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Atmospheric Release Advisory Capability: Real-Time Modeling of Airborne Hazardous Materials

Thomas J. Sullivan,* James S. Ellis,* Connee S. Foster,* Kevin T. Foster,* Ronald L. Baskett,+ John S. Nasstrom,+ and Walter W. Schalk III+

Abstract

The Atmospheric Release Advisory Capability (ARAC) at Lawrence Livermore National Laboratory is a centralized federal project for assessing atmospheric releases of hazardous materials in real time. Since ARAC began making assessments in 1974, the project has responded to over 60 domestic and international incidents. ARAC can model radiological accidents in the United States within 30 to 90 min, using its operationally robust, three-dimensional atmospheric transport and dispersion models, extensive geophysical and dose-factor databases, meteorological data acquisition systems, and experienced staff. Although it was originally conceived and developed as an emergency response and assessment service for providing dose-assessment calculations after nuclear accidents, it has proven to be an extremely adaptable system, capable of being modified to respond also to nonradiological hazardous releases. In 1991, ARAC responded to three major events: the oil fires in Kuwait, the eruption of Mt. Pinatubo in the Philippines, and an herbicide spill into the upper Sacramento River in California. Modeling the atmospheric effects of these events added significantly to the range of problems that ARAC can address and demonstrated that the system can be adapted to assess and respond to concurrent, multiple, unrelated events at different locations.

1. Introduction

In 1972, ARAC began as an Atomic Energy Commission (AEC) research project. Its mission was to develop a centralized means of predicting radiation dose levels and surface contamination from accidental atmospheric releases of nuclear materials at AEC facilities. The initial computer models developed by ARAC for this purpose substantially improved the ability of emergency response personnel to make real-time assessments of the potential consequences of such an accident (Dickerson and Orphan 1976).

Under the auspices of the U.S. Department of Energy (DOE)—which replaced the AEC—ARAC's mission evolved to include providing its services to 70 designated facilities within the DOE and U.S. Department of Defense (DOD) communities, in addition to maintaining its ability to respond to radionuclide or other hazardous material releases anywhere in the United States. Currently, ARAC is coupled to specialized DOE emergency response and assessment organizations such as the Accident Response Group (ARG), the Federal Radiological Monitoring and Assessment Center (FRMAC), and the Radiological Assistance Program (RAP). Federal agencies can request ARAC's services for radiological accidents through the DOE as specified in the U.S. Federal Radiological Emergency Response Plan.

During the past 18 years, ARAC personnel have participated in a variety of exercises and have assessed actual radiological releases that range from small accidental ventings to the Chernobyl reactor disaster (Lange et al. 1988; Gudiksen et al. 1989). Each new situation has helped identify areas in which ARAC's emergency response service could be improved. As a consequence, much of ARAC's growth has resulted from "lessons learned" being transformed into new capabilities (Sullivan 1988).

For example, in 1976, early in the history of ARAC, a train accident in North Carolina revealed that the availability of real-time meteorological data automatically formatted for use in the dispersion models was essential to a rapid response. In 1978, the unique request by the DOE to estimate the atmospheric consequences of Russian nuclear-powered COSMOS satellites burning up during reentry led the ARAC team to develop a high-altitude, particle-fall model. As a result, in 1981 ARAC was prepared for the reentry of COSMOS 1402. ARAC's largely manual response to the 1979 Three Mile Island accident indicated the need for automated, on-line, U.S. topography and geography databases (Knox et al. 1981). The 1986 Chernobyl accident propelled ARAC to implement continental- to hemispheric-scale models supported by worldwide terrain and mapping data (Sullivan 1991).

In 1991, ARAC experienced an unprecedented demand for its emergency services. The first request came on 16 January 1991, just as Operation Desert

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Storm began in the Persian Gulf. DOE Headquarters asked ARAC to model the hypothetical dispersal of chemical warfare agents that might be carried on SCUD missiles. This request was closely followed by two others asking ARAC to model the dispersal of radioactive material that might be released from bombed Iraqi nuclear reactors and to prepare realistic evaluations of hypothetical and real oil fire scenarios that might affect aircraft and weapon system operations. This last effort paid off in the postwar period, when ARAC was able to use its newly developed oil fire assessment tools to forecast the position of the smoke plume from the fires set by the Iraqis in Kuwait's oil fields. These forecasts continued through 6 November 1991, when the last fire was extinguished. On 14 June 1991, and in the midst of work on the smoke plumes in Kuwait, Mt. Pinatubo in the Philippines erupted. The U.S. Air Force asked ARAC to forecast the locations and concentrations of the ash plumes from this volcano. They used this information to select safe flight corridors through the ash-filled sky, which helped in the evacuation of Americans from areas endangered by the volcano. Finally, on 15 July 1991, ARAC was asked to model airconcentration of toxic gases resulting from the photodissociation of metam sodium herbicide. The herbicide had spilled from a railroad tank car into California's upper Sacramento River and traveled 80 km to Lake Shasta. The State of California Office of Emergency Services requested that ARAC model the concentration of the material released from the lake's surface, but not from the earlier, more severe release along the river.

While meeting these challenges in 1991, ARAC tested the reasonableness of its models and added significantly to the range of problems that it could address. It also proved the reliability of the system, which had been adapted to assess and respond to concurrent, multiple, unrelated events at different locations.

