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Volcanic-ash hazard to aviation during the 2003–2004 eruptive activity of Anatahan volcano, Commonwealth of the Northern Mariana Islands

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Abstract

Within the Commonwealth of the Northern Mariana Islands (CNMI), Anatahan is one of nine active subaerial volcanoes that pose hazards to major air-traffic routes from airborne volcanic ash. The 2003–2004 eruptive activity of Anatahan volcano affected the region's aviation operations for 3 days in May 2003. On the first day of the eruption (10 May 2003), two international flights from Saipan to Japan were cancelled, and several flights implemented ash-avoidance procedures. On 13 May 2003, a high-altitude flight through volcanic gas was reported, with no perceptible damage to the aircraft. TOMS and MODIS analysis of satellite data strongly suggests that no significant ash and only minor amounts of SO_2 were involved in the incident, consistent with crew observations. On 23 May 2003, airport operations were disrupted when tropical-cyclone winds dispersed ash to the south, dusting Saipan with light ashfall and causing flight cancellations there and at Guam 320 km south of the volcano. Operational (near-real-time) monitoring of ash clouds produced by Anatahan has been conducted since the first day of the eruption on 10 May 2003 by the Washington Volcanic Ash Advisory Center (VAAC). The VAAC was among the first groups outside of the immediate area of the volcano to detect and report on the unexpected eruption of Anatahan. After being contacted about an unusual cloud by National Weather Service forecasters in Guam at 1235 UTC on 10 May 2003, the VAAC analyzed GOES 9 images, confirming Anatahan as the likely source of an ash cloud and estimating that the eruption began at about 0730 UTC. The VAAC issued its first Volcanic Ash Advisory for Anatahan at 1300 UTC on 10 May 2003 more than 5 h after the start of the eruption, the delay reflecting the difficulty of detecting and confirming a

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surprise eruption at a remote volcano with no in situ real-time geophysical monitoring. The initial eruption plume reached 10.7–13.4 km (35,000–44,000 ft), well into jet cruise altitudes; thereafter, the maximum plume height decreased and during the rest of the eruption usually did not exceed ~5 km (~17,000 ft), which lessened the potential hazard to aircraft at higher cruise altitudes. Drifting ash clouds commonly extended hundreds of kilometers from the volcano, occasionally as far west as the Philippines. Over the course of the eruptive activity in 2003–2004, the VAAC issued 323 advisories (168 with graphical depictions of ash clouds) for Anatahan, serving as a reliable source of ash-cloud information for aviation-related meteorological offices and air carriers. With a record of frequent eruptions in the CNMI, continued satellite and in situ real-time geophysical monitoring is needed at Anatahan and other Marianas volcanoes so that potential hazards to aviation from any future eruptive activity can be quickly and correctly assessed.

Keywords: volcanic hazards; volcanic-ash clouds; aviation safety; remote-sensing surveillance; SO_2

1. Introduction

Since eruptive activity began on 10 May 2003 at Anatahan Volcano in the Commonwealth of the Northern Mariana Islands (CNMI), the volcano has been monitored by satellite-based sensors in near-real time for production of volcanic-ash clouds, which are known to cause significant damage to aircraft inflight. The overall exposure of aviation to potential volcanic-ash hazards from CNMI volcanoes is significant. Heavily traveled air-traffic routes in the region are north–south, connecting Japan and Korea to Guam, Saipan, Australia, and New Zealand. The economies of Guam and Saipan rely heavily on commercial aviation for cargo trade and tourism. Drawing about 1,000,000 visitors per year, Guam is the biggest tourist destination in Micronesia, followed by Saipan with about 400,000 visitors per year. On average, more than 1200 passengers and 86,000 lb of cargo fly in and out of Saipan each day (Saipan Commonwealth Port Authority, 2002 statistics). In addition, there are substantial military air operations based at Guam.

Although to date the 2003–2004 eruptive activity of Anatahan has been minor overall, it nevertheless presents a worthwhile case study of operational ash-cloud monitoring. Being a little-known, uninhabited volcanic island with no in situ real-time seismic monitoring and no forecast of imminent activity, Anatahan unexpectedly forced an operational response by various meteorological and aviation-related groups that largely had been unaware it was a potentially active volcano. After a somewhat tentative start, that operational response steadied and developed into the routine vigilance required to provide ash-hazard information to the aviation sector for the duration of the eruptive activity.

2. Volcanic-ash hazards to aviation

Over the past 25 years, the threat to aviation from airborne volcanic ash has been widely recognized and documented (Casadevall, 1994; Miller and Casadevall, 2000; Guffanti and Miller, 2002). Eruption columns rise quickly from their source vents at velocities of 5 to >180 m/s and can be energetic enough to reach cruise altitudes of jet aircraft and beyond, to 45 km (Self and Walker, 1994). The larger pieces of tephra (>50 μm in diameter) fall out of the column within minutes to hours and are deposited near the volcano, while the smaller ash particles can remain suspended in the atmosphere for days. Once ejected into the stratosphere, ash, gas, and aerosol droplets are spread by winds aloft as a diffuse cloud of small particles having insufficient reflectance for detection by weather radars onboard aircraft.

Airborne ash particles, upon impact with aircraft traveling at speeds of several kilometers per minute, cause abrasion damage to forward-facing surfaces, including windscreens, fuselage surfaces, and compressor fan blades in turbine engines. Moreover, the melting temperature of the glassy silicate rock material that comprises an ash cloud (about 700–1100 °C) is lower than the operating temperatures of modern jet turbine engines (nearly 2000 °C in the combustion chamber); consequently, ash particles ingested into such engines can melt in hot sections and then accumulate as re-solidified deposits in cooler parts of the engine. The overall result of an aircraft's flying into an ash cloud can be degraded engine performance (including flame out and loss of thrust power), loss of visibility, and failure of critical navigational and operational instruments (Dunn and Wade, 1994).

An ash cloud eventually dissipates as ash particles settle out of the atmosphere. However, the threshold concentration at which ash poses no harm to aircraft is not known, and indeed, may never be characterized fully for all situations involving aircraft. It is usually assumed that ash identifiable on satellite images continues to present a hazard to aircraft (International Civil Aviation Organization, 2001). Accordingly, the consensus of the aviation community is that if an ash cloud can be discerned, visually by a pilot or on satellite images, it should be avoided. Ash-cloud avoidance requires effective communication among diverse specialists–volcanologists, meteorologists, pilots, dispatchers, and air-traffic controllers–and across global airspace boundaries. With timely and proper notification of the occurrences of explosive eruptions and the whereabouts of airborne ash, aircraft can be routed to avoid ash-cloud encounters.

