# The 1991 Pinatubo Eruptions and Their Effects on Aircraft Operations

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## ABSTRACT

The explosive eruptions of Mount Pinatubo in June 1991 injected enormous clouds of volcanic ash and acid gases into the stratosphere to altitudes in excess of 100,000 feet. The largest ash cloud, from the June 15 eruption, was carried by upper level winds to the west and circled the globe in 22 days. The June 15 cloud spread laterally to cover a broad equatorial band from about 10°S. to 20° N. latitude and contaminated some of the world's busiest air traffic corridors. Sixteen damaging encounters were reported between jet aircraft and the drifting ash clouds from the June 12 and 15, 1991, eruptions. Three encounters occurred within 200 kilometers from the volcano with ash clouds less than 3 hours old. Twelve encounters occurred over Southeast Asia at distances of 720 to 1,740 kilometers west from the volcano when the ash cloud was between 12 and 24 hours old. Encounters with the Pinatubo ash cloud caused in-flight loss of power to one engine on each of two different aircraft. A total of 10 engines were damaged and replaced, including all four engines on a single jumbo jet. Following the 1991 eruptions, longer term damage to aircraft and engines related to volcanogenic $SO_2$ gas has been documented including crazing of acrylic airplane windows, premature fading of polyurethane paint on jetliners, and accumulation of sulfate deposits in engines.

Ash fall in the Philippines damaged aircraft on the ground and caused seven airports to close. Restoration of airport operations presented unique challenges, which were successfully met by officials at Manila International Airport and at Cubi Point Naval Air Station, Subic Bay. Lessons learned in these clean-up operations have broad applicability worldwide.

Between April 12 and June 9, 1991, Philippine aviation authorities issued at least eight aeronautical information notices about the preeruption restless state of Mount Pinatubo. The large number of aircraft affected by the Pinatubo ash clouds indicates that this information either did not reach appropriate officials or that the pilots, air traffic controllers, and flight dispatchers who received this information were not sufficiently educated about the volcanic ash hazard to know what to do with the information.

**Note to readers:** Figures open in separate windows. To return to the text, close the figure's window or bring the text window to the front.

## INTRODUCTION

Jet aircraft are damaged when they fly through clouds containing finely fragmented rock debris and acid gases produced by explosive volcanic eruptions (Casadevall, 1992). Clouds of volcanic ash and corrosive gases cannot be detected by weather radar currently carried aboard airplanes, and such clouds are difficult to distinguish visually from meteorological clouds. In the past 15 years, there have been more than 80 in-flight encounters between volcanic ash clouds and commercial jet aircraft.

The explosive eruptions of Mount Pinatubo volcano in the Philippines in June 1991 injected enormous clouds of volcanic ash and gases into the stratosphere to altitudes in excess of 100,000 ft. Within several days of the June eruptions, at least 16 commercial jet airplanes had been damaged by in-flight encounters with the drifting ash clouds from Pinatubo. Closer to the volcano, ash fall in the Philippines damaged about two dozen aircraft on the ground and affected seven airports. This report describes the effects of the 1991 Pinatubo eruptions on aircraft and airports, seeks to understand why so many encounters occurred, and reviews the solutions to the ash-cloud hazard reached by Philippine authorities.

# THE 1991 ERUPTIONS

From June 12 to 16, 1991, Mount Pinatubo erupted at least 16 times to produce eruption columns that penetrated the tropopause at an altitude of 53,000 ft and entered the stratosphere (Wolfe and Hoblitt, this volume). These eruptions were detected by visual observations, seismic recordings, and barograph records and weather radar observations at Clark Air Base and Cubi Point Naval Air Station. Upper level winds generally carried ash from the volcano to the west and southwest (Oswalt and others, this volume), contaminating airspace in the Hong Kong, Bangkok, Ho Chi Minh, and Singapore Flight Information Regions.

Through July 1991, eruptions from the crater were less frequent and of decreasing vigor. However, beginning late in July 1991 and continuing at least throughout 1994, smaller, secondary explosions began to occur from sites on the slopes of the volcano. Heating of rainwater through contact with the still-hot deposits of pyroclastic material from the June 1991 eruption caused steam explosions that produced ash clouds to 60,000 ft in altitude. Unlike the magmatic eruptions in June 1991 for which pre-eruption warnings could be given (Harlow and others, this volume), secondary explosions took place with no precursory seismic activity.

The first large ash-producing eruption of Mount Pinatubo took place at 0851 local time (0051 G.m.t.) on June 12, 1991. Analysis of satellite images indicates that the ash cloud from the June 12 eruption was carried by upper level winds at speeds of approximately 15 to 20 m/s along a heading of 215° from the volcano (Potts, 1993), into the airspace west of Manila. At least three aircraft flew into this ash cloud (table 1). The first aircraft encounter was on June 12, 1991, at 1220 local (0420 G.m.t.) at a site approximately 170 km southwest of the volcano (fig. 1). The second encounter took place at 1630 local (0830 G.m.t.) and occurred at a site approximately 1,000 km west of the volcano (fig. 1). The position of the third encounter is unknown. While these encounters were reported in the national and international news media, the gravity of the volcanic threat to aviation safety was not fully appreciated until the days after the June 15 eruption.

Figure 1. Location of positions of encounters between jet airplanes and the ash clouds from the June 1991 eruptions of Mount Pinatubo. Numbers indicate incidents listed in table 1.

The most powerful eruptions and the largest ash clouds from Pinatubo were on June 15 (Koyaguchi and Tokuno, 1993; Wolfe and Hoblitt, this volume). The patterns of ash dispersion of these clouds were complicated by the passage of Typhoon Yunya (Oswalt and others, this volume). Under normal weather conditions for the season, ash would have moved to the west-southwest. However, counterclockwise winds associated with the typhoon forced the proximal ash cloud to the south and over the Olongapo-Subic Bay area (Paladio-Melosantos and others, this volume). The heavy tropical rainfall associated with the typhoon saturated the ash as it fell, and loading of airport hangars and facilities with water-saturated ash caused extensive damage to facilities at Cubi Point, Clark, and Basa airports (fig. 2) (see fig. 4 in Casadevall, 1992).

Figure 2. Airports in the Manila area affected by ash from the June 15, 1991, eruptions of Mount Pinatubo.

