DEVELOPMENT OF A REAL-TIME ATC VOLCANIC ASH ADVISORY SYSTEM BASED ON THE FUTURE AVIATION WEATHER SYSTEM[1]

By James E. Evans

ABSTRACT

The overall U.S. air traffic control (ATC) decision-making and communications system should incorporate volcanic ash as a type of aviation weather hazard into the planned aviation weather system, which will be deployed in the United States starting in 1996. This weather system is based on the concept of a four-dimensional (4-D) (3 spatial dimensions and time) gridded database for current and predicted hazard locations with a variety of graphics products tailored to the needs of various users. Real-time information from ground sensors, air-carrier aircraft, unmanned air vehicles, and satellites would be used to estimate the current and predicted locations of hazardous ash. To achieve this system, research is needed on defining harmful ash densities, determining an optimal approach for estimating the density and extent of ash clouds, and validating models for predictions regarding ash clouds.

INTRODUCTION

Inadvertent ingestion of volcanic ash by jet engines has caused exstensive damage to a number of aircraft recently and could have caused fatal accidents in at least three cases. The operational system used to cope with the 1989–90 eruptions of Redoubt Volcano in Alaska utilized trajectory analysis to estimate ash locations with current textual aviation weather advisories (e.g., significant meteorological advisory (SIGMET), notices to airmen (NOTAM), or center weather advisory (CWA)) as a principal means of conveying information to pilots and controllers (Mostek, 1991; Heffter and others, 1991; Murray and others, this volume; Hufford, this volume; D'Amours, this volume). Manually generated graphics were distributed by facsimile (Criswell, 1991) to planners but not to pilots or controllers. Consequently, visual observations of ash clouds by pilots (or the lack thereof) were critical to air traffic control decision making (Criswell, 1991, Haeseker, 1991). This system had failures in assisting

pilots to avoid hazardous ash-cloud encounters and has a tendency for "over warning," which negatively impacts air operations and damages the credibility of the advisory program. A major problem that may arise with operational planning based on trajectory analysis to delineate the region of hazard in a relatively short period (e.g., 24 hours) after an eruption has occurred is that the possible area of warning for an ash encounter may be enormous.

From the viewpoint of surveillance and information dissemination, the recommended system (fig. 1), treats volcanic ash as a type of spatially extended aviation weather hazard similar to in-flight icing. Real-time information from ground, aircraft, and satellite sensors would be combined with the numerical-model predictions of ash transport to provide real-time, current and predicted locations of various levels of ash concentration in the 4-D gridded database generated by the aviation gridded forecast system (AGFS). This 4-D database would be used to disseminate graphical depictions of the current and predicted ash locations by the aviation weather product generator (AWPG).

A key element of the recommended system is the determination of spatial location of damaging ash concentrations (as opposed to the current estimates of an unspecified ash concentration over very large geographical areas). A number of options are considered for achieving this capability. Particular attention is paid to the ongoing validation of ash-location and concentration estimates as the ash clouds move away from the immediate vicinity of the volcano. This paper concludes with some recommendations for the research and development program and system-deployment decisions that will be needed to achieve an operationally useful system.

Related proposals for an integrated detection and warning system have been made by Harris (this volume), D'Amours (this volume) and Stunder and Heffter (this volume). D'Amours, and Stunder and Heffter, principally treat the prediction problem without addressing how the initial ash-cloud 3-D spatial distribution will be determined. Harris suggests estimating ash-cloud parameters from the amplitude and duration of eruption-related harmonic tremor with subsequent ash-location forecasting by trajectory analysis. By contrast, we suggest the use of radars and sensors carried
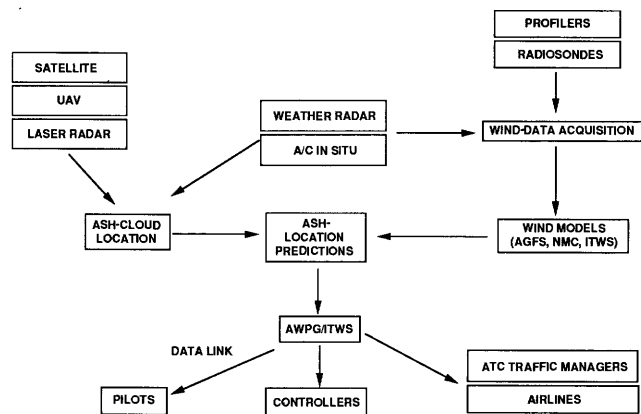
Figure 1.   Major elements of recommended volcanic-ash-advisory system for aviation. Gridded wind forecasts are combined with ash locations measured near and downwind of volcanoes to generate 4-D, predicted locations of ash clouds. Distribution of the 4-D ash locations are accomplished by the FAA/NWS (Federal Aviation Administration/National Weather Service) weather-information systems. UAV, unmanned aircraft vehicle; A/C, aircraft; AWPG/ITWS, aviation weather product generator/integrated terminal weather system; AGFS, aviation gridded forecast system; NMC, national meteorological center; ATC, air traffic control.

by a dedicated, unmanned aircraft vehicle (UAV) to estimate the initial concentration; the use of full, 4-D, gridded models to estimate future ash locations; and the use of airborne measurements by air-carrier aircraft and dedicated UAV's to validate the estimated ash concentrations.

