The February 2001 Eruption of Mount Cleveland, Alaska: Case Study of an Aviation Hazard

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ABSTRACT

Mount Cleveland, Alaska (52°49′N, 169°57′W), located on Chuginadak Island, erupted on 19 February 2001. The atmosphere–volcanic plume interactions that occurred as part of this event led to several serious encounters of commercial aircraft with the ash. A number of continental and oceanic air traffic control areas were affected. Here, a detailed case study of the eruption, subsequent movement of the airborne plume, and operational response is presented. The likelihood of such encounters in the future may be reduced as a result of lessons learned from this event. Some potential new assets for improving the detection of and response to the airborne volcanic ash hazard to aviation also are discussed.

1. Introduction

Airborne volcanic ash threatens aviation as soon as the volcano erupts (Miller and Casadevall 1999). Many aircraft have experienced life-threatening encounters that resulted in expensive repairs or equipment replacement (ICAO 2001). Onboard radars can only occasionally detect concentrated ash within or near eruption plumes. They cannot generally detect dilute airborne ash plumes that compound the potential hazard. Only total avoidance of the ash ensures flight safety (Campbell 1994; Hinds and Salinas 1998). Such avoidance cannot now be achieved, although operational units strive to do so.

Operational issuance of warnings, advisories, and information requires a rapid, accurate detection of the eruption and continued tracking of its ash plume (Miller 1994; Hufford et al. 2000). Many scientific and operational challenges make the needed real-time response difficult (Servranckx 1999). Because most active volcanoes are located in remote and seismically uninstrumented sites (e.g., Mount Cleveland, Alaska), the operational response has relied heavily on satellite remote sensing, including the ''split-window'' method of detection. It evaluates the Advanced Very High Resolution Radiometer (or equivalent) 11-μm (T_4) and 12-μm (T_5) brightness temperature difference ($\Delta T = T_4 - T_5$). Meteorological clouds have positive ΔT (Yamanouchi et al. 1987), and volcanic plumes have negative ΔT (e.g., Prata 1989). Class separation is especially difficult as ΔT approaches 0. In fact, volcanoes with low levels of silicate in their plumes (e.g., Soufriere Hills, Montserrat; Bogoslof, White Island, New Zealand) are especially difficult to differentiate from meteorological clouds. See Simpson et al. (2000) for details.

The Smithsonian Institution volcano catalog (Simkin and Siebert 1994) lists 268 volcanoes in Alaska, Kamchatka, and the Kurile Islands that have been active over Holocene time (<10 000 yr BP). Of these, 158 have been active over historical time, and most flights that transit the Arctic/North Pacific fly near them. Features of the polar atmosphere (e.g., large amounts of cloud cover, arctic haze, high shear), however, make accurate tracking of an ash plume difficult.

This case study 1) describes the meteorological conditions present when Mount Cleveland erupted, 2) identifies some of the difficulties associated with the real-time detection and response to such an event, 3) highlights some strengths and weaknesses of the currently available satellite remote sensing methods in detecting the ash cloud from Mount Cleveland, 4) documents several serious encounters of commercial aircraft with the volcanic ash plume, 5) describes the meteorological operational response to the eruption and factors that affected it, and 6) suggests specific areas of improvement for future events. The paper neither assigns blame nor focuses on errors that might have been made in response

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TABLE 1. Airborne volcanic ash sightings by commercial pilots (PIREPs filed with FAA). PIREPs 2, 2b, 3, 4, and 6 were distributed on the WMO GTS. PIREPs 1, 5, and 7 were received at the FAA Oakland and/or Anchorage air route traffic control centers.

Date (2001)	Time (UTC)	Identifier	Location		Aircraft	Flight level	Remarks
			Lat (N)	Lon (W)			
19 Feb	1833	1	52°49′	169°57′	B-99	—	First aircraft report regarding eruption.
19 Feb	2210	2	54°	169°	DC-10	350	Ash moving SSE at FL 350 at 25 kt. [Note: based on the full pilot report, satellite imagery, and meteorological data, there is good evidence that the reported wind direction at flight level (156° at 25 kt) was mistaken for the direction of motion of the ash cloud. We believe that the correct direction was NNW. Another possibility is that the word "from" was forgotten (i.e., the PIREP should simply read "ash moving from SSE at 25 kt").]
19 Feb	2112	2b	52°43′	169°19′	PA-31	100	Ash plume first layer tops 100 drifting 120°, second layer top 250/300 drifting 330–360.
19 Feb	2257	3	53°54′	166°32′	B-737	340	Plume at all levels drifting ESE.
20 Feb	0135	4	48°30′	162°	B-747	360	Ash and sulfur odor in cockpit.
20 Feb	0150	5	49°10′	168°	—	360	Cinders and sulfur odor in cockpit.
21 Feb	0543	6	64°45′	165°26′	DC-6	100	Can see volcanic ash plume well above present altitude extending northward along the coast of the Seward Peninsula.
22 Feb	1408	7	37°	123°	B-747	300	Particles and strong odor in the cockpit.

to the eruption. Rather, the likelihood of future aircraft–volcanic ash encounters may be reduced as a result of lessons learned from this event.

2. Definition of serious encounter

Responsibility for a volcanic hazard in the United States is shared by several agencies. Thus, a ''serious encounter'' often has an agency-specific meaning. This paper deals with the interaction among airborne volcanic ash, the atmosphere, and aircraft. The National Weather Service (NWS) is the U.S. agency charged with meeting International Civil Aviation Organization (ICAO) needs in this area. ICAO (2001) defines an ash-encounter severity index (scale of 0–5). Three of the pilot reports for the Mount Cleveland eruption (Table 1) have an index value of 0 or 1. The occurrence of any of the criteria defining the index is sufficient to classify the encounter as serious (R. Romero, ICAO Meteorological Section, 2001, personal communication). Given this definition, the fact that ICAO recognizes the pilot as an official observer who is required to report weather hazards encountered while in flight, and that total avoidance of volcanic ash is desired, we assert that the Mount Cleveland aircraft–ash encounters must be considered to be serious.

3. Mount Cleveland volcano

Mount Cleveland (52°49′N, 169°57′W) is a symmetrical andesitic stratovolcano located on the western half of Chuginadak Island, 490 km west of the tip of the Alaskan Peninsula (Fig. 1a). It is part of the east-central portion of the Aleutian arc commonly called the Islands of the Four Mountains. It composes the western half of the island, it has a basal diameter of 8 km, and its summit vent is about 1730 m above sea level (ASL). No caldera is present, and all current activity is centered on the summit vent, from which numerous large lava flows have issued.

Because this area is uninhabited, historical information on eruptive activity is sparse. Mount Cleveland probably has erupted at least 14 times since 1893. Persistent fumarolic activity was observed in the 1980s and 1990s, with periodic reports of ash, steam, minor lava flows, summit incandescence, active lava fountaining, and dome building within the summit crater. Eruption plumes up to about 10 km ASL occurred in August of 1987 and May of 1994. Thus, it is one of the most active volcanoes in the Aleutian chain.

4. Case study: Meteorological conditions, remote sensing, and modeling

a. Meteorological background

1) THE POLAR ATMOSPHERE

Upper-air observations (Table 2) from relevant Alaskan NWS stations (Fig. 1a) show that the upper troposphere for all of these stations was extremely dry. Four of these stations (St. Paul Island, Bethel, King Salmon, McGrath) were also very dry in the lower troposphere. For these stations, moisture was confined to a shallow boundary layer (<200 m). A deep moist lower layer characterized Cold Bay (1844 m), Anchorage (2400 m), and Yakutat (2900 m).

Radiosonde data from stations near to and downwind of Mount Cleveland showed a general pattern of wind from the south at greater than 25 kt (12.9 m s^{-1}) above 300 hPa (8750 m) and from the north-northwest at 35 kt below 300 hPa, producing a strong shear near 8750 m.

