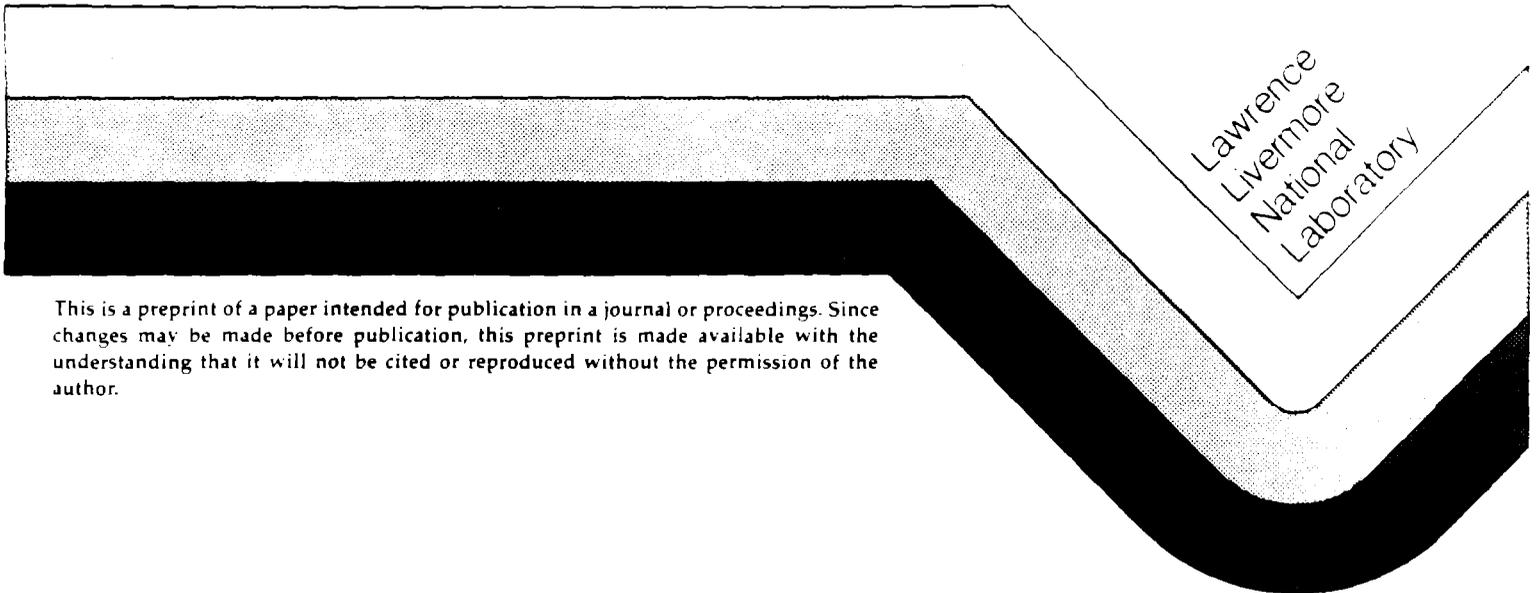# Ash Cloud Aviation Advisories

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DISCLAIMER

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Abstract

During the recent (12–22 June 1991) Mount Pinatubo volcano eruptions, the U.S. Air Force Global Weather Central (AFGWC) requested assistance of the U.S. Department of Energy's Atmospheric Release Advisory Capability (ARAC) in creating volcanic ash cloud aviation advisories for the region of the Philippine Islands. Through application of its three-dimensional material transport and diffusion models using AFGWC meteorological analysis and forecast wind fields ARAC developed extensive analysis and 12-hourly forecast ash cloud position advisories extending to 48 hours for a period of five days. The advisories consisted of "relative" ash cloud concentrations in ten layers (surface–5,000 feet, 5,000–10,000 feet and every 10,000 feet to 90,000 feet). The ash was represented as a log-normal size distribution of 10–200 μm diameter solid particles. Size-dependent "ashfall" was simulated over time as the eruption clouds dispersed. These products were distributed to the AFGWC (Offutt AFB, Nebraska) and Headquarters First Weather Wing (Hickam AFB, Hawaii) for further distribution to U.S. Air Force weather units throughout the Pacific region who were supporting the evacuation of U.S. personnel from the Philippines. Except for an internal experimental attempt to model one of the Mount Redoubt, Alaska, eruptions (12/89), ARAC had no prior experience in modeling volcanic eruption ash hazards.

For the cataclysmic eruption of 15–16 June, the complex three-dimensional atmospheric structure of the region produced dramatically divergent ash cloud patterns. The large eruptions (>7–10 km) produced ash plume clouds with strong westward transport over the South China Sea, Southeast Asia, India and beyond. The low-level eruptions (<7 km) and quasi-steady-state venting produced a plume which generally dispersed to the north and east throughout the support period.

Modeling the sequence of eruptions presented a unique challenge. Although the initial approach proved viable, further refinement is necessary and possible. A distinct need exists to quantify eruptions consistently such that "relative" ash concentrations relate to specific aviation hazard categories.

Introduction

The Atmospheric Release Advisory Capability (ARAC) is a real-time emergency response and preparedness service that was developed and has been operating at the Lawrence Livermore National Laboratory (LLNL) in Livermore, California, for the past 17 years. ARAC is a national resource with a suite of dispersion models to simulate the consequences of accidental releases of material into the atmosphere on local to global scales. Funded by the Departments of Energy (DOE) and Defense (DOD), the primary role of ARAC has been to provide calculations for radiological releases. Any U.S. federal agency can request the services of ARAC through DOE as delineated in the Federal Radiological Emergency Response Plan.

This paper provides a background on how ARAC has responded to other than radioactive material releases, summarizes its modeling system, and focuses on its response to the June 1991 eruption of Mount Pinatubo, Luzon, the Philippines, as requested by the United States Air Force.

Background

Since the beginning of operation in 1974, ARAC has been involved in over 600 responses, primarily exercises with its supported agencies. In accordance with its charter, ARAC has been used for major domestic radiological events and some international events where the U.S. government had interests. In addition, as Table I indicates, ARAC has also been used for nonradiological releases within the United States. In fact, requests for assistance involving non-radiological releases have equaled those involving radioactive releases.

