Effects of the 1992 Crater Peak Eruptions on Airports and Aviation Operations in the United States and Canada

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ABSTRACT

Crater Peak vent on the south side of Mount Spurr volcano, 67 nautical miles (125 km) west of Anchorage, Alaska, erupted on June 27, August 18, and September 16–17, 1992. Each eruption produced an ash column that rose to between 43,000 and 49,000 ft (13 and 15 km) above sea level. Although drifting ash clouds from the three eruptions disrupted air traffic over Alaska, western Canada, and the central conterminous United States, no aircraft were damaged by encounters with the ash clouds.

Ashfall from the August 18 eruption deposited from 1/16" to 1/8" (1 to 3 mm) of ash in Anchorage and caused Anchorage airports to close or curtail operations for several days. The cost of removing the ash from the airports, including the cost of protecting and cleaning aircraft caught on the ground in Anchorage is estimated at $683,000. The net passenger revenues lost owing to flight cancellations while Anchorage airports were closed are estimated at $276,000.

Because encounters with volcanic ash clouds from the 1989–90 eruptions of Redoubt Volcano caused serious damage to five passenger airplanes, there has been a high level of concern in the aviation community about volcanic ash and the threat it presents to aviation safety. The lack of encounters between airplanes and ash clouds from the Mount Spurr eruptions reflects better understanding and increased awareness about the hazards of volcanic ash. Since 1990, a number of improvements have been made to reduce hazards resulting from volcanic ash. These improvements have resulted from major initiatives by Federal and international regulatory agencies and by aviation associations and include: (1) improved warnings of eruptions provided by increased monitoring of Cook Inlet volcanoes, (2) improvements in the detection and tracking of volcanic ash clouds, (3) improved education of pilots and flight dispatchers, and (4) streamlining the ways in which information and warnings are communicated among the agencies concerned with aviation safety.

INTRODUCTION

Recent eruptions at Redoubt Volcano in Alaska and Pinatubo Volcano in the Philippines provided pilots, aircraft operations personnel, meteorologists, and volcanologists considerable experience in reacting to the presence of volcanic ash clouds and the resulting effects of ash on aviation safety (Casadevall, 1992; 1994a). The 1989–90 eruptions of Redoubt Volcano produced ash clouds which damaged five jet airliners (Casadevall, 1994b). The June 1991 eruptions of Pinatubo produced large ash clouds that were involved in at least 16 damaging encounters with jet airliners (Casadevall and Delos Reyes, 1991).

Mount Spurr (11,070 ft, 3,374 m) is one of three volcanoes in the Cook Inlet area of south-central Alaska that have erupted in the past decade. Eruptions of the Crater Peak vent (6,990 ft, 2,130 m) on the south side of Mount Spurr on June 27, August 18, and September 16–17, 1992, produced ash columns that rose to

43,000 to 49,000 ft (13 to 15 km) above sea level (Eichelberger and others, this volume). Upper-level winds carried ash from the three eruptions into airspace over south-central and eastern Alaska and western Canada. Ash from the eruptions in June and September was also carried over northern and central parts of the United States (fig. 1). This report evaluates the communication between agencies of information available at the time of the eruptions, describes the movement of the three Mount Spurr ash clouds, and examines the effects of the clouds on aviation operations.

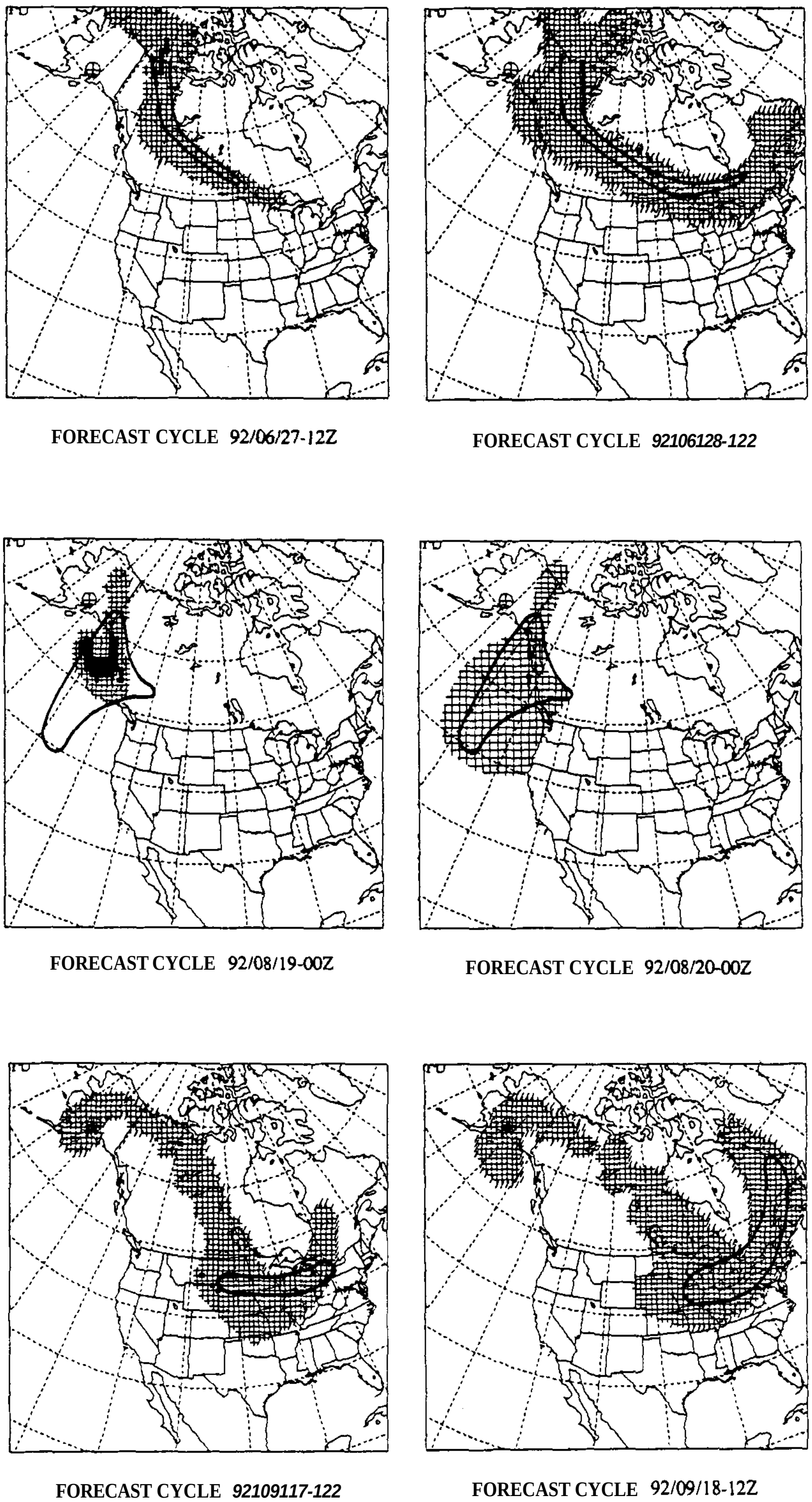

Figure 1. Comparative trajectories of the ash clouds from the June, August and September 1992 eruptions from Mount Spurr volcano, Alaska. Solid lines are ash cloud boundaries determined from composite satellite images. Patterned areas are cloud positions forecast by the volcanic ash forecast transport and dispersion (VAFTAD) model of Heffter and Stunder (1993). Modified from Heffter and Stunder (1993).