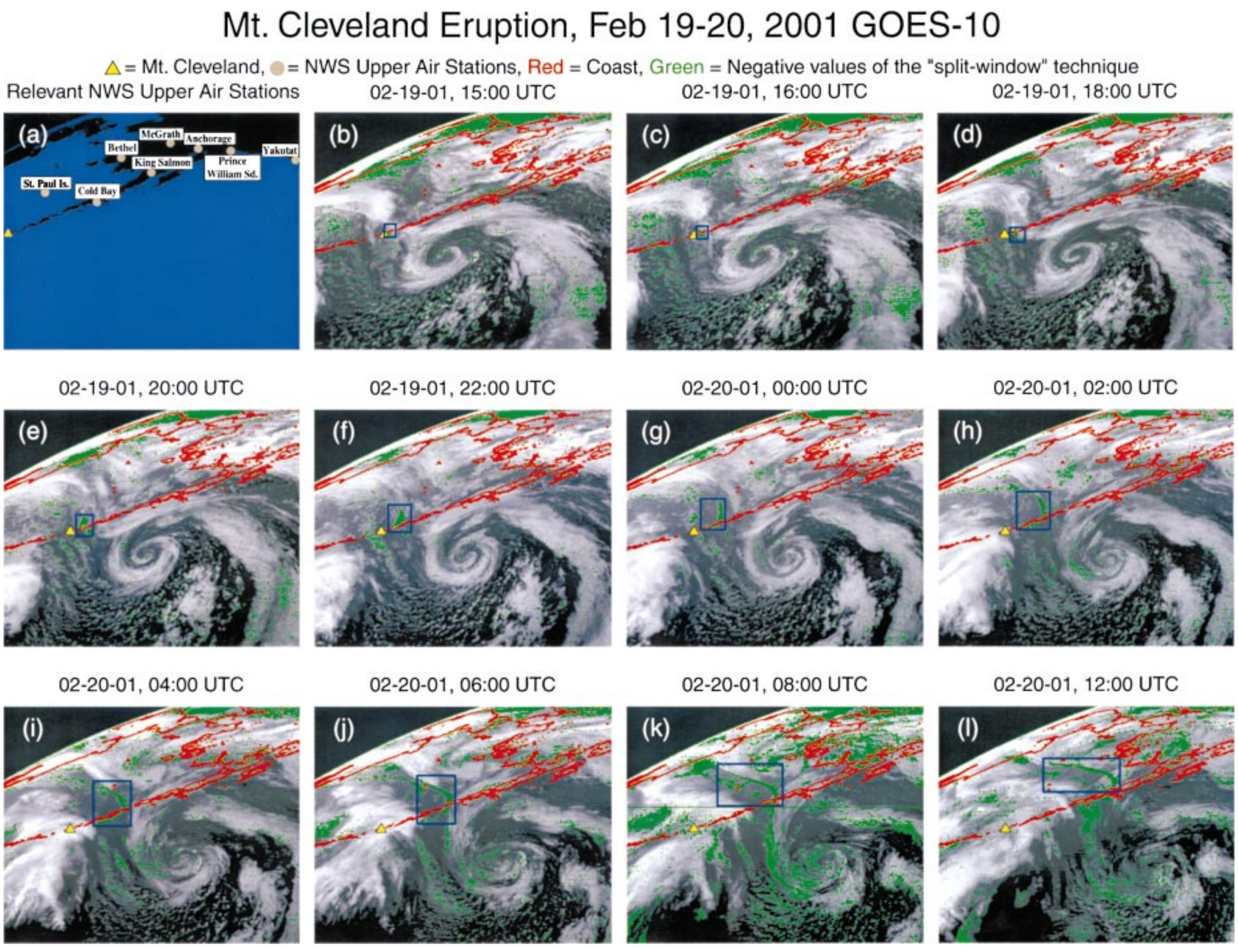

FIG. 1. (a) Upper-air stations; (b)–(l) time series of *GOES-10* 11-μm BT data. See the text for details.

2) THE EXTRATROPICAL INFLUENCE

An extratropical storm originated east of Japan, continued eastward across the Pacific south of the Aleutian Islands, and followed the typical storm track into the Gulf of Alaska. The storm is clearly visible in *Geostationary Operational Environmental Satellite-10* (*GOES-10*) 11-μm brightness temperature (BT) data for the period (Fig. 1). Its low pressure center varied from 969 (0000 UTC 20 February 2001) to 1006 hPa. Winds south of the eastern Aleutians/Alaska Peninsula were dominated by this extratropical storm.

There are no radiosonde data to compute the total precipitable water vapor for the extratropical storm, but *GOES-10* sounder data at 0600 UTC 20 February 2001 were examined. This 19-channel instrument measures atmospheric moisture profiles. Errors are within 15% of radiosonde data for the same site (D. G. Gray 1998, personal communication). Cloud-free fields of view (10 km at nadir) were used to generate the profiles. Data from four sites within the comma cloud of the extratropical storm were analyzed using Man–Computer Interactive Data Access System software at the University of Wisconsin. Total precipitable water ranged from 1.06 to 1.32 in. Thus, air associated with the extratropical storm was about 4–6 times wetter than the dry polar air north of the Aleutians (also see Table 2).

b. Remote sensing of the Mount Cleveland ash plume

1) OVERVIEW

Radiosonde data at Cold Bay, Alaska (Fig. 1a), indicated high-level winds from the SSW at 35 kt. Below 350 hPa, however, the winds were from the NNW at 35 kt. Pilot reports (PIREPs) (Table 1) are consistent with the radiosonde data; north of the Aleutian Islands the ash moved primarily NNE whereas south of the Aleutians it moved primarily SSE.

The Arctic air was dry. The extratropical storm, however, brought moisture and optically thick clouds into the region south of the Aleutians. These meteorological conditions made the split-window technique much more effective in detecting the ash plume north of the Aleutians than south of them [see Simpson et al. (2000) for factors restricting the operational effectiveness of the

TABLE 2. NWS upper-air observations [TP is tropopause height, FRZ is freezing level, PW is total precipitable water, and RH is relative humidity (total column)].

Time (UTC)	Location	Lat (N)	Lon (W)	WMO No.	TP (m)	FRZ (m)	PW (in.)	RH (%)
			20 Feb 2001					
1200	Bethel	60°46.79′	161°50.28′	70219	9860	0	0.20	36.8
0000	St. Paul Island	57°10.04′	171°13.23′	70308	9018	127	0.28	60.9
0000	Cold Bay	55°12.34′	162°43.46′	70316	9662	31	0.32	83.0
1200	Cold Bay	55°12.34′	162°43.46′	70316	9711	420	0.37	67.6
			21 Feb 2001					
0000	Anchorage	61°10.46′	149°59.77′	70273	9841	703	0.40	84.2
1200	Anchorage	61°10.46′	149°59.77′	70273	9502	95	0.38	68.5
0000	King Salmon	58°40.61′	156°38.95′	70326	9457	171	0.18	34.3
0000	McGrath	62°57.17′	155°36.35′	70231	9463	0	0.18	44.2
0000	Yakutat	59°30.20′	139°39.61′	70361	10080	987	0.42	78.7
1200	Yakutat	59°30.20′	139°39.61′	70361	9897	565	0.44	62.1

split-window technique]. Thus, each region is treated separately.

2) THE NORTH-NORTHEAST COMPONENT OF THE PLUME

A time series of *GOES-10* 11-μm BTs (Fig. 1) starts at 1500 UTC 19 February 2001. The blue boxes bound the major features of the volcanic ash plume northward of the Aleutians. Pixels identified as airborne volcanic ash by the current operational split-window technique ($T_4 - T_5 < 0$) appear green. Other threshold values (e.g., -0.5 K) have also been studied (Schneider et al. 1995). For a variety of reasons (e.g., Simpson et al. 2000; Schneider et al. 1995; Prata 1989), the split-window technique can either underdetect or overdetect airborne volcanic ash. A reliable negative threshold to differentiate volcanic ash from other meteorological phenomena has not yet been determined. In fact, a unique threshold suitable for different types of volcanic plumes and atmospheres probably does not exist, and it may very well vary between different sensors. Ice and water, when mixed with volcanic debris, for example, yield a ΔT that may be positive, negative, or zero; the optically thick case may be the most difficult to interpret (Prata and Barton 1994). Nonetheless, the split-window method detects a clearly discernible airborne volcanic ash signal in *GOES-10* data northward of the Aleutians. Many of the pixels (green) north and far away from the blue boxes, however, are probably not volcanic ash.