The ash hazard to aviation is not rare on a worldwide scale, given that many major air routes overlie the world's volcanically active regions (Casadevall et al., 1999). Miller and Casadevall (2000) estimate that volcanic ash can be expected to be in air routes at altitudes greater than 9 km (30,000 ft) for roughly 20 days/year worldwide. From 1973 to 2003, 101 encounters of aircraft with airborne volcanic ash have been documented (Guffanti et al., 2005). This number is a minimum value because some encounter incidents are not made public.

Because of the global scope of the ash hazard to aviation, an international approach has been developed to address the threat. As part of the International Airways Volcano Watch under the auspices of the International Civil Aviation Organization (ICAO), nine regional Volcanic Ash Advisory Centers (VAACs; Fig. 1) were established in the mid-1990s

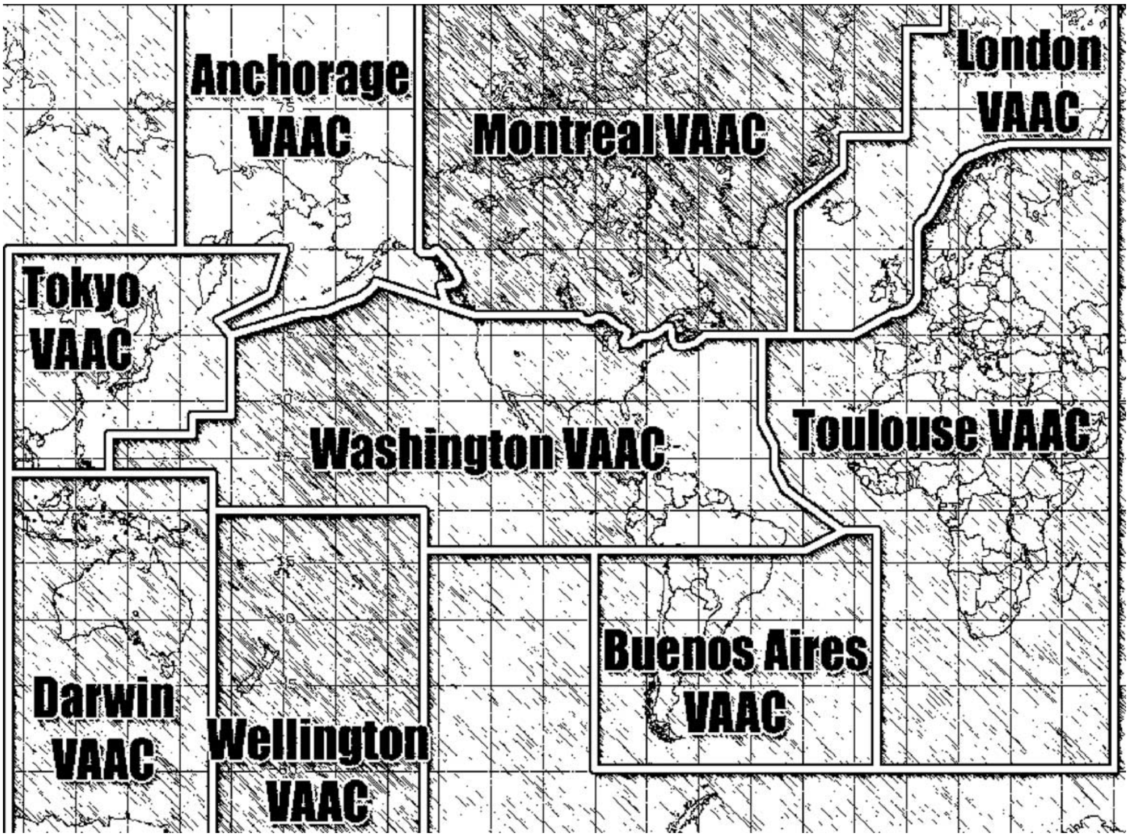


Fig. 1. Map showing areas of responsibility of the nine Volcanic Ash Advisory Centers (VAACs) worldwide. Anatahan is located in Mariana Islands in westernmost part of the Washington VAAC area. Map courtesy of the Bureau of Meteorology, Darwin, Australia.

to provide advisories about the location and movement of ash clouds to the worldwide system of aviation-related meteorological watch offices (MWOs). As an ash cloud drifts, responsibility for monitoring it passes from one VAAC to the next. VAACs use volcano-observatory reports, pilot reports, geostationary and polar-orbiting satellite data, and ash-dispersion models as the basis for their advisories. Upon receiving a VAAC ash advisory, a MWO then decides whether to issue a Significant Meteorological Advisory (SIGMET), giving the location and forecasted direction of the ash cloud. A SIGMET is the official warning about various intense and/or extensive weather phenomena of concern to pilots, dispatchers, and operators of aircraft.

In the United States, the National Oceanic and Atmospheric Administration (NOAA), the Federal Aviation Administration (FAA), the U.S. Geological Survey (USGS) and the Air Force Weather Agency (AFWA, which provides ash-cloud notifications for the U.S. Department of Defense and serves as the backup to the Washington VAAC) collaborate to share data and continually refine communication protocols so that eruption and ash-hazard information quickly reaches commercial and military pilots, dispatchers, and air-traffic controllers. Anatahan and the other eight active CNMI volcanoes fall under the responsibility of the Washington VAAC, a unit within NOAA's National Environmental Satellite Data and Information Service and located near Washington, DC. The Washington VAAC uses geostationary and polar-orbiting weather satellites operated by the United States and other countries to detect volcanic-ash clouds on a 24/7 basis in the conterminous United States, Hawaii and the surrounding Pacific, the Caribbean and Central America, and South America as far south as latitude 10°S to encompass Ecuador.

3. Operational ash-cloud monitoring by the Washington Volcanic Ash Advisory Center

The Washington VAAC's area of responsibility contains approximately 250 active volcanoes (Simkin and Siebert, 1994), 19 of which have produced ash clouds detected by the W-VAAC since 1997; numerous additional volcanoes occur near boundaries with other VAACs, including six that have produced ash clouds that moved into the Washington VAAC's area. Along with volcanic-ash cloud detection and notification, staff of the VAAC also is responsible for analyzing snow and ice coverage in the Northern Hemisphere, detecting and tracking fire and smoke, tracking and estimating the intensity of global tropical cyclones, and monitoring heavy precipitation in the United States. To manage its workload, the Washington VAAC identifies a roster of restless and erupting volcanoes that receive regular daily visual surveillance of satellite images, as often as 4–48 times a day (every 6–0.5 h) depending on the level of activity and data availability. As explained elsewhere in this volume, Anatahan had not erupted in historical time before 2003; two known swarms of earthquakes occurred in 1990 and 1993 that in retrospect may have been early indications that new magma had been intruded. An imminent eruption was not expected, and Anatahan was not under regular surveillance by the Washington VAAC.