Prior to the 1992 eruptions, Mount Spurr last erupted on July 9, 1953, with a single explosive eruption that sent ash to a maximum estimated elevation of 70,000 ft (21.3 km) (Juhle and Coulter, 1955). Upper-level winds carried ash from that eruption over Anchorage, 67 nautical miles (125 km) east of the volcano, and from 1/8" to 1/4" (3 to 6 mm) of ash fell at Anchorage Airport and Elmendorf Air Base; this ashfall resulted in closing the airports for several days and disrupting civilian and military airport operations for several weeks (Juhle and Coulter, 1955; Wilcox, 1959). In addition to the airport closures, at least three F-94 military jets were damaged after flying into the eruption cloud. Ash also covered several C-124 transport aircraft (Globe Trotters) that were parked at Elmendorf; ash removal from these aircraft took 10 days (U.S. Air Force, 1955).

Whereas no damaging encounters between airplanes and ash clouds were reported for the 1992 Crater Peak eruptions, the ash clouds did disrupt air traffic over Alaska, Canada, and the northern and central United States. In addition, the removal of ash and the cleaning of airport facilities and airplanes required temporary suspension of operations at Anchorage airports for several days following the August 18 eruption.

COMMUNICATIONS

Prompt and direct communication of factual information about Mount Spurr's activity between the aviation community, meteorologists, and volcanologists was a key element in determining pilot response to the eruptions, just as it had been during the 1989–90 Redoubt eruptions (Brantley, 1990; Casadevall, 1994b). Beginning with the Redoubt eruptions, the main source of timely factual information about the activity of Alaskan volcanoes has been the volcano update issued by the Alaskan Volcano Observatory (AVO). The update is normally released weekly and may be supplemented with a level of concern color code that is based primarily on seismic activity and field observations. The color code uses one of four colors (Green, Yellow, Orange, or Red) to succinctly describe the status of the volcano when an eruption is expected or is in progress. Green refers to the normal or noneruptive state of the volcano. Yellow indicates that the volcano is restless with elevated seismic activity and the possibility of a plume of gas and steam rising several thousand feet above the volcano. Orange indicates that a small ash eruption is expected or confirmed with plumes not likely to rise above 25,000 ft (7.6 km) above sea level. Red indicates that a major explosive eruption is in progress or is expected within the next 24 hours with potentially hazardous ash plumes expected to exceed altitudes of 25,000 feet (7.6 km) or more. Changes in this information are issued at anytime, 24 hours a day, as events at the volcano demand (Alaska Interagency Operating Plan, 1993).

During an eruption, updates are communicated immediately by telephone to the Anchorage Area Control Center, the Anchorage National Weather Service office, the Alaska Department of Emergency Services, and the U.S. Air Force at Elmendorf Air Base. Simultaneously, the update is sent by telephone facsimile to a wide user community including Anchorage International Airport and the airlines.

Concern that a future eruption of Mount Spurr would affect Anchorage in a manner similar to the 1953 eruption prompted scientists to initiate seismic monitoring of the volcano beginning in 1981. Since 1989, the AVO has maintained a network of as many as 10 seismometers on the volcano (Power and others, this volume). Beginning in August of 1991, intermittent swarms of small magnitude, shallow earthquakes were detected beneath Crater Peak. After a slightly larger swarm on February 5, 1992, AVO described the increased seismicity in the update of February 7, 1992 (table 1). Between February 7 and June 26, AVO issued 19 additional updates that described the activity of the volcano, including a special update issued on June 8. This special update contained analyses of increased seismicity and other monitoring data then available, such as rates of gas emission (Doukas and Gerlach, this volume) and physical and chemical changes to the small lake within Crater Peak vent (Keith and Thompson, this volume). On June 26, AVO used the color code Yellow to describe the status of the volcano. The 1992 eruptions of Mount Spurr began at 7:04 a.m. ADT (1504 UT) on June 27.

ACKNOWLEDGMENTS

We would like to express our appreciation for information about the eruptions provided by James Lynch and Grace Swanson of the NOAA-National Environmental Satellite, Data and Information Service, Synoptic Analysis Branch. For the meteorological analysis of the September eruption, we are grateful to David Helms (NASA-Johnson Space Center). For information about the effects on the Cleveland Air Traffic Center, we thank Thomas Howell (FAA). We also greatly appreciate discussions and the unpublished reports provided by Larry Michou (Anchorage International Airport), Captain Terry Spurgeon (Transport Canada), and Carl Shapiro (USGS). Reviews of this paper by John Pallister and Tom Miller of the USGS helped to improve the clarity of the presentation and are appreciated.

Table 1. Summary of activity from volcano updates issued by the Alaska Volcano Observatory concerning the June 27, 1992, eruption of Mount Spurr volcano.

Date	Time (ADT)	Update
2/07/92	--	First mention of increase in seismic activity at Mount Spurr. Minor increase in seismic activity had been detected previously, starting in August 1991.
3/13/92–6/05/92	--	Continuing mention of increased seismic activity made in weekly updates.
6/08/92	--	Extended update on Mount Spurr seismicity released.
6/09/92–6/26/92	--	Weekly updates mentioned increased seismicity.
6/26/92	4:30 p.m.	At 12:04 p.m. continuous tremor began. Second update issued at 4:30 p.m. on 6/26/92 describing increased seismicity. Color code Yellow declared.
6/27/92	8:00 a.m.	Eruption tremor began at 7:04 a.m. Visual verification of ash column to approximately 17,000 ft (5.2 km). Color code raised from Yellow to Orange.
6/27/92	9:15 a.m.	Ash column rose to greater than 30,000 ft (9 km). Color code raised from Orange to Red.
6/28/92	9:00 a.m.	Color code reduced from Red to Yellow.
6128192–7/07/92	--	Updates issued 6/28, 6/29, 6/30, 7/1, 712, 7/3, 7/6, 7/7. Color code remained at Yellow.
7/08/92	3:00 p.m.	Color code reduced to Green.
7/10/92	3:30 p.m.	Weekly updates resumed; color code remained at Green.

1992 CRATER PEAK ERUPTIONS

The three Crater Peak eruptions in 1992 each lasted from 3.5 to 4 hours, produced pyroclastic material of andesitic composition (Neal and others, this volume), and generated eruption columns that rose to between 43,000 and 49,000 ft (13 to 15 km) above sea level (Rose and others, this volume) (table 2). Each eruption also produced large clouds of volcanic ash and gas that affected air traffic and operations over a wide area of the United States and Canada (fig. 1).

JUNE 27, 1992, ERUPTION

The June 27, 1992, eruption of Mount Spurr's Crater Peak vent produced approximately 12 million cubic meters of andesitic tephra (Neal and others, this volume) and the maximum altitude of the eruption column, as detected by ground-based radar, was approximately 48,000 ft (14.5 km) (Rose and others, this volume). The forecast movement of the June 27 ash cloud during the first 24 hours was first communicated in the AVO updates issued on June 27 (table 2) and was based on analysis of the forecast upper-level winds. The projected path of the cloud indicated it would travel north of the volcano toward Denali National Park (Mount McKinley) and the Beaufort Sea and remain well clear of the Anchorage area. By June 28, upper-level winds changed direction toward the southeast and by June 29, the cloud had moved southeastward and was transported over western Canada toward the conterminous United States (Heffter and Stunder, 1993) (fig. 1).

On June 27, shortly after notification of the start of the eruption by AVO, the National Oceanic and Atmospheric Administration (NOAA) and the Federal Aviation Administration (FAA) activated their volcanic hazards alert plan, which remained in effect for 5 days. The Synoptic Analysis Branch (SAB) of NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) used imagery from the geostationary operational environmental satellite (GOES) and forecast trajectories for the ash clouds (Heffter and Stunder, 1993) to track the June 27 cloud through July 2 when it became indistinguishable from weather clouds over southwestern Canada (J. Lynch, NOAA, written commun., 1992). During this period, SAB issued 19 bulletins about the position and movement of the ash cloud to the Anchorage National Weather Service forecast office, to the National Meteorological Center, to the National Aviation weather advisory unit in Kansas City, to the FAA, and to AVO.