Space–time variation in the NNE plume was tracked by temporal compositing ($\Delta t = 2$ h) of plume signatures computed from *GOES-10* data taken from 1400 UTC 19 February to 1400 UTC 21 February 2001 using the split-window technique. The classification is laid down on top of a base image with land and deep space shown as black and ocean shown as light blue. To aid visual enhancement, pixels with a $\Delta T \geq -1$ or that occurred as isolated pixels with $\Delta T < -1$ were not overlaid onto the base map. The composite (Fig. 2) clearly shows movement of the NNE plume from the source, up the Alaskan Peninsula, and over southwest Alaska. A high pressure region occurred over north-central interior Alaska; it deflected part of the NNE plume SSE into the region of Prince William Sound (Fig. 3).

3) THE SOUTH-SOUTHEAST COMPONENT OF THE PLUME

The Alaska Volcano Observatory estimated that the eruption began at about 1500 UTC 19 February 2001. Some PIREPs (Table 1, PIREPs 2b and 3) provide visual evidence of airborne volcanic ash generally moving in an ESE and/or SSE direction between flight levels (FL) 340 and 360 for about a 10-h period after the estimated start of the eruption.

The split-window technique detected a SSE component of the plume from about 1600 UTC 19 February 2001 through about 0000 UTC 20 February 2001 (Figs. 1c–g, blue boxes). These signatures, consistent with the PIREPs cited above, are distinct from the NNE plume described earlier. Much of the SSE plume was entrained into the comma cloud of the extratropical storm during the initial hours of the eruption (Fig. 1).

By 0800 UTC 20 February 2001 the NNE plume was near Cold Bay. Here, part of it was entrained into the high-level deformation zone associated with the comma cloud head of the extratropical storm (Fig. 1k). This deformation and entrainment process added to the total component of ash being transported at high elevation by the SSE plume.

The extratropical storm emphatically complicated interpretation of the split-window volcanic ash retrieval. During the well-developed stage of an extratropical storm, the comma cloud consists of distinct cold dry bands and warm moist bands. Although strong vertical motions occur in comma clouds prior to frontal occlusion, little horizontal mixing occurs across the bands. Volcanic ash is more easily detected by the split-window technique in the colder, drier bands. Once frontal occlusion has occurred, the storm generally weakens and the well-developed distinct bands dissipates. Available

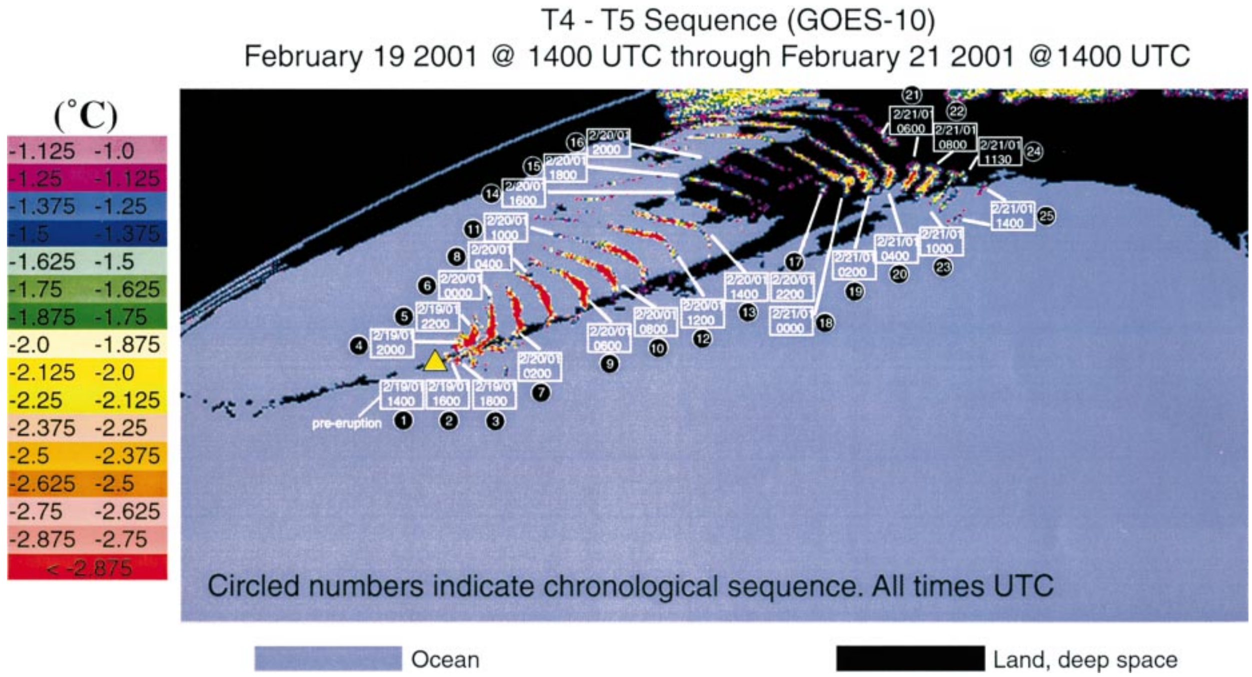

FIG. 2. Temporal composite of the NNE plume. See the text for details.

moisture now complicates tracking of volcanic ash with the split-window technique (Fig. 1l).

Upper-level air support for the extratropical storm significantly weakened by 1200 UTC 20 February 2001 (Fig. 1l). The SSE transport of the plume continued long after the absence of discernible upper-level cloud evidence in the satellite data.

c. Numerical simulations

Two operational models are used for emergency response at the Canadian Meteorological Centre (CMC). A simple three-dimensional Lagrangian trajectory model (CMC 2001) quickly estimates the origin or destination of an air ''parcel'' from a specific point in time and space but does not include processes such as diffusion or mixing of the pollutant. Diagnostic, prognostic, and time-forward or -backward modes are supported. Hereinafter, it is called the trajectory model.

The second model, the Canadian Emergency Response Model (CANERM), is a three-dimensional Eulerian model for medium- to long-range transport of pollutants (volcanic ash, radioactive plumes, etc.) in the atmosphere (Pudykiewicz 1988; CMC 2001). It is used when the space–time structure of the wind is complex or when the release of the pollutant occurs over many hours or days. The source of emission is modeled as a virtual source (Pudykiewicz 1989). It accounts for subgrid-scale effects near the point of release and is implemented as a 3D Gaussian function. Simulations compare well with data from field experiments (D'Amours 1998). The operational version of CANERM used at CMC has 25 vertical eta levels and horizontal grid spacing of 5–50 km.

Meteorological data used by both models are provided by the CMC global data assimilation and forecast systems. The simulations of the Mount Cleveland eruption shown herein were produced using the following initial conditions: 1) horizontal grid, 25 km; 2) horizontal distribution at the source, Gaussian using a standard deviation of 1 grid point; 3) vertical distribution at the source, constant from the surface to 10 668 m (FL 350); 4) eruption start, 1500 UTC 19 February 2001; and 5) eruption duration, 1 h.

Ash trajectories depicting the ''visual volcanic ash cloud'' were computed with CANERM for three flight-level ranges: surface–FL 200, FL 200–FL 350, and FL 350–FL 600 (ICAO 1998). Note that there is no internationally accepted definition of a visual volcanic ash cloud. A single value for all situations may not exist. For CANERM, the threshold value defining this quantity (100 μg m^{-3} average layer volcanic ash density) was obtained from modeling studies of the 1992 eruptions of Mount Spurr (Keith 1995). Because of the large uncertainties involved, the operational CANERM charts normally display values starting at 10 μg m^{-3}. The 10 μg m^{-3} contour frequently overestimates the area covered by the ash cloud when compared with that detected by satellite, especially at some distance (space and/or time) from the source. Little ash appeared above FL 350 in the simulations; results above FL 350 are not shown.

