite Services Division
National Oceanic and Atmospheric Administration / National Weather Service
University of Alaska Fairbanks Geophysical Institute
World Meteorological Organization

For more information contact:
U. S. Geological Survey
Alaska Volcano Observatory
4200 University Drive
Anchorage, AK 99508
Tel. (907) 786-7497

http://www.avo.alaska.edu
http://volcanoes.usgs.gov
http://www.ssd.noaa.gov/VAAC/
http://www.icao.int/icao/en/anb/met/index.html#Doc9766

See also *U.S. Geological Survey's Alert Notification System for Volcanic Activity* (USGS Fact Sheet 2006-3139); *What are Volcano Hazards?* (USGS Fact Sheet 002-97); and *Volcanic Ash Fall—A Hard Rain of Abrasive Particles* (USGS Fact Sheet 027-00)

This Fact Sheet and any updates to it are available online at
http://pubs.usgs.gov/fs/2010/3116/