Analysis of images from the advanced very high resolution radiometer (AVHRR) aboard the NOAA-11 polar-orbiting satellite also detected the cloud over western Canada (Aviation Week and Space Technology, 1992). The sulfur dioxide in the eruption cloud was detected using the total ozone mapping spectrometer (TOMS) aboard the Nimbus 7 satellite and the cloud was tracked through July 3. The eruption cloud contained approximately 200,000 tons of sulfur dioxide gas (Bluth and others, this volume), a mass comparable to the 175,000 tons emitted by the December 15, 1989, eruption of Redoubt Volcano (Schnetzler and others, 1994).

No airplanes flew into the June 27 ash cloud. The only modification of commercial air-traffic patterns in Alaska owing to the eruption was the rerouting of flights from Anchorage to Nome and Anchorage to Kotzebue on June 27 to avoid the ash-contaminated airspace north of Mount Spurr. Several ski-equipped charter flights used to service climbers on Mount Denali were canceled on June 27 and 28 because of ashfall on the Denali snowfields. This situation improved by June 29 after fresh snow covered the ash.

On June 29, the pilot of a daytime domestic flight in Canada reported that he had passed through a 1,000-ft- (300-m)-thick brownish haze layer at 28,000 ft (8.5 km) altitude as his aircraft descended into Winnipeg (T. Spurgeon, Transport Canada, written commun., 1993). Fortunately, the cloud had been strongly diluted by the time it entered Canadian airspace and there were no reports of ashfall or damage to aircraft in Canada.

AUGUST 18, 1992, ERUPTION

The first indication of eruptive activity on August 18 was a pilot report received at 3:48 p.m. ADT (2348 UT) that ash was rising from 1,000 to 2,000 ft (300–600 m) above Crater Peak. There were no clear seismic precursors to the August eruption, and the eruptive activity reported by the pilot was related to weak tremor that began at 3:41 p.m. ADT (2341 UT) (McNutt and others, this volume). After several additional pilot reports of this low-level ash column and analysis of the weak tremor, AVO raised the color code alert from Green to Yellow at 4:25 p.m. ADT (0025 UT). At 4:42 p.m. ADT (0042 UT), strong eruption-related tremor began to record on the seismic station closest to the vent, and at 4:45 p.m. ADT (0045 UT) AVO telephoned authorities at Anchorage International Airport and Elmendorf Air Base to advise them of the tremor. Authorities at Merrill Field were notified by AVO through the State of Alaska Department of Emergency Services. Following further increase in tremor and notification by the National Weather Service that the Kenai radar had detected an ash column rising above the volcano to more than 35,000 ft (11 km), AVO issued an update at 4:48 p.m. ADT (0048 UT) and declared color code Red.

The maximum column height of 45,000 ft (13.7 km) was detected by radar at 4:55 p.m. ADT (0055 UT) (Rose and others, this volume). The eruption lasted for more than 3 hours and eruption tremor began to decline by 8:10 p.m. ADT (0410 UT). AVO lowered the color code from Red to Orange at 9:30 p.m. ADT (0530 UT) on August 18, and further reduced the level to Yellow at 8:30 a.m. ADT (1630 UT) on August 19. During the August eruption, the NOAA SAB issued 21 bulletins that periodically updated the position of the ash cloud and included the trajectory forecasts of cloud position and movement (J. Lynch, NOAA, written commun., 1993).

The August eruption produced 14 million cubic meters of tephra (Neal and others, this volume). The ash column, measured by radar, rose as high as 45,000 ft (13.7 km) in altitude (Rose and others, this volume), and upper-level winds carried the ash eastward toward Anchorage (table 2). Approximately 1/16" to 1/8" (1 to 3 mm) of fine sand-size ash fell in the Anchorage area between 8:20 p.m. ADT (0420 UT) and 11:00 p.m. ADT (0700 UT); as a result, the three Anchorage airports were closed for several days (figs. 2, 3) (Casadevall, 1993).

SEPTEMBER 16–17, 1992, ERUPTION

Following the August eruption, AVO maintained a color code of Yellow because levels of seismic activity remained elevated. The update on September 9 drew attention to the first increase in seismic activity since the August eruption, and the update on September 11 stated that an eruption was possible within the next few days or weeks. On September 16, the first phase of a new eruption at 10:36 p.m. ADT (0636 UT) was indicated by increased seismic activity and by pilot reports from Kenai, Alaska (table 3). AVO immediately initiated its calldown and in response to the telephone notification of the eruption from AVO and pilot reports, the National Weather Service issued a notice of significant meteorological event (SIGMET) for the eruption at 10:40 p.m. ADT (0640 UT) (fig-

Table 2. Comparison of the 1992 Mount Spurr volcano eruptions to 1953 Mount Spurr volcano and 1989 Redoubt Volcano eruptions.

[DRE, dense rock equivalent; TOMS, total ozone mapping spectrometer; SAB, Synoptic Analysis Branch, NOAA National Environmental Satellite Data and Information Service (J. Lynch, written commun., 1993)]

Date of eruption	Maximum altitude of eruption column (km)	Tephra volume (DRE X 10^6 m^3)	Sulfur dioxide (megatons)	Traceable on TOMS	Number of SAB bulletins issued	Pilot reports
			Mount Spurr volcano			
June 27, 1992	14.5	12	200±60	to 7/3	19	--
August 18, 1992	13.7	14	4001120	to 8/26	21	--
September 17–18, 1992	13.9	15	230±70	to 9/21	18	to 9/21
			Mount Spurr volcano			
July 9, 1953	<21.5 (pilot estimate)	not available	not available	not available	none issued	--
			Redoubt Volcano			
December 15, 1989	>12 (pilot estimate)	not available	175	to 12/19	22	--

Figure 2. Road graders scrape ash from runways at Anchorage International Airport on August 19, 1992. Road scrapers could effectively move the ash only after it had been sprayed and dampened with water. However, too much water produced a slurry that could not be moved effectively. Dampened ash was scraped into furrows and then scooped up using front-end loaders. Some ash resuspended in the air would settled back onto runways and planes, and thus delayed aircraft cleanup. Photograph by Erik Hill courtesy of Anchorage Daily News.

Figure 3. Maintenance crew removing ash from wing of a Reeve Aleutian Airways Boeing 727-100 aircraft on August 19, 1992, at Anchorage International Airport. Photograph by Erik Hill courtesy of Anchorage Daily News.

ure 4). AVO increased the color code to Red in the volcano update issued at 10:45 p.m. ADT (0645 UT). The most intense phase of the eruption began shortly before midnight on September 17 and lasted for about 4 hours. At 4:00 p.m. ADT (0000 UT) on September 17, the color code was reduced to Orange where it remained until September 24 when it was further reduced to Yellow.

The September ash cloud was noteworthy in several ways. Although, the volume of magma erupted, and the basic dimensions of the eruption column and the ash cloud were similar to the two previous eruptions (table 2), the cloud traveled as a coherent mass for 5 days after the eruption. It remained visible during that time to ground observers, pilots, and even to astronauts aboard Space Shuttle mission STS 47. The cloud moved east, passed north of Anchorage and deposited about 1/16" (1 mm) of ash at Willow, Palmer, and the along Parks Highway in Alaska. It continued across western and south-central Canada, then down into the central United States by September 19 before moving back into eastern Canada and eastward over the North Atlantic by September 21 (fig. 1) (Schneider and others, this volume).

Table 3. Pilot reports (PIREPs) and ground observations of ash-cloud locations for the September 16–17, 1992, eruption of Mount Spurr volcano, Alaska.