For volcano surveillance, the Washington VAAC relies heavily on geostationary meteorological satellites because of their higher temporal resolution (images usually available within 15–30 min) which is extremely important for relaying timely information to the aviation community. However, other satellite platforms/sensors are monitored as well, including the NOAA Advanced Very High Resolution Radiometer (AVHRR) and NASA Moderate Resolution Imaging Spectrometer (MODIS). These sensors are on polar-orbiting satellites and provide higher spatial-resolution imagery (up to 1-km pixels compared to up to 4-km pixels for geostationary) with more spectral channels to utilize for ash detection than those on geostationary satellites but typically are not as timely; as much as 3 h can elapse from the polar-orbiting overpass of the volcano until the data files are downloaded to a ground station, processed, and made available for viewing at the W-VAAC.

For aviation purposes, the height (top) of an ash cloud and the wind field that disperses it are critical information needed to prevent encounters of aircraft with ash. In its advisories, the Washington VAAC will cite cloud-height estimates received from ground observers or pilots. To verify observer reports, or if they are lacking, the VAAC estimates heights by comparison, between timed satellite images, of the change in ash-cloud location with profiles of wind speed by altitude. The best source of wind speed and height data is by radiosonde measurement. Unfortunately, radiosonde launches are temporally and spatially sparse in many regions of the world, so the Washington VAAC analysis typically involves using numerical forecast models.

In the case of Anatahan, National Weather Service forecasters at the Guam MWO first noted an unusual, rapidly developing cloud at 1030 UTC (2030 local time) on 10 May 2003 using the 10.7-μm (infrared) channel on the Geostationary Operational Environmental Satellite (GOES) 9. Unsure of what they were detecting, the Guam forecasters contacted the Honolulu MWO at 1205 UTC for advice and then issued the first SIGMET at 1225 UTC. The Guam MWO contacted the W-VAAC at 1235 UTC. The staff of the Washington VAAC examined available satellite images and confirmed that the feature was a volcanic ash cloud, apparently from an eruption of Anatahan.

The ash cloud was barely discernible on the 0755 UTC visible image and not at all on the previous image at 0718 UTC, leading the Washington VAAC to conclude that the eruption started at ~0730 UTC on 10 May 2003 (~1730 local time and date). Owing to the remote location of the uninhabited island, no visual confirmation of the onset of the eruptive activity was made. Retrospective analysis of seismic and tilt data from non-real-time instruments on the island indicates that nearly continuous seismicity and deformation began at 0620 UTC and 0600 UTC, respectively (Posgay et al., this issue). Fig. 2 shows the first GOES 9 image (visible spectrum) of the developing ash cloud that is of good enough quality to be reprinted here (at 0818 UTC, less than 1 h after the start of the eruption).

The Washington VAAC issued its first Volcanic Ash Advisory for Anatahan at 1300 UTC (2300 local time) on 10 May 2003, 25 min after being contacted by the Guam MWO and roughly 5 h after the estimated start of the eruption. The entire text of that first Volcanic Ash Advisory and an accompanying graphical depiction of the extent of the ash cloud, based on visual examination of visible-spectrum images from the GOES 9 weather satellite are shown in Fig. 3. The advisory text follows a standard format. In its "Remarks" section, the advisory states that "Satellite imagery shows possible eruption with high level ash estimated at FL350 moving south at 35 knots and lower level ash estimated at FL150 moving west at 15 knots. Anatahan has not erupted in recent times but plume is closest to its location so identity of volcano not certain." (Note: FL350 = flight level of 35,000 ft = 10.7 km; FL150 = flight level of 15,000 ft = 4.5 km.).

Early on the morning of 11 May 2003 (local time and date), the eruption was witnessed visually by

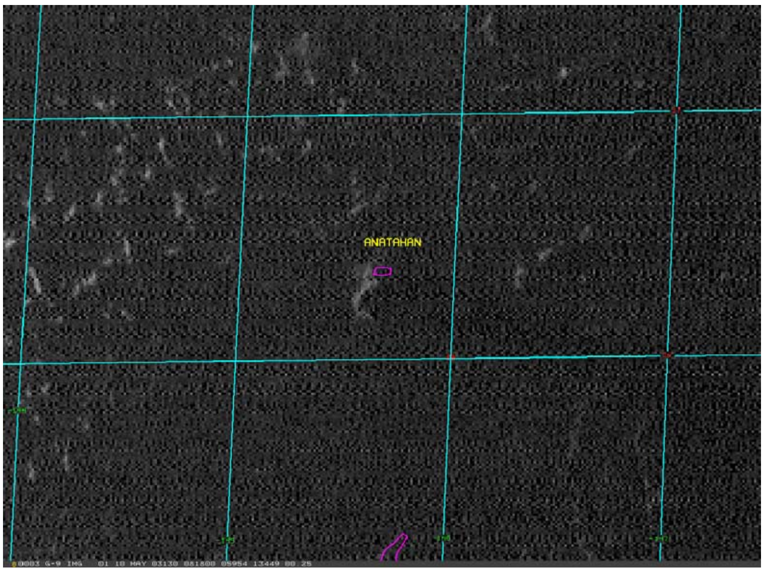
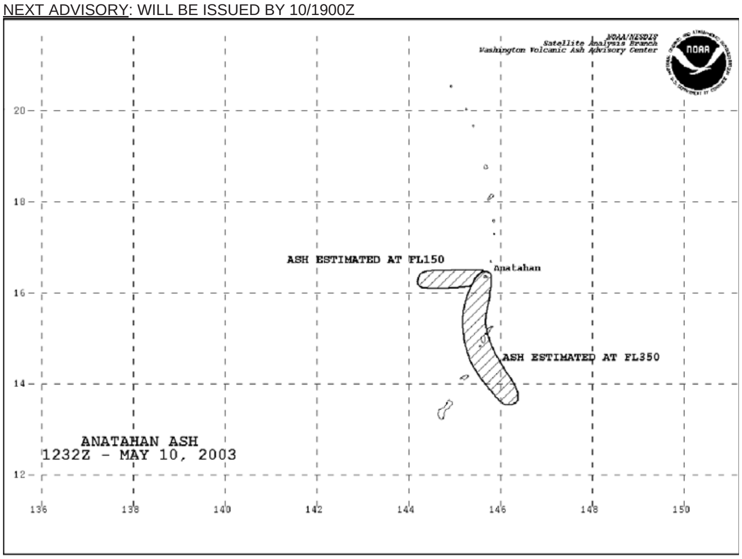
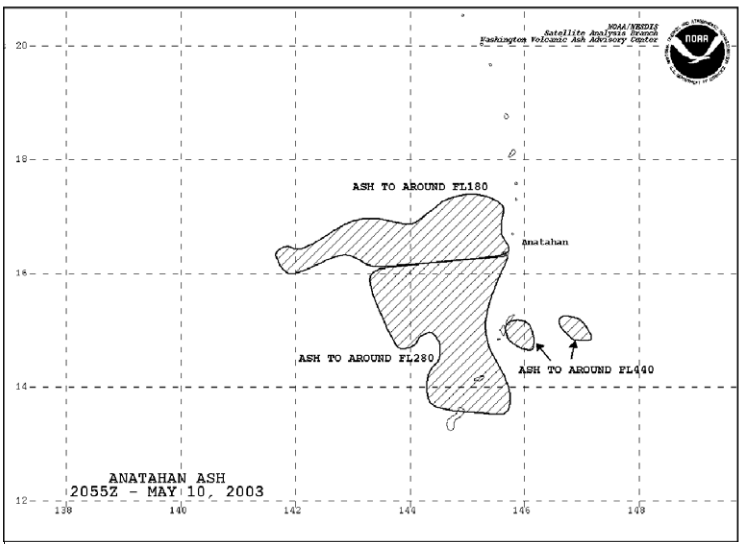