THE PLANNED AVIATION WEATHER SYSTEM

The Federal Aviation Administration (FAA) and National Weather Service (NWS) are currently deploying a number of sensors useful for ash surveillance and for measuring meteorological quantities (e.g., wind and clouds) that relate to ash transport and surveillance. The next-generation weather radars (NEXRAD) being procured for en-route airspace are significantly more capable of ash detection than current NWS radars—they also provide radial-velocity estimates (Stone, this volume). NEXRAD routinely produces graphical products, such as maps of echo tops and layered reflectivities, that can be used directly by ATC planners and controllers to provide some safety information on ash clouds while they are detectable by the radar. Additionally, NEXRAD has algorithms to analyze 3-D features of storms and extract pertinent aviation variables, such as the presence of hail and tornadoes. This computation capability could be adapted to automatically estimate the spatial extent of an ash cloud as an input to subsequent prediction programs.

The knowledge of the state of the atmosphere downwind of the volcano will be greatly expanded as a result of improved wind sensors and analysis systems. National

Oceanic and Atmospheric Administration's (NOAA) forecast systems laboratory has been developing the aviation gridded forecast system, which is a high-resolution, state-of-the-atmosphere estimation system that plays a key role in the recommended system. The AGFS, which will be tested in 1994 and implemented nationally in 1996, uses the current balloon atmospheric soundings (Holland and others, 1992), the aircraft communications addressing and reporting system (ACARS), and profiler data (Hassel and Hudson, 1991), as well as numerical-forecast-model results to create a high-resolution (30-km horizontal resolution, 25 vertical levels, hourly estimates based on a 6-hour analysis cycle), gridded database of meteorological variables (e.g., winds, temperature) and aviation weather impact products (e.g., cloud locations) using the mesoscale analysis and prediction system (MAPS) (Schlatter and Benjamin, this volume). Owing to computer-load constraints, the initial coverage for the AFGS will be for the continental United States. However, the computational algorithms used have been adapted for Alaska and could be implemented locally. Extension of AGFS/AWPG coverage to western Canada may also be warranted. It should be noted that the AGFS/AWPG will provide many economic benefits to aviation in that area, including better wind estimates for air routes from the United States to Japan.

Reliable real-time dissemination of ash-location information to pilots and controllers is essential. Fortunately, the distributed nature of the volcanic-ash hazard is quite analogous to many weather phenomena. A key element in the weather-information-dissemination system will be the regional and national AWPG (fig. 2), which utilizes the information from NEXRAD and gridded state-of-the-atmosphere information, such as that provided by the AGFS, to create real-time aviation terminal weather products for a variety of users and systems (Sankey and Hansen, 1993). The regional AWPG (RAWPG), associated with the various FAA enrollee centers, is a very attractive vehicle for display of the real-time and predicted ash locations to en-route controllers and various traffic management units because it also will communicate alphanumeric and graphical weather information to pilots via the data-link processor. The AWPG should be operationally available in the 1997–98 time frame. Real-time ash-location estimates would be provided both graphically and in text, to en-route air traffic controllers, flight service station specialists, and pilots to assist in tactical decision making. Since the initial AWPG graphical products would be created and distributed by commercial vendors such as Atmospheric Research Systems, Inc. (ARSI on fig. 2), airline dispatch, airport operators, and others would have ready access to the same information as FAA users.

It is also important that high resolution information be available in the terminal area of major airports that may be affected by ash clouds. Studies of aircraft routes in the vicinity of storms have shown that pilots will fly much closer to hazardous regions in conducting landing and takeoff operations than they would while en route, where they would

deviate to avoid a hazardous region. In addition, pilots are particularly concerned about the operations disruption from overly conservative hazard warnings in the terminal area. The integrated terminal weather system (ITWS) provides very high resolution, gridded analyses (2-km horizontal grid, 5-minute update), as well as dissemination of weather information for the terminal area based on information from the AWPG, Weather Forecast Office (WFO), and the FAA/National Weather Service terminal-area sensors (Evans, 1991b; Albers, 1992). The ITWS has access to a wide variety of weather sensors in and around the terminal area, such as the terminal Doppler weather radar (TDWR), and could easily be augmented to include ash-location information from other sensors, such as laser radars. The ITWS will include color displays for terminal-area traffic managers as well as graphical information for terminal radar approach control facility (TRACON) controllers. ITWS prototypes will commence long-term operationally oriented demonstrations in 1994—the ITWS will be operationally deployed in 1999 (Sankey and Hansen, 1993).