A large mass of the June 15 ash was injected to altitudes above the influence of Typhoon Yunya. The June 15 cloud was carried by upper level winds to the west and circled the globe in approximately 22 days. This cloud spread longitudinally to cover a broad equatorial band from about 10° S. to 20° N. lat, contaminating some of the world's busiest air traffic corridors in the Southeast Asia region. At least 13 aircraft flew into the ash cloud from the June 15 eruption (table 1). Movement of the June ash cloud was detected by the Japanese geostationary meteorological satellite (GMS) (Tanaka and others, 1991; Tokuno, 1991; Potts, 1993; Koyaguchi, this volume); by the total ozone mapping spectrometer (TOMS) aboard the Nimbus-7 polar-orbiting satellite (Bluth and others, 1992); and by the advanced very high resolution radiometer (AVHRR) aboard the NOAA-10 and -11 polar-orbiting satellite (Schneider and Rose, 1992; Potts, 1993; Lynch and Stephens, this volume). Observations of the eruptions from these satellites were important for detecting and tracking the ash clouds. The relevance of these observations to aviation operations is reviewed here.

Table 1. Encounters between aircraft and volcanic ash clouds from June 1991 eruptions of Pinatubo.

[uk, unknown; na, not applicable; EGT, exhaust gas temperature; all latitudes are north and all longitudes are east]

| Incident number | Date | Time (G.m.t.)[1] | Location | Latitude | Longitude | Altitude (feet) | Aircraft type | Comments |
|---|---|---|---|---|---|---|---|---|
| 91-01 | 6/12/91 | 0420 | 170 km from volcano; 60 nautical miles from LUBANG along air route B460. | 14°00' | 119°30' | 37,000 | 747-300 | During a 3-min encounter with volcanic ash, crew experienced thin haze inside aircraft that smelled like a burning electrical wire. Aircraft landed safely at Manila Airport. Aircraft and engines were inspected and serviced at Manila in accordance with recommended procedures. When aircraft attempted to depart, its four engines had a strong vibration, and aircraft was grounded at Manila for detailed maintenance and replacement of all four engines. |
| 91-02 | 6/12/91 | uk | 720 km west of volcano on route from Singapore to Tokyo. | 13°50' | 113°50' | 37,000 | 747-400 | No significant damage to aircraft when inspected on ground in Tokyo. |
| 91-03 | 6/12/91 | 1630 | Approx. 1,000 km from volcano; between way points ADPIM and | 11°10' | 112°10' | 33,000 | DC-10 series 40 | Flight from Kuala Lumpur to Tokyo; observed a discharge phenomena on windshield for 20 min. Ground inspection at Narita revealed no |

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| | | | LAVEN. | | | | | damage. Encounters 3 and 11 involved same aircraft. |
| 91-04 | 6/15/91 | 1740 | Approx. 1,150 km from volcano; between way points SUKAR and CAVOI. | 13°10' | 110°50' | 29,000 | 747-400 | Aircraft encountered ash cloud at 29,000 ft at approximately 600 nm west of volcano. Crew observed St. Elmo's fire on the windshield and a scent similar to an electrical fire in the cockpit for 6 to 8 min as they went through the ash. There was no abnormal indication in the cockpit. The crew observed a green echo, which seemed to be ash on weather radar, but it disappeared when they were clear of the ash. Flight attendants reported thin (whitish) fog in the cabin, most dense in the upper deck compartment, followed by the forward cabin. The flight was continued to Tokyo, where engine inspection revealed that all four engines were damaged and were replaced. First-stage nozzle guide vane cooling air holes were 70-80% blocked. Other damage occurred to the cockpit windows, cabin windows, Pitot static probes, landing light covers, navigation lights, and all leading edge areas. |
| 91-05 | 6/15/91 | 1547 | Over Vietnam on route from Hong Kong to Singapore; in Bangkok FIR. | 13°00' | 108°00' | uk | 747-SP | Ash and sulfur odor, electrostatic discharge, blue-green light over Vietnam. Ground inspection revealed no significant damage, and aircraft continued in service. |
| 91-06 | 6/15/91 | uk | uk | uk | uk | uk | 747-200 freighter | Aircraft flew through "heavy volcanic ash." Cockpit and cabin areas were contaminated with volcanic ash. No additional information available. |
| 91-07 | 6/15/91 | uk | Route between Tokyo and Singapore. | uk | uk | 35,000 | 747-251 | Flight from Narita to Singapore was rerouted to Manila due to weather in Singapore area. En route to Manila, |

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| | | | | | | | | encountered volcanic ash cloud at 35,000 ft for approximately 12 min and was then diverted to Taipei. Engines set at cruise. Sparks were noted coming from windows and Crew reported hearing ash hit the aircraft. EGT for all four engines rose 40-50°C and started to fluctuate. One hour later all EGTs were back to normal. Ground inspection in Taipei revealed no significant damage to exterior or to engines. Aircraft continued in service. |
| 91-08 | 6/15/91 | uk | <200 km from volcano; on approach to Manila from south. | uk | uk | uk | DC-10 series 30 | Flight from Sydney to Manila encountered ash on approach to Manila from south. Engines set at low power but found to contain "lots of ash" when inspected after landing. Exterior abrasion visible, including engine cowls. |
| 91-09 | 6/15/91 | uk | Route between Singapore and Osaka. | uk | uk | uk | 747-300 | Aircraft was in ash cloud for 29 min while en route from Singapore to Osaka. Date of encounter uncertain, probably 6/15; one report indicates 6/19. Inspection of aircraft exterior showed no significant damage. Engines #1 and #4 were replaced; "90% of the first-stage turbine blades have bullseyes on the airfoil's mid-span pressure side and some first-stage vane leading edge ash buildup at 3 o'clock position." |

Table 1. Encounters between aircraft and volcanic ash clouds from June 1991 eruptions of Pinatubo--Continued.

| Incident number | Date | Time (G.m.t.)[1] | Location | Latitude | Longitude | Altitude (feet) | Aircraft type | Comments |
|---|---|---|---|---|---|---|---|---|
| 91-10 | 6/15/91 | 1545 | Route between Hong Kong and Mauritius. | uk | uk | 31,000 | 747-200B | Incident 91-10 involved same aircraft as incident 91-16. |
| 91-11 | 6/15/91 | 1730 | Approx. 1,050 km from | 15°15' | 110°30' | 29,000 | DC-10 series 40 | Flight from Kuala Lumpur to Tokyo; |