Fig. 2. NOAA GOES 9 visible-spectrum image of the developing ash plume from the eruption of Anatahan volcano at 0818 UTC (1818 local time), less than 1 h after the start of the eruption on 10 May 2003. Sunlight is rapidly fading at the time the image was obtained.

A. *10 MAY 2003* - 1300 UTC -- Has Graphic Attached
VXX22 KWBC 101307Z VOLCANIC ASH ADVISORY
ISSUED: 2003MAY10/1300Z
VAAC: WASHINGTON
VOLCANO: ANATAHAN 0804-20
LOCATION: N1621E14540
AREA: MARIANA ISLANDS
SUMMIT ELEVATION: 2585 FT (788 M)
ADVISORY NUMBER: 2003/001
INFORMATION SOURCE: GUAM MWO. GMS IMAGERY. GFS MODEL WINDS FORECAST. UPPER AIR SOUNDING
ERUPTION DETAILS: ERUPTION APPEARS TO START AT ABOUT 10/0730Z.
OBS ASH DATE/TIME: 10/1232Z
OBS ASH CLOUD: SFC/FL350 25 NM WIDE LINE OF ASH EXTENDING BETWEEN N1621E14540 N1500E14520 N1343E14612 MOVING S 35 KNOTS. SFC/FL150 20 NM WIDE LINE OF ASH EXTENDING BETWEEN N1621E14540 N1618E14412 MOVING W 10-15 KNOTS.
FCST ASH CLOUD +6H: SEE SIGMETS AND VAFTAD
REMARKS: SATELLITE IMAGERY SHOWS POSSIBLE ERUPTION WITH HIGH LEVEL ASH ESTIMATED AT FL350 MOVING SOUTH AT 35 KNOTS AND LOWER LEVEL ASH ESTIMATED AT FL150 MOVING WEST AT 15 KNOTS. ANATAHAN HAS NOT ERUPTED IN RECENT TIMES BUT PLUME IS CLOSEST TO ITS LOCATION SO IDENTITY OF VOLCANO NOT CERTAIN.
NEXT ADVISORY: WILL BE ISSUED BY 10/1900Z



B.



observers in the vicinity of the island. A small research ship carrying scientists funded by the National Science Foundation and personnel from the CNMI's Emergency Management Office (EMO) was approaching the island as part of a long-planned expedition. At ~1900 UTC on 10 May (~0500 on 11 May, local time and date), this group witnessed an ash column rising from the volcano's crater (Posgay et al., this issue).

The initial eruption plume reached 10.7 km (35,000 ft; Fig. 3A); approximately 8 h later, small, detached parts of the plume had reached 13.4 km (44,000 ft; Fig. 3B). Thereafter, the maximum cloud height decreased, and during the rest of the eruption usually did not exceed ~5 km (~17,000 ft).

Over the course of the 2-month-long eruptive phase in 2003, the eruption of Anatahan produced ash identifiable on weather-satellite images on 54 out of 75 days. Ash commonly extended hundreds of kilometers from the volcano; occasionally, ash was detected as far west as the Philippines. From 10 May to 16 July 2003, the Washington VAAC issued 289 ash advisories for Anatahan, typically four per day. In concert with the Washington VAAC, the Guam MWO issued volcanic ash SIGMETs every 6 h. The final VAAC advisory and SIGMET in 2003 were issued on 20 July 2003. Washington VAAC ash advisories (including graphical depictions of the areas and heights of detected ash clouds) are online and archived at http://www.ssd.noaa.gov/VAAC/.

Limited real-time seismic monitoring of Anatahan by the USGS Volcano Hazards Program and CNMI EMO began in early June 2003 (White et al., this issue) about a month after the start of the eruption. USGS volcanologists had worked with the Washington VAAC on responses to eruptions in Mexico and Central America and generally understood its operational role with respect to aviation hazards. From June 2003 onward, the Washington VAAC and Guam MWO have been included in the high-priority telephone call-down list of the USGS duty seismologist for monitoring Anatahan to directly receive timely updates of significant changes in volcanic activity. Subsequently, the FAA control facility in Guam and AFWA also were added to the call-down list.

After a pause of about 8 months, eruptive activity resumed at Anatahan on 30 March 2004 with a significant increase in seismic activity but little ash production. This time, the Washington VAAC received timely telephone notification of increased activity with possible ash emission from the USGS/EMO monitoring group. During 2004, eruptive activity has been localized to the near-crater area with very low-level ash emission that usually was not visible on VAAC imagery. The Washington VAAC and Guam MWO have coordinated the issuance of occasional advisories appropriate for the low level of activity.

A timeline of Washington VAAC major actions and observations during the 2003–2004 Anatahan activity is given in Table 1. Recognizing that conditions at the volcano could rapidly change, the Washington VAAC continues to keep Anatahan on its roster of volcanoes needing regular surveillance for the foreseeable future.

4. Hazards to aviation from the 2003 eruptive activity

An analysis of air traffic from November 2002 to October 2003 by Airservices Australia (Christopher Bruce, written communication, 2003) reveals that over 1,000,000 flights of large commercial aircraft (>20 tons maximum take-off weight, flying distances >100 km, excluding military, freight, private, and charter civilian flights) occurred in the area of the Western Pacific and Eastern Asia (including Malaysia, Indonesia, the Philippines, and Papua New Guinea) that potentially could be affected by major eruptions from CNMI volcanoes. Nearly 25,000 flights of large commercial aircraft and ~18,000 flights of smaller, mostly inter-island traffic occurred in the immediate vicinity of CNMI and Guam over the same time period.

