Encounters of Aircraft with Volcanic Ash Clouds: A Compilation of Known Incidents, 1953–2009

By Marianne Guffanti, Thomas J. Casadevall, and Karin Budding

We actively seek corrections and additions to the information presented here. Persons who have corrections or additional data pertaining to incidents already in the database or who have data about previously unreported incidents are urged to contact the authors.

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Contents

Figure

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
micrometer (µm)	0.00003937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square hectometer (hm^2)	2.471	acre
square kilometer (km^2)	247.1	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (in^2)
square hectometer (hm^2)	0.003861	section (640 acres or 1 square mile)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F–32)/1.8

Encounters of Aircraft with Volcanic Ash Clouds: A Compilation of Known Incidents, 1953–2009

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Abstract

Information about reported encounters of aircraft with volcanic ash clouds from 1953 through 2009 has been compiled to document the nature and scope of risks to aviation from volcanic activity. The information, gleaned from a variety of published and other sources, is presented in database and spreadsheet formats; the compilation will be updated as additional encounters occur and as new data and corrections come to light. The effects observed by flight crews and extent of aircraft damage vary greatly among incidents, and each incident in the compilation is rated according to a severity index. Of the 129 reported incidents, 94 incidents are confirmed ash encounters, with 79 of those having various degrees of airframe or engine damage; 20 are low-severity events that involve suspected ash or gas clouds; and 15 have data that are insufficient to assess severity. Twenty-six of the damaging encounters involved significant to very severe damage to engines and (or) airframes, including nine encounters with engine shutdown during flight. The average annual rate of damaging encounters since 1976, when reporting picked up, has been approximately 2 per year. Most of the damaging encounters occurred within 24 hours of the onset of ash production or at distances less than 1,000 kilometers from the source volcanoes. The compilation covers only events of relatively short duration for which aircraft were checked for damage soon thereafter; documenting instances of long-term repeated exposure to ash (or sulfate aerosols) will require further investigation.

Of 38 source volcanoes, 8 have caused 5 or more encounters, of which the majority were damaging: Augustine (United States), Chaiten (Chile), Mount St. Helens (United States), Pacaya (Guatemala), Pinatubo (Philippines), Redoubt (United States), Sakura-jima (Japan), and Soufriere Hills (Montserrat, Lesser Antilles, United Kingdom). Aircraft have been damaged by eruptions ranging from small, recurring episodes to very large, infrequent events. Moderate-size (Volcanic Explosivity Index 3) eruptions are responsible for nearly half of the damaging encounters. Vigilance is required during the early phases of eruptive activity when data about ash emission may be the most limited and warning capabilities the most strained, yet the risk the greatest. The risk-mitigation strategy for minimizing damaging encounters continues to rely on the combination of real-time volcano monitoring and rapid eruption reporting, detection and tracking of ash clouds in the atmosphere using satellite-based sensors, dispersion modeling to forecast expected ash-cloud movement, and global dissemination of specialized warning messages.

Introduction

In the decades since severely damaging encounters of passenger jets with volcanic ash clouds occurred in 1982 (from the eruption of Mount Galunggung, Indonesia) and 1989 (from the eruption of Redoubt Volcano, United States), the ash hazard to aircraft has become widely recognized by the aviation sector worldwide, and a global strategy of ash avoidance has been devised (Casadevall, 1994; Miller and Casadevall, 2000; Albersheim and Guffanti, 2009). The widespread, nearly week-long closure of airspace over Europe and the North Atlantic as a result of the 2010 eruption of Eyjafjallajökull Volcano in Iceland further broadened interest in understanding the potential risks of encounters of aircraft with volcanic ash, particularly in light of new policies formulated by authorities for the European and North Atlantic region to allow flights through ash-contaminated airspace under certain conditions (for details, see the Web site of the International Civil Aviation Organization (ICAO) International Volcanic Ash Task Force at http://www2.icao.int/en/anb/met-aim/met/ivatf/Lists/Meetings/AllItems.aspx/).

This compilation of known encounters of aircraft with volcanic ash from 1953 through 2009 is published to document the scope of the aviation risk from ash clouds and to aid the risk-mitigation decisions of civil aviation authorities, meteorological agencies, jet-engine and airframe manufacturers, and airlines worldwide. Data from events in 2010 are still being analyzed at the time of publication of this report. ICAO published a compilation of encounters through 1993 based on unpublished data of Thomas Casadevall and Karin Budding of the U.S. Geological Survey (USGS), with mention of additional incidents through 2000 (ICAO, 2007). Building on the data from Casadevall and Budding, Guffanti and others (2004) presented a summary of information about encounters from 1973 through 2003. In the present report, new data and previously acquired data have been organized into one unified compilation. To the extent possible, the compilation includes information about the conditions of the encounter (such as location, date and time, altitude, duration, type of aircraft, and severity of effects observed by the flight crew and of damage to the aircraft) and the volcanic source of the ash cloud. Identification of commercial operators of affected aircraft is *not* included in the database. The compilation is given in appendix 1 of this report in two forms: in appendix 1A as a Microsoft Access database and in appendix 1B as a Microsoft Excel spreadsheet. The database fields are explained in appendix 2, which also contains the disclaimer.