The current ARAC system has evolved according to the requirements and expectations of its supported agencies as well as its experience with responses.[1] For example, early in the history of ARAC, a 1976 North Carolina train accident revealed that real-time meteorological data automatically formatted for use in the dispersion models was essential to a rapid response. In 1978, the unique request by DOE to estimate the atmospheric consequences of the Russian nuclear-powered COSMOS-954 satellite resulting from reentry burn-up caused the ARAC team to develop a high-altitude particle fall model. As a result, ARAC was prepared for the subsequent COSMOS 1402 reentry in 1981. ARAC's largely manual response to the 1979 Three Mile Island accident and the 1980 Titan II missile accident showed the need for on-line U.S. topography and geography data bases. The 1986 Chernobyl accident propelled ARAC to implement continental-to-hemispheric scale models supported by world-wide meteorological, terrain, and mapping data.

Each response has resulted in expanded capabilities. Consequently, for example, ARAC, with some adaptation to a new AFGWC wind model data source, was ready with the necessary models and data bases to simulate the daily regional-scale smoke and soot concentrations from the Kuwaiti oil fires in the Persian Gulf region from May to October 1991.[2]

TABLE I. Notable ARAC Responses

YEAR	LOCATION	SOURCE	RELEASE
1976	North Carolina	Train Accident	Uranium hexafluoride*
1978	Northern Canada	COSMOS 954 Reentry	Fission products
1979	Three Mile Island Harrisburg, Penn.	Nuclear Power Plant	Mixed fission products
1980	Damascus, Arkansas	Titan II Missile	Missile fuel*
1981	Indian Ocean	COSMOS 1402 Reentry	Fission products
1982	South Carolina	Savannah River Plant	Hydrogen sulfide leak*
1986	Gore, Oklahoma	Sequoyah Fuels Plant	Uranium hexafluoride*
1986	Chernobyl, USSR	Nuclear Power Plant	Mixed fission products
1988	Miamisburg, Ohio	Mount Plant	Tritium gas release
1989	Amarillo, Texas	Pantex Plant	Tritium gas release
1991	Persian Gulf	Nuclear Facilities Kuwait Oil Fires	Mixed fission products Smoke*
1991	Philippines	Mt. Pinatubo	Volcanic Ash*
1991	Northern California	Railroad Car Spill	Toxic gas products*
1992	Sosnovy Bor, Russia	Nuclear Power Plant	Radioactive gas

*Release involved toxic chemicals

ARAC System

The original concept, prototype development, and initial operations from 1974 to 1982 were supported by DOE. From 1983 to 1986 the system was redesigned and a high level of automation was implemented to support up to 100 facilities within the DOE-DOD nuclear community. Figure 1 depicts the automated flow of information during an ARAC emergency response with the current system. This simplified diagram represents only the top-level system functions of the ARAC Emergency Response Operating System (AEROS) that contains over a million lines of computer code. AEROS automatically assembles necessary information for the model run stream once the minimum accident data have been entered with the "problem questionnaire." The questionnaire may either be completed on a computer system at one of the remote support facilities or manually entered at the ARAC center based on information gathered
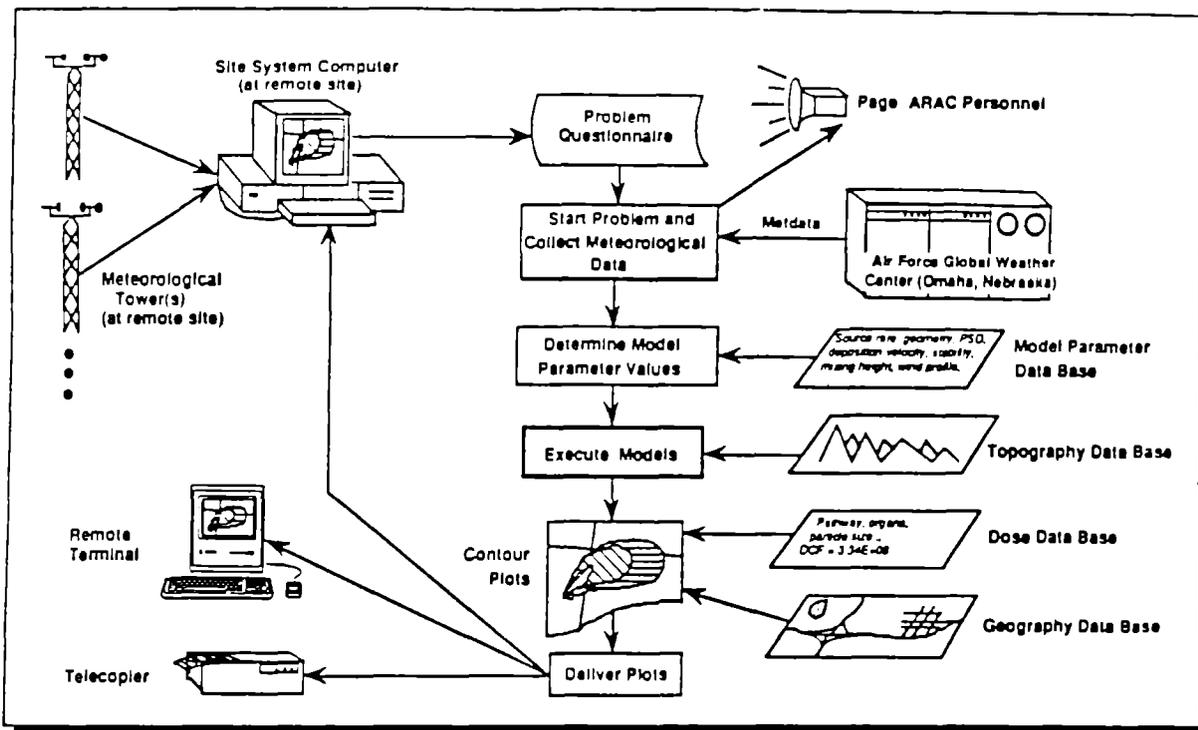
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Figure 1. ARAC Emergency Response Operating System functions

A meteorological data interpolation code (MEDIC) initializes winds in the three-dimensional volume to be modeled. Relevant topography is applied at the lower boundary, then the calculus-of-variation code known as MATHEW[3] imposes mass-consistency in order to provide non-divergent flow fields for the dispersion model. The Atmospheric Diffusion Particle-in-Cell (ADPIC)[4] model is a Lagrangian particle code which provides the dispersion physics for a wide range of substances, e.g., gases, solid particles, radioactive and non-radioactive material, etc.[5]

Typical model results include plots of deposition of material on the ground, instantaneous and time-integrated doses, or air concentrations at selected levels above ground. Species or sources may be combined as required and contoured according to specified isopleth values. A legend is shown on each plot that describes the release, species involved, source type, units and valid time for the contours.