[Numbers refer to reporting sites shown in fig. 5. AK, Alaska, Yk. Tr., Yukon Territory; Sask, Saskatchewan; Albta., Alberta; SD, South Dakota; ND, North Dakota; NE, Nebraska; IL, Illinois; IA, Iowa; MN, Minnesota; PA, Pennsylvania; OH, Ohio, Ont., Ontario; WI, Wisconsin; NY, New York; MI, Michigan, Lab., Labrador, N. Brs., New Brunswick; Latitude and longitudes given in degrees and tenths of degrees. Time given is Universal Coordinated Time (UT). Altitude given in feet above mean sea level, or for values greater than 18,000 ft, relative to a barometric pressure of 29.92 inches Hg. Single entries indicate the base of the cloud; second entry indicates top of the cloud. Pilot reports compiled by NOAA Synoptic Analysis Branch (G. Swanson, NOAA, written commun., 1993) and by Transport Canada Aviation (T. Spurgeon, Transport Canada, written commun., 1993)]

Number	Location	State/ Province	Lat.	Long.	Date	Time	Altitude/ Observation
1	Mount Spurr	AK	61.3	152.2	09/17	0636	
2	Kenai	AK	60.62	151.19	09/17	0637	ground observation
2	Kenai	AK	60.62	151.19	09/17	0646	ground observation
3	Anchorage	AK	61.15	150.21	09/17	0713	
2	Kenai	AK	60.62	151.19	09/17	0745	35,000 4,0000
2	Kenai	AK	60.62	151.19	09/17	0746	ground observation
2	Kenai	AK	60.62	151.19	09/17	0757	
3	Fire Island	AK	61.15	150.20	09/17	0800	
2	Kenai	AK	60.62	151.19	09/17	0804	ground observation
3	Anchorage	AK	61.15	150.21	09/17	0821	19,000 29,000
3	Anchorage	AK	61.15	150.21	09/17	0835	
3	Anchorage	AK	61.15	150.21	09/17	0838	
3	Anchorage	AK	61.15	150.21	09/17	0846	10,000
2	Kenai	AK	60.62	151.19	09/17	0846	ground observation
3	Anchorage	AK	61.15	150.21	09/17	0853	21,000 37,000
3	Anchorage	AK	61.15	150.21	09/17	0900	31,000 32,000
4	Snowshoe Lake	AK	62.03	146.68	09/17	1447	ground observation
5	Gulkana	AK	62.15	145.45	09/17	1449	ground observation
3	Anchorage	AK	61.15	150.21	09/17	1452	ground observation
2	Kenai	AK	60.62	151.19	09/17	1455	
6	Talkeetna	AK	62.30	150.10	09/17	1457	ground observation
1	Mount Spurr	AK	61.3	152.2	09/17	1501	35,000
7	Watson Lake	Yk. Tr.	60.07	128.48	09/17	1620	35,000
8	White River	Yk. Tr.	61.35	139.00	09/17	1650	
9	Beaver Creek	Yk. Tr	62.45	140.62	09/17	1656	ground observation
10	Lake Laberge	Yk. Tr	61.17	135.17	09/17	1850	6500
11	Whitehorse	Yk. Tr.	60.72	135.03	09/17	2012	
12	Dawson	Yk. Tr.	64.07	139.42	09/17	2141	5,000
13	Carmacks	Yk. Tr.	62.10	136.32	09/17	2200*	ground observation
13	Carmacks	Yk. Tr.	62.10	136.32	09/17	2300	9,000
14	Palmer	AK	61.59	149.08	09/17	2352	ground observation
3	Anchorage	AK	61.15	150.21	09/18	0757	
15	Fairbanks	AK	64.80	148.01	09/18	0757	
16	Lumsden	Sask.	50.67	104.89	09/18	1250	29,000 38,000
17	Calgary	Albta.	51.12	113.88	09/18	1430	22,000 25,000
18	Pierre	SD	44.40	100.16	09/18	1513	33,000 35,000
19	Swift Current	Sask.	50.30	107.69	09/18	1520	29,000 37,000
18	Pierre	SD	44.40	100.16	09/18	1528	33,000 42,000
20	Empress	Albta.	50.56	110.01	09/18	1650	33,500
3	Anchorage	AK	61.15	150.21	09/18	1705	sulfur odor noted 7,500
3	Anchorage	AK	61.15	150.21	09/18	1715	sulfur odor noted 7,500
21	Minot	ND	48.26	101.29	09/18	1845	20,000
22	Scottsbluff	NE	41.90	103.48	09/18	2110	37,000
20	Empress	Albta.	50.56	110.01	09/18	2246	24,000 33,000
23	Northbrook	IL	42.22	87.95	09/18	2301	30,000
24	Sioux Falls	SD	43.65	96.78	09/18	2324	27,000
21	Minot	ND	48.26	101.29	09/18	2328	33,000
25	Cedar Rapids	IA	41.89	91.79	09/18	2334	
25	Cedar Rapids	IA	41.89	91.79	09/18	2334	27,000
26	Minneapolis	MN	44.88	93.29	09/19	0052	ground observation

Table 3. Pilot reports (PIREPs) and ground observations of ash-cloud locations for the September 16–17, 1992, eruption of Mount Spurr volcano, Alaska—Continued.

Number	Location	State/Province	Lat.	Long.	Date	Time	Altitude) Observation
27	Ellwood City	PA	40.83	80.21	09/19	0116	35,000
28	Dayton	OH	39.90	84.22	09/19	0141	11,000
26	Minneapolis	MN	44.88	93.29	09/19	0154	ground observation
29	Windsor	Ont.	42.25	82.83	09/19	0200	27,000
30	Rochester	MN	43.78	92.60	09/19	0252	
26	Minneapolis	MN	44.88	93.29	09/19	0253	ground observation
31	Regina	Sask.	50.50	104.63	09/19	0320	17,300 20,500
26	Minneapolis	MN	44.88	93.29	09/19	0354	ground observation
1	Mount Spun	AK	61.3	152.2	09/19	0444	steam observed 15,000
32	Milwaukee	WI	42.95	87.90	09/19	0653	ground observation
32	Milwaukee	WI	42.95	87.90	09/19	0950	ground observation
33	Dunkirk	NY	42.49	79.28	09/19	1220	28,000 33,000
34	Rosewood	OH	40.29	84.04	09/19	1250	23,000
35	Flint	MI	42.97	83.74	09/19	1315	28,000
36	Waterville	OH	41.45	83.64	09/19	1315	18,000 20,000
37	Buffalo	NY	42.93	78.65	09/19	1317	24,000 28,000
38	Dryer	OH	41.36	82.16	09/19	1437	18,000 21,000
39	Hayes Center	NE	40.45	100.92	09/19	1500	35,000 37,000
38	Dryer	OH	41.36	82.16	09/19	1538	18,000 23,000
40	Slate Run	PA	41.51	77.97	09/19	1543	21,000
41	Tidoute	PA	41.71	79.42	09/19	1543	18,000 33,000
42	Clarion	PA	41.15	79.46	09/19	1543	18,000 23,000
41	Tidoute	PA	41.71	79.42	09/19	1543	30,000 33,000
39	Hayes Center	NE	40.45	100.92	09/19	1543	31,500 37,600
43	McCook	NE	40.20	100.59	09/19	1553	28,000 33,000
44	Ottawa	Ont.	45.42	75.70	09/20	0123	19,000 23,000
	S. Labrador	Lab.	52.90	62.33	09/20	2025	35,000
	London	Ont.	42.98	81.25	09/20	2230	35,000 37,000
	Saint John	N.Brs.	45.27	66.07	09/21	1123	30,000 35,000
	Digby	Nova Scotia	44.55	66.79	09/21	1825	25,000

* report received at 2125 UT noting time of observation was 2200 UT.