The compilation of encounters in appendix 1 comprises a minimum number of incidents because encounters are not reported consistently. Furthermore, the compilation covers only events of relatively short duration for which aircraft were checked for damage soon thereafter; instances of long-term repeated exposure to ash (or sulfate aerosols), which could shorten lifetimes of aircraft parts and time between maintenance, are not captured adequately herein. Data have been gleaned from a variety of published and other sources, the latter including reports from pilots and dispatchers received by Air-Traffic Control Centers and Volcanic Ash Advisory Centers and passed on to the USGS and the Smithsonian Institution. Information about a particular encounter typically is incomplete; in some cases, not much more is known than the date an encounter occurred, a brief mention of the outcome of the encounter, and the volcanic source of the ash cloud. References to the data sources are given in appendix 3.

We hope that publication of this compilation will encourage more reporting of encounters by the aviation industry and civil aviation authorities. We actively seek corrections and additions to the information presented here. Persons who have corrections or additional data pertaining to incidents already in the database or who have data about previously unreported incidents are urged to contact the authors.

Characteristics of Encounters

Severity of Encounters

The documented incidents in appendix 1 vary greatly in the nature of effects observed by the flight crews during encounters and the severity of damage to aircraft. Some aircraft sustained no apparent damage, and the only indications of encounters were reports by the flight crews of the acrid smell of sulfur dioxide or electrostatic discharge on the windscreen. Other aircraft experienced in-flight degradation of engine performance, even to the point of ignition flameout and loss of engine thrust power or failure of critical navigational and operational instruments.

To gage severity of individual encounters, an index was formulated in 1994 by Tom Casadevall and Karin Budding (in consultation with engine and airframe manufacturers and the Air Line Pilots Association) and endorsed by ICAO. Table 1 is a slightly modified version of the severity index published by

Table 1. Severity index for encounters of aircraft with volcanic ash clouds.

[Modified from ICAO (2007) by addition to class 0 of criteria about observation of anomalous haze and ash reported or suspected by flight crew and by addition to class 1 of a criterion about ash deposits on exterior of aircraft]

Class	Criteria
0	• Sulfur odor noted in cabin. • Anomalous atmospheric haze observed. • Electrostatic discharge (St. Elmo's fire) on windshield, nose, or engine cowls. • Ash reported or suspected by flight crew but no other effects or damage noted.
1	• Light dust observed in cabin. • Ash deposits on exterior of aircraft. • Fluctuations in exhaust gas temperature with return to normal values.
2	• Heavy cabin dust. • Contamination of air handling and air conditioning systems requiring use of oxygen. • Abrasion damage to exterior surfaces, engine inlet, and compressor fan blades. • Pitting, frosting, or breaking of windscreen or windows. • Minor plugging of pitot-static system, insufficient to affect instrument readings. • Deposition of ash in engine.
3	• Vibration or surging of engine(s). • Plugging of pitot-static system to give erroneous instrument readings. • Contamination of engine oil or hydraulic system fluids. • Damage to electrical or computer systems. • Engine damage.
4	• Temporary engine failure requiring in-flight restart of engine.
5	• Engine failure or other damage leading to crash.

ICAO (2007). The index has six classes, ranging from 0 (lowest severity) to 5 (crash). The criteria that define each class are based on the types of damage or conditions reported during actual encounters. Severity class 0 incidents are characterized by sulfurous smells in the cockpit with no resulting damage to the aircraft; severity class 1 also comprises nondamaging incidents, but “dust” (ash) particles were observed in the cabin or were deposited on the exterior of the aircraft. Severity classes 2–5 constitute damaging encounters; fortunately, no encounters of severity class 5 have occurred to date. A table showing the factors used to assign a severity class to each encounter is given in appendix 4.

As mentioned above, encounters are underreported overall, but the lowest severity (class 0) incidents in the database especially are underrepresented. Pilots are encouraged by ICAO and airline guidance to report anomalous sulfur smells to air traffic control centers and airline dispatch centers, but such reports are not comprehensively collected and disseminated for further use. The uneven nature of reporting the occurrence of sulfurous odors reduces the utility of counting the number of incidents in that class. Moreover, the significance of severity class 0 with respect to the presence of ash is ambiguous. Volcanic activity is the only source of large amounts of sulfur gases (primarily sulfur dioxide) at cruise altitudes of jet aircraft (Carn and others, 2009), and the smell of sulfur gases in the cockpit may indicate volcanic activity that has not yet been detected or reported and (or) possible entry into an ash-bearing cloud. However, the smell of sulfur gases by itself is not necessarily an indicator of the presence of hazardous amounts of ash particles. In some cases when sulfur odors are detected, there may be little ash in the cloud owing to ash fallout during prior dispersion of the cloud or to separation of the ash and gas components of the cloud as dispersion progresses (Bluth and Rose, 2004; Carn and others, 2009). Accordingly, severity class 0 incidents should be described as aircraft encounters with suspected volcanic ash *or gas* clouds.