After a quality assurance review by an assessment meteorologist, the plots may be transmitted to a supported site computer by modem or faxed to the emergency response manager. The time to create and deliver plots to a supported site computer can be as little as 15 to 30 minutes after receipt of accident information. For nonradiological incidents, the response time depends on the complexity of the source term, the availability of meteorological data, and the preparation of unique model input parameters.[6,7]

Typically, ARAC response time is equally split between computer (or voice) communications with the site, automated (or manual) model input preparation, model execution, and human interaction with the system. ARAC currently uses 7 million

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instruction per second Digital Equipment Corporation (DEC) VAX 8550 computers to run the models and micro-VAXes to communicate with DEC PC350/380 site computers at 1200 baud. In 1992–93 ARAC plans to upgrade the VAXes with machines that are six times faster, and begin replacing the site computers with Unix-based workstations communicating with ARAC at 9600 baud.

Mount Pinatubo Response

During the recent (12–22 June 1991) Mt. Pinatubo volcano eruptions, the U.S. Air Force Global Weather Central (AFGWC) requested assistance of the U.S. Department of Energy's Atmospheric Release Advisory Capability (ARAC) in creating volcanic ash cloud aviation advisories for the region of the Philippine Islands. The advisories were to aid in the evacuation of U.S. military and dependent personnel from the region. Except for an internal experimental attempt to model one of the Mount Redoubt, Alaska eruptions (12/89), ARAC had no prior experience in modeling volcanic eruption ash hazards. Through application of its three-dimensional material transport and diffusion models using AFGWC meteorological analysis and forecasts winds fields ARAC developed extensive analysis and 12-hourly forecast ash-cloud-position advisories extending to 48 hours. For a period of five days, the advisories consisted of "relative" ash cloud concentrations in ten layers (sfc–5,000 ft, 5,000–10,000 ft and every 10,000 to 90, 000 ft.). The ash was represented as a log-normal distribution of solid particles ranging from 10–200 microns in diameter simulating ash cloud dispersion and size-dependent "ashfall" over time as the eruption clouds dispersed. These products were distributed to the AFGWC (Offutt AFB, Nebraska) and Headquarters, First Weather Wing (Hickam AFB, Hawaii) via facsimile for further distribution to U.S. Air Force weather units throughout the Pacific region.

Model Data Requirements

In order to satisfy the request for ash cloud advisory forecasts, ARAC required physical information about the events (source terms to the model) such as location, times/duration of eruptions, height and width/diameter of release and ash size/density properties. The U.S. Air Force provided the majority of this event related information. The ash particle information was gleaned from El Chicon and Mount St. Helens scientific reports.

Initially, ARAC's "hemispheric" models (developed in response to the Chernobyl accident) were used, because twice daily northern hemisphere wind field analyses are routinely received and archived at ARAC. With AFGWC priority assistance, ARAC began receiving forecast wind data for 15 standard pressure levels of the atmosphere (see, for example, Figure 2) extending to 10 millibars or approximately 100,000 feet in altitude. Data to these heights were required because of the reported/estimated eruption heights of 25–30 kilometers on 14–15 June.
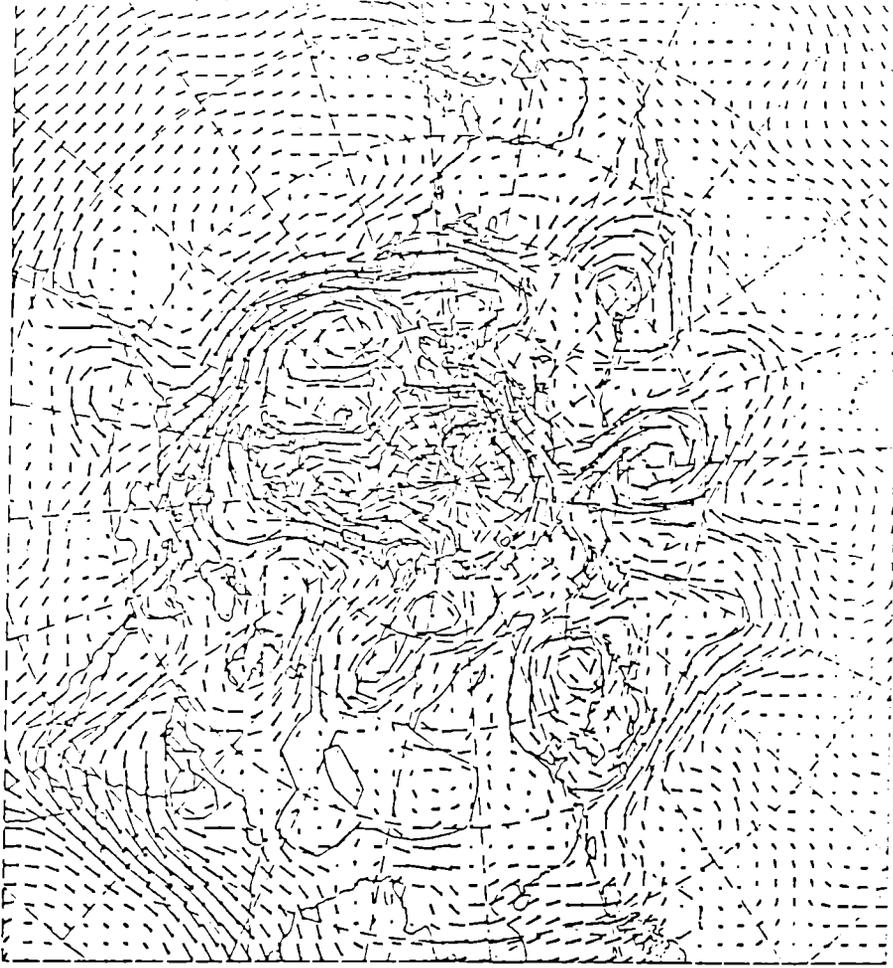
Figure 2. Typical 700 mb (H Pa) level wind field for 20 June 1991 at 0000 GMT.