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| | | | volcano; between way points SUKAR and CAVOI, 120 nautical miles from CAVOI. | | | | | observed a discharge phenomena on windshield for 25 min. Ground inspection at Narita revealed no damage. Encounters 3 and 11 involved same aircraft. |
| 91-12 | 6/15/91 | 1910 | Approx. 1,050 km from volcano; between way points SUKAR and CAVOI, 120 nautical miles from CAVOI. | 15°15' | 110°30' | 29,000 | DC-10 series 40 | Flight from Singapore to Osaka; crew observed a discharge phenomena on windshield for 30 min. Ground inspection at Narita revealed no damage. |
| 91-13 | 6/15/91 | 0910 | Approx. 100 km from volcano; flight from Manila to Hong Kong. | uk | uk | uk | 747-428 | After takeoff from Manila, airplane skirted a volcanic ash cloud. On the ground in Hong Kong, black marks were noted on the exterior of the left wing. Engines were borescoped and no discrepancies were found. Airplane continued to Delhi. Preparing to leave Delhi, unable to start engine #1. Fuel pump was replaced and additional inspections of airplane revealed no damage. Airplane continued to Paris. |
| 91-14 | 6/16/91 | uk | Route between Kuala Lumpur and Kota Kinabalu. | uk | uk | uk | 737-200 freighter | Indications that aircraft flew through volcanic ash cloud were apparent only after aircraft underwent ground inspection in Kuala Lumpur, which revealed abrasion of plexiglass landing light covers and navigation lights, which were totally opaque. Cowling intakes were abraded and rough to the touch, while compressor blades were remarkably clean. Landing gear bays were covered in ash with ash sticking to oily surfaces. No apparent damage to windshields. |
| 91-15 | 6/17/91 (?) | uk | Flight likely on Tokyo to Singapore | uk | uk | uk | DC-10 | Airplane reportedly encountered ash from Pinatubo on June 17. #3 |

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| | | | route. | | | | | engine was reported to have been shut down in flight; ash encounter may have caused in-flight shutdown. Inspection of engines revealed "heavy deposits" of what was presumed to be volcanic ash. No information about flight route, encounter duration, and such. |
| 91-16 | 6/17/91 | 0412 | 930 km from volcano; 50 nautical miles east of way point IDOSI on route A901. | 19°30' | 112°40' | 37,000 | 747-200B | Flight from Johannesburg to Taipei via Mauritius. Encounter occurred at 37,000 ft 50 nm east of way point IDOSI on route A901; entered a cloud at 0412 G.m.t.; temperature increased from -48°C to -37°C in 2 min; aircraft descended to 29,000 ft and landed at 0540 G.m.t.; engine #1 surged and was shut down; engine #4 lost power; descended to 29,000 ft to restart #1. Aircraft landed safely at Taipei. Service terminated. Engine #1 replaced and aircraft returned to South Africa on 6/21 for further inspection. |
| 91-17 | 6/15/91 | na | Aircraft on ground at Manila International Airport. | 14°30' | 121°00' | On ground | L-1011 | Maintenance crew attempted to remove volcanic ash from window by using wiper blades. Resulted in abrasion of windows, which required replacement. |
| 91-18 | 6/15/91 | na | Aircraft on ground at Cubi Point Naval Air Station. | 14°47' | 120°16' | On ground | DC-10 series 30 | Aircraft landed at Cubi Point Naval Air Station on June 14, 1991, just prior to start of major eruption. Up to 6 in of ash accumulated on aircraft, including wings and horizontal stabilizer, and caused it to tilt back on the tail. Weight of ash was approximately 32 $lb/ft^2$. Aircraft suffered some damage to exterior of tail fuselage, rear pressure bulkhead, and |

APU compartment. See figure 6.

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[1] Add 8 h to G.m.t. to attain local time in the Philippines.

## GEOSTATIONARY METEOROLOGICAL SATELLITE (GMS) OBSERVATIONS

Visible and infrared imagery from the GMS satellite allowed scientists to track the development of the June 15 ash cloud in images made hourly (Tokuno, 1991). Figure 3 shows the development of the ash cloud from the cataclysmic June 15 eruption and the position of the leading edge of the cloud at 3-h intervals. The cloud advanced to the west and south-southwest, in two principal lobes with headings of 250° and 210°. The advance rates for both lobes was approximately 26 m/s averaged over the 24 h after the cataclysmic eruption.

Figure 3. Shape and position of leading edge at 3-h intervals of Pinatubo ash cloud from June 15, 1991, eruptions. Data from GMS-4 visible band (modified from Tokuno, 1991).

An important feature of the GMS imagery was its immediate availability and ease of interpretation. This permitted prompt mapping of the outline and westward advance of the cloud in near real-time. Using this GMS imagery on June 15-16, 1991, meteorologists of NOAA's Synoptic Analysis Branch (SAB) issued frequent bulletins about the location and movement of the Pinatubo ash clouds to the Federal Aviation Administration (FAA) and to the United States Geological Survey (USGS) (Lynch and Stephens, this volume). This information was used on June 15 and 16 in discussions with flight dispatchers to track the position of the cloud and to verify pilot suspicions about encounters between jetliners and the ash cloud over the South China Sea and Vietnam.

## TOTAL OZONE MAPPING SPECTROMETER (TOMS) OBSERVATIONS

The total ozone mapping spectrometer detected the $SO_2$ gas contained in the Pinatubo cloud, and data from TOMS were used to map the movement of the cloud (Bluth and others, 1992). However, unlike the GMS imagery, which is available hourly, TOMS data are available only once daily and require extensive computational processing before interpretation is possible.

The leading edge of the $SO_2$-rich cloud from the June 15-16 eruption, moved in a westerly direction (265°) at approximately 35 m/s, while the axis of the highest density portion of the $SO_2$ cloud was more southwesterly (250°) and moved at approximately 26 m/s (Bluth and others, 1992). The main mass of the $SO_2$ cloud was approximately coincident with the southwest (250°) lobe of the June 15 cloud as detected by GMS observations. The absence of detectable $SO_2$ in the area of the south-southwest (210°) lobe seen on the GMS imagery may reflect masking of the this portion of the cloud by the ash or by higher water vapor content in the troposphere.

The $SO_2$ content of the June 15 cloud was approximately 20 Mt, the largest mass of $SO_2$ erupted by a volcano since the start of TOMS observations in 1978 and more than 3 times larger than mass of $SO_2$ from the eruption of El Chichón Volcano, Mexico, in 1982 (Bluth and others, 1992). Most of the $SO_2$ from Pinatubo was injected into the stratosphere, where some portion is still detectable through June 1994.