Because of the highly uneven reporting and ambiguous nature of severity class 0 incidents, we distinguish that class from the other classes, which are based on less ambiguous indicators of the presence of volcanic ash. Accordingly, we report 129 incidents (table 2) described as follows:

- 94 known ash encounters (severity classes 1–4), of which 79 are reported to have involved airframe or engine damage (severity classes 2–4). Included in the 94 are 3 incidents with data sufficient to determine that the severity is not 0 but insufficient to further specify severity as 1, 2, 3, or 4.
- 20 incidents with suspected ash or gas clouds (severity class 0)
- 15 incidents with insufficient data to assign a severity class

Of the 79 damaging encounters, 26 are rated as significantly to severely damaging (severity classes 3 and 4). Nine encounters rated as class 4 have occurred from 1980 until as recently as 2006 (table 3). Some salient characteristics of the class 4 incidents, which involved in-flight loss of engine thrust power, bear emphasis:

Table 2. Number of aircraft encounters with volcanic ash according to severity class, 1953–2009.

Severity class	Number	Subtotal
Class 5	0	
Class 4	9	
Class 3	17	
Class 2	53	
Subtotal of damaging encounters with ash		79
Class 1	12	
Class >0	3	
Subtotal of encounters with ash		94
Class 0 (suspected ash or gas encounters)	20	
Incidents with insufficient data to assign severity	15	
Total incidents reported	129	

- The time elapsed from the start of the eruptive event to the subsequent encounter (delta time) is known or estimated for seven of the nine incidents. Those seven incidents occurred within 24 hours of start of the eruptive event, with four known to have occurred within 2.5 hours.
- The distance between the source volcano and the encounter location (delta distance) is known for six of the nine incidents. Distances ranged from close (~100 kilometers [km]) to distant (930 km).
- Some encounters occurred in daylight.
- Three of the nine encounters involved temporary loss of power in *all* engines.
- When known, encounter duration was not long (2–13 minutes).

Melting and resolidification of ash within jet turbine engines have been identified as the primary mechanisms responsible for engine failure in an ash encounter. The melting temperature of the magmatic silicate glass in ash is lower than the operating temperatures of modern turbine engines (Swanson and Beget, 1994); consequently, ingested ash particles can melt in hot sections and then accumulate as re-solidified deposits in cooler parts of the engine, causing ignition flame-out and engine shutdown (Dunn and Wade, 1994; Przedpelski and Casadevall, 1994). In two encounters ranked as class 4 (incidents 1982–03 and 1989–05), climb out from the cloud at maximum thrust was identified as a key operational condition for engine shutdown. When engine power increased, more ash-laden air was ingested by the jet turbines and combustion temperatures were raised; thus, conditions favorable for substantial melting of ash particles were met. This lesson has

Table 3. Summary of encounters in severity class 4.

[The incident ID is the unique identifying number from appendix 1. Delta distance is the distance between the source volcano and the encounter location; delta time is the elapsed time from the start of the eruption to the encounter. ISD means insufficient data to estimate delta distance or delta time. Units: hr, hour; km, kilometer; min, minute]

Incident ID	Encounter date	Source volcano	Encounter altitude (km)	Encounter duration (min)	Delta distance (km)	Delta time (hr)	Aircraft type	Comments
1980–03	25 May 1980	Mount St. Helens, United States	4.6–4.9	~4	~100	~2.5	L–100 (C–130)	2 of 4 engines shut down by crew at night.
1982–03	24 June 1982	Galunggung, Indonesia	11.3	13	150	~2	B747	4 of 4 engines failed at night.
1982–06	13 July 1982	Galunggung, Indonesia	10.1	Unknown	ISD	~2	B747–200B	3 of 4 engines failed plus 1 to idle at night.
1989–05	15 Dec. 1989	Redoubt, United States	7.6	~8	150	1.5	B747–400	4 of 4 engines failed in Arctic summer night.
1991–17	17 June 1991	Pinatubo, Philippines	11.3	2	930	ISD	B747–200B	2 of 4 engines failed in daytime.
1991–18	17? June 1991	Pinatubo, Philippines	Unknown	Unknown	ISD	ISD	DC–10	1 of 3 engines failed.
1991–21	27 June 1991	Unzen?, Japan	11.3	Unknown	ISD	<24?	DC–10	2 of 3 engines failed.
2001–02	29? July 2001	Soufriere Hills, Lesser Antilles	Unknown	Unknown	<500	<24	B767–400	1 of 2 engines failed at night.
2006–03	17 July 2006	Manam?, Papua New Guinea	11.9	7	~250	<24	Gulfstream II	2 of 2 engines failed in daytime.

been incorporated into guidance to pilots about recommended actions to take during an encounter (Campbell, 1994; Guffanti and Miller, 2002).