Time series of the CANERM forecast of visual ash plume from the Mount Cleveland eruption from the surface to FL 200 and from FL 200 to FL 350 (Figs. 4a,b;

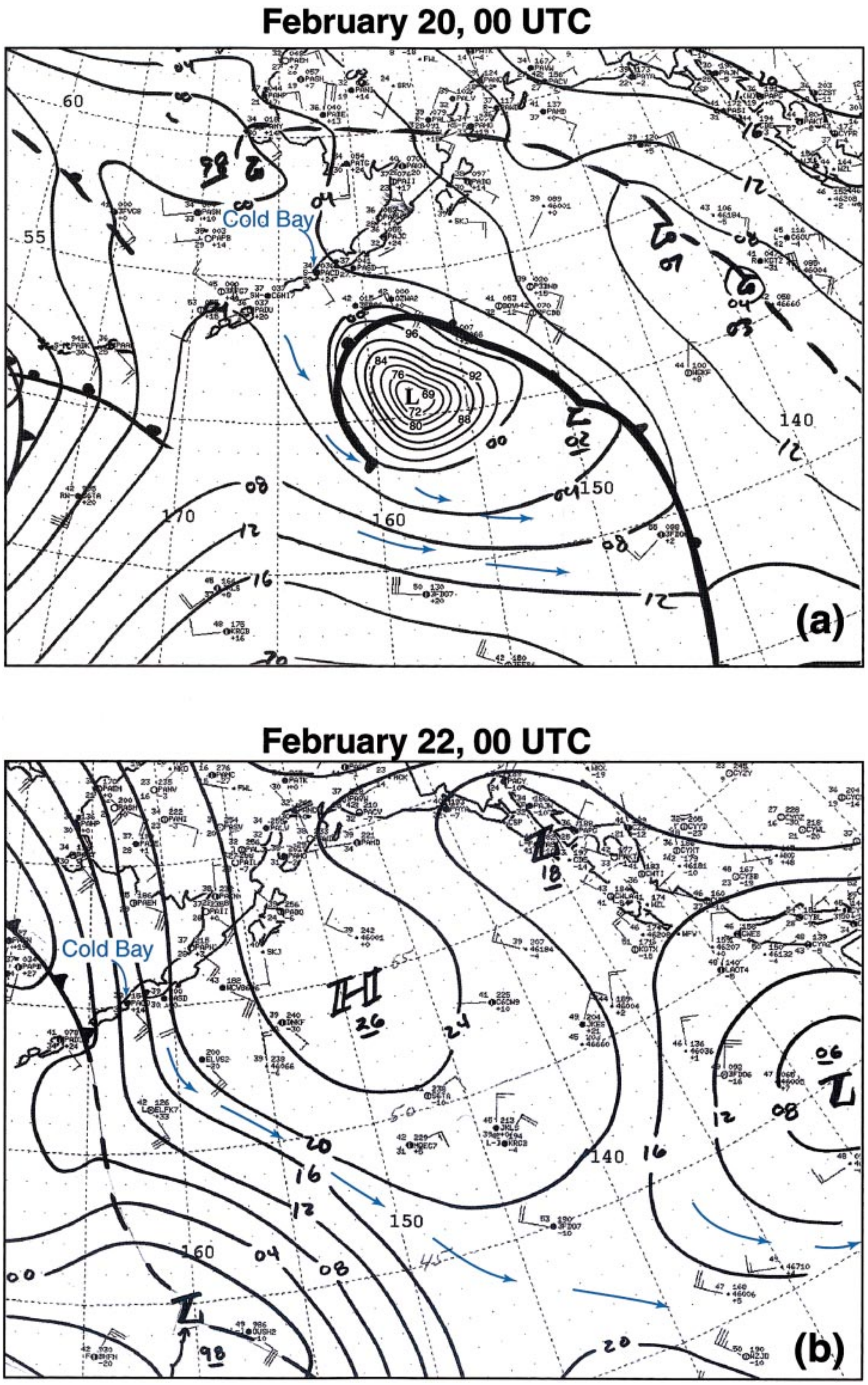

FIG. 3. (a) Surface analysis showing the extratropical storm. A high over Alaska deflected part of the NNE plume into Prince William Sound. (b) Extratropical storm 48 h later.

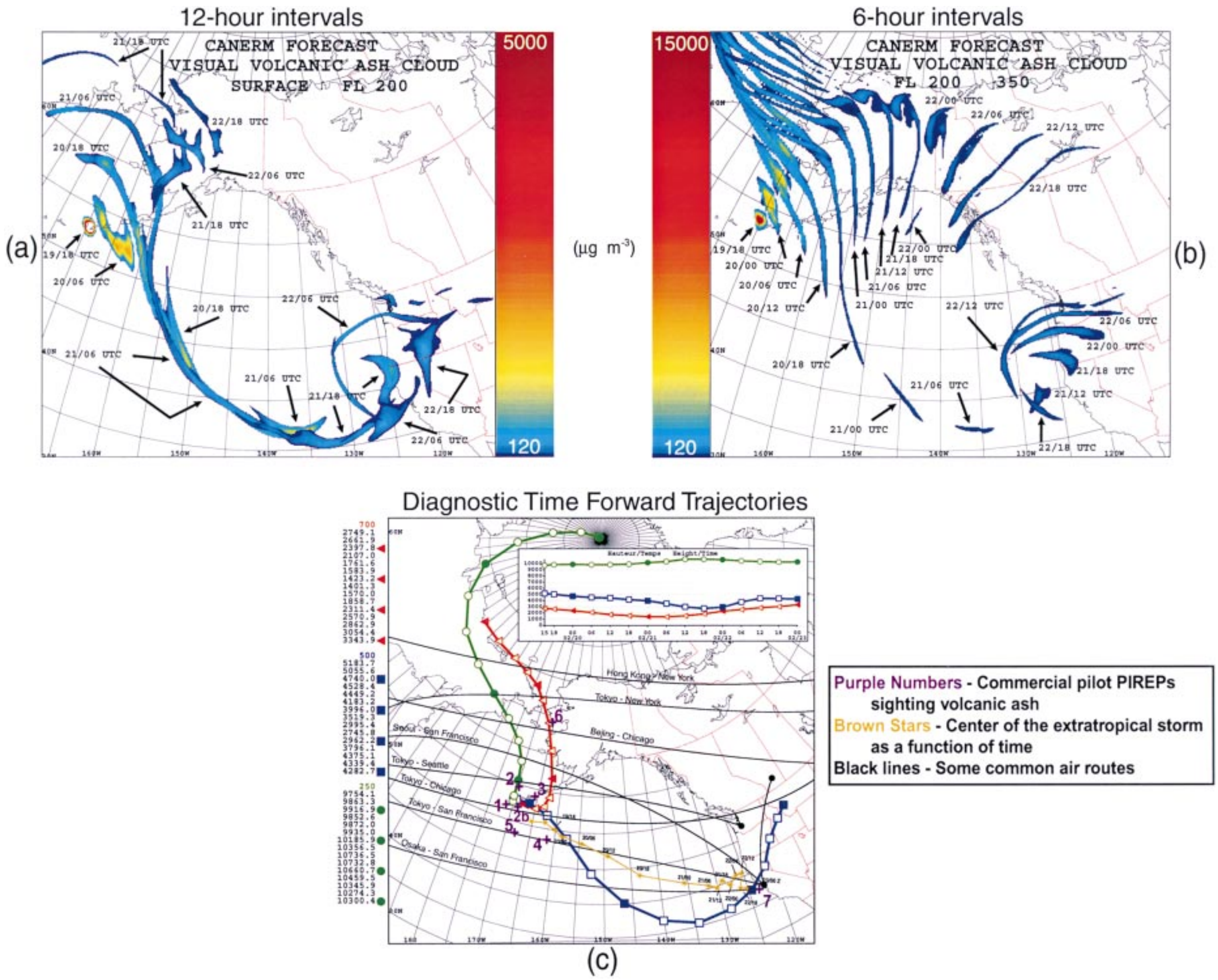

FIG. 4. CANERM forecasts of visual volcanic ash plume in layer from (a) the surface to FL 200 and (b) FL 200 to FL 350. (c) Diagnostic time-forward trajectories starting at 1500 UTC 19 Feb 2001 for 700, 500, and 250 hPa. See the text for details.

with a 120 μg m^{-3} threshold to allow a better separation of the ash plume at various times) agree reasonably well with the trajectories of the ash plume inferred independently from satellite data: 1) at high levels, most of the ash initially moves NNE (FL 200–FL 350); 2) at the lower flight level (surface–FL 200) the ash centroid moves toward the SSE; 3) later in the simulation (1200 UTC 20 February) the SSE transport of volcanic ash increases consistent with entrainment by the extratropical storm (see Fig. 1j and related discussion); and 4) transport continues in a SSE direction long after evidence for upper-level air support for the storm has vanished from the satellite data.