2. Staff, facilities, and operations

The original ARAC concept, prototype development, and initial operations from 1974 to 1982 were solely supported by the 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 (Dickerson et al. 1985). Since 1987, ARAC has been cofunded by the DOE and DOD. This funding currently supports a staff of 32 (about half operations staff and half computer scientists), a VAX-based computer system, and 70 remote-site computer systems. For radiological incidents at ARAC-supported facilities, the time to create and deliver plots to the site's computer can be as short as 10 to 15 min after the 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.

Figure 1 depicts the ARAC Emergency Response Operating System (AEROS) network; Fig. 2 is a simplified diagram of its top-level functions. AEROS, which contains over a million lines of computer code, automatically assembles necessary information for the model run stream once the minimum incident data have been entered into the computer system with the on-line "problem questionnaire." ARAC typically starts the response on a "local" to "regional" scale (10 to 200 km). As the response evolves, the operations staff can expand or contract the model grid proportional to the extent of the hazard. Responses to hazardous atmospheric releases can be initiated in two ways.

- Operations staff at the central ARAC facility can complete the on-line questionnaire using accident information received by telephone from the site coupled with defaults from on-line databases.
- Remote-site personnel can enter accident information directly into their site's on-line questionnaire. This information is automatically transmitted to

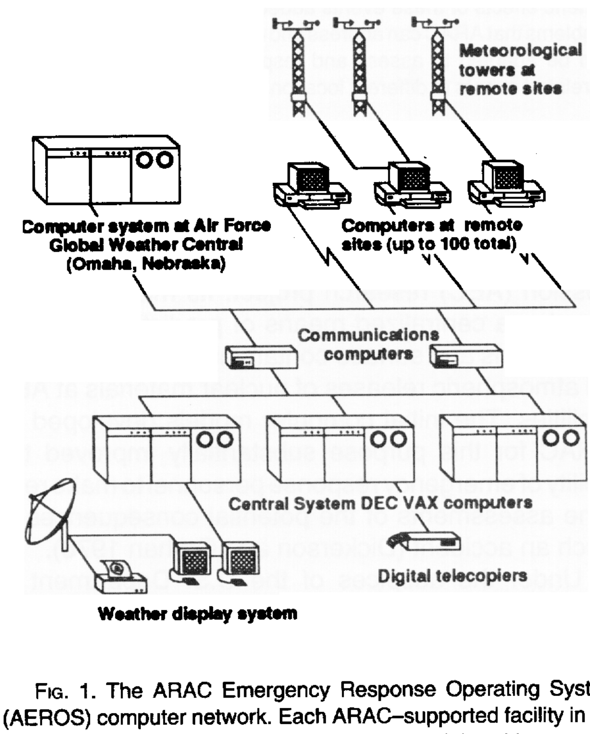

FIG. 1. The ARAC Emergency Response Operating System (AEROS) computer network. Each ARAC–supported facility in the system has a desktop computer for entering initial accident reports and one or more meteorological towers for providing the latest weather data. High-speed data links transmit this information to ARAC's computer center for use in atmospheric models.

ARAC's central facility from the site computer via a 1200-baud modem.

In both cases, either operator can easily initiate an ARAC response with a simple menu choice that causes the questionnaire to be displayed and then prompts the operator for accident information such as time, location, and type of release. The request for an ARAC response immediately triggers a paging system that alerts ARAC's staff and sets in motion the acquisition of all available regional and site weather data for input into the model calculations. Within minutes, all model input data are in the central system. ARAC personnel then simulate the release with complex dispersion models that account for the effects of local terrain, prepare graphical plots of the contamination overlaid on the local geography, and distribute these plots to on-site authorities.

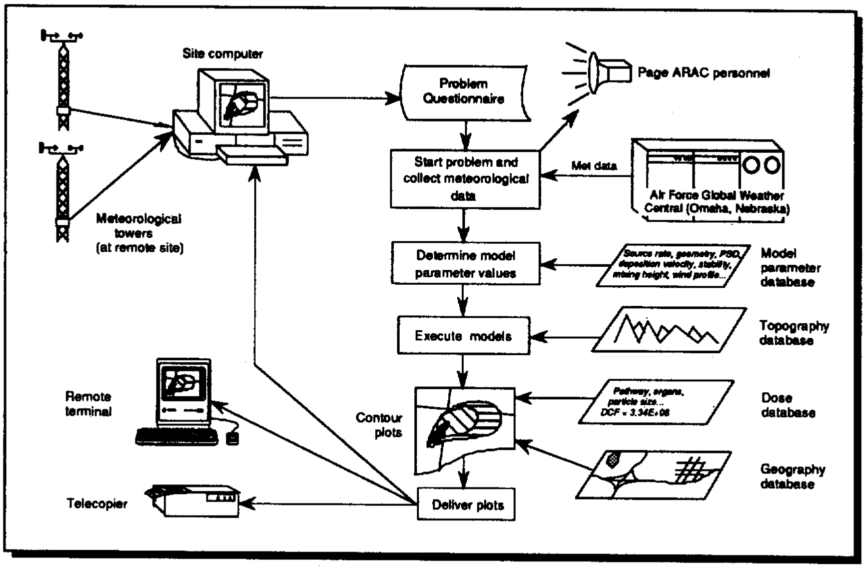

FIG. 2. The primary functions of the AEROS computer network.