A quantitative estimate of the concentration of ash particles in the ash cloud has been published for the Redoubt class 4 incident (1989–05). The ash concentration at an altitude of 7.6 km (25,000 feet [ft]) at a distance of 150 km northeast of the volcano and at 1.5 hours after the onset of the ash-producing event was estimated as 2 grams per cubic meter (g/m^3) by Przedpelski and Casadevall (1994) on the basis of the rate of nozzle-deposit buildup compared to the rates measured during engine tests conducted by Dunn and Wade (1994).

Incident 1991–17 on 17 June 1991 (table 3) is notable in that prolonged exposure to dilute ash may have contributed to significant damage. That incident involved the same aircraft (a B747–200B) as incident 1991–14; both flights were operating between South Africa and Southeast Asia in the aftermath of the June 1991 eruption of Mount Pinatubo. In both encounters, the aircraft was operating in airspace at distances in excess of 500 km from the volcano. In event 1991–14 on 15 June 1991, the crew noted static discharge lasting approximately an hour, but all engine parameters were normal during flight, and no problems were experienced with any of the aircraft systems. Two days later (incident 1991–17), the aircraft flew for several hours through an area coincident with remote-sensing evidence of an ash cloud before one engine lost power and a second engine was shut down by the crew. During descent, the engine that had been shut down was restarted, and the aircraft made a successful landing. These events raise the possibility of significant damage from cumulative exposure to dilute ash.

The 2006 Gulfstream II incident (2006–03) in table 3 is notable for involving a different mechanism for engine shutdown than melted ash (Tupper and others, 2007). The aircraft was flying over Papua New Guinea at 11.9 km (39,000 ft) in apparently clear air with no ash or sulfurous odors noted by the cockpit crew. Between 39,000 ft and descent to 24,000, both engines failed and then were restarted; the aircraft landed safely. The operator and engine manufacturer conducted a thorough investigation, including borescope analysis of the engine and fuel analysis. The manufacturer concluded that a cylindrical filter in each fuel-flow regulator may have become blocked by volcanic ash, which at that altitude could have caused loss of fuel flow and thus engine shutdown; on descent, the increasing pressure would have substantially cleared the filter and allowed the engine to restart. The likely source of the ash was an eruption of Manam Volcano in Papua New Guinea.

Of note in this compilation is an engine-shutdown encounter that occurred in July 2001 (incident 2001–02). Only very sparse information is available for this incident, gleaned from the Aviation Safety Reporting System (ASRS) maintained by the National Aeronautics and Space Administration (http://asrs.arc.nasa.gov/search/database.html). The crew of a B727 on a nighttime descent into San Juan, Puerto Rico, learned of volcanic ash in their vicinity after hearing a nearby aircraft (a B767–400) declare "an emergency and divert into San Juan with an engine shutdown due to volcanic ash." Although no day was given in the ASRS report, the growing lava dome of Soufriere Hills Volcano on the island of Montserrat in the Lesser Antilles collapsed the evening of 29 July 2001, releasing large pyroclastic flows and associated ash clouds. That singular volcanic event was the likely source of the ash cloud and suggests that the date of the encounter, which occurred at a distance less than 500 km from Soufriere Hills Volcano, also was 29 July 2001.

The 17 encounters rated as severity class 3 did not involve engine shutdown; nevertheless, some have been very dangerous. For example, in 2000 (incident 2000–03), a B737–800 nearing Japan's Narita Airport flew into an ash cloud from an eruption that had occurred about an hour earlier at Miyake-jima Volcano, located about 200 km from the airport. The aircraft's engines continued to function, but the flight management computer and electronic engine controls failed. Handicapped further by severe loss of visibility due to abrasion of all but a small part of the windscreen, the crew still managed a safe landing. Soon thereafter on the same day, a B747 had a similar experience, sustaining major engine and windshield damage (Tupper and others, 2004).

The 2008 eruption of Chaiten Volcano in southern Chile offers another cautionary example of hazardous situations for aircraft. Five encounters of aircraft with volcanic ash clouds are known to have occurred during the week of the 2–6 May 2008 eruption. Two of these encounters (2008–01 and 2008–02) occurred at low altitudes (less than 2 km) near the airport in Bariloche, Argentina, about 225 km from the volcano. The aircraft landed safely after encountering ash but subsequently experienced loss of power during takeoff and were found to have sustained major engine damage.

Incidents rated as severity class 2 make up more than half of the encounters with known ash (53 of 94 incidents). Most involve exterior abrasion, including of cockpit windshields. A notable set of 14 encounters in this class is related to eruptive activity at Sakura-jima Volcano, Japan, which is only 10 km from Kagoshima Airport. The repeated occurrence of encounters near Sakura-jima in the 1970s and 1980s led to the development of a successful monitoring and aviation-warning system at the volcano (Onodera, 2004) that has decreased substantially the frequency of encounters there.