## ADVANCED VERY HIGH RESOLUTION RADIOMETER (AVHRR) OBSERVATIONS

Multispectral digital imagery from the advanced very high resolution radiometer provides imagery of the Southeast Asia region about every 4 h. AVHRR data have been used previously to discriminate volcanic clouds from meteorological clouds (Prata, 1989; Holasek and Rose, 1991; Wen and Rose; 1994; Schneider and Rose, 1994; Schneider and others, in press). Volcanic clouds can be distinguished from meteorological clouds by calculating an apparent brightness temperature difference ($\Delta T$) between corrected temperature values derived from band 4 (10.5-11.3 µm) and band 5 (11.5-12.5 µm) of the AVHRR. Volcanic clouds and dust clouds have negative band 4 minus band 5 $\Delta T$ values (Prata, 1989), while meteorological clouds have positive $\Delta T$ values (Yamanouchi and others, 1987). Young volcanic clouds that contain large amounts of water and ice are spectrally similar to meteorological clouds (positive $\Delta T$). As the ash cloud ages and disperses, it develops a fringe of negative $\Delta T$ values that extend to the entire volcanic cloud as it continues to dry out (Schneider and others, in press). Two examples demonstrate the method as applied to Pinatubo clouds.

Figure 4 is an AVHRR band 4 thermal image collected by NOAA-10 on June 14, 1991, at 0729 local (2329 G.m.t.), about 18 h before aircraft encounter 91-04. The image shows the top of a circular ash cloud overlying meteorological clouds associated with Typhoon Yunya and also shows diffuse clouds extending from the circular cloud westward toward the coastline of Vietnam. Comparison between the location of the ash cloud, as determined by AVHRR, and the $SO_2$ cloud measured by TOMS at 1145 local 0345 (G.m.t.) on June 15, 1991 (Bluth and others, 1992), shows a strong correlation (Schneider and Rose, 1992) and suggests that these diffuse clouds are of volcanic origin.

Figure 4. Band 4 thermal AVHRR image collected by NOAA-10 on June 14, 1991 at 2329 G.m.t. (0729 local), more than 18 h before aircraft encounter 91-04 (table 1). Image shows a circular eruption cloud overlying meteorological clouds associated with Typhoon Yunya and diffuse clouds extending from the circular cloud westward toward the coastline of Vietnam.

An image collected on June 16, 1991, at 1451 local (0651 G.m.t.), following the climactic eruption (fig. 5A) shows a large cloud mass extending from the Philippines, southwest to the island of Borneo, and west to the Malay Peninsula. By this time, at least eight additional aircraft had flow into the ash cloud (table 1). The apparent $\Delta T$ image (fig. 5B) clearly defines a fringe of negative $\Delta T$ values that we interpret to be the edge of the volcanic cloud. The interior of this cloud shows positive $\Delta T$ and is spectrally similar to meteorological clouds, owing to both the large droplet size and the large amount of water incorporated into the cloud during eruption. These results demonstrate that a simple technique can be used to define the limits of a very large volcanic cloud. In fact, the technique is apparently more sensitive for dispersed regions of the cloud such as the edges than for the dense interior.

Figure 5A. Band 4 thermal AVHRR image collected by NOAA-11 on June 16, 1991, at 0652 G.m.t. (1452 local), following the climactic eruption, shows a large cloud mass extending from the Philippines southwest to the island of Borneo and west to the Malay Peninsula.

Figure 5B. Apparent brightness temperature difference image clearly defines a fringe of negative temperature difference values, which we interpret to be the edge of the volcanic cloud. The interior of this cloud shows positive temperature difference and is spectrally similar to meteorological clouds, owing to the large amount of water incorporated into the cloud during eruption.

As with the TOMS data, AVHRR imagery must be processed prior to interpretation. Current research aims to reduce the processing time in order to make AVHRR imagery useful for operational applications such as defining the extent and movement of volcanic ash clouds (Potts, 1993; Schneider and Rose, in press) and determining the range of particle sizes and concentrations in the cloud (Wen and Rose, 1994).

## AIRCRAFT ENCOUNTERS WITH ASH

At least 20 commercial jet aircraft were involved in incidents related to volcanic ash from the June 1991 eruptions. Sixteen in-flight encounters occurred between June 12 and 18; at least two encounters involved loss of engine power. In addition to the numerous in-flight encounters, about two dozen airplanes on the ground in the Philippines were also damaged by Pinatubo ash (fig. 6).

Figure 6. DC-10 jumbo jet on the ground at Cubi Point Naval Air Station. (U.S. Navy photograph by R. L. Rieger.)

The costs associated with these incidents are difficult to determine and include direct costs from damage to aircraft in the air and on the ground, delays, cancellations, and rerouting of flights, and closure and clean-up efforts at airports. A figure widely discussed in Manila in 1991 is that costs to aviation, including repair of aircraft damaged in flight, exceeded $100 million (P. Pacete, Manila Airport Operators' Council, oral commun., 1991). This figure does not include the costs of airport repair and cleanup for Manila International Airport and for Clark, Cubi Point, Basa, and Sangley Point military airports. Nor does this figure include costs associated with damages related to the gas cloud such as crazing of acrylic windows, fading of exterior paint, and accumulation of sulfate deposits in engines.

Table 1 summarizes information available to us about the timing and location of each encounter, as well as information about the nature of the encounter and the damage to the airplane. These data are important in efforts to correlate information about the nature and timing of encounters with information about cloud movement and position determined from analysis of satellite images and from cloud trajectory forecasts. Information for table 1 is from many sources including airline companies, engine and airframe manufacturers, and reports from pilots. The detail of information was variable, especially concerning the locations of encounters and damage. In some cases, carriers were reluctant to discuss encounters, owing to concerns over possible future liability. In other cases, pilots may have been unaware that their aircraft had flown through an ash cloud, and damage to the aircraft might not have been noticed until the aircraft was later inspected on the ground. This partly explains why there are position data for only 11 of the incidents (fig. 1; table 1).

Three encounters occurred within the Manila Flight Information Region (FIR) within 200 km from the volcano (fig. 1). Seven of the eleven encounters occurred within the Hong Kong FIR to the west of Manila at distances of 720 to 1,150 km from the volcano (fig. 1). At least four additional encounters were along Tokyo-Singapore and Hong Kong-Singapore routes and likely were within the Hong Kong FIR. One encounter occurred over Vietnam in the airspace controlled by the Bangkok FIR. One encounter occurred between Kuala Lumpur, Malaysia, and Kota Kinabalu, Sabah, Malaysia.