Typically, ARAC's response time is equally divided among computer (or voice) communications with the site, automated (or manual) model input preparation, model execution, and human interaction with the system. ARAC currently uses 35 000 000 instructions s^{-1} (Mips) Digital Equipment Corporation (DEC) VAX 6610 computers to run the models and microVAXs to communicate with DEC PC350/380 site computers. Each of the facilities supported by ARAC has one or more meteorological towers that automatically transfer data directly into the on-site computer via modems every 15 min. In late 1993, ARAC began replacing the site computers with UNIX-based workstations that communicate with ARAC at 9600 baud and provide site users with a processor 100 times faster than the DEC PCs.

3. ARAC databases and computer codes

a. Databases

The ARAC computer codes combine real-time meteorological data with topographical data to calculate a detailed treatment of atmospheric dispersion that is three-dimensional, terrain-influenced, and spatially and temporally varying. Default data files and detailed site notebooks are maintained for all supported sites, and a worldwide library of potential accident sites is available, including locations such as nuclear power plants, fuel-cycle facilities, and similar installations.

During an ARAC response, hourly surface and twice-daily upper-air meteorological data are automatically acquired from ARAC's dedicated 19 200-baud link to the U.S. Air Force Global Weather Central (AFGWC). In < 2 min, these data can be received, decoded, and formatted for input to the model. Depending on the situation, meteorological variables such as atmospheric stability, mixing height, and vertical wind power-law profile parameters can be either determined automatically using on-line algorithms or input manually by the assessment meteorologist who is running the computer codes. A variety of source-term inputs such as release rate, source geometry, particle-size distribution, and deposition velocity are calculated from the questionnaire information and on-line databases.

The geographic databases provide mapping information on scales ranging from buildings and streets on the local scale to country outlines on the hemispherical scale. For general map coverage of the United States, ARAC uses the U.S. Geological Survey (USGS) 1:2 000 000 Digital Line Graph (DLG) database (Walker 1989). ARAC's on-line topographical database is derived from the Defense Mapping Agency's Digital Terrain Elevation Data covering much of the world with 0.5-km resolution and NOAA's ETOPO5 data covering all of the world at 5-min (10.0 km) resolution. The DOE's dose-factor database contains estimates of dose-conversion factors for internal and external exposure for nuclides of concern. In the future, ARAC plans to add a population database.

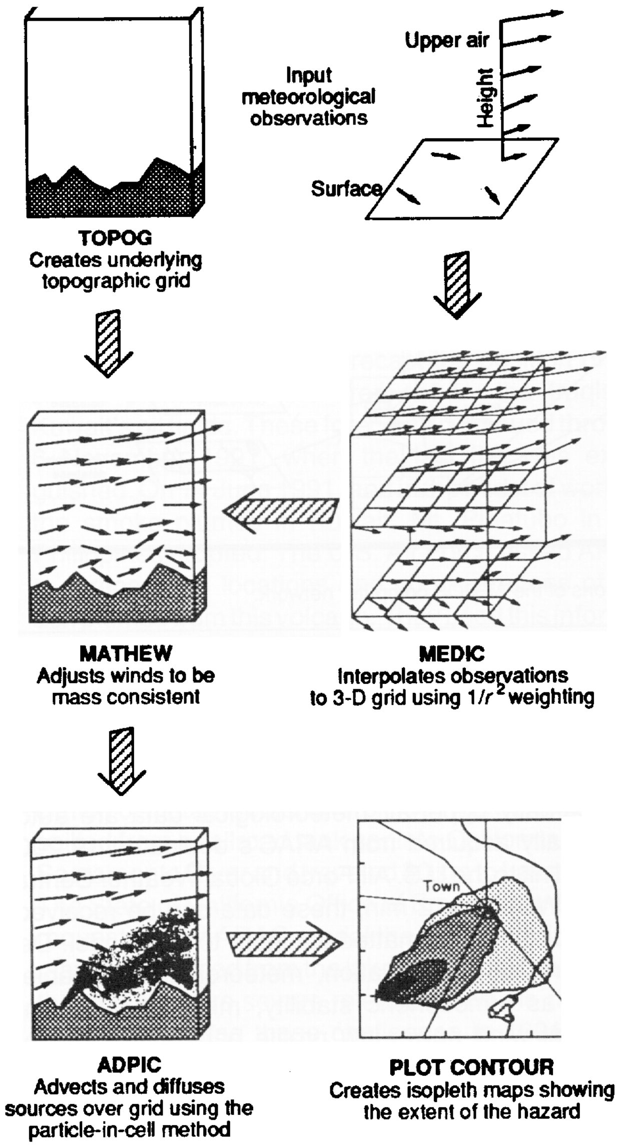

FIG. 3. Sequential run stream of ARAC's primary models used in calculating emergency response hazard assessments.

b. Computer codes

At the foundation of the ARAC modeling effort are two diagnostic, finite-difference computer codes: MATHEW (Mass-Adjusted Three-Dimensional Wind Field) (Sherman 1978), and ADPIC (Atmospheric Diffusion Particle-In-Cell) (Lange 1978). These codes are used in conjunction with TOPOG (a topographic grid generation code), MEDIC (Meteorological Data Interpolation Code), PLOT CONTOUR (a graphical contour plot generator), PERSPEC (a code for visualizing terrain), and DOSE (an application of radiological dose factors code). These codes make up ARAC's primary diagnostic dispersion modeling system. Figure 3 illustrates the basic MATHEW/ADPIC run stream that culminates in the hazard-assessment product. The typical run of this system takes about 5 to 10 min of VAX CPU time at 35 Mips to complete, including the automated preparation of the input files.