Two specific class 2 encounters bear mention because they show that layers or lenses of ash-contaminated air can persist in the stratosphere for many days and can contain enough fine ash particles to cause modest but noticeable aircraft damage. On 23–24 November 2002, two aircraft over Micronesia (incidents 2002–01 and 2002–02) northeast of Papua New Guinea encountered a volcanic cloud that Tupper and others (2006) concluded was not from a nearby source but had drifted a great distance. One aircraft reported typical indicators of entry into an ash cloud—intense St. Elmo's fire and light white "smoke" with "burn smells." Three pitot tubes were later found to contain ash particles and were replaced (pitot tubes are used to determine aircraft airspeed, a crucial parameter during all phases of flight); some light abrasion was found on the engine air inlets, but no damage on the wind-

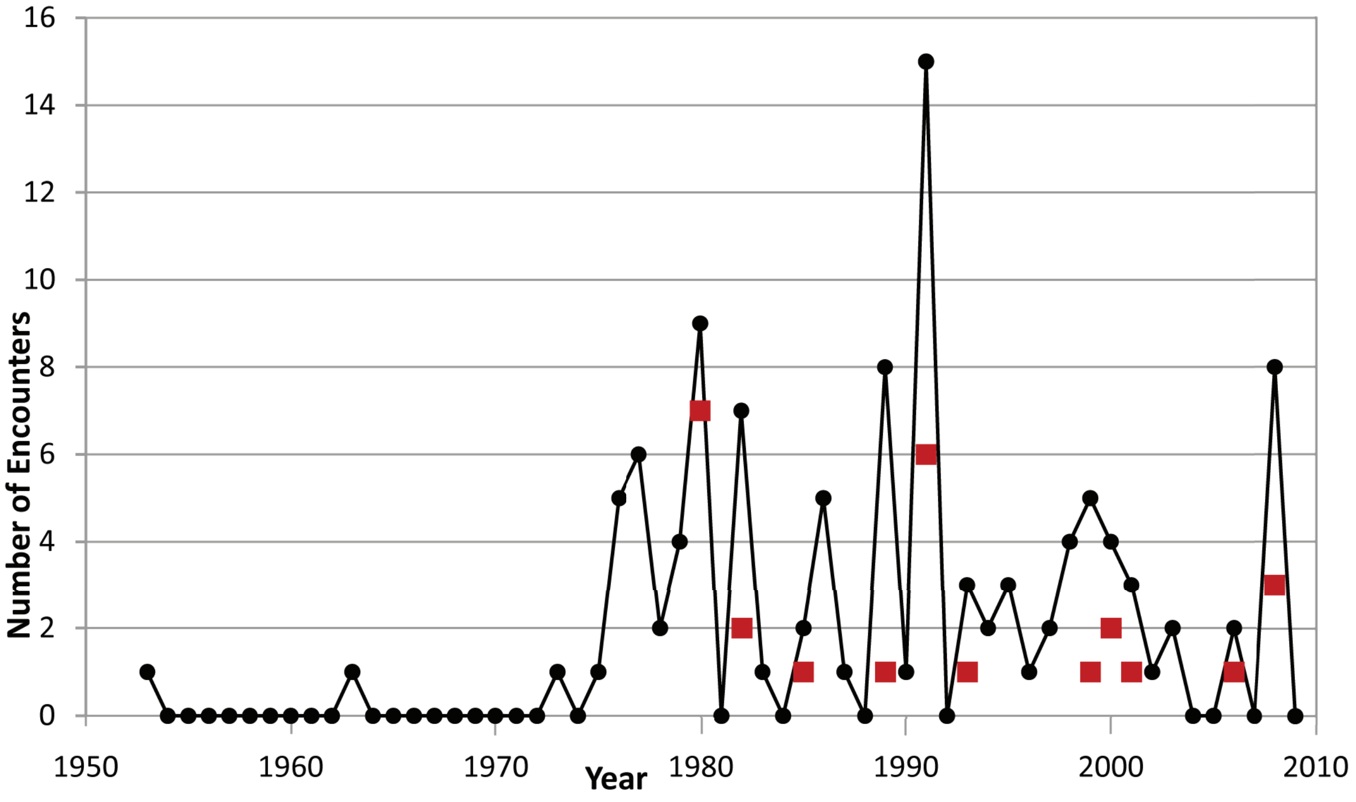

Figure 1. Annual frequency of aircraft encounters with volcanic ash clouds, 1953–2009 (excluding severity class 0 incidents). The number of higher severity encounters (classes 3 and 4) in various years is indicated by red squares.

screen or internal engine damage was reported. The flight crew of the second aircraft observed the cloud and smelled a slight odor, but no damage was found. On the basis of backward and forward wind trajectories and dispersion forecasts, as well as analysis of satellite imagery, Tupper and others (2006) proposed the probable source of the volcanic cloud as the 3–5 November eruption of Reventador Volcano in Ecuador. If so, that eruption cloud would be the oldest (approximately 20 days) and furthest traveled (approximately 14,000 km) known to have caused damage to an aircraft.