## DAMAGE

When a jetliner flying in excess of 400 knots (740 km/h) enters a cloud of finely fragmented rock particles, the principal damage will be abrasion of the exterior, forward-facing surfaces and accumulation of ash into surface openings (Casadevall, 1992). An example of the exterior damage to one jumbo jet after an encounter with a Pinatubo ash cloud is shown schematically in figure 7. Ingestion of ash into the engines will cause abrasion damage, especially to compressor fan blades. Because jet engines operate at temperatures in excess of 700°C, melting of ash and accumulation of this ash in the turbine section is an important problem as well (Przedpelski and Casadevall, 1994). Remelted ash may block the passage of air through the engines and cause the engine to stop. In an least one airplane (incident 91-04 in table 1), first-stage nozzle guide vane cooling holes were 70 to 80 percent blocked.

Figure 7. Damage to exterior surfaces of a 747-400 jumbo jet following an encounter with the June 15, 1991, ash cloud from Mount Pinatubo.

The majority of the Pinatubo encounters occurred at distances of up to 2,000 km from the volcano with an ash cloud that was at least 12 h old. The aging of the ash cloud allowed the coarser ash to settle from the cloud and prevented some of the more severe damage such as that which occurred to jumbo-jet aircraft from earlier encounters with volcanic ash (Smith, 1983; Tootell, 1985; and Casadevall, 1994). In the Pinatubo case, there were few reports of abrasion of forward-facing cabin windows, so it is suggested that particles larger than about 30 μm in diameter had already settled from the cloud. Particles smaller than this diameter are efficiently swept over the window surface by the slipstream and do not impact the window surface (Pieri and Oeding, 1991).

Longer term damage related primarily to the $SO_2$ gas and sulfuric acid aerosols produced by the eruption (Self and others, this volume) did not become apparent until months after the eruption. Some Asian-based carriers noted that jet engines on their airplanes have accumulated deposits of sulfate minerals such as anhydrite and gypsum in the turbine. This material blocked cooling holes in the first-stage nozzle guide vane at the inlet to the turbine section of the engine and thereby interfered with the cooling of the turbine. As a result, engines overheated. The sulfate deposits found in the turbine section appear to be related to ingestion and oxidation of $SO_2$ and sulfuric acid aerosols that originated in the Pinatubo eruption clouds of June 15 (Casadevall and Rye, 1994).

Additional problems related to the acidic aerosols include the increased incidence of crazing of acrylic windows (Berner, 1993) and fading of polyurethane paint on jetliners (T.M. Murray, Boeing, written commun., 1993). Unlike the circumstances involving in-flight encounters with the ash clouds, which were largely restricted to the region west of the volcano, the gas cloud from Pinatubo has been widely dispersed throughout the Northern Hemisphere and has thereby affected aircraft that fly in this airspace. A similar increase in the incidence of window crazing was observed for several years following the eruptions of El Chichón Volcano in 1982 (Rogers, 1984; 1985; Bernard and Rose, 1990). Pinatubo erupted nearly 3 times more $SO_2$ than did El Chichón (Bluth and others, 1992). Thus, the types of problems related to volcanogenic sulfur gas and sulfuric acid aerosols may be expected to persist longer following the Pinatubo activity than after El Chichón.

In addition to the airplanes that encountered the ash cloud while in flight, about two dozen airplanes were caught unprotected on the ground by the June 15 ash fall. Advance warning of the eruption enabled U.S. Air Force officials to evacuate jet aircraft from Clark Air Base (fig. 2) before the first explosive eruption on June 12. However, a squadron of 11 obsolete F-5 jets of the Philippine Air Force parked at Basa Air Base was covered by ash from the June 15 eruption.

At Cubi Point Naval Air Station (fig. 2) one C-130 transport, one C-141 transport, and one DC-10 cargo jet (fig. 6) were covered by 15 to 20 cm of ash from the June 15-16 eruptions. The accumulation of water-saturated ash on the wings, horizontal stabilizers, and fuselages of these aircraft caused two of the aircraft to rotate back on their tails. The water-saturated ash on the DC-10 weighed approximately 32 $lb/ft^2$ (R. Rieger, U.S. Navy, oral commun., 1991). The DC-10 suffered minor damage to the tail fuselage, the rear pressure bulkhead, and the auxiliary power unit compartment.

In Manila, at least eight jumbo-jet passenger airplanes were on the ground during the June 15-16 ash fall. Because of ash on the runways, these aircraft could not depart until June 19. Fortunately, ash fall in Manila was relatively light (< 0.5 cm). Since hangar space was limited, most aircraft were adequately protected by plastic sheeting and duct tape placed over windows and openings in the aircraft surfaces and engines. Windshields on several aircraft were abraded when window wipers were used to remove ash.

# AIRPORTS

Ash from the June 15-16, 1991, eruption caused the closing of civilian airports at Manila, Puerto Princesa, and Legaspi and military airfields at Clark Air Base, Basa Air Base, Sangley Point Air Base, and Cubi Point Naval Air Station (fig. 2). At Manila's Ninoy Aquino International Airport (NAIA) and Sangley Point Air Base, between 0.5 and 1 cm of fine sand to powder-size ash fell in a mostly dry condition on June 15-16, 1991. This ash caused these airports to close for 4 days until ash could be removed from runways, taxiways, and apron surfaces (Casadevall, 1993). Normal operations at NAIA resumed on July 4, 1991.

Volcanic ash on airport surfaces caused reduced visibility and affected aircraft maneuvering, especially when the ash was wet. Ash on airport surfaces was ingested into engines during taxiing, takeoffs, and landings and also contaminated landing gear assemblies and brakes. Ash fall from a minor eruption on July 17, 1991, deposited less than 1 mm of ash over the Manila area, and NAIA was closed for ash removal from 1700 on July 17 through 1900 on July 18. While landing on July 19, one jumbo jet skidded off the runway because of reduced braking action on wet ash.

The principal damage to airport surfaces and buildings at Clark, Cubi Point, and Basa was caused by the accumulation of from 15 to 20 cm of water-saturated sand to fine gravel-size ash. The weight of the wet ash, combined with the ground shaking from the earthquakes during June 15, led to the collapse of a large number of airport buildings including hangars at Clark, Cubi Point, and Basa (see fig. 4 in Casadevall, 1992). Buildings that remained standing were usually those from which ash was removed as it fell (B. Wood, U.S. Navy, oral commun., 1991). Acidic gases adsorbed to the wet ash formed $H_2SO_4$, which corroded metal-roofed buildings, airport electrical systems, ground service equipment, and aircraft that were not properly cleaned immediately after the ash fall (C.M. Navarro, Philippine Airlines, oral commun., 1992). The dried ash hardened to a concretelike consistency that made subsequent removal more difficult and costly.