The 2003–2004 eruptive activity of Anatahan has been relatively minor overall; during much of the eruption, ash plume and cloud heights did not exceed 5 km, which lessened the potential hazard to aircraft at higher cruise altitudes. Nonetheless, the eruption dis-

Fig. 3. (A) Volcanic Ash Advisory issued by the Washington Volcanic Ash Advisory Center on 10 May 2003 at 1300 UTC (image at 1232 UTC) with accompanying graphic; hatchured areas depict areas of volcanic-ash clouds as interpreted from satellite-image analysis. FL=Flight Level (altitude) in hundreds of feet. (B) Volcanic Ash Advisory graphic issued on 10 May 2003 at 2230 UTC (image at 2055 UTC).

Table 1
Washington VAAC timeline of actions during the 2003–2004 Anatahan eruptive activity

Date/Time		VAA number	Highlight
2003			
May 10	~0730 UTC		approximate onset of eruption (determined retrospectively)
	0755		ash cloud first observable (retrospectively) in satellite imagery
	1026		HL ash at FL350+ located (retrospectively) over Saipan
	1030		Guam MWO notices rapidly growing unusual cloud over Anatahan
	1227		Guam MWO issues first SIGMET
	1300	1	W-VAAC issues first VAA with HL ash FL350 moving S; ML ash moving W at around FL150
	1400	1	HL ash located over Guam
	2230	3	HL ash estimated higher (to FL440) moving SE
May 11	0400	4	HL dissipating; maximum height now at FL290
	0950	5	western extent of ML ash 136.5E; last detection of HL ash (FL250)
May 12	1600	10	low-level (LL) plume cannot be seen; ML (FL180) extends to 127.5E just NE of the Philippines
May 13	1150	13	report of fight through volcanic gas by Boeing 747 (sulfurous smell) at FL330; ML plume extends to just miles off Catanduanes island and Eastern Luzon
May 14	1015	17	very diffuse ash/haze over Eastern Philippines
May 16	0400	24	ML ash E of Philippines and W of Anatahan is too diffuse to detect; LL plume continues W of volcano (10,000 ft)
May 21	0550–1500	45–47	height of plume increasing FL070 to FL120 to FL190; increased eruptive activity?
May 22	0200	48	US Air Force “hurricane-hunter” observes ash during reconnaissance on Typhoon 04W Chan-Hom
	0900	50	LL ash over Saipan and Guam; pilot reports ash at FL070; becoming cloudy due to approach of Chan-Hom
May 23	0500	54	possible LL ash over Guam
	1100	55	LL ash detection over NE Guam
	2305	57	LL plume directly over Saipan; ash beginning to move E under influence of Chan-Hom
May 26	1930	68	surface report from West Tinian (15.0N 145.6E) of volcanic ash fall; large area of ash N to E of volcano out to 156.5E
	2300	69	pilot report of ash FL220 to FL260; increase in activity (stronger exhalation?)
May 27	0150	69	second surface report from West Tinian of volcanic ash fall
	0500	70	aforementioned increased activity plume moving SE (FL200)
	1700	72	winds shift ash movement from Northeast toward NW; large LL eastern plume and ML SW-moving plume dissipate
May 30–June 4			cloudy over volcano
June 4	1100	104	ash identifiable in satellite imagery again; ML plume (FL150) moving Northwest; LL plume (FL100) moving W
June 4–June 13			ongoing LL plume (FL100); night-time detection of ash becomes difficult on GOES-9 due to low level and lower ash density
June 24	0800	186	pilot report helps to increase LL plume height to FL160

Table 1 (*continued*)

Date/Time		VAA number	Highlight
June 27	1600	200	first end VAA; ash is no longer detectable, even on a clear day
June 28	0830	201	LL ash detectable again, from now until end of 2003 eruption; plume tends to be W moving, weak, narrow, only seen on GOES visible and polar orbiting imagery, and maximum heights around 8000 ft
July 1	1400	214	Air Force Weather Agency issues VAA during a test of back-up procedures
July 16	0625	274	last graphic (visible ash on satellite imagery) produced for Anatahan
July 20	0100	289	last volcanic ash advisory written by the W-VAAC until 2004 event
July 20	0130	289	last SIGMET written by Guam MWO
2004			
April 14	0440		increased seismic activity at Anatahan reported to W-VAAC by USGS
	0455	1	first VAA by W-VAAC; ash not identifiable on satellite imagery due to cloudiness; LL ash estimated at 2000 ft by USGS
	0846	2	ash still not seen; ended advisories
April 24	0125		estimated eruption time by the W-VAAC using satellite imagery
	0303	3	first VAA sent by W-VAAC after confirmation by USGS; the LL plume was estimated at 6000 ft and was 5 NM wide and extended 40 NM toward the Northwest
	0407	3	Guam MWO issues first SIGMET based on VAA information
	0420	4	special VAA sent with graphic of ash
	0948	5	LL ash extends to cloudy region near 20N 142E
	1052	5	USGS reports a second increase in seismic activity
	1524	6	LL plume not detected at night; a hotspot was seen on thermal IR channel
	2126	6	Guam MWO cancels SIGMET
	2133	7	visible imagery did not show an LL plume; advisories were ended
June 28			tropical cyclone 11W (Tingting) knocked out the only seismic station
July 2	0500		very light LL steaming with possible light ash was observed on satellite imagery near the island; estimated less than 3000 ft; no action taken by W-VAAC due to limited scope of event
	2200		USGS contacts W-VAAC about light ash from surface to 2000 ft; Guam MWO contacted—no further actions taken
July 14	1026	8	slightly higher density LL ash seen in visible imagery; height not exactly known but estimated below FL050
July 15	2000	14	LL ash plume is too diffuse to see but continuing advisories under a request by local officials
September 29			responsibility for issuing volcanic ash SIGMETs changed from Guam MWO to Honolulu MWO

VAA number is identification number of particular Volcanic Ash Advisory issued by the VAAC. Times are given in Universal Time Coordinates (UTC). UTC is 10 h behind local time (and 1 day behind the Marianas with respect to the International Date Line.) FL=flight level in hundreds of feet (e.g., FL350=35,000 ft). HL=high level, ML=mid-level=LL, low level, NM=nautical miles.

rupted aviation operations in various ways on 3 days in May 2003. The initial eruption plume on 10 May 2003 reached 10.7–13.4 km (35,000–44,000 ft), well into jet cruise altitudes. Two international flights from Saipan to Japan were cancelled that day, many flights implemented ash-avoidance procedures, and one aircraft received a special inspection after concern about proximity to the ash cloud but no damage was observed (Noriyuki Todo, oral communication, 2003). On 13 May 2003, an aircraft unintentionally flew through volcanic gas from the eruption, with no perceptible damage to the aircraft. On 23 May 2003, light ashfall at Saipan International Airport caused flight cancellations there and at Guam 320 km south of the volcano.