Individual diagnostic time-forward trajectories (Fig. 4c) are consistent with PIREPs sighting ash (Table 1). The purple numbers in Fig. 4c indicate a specific PIREP. The predicted position at 1200 UTC 22 February is consistent with the probable ash encounter of a Boeing-747 (B-747) aircraft off the coast of California (37°N, 123°W). Ash entrained by the comma cloud of the extratropical storm would have followed a trajectory similar to that in blue.

Figure 5a is a different backward diagnostic trajectory using the exact date, time, location, and flight level of PIREP 7 off of California. The 9.1-km (FL 300) trajectory does not come close to Mount Cleveland. The 3.0-km one, however, tracks back directly to Mount Cleveland between 1200 and 1800 UTC on 19 February. Possible reasons for the apparent inconsistency between the back trajectory at FL 300 and PIREP 7 include the following. 1) If the plane encountered volcanic ash at FL 300, errors in and limited space–time resolution of the diagnostic wind field used to drive the trajectory model could result in a bad back trajectory. This reason is very unlikely based on many trajectory case studies done at CMC. 2) The plane encountered volcanic ash at a different encounter time, altitude, or location from those of PIREP 7 (e.g., the B-747 either was in ascent or descent at the time of either the encounter or the PIREP). 3) The plane did not encounter volcanic ash.

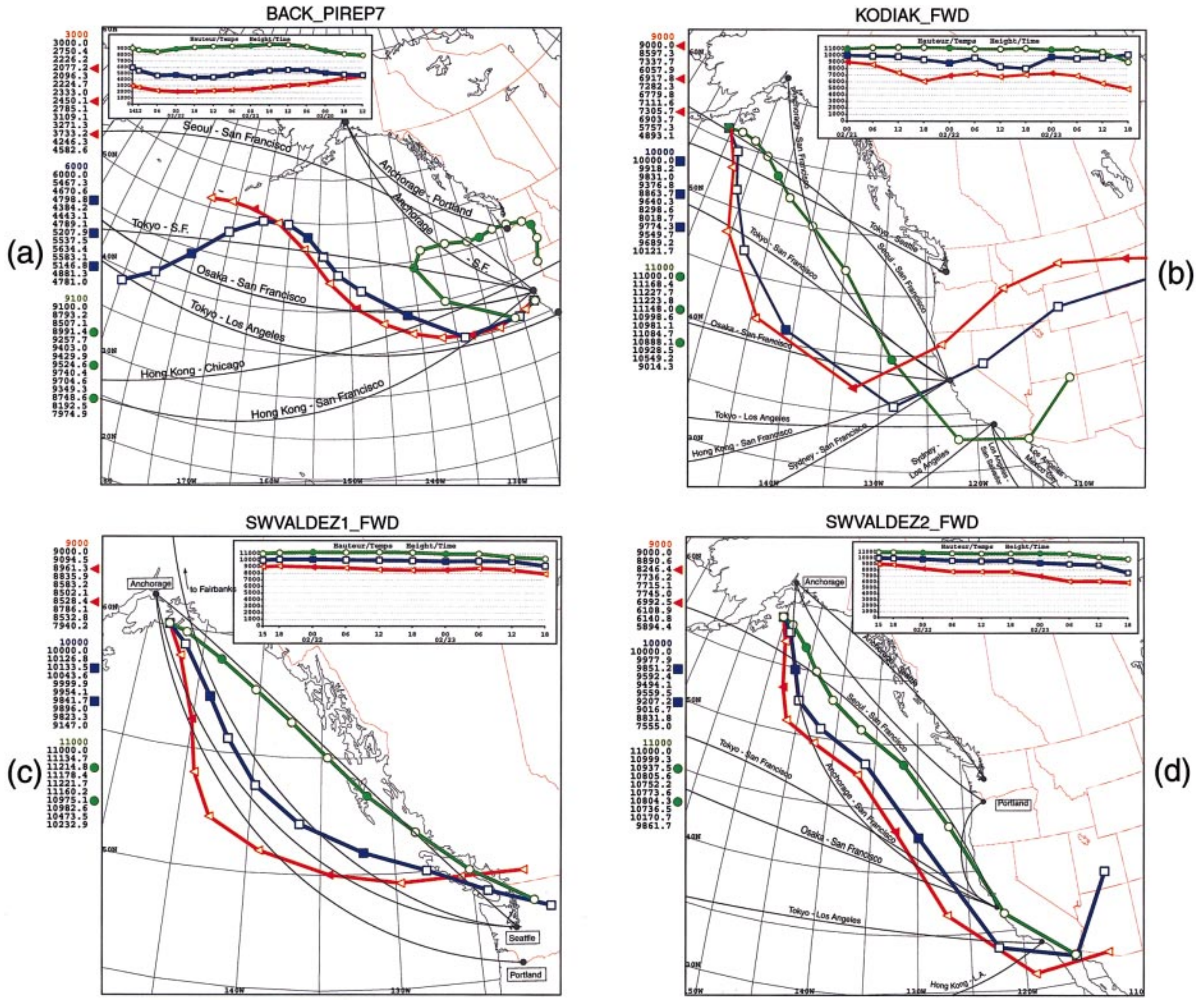

FIG. 5. (a) Diagnostic time-backward trajectories at 3.0, 6.0, and 9.1 km from the location of PIREP 7 at 1400 UTC 22 Feb. (b) Diagnostic time-forward trajectories at 9.0, 10.0, and 11.0 km using Kodiak Island as source at 0000 UTC 21 Feb. (c) Same as in (b) but with a point southwest of Valdez as source at 1500 UTC 21 Feb. (d) Same as in (c) but with source point moved eastward. Some air routes are shown (black). See the text for details.

If we assume that volcanic ash was encountered, then back-trajectory modeling (Fig. 5a) strongly suggests that it came from the Mount Cleveland eruption and that the altitude of the encounter was significantly lower than FL 300 of PIREP 7. This finding has important implications (see below).

The satellite data (Fig. 2) and the surface analysis (Fig. 3) indicate that part of the NNE plume was deflected by the high pressure system over central Alaska toward both Kodiak Island and into Prince William Sound. Forward-trajectory model simulations, using Kodiak Island and a point southwest of Valdez, Alaska, as source points, produce trajectories (Figs. 5b and 5d, respectively) consistent with the advection of ash toward California, but the timing of the ash is not totally consistent in time or space with PIREP 7. Thus, we postulate that if the plane encountered ash, it was at a lower altitude than FL 300 and that the ash came from the SSE component of the plume.

Strong horizontal and vertical shear characterized the wind field during this event. A different time-forward diagnostic trajectory model simulation for a second point southwest of Valdez (Fig. 5c) shows a different ash trajectory than that in Fig. 5d; this difference is consistent with differences in the wind field as one moves the source from west to east.