COMMUNICATIONS ABOUT CLOUD MOVEMENT

Pilot reports and ground observations played a critical role in the tracking of the ash cloud from the September 16–17 eruption (table 3; fig. 5). The earliest altitude estimate of 15,000 ft (4.6 km) for the top of the main eruptive column was made by a pilot and was received at 0637 UT (table 3). A pilot report received at 0821 UT estimated the top of the eruption column at between 19,000 and 29,000 ft (5.8–8.8 km); this report corroborated the initial estimates of cloud tops at 28,000 ft (8.5 km), as determined from C-band radar at Kenai, Alaska (Rose and others, this volume). The ash cloud was tracked using images from the geostationary GOES satellite, images from the TOMS (Bluth and others, this volume), and from the AVHRR (Schneider and others, this volume) detectors aboard polar-orbiting satellites. Pilot reports (table 3; fig. 5), radiosonde analysis, and forecast upper-level wind data were incorporated from the beginning of the eruption to indicate where the cloud would move (Heffter and Stunder, 1993). These observations were summarized in 18 volcanic hazard alert bulletins issued for the aviation community by NOAA's SAB (J. Lynch, NOAA, written commun., 1993). In addition to written descriptions of the ash cloud, these bulletins contained graphical information showing the location of the ash cloud.

For pilots in the air as well as those preparing for flight, the more succinct SIGMETs were the principal form of information about the ash cloud. These SIGMETs are in an abbreviated text format (fig. 4) and are derived from information in pilot reports, from AVO, from the volcano hazard alert bulletins, and from satellite images. For the September eruption of Crater Peak, the SIGMETs provide a rich source of data about the movement of the ash cloud. The initial SIGMET, ALFA 1, (fig. 4) was issued from Anchorage at 0648 UT on September 16, 12 minutes after the initial eruptive phase and 3 minutes after the AVO color code was changed to Red. That AVO was listed

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WSPN1 PANC 170649
ANCA WS 170648
PAZA SIGMET ALFA 1 VALID 1606401161040 PANC-
ALASKA VOLCANO OBSERVATORY RPTS THAT MT SPURR VOLCANO AT
61.3N LAT/152.2 LONG HAS ERUPTED AT 10362.
TOPS INFORMATION NOT YET AVAILABLE. ANY ASH PLUME WL MOV NE-E.
A FOLLOW UP SIGMET TO BE ISSUED ASAP. NC.

WSPN1 PANC 170716
ANCA WS 170716 COR
PAZA SIGMET ALFA 1 VALID 1606401161040 PANC-
ALASKA VOLCANO OBSERVATORY RPTS THAT MT SPURR VOLCANO AT
61.3N LAT1152.2 W LONG HAS ERUPTED AT 06362.
TOPS INFORMATION NOT YET AVAILABLE. ANY ASH PLUME WL MOVE NE-E.
A FOLLOW UP SIGMET TO BE ISSUED ASAP. NC.

WSPN1 PANC 170844
ANCA WS 170841
PAZA SIGMET ALFA 2 VALID 1608401161240 PANC-
ALASKA VOLCANO OBSERVATORY RPTS THAT MT SPURR VOLCANO AT
61.3N LAT/152.2 W LONG ERUPTED AT 06362 AND 0804Z. THE 0804Z
ERUPTION WAS MUCH STONGER WITH AN ASH PLUME TO AT LEAST FL400
CONFIRMED BY WEATHER RADAR RHI. WINDS WL MOVE THE ASH TO THE ENE
THEN E. THUS VOLCANIC ASH IS PSBL BLW FL450 WI 90NM EITHER SIDE OF
A LN FM MT SPUR (61.3N 152.2W) TO ORT. INCRG.

WSPN1 PANC 171225
ANCA WS 171223
PAZA SIGMET ALFA 3 VALID 1612401161640 PANC-
AN ERUPTION OF MT SPURR VOLCANO AT 61.3N LAT/152.2 W LONG CONTINUED
FM 08042 TILL NEARLY 11002 WITH WEATHER RADAR INDICATING ASH TO FL 450
THRU THE PD. WINDS WL CONT TO MOVE THE ASH TO THE ENE THEN E.

VOLCANIC ASH IS PSBL BLW FL450 WI 60NM EITHER SIDE OF A LN
FM MTSPUR (61.3N 152.2W) TO GKN TO 62.0N 140.8W WITH THE MAX
CONCENTRATION XPCTD FM FL200-FL350. NC.
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Figure 4. Notices of significant meteorological conditions (SIGMETS) issued by Anchorage National Weather Service Office for the September 16–17, 1992, eruption of Mount Spurr volcano, Alaska. Official record compiled by National Climatic Data Center, Asheville, North Carolina.

as the source of the information for the eruption indicates the good coordination between AVO and the National Weather Service during the eruption. No cloud-top information was given because the initial phase was not observed on radar. An error in the start time of eruption was corrected by reissuing SIGMET ALFA 1 at 0716 UT.

SIGMET ALFA 2 was issued at 0841 UT, 38 minutes after the onset of the main eruptive phase at 0803 UT (fig. 4), and it stayed in effect for the remainder of the eruption. Based on reports from the Kenai radar, SIGMET ALFA 2 informed pilots that the top of the ash cloud had reached 45,000 feet. This SIGMET also contained a forecast of a 180-nautical-mile-wide track for the ash cloud based on the volcanic ash forecast model (Heffter and Stunder, 1993).

The first notification to pilots of the eruption's end at 1100 UT came from SIGMET ALFA 3 (fig. 4), issued at 1223 UT on September 16. All volcano SIGMET notices from Anchorage were canceled by a SIGMET issued at 0449 UT on September 18, stating that the last reported ash cloud sighting in Alaska was at 2200 UT on September 17.