4.1. Analysis of ash-cloud conditions leading up to and during the 13 May 2003 incident

Fortunately, the incident on 13 May 2003 did not have damaging consequences. The incident involved a Boeing 767-319 en route between Japan and New Zealand with 62 people on board. At 1150 UTC at a position of N17°35′, E142°36′ and an altitude of 10 km (33,000 ft), the crew experienced a strong sulfur smell for approximately 3 min in the flight deck. Sulfur smell in the cockpit is known to be a signal of entry into a volcanic ash cloud, but other signals such as heavy cabin dust, frosting of windows, erroneous instrument readings, or engine surging would be expected as well during a severe encounter with ash (International Civil Aviation Organization, 2001). After consultation with the air traffic center in Guam and the airline's flight dispatch office, the effect of the incident on the aircraft was deemed negligible, and the flight proceeded safely to its destination.

The Washington VAAC issued four volcanic-ash advisories with accompanying graphics on 13 May, none showing ash to 33,000 ft. The location of the incident is shown on the Volcanic Ash Advisory graphic based on imagery at 1502 UTC (Fig. 4) and plots between two depicted ash areas with tops at 4.9 km (16,000 ft) and 2.4 km (8000 ft).

To confirm that the 13 May 2003 incident did not involve entry into ash, a retrospective analysis of the eruption cloud at the time of the aircraft report was done using satellite data from the ultraviolet TOMS (Total Ozone Mapping Spectrometer), and the infrared MODIS (Moderate Resolution Imaging Spectroradiometer). For a complete satellite study of emissions from Anatahan, see Wright et al. (this issue). The TOMS instrument and retrieval procedures are described in Krueger et al. (1995). TOMS provides once daily images, at a nadir resolution of 39 km. MODIS methodology for detection of SO_2 and ash has been described by Watson et al. (2004). Two MODIS sensors are in operation, providing multiple coverages each day at 1 km resolution. Local radiosonde data (accessed from the NASA/Goddard Automailer, maintained by the Atmospheric Dynamics

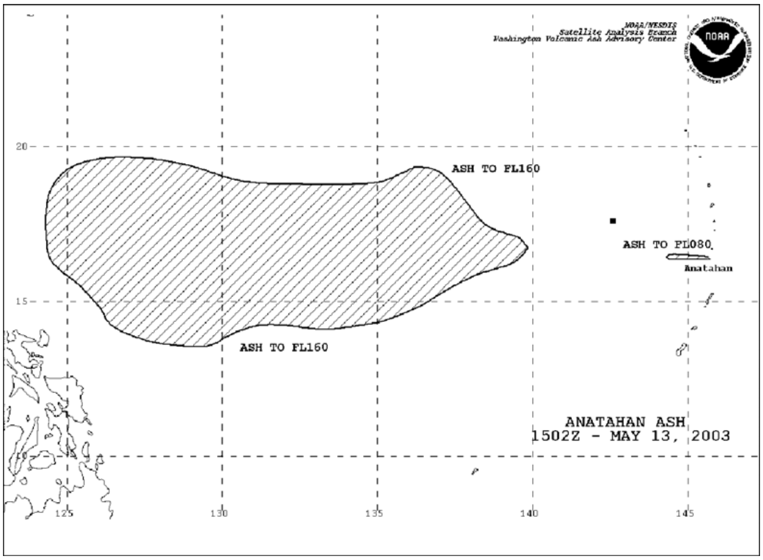


Fig. 4. Graphic accompanying the Volcanic Ash Advisory issued at 1600 UTC on 13 May 2003 (image at 1502 UTC) by the Washington Volcanic Ash Advisory Center. Hatched areas depict volcanic ash discernible on meteorological satellite visible-spectrum images. Approximate location of an aircraft during reported incident shown by small filled square.

Branch, http://code916.gsfc.nasa.gov) were examined to determine wind conditions in the region.

During the time from the eruption on 10 May to the incident on 13 May, winds exhibited strong vertical shearing and helped to define the cloud heights. Low-level winds (up to 2.5 km in altitude) were consistently 5–15 m/s to the west. High-level winds (~8.5–13 km in altitude) were, conversely, typically 5–20 m/s to the east. Winds from 2.5 to 8.5 km were consistently 5 m/s, but varied in direction to the northwest, southwest south, and southeast. At 1200 UTC on 13 May 2003 (close to the time of the incident), radiosonde data indicate winds were 5 m/s to the west up to 7.5 km altitude; between 8.5 and 13 km, winds were 15–20 m/s to the east.

The TOMS overpass timing was such that the first detection of the eruption was 0025 UTC on 11 May 2003. Anatahan itself was located in an “orbital gap.” (Earth Probe orbits do not cover the whole Earth each day, producing a ~500 km gap between orbital swath coverage at equatorial latitudes.) A small cloud was observed approximately 400 km off Anatahan to the southeast (Fig. 5). Both ash and SO_2 were detected in roughly coincident locations, extending east–west; a minimum SO_2 cloud mass was 30 kilotons. On 12 May, TOMS observed the ash and SO_2 clouds at 0115 UTC. The SO_2 cloud stretched in a northwest–southeast direction: from just west of the island to roughly 1200 km southeast from Anatahan. Radiosonde data are consistent with the cloud ranging in height from 5 km (NW) to 10–12 km (SE). The SO_2 cloud mass was determined to be 40 kilotons. In contrast, the ash cloud was confined to a smaller region, centered 600 km west of Anatahan. At this time, the eastern edge of the ash cloud was located very close to the eventual aircraft position but would had to have been at or below 5 km to be consistent with radiosonde data. By 0205 UTC on 13 May, the SO_2 cloud could not longer be detected by TOMS. The ash cloud had drifted west with its lagging (eastern) edge several hundred kilometers west of the incident point, still at approximately 5 km, well below the altitude of the aircraft. On 14 May, no evidence of ash was observed.