Frequency of Encounters

The annual frequency of ash encounters (excluding unreliably reported severity class 0 incidents) has ranged from 0 to 15 (fig. 1). The high value of 15 in 1991 includes 8 ash encounters related to the eruption of Mount Pinatubo, an eruption of a size (Volcanic Explosivity Index [VEI] 6) that is infrequent on a decadal timescale and the largest to occur within the timeframe of this database. From 1976, when reporting of encounters picked up, through 2009, the average annual rate of damaging encounters has been approximately 2 per year. The 26 high-severity encounters (classes 3 and 4) have occurred sporadically between 1980 and 2008.

Times and Distances of Encounters from Source Volcanoes

Ash clouds eventually dissipate in the atmosphere as the particles progressively disperse, fall out by gravitational settling, and (or) are removed by precipitation. To constrain the question of how long ash clouds remain hazardous during that process, we have estimated the times and distances of encounters from their source volcanoes.

Table 4 presents data about the relationship between encounter severity and the time elapsed since the start of ash production at the source volcano and the occurrence of the subsequent encounter (delta time). Dates and times of ash production for many incidents were determined from the Smithsonian Institution's monthly Bulletin of the Global Volcanism Network (see data sources in appendix 3); if possible, the occurrence of a specific explosive event within a longer eruptive period was identified. For many encounters, only the day of the encounter and the day of eruptive activity were known; thus, many estimates of delta time are general (for example, <24 hours if both encounter and eruptive event occurred on the same day). We also note that determining the time elapsed since the *end* of ash production also is important, but eruption cessation times often are ambiguously documented or not reported.

Table 4. Number of encounters according to severity class and delta time for the 97 encounters for which both severity and delta time can be estimated.

[Delta time is the time elapsed between the start of ash production at the source volcano and the subsequent encounter]

Severity class	Delta time		
	<24 hours	24–48 hours	>48 hours
0	13	1	5
1	10	0	2
2	41	1	2
3	13	0	2
4	7	0	0

Table 5. Number of encounters according to severity class and delta distance for the 83 encounters for which both severity and delta distance can be estimated.

[Delta distance is the distance between the source volcano and the encounter. Unit: km, kilometers]

Severity class	Delta distance	
	<1,000 km	>1,000 km
0	9	11
1	6	2
2	35	4
3	8	2
4	6	0

Of the 66 damaging encounters (severity classes 2–4) for which both severity and delta time can be estimated, 92 percent occurred within 24 hours of the start of eruptive activity; a handful (4) occurred more than 48 hours later. With respect to the 31 nondamaging incidents (severity classes 0 and 1) for which both severity and delta time can be estimated, 74 percent occurred within 24 hours after the start of eruptive activity.

Table 5 presents data about the relationship between encounter severity and the estimated distance between the source volcano and the encounter (delta distance). For most incidents, latitude and longitude of the encounter location or a measurement of delta distance is not included in the original report, and many of our estimates in this study are quite approximate. To avoid over-analysis of approximate data, we divide delta distance into two groups, <1,000 km and ≥1,000 km; the 1,000-km demarcation encompasses the location of incident 1991–17, a class 4 encounter that occurred 930 km from Mount Pinatubo.

Table 6. Number of encounters according to severity class and duration for the 33 incidents having values for both severity and duration.

Severity class	Duration			
	<5 min	>5–10 min	>10–20 min	>20–30 min
0	1	4	1	3
1	2	1	2	1
2	6	1	0	0
3	2	3	0	1
4	2	2	1	0

Of the 55 damaging encounters for which both severity and delta distance can be estimated, 89 percent occurred within 1,000 km of their source volcanoes. Although this is a strong majority of damaging encounters, we note that six ncidents occurred 1,000 km or more away. With respect to the 28 nondamaging incidents (severity classes 0 and 1) for which both severity and delta distance can be estimated, a notably greater proportion, nearly half, occurred more than 1,000 km from their source volcanoes.

In summary, the data in tables 4 and 5 indicate that most—but not all—damaging encounters occur within 24 hours of the onset of ash production or at distances less than 1,000 km from the source volcanoes. Because there are exceptions to these values, relying solely on them as universal thresholds for fly/no fly decisions is problematical.

Duration of Encounters

Encounter duration is the length of time an aircraft spent in the ash cloud as estimated by the flight crew. Duration data are both sparse and ambiguous—sparse in that duration is reported for only 33 incidents and ambiguous in that the flight crew may have been unaware of transit through dilute portions of an ash cloud before signs of ash became evident. Nevertheless, one trend is apparent from the limited data given in table 6. Typically, damaging encounters had shorter reported durations than nondamaging encounters. Of the 18 damaging encounters for which duration has been reported, all but 2 had durations of less than 10 minutes, whereas nearly half of 15 low-severity, nondamaging encounters had durations of more than 10 minutes. This difference suggests that damage occurred quickly after entries into clouds and (or) that pilots sought to exit the clouds as soon as serious effects were noticed (or had to exit because of rapid aircraft descent during engine shutdown).