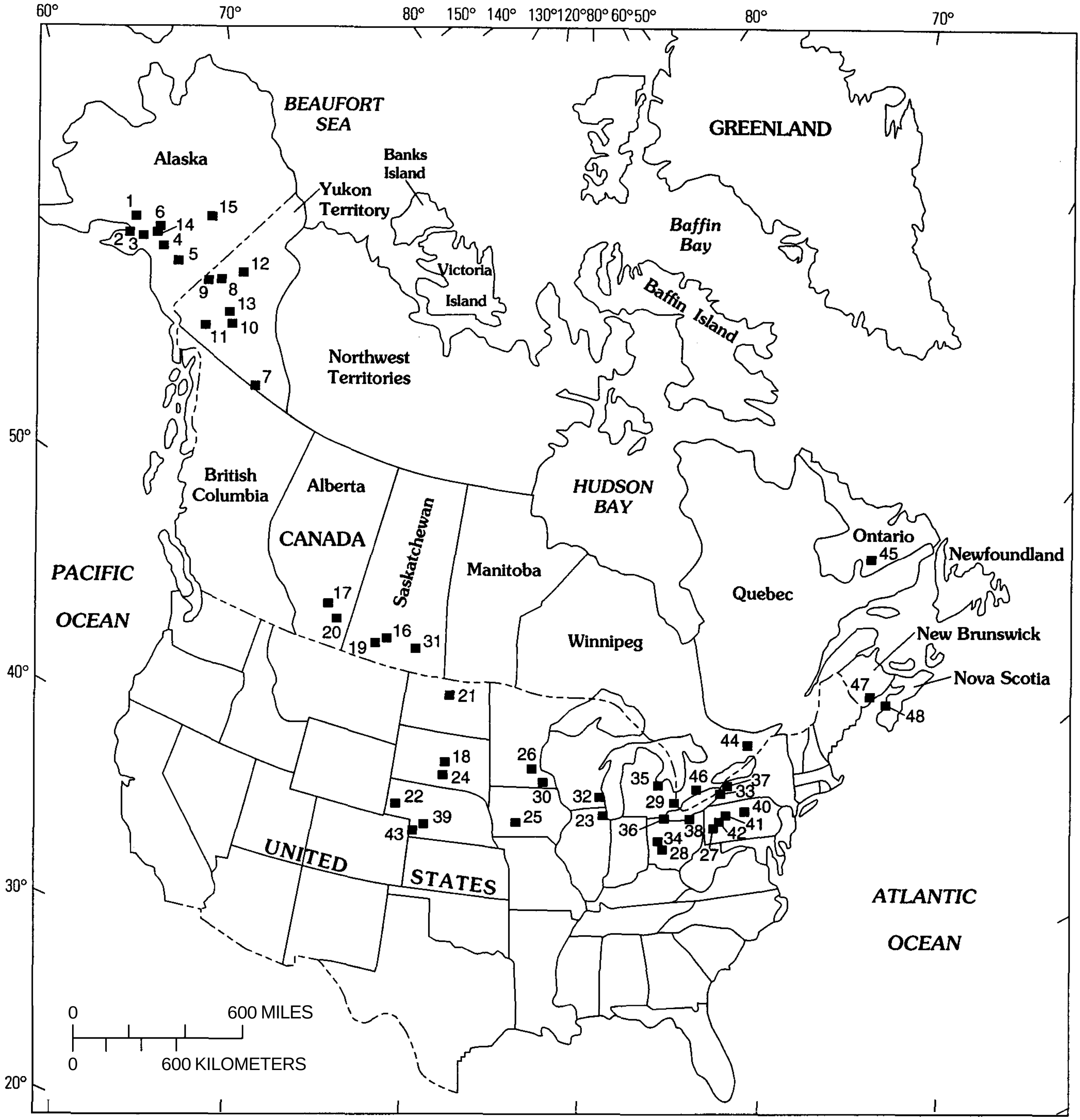

Figure 5. Positions of aircraft reporting visual observations of the September eruption cloud from Mount Spurr volcano, Alaska, as it traveled across North America. Numbers refer to locations of reporting sites listed in table 3. List compiled from data provided by G. Swanson (NOAA Synoptic Analysis Branch, written commun., 1993) and T. Spurgeon (T. Spurgeon, Transport Canada, written commun., 1993).

Satellite tracking of the cloud in Alaska and in the Yukon Territories was assisted by 24 reports from pilots and ground observers (table 3). At 0400 UT on September 18, after the cloud had been tracked into northwestern Alberta on satellite images, it became obscured by cirrus clouds (*G.* Swanson, NOAA, written commun., 1993). The next pilot sightings of the cloud were from Lumsden, Saskatchewan, and Calgary, Alberta, at 1250 UT and 1430 UT on September 18. These reports were followed by observations of the cloud from several sites in South Dakota (table **3;** fig. 5). This information was communicated to pilots through a series of SIGMETs issued from Canada and from the conterminous United States.

Eleven SIGMETs were issued by Canadian authorities starting at 1500 UT on September 17 for broad areas of British Columbia, Yukon Territories, Alberta, and Saskatchewan; these SIGMETs were based on computer model predictions for September 17 and 18. These SIGMETs stated that the ash cloud had weakened considerably, but they still advised caution. The Lumsden, Saskatchewan, pilot report (table 3) was issued as part of a SIGMET message from Edmonton at 1401 UT on September 18th, a gap of 14 hours from the last pilot report of a visual sighting at 0007 UT.

SIGMET XRAY 1, issued at 1445 UT on September 18 from both Salt Lake City and Chicago, was the first SIGMET issued in the conterminous United States, and was based on analysis of satellite imagery. This SIGMET was followed by SIGMET XRAY 2 issued at 1555 UT that was based on pilot reports over South Dakota that had been received at 1544 UT.

Twenty-five pilot reports of the cloud were recorded in the conterminous United States for September 18 and 19 (table 3), prior to the receipt of the first notification at the Cleveland Air Traffic Control Center at 1000 UT on Saturday September 19 (Howell, 1993). Fourteen additional pilot reports were recorded on September 19, including three from northeastern Nebraska. Additional pilot reports of the ash cloud continued through September 21 (table 3). The pilot reports agree well with satellite observations of ash cloud movement and validate the forecasts of cloud trajectory (Heffter and Stunder, 1993).

COHERENCY OF THE SEPTEMBER CLOUD

The remarkable coherency of the September ash cloud apparently resulted from meteorological conditions that persisted for several days after the eruption and which prevented the diffusion and dilution of the cloud. The ash cloud was injected into dense cirrostratus and altostratus clouds associated with a surface low-pressure system centered over the eastern Bering Sea. At the time of the eruption, the crest of an upper-level ridge was located at approximately 33,000 ft (10 km) over Mount Spurr. Winds at this level carried the ash east and northeast of the volcano (D. Helms, NASA, written commun., 1993).

GOES-7 satellite images showed the ash cloud as it passed beyond the layer of cirrostratus clouds over eastern Alaska and moved southeast in the polar-front jet stream toward Canada. Pilot reports documented the reappearance of the ash cloud during the morning of September 18 at about 1500 UT (figs. 5, 6; table 3). At that time, the cloud was observed forming one or more layers between 29,000 and 45,000 ft (8.8–13.7 km) in the area between western Saskatchewan and Lake Superior where an intensifying low pressure system was located.

On September 19, the ash cloud arrived in the airspace between the Great Lakes and the Mississippi Valley, trapped in the boundary of the polar jet stream. The low-pressure system that was located over Lake Superior on September 18 had moved northeast to-

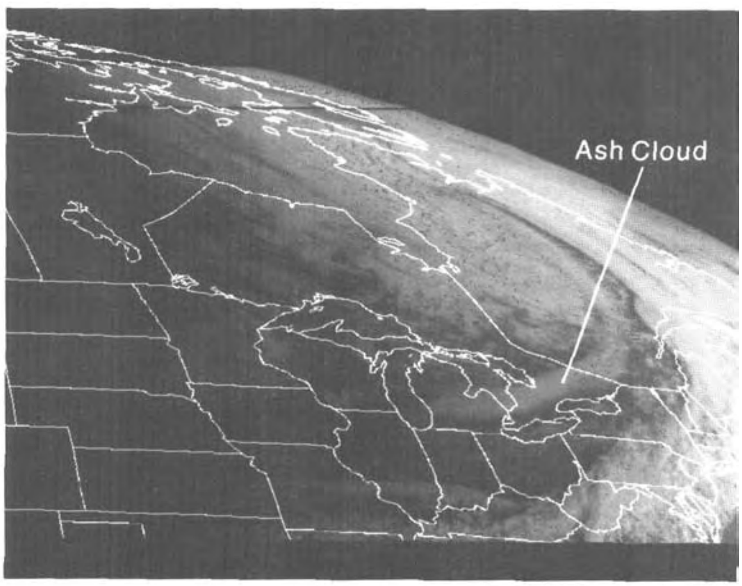

Figure 6. Image from GOES-7 satellite at dawn of September 19, 1992 (1200 UT) showing ash cloud from Mount Spurr volcano, Alaska. Cloud extends from eastern Michigan northeastward into the Canadian Maritime provinces.

ward Hudson Bay, Canada, and developed into a fully occluded system by September 19. During September 19, the ash cloud moved northeast over the St. Lawrence Seaway and ash particles were apparently concentrated because of the confluent nature of the upper-air flow (D. Helms, NASA, written commun., 1993). Through September 21, the cloud continued to move as a coherent mass visible on GOES-7 images as well as on AVHRR images (Schneider and others, this volume). Occasional pilot reports described the cloud over eastern Canada and even over the North Atlantic region (table 3; fig. 5).