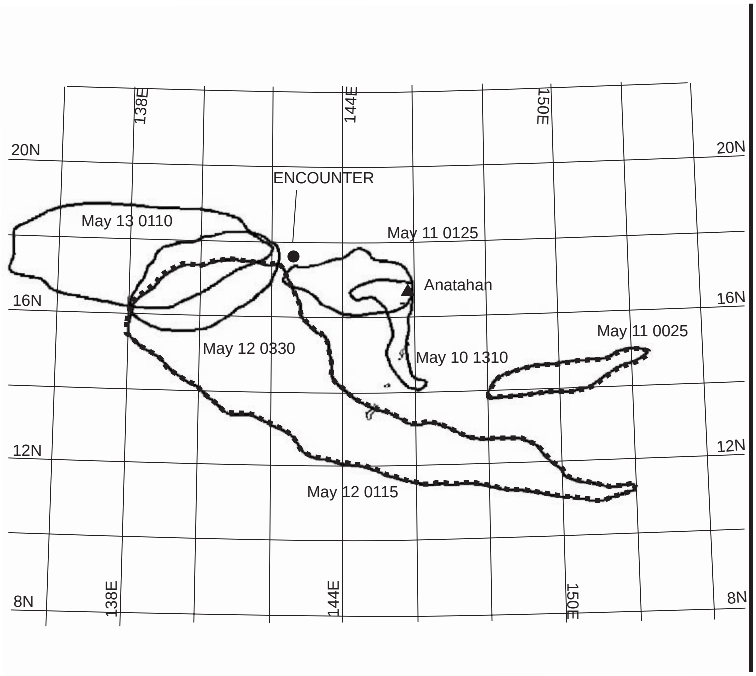


Fig. 5. Composite plot of boundaries of ash cloud (MODIS infrared bands 31–32; cloud outlines in solid line) and SO_2 cloud (TOMS ultraviolet data; cloud outlines in dashed line) with time, following the 10 May 2003 eruption of Anatahan. The composite clearly shows the physical separation of ash and gas components. Location of 13 May 2003 report of entry into volcanic gas shown by large dot.

The ash cloud was tracked by MODIS from the 10 May eruption to past the 13 May 2003 incident (Fig. 5). On images at 1310 and 1555 UTC on 10 May, the cloud was observed over Anatahan stretching in two distinct directions, 150 km to the west and 250 km to the south. Radiosonde data suggest the western portion was at or below 5 km and the southern lobe at 6–10 km. By 0125 UTC on 11 May, the southern portion of the cloud was no longer observable, and the only detectable ash cloud consisted of a west-trending plume from 142°E to 145.5°E at a height of roughly 5 km. By 1640 UTC on 11 May, the ash cloud stretched from 139°E to 144°E, still drifting to the west. By 0330 on 12 May, the cloud maintained the westward drift with the trailing edge now at 142°E. On 13 May, the 0110 UTC image showed the ash cloud as dispersed into many small portions between 132°E and 142°E. The 1205 UTC image revealed no ash signal in the vicinity of the incident. However, a low-altitude ash cloud was observed streaming several hundred kilometers west-southwest from Anatahan.

The 13 May 1205 UTC MODIS image also was examined for SO_2. In the vicinity of the reported incident, there were traces of (potential) SO_2; however, the levels were at near-background and could not be unambiguously discriminated from water vapor. Peak values of 10 DU (Dobson Units) were recorded; this corresponds to roughly 300 kg of SO_2 within a 1-km^2 MODIS pixel.

In summary, winds at the time of the 10 May 2003 eruption produced a strong vertical shearing, which separated different portions of the plume (Fig. 5). The high-level (~6–10 km) ash and gas drifted to the south at about 10 m/s (36 km/h), whereas the lower level (primarily 5 km and below) components were directed

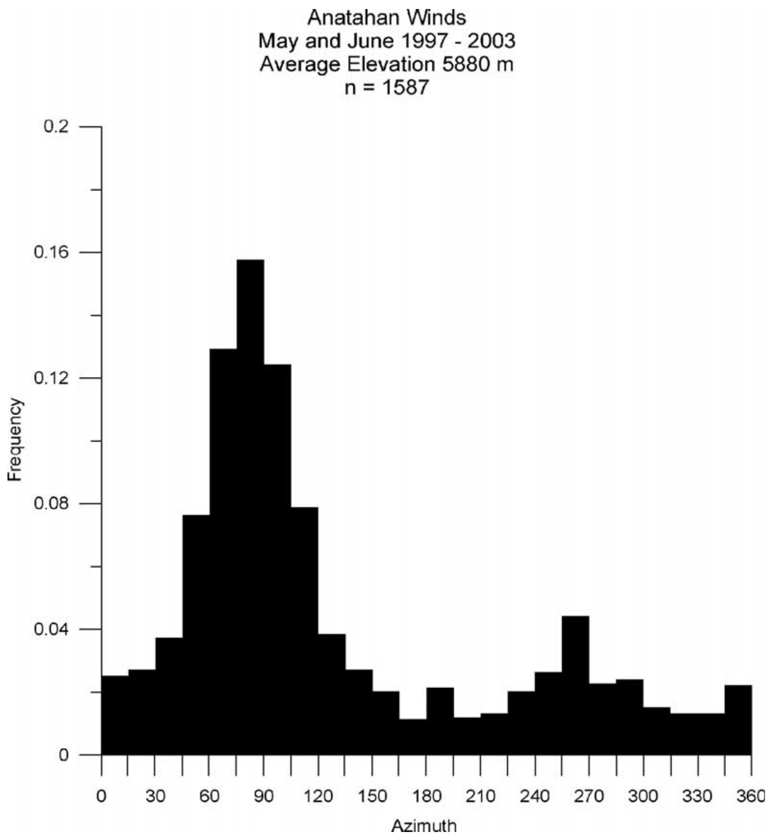


Fig. 6. Histogram of frequency of wind directions at an altitude of 5878 m in the region of the CNMI for the months of May and June for the years 1997–2003. (Wind data from NOAA Global Forecast System).

to the west, at approximately 5 m/s (18 km/h). The south lobe of the ash cloud dispersed rather quickly and was lost to satellite view after 24 h. The west lobe of the ash cloud continued to drift to the W at speeds of 5–15 m/s, expanded in area, and was observed to disperse after approximately 3 days after the eruption. The SO_2 cloud also appears to have been sheared in two directions and vertically separated, with the SO_2 plume diverging to both the south and west. In contrast to the ash, the bulk of the SO_2 must have been at higher altitudes and traveled to the south and east before dispersing below detection limits; thus, the ash-rich and gas-rich clouds became physically separated. Separation of ash and gas in volcanic clouds was first documented by Bluth et al. (1994) following the 1982 Galunggung eruption, and many cases of separation have since been observed. Low-level portions of the westward-drifting SO_2 plume were suggested, but not clearly defined, by the MODIS data in the vicinity of the incident on 13 May 2003.

The combination of satellite and wind data suggests that the ash components of the Anatahan cloud were unlikely to have interacted with the aircraft, which is consistent with crew observations and the outcome of no damage to the aircraft. In addition to TOMS and MODIS imagery that tracks the cloud components for several days, a MODIS satellite image of the region occurred only 15 min past the reported incident and provides a good evaluation of the cloud conditions. The ash at the aircraft altitude was clearly traveling in a different direction (south and southeast) and dispersed below detection in the area of the incident well before 13 May 2003. The ash cloud that was closest to the incident location was at or below 5 km and also had drifted westward past the location by 13 May.