Topography databases (Walker 1985) provide information for determining how wind fields are influenced by underlying terrain. In 2 to 5 min, ARAC's operations staff can create a terrain file with a resolution 0.5 km $\times$ 0.5 km and can display images of the mountains, valleys, seashores, and plains for almost any part of the world. In a typical ARAC regional response, TOPOG produces an Eulerian grid with block-form terrain for the lower boundary of the model system. The model domain is typically divided into 35 000 cells with an array of 50 $\times$ 50 horizontal cells and 14 evenly spaced vertical layers.

MEDIC uses an inverse-distance-squared ($1/r^2$) weighting of wind speed and direction observations and wind-profile laws to extrapolate horizontal wind vectors to the face of each grid cell. Because this extrapolation does not account for terrain, it can yield winds that blow through instead of around mountains and across rather than along the valleys. To correct such impossible results, each grid cell that is below the terrain (e.g., under a mountain or ridge) is marked to prohibit air from entering it. MATHEW then applies a calculus-of-variation technique to create a mass-consistent, nondivergent flow field over the block-form terrain. Vertical velocities are generated by enforcing the mass conservation (or continuity) equation on each grid cell, ensuring that the same amount of air leaves each box as enters it. The relative magnitude of adjustments to the horizontal and vertical wind components are governed by atmospheric stability, calculated from surface observations. Because this is a purely diagnostic model, thermally driven flows such as sea breezes, slope flows, or convection motion are not created in the calculation. Resolving these features relies to a great degree on the representativeness of input wind observations. The wind field calculated by MATHEW provides the three-dimensional mean wind components for ADPIC.

ADPIC is a Lagrangian particle-in-cell code that provides the dispersion physics for a wide range of emissions, such as neutrally buoyant gases, and/or particles, including radioactive and nonradioactive materials. Up to 20 000 marker particles are available to represent as many as nine different sources or species in a single model run. These sources can be simultaneously injected into the wind field, with each source having its own release rate, particle size distribution, deposition velocity, and plume-rise characteristics. Plume rise is controlled by the amount of heat energy released, the height of the inversion, the stability of the atmosphere, and the wind speed profile in the planetary boundary layer. The height of the inversion and the stability of the atmosphere can be specified as a function of time, but they are currently uniform over the model domain. Sources may be either instantaneous puffs or continuous plumes with time-varying release rates. Radioactive decay, particle size–dependent gravitational settling, dry deposition, and precipitation scavenging are computed during each time step for each source. Four inner nested grids with 2, 4, 8, and 16 times the resolution of the primary grid cell provide higher resolution near sources.

Dispersion of ADPIC marker particles can be described by two basic processes: transport by the mean wind and diffusion by turbulence. MATHEW provides the mean winds for use by ADPIC. The operational version of ADPIC uses parameterizations for horizontal and vertical eddy diffusivities (K theory) and solves the advection–diffusion equation using a particle-in-cell technique (Lange 1989). The parameterizations of the eddy diffusivities are based on Obukhov length, mixed-layer height, surface roughness, and wind speed.

For radionuclides, the DOSE code determines dose factors for the desired individual organs or the whole body through inhalation, immersion, or ground-exposure pathways. Because the models were designed for radiological incidents, they do not calculate either chemical changes in species or photochemical reactions.

PLOT CONTOUR produces a variety of plots using a geographic map overlay. Typical model results include plots of material deposited on the ground, instantaneous and time-integrated doses, or air concentrations at selected levels above the ground. Species or sources may be combined as required and contoured according to specified isopleth values. The plots generated by PLOT CONTOUR include legends that describe the release, the species involved, and type, units, and valid time for the contours. After a quality assurance review by an assessment meteorologist, the plots can be transmitted by modem to a computer at ARAC-supported sites or can be faxed to the emergency response manager.

4. Model evaluations

To quantify model accuracy, more than a dozen model-evaluation studies have been performed over the years in a variety of settings and scales. Figure 4 illustrates and Table 1 lists the MATHEW/ADPIC evaluations on the local-to-regional scales (1 to 100 km) over the last 20 years as summarized by Dickerson and Ermak (1988), Lange (1989), Foster and Dickerson (1990), and Lange (1992). Each individual evaluation used the most stringent statistical comparison, where measurements are paired with model calculations in *both* space and time. Also, all tracer samples were used. The sources include neutrally buoyant tracers released both as surface and elevated point sources. The studies are categorized as "simple," involving flat or rolling terrain with relatively steady meteorology, or "complex," involving rolling to complex terrain or complex meteorology, such as sea breezes, mountain–valley flows, or changing winds during the tracer release.

Results show that the MATHEW/ADPIC models estimated the air concentrations of the tracer to within a factor of 2 of the measured values 20% to 50% of the time, and to within a factor of 5 of the measurements 35% to 85% of the time, depending on the complexity of the meteorological conditions, the terrain, and the release height. A factor of 2 means that the model calculated between twice and half the observed value. Each study typically represents hundreds to thousands of 20- to 60-min averaged ratios of measured to modeled values of the concentration of the tracer in ground-level air. Using ratios to compare model results with observations gives every data point equal weighting, regardless of the magnitude of the concentration. This method provides a measure of relative model performance between experiments, but it does not offer any details about the model's bias. Also, the method favors the low concentrations usually present at the edges of the plume.