Altitude

Encounter altitudes are reported for 69 incidents (appendix 1), most of which (45) occurred at altitudes greater than 7.6 km (about 25,000 ft), where winds aloft disperse ash widely and where jet aircraft spend most of their travel time. However, severity class 2 encounters commonly happened at altitudes less than 7.6 km, probably in part because lower altitude encounters tend to occur in the vicinity of erupting volcanoes where larger ash particles capable of abrasion (a defining criterion of class 2) would be present.

Volcanic Sources

Thirty-eight source volcanoes, located in 16 countries around the world, have produced ash clouds encountered by aircraft. Table 7 lists the source volcanoes and the number of damaging encounters associated with each one. Eight volcanoes have caused five or more encounters, of which the majority were damaging: Augustine (United States), Chaiten (Chile), Mount St. Helens (United States), Pacaya (Guatemala), Pinatubo (Philippines), Redoubt (United States), Sakura-jima (Japan), and Soufriere Hills (Lesser Antilles). Four of these volcanoes (Pinatubo, Chaiten, Soufriere Hills, and Mount St. Helens) had not previously been active in the era of modern flight, and, as is common with long-quiescent volcanoes, they produced significantly large eruptions. The 1980 eruptive activity of Mount St. Helens is notable in that it involved a large number of encounters (9), all of them damaging, and included the first reported in-flight engine shutdown incident (a military turboprop aircraft).

Size of eruptions is characterized approximately by the Volcanic Explosivity Index (VEI) of Newhall and Self (1982) which incorporates ejecta volume, plume height, and duration of explosive activity into an open-ended, logarithmic scale. Aircraft have been damaged by eruptions ranging from small (VEI 2), recurring episodes (for example, Etna, Italy, 1989) to very large (VEI 6), infrequent events (for example, Pinatubo, Philippines, 1991). Moderate-size (VEI 3) eruptions

Table 7. List of source volcanoes and associated encounters.

[Damaging encounters are in severity classes 2–4 (table 1). ISD means insufficient data to assign a severity class. Asterisk indicates that the number of damaging encounters includes engine-shutdown incident(s)]

Volcano and country	Number of encounters	Number of damaging encounters
Anatahan, Commonwealth of the Northern Mariana Islands, United States	1	0
Asama, Japan	1	1
Augustine, United States	8	6
Cerro Hudson, Chile	3	0
Chaiten, Chile	6	4
Cleveland, United States	1	0
Colo, Indonesia	2	0
El Chichon, Mexico	1	1
Etna, Italy	2	2
Fuego, Guatemala	1	1
Galunggung, Indonesia	4	4*
Guagua Pichincha, Ecuador	2	ISD
Hekla, Iceland	1	1
Irazu, Costa Rica	1	1
Kasatochi, United States	1	0
Kliuchevskoi, Russia	1	ISD
Langila, Papua New Guinea	1	0
Manam, Papua New Guinea	3	1*
Miyake-jima, Japan	4	2
Mount St. Helens, United States	9	9*
Nevado del Ruiz, Colombia	1	1
Okmok, United States	1	0
Oshima, Japan	4	2
Pacaya, Guatemala	5	4
Pinatubo, Philippines	17	8*
Popocatepetl, Mexico	4	ISD
Rabaul, Papua New Guinea	4	ISD
Redoubt, United States	7	6*
Reventador, Ecuador	2	1
Ruapehu, New Zealand	2	0
Sakura-jima, Japan	14	13
Soputan, Indonesia	1	1
Soufriere Hills, Montserrat, Lesser Antilles, United Kingdom Overseas Territory	5	3*
Spurr, United States	2	1
Tungurahua, Ecuador	1	ISD
Ulawun, Papua New Guinea	1	1
Unzen, Japan	2	1*
Usu, Japan	3	3

are responsible for nearly half of the damaging encounters (39 of 79).

A VEI rating is assigned by human observers at the end of an eruptive episode that may last days to years and is not read instrumentally or calculated. Because of the considerable imprecision inherent in assigning VEI ratings to eruptions, we do not make quantitative analyses of VEI ratings compared to other parameters in this study.

Discussion

This report documents recurring hazards and risks to aviation from volcanic ash clouds and provides a starting point for more in-depth analysis of individual encounters. The number of known damaging encounters (79) and their occurrence in diverse regions of the world as recently as 2008 demonstrate that ash clouds continue to pose substantial risks to safe and efficient air travel globally.

Most of the damaging encounters occurred within 24 hours of the onset of ash-producing eruptions or within 1,000 km of the source volcanoes—that is, where relatively high ash concentrations would be expected, although the data in this report are insufficient to quantify threshold ash concentrations for those conditions. Importantly, there are enough encounters that are exceptions to those conditions to caution against assuming that a cloud is harmless if it is older than a day or if it extends beyond the vicinity of its source volcano.