OPERATIONAL REQUIREMENTS FOR AN ASH ADVISORY SYSTEM

No operational requirements have yet been formally stated by the FAA for a volcanic-ash-advisory system. The growing experience with providing operational hazardous-weather products is germane to assessing the requirements for volcanic ash surveillance. In particular, warnings of wind shear due to microbursts and gust fronts have been provided operationally to terminal controllers and supervisors at three different major airports since 1988 (Evans, 1991a). The operational analyses (Stevenson, 1991) carried out in conjunction with these and other tests and demonstrations suggest the following guidelines:

1. Air-traffic-control personnel and aircraft pilots should not be expected to interpret meteorological and ash-location data from sensors to assess the degree of hazard.
2. A sound technical basis for the hazard levels (e.g., tolerable time exposure to various ash concentrations) yielding ash alerts is essential for design of an effective advisory system.
3. Operational requirements for minimum acceptable levels for hazard detection and false-alarm probabilities must be closely related to the expected operational disruption. For example, false-alarm probabilities that were operationally acceptable in low-wind-shear environments were found to be operationally disruptive in high-traffic environments with frequent wind-shear events (Stevenson, 1991).
4. Informal systems users groups (e.g. representatives from airlines, pilot groups, airport authorities,
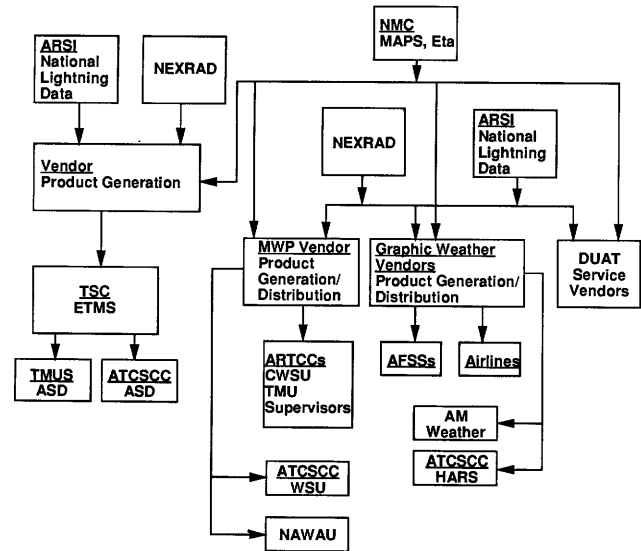
Figure 2. Planned aviation weather product generator system when deployed in 1996. Graphical weather products derived from 3-D, gridded database are distributed to FAA en-route and terminal facilities by the meteorological weather processor (MWP) and via aircraft situation displays (ASD) used for traffic management. Flight service stations (AFSS) and airline users will receive similar graphical products from commercial vendors. AM Weather, NOAA aviation weather program broadcast on the Public Broadcasting System; ARSI, Atmospheric Research Systems, Inc.; ARTCC, air route traffic control center; ATCSCC, air traffic control system command center; CWSU, Center Weather Service Unit; DUAT, direct-user access terminal; Eta, estimated time of arrival; ETMS, enhanced traffic management system; HARS, high-altitude routing system; MAPS, mesoscale analysis and prediction system; NAWAU, national weather advisory unit; NEXRAD, next-generation weather radar; NMC, National Meteorological Center; TMUS, traffic management units; TSC, transportation system center; WSU, weather service unit.

aviation administrations, safety boards, researchers, and information providers) that periodically review the scientific knowledge, operational needs, system performance, and operational use of the products can be very useful for reaching rapid operational acceptance and utility for a new system capability such as the recommended volcanic-ash-advisory system.

A major problem in developing an effective ash-advisory system is the poor understanding of tolerable levels of ash ingestion for the engine type of concern to air carriers. Although several very useful studies have been carried out (Dunn and Wade, this volume; Przedpelski and Casadevall, this volume), there appears to be no published experimental or simulation data on damage to high-bypass engines as a function of ash concentration and exposure duration. Obtaining improved information on tolerable ash concentrations/exposure durations is essential for the development of an improved ash-advisory system.

ASH-CLOUD-CHARACTERIZATION OPTIONS

Another essential element of the proposed system is improved initial estimates of the spatial distribution of operationally significant ash concentrations including ash type, particle size, and density in both clear air and in the presence of weather clouds. It is very important that the system have some capability to automatically accomplish this objective in the presence of clouds because many of the potentially active areas may be cloud covered during significant portions of the year.