One of the earliest model evaluations was sponsored in 1971 by the National Oceanic and Atmo-

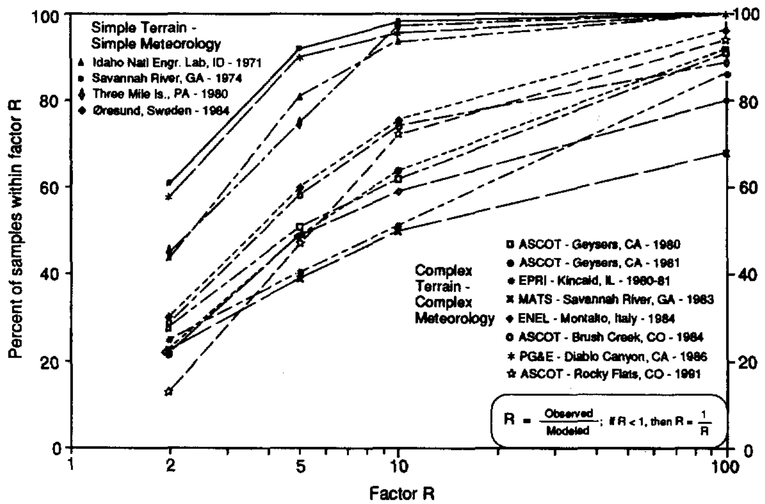

Fig. 4. Accuracy of MATHEW/ADPIC models from comparisons with 12 local- to regional-scale field studies. Each curve is derived from hundreds to thousands of ratios of individual observations to model calculations, paired in time and space.

TABLE 1. Summary of local- to regional-scale evaluations of MATHEW/ADPIC.

Sponsor	Location	Date	Topography/meteorology	Atmospheric stability	Release height (m)	Sampler distance (km)
NOAA	Idaho National Engineering Lab, Idaho	1971	Flat to rolling plain/ daytime flows	Slightly unstable	Surface	5 to 90
SRP	Savannah River Plant, South Carolina	1974	Rolling coastal plain/ daytime flows	Slightly unstable	62	3 to 30
DOE	Three Mile Island, Harrisburg, Pennsylvania	1980	Flat river valley/diurnal flow	All	60	1 to 8
EPRI	Kincaid, Illinois	1980–81	Flat plain	All	187*	1 to 50
ASCOT	Geysers Geothermal Area, California	1980	Coastal interior valley/ nocturnal drainage	Stable	Surface and 60	0.5 to 10
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MATS	Savannah River Plant, South Carolina	1983	Rolling coastal plain/ daytime flows	Neutral to unstable	62	30
ENEL	Montalto, Italy	1984	Coastal plain/sea breeze	Unstable	10 and 50	1.5 to 6.5
ASCOT	Brush Creek, Colorado	1984	Mountain valley/ nocturnal drainage	Stable	Surface and 220	0.5 to 10
Risø	Øresund Strait, Sweden–Denmark	1984	Flow over cold water to land	Neutral	95	22 to 42
PG&E	Diablo Canyon Nuclear Power Plant, California	1986	Mountainous coast/sea breeze	Neutral	1.5 and 71	0.5 to 40
ASCOT	Rocky Flats Plant, Colorado	1991	Plateau at base of mountain range	Stable and neutral	10	8 and 16

*Plus plume rise.

spheric Administration (NOAA) at the Idaho Falls National Reactor Test Station, now Idaho National Engineering Laboratory (Lange 1978). Using 36 samplers over rolling terrain, the plume from a 3-h methyl iodine release with ^{131}I was well documented across four arcs about 5, 15, 45, and 90 km downwind. The relatively steady southerly flow gave the study its "simple" meteorology. The model performed reasonably well with 80% of the calculations within a factor of 5 of the 3-h integrated measurements.

Another of MATHEW/ADPIC's best performances was for the 1974 Savannah River Plant (SRP) tracer, while one of the least accurate results was for the 1983 Mesoscale Atmospheric Transport Study (MATS), also at SRP. Conducted at the same site under similar meteorological conditions, the studies would presumably produce similar results. However, the 1974 study (Lange 1978) is rated as simple meteorology because the wind direction was relatively steady for the first 15 km on site and for another 15 km off site. The meteorology during the 1983 experiment was complex because the wind changed direction over the 30-km transport distance. The wind direction measured by on-site towers did not accurately represent the flow off site, which was not measured. Consequently, compared to the observations, the model shifted the location of the plume centerline along the arc 30 km from the source. A correction of 8 degrees in the model input wind direction resulted in a performance equivalent to the 1974 study. The 1983 MATS study and several subsequent model evaluations have repeatedly shown that the model's performance is most sensitive to the accuracy of the wind direction inputs (Lange 1989). Allowance for a ±5° error in wind direction inputs dramatically shifts the curves in Fig. 4 from 10% to 40% upward.

Another challenging model evaluation was the 1980–1981 Electric Research Power Institute (EPRI) Plume Model Validation study at the coal-fired Kincaid Generating Station in central Illinois. These results depended strongly on the accurate representation of the final plume rise from the 187-m stack during neutral and unstable conditions. The complex meteorological conditions during the morning and evening transition periods after sunrise and sunset were the reason for the relatively low model performance for the EPRI Kincaid study (Peterson and Lange 1985).

The 1980 purge of ^{85}Kr from the damaged Three Mile Island Nuclear Power Plant in Harrisburg, Pennsylvania, made for an interesting model evaluation study. A relatively small number of 24-h surface measurements coupled with short-term helicopter data gave a small dataset for evaluation. Samples covered the range of diurnally varying conditions on the local scale in the immediate vicinity of the Susquehanna River Valley. Foster and Dickerson (1990) show relatively good model performance for the channeled valley flow.