5. Case study: Analysis and discussion

a. Synthesis of the Mount Cleveland, Alaska, February 2001 eruption

On 19 February 2001 Mount Cleveland produced a volcanic ash plume to FL 350–FL 360 as confirmed by several PIREPs (Table 1). Part of the plume moved in a north-northeast direction (Fig. 2). The split-window technique successfully tracked the NNE plume because atmospheric conditions (e.g., relatively small amounts of cloud cover, dry atmosphere; Table 2) generally were favorable for detection. By 21 February 2001, a high pressure system over north-central Alaska deflected part of the NNE plume into Prince William Sound.

From the onset of the eruption, a separate component of the plume traveled in the SSE direction. Ash in the SSE plume at FL 340–FL 360 was confirmed by PIREPs shortly after the eruption began (Table 1). PIREPs also confirmed that SSE transport of volcanic ash continued for several days after the eruption. There unfortunately is a 56-h gap between PIREP 6 and PIREP 7, which made it very hard to assume a priori that ash would be aloft so long, although there are well-documented cases of long-lived ash plumes.

Meteorological factors compromised satellite-based detection of the SSE plume using the split-window technique. First, as the NNE plume moved toward Cold Bay, it encountered a thin, intense high-level shear zone. Part of the volcanic ash in the NNE plume was advected south by the southward portion of the shear zone and entrained into the comma cloud of an extratropical storm that had moved into the area (Fig. 1). This entrained material (particles typically less than 100 μm in size with typical residence times of many days) contributed to the overall component of the airborne volcanic ash headed SSE.

Moisture bands and optically thick clouds associated with the extratropical storm prevented satellite detection of the enhanced SSE plume (original component plus material entrained from the NNE plume near Cold Bay) by the split-window technique. To be specific, the $T_4 - T_5$ signature of the NNE plume was much stronger and more spatially/temporally coherent than that of the SSE plume because of different meteorological conditions north and south of the Aleutians, even though the SSE plume was enhanced by entrainment of ash from the NNE plume near Cold Bay. As upper-level air support for the extratropical storm weakened, moisture mixed across bands in the comma cloud. The $T_4 - T_5$ signal eventually became so difficult to interpret that volcanic ash in the SSE plume could no longer be clearly identified, and warnings were ended. The operational focus then shifted entirely to the NNE portion of the plume. As the CANERM model suggests, some volcanic ash unfortunately appears to have been transported SSE. Indeed, on 22 February 2001, a B-747 aircraft encountered what appeared to be volcanic ash off of the coast of California (37°N, 123°W). The altitude of the plane at the time the PIREP was produced was FL 300. The PIREP states, ''particles and strong (sulfur) odor in the cockpit.''

b. *Analysis of an operational response*

Operational response to an airborne volcanic ash hazard requires rapid, accurate detection of the volcanic eruption and continual tracking of its ash plume. To initiate predictive models, the forecaster must know the initial height and horizontal extent of the plume and the vertical profiles of wind speed and direction at the eruption site and downwind of the volcano. Constant coordination among responsible agencies is needed (Hufford et al. 2000). For this eruption, several operational issues arose that could have seriously jeopardized aircraft.

1) RAPID NOTIFICATION

The Alaskan Interagency Operating Plan for Volcanic Ash Episodes (NWS 2001) assigns the U.S. Geological Survey Alaska Volcano Observatory (AVO) with the task of alerting the aviation community, government agencies, and the public to the potential or actual eruption of a volcano. NWS has the responsibility to provide all parties with warnings, forecasts, and advisories for airborne volcanic ash. The plan also requires NWS to assist the AVO in monitoring volcanic eruptions whenever it can.

Notification of the event did not occur until about 3.5 h after the estimated initial eruption. The split-window method showed strong negative values in a *GOES-10* image at 1500 UTC. A PIREP was received at 1833 UTC stating that the volcano had erupted. The aviation community was warned by an Alaskan Aviation Weather Unit (AAWU) significant weather warning (SIGMET) issued at 1835 UTC followed by a Volcanic Ash Advisory Statement (VAAS) alert at 1940 UTC. By this time, the split-window satellite imagery showed the airborne ash in diffluent flow. The NNE portion had extended northward 120 km while the SSE portion extended 150 km SSE from Mount Cleveland, and the ash had entered into the major air routes. See the appendix for a more detailed assessment of the initial timing of the eruption.

2) PLUME HEIGHT ASSIGNMENT

The initial cloud-height estimates of 30 000 ft for the NNE plume and 17 000 ft for the SSE plume came from an AVO information release issued at 1930 UTC. The VAAS alert issued at 1940 UTC by the AAWU gave an estimated height of 30 000 ft for both the NNE and SSE plumes. The second SIGMET issued by the AAWU at 2019 UTC continued to estimate the NNE and SSE plume heights at 30 000 ft. The third SIGMET issued at 2203 UTC put the SSE plume height at 10 000 ft based on PIREP 2b (Table 1). Air carriers continued to operate in this zone in the absence of any recommendation to the contrary by regulatory agencies. However, subsequent PIREPs (Table 1) all indicated that both ash portions were near 35 000 ft, right in the flight path. The fourth SIGMET issued at 0220 UTC 20 February had tops of FL 200–FL 400 for the NNE plume and FL 200 for the SSE plume. For the latter plume, SIGMETs were also issued by the Kansas City Aviation Weather Center for the Oakland Oceanic Flight Information Region (FIR) at 2110 UTC 19 February (tops at FL 120) and at 0313 UTC (tops at FL 200), 0923 UTC (tops at FL 400), and 1513 UTC (tops at FL 350) on 20 February. The 1513 UTC SIGMET was canceled at 2017 UTC when the SSE ash plume was judged as dissipated. Thus, significant differences existed for the SSE plume-height estimates between the SIGMETs for the Anchorage Oceanic and Oakland Oceanic FIRs. This must have been problematic for aircraft in the area, especially at the FIR boundaries.

3) Reliance on split-window technique

The split-window technique worked well for the NNE plume. The atmosphere north of the Aleutians was relatively cold and dry. However, the SSE plume was entrained into the extratropical cyclone moving eastward south of the Aleutians. With time, portions of the NNE plume as well as the SSE plume were entrained into the moist environment of the storm. The split-window signal could no longer be distinguished from noise, and the ash moving SSE could no longer be tracked using this method. The AVO quit reporting on the southern ash after 0100 UTC 20 February, and the NWS ceased to warn on the southern ash after 1810 UTC 20 February.

4) Coordination between the volcanic ash advisory centers

A coordination call was made between the Anchorage and Washington VAACs before the SSE plume advected across the boundary separating their respective areas of responsibility. This ensured continual warnings and advisories to the aviation community. The possibility of handing off responsibility from the Anchorage to the Washington VAAC was discussed, but Anchorage kept responsibility. The Washington VAAC sent messages referring users to the Anchorage VAAC messages. These actions were taken in accordance with established ICAO procedures (ICAO 2000). Coordination was also done between the VAACs and the Meteorological Watch Offices that issued SIGMETs for the Anchorage Oceanic and Continental and Oakland Oceanic FIRs. However, it appears that the coordination process was not thorough enough and that this contributed to significant differences in the SSE plume-height estimates between the Anchorage Oceanic and Oakland Oceanic FIRs' SIGMETs. The warnings to aviation for the SSE plume were terminated once the volcanic ash was no longer detected in satellite data and in the absence of significant new PIREPs. Thereafter, all efforts only tracked the NNE ash plume.

For the NNE plume, coordination calls were also made between the Anchorage and Montreal VAACs in accordance with ICAO (2000). Anchorage VAAC maintained the lead responsibility because the NNE plume dissipated before reaching Canadian airspace.

c. Lessons learned

This case study provides several lessons that should help the responsible agencies to meet the aviation industry's stated requirements with regard to the airborne volcanic ash hazard.

1) Early detection

A 5-min posteruption pilot notification mandated by the aviation community is a real and immediate safety need (Foreman 1994; Salinas 1999; E. Miller 2001, personal communication). There unfortunately is no currently available civilian system that meets this need. Thus, it is not surprising that a 5-min warning was not met for this eruption. Notification occurred about 3.5 h after the eruption started. From an aviation safety perspective, this time lag is clearly unacceptable. It highlights the need 1) to place instruments near more volcanoes likely to pose an aviation hazard; 2) to develop a more reliable satellite-based detection technique, especially to monitor uninstrumented volcanoes; and 3) to develop an automatic and reliable warning system for aviation.