## AIRPORT CLEANUP

Airport officials in the Philippines tried a variety of techniques to remove and dispose of volcanic ash. The principal problem was that winds continually resuspended the ash and recontaminated previously cleaned surfaces. The first attempts at NAIA on June 16 to remove the ash utilized a vacuum sweeper and pressurized water. This method left some ash that was resuspended by wind after it dried. Manual sweeping of the runway and taxiway surfaces to accumulate the ash into furrows was finally settled on as the most effective method of ash removal. The furrows of ash accumulated at the edges of runways and taxiways were either collected into bags for removal and disposal or were stabilized by covering with emulsified asphalt, which acted as a binder for the ash. The emulsified asphalt was also sprayed on ash-covered infield areas adjacent to runways, taxiways, and aprons and proved to be the most effective method for restoring airport surfaces to safe operation. Ash removal proceeded in a stepwise manner that focused first on the main runway and taxiways. Once these were cleared, aircraft were towed to and from the runway in order to prevent resuspension of ash by airplane engines.

The greater thickness of ash (15 to 20 cm) in the Olongapo-Subic Bay area required a more intensive effort for ash removal at Cubi Point NAS. Officials at Cubi Point took an aggressive approach to ash removal and utilized a contingent of 1,800 personnel and a full complement of earth-moving equipment of a U.S. Navy Construction Battalion (Seabees) that was in Subic Bay in transit to the U.S.A. from Operation Desert Storm. After experimentation with sweepers and washing, officials settled on a procedure similar to that used at NAIA, where road graders scraped ash into furrows. The accumulated ash was loaded into dump trucks and dumped at the southwest edge of the runway in a designated landfill. The scraping-loading-dumping operation still left a residue of fine ash on the runway surface which was swept and washed onto the grass infield and covered with emulsified asphalt. Partial operations were restored at Cubi Point NAS by June 26, 1991, but ash removal activities continued through 1991. Clark and Basa reopened for limited operations in 1992. However, at Clark, ash falls from secondary explosions have repeatedly closed down even limited operations. Ash from the secondary explosions has rarely affected Cubi Point.

# COMMUNICATIONS

Prior to the 1991 eruptions of Pinatubo, there had been no encounters between airplanes and ash clouds in Philippine airspace. During the eruptions of the Philippine volcano Mayon in 1984, the Philippine Bureau of Air Transportation (now the Air Transportation Office) developed Air Traffic Section procedure order 3-84 for dealing with the hazard of ash clouds. Procedure 3-84 specified that communication of information about volcanic activity was to be coordinated with the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and that aeronautical information to pilots and contingency flight routing to bypass areas affected by volcanic ash would be coordinated through the Manila Area Control Center (ACC). These procedures formed the basis for procedures implemented during the Pinatubo emergency. The Manila Flight Information Region (FIR) encompasses Luzon Island and extends for approximately 750 km to the west and borders the Hong Kong, Bangkok, and Ho Chi Minh Flight Information Regions. Control of air traffic and communications with aircraft within the Manila FIR is handled by the Manila ACC.

By international agreement, information about conditions that pilots might encounter while flying is supplied by use of aeronautical information notices known as NOTAMs and meteorological information notices known as SIGMETs. These are issued by authorities in the ACC and are passed by teletype to air traffic controllers and airline flight dispatchers for relay to pilots either during preflight briefings or by radio to flights already en route. Information used in NOTAMs and SIGMETs may come from a variety of sources including reports from pilots, air traffic services, meteorological services, and in the case of volcanic activity, from ground-based volcano observers.

In the Philippines, the first NOTAM alerting pilots about Mount Pinatubo was issued by the Flight Observation Briefing Service (FOBS) at the Air Transportation Office (ATO), Manila International Airport (NAIA) on April 12, 1991 (appendix 1), 10 days after unrest of the volcano was first detected. From April 12 through June 9, at least eight additional NOTAMs were released by ATO. Discussions between the authors and members of the Manila Airport Operators' Council (AOC) and Board of Airline Representatives in July and August 1991 indicated that few airline dispatchers could recall that NOTAMs about the volcano had been issued prior to June 9. Several said that they had paid little attention to the notices because the activity of Mount Pinatubo at that time had consisted only of low-altitude emission of white steam. Since the volcano had not yet revealed an explosive nature, there was a perception that it posed little hazard to aircraft safety. In addition, many airline authorities and aviation officials told us that, at the time, it was not conceivable to them that an ash cloud would move beyond Luzon Island.

The large number of encounters with the Pinatubo ash cloud (table 1), including several encounters that involved airplanes from the same company, reflects a major breakdown in the way that information about the ash cloud hazard was communicated and the ways that users responded to the information. This breakdown occurred at several levels, including between adjacent FIRs as well as within individual airline companies.

To meet the unprecedented demands on the air traffic control system by the Pinatubo eruption, Philippine authorities acted quickly to streamline the collection and issuance of information about the activity of the volcano. By late June, several new communications links were established between aviation authorities, airline companies, meteorological agencies, and volcanologists. Important additions to the existing communication network were the airline companies as represented by the Manila AOC and the Board of Airline Representatives (BAR). To the existing network, the AOC and the BAR were able to add company pilot reports, weather observations, and perhaps most importantly, direct communications with the pilots in the cockpit.

A series of meetings in July and August 1991 between PHIVOLCS scientists and officials of ATO, the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA), the Manila Airport Authority, and airline management resulted in the streamlining of information flow. Under the revised notification plan, PHIVOLCS directly relayed information of eruptions to the FOBS office of the ATO. The FOBS/ATO office issues NOTAMs about Pinatubo's activity after receiving information from PHIVOLCS and following consultation with PAGASA to verify the forecast of prevailing wind drift. This interaction is facilitated at Manila International Airport, where the PAGASA and FOBS offices are adjacent to one another.