Eruption Characterization for the Model

After some initial experimentation with representation of these large explosion clouds it was decided to model the ash cloud injections as large cylindrical volumes of several kilometers radius and vertical extent to serve as the basic geometry for release of the model "marker" particles. A log-normal particle size distribution spanning the 10–200 μm diameter range was selected; particle density was chosen as 1.45 grams per cubic centimeter. Since several eruptions were to be modeled concurrently, a scaled (relative) release rate proportional to explosive energy (estimated from cloud top) was approximated as shown in Table II using explosion scale algorithms maintained at ARAC. The relative scale and chronology of the eruptions modeled are depicted in Figure 3.

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TABLE II. Scaled "Relative" Release Rate

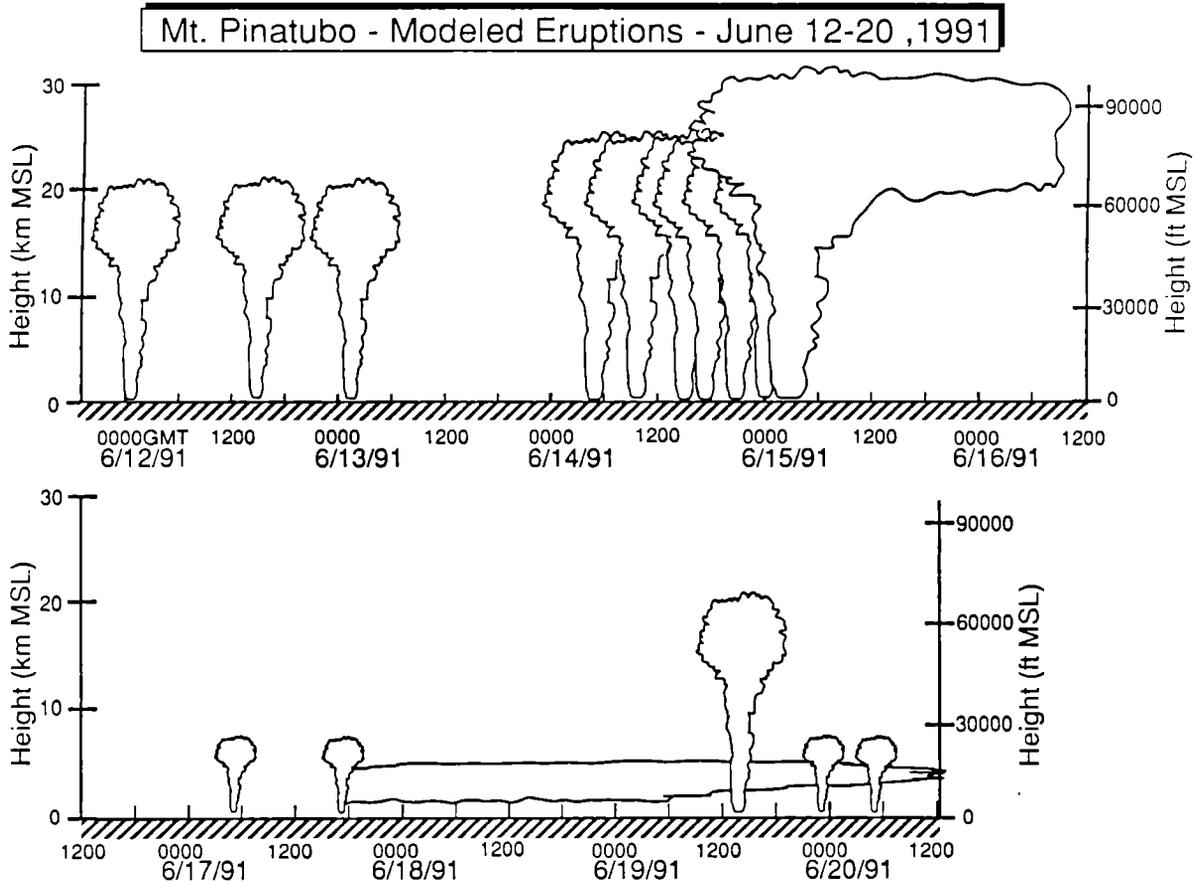| Estimated Cloud Top (km)	TNT Equivalent Energy (kt)	Proportional Release Rate
30	6,000	1.
25	3,000	.5
19	500	.08
7	7	.001
4	4	.00066

Particle size distribution

10 — 200 micron diameter

Figure 3. Time sequence and relative eruption heights of events included in the ARAC ash cloud model calculations for the period 12-20 June 1991