The aviation community's requirement for notification to pilots within 5 min after an eruption commences is difficult but not impossible. The U.S. Air Force (USAF) Defense Support Program (DSP) orbital system uses infrared imaging from geostationary orbit to detect ballistic missile launches and discerns missile trajectories within 40–50 s of launch. More advanced systems (e.g., USAF space-based infrared systems) will reduce this time to less than 20 s and are radiometrically even more sensitive (Wall 1999). DSP imagers routinely detect the initial thermal signatures of volcanic explosions large enough to inject ash to 10 km ASL or more (thus relevant to commercial air traffic) with characteristic decay times on the order of 1–3 min (D. Pack 2000, personal communication). These classified data are not available in real time, but they do show that prompt detection of eruptions is possible. Civilian aviation needs a similar system.

2) Height assignment and importance of pilot reports

Height assignments for both the NNE and SSE plumes were in error. In fact, the error for the initial SSE height assignment was very significant, with tops ranging from FL 100 to FL 200. It was adjusted to FL 400 afterward. Recognizing the error in satellite-based estimates of cloud height, one might be inclined to recommend that height assignments only be issued after the satellite-based retrieval has been validated with PIREPs. Regulations, however, require warnings issued by meteorological services to include the base and top of the volcanic ash cloud (ICAO 1998). PIREPs provide valuable information, but they also sometimes contain inaccuracies or errors (e.g., PIREP 2 in Table 1) and must be examined carefully by operational meteorologists. Still, PIREPs should be actively sought and monitored to provide the most accurate, up-to-date information on plume height. The most reliable PIREP is one that documents a direct encounter with volcanic ash (e.g., Table 1). It unfortunately cannot usually place either upper or lower bounds on its height or its areal extent.

More frequent and detailed PIREPs, distributed in real time to the meteorological services and other relevant agencies, are needed. PIREPs 1, 5, and 7, for example, were not distributed on the World Meteorological Organization (WMO) Global Telecommunication System (GTS), implying that many meteorological services never received them. PIREPs also should clearly indicate both the flight level/location/time at which the report is made *and* the level(s)/location/time at which the odor/ash were encountered. A change of a few kilometers in the vertical position of the encounter can dramatically change the predicted source location, date, and time (Figs. 4 and 5).

Accurate height assignments of airborne volcanic ash are critical to aviation. Commercial aircraft (e.g., Boeing 747) typically do not exceed 42 000 ft. Over the midlatitude ocean, they often fly at 39 000 ft or less. If a low height assignment is given by a responsible agency, then a carrier may decide to fly over the ash based on perceived safety and cost. Rerouting is expensive; airline-provided estimates of additional costs associated with rerouting of aircraft [Los Angeles, California (LAX)–Tokyo, Japan (TYO); Portland, Oregon (PDX)–Nagoya, Japan (NGO)] for the Mount Cleveland eruption were $5500 and $6000, respectively, per flight (J. Luisi, Delta Airlines, 2001, personal communication). If the height assignment is incorrect, aircraft may encounter volcanic ash until a PIREP sighting ash is filed with the Federal Aviation Administration (FAA). Once a PIREP indicates a bad operational height assignment, airlines reroute to avoid the ash. Given this fact and the difficult, sometimes impossible, task of accurately estimating the base and top of the ash cloud when meteorological clouds are present, is it not desirable for aviation warnings to include information on uncertainty, especially regarding heights? If this information were provided, then a more realistic picture would emerge. The method of height assignment also should be coded in the warning message.

3) Reliance on satellite data and the $T_4 - T_5$ split-window technique

The Mount Cleveland event shows the split-window technique can produce very different results when ash from the same volcano advects and diffuses into different atmospheric environments. The lack of an easily discernible ash signal for the SSE plume 24–30 h after the eruption shows that, in general, better and more robust detection methods are needed. Evidence strongly suggests that different instrumentation and retrieval algorithms are required to improve accurate detection of ash under arbitrary conditions (Simpson et al. 2000). This requirement will require a significant investment of time and financial resources in research and development and subsequent careful transfer of new capabilities to the operational environment.

4) Role of ice

The freezing point was very low throughout the region (Table 2). The extratropical storm brought moist air into the normally dry Arctic atmosphere south of the Aleutians. Volcanic ash particles, especially those in the region of the extratropical storm, would serve as condensation nuclei for ice formation. Ice coating of volcanic ash masks its radiative properties; a positive ΔT produced by the ice coating belies the presence of the hazardous ash beneath it. We assert that the good detection of the NNE plume and poor detection of the SSE plume by the $T_4 - T_5$ volcanic ash detection algorithm is consistent with the preferential formation of ice due to moisture brought into the region SSE of the Aleutians by the extratropical storm. Ice has also played a similar role in other eruptions (e.g., Rose et al. 1995).

Scouring of aircraft surfaces often has been associated with a volcanic ash encounter. Ice, however, has a very low Moh hardness rating as compared with those of typical aircraft surfaces. Thus, ice coatings on ash also prevent/greatly reduce the abrasion of aircraft surfaces sometimes associated with volcanic ash encounters. The absence of scouring does not preclude a volcanic ash encounter and should not be used as a negative volcanic ash indicator. Indeed, the February 2000 encounter of a National Aeronautics and Space Administration (NASA) DC-8 aircraft with ice-coated volcanic ash from Hekla Volcano, Iceland, produced little or no visible scouring but resulted in $3 million in engine damage (Pieri et al. 2002). Ice also played its other critical role (impeded satellite-based detection) in this incident (Simpson et al. 2001; Pieri et al. 2002).

5) When should warnings be ended?

The absence of a clear discernible signal in either the split-window data or PIREPs for the SSE plume caused termination of the Oakland Oceanic FIR SIGMETs at 2017 UTC 20 February. The CANERM model, however, indicated that SSE transport of volcanic ash was possible well beyond that time and, in fact, as far in space and time as the B-747 PIREP off the coast of northern California. A retrospective conclusion is easily made. Operational meteorologists, however, must make crucial real-time decisions regarding the model accuracy and whether a model is appropriate for a specific event. This is a difficult task, given the often stressful conditions associated with a real-time response to dangerous events.

Airborne volcanic ash can pose a danger to aircraft for 2–3 days after the eruption and it can be undetectable with current satellite techniques. Lack of good PIREPs (the gap between PIREPs 6 and 7 is 56 h) leaves ash transport and dispersion models as the sole remaining tool. Models can provide invaluable estimates of the spatial and temporal displacement of the volcanic ash plume, but they also suffer from inherent uncertainties and assumptions (e.g., source term, vertical distribution, duration of release, amount of ash released, plume height, wind forecast errors). Advisory and warning messages, based solely on models, are not ideal because they may imply to airlines that forecasters actually know more than what they really do. Yet, when no other information is available, model information is invaluable.

The criteria for displaying volcanic ash on the forecast charts is based on a visual ash cloud (ICAO 1998). Yet, there is no quantitative or scientifically based definition of this variable. This problem has been raised on a number of occasions, including at international meetings, but there is no simple way of defining it. Visual ash cloud sighted by a pilot may be different from that detected by a satellite or predicted by a model. Forecasters can play with contouring of the predicted ash plume or use so-called ash-reduction schemes for the model source term eruption parameters. As seen above, the forecasters could decide to adjust the threshold value defining the model output ash plume and the corresponding contouring on the charts based on real-time data. These modifications unfortunately may at times introduce additional uncertainties and complications for nonspecialist users trying to interpret the ash charts.