### ALERT CODE

To simplify communications with public officials, a numerical volcano alert code was introduced by PHIVOLCS in May 1991 (Tayag and others, this volume). Aviation officials adopted the alert code and designated corresponding flight restrictions and contingency routings for air traffic under each alert level. Under the original code, the appearance at the surface of new lava indicated an eruption was in progress and required that the original Alert Level 5 be maintained, even though little or no ash might be produced. Revision of the code became necessary after July 1992, when seismicity and nonexplosive growth of a lava dome (Tayag and others, this volume) required that PHIVOLCS maintain the highest alert at Alert Level 5 even though the eruption produced little or no ash. With the revised code, adopted on November 27, 1992, Alert Level 5 specifies a *hazardous explosive eruption in progress with pyroclastic flows and (or) eruption column rising at least 6 km or 20,000 ft above sea level.* Because dome growth after July 1992 was nonexplosive, PHIVOLCS lowered the alert level during nonexplosive dome growth from Alert Level 5 to 2 *(moderate level of seismic, other unrest, with positive evidence for involvement of magma)* on December 8, 1992, and normal air traffic routing near the volcano was resumed. This alleviated the increased operating costs associated with flying the longer distance contingency routings as required when operating under the original Alert Level 5 (C.M. Navarro, Philippine Airlines, written commun., 1992).

## LESSONS LEARNED

The large number of damaging encounters between airplanes and the ash clouds from the 1991 eruptions of Pinatubo prompted volcanologists, meteorologists, and aviation authorities to reevaluate the hazard that these clouds present to aviation safety and how available technology and operational procedures can be applied or modified to mitigate the ash hazard.

### DETECTION AND TRACKING OF THE ASH CLOUDS BY REMOTE SENSING METHODS

Satellite-based remote sensing methods provided information for the detection and tracking of the Pinatubo ash clouds. To be of maximum benefit to aviation, these data should be collected at a central station, quickly and succinctly interpreted, and widely broadcast and disseminated in a form that is understandable to users including airline dispatchers and pilots. Delays of minutes to hours reduce the value and utility of the information. On June 15, tracking of ash clouds by meteorologists in the United States and Japan by use of the hourly GMS images gave timely information about ash cloud position. However, this information did not reach Philippine authorities in time to be incorporated into operational applications. Indeed, most countries do not have immediate access to satellite-based sensors to monitor ash cloud movement. It is important for countries with satellite capabilities to determine the extent and movement of ash clouds to pass on such information quickly to countries and agencies at risk from drifting ash clouds. Following the Pinatubo emergency, the World Meteorological Organization and the International Civil Aviation Organization have requested the assistance of the governments of Australia, Japan, and the United States to develop satellite techniques that would provide warning of ash cloud movement that threatens aviation safety in areas where satellite data are not available.

### COMMUNICATIONS

Warnings about volcanic eruptions commonly are given too late to prevent in-flight encounters. However, in the Pinatubo case, information about the restless state of the volcano was available in aeronautical notices issued by Philippine authorities up to 2 months before the first eruption in June. Our analysis of the large number of aircraft affected by the Pinatubo ash clouds indicates that information and warnings about the hazard of volcanic ash either did not reach appropriate officials in time to prevent these encounters or that those pilots, dispatchers, and air traffic controllers who received this information were not sufficiently educated about the volcanic ash hazard to know what steps to take to avoid ash clouds.

The key to communicating information about volcanic eruptions in a timely and readily understandable form is to involve all interested groups (geologists, meteorologists, pilots, and air traffic controllers) in the development of information and to streamline the distribution of this information between essential parties. During the Pinatubo crisis, Philippine authorities established practical and straightforward procedures for addressing the volcanic threat. These included regular meetings between all agencies involved with addressing the volcanic threat to aviation safety. Beyond the Philippines, communications must include realtime communications between Flight Information Regions. An important element of any communications plan is frequent exercising of the plan to insure that information users are not caught off-guard by the sudden appearance of information about a restless or erupting volcano.

Applying these lessons, the International Civil Aviation Organization (ICAO) has requested that coordination efforts similar to those used in the Philippines be established for other countries in the Asia-Pacific region (Casadevall and Oliveira, 1993) and in South America. Accuracy and timeliness of SIGMETs are additional issues that have been addressed by ICAO (ICAO, 1992). In particular, ICAO regulations now require that an outlook advisory be included with SIGMETs describing volcanic activity. The outlook is valid for a period of 4 to 12 h and is developed by using information from satellite tracking of the cloud and from trajectory forecast models such as the volcanic ash transport and diffusion model of Heffter and Stunder (1993).

## EDUCATION

In our study, we found that often, warnings about volcanic eruptions are passed to decisionmakers including pilots, flight dispatchers, and air traffic controllers who are not adequately informed about the nature of volcanic clouds to know how to use such information to safeguard the airplane and its passengers. Regular and repeated training of pilots and aviation officials about volcanic hazards must be a component in flight safety training (Boeing, 1992).

We also found that volcanologists were seldom aware of the hazards related to far-drifting clouds of volcanic ash. With their traditional focus on the flowage hazards (ash flows, lava flows, mud flows) that affect the slopes and lower flanks of the volcano itself, volcano scientists have rarely treated volcanic ash clouds in their assessments of volcanic hazards. The hazards posed by drifting ash clouds, not only near an erupting volcano but at considerable distances downwind, must be described and assessed by scientists who evaluate hazards, especially for volcanoes that erupt explosively.

## LONG-TERM DAMAGE

In addition to the aircraft damage that was immediately evident in the days following the June 15 eruption, damage related primarily to $SO_2$ gas has been reported by some airline companies and manufacturers. One year after the eruption, in June 1992, there was an incident involving loss of engine power on a jumbo jet owing to accumulation of sulfate deposits in jet engines. Isotopic studies of these deposits suggest that the sulfate is derived from the ingestion and oxidation of $SO_2$ and sulfuric acid aerosols that originated in the Pinatubo eruption cloud of June 15 (Casadevall and Rye, 1994). Related problems recognized in 1992 such as the increased incidence of crazing of acrylic windows (Berner, 1993) and fading of polyurethane paint on jetliners are also due to volcanogenic sulfuric acid droplets in the atmosphere. Frequent inspections of aircraft should reveal any corrosion problems due to volcanogenic sulfur gases.

# SUMMARY

The 1991 eruptions of Mount Pinatubo produced enormous clouds of volcanic ash and corrosive gases. In the days after the eruptions, these clouds had an immediate impact on air traffic routes and aircraft flying in the Southeast Asia region. In addition, the corrosive gases from Pinatubo continue to affect aircraft through 1993.