EFFECTS ON AVIATION OPERATIONS

All three of the 1992 eruptions of Mount Spurr's Crater Peak vent temporarily disrupted air traffic over Alaska and western Canada. The ashfall from the August 18 eruption caused the temporary closing of the three Anchorage airports. The ash cloud from the September 16–17 eruption disrupted air traffic routing around the volcano, and several days later also disrupted traffic in the congested air corridors of the central United States, especially in the airspace managed by the Cleveland Air Traffic Center (ATC) (Howell, 1993).

AUGUST 18 ERUPTION AND ANCHORAGE AVIATION OPERATIONS

The August 18 eruption deposited approximately 1/16" to 1/8" (1 to 3 mm) of ash in the Anchorage area and resulted in the closing of the three Anchorage airports for several days. The recovery of Anchorage flight operations from the August 18 eruption required that time and money be spent to remove and clean ash from airport facilities and airplanes. The removal of ash from airport facilities and surfaces required a response effort similar to that used for snow removal. Details of the ash-removal operations at the Anchorage airports are reported in Casadevall (1993). In addition to costs associated with ash removal, the cancellation of flights resulted in the loss of revenue to both air carriers and the airport authority.

We tried to establish figures for the costs associated with the August 18 ashfall as one means to evaluate the potential benefits derived from monitoring and surveillance of the volcano as well as mitigation efforts. We report the costs associated with cleaning of the three Anchorage airports to return them to operational status, the costs associated with protecting and cleaning the planes on the ground, and the costs to the air carriers of passenger revenue lost owing to cancellation of flights. Airport officials kept records of the costs associated with the cleanup of buildings and runway and taxiway surfaces at the three Anchorage airports (fig. 2). These costs related largely to employee compensation and minor costs for filters, spare parts, and maintenance of equipment used for cleanup activities and totaled approximately $653,000. (L. Michou, Anchorage International Airport, in Casadevall, 1993).

Due to the lack of hanger space, about 30 passenger and cargo aircraft were caught unprotected on the ground at Anchorage International Airport and at Elmendorf. Prior to the ashfall, efforts were made to cover and protect these aircraft, and following the ashfall, the aircraft had to be cleaned (fig. 3) and inspected before they were returned to service. For wide-body jets, one manufacturer recommends a total of 30 person hours for preparing an airplane for ashfall (Casadevall, 1993). If a comparable time is spent cleaning an aircraft, the total time spent is approximately 60 person hours, which at a labor rate of $20 per hour computes to a cost of approximately $1,200 per wide-body airplane. For smaller passenger and cargo jets, we estimate approximately $900 per airplane. Labor costs for protecting and cleaning the 20 wide-body and 10 smaller aircraft caught on the ground are estimated to total $33,000.

The August 18 eruption and ensuing ash cloud caused cancellation of more than 100 domestic and international flights. Unfortunately, we have not been able to recover actual values associated with canceled operations such as the loss of landing fees, fuel-flowage fees, and concession fees. To estimate the revenue lost from these cancellations, we adopted the approach that was developed by Tuck and Huskey (1992) in an analysis of revenue loss attributable to the Redoubt Volcano eruption. In the Redoubt analysis, Tuck and Huskey (1992) calculated the value of $46.03 per passenger for net revenues lost to the carriers through flight cancellation. Applying this value to the Mount Spurr situation, using an average of 2,000 passengers per day for the summer tourist season, times 3 days of lost revenue, yields an estimated revenue loss of $276,000.

These costs are probably a conservative measure of several costs associated with disruptions to aviation operations due to the August 18 eruption. We have not included costs associated with loss of cargo service, loss of transit of international passengers, and loss of landing fees, fuel flowage fees, and concession fees. Secondary or indirect costs associated with the disruption, such as loss of revenues from car rentals, hotels, and meals were not considered.

SEPTEMBER 16–17,1992, ERUPTION AND AIR TRAFFIC IN THE CLEVELAND AREA

Ash from the September 16–17 eruption caused a major disturbance on September 19 to air traffic managed by the Cleveland Air Traffic Center (ATC) (Howell, 1993). This center is responsible for en-route operations in an area bounded by Saginaw, Michigan; Syracuse, New York; Elkins, West Virginia; and Fort Wayne, Indiana. This airspace includes the major terminal areas of Detroit, Cleveland, and Pittsburgh.

The first report of a volcanic ash cloud was received at Cleveland Center on September 19, 1992 at 1000 UT (6:00 a.m EDT) as a SIGMET from the National Weather Service. The ash cloud was reported to extend from Milwaukee, Wisconsin to Sherbrooke, Quebec, a distance of 710 nautical miles (1,320 km), at an altitude of 30,000 ft (9.1 km) (figs. 5, 6). Subsequent pilot reports through September 19 track the ash cloud moving steadily to the southeast. The last position reported for the cloud was over the Johnstown, Pennsylvania, area at about 1600 UT (table 3). The altitude of the cloud from pilot reports varied from 18,000 ft to 33,000 ft (5.5 to 10 km) and higher.

Because the precise altitude of the top of the ash cloud was not well known, aircraft reporting to the Cleveland center elected to descend below the cloud rather than to climb and fly over the cloud. When en-route aircraft were forced to descend below the base of the ash cloud at 18,000 ft (5.5 km), they entered the low-altitude sectors designed for managing the flow of arriving and departing aircraft. With this influx of aircraft from the high-altitude sectors, the low-altitude sectors quickly became saturated with air traffic (fig. 7). This influx caused numerous delays of as much as 30 minutes for aircraft departing terminals under