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Results

By the conclusion of the first response day, ARAC had produced the first set of ash cloud advisory products as shown in Figure 4 using the hemispheric scale model discussed previously. Plots of "relative" ambient concentrations were generated for
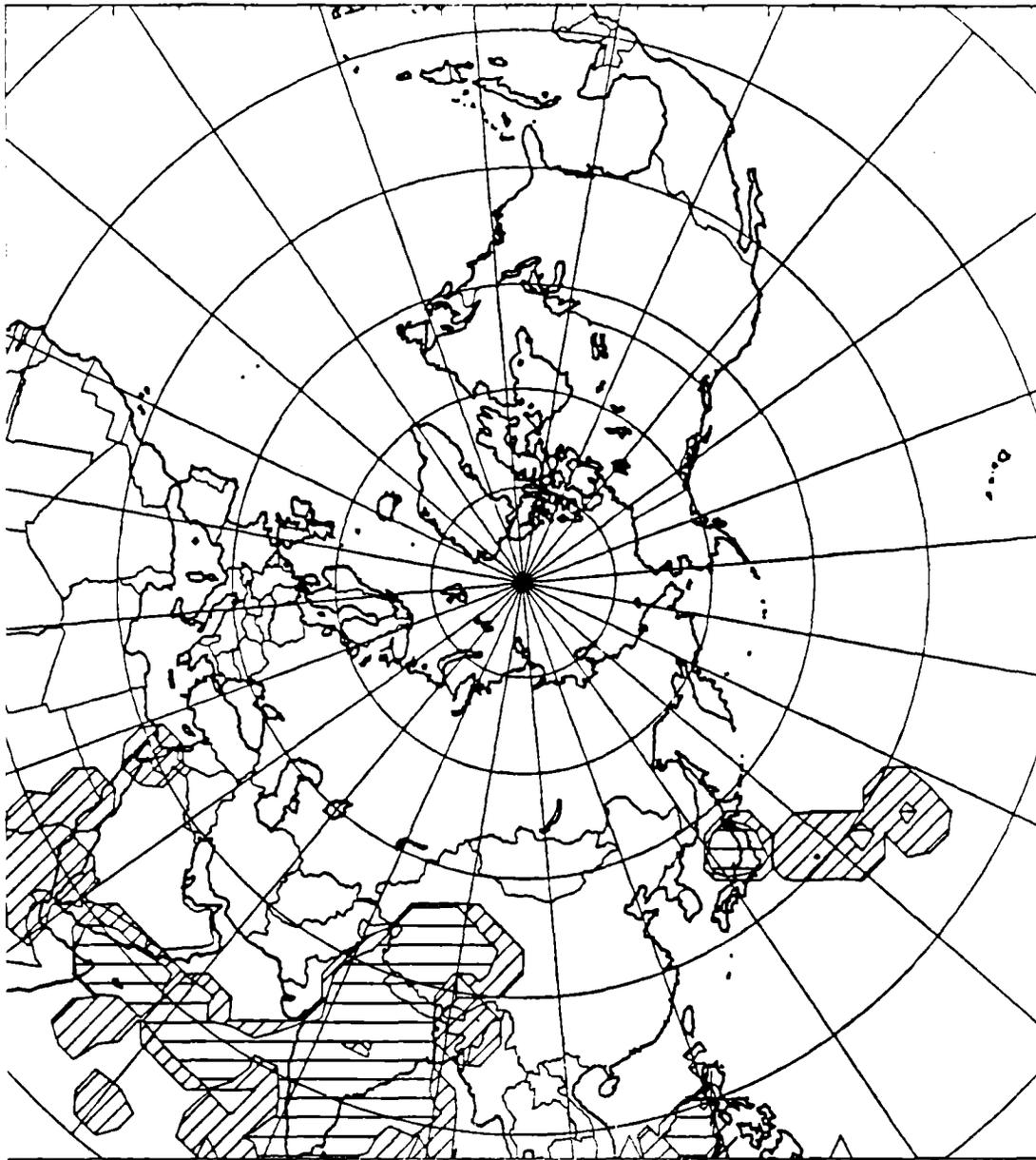

Figure 4. An example of first "ash cloud advisory" map prepared for the USAF on a hemispheric scale. This plot was for the 20–30,000 feet altitude layer valid at 0000 GMT, 20 June 1991. The "ash" levels are relative to the initial release as discussed in the text.

consecutive 12 hour intervals extending to 48 hours for 10 layers (surface–5,000 feet, 5,000–10,00 feet, etc. to 80–90,000 feet) as specified by the Air Force. In an attempt to delineate the potentially hazardous areas, relative concentration divisions of "heavy/dense", "moderate," and "light/diffuse" ash were chosen by identifying the highest two orders of magnitude, the next largest two orders of magnitude, and then the remaining concentrations, respectively. Internal to the model a "normalized, unit source" was selected due to the complete lack of actual data concerning the mass of the eruptions.
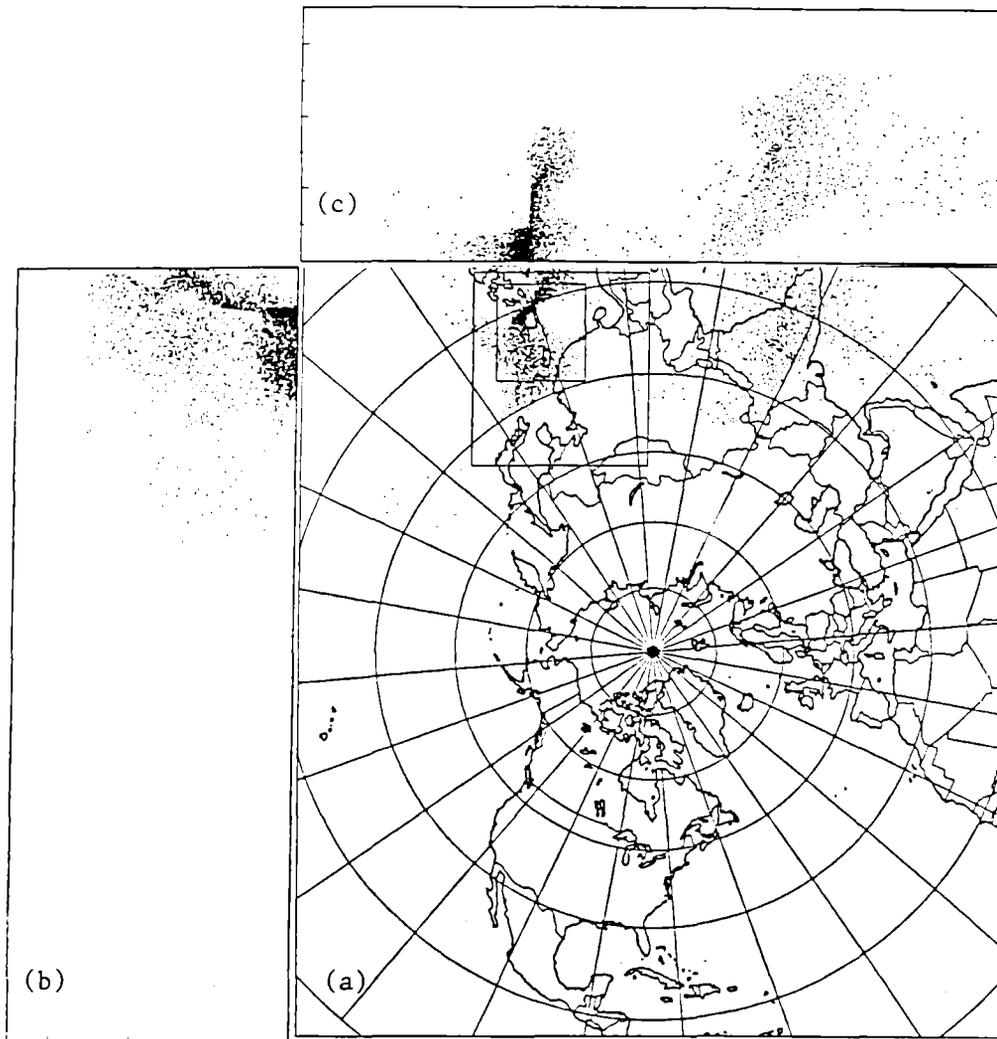
Figures 5a, b, and c. The particle model representation of the dispersing ash clouds for all eruptions from 12–20 June 1991, including the most recent eruption of 1425 GMT on 19 June 1991; a) overhead view; b) side view from right to left of the overhead view, i.e., down the axis of the plume and c) side view from bottom to top (or across the pole) of the overhead revealing the vertical structure of the recent eruption and the more dispersed debris from the cataclysmic eruption (of 15 June 1991) over India (grid top extends to 35,000m).