Weather radars can provide 3-D ash-cloud characterization through rain clouds. However, three problems arise: determination that an eruption is underway, discrimination between rain and ash clouds, and estimating the pertinent parameters of an ash cloud. The initial determination of an eruption and discrimination between rain and ash clouds can be based on a variety of clues, including seismic tremors (Harris, this volume), lightning (Hoblitt, 1991), and satellite observations (Matson and others, this volume; Schneider and Rose, this volume). Initially, the determination that an eruption has occurred and delineation of ash-cloud regions (e.g., by entering bounding polygons) would be accomplished manually by Central Weather Service Unit (CWSU) meteorologists using information from sensors as well as from volcanologists. Estimation of ash-cloud parameters would then be accomplished automatically using volume-scanned radar data within the bounding polygon regions.

Estimating the distribution of ash-particle sizes and types cannot be directly accomplished with the microwave weather radars of greatest interest (Harris and Rose, 1983; Stone, this volume) or from current satellites in a time frame compatible with a real-time advisory system. Harris and Rose (1983) have discussed estimating ash-cloud parameters from radar data by using ash-fall data. It may be possible to utilize their technique for real-time estimation in situations where ash-fall measurements have been made on similar previous eruptions.

The use of a dedicated, multi-wavelength laser may also be useful in estimating particle sizes when the cloud cover permits. However, the high rate of attenuation in either ash clouds or rain clouds makes lasers an unattractive choice as a sole means of ash surveillance, particularly from ground-based locations. For example, the University of Washington measurements of Redoubt Volcano plumes showed cases where the ash in an upper layer cloud was not detected due to attenuation of the laser beam by a lower altitude, dense cloud (Hobbs and others, 1991). Similar measurements using lasers and in-situ sampling are needed for ash prediction model verification. However, suitable manned aircraft are expensive to operate and may not be available on short notice.

A UAV with instruments (payload of approximately 150–200 lb) is an attractive option for directly measuring ash concentrations and transporting lasers for ash-cloud mapping. Advances in UAV designs, autonomous guidance and worldwide availability of navigation aids and communications have made UAV's cost effective for atmospheric soundings. It appears (P. Jarvinen, Lincoln Laboratory, written commun., 1992) that the engine of a UAV can be protected from ash-particle ingestion, and impact erosion by ash particles can be kept to manageable levels. The piston-powered Amber UAV is particularly attractive at this time due to its technical characteristics (38 hours endurance at 17,000 ft altitude; operation up to altitudes of 28,000 ft—up to 40,000 ft with a turbocharger—a 70–100-lb internal payload; a 100-lb external payload) and because several U.S. Government owned Amber systems may be available. The proposed mode of operation would be to map ash-cloud extents in a vertical plane normal to the axis of the plume at some selected distance downwind of the volcano (far enough to avoid the large fragments that rapidly precipitate out of the cloud). The downwind spatial distribution of the ash cloud would be updated on a schedule dictated by the winds and the demonstrated capability of the ash-prediction models. It should be noted that there are a number of small-scale turbulence and mesoscale weather features that are not captured in the improved forecast models that will utilize the MAPS grid. Consequently, it appears necessary for the foreseeable future to have the ability to validate ash-cloud predictions downwind on an ongoing basis until ash density is no longer at hazardous levels.

It may be cost effective to instrument some air-carrier aircraft that operate in areas with many volcanoes, such as the North Pacific and Alaska regions. Data from in situ volcanic-ash-detection sensors could be reported over the ACARS link. The information from such aircraft would be used principally to provide additional confirmation of the accuracy of ash predictions and to provide a "heads up" warning to pilots of situations in which the ash densities were approaching levels that could damage the aircraft. For example, if the aircraft were to encounter much higher ash or volcanic gas concentration levels than were predicted, the ACARS could be used to identify cases where the prediction-model estimates were significantly in error. The advantage of using ACARS in this context is that the ash-prediction systems will already be accessing the ACARS data on a continuing basis in real time. Consequently, corrections to the predicted ash-cloud-concentration estimates could be generated quickly and transmitted to the aviation community.

CONCLUSIONS AND RECOMMENDATIONS

The aviation weather system currently under development by the FAA and NWS should play a critical role in the development of a more effective, real-time, volcanic-ash-advisory system based on the generation and dissemination

of a graphical, 4-D, volcanic-ash product. A number of research and programmatic challenges exist including:

1. Quantitative assessment of ash concentrations that may be of concern for flameout of modern, high-bypass jet engines;

2. Development of an effective system for unambiguous 3-D ash-concentration measurements near and downwind of erupting volcanoes;

3. Validation of the accuracy of models that predict the spatial distribution of ash; and

4. Refinement of the human/machine interface for the system (e.g., by rapid prototype testing).

A product-users group should be established to provide feedback and suggestions as the ash-advisory system evolves. Extending the coverage of the AGFS/AWPG system to Alaska and the western portion of Canada is essential.

ACKNOWLEDGMENTS

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