Unlike earlier volcanic eruptions such as those from Redoubt Volcano in 1989-90, where jet aircraft flew into ash clouds owing largely to lack of adequate information about the position and nature of the ash cloud (Casadevall, 1994), the clouds from the Pinatubo eruptions were well known and described in the aeronautical information available to pilots and dispatchers. However, for various reasons, this information was not widely incorporated by the airline companies into their operational planning.

Within days after the cataclysmic eruption in mid-June, Philippine authorities acted quickly to establish an interagency plan to streamline the collection and flow of information between field observers and pilots. This system relied heavily on the involvement of the Airline Operators' Council and Board of Airline Representatives of Manila International Airport, in cooperation with scientists of PHIVOLCS, PAGASA, and the authorities of the Manila Airport Authority. This plan continues in effect more than 4 years after the eruption and has been selected and promoted by ICAO as an example of a particularly effective operational model for other countries of the world facing the volcanic threat to aviation safety (Casadevall and Oliveira, 1993).

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**Appendix 1.** Chronology of NOTAMs (Notices to Airmen) Issued by Manila Flight Information Region To Warn of Pinatubo Activity (ICAO, Montreal, and JAL, Tokyo, unpub. data, 1991).

[The following chronology indicates the NOTAM number and time of issuance. The activity of Mount Pinatubo began on April 2, 1991, with a series of phreatic explosions from a fissure on the north side of the volcano. The first NOTAM (B513) was issued April 12]

April 2: First eruption of Pinatubo.

April 12: First NOTAM (B513) issued: "Pinatubo volcano ... steaming activity was moderate with considerable amount of white steam plume with a height from 250 to 400 m from vent and drifting SW direction and in abnormal condition. All pilots are advised to exercise extreme caution and avoid flying over the area."

April 24: Manila Area Control Center (ACC) replies to carrier inquiry that "... all concerned will be notified within 10 minutes after receiving the actual eruption [notification] from PHIVOLCS."

May 3: NOTAM B513 is revised as NOTAM B634 with revision of plume height.

June 5: PHIVOLCS upgraded Pinatubo warning from Alert Level 2 to Alert Level 3.

June 7: PHIVOLCS upgraded Pinatubo warning from Alert Level 3 to Alert Level 4.

June 8: JAL notifies AOC carriers at NAIA that PHIVOLCS upgraded Mount Pinatubo warning level to Alert Level 4, meaning that an eruption may occur within 24 hours.

June 9: Pinatubo erupts: NOTAM B634 is revised and reissued as NOTAM B797 to notify that Pinatubo had erupted at 1425 local time (0625 Z). PHIVOLCS upgrades Pinatubo warning to Alert Level 5, the highest level.

June 10: NOTAM B808 is revised and reissued as NOTAM 818.

June 12: Philippine Independence Day.

NOTAM B818 is revised and reissued as NOTAM B834 and B835 to notify of eruption at 0855 local time (0055 Z).

June 13: NOTAM 844 issued at 0830 local time (0030 Z) following June 12 eruption; NOTAM 848 issued at 1145 local time (0345 Z), closing airways in aftermath of encounter 91-01.

June 14: NOTAM B865 issued 10:43 local time (0243 Z) to warn of possible presence of volcanic ash in a designated area and up to 50,000 feet altitude.

Several NOTAMs are issued between 1309 local time on June 14 and 0556 local time on June 15 (0509 and 2156 Z). Data for additional NOTAMs were typically from pilot reports, Clark Air Base and Cubi Point NAS, and public radio reports. Data from PHIVOLCS were minimal.

Advisory sent at 1452 local time (0652 Z) indicated "... PRESENCE OF TROPICAL DEPRESSION YUNYA ... WILL INVITE VOLCANIC ASH TO MOVE TO SOUTHEAST TO MANILA FROM MT. PINATUBO."

June 15: NOTAM B882 was issued 0930 local time (0130 Z), closing additional airways.

NOTAM B884 was issued 1027 local time (0227 Z) notifying of two eruptions of Pinatubo.

Several NOTAM were issued during the day. Manila Airport began to receive ash fall at 1535 local time (0735 Z) with a continuous light to moderate rain.

NOTAM B891 issued (1315 Z) to say Manila Airport operations were suspended due to ash fall.

At 0144 Z, airports at Legaspi and Puerto Princesa report presence of volcanic ash.

| | |
|---|---|
| | From 1100 to 2100 Z, Manila area experienced about 1 cm of ash fall. |
| June 18: | NOTAM B912 issued at 1850 local time (1050 Z) to say that Manila Airport was open to propeller aircraft. |
| | NOTAM B913 issued at 1905 local time (1105 Z) to say airport is open to departing jet aircraft, which are towed to runway from ramp. |
| June 19: | Five jet aircraft depart between 0800 and 1300 local time (0000-0500 Z). |
| | At 1800 local time (1000 Z), two aircraft land (one 747, one DC-10). |
| June 26: | Airport reopened with restrictions. |
| July 4: | Airport reopened completely for normal operations. |
| July 17: | Airport closed for 12 hours starting at 1700 local time (0900 Z) because of light ash fall. |
| July 19-present: | Airport opened for normal operations. |

## **Appendix 2.** Acronym glossary.

| | |
|---|---|
| ACC | Area Control Center |
| AOC | Airport Operators' Council |
| APU | auxiliary power unit |
| ATO | Air Transportation Office |
| AVHRR | Advanced Very High Resolution Radiometer |
| BAR | Board of Airline Representatives |
| EGT | exhaust gas temperature |
| FIR | Flight Information Region |
| FOBS | Flight Observation Briefing Service |
| GMS | Geostationary Meteorological Satellite (Japanese Meteorological Agency) |
| ICAO | International Civil Aviation Organization |
| NAIA | Ninoy Aquino International Airport (Manila International Airport; also Villamor Air Base of the Philippine Air Force) |
| NAS | U.S. Naval Air Station (Cubi Point NAS, for example) |
| NDCC | National Disaster Control Center |
| NOAA | National Oceanic and Atmospheric Administration |
| NOTAM | Notice To Airmen |
| PAGASA | Philippine Atmospheric, Geophysical, and Astronomical Services Administration |
| PHIVOLCS | Philippine Institute of Volcanology and Seismology |
| PVO | Pinatubo Volcano Observatory |
| RDCC | Regional Disaster Control Center |
| SAB | Synoptic Analysis Branch |
| SIGMET | Significant Meteorological Event Notification |
| TOMS | Total Ozone Mapping Spectrometer |
| USGS | United States Geological Survey |

PHIVOLCS | University of Washington Press | U.S.Geological Survey

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