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Unfortunately, the meteorological and dispersion model domain boundary was close to the eruption site with the consequence that these calculations were of limited utility to the south and southwest of Mt. Pinatubo. They did, however, cover the primary evacuation route from Cebu to Guam which remained ash free as Figure 5 reveals.

Shortly after transmission of the first calculations, the Air Force requested comparable advisories for a more detailed sub-region of a few thousand kilometer extent centered on the Philippines. Figure 6a and b delineate this new model sub-domain and
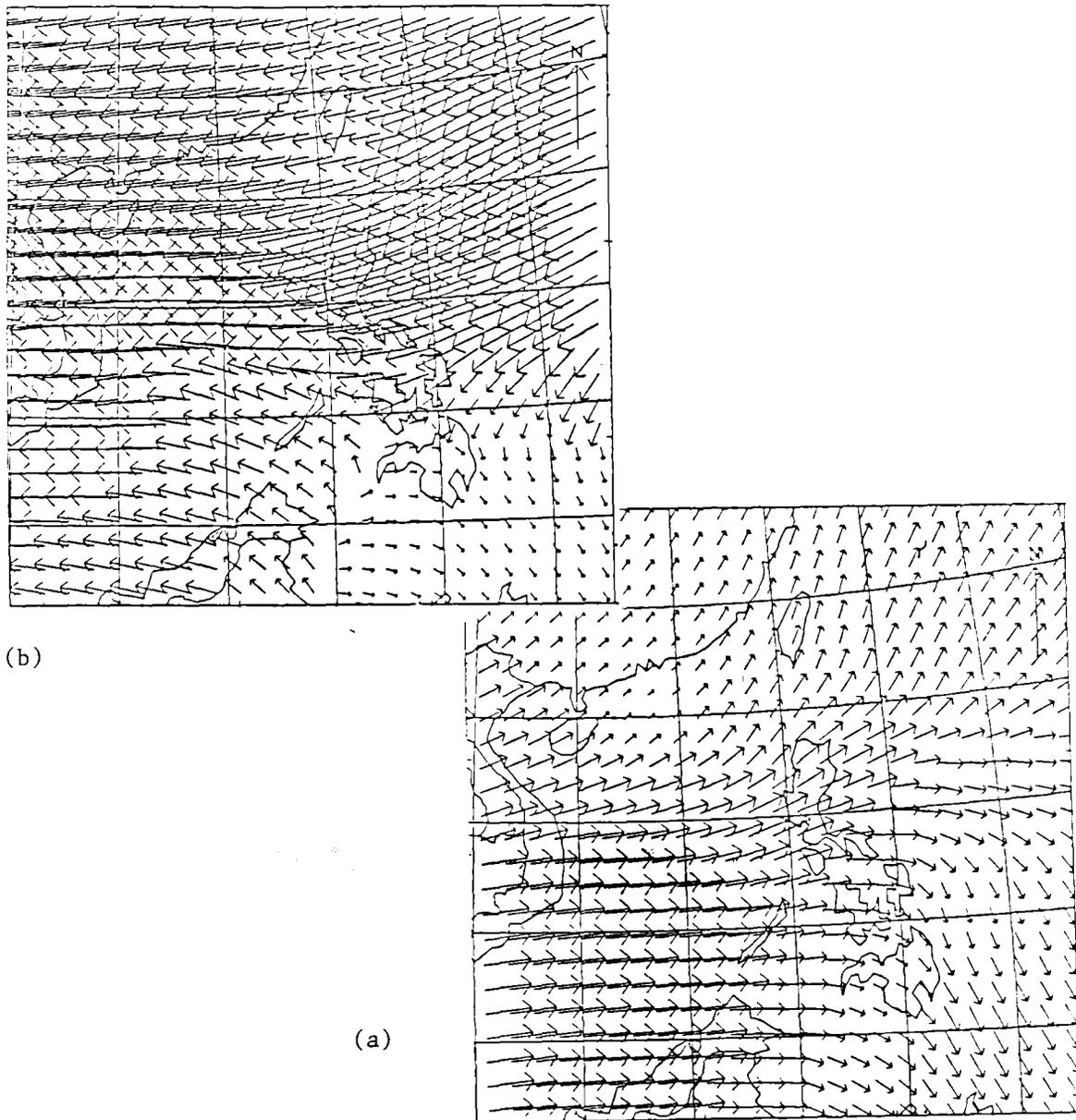

(b)

(a)

Figure 6a, b. Details of the regional calculations for the 19 June 1991 eruption event (during the U.S. military air evacuations); a) lower atmosphere (2500 m, ~ 7500 ft.) winds; b) upper atmosphere (15,000 m, ~ 50,000 ft) winds.