The DOE Atmospheric Studies in Complex Terrain (ASCOT) program provided numerous tracer datasets over the last decade primarily during nocturnal drainage flows in complex terrain. The hilly Geysers Geothermal Area in California's Coast Range mountains 120 km north of San Francisco presented a unique challenge. Not only was the Andersen Creek study area complex, but also the sea-breeze flows above the valley occasionally eroded the top of the stable down-valley winds (Lange 1989). Using the 1980–81 Geysers datasets, Porch and Rodriguez (1987) confirmed that the inverse-distance-squared weighting of wind observations to initialize MATHEW performs as well as more sophisticated schemes for the local scale in complex terrain. Tesche et al. (1987) also independently evaluated MATHEW/ADPIC and compared its results with three other first-order closure numerical models using the 1980–81 Geysers data. The 1984 ASCOT dataset from the more channeled nocturnal drainage in the deep Brush Creek Valley of western Colorado provided relatively steady-state conditions with better model performance.

An important development based on the extensive surface and upper-air measurements during the ASCOT studies in the 1980s was a better parameterization of the vertical profile of the horizontal diffusivities (Lange 1989). Using multiple tethersonde and sound detection and ranging (sodar) systems, horizontal diffusivity profiles were related to the surface and upper-air measurements of the standard deviation of wind direction. These profiles improved model performance when compared to the previous method of determining diffusivities from the gridwide stability class. The most recent ASCOT-supported tracer study at Rocky Flats Plant in Colorado during the winter of 1991 involved shallow drainage flows descending off the Front Range of the Rockies. Small-scale terrain channeling and plume meandering made this setting difficult to model and produced relatively large underpredictions (Lange 1992).

Several studies were conducted in coastal environments. The 1984 Italian Electricity Board (ENEL) local-scale experiment at Montalto, Italy, revealed a complex vertical wind structure that resulted in moderately low model performance (Desiato and Lange 1985). Also in 1984, intermediate model performance was obtained for the strong wind flow over the Øresund Strait between Sweden and Denmark for the study sponsored by Risø National Laboratory (Gryning 1985). The cold water of the Øresund Strait produced a shallow stable surface layer that controlled the vertical mixing (Gudiksen and Gryning 1988). In contrast, Pacific Gas & Electric Company's (PG&E) 1986 study at the Diablo Canyon Generating Station on the coast near San Luis Obispo, California, showed excellent model performance in a setting with complex meteorology and terrain. This was probably due to ample and well-placed meteorological observations, both at the surface and in the upper air. Surface stations included valley and mountaintop locations. Three sodars were used to measure the vertical profiles. As was demonstrated in the ASCOT program, the quantity and representativeness of meteorological observations is key to generating a reasonable wind field. Crucial to modeling a release with any vertical extent are vertical wind profiles representative of the modeling domain. The Diablo Canyon study was used to quantify the improvement gained by using on-site sodar data versus extrapolating distant radiosonde soundings (Nasstrom et al. 1990). The other key to controlling diagnostic wind fields is the horizontal extent of surface station influence. Because of the difficulty in determining this influence objectively in complex settings, the assessment meteorologist must sometimes modify the input data based on a manual analysis of the winds to produce an accurately modeled wind field.

Other unique local-scale studies have been conducted by ARAC. A time-dependent cloud-rise model based on Boughton and DeLaurentis (1987) was implemented to estimate hazards from a toxic particulate cloud generated by explosions. Comparisons of model estimates to peak downwind deposition and air-concentration measurements from these releases are within a factor of 2 more than half the time.

MATHEW/ADPIC models have also been evaluated on the long-range or continental scale (>1000 km). The joint U.S.–Canadian 1983 Cross-Appalachian Tracer Experiment (CAPTEX) provided one of the first long-range datasets. Although the modeled wind field produced some misalignments of the observed plume centerline, modeled concentrations unpaired in space compared well with measurements and demonstrated no systematic bias (Rodriguez 1987). Better results were obtained in the early 1987 Across North America Tracer Experiment (ANATEX) using spatially varying mixing heights and the National Weather Service's Nested Grid Model wind field (Rodriguez and Cederwall 1990). In 1991, ARAC participated in another long-range study, the Atmospheric Transport Model Evaluation Study (ATMES), which was based on European radiological measurements taken during the Chernobyl accident in April 1986. A total of 21 institutions from 14 different countries participated in the study, which was sponsored by the International Atomic Energy Agency (IAEA), the World Meteorological Organization (WMO), and the Commission of the European Communities (CEC). MATHEW/ADPIC results were within a factor of 2 for 20% and a factor of 5 for half of the 245 surface ^{131}I and ^{137}Cs air concentration data taken over 14 days on a 5000-km × 5000-km grid of Europe (Lange and Foster 1993). Of the 21 participants, MATHEW/ADPIC ranked first in total deposition of ^{137}Cs and fourth overall in the surface-air concentrations. ARAC is currently participating in another CEC–IAEA–WMO-sponsored tracer study, the European Tracer Experiment (ETEX).

TABLE 2. Some ARAC responses over the history of the project.