The aircraft intersected some SO_2 component of Anatahan's eruption cloud, based on the fact that the crew smelled it. Although satellite evidence indicates the gas cloud had largely dispersed to near background levels, the human nose is much more sensitive to SO_2 than satellite sensors. The main portion of erupted SO_2 drifted to the south and southeast of Anatahan, out of the flight path. One possibility is that as the westward-drifting portion of the SO_2 cloud continued to rise (whereas ash particles settle gravitationally with time), the cloud could have been driven back towards Anatahan by higher level winds from the west. This would bring the remnants of the SO_2 cloud within the vicinity of the reported incident.

4.2. Analysis of airport disruptions

Because of seasonal wind patterns in the Marianas region, the disruption of airport operations well south of Anatahan at Saipan and Guam had a moderate likelihood of occurring during the eruption. Our analysis of the winds aloft from the period 1997–2003 (using data from the NOAA four-times-daily final run of the Global Forecast System) indicates that winds at 5.9 km altitude blew from the octant between 330° and 15° (i.e., toward Saipan and Guam) 9% of the time in the months of May and June (Fig. 6) and 27 days/year on average. In the same time period of 1997–2003, winds at 9700 m (jet cruise altitudes) blew toward Saipan and Guam 34 days/year on average.

At 0200 UTC on 23 May 2003, a U.S. Air Force "hurricane-hunter" aircraft reported seeing (but not entering) volcanic ash while on a reconnaissance mission into Tropical Cyclone 04W (Chan-Hom). That

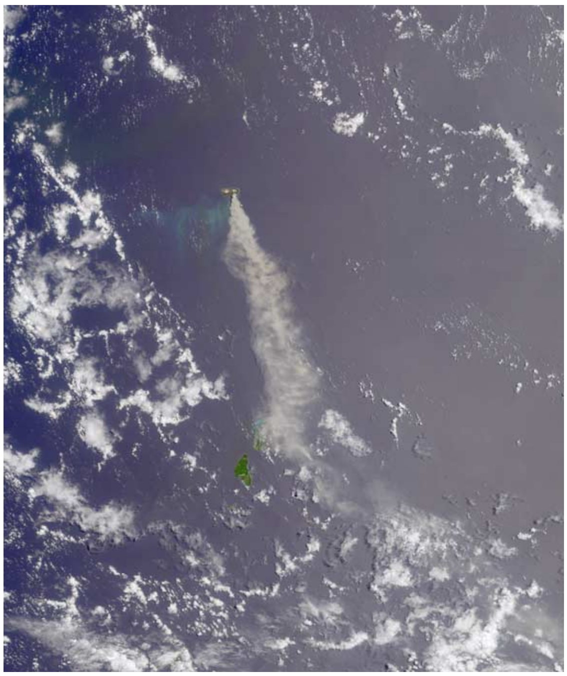


Fig. 7. MODIS visible-spectrum image of ash cloud from Anatahan on 23 May 2003. Ash cloud extends hundreds of kilometers south of Anatahan Volcano, over Saipan and past to Guam.

report indicated ash from the surface to 5.8 km (19,000 ft) drifting west-southwest. As the day progressed, winds became more northerly, and cyclone winds pushed ash from Anatahan south to Saipan and Guam (Fig. 7). The top of the ash cloud was estimated by the Washington VAAC to be 5.2 km (17,000 ft). The report from Saipan was that 1–2 mm of ash fell on the island. The light ashfall disrupted operations and caused six flight cancellations on 23 May 2003 at the international airports in Saipan and Guam (Wunderman, 2003). Normal airport operations commenced the following day. Worldwide, there have been numerous instances of airport disruptions and even closures after light ashfall from other eruptions (Guffanti et al., 2003).

5. Conclusions

The relatively remote location of the Northern Marianas volcanoes belies their potential hazards and economic impact both locally and internationally. The nine active subaerial volcanoes in the CNMI are upwind of heavily used commercial and military air routes that link Saipan and Guam to Asia and the rest of the Western Pacific, the source of much of the economic vigor of CNMI and Guam. North–south air routes linking North Asia with the Philippines, Australia, and New Zealand are also vulnerable to Northern Marianas' volcanic eruptions.

Even the relatively minor eruptive activity of Anatahan in 2003–2004 affected aviation operations in the Marianas region; flights were cancelled or rerouted on 2 days (10 and 23 May 2003), and a non-damaging high-altitude incident of an aircraft flying through volcanic gas on 13 May 2003 was documented. Operational monitoring of ash clouds produced by Anatahan has been conducted since the beginning of the eruption on 10 May 2003 by the Washington Volcanic Ash Advisory Center (VAAC). The many Volcanic Ash Advisories issued by the VAAC (323 as of 31 November 2004) have been a reliable source of ash-cloud information for air carriers and aviation-related meteorological offices.

More than 5 h elapsed from the onset of unexpected eruptive activity at Anatahan to the issuance of the first Volcanic Ash Advisory by the Washington VAAC. Had Anatahan been seismically monitored in real time before the start of eruptive activity, this delay could have been much shorter and dissemination of ash-hazard information to the aviation sector could have been more rapid. Moreover, the area was cloud-free during and after the eruption. As documented by Tupper et al. (2004) for recent eruptions in the Western Pacific, had there been a tropical storm in the area, the eruption could not have been detected by meteorological-satellite sensors for a much longer time. As it was, with no notification of airborne ash for several hours including the onset of darkness, the mitigation system to prevent encounters was weakened. Luckily, no damaging encounters appear to have occurred.

Satellite detection of ash and gas clouds is useful in evaluating the potential damage caused by aircraft encounters with volcanic clouds. In this case, analysis of satellite data strongly suggests that no significant ash and at most only minor amounts of SO_2 were involved in the 13 May 2003 incident, consistent with crew observations. This type of analysis may be economically useful to airlines when considering whether or not to service engines and other aircraft components after a reported encounter.

Since 1900, volcanoes in the CNMI have erupted every 3–5 years on average (Simkin and Siebert, 1994). Much larger eruptions than the Anatahan activity (to date) can happen in the Marianas. On 15 May 1981, Mount Pagan produced a large eruption with an ash column to more than 52,000 ft. Ashfall was reported on Saipan and Guam, up to 500 km south of the volcano, on the following day (Banks et al., 1984), and the ash cloud was trackable for 1000 km using single-band infrared images (Sawada, 1987). That eruption occurred before the effects of ash on aircraft and airports were widely recognized, and reports of disruptions to the air-traffic system do not seem to exist. If a similar event occurred at the present time, the effects on air travel in the Western Pacific would be wide ranging.

As of November 2004, only two of the volcanic islands in the CNMI have even rudimentary seismic monitoring, and the rest of the volcanoes are not instrumented, making early forecasts and warnings of eruptive activity virtually impossible. Continued satellite and expanded real-time seismic and other in situ monitoring is needed at Anatahan and other CNMI volcanoes so that potential hazards to aviation from any future eruptive activity can be quickly and correctly assessed.

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