also reveal the complex, sheared windflow regimes at 2,500 and 15,000 meters on 18 June 1991. In order to prepare these calculations for the sub-region, it was necessary to extract grid point profiles from the hemispheric data grids and merge them with available regional rawinsonde data. At the time of the eruptions, this was a manual process; now it is substantially automated. Using the same "source" scaling parameters and preceding eruptions, Figures 7a, b and c reveal the model representation of the 19 June 1991,
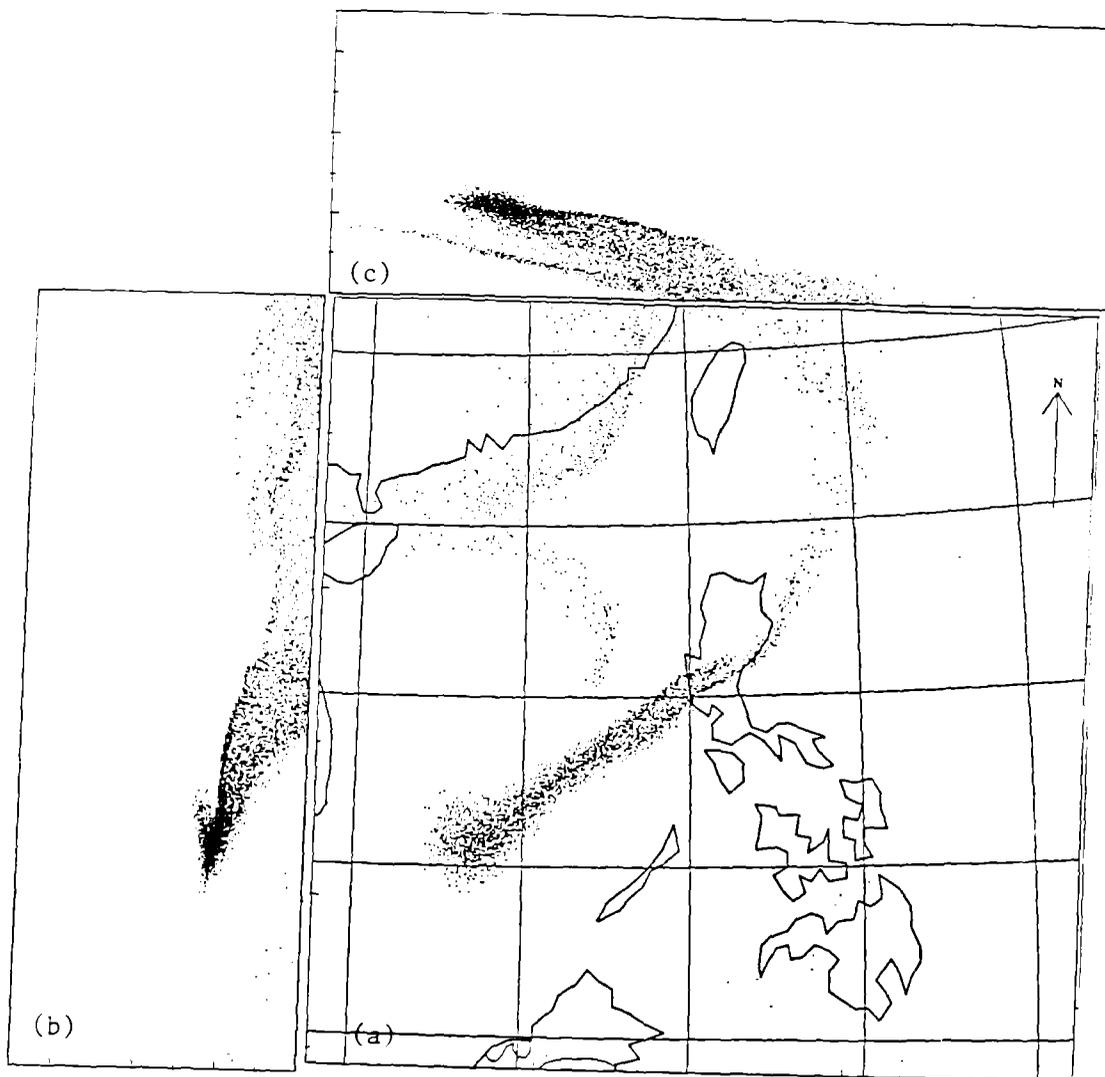

Figure 7. a) Overhead "particle cloud" view for the regional grid calculations of the 19 June 1991 eruption; b) viewed from east to west and c) viewed from south to north.

1425GMT eruption after nine hours of dispersal simulation. Note the dominant plume of ash transported west southwest over the South China Sea by the strong high altitude winds. A low altitude, meandering plume (from residual venting between major eruptions) stretches north around Taiwan and wraps back around along the South China coast. Vertical cross-section views of the 19 June 1991 eruption plume at 0000 GMT on