Year	Location	Source	Release
1976	North Carolina	Train accident	Uranium hexafluoride
1978	Northern Canada	COSMOS 954 reentry	Fission products
1979	Harrisburg, Pennsylvania	Three Mile Island 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, former Soviet Union	Nuclear Power Plant	Mixed fission products
1988	Miamisburg, Ohio	Mound Plant	Tritium gas
1989	Amarillo, Texas	Pantex Plant	Tritium gas
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, former Soviet Union	Nuclear power plant	Radioactive gases
1993	Richmond, California	Railroad tank car	Sulfur trioxide

About a year after Chernobyl, on 26 February 1987, the accidental venting from an underground nuclear device at Semipalatinsk in south-central Russia produced a limited dataset to evaluate ADPIC on a hemispheric scale. The eight-day time history of 24-h average ^{133}Xe concentrations at Freiburg, Germany, was reconstructed with reasonable fidelity (Rodriguez and Peterson 1989). Air concentrations on the highest day were estimated within a factor of 2 and on the other days within a factor of 5.

Although model accuracy has been quantified for many different settings and scales, communicating the overall uncertainty on the ARAC plot remains elusive. Frequently, the emergency response manager receiving an ARAC plot wants to know the error associated with the location of a contour or the accuracy of a concentration at a particular location. Currently, the answer is that at best the MATHEW/ADPIC models are within a factor of 2. This is true for the majority of points within the plume, especially if an allowance for ±5° error in wind direction is taken into account.

5. Responses

During the past 18 years, ARAC has responded to more than 60 alerts, accidents, and disasters, and to over 500 exercises. The characteristics of selected past responses are listed in Table 2. Three recent incidents, the oil fires in Kuwait (Ellis et al. 1992; Sullivan et al. 1992a), the eruption of Mt. Pinatubo in the Philippines (Sullivan et al. 1992b), and the herbicide spill in California's upper Sacramento River (Baskett et al. 1992), illustrate ARAC's capabilities.

a. Kuwait

During the last few days of February 1991, at the end of the Persian Gulf War, an estimated 605 oil wells were set on fire, causing an unprecedented environmental disaster in the region. During April 1991, two working groups, one sponsored by the World Meteorological Organization (WMO) in conjunction with the World Health Organization (WHO), and the other consisting of members of the U.S. government's scientific community, proposed airborne sampling programs to evaluate and assess the local and global atmospheric and meteorological consequences of these fires. ARAC was asked to forecast the location and density of the smoke plumes in support of these research aircraft missions. ARAC provided information for the flight planning, in particular, detailed locations of the entire plume. For the longer flights, the models were useful to indicate edges of the plume that were too diffuse to see several hundred kilometers downwind from the oil fires.

The aircraft measurement program was conducted in two 4-week-long stages that began in early May and mid-July 1991, respectively. Shortly after the flights began, the agencies involved, including the National Science Foundation, DOD, DOE, the Environmental Protection Agency, NOAA, the National Center for Atmospheric Research, and Battelle Pacific Northwest Laboratories (PNL), requested copies of ARAC's calculations and forecasts. In addition, WMO headquarters in Geneva and institutions and supporting contractors in the Middle East and in Washington, D.C. requested the plots. Concurrently, the WMO encouraged local governments to acquire a variety of meteorological and air pollutant measurements because these data would be useful in future evaluations of the effect of the oil fire plumes on the region. To focus these data collection efforts, the WMO requested the calculations be distributed to affected countries. Thus, by early June 1991, ARAC was also faxing its calculations to Iran, Kuwait, Pakistan, Oman, Bahrain, Qatar, Yemen, Turkey, and Saudi Arabia—a total of 20 agencies and countries were receiving daily ARAC calculations.

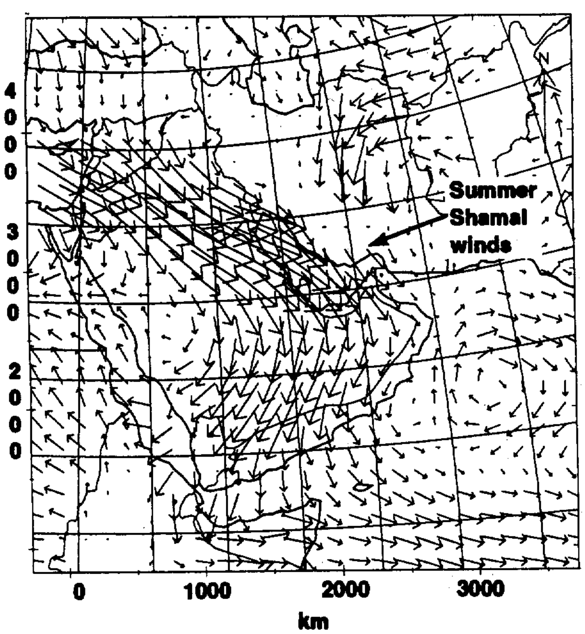

FIG. 5. Wind field at an altitude of 1700 m over the Persian Gulf region at 1200 UTC on 3 June 1991, as calculated by the MATHEW mass-conservation wind field code.

Since meteorological observations in the Persian Gulf region were sparse, ARAC used the AFGWC's newly implemented regional prognostic meteorological model called the Relocatable Window Model (RWM). The RWM generated the wind component data on a grid with a horizontal gridpoint spacing of about 90 km and vertical levels at the surface, at 305, 610, and 1525 m, and then in 1525-m increments up to 9150 m. ARAC interpolated the data to a 3200-km horizontal, 6-km vertical, regional grid with 40 × 40 horizontal grid cells and 14 vertical layers. Forecast wind data were valid 0, 6, 18, 24, and 36 h from both 0000 and 1200 UTC. Twice daily, ARAC used the RWM wind data and the regional terrain for input to MATHEW to produce forecasts out to 36 h. The terrain data were extracted from ETOPO5, a 10-km-resolution, worldwide digital database that ARAC developed based on NOAA 5-min-resolution data (Walker 1985).