Eruptions do not have to be large to pose hazards to aircraft. Great vigilance is required just prior to and during the early phases of eruptive activity when data about ash emission usually are the most limited and warning capabilities the most strained, yet the risk the greatest. Worldwide, most hazardous volcanoes are not monitored in real time (Ewert and Newhall, 2004), and eruptions can go undetected for hours at volcanoes where the only monitoring is by satellite surveillance (see for example, Guffanti and others, 2005). Even if a volcano is monitored to some degree, the volcanic input parameters necessary for robust ash-dispersion forecasts—such as plume height, mass eruption rate, and distribution of particle sizes and mass within the plume—may be only very rough estimates. Thus, airline operators and regulators cannot assume that precise warnings necessarily will be available during the period of greatest risk.

Beyond the obvious general trend in these data that damage is more likely in areas of newly released ash close to the source volcano, much uncertainty remains about quantifying aircraft exposure to ash. Well-constrained dispersion modeling provides a means to estimate concentrations of airborne ash in space and time, but exposure of a specific aircraft involves consideration of additional variables such as duration of transit in the cloud and the amount of ash ingested by the engine. Also, the effects of cumulative flights through low-concentration ash clouds are poorly constrained, as are the roles of ash-particle size and composition in causing aircraft damage. These are topics for further investigation.

Preventing encounters that affect the safety and efficiency of flight—whether by strict avoidance of ash-contaminated airspace or by defining zones of tolerably low ash concentrations that can be transited with minimal harm—requires rapid, reliable communication of information about the occurrence of explosive eruptions and the locations of ash clouds worldwide to dispatchers, pilots, and air traffic controllers. Under the aegis of ICAO's International Airways Volcano Watch (ICAO, 2007), various countries have marshaled a diverse set of capabilities to produce the needed warnings: real-time volcano monitoring and rapid eruption reporting, detection and tracking of ash clouds in the atmosphere using satellite-based sensors, dispersion modeling to forecast expected ash-cloud movement, and global messaging and communications systems to get warnings to the cockpit. Improvements in the following capabilities would help minimize encounters in the future:

- Real-time monitoring of more currently uninstrumented volcanoes with ground-based geophysical networks would increase the ability of volcano observatories to provide situational awareness of precursory unrest as well as timely eruption reports to the aviation sector. Assessing the aviation-threat potential of volcanoes that could generate explosive ash-producing eruptions (see, for example, the assessment methodology of Ewert, 2007) would allow appropriate national volcanological and meteorological agencies to prioritize where monitoring would be useful for mitigating aviation risk.

- Optimizing future satellite-based sensors and retrieval algorithms for ash detection would augment current techniques that use systems that were designed for other purposes. New data integration and visualization software tools would allow easier geospatial and temporal comparisons of data from different sources.

- Improving numerical dispersion models to incorporate realistic eruption-source parameters and ash-removal processes would improve forecasts of ash-cloud location, concentration, and longevity. Improved numerical weather models are needed, especially in the tropics. Improved capabilities to rapidly determine ash-cloud altitudes are important for accurate dispersion modeling.

- Ground-based and airborne sampling of ash clouds would provide much needed observational data on how ash concentrations in the atmosphere vary in space and time. Assimilation of cloud-sampling data, as well as remote-sensing data, into dispersion models is a promising new direction for improving ash-cloud forecasts.

- Placing sensors onboard aircraft could provide a tactical means to avoid ash-contaminated airspace under some circumstances, although such sensors would not eliminate the need for the strategic approach of widely disseminated volcanic ash advisories, warnings, and forecasts based on eruption reports, satellite data, and dispersion models.

- Refining and testing communication protocols would make information flow more effective among the diverse parties involved in dealing with ash hazards to aviation.

In closing, we emphasize that more reporting and sharing of information about actual ash-cloud encounters are needed to gain deeper understanding of the volcanic, meteorological, and operational conditions under which encounters occur, to identify needed research and engineering investigations, and to improve risk-mitigation strategies. As new information comes to light, we anticipate future updates and supplementary analysis of the information in this report.

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Appendixes 1–4

To obtain the entire Data Series 545 report, download this text file and appendixes 1–4, which are available as separate files. Click on the links below.

Appendix 1 is available in two formats: 1A is a Microsoft Access database, and 1B is a Microsoft Excel spreadsheet. Appendixes 1A and 1B contain the same information except in the column titled "ENC & damage summary"; that column has the narrative summary of the conditions of the encounter, any damage sustained by the aircraft, and pertinent aspects of eruptive activity at the source volcano. In appendix 1A (Access database file), this is an OLE object field that may contain images, whereas in appendix 1B (Excel spreadsheet file), this is a text-only memo field.

Appendix 1A. Compilation of encounters of aircraft with volcanic ash clouds, 1953–2009, as a Microsoft Access database file (.mdb).

Appendix 1B. Compilation of encounters of aircraft with volcanic ash clouds, 1953–2009, as a Microsoft Excel 93–2007 spreadsheet file (.xls).

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Appendix 2. Explanation of database fields and disclaimer.

Appendix 3. Sources of data in the database.

Appendix 4. Severity factors for each incident in appendix 1, documenting how severity class was assigned.

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