Forecasters ultimately are faced with the difficult task of deciding when to end advisory and warning messages once the plume is no longer detected by available means. Again, there is no easy answer to this problem. The ''unofficial'' general rule used by operational meteorologists is to end the messages within a few hours after ash is no longer detected by either satellite or a PIREP. If ended too early, a false sense of security is conveyed, and soon the warning may be reissued. If, however, there is no longer evidence of volcanic ash, a different problem is faced: pressure from the airlines to cancel the warnings. Thus, forecasters might tend to end the warnings quickly once detection has stopped. For this event, maintaining the warning until PIREP 7 was issued would have been nearly impossible because nothing had been detected or reported in the prior 56 h. This is the real-time operational reality. A careful ICAO review of criteria for terminating a warning seems appropriate, especially given current restrictions in satellite-based detection of airborne volcanic ash.

6. Conclusions

This case study examined a large number of complex interactive issues that operational units face during a real time volcanic response. The challenges include the following:

- responding quickly and accurately while at the same time dealing with large uncertainties,
- detecting volcanic ash with satellites,
- assessing ash plume tops and bases with incomplete and at times conflicting information,
- defining eruption parameters and initial conditions to run the dispersion model,
- interpreting modeling results,
- coordinating information between adjacent VAACs to ensure a smooth transition at the boundary between their respective areas of responsibility, and
- deciding on when to terminate warnings to aviation in the absence of pilot reports or satellite detection.

All have a direct impact on detection, rapid alert, and timely delivery of reliable advice. The fundamental objective is clear: to keep aircraft and volcanic ash completely separated. Uncertainty is a major impediment to achieving this end and is likely to remain so in the foreseeable future. Still it is our hope that as a result of this case study the following recommendations may help to reduce uncertainty for the benefit of aviation safety and operational response efficiency:

1) More frequent and detailed volcanic ash PIREPs are needed. When ash is present, they should clearly indicate both the flight level/location/time at which the report is made *and* the level(s)/location/time at which the odor/ash were encountered. In specific situations and geographical areas, PIREPs of ''no ash'' would also provide valuable information in defining the extent of the ash cloud.
2) A thorough study of the spectral characteristics of airborne volcanic ash to identify the optimal wavelengths for sensors on future satellites should be conducted.
3) Regular coordination and response exercises should be conducted between adjacent VAACs and meteorological watch offices.
4) The possibility of assessing qualitatively the real-time potential for a long-lived ash plume based on the amount of horizontal spreading of the plume as a function of time in the dispersion model should be investigated.

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APPENDIX

Experimental Results: Start Time of the Eruption

An accurate start time for a volcanic eruption is important, but often it is uncertain, especially for seismically uninstrumented volcanoes. The AVO estimated a start time of 1500 UTC 19 February 2001 for this eruption. A refinement of the sequence of events now is possible because a PenAir commercial airline pilot (B. Mees) took aerial photographs of Mount Cleveland. Prior to the eruption, the summit was covered with ice and snow. The eruption melted much of it. If a significant part of the resulting surface water were entrained into the volcanic plume, then a signal should occur in *GOES-10* 6.7-μm data; it provides an estimate of upper-tropospheric water vapor.

Figure A1a shows the 6.7-μm BT (°C) at 1700 UTC 19 February 2001 (8-km spatial resolution at nadir). Figure A1b is a magnification of the region near the water vapor burst visible in Fig. A1a. Figure A1c shows hourly time series of the mean 6.7-μm BT computed over four regions (400, 144, 64, and 16 km^2) around the center of the water vapor burst. Figure A1d shows the locations of these four areas relative to the center of the water vapor burst. Colder 6.7-μm BTs indicate enhanced water vapor absorption in the upper tropopause near Mount Cleveland. Relatively low level volcanic activity is implied before 1700 UTC, when the major event started. It corresponds to the coldest 6.7-μm BT. The first PIREP report clearly citing ash over Mount Cleveland occurred at 1833 UTC (Table 1). By 2000 UTC almost all the surface snow and ice had melted. Thereafter, the enhanced water vapor signal declined.

The 6.7-μm data may provide a new tool to monitor volcanoes and may help to establish start times of an

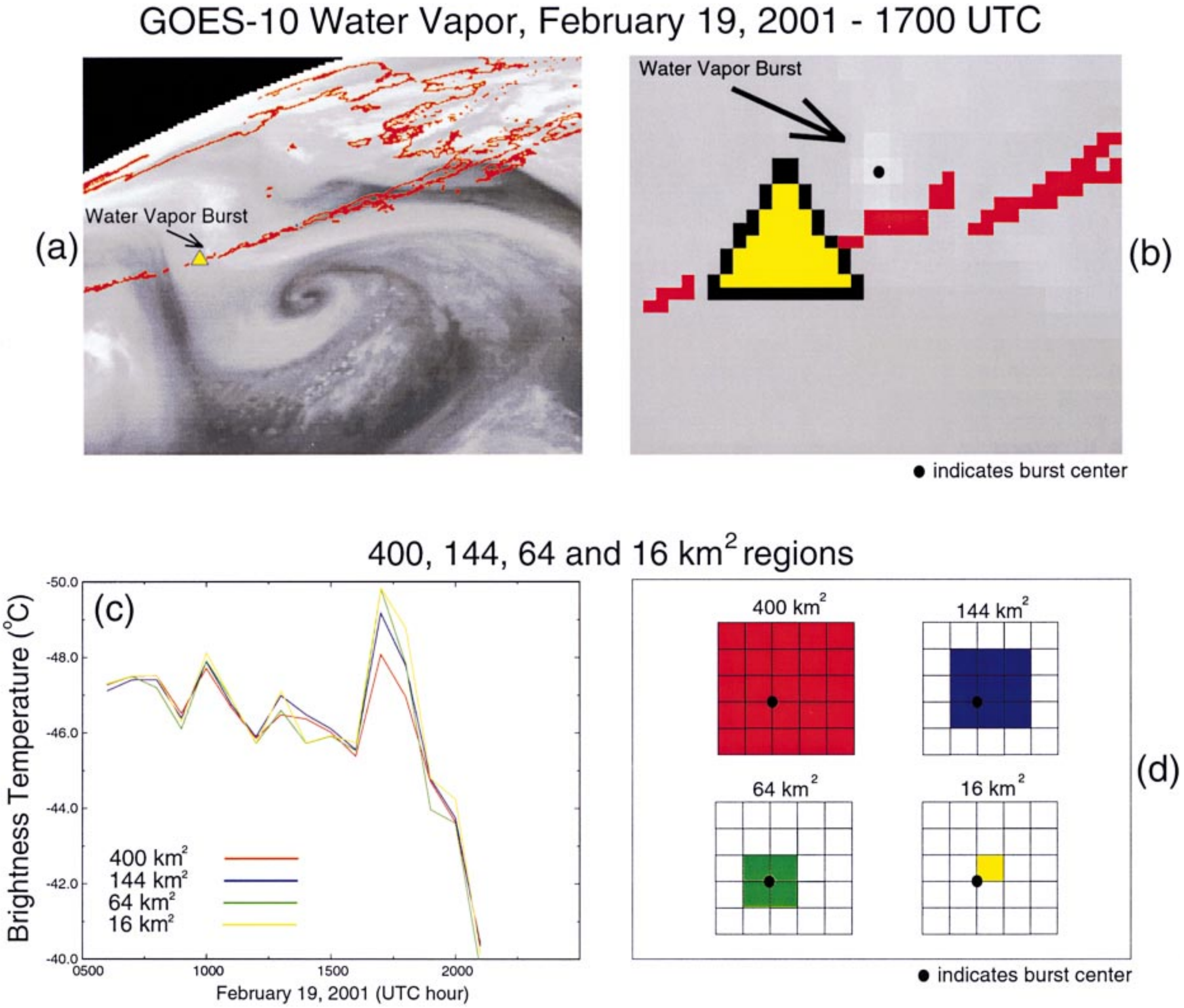

FIG. A1. (a) *GOES-10* 6.7-μm BT showing water vapor burst [black solid circle (●)]. (b) Magnified view of (a). (c) Time series of mean 6.7-μm BTs computed over different regions [shown in (d)] surrounding the water vapor burst.

eruption. More work, however, is required before a practical operational procedure can be developed, tested, and adapted for general use. Ambient atmospheric conditions may preclude its use for a specific eruption.

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