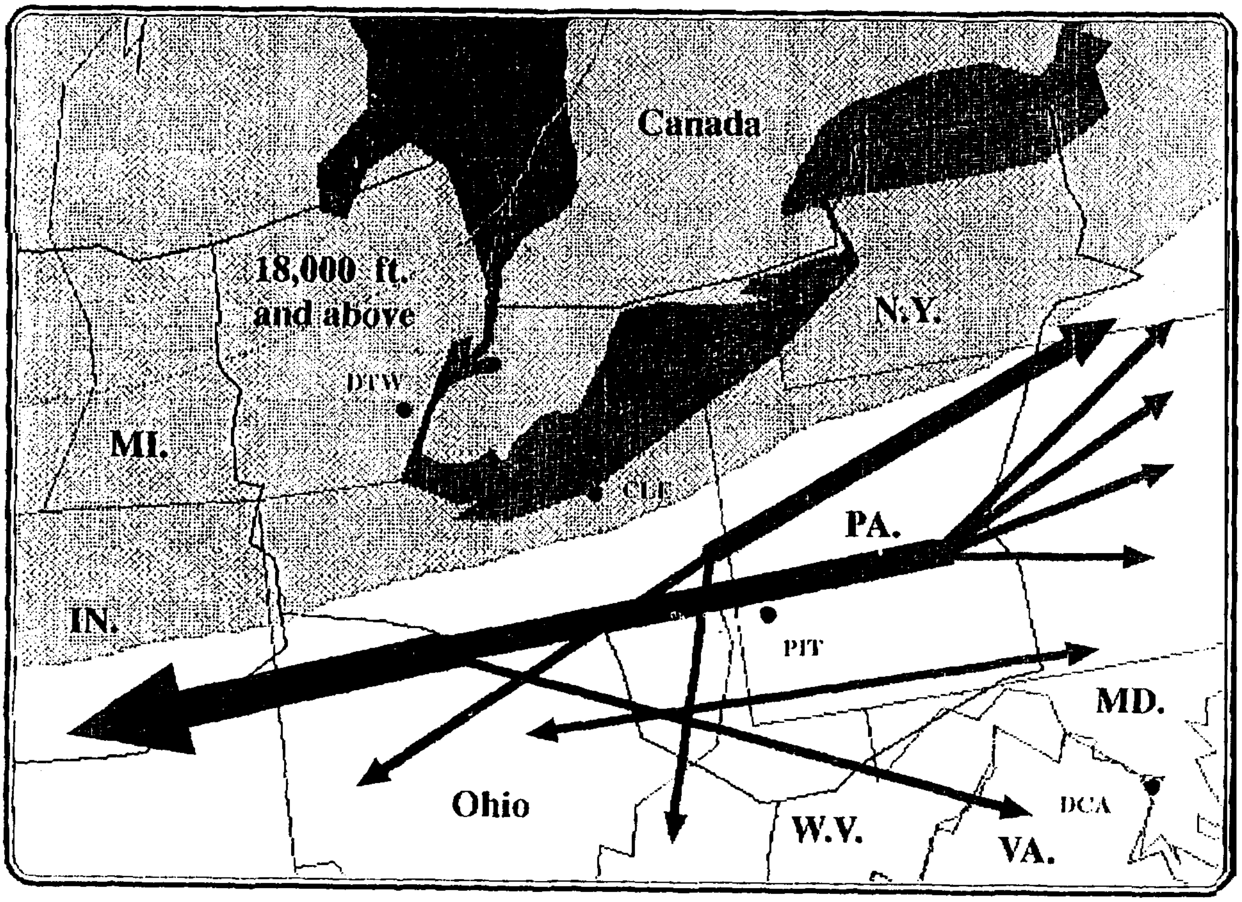

Figure 7. Schematic diagram of airspace around Cleveland Area Traffic Control Center, September 19, 1992 (1317 UT) showing compression of air routes as a result of the southward incursion of the Mount Spurr ash cloud (adapted from Howell, 1993). Dark shaded area shows outlines of Great Lakes. Light shaded area shows extent of ash cloud as interpreted from satellite imagery. Principal air routes are shown with heavy black line; arrows indicate direction of movement; line thickness indicates relative loads along the routes. DTW = Detroit; CLE = Cleveland; PIT = *Pittsburgh; DCA = Washington/Dulles.*

the control of the Cleveland ATC. As the ash cloud continued eastward, more pilots requested changes to their flight plans and additional disruptions to normal air-traffic flow took place. Air traffic operations in the airspace controlled by the Cleveland ATC returned to normal by 2300 UT on September 19 (Howell, 1993).

DISCUSSION

The three ash clouds produced by the Crater Peak vent of Mount Spurr in 1992 were each comparable in size and volume. The effects each cloud had on aviation operations were largely determined by wind dispersal patterns. The June eruption cloud had relatively little effect on air traffic because the southerly winds moved the cloud north away from busy air routes. The August eruption affected Anchorage airports because the west winds carried the ash into the Anchorage area. The September ash cloud affected the busiest en-route region in North America. Fortunately, by the time of the third eruption, the hazard notification system between the ground and air observers in and around Alaska had been used several times and was working efficiently (R. Hutcheon, NOAA, oral commun., 1993). However, in the conterminous United States, where the September ash cloud had not been expected, the air-traffic control system was forced to adjust to the cloud with additional disruption to service. Concerns about the safety aspects of this unique cloud, including its age and far-traveled nature, prompted the FAA to convene a special workshop on volcanic ash clouds held in April 1993 (Federal Aviation Administration, 1993b).

The eruption in September was distinctive because the meteorological conditions kept the ash cloud intact and visible to pilots along major air routes for about 100 hours after the eruption (table 3). The September cloud affected the air-traffic system of the conterminous United States as it passed through the heavily traveled north-central air corridor. However, no mechanical problems were recorded and the Cleveland ATC responded in an exemplary way to this major distortion of air routes. Flight delays were the only consequence of the September eruption.

The lack of damaging encounters between aircraft and ash clouds from the 1992 Crater Peak eruptions underscores the recent improvements in the ways that volcanic hazards are being addressed by personnel concerned with aviation operations. Many of the improvements in the hazard warning operations came following the 1989-90 Redoubt eruptions from national and international efforts (Casadevall, 1992, 1994a; ICAO, 1992; Casadevall and Oliveira, 1993; Hickson, 1994) to address the problem of aircraft encounters with volcanic ash. Specific advances include improved monitoring of Cook Inlet volcanoes by the Alaska Volcano Observatory (AVO, 1993); improved monitoring of meteorological conditions in the Cook Inlet region by the National Weather Service (Hufford, 1994); increased awareness and reporting of ash clouds by pilots (Fox, 1994); and refinement and utilization of computer-based forecasting of ash cloud trajectories and particle distribution (Heffter and others, 1990; Heffter and Stunder, 1993; Ellis and others, 1993; Tanaka, 1994).

Since the Redoubt eruptions, the Anchorage office of the National Weather Service has improved its ability to detect and track ash clouds (Hufford, 1994). These improvements include the installation in 1992 of a portable C-band radar on the Kenai Peninsula, which provided immediate detection of the Mount Spurr eruption columns (Rose and others, this volume). Installation of a NEXRAD (WSR-88D) weather radar system (Klazura and Imy, 1993) at Kenai in January 1994, offers several technical advances over conventional C-band weather radar and should enhance the ability to detect the onset of an ash-producing eruption from Cook Inlet volcanoes, the height of the eruption column, and the initial movement of the ash cloud away from the volcano. A newly installed wind profiler at Kenai combined with conventional radiosonde data and with wind data from aircraft overflying the area provide improved wind data for trajectory forecast models. Finally, the satellite downlink capabilities and digital-image processing have been upgraded both at the Anchorage National Weather Service office (Hufford, 1994) and at the University of Alaska in Fairbanks (Dean and Whiting, 1994) for operational application to detect and track ash clouds.

Moreover, the communication of information and warnings among agencies concerned with aviation safety has improved significantly since the 1989–90 eruptions of Redoubt Volcano (Casadevall and others, 1992; FAA, 1993a). In particular, the AVO volcano updates and color code and the volcano hazard bulletins issued by the SAB have been developed and tailored to the requirements of the aviation community in terms of timeliness and message content. In addition, agencies in Alaska have established interagency procedures and operational plans that specifically address the needs of the Alaskan theater of aviation operations (Alaska Interagency Operating Plan, 1993). Recent improvements have also been made in communications between remote field stations and aviation operations in Russia and Alaska (Miller and Kirianov, 1993) in a continuing effort to improve air safety in the North Pacific region.

Future research to mitigate ash-cloud hazards should include testing of the NEXRAD radar for detecting and tracking ash clouds, validation of remote-sensing data such as AVHRR and TOMS data, and validation of trajectory forecast models. This research would benefit from in-situ study of ash clouds, including use of unmanned vehicles to sample ash clouds (Riehle and others, 1994). More attention must be given to improve seismic monitoring of volcanoes in remote areas. Field studies are also needed to evaluate the explosivity of volcanoes, especially in remote regions such as the Kurile–Kamchatka–Aleutian volcanic arc, which parallels some of the world's busiest air routes.

SUMMARY

Ash clouds produced by the three eruptions of Mount Spurr's Crater Peak vent were comparable in size and volume to the ash clouds from the December 1989 eruptions of Redoubt Volcano (table 2), which damaged five commercial jets. Fortunately, the 1992 Crater Peak eruptions caused no damage to aircraft en-route. Like several of the Redoubt eruption clouds, the three Mount Spurr clouds also entered Canadian airspace. Two of the clouds entered airspace over the conterminous United States and significantly disrupted the flow of air traffic. This frequent incursion of ash clouds from eruptions of Cook Inlet volcanoes into Canadian and conterminous U.S. airspace highlights the need for timely communications about the threat to aviation safety from drifting ash clouds. In response to these events, U.S. and Canadian meteorologists, volcanologists, and aviation officials continue to develop procedures to provide timely warnings and advisories to pilots about drifting clouds of volcanic ash.

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