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20 June show the simulated "ashfall" from the southwestward transported upper plume (5–15,000m) and lesser low-level plume. The resulting dispersing ash cloud(s) are shown in Figure 8 a–c, revealing the different structures of the northeast (lower level) ash stem and vent clouds and the southwest (upper level) main explosion cloud and ashfall from the above stratospheric injection. Figure 8d is a verifying AFGWC analysis. Immediately evident is the sloped, upper cloud and particle fallout structure being driven to the southwest by the higher altitude winds while the lower "stem" and continuous lower-level post eruption "venting" ash cloud is being swept northeast then northward. Note the need for a much broader cloud near the source point in the ARAC calculations.
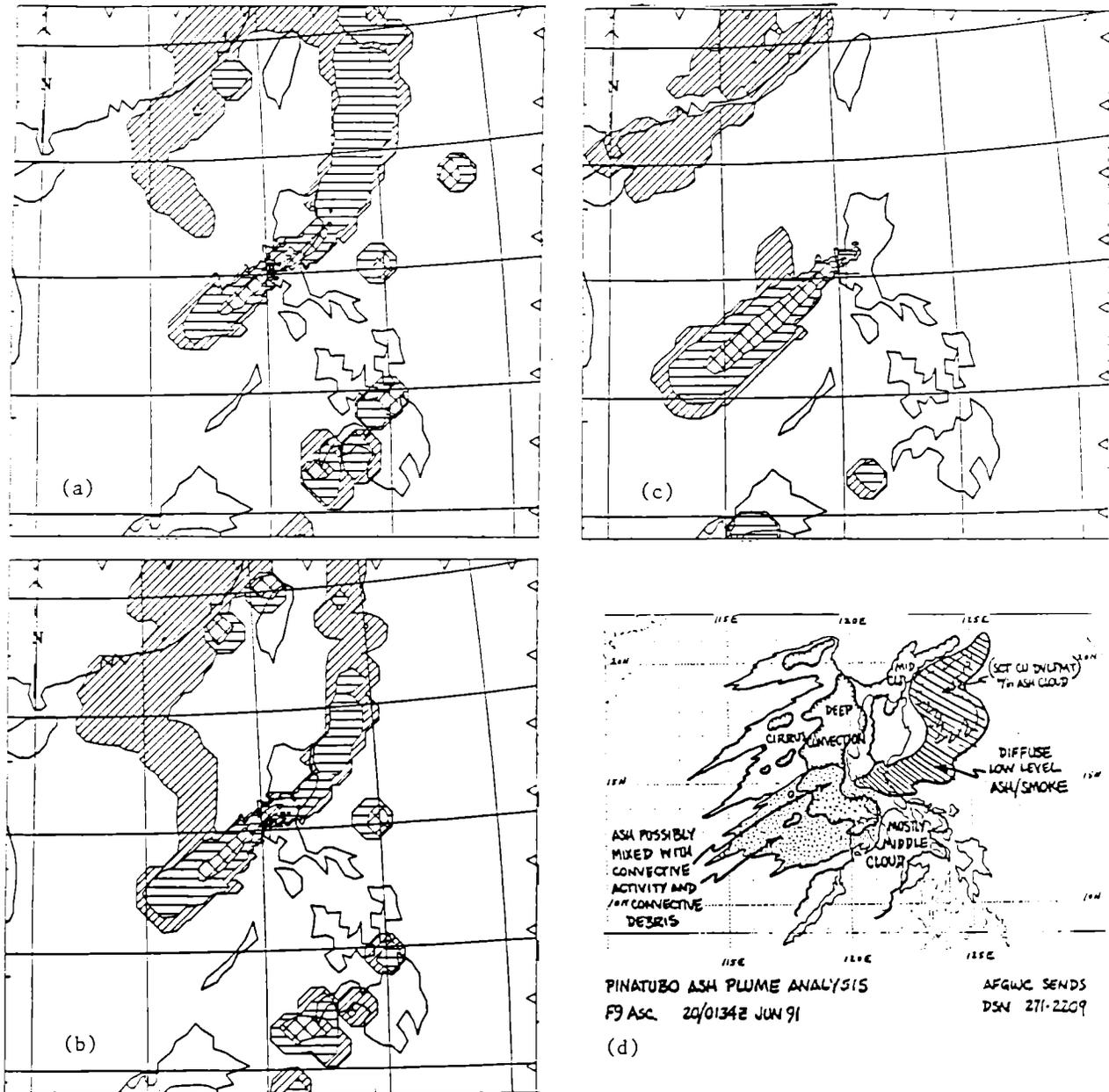

Figure 8 a–d. The relative ash concentration isopleths for three altitude layers a) 5,000–10,000 ft.; b) 10,000–20,000 ft. and c) 20,000–30,000 ft.; d) provides an AFGWC realtime satellite cloud and ash analysis which serves as a verification.

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For the cataclysmic eruption of 15–16 June, the complex three-dimensional atmospheric structure in the region produced dramatically divergent ash cloud patterns. The large eruptions (> 7–10 km) produced ash plume clouds, with strong westward transport over the South China Sea, Southeast Asia, the Bay of Bengal, toward India and beyond. It is the downwind transport, diffusion and ash fallout of these enormous stratospheric intrusions which resulted in the numerous aircraft encounters with the ash clouds and engine damage. The low-level eruptions (< 7 km) and quasi-steady-state venting produced a plume which generally dispersed to the north and east throughout the support period.

Potential Advisory Improvements

These results show the detailed ash cloud structure achievable with the ARAC three-dimensional modeling system. Although the initial approach proved viable (and successful), further refinement is possible. A distinct need exists to quantify eruptions consistently such that "relative" ash concentrations relate to specific aviation hazards. Research and collaboration with the volcanology community could possibly produce an "eruption mass" estimation methodology correlated to seismic detection or eruption height. Particle sizes, density and other relevant characteristics should be refined. Databases of all known/potential volcanoes with their locations and characteristics could be prepared; links to volcanologist's alerting networks could be established.

Potential Value to Aviation

A few immediate advantages of the ARAC hazard modeling system are 1) advisory products not limited or affected at night; 2) natural clouds do not obscure or affect the modeling technique (as, for example, satellite detection based techniques); 3) unaffected routes/areas are apparent; 4) altitude layers can be differentiated; 5) ash cloud dispersion calculated with winds comparable to aircraft computerized flight plans and 6) the advisories are easily interpreted graphic charts. Coupling of aviation operations with this type hazard modeling provides a demonstrated, viable method to keep aircraft from unseen, unanticipated exposure to volcano ash cloud hazards.

Assuming an interest in the aviation community, a protocol could be established for generation of precautionary calculations; i.e., pre-eruptive, as well as during and post eruption until all hazardous quantities of ash are removed from the atmosphere/airspace. A system for dissemination of these results would need to be determined in order that the advisories reach all the potentially impacted aircraft, carriers, air traffic control and airport authorities. With such a capability integrated into global aviation, the hazard due to flight operations in areas of volcanic eruption threat or activity could be well defined and appropriately avoided by rerouting, rescheduling, etc. Terminals at risk could also be avoided thus minimizing the risk of aircraft damage as well as risk of loss of utilization due to grounding—either of which could have substantial economic impacts.

Summary

Modeling the sequence of eruptions presented ARAC another unique challenge. Based on the results achieved, it is concluded that application of this modeling methodology could provide enhanced safety for the aviation industry/community in the event of volcanic eruptions. The modeling system improvements outlined must be developed if ARAC were to be considered for future involvement in a volcanic ash cloud

hazard advisory type service. The U.S. Department of Energy, as manager for the ARAC program, must approve any extension of this emergency response service into this area of natural hazard mitigation utilization before such service could be routinely provided. Technology transfer to nongovernment organizations is a possible alternative, provided a technically competent organization with strong meteorological and aviation interests assumes responsibility for generation of the advisories.

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