Figure 5 is an example of a lower-level wind field over the region selected for the smoke-dispersion calculations after being adjusted for terrain by MATHEW (Ellis et al. 1992). Kuwait is near the center of the grid; Iraq and Iran are to the north, and the Arabian peninsula and the Arabian Sea are to the south. The horizontal wind field (shown at 1700 m above sea level) is bounded on the east side of the Persian Gulf by the higher terrain in western Iran. The higher-speed winds, represented by longer vectors, that come from the northwest direction and travel along the eastern side of the Arabian peninsula and over the Persian Gulf are known as the "Summer Shamal" winds. These winds are quite persistent from late spring to late summer (they loft silt and fine sand into the air from the Tigris–Euphrates river valley and

)
(b)

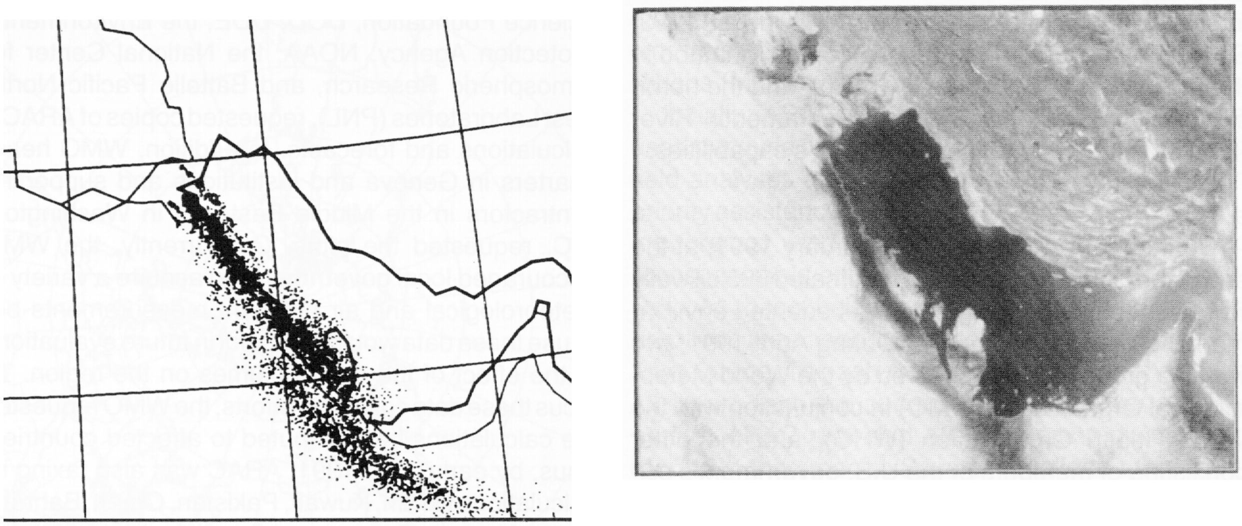

FIG. 6. Spreading smoke from the oil fires in Kuwait on 26 May 1991: (a) the 0000 UTC forecast of the plume structure and location prepared by ARAC for the U.S. research flights, and (b) the U.S. Air Force Defense Meteorological Satellite Program visible-wavelength satellite photograph taken at 0532 UTC.

then transport it southeastward). Because there is often a flow from the north over the gulf region and then eastward over the Arabian Sea to the south, the wind field over the entire region is quite complex. The summer monsoon frequently contributes to a nearly opposite flow toward the northeast along the southern coast of the Arabian Peninsula.

For ARAC's calculations, eight oil fields were grouped into three source regions: the south field (Burgan, Ahmadi, and Magwa) with 89.1% of the 4.3 million barrels per day, the north field (Raudhatain, Sabriya, and Bahrah) with 8.1%, and a third source region called the "other" field (Minagish and Umm Gudair) with 2.8%. The fraction of the combusted oil that went into particulate smoke (the smoke emission factor) was taken to be 2.0% (Laursen et al. 1992). The specific extinction factor used to calculate the optical depth[1] of the smoke was estimated from measurements to be 6.0 m^2 g^{-1} (Weiss and Hobbs 1992).

Each source region had its own release rate, particle size distribution, mean deposition velocity, and plume-rise characteristics. A total of 20 000 marker particles were used to represent all sources. The smoke particles were given a median diameter of 0.3 μm and a deposition velocity of 1.0 cm s^{-1}. For the fires, plume rise was controlled by the amount of heat energy being released, the inversion height, the stability of the atmosphere, and the wind speed in the atmospheric boundary layer. ARAC modeled a diurnal cycle: boundary-layer depth ranged from 500 m during the night to 1200 m during the day, and stability ranged from Pasquill class E (stable) at night to class B (moderately unstable) during the day.

The results of ARAC's modeling are shown in Figs. 6 and 7. Figures 7a–d show two ways of displaying the dispersal of the smoke plumes; Fig. 7e, a satellite image taken 4 h before the time of the ARAC predictions, reveals close agreement with the main segments of the plume over central Saudi Arabia and indeterminate agreement with the older, more dispersed eastern segment of the plume. We found that matching the satellite observations strongly depended on our ability to estimate the mixing height, the level that trapped the smoke (Sullivan et al. 1992b).

After ARAC completed the 3200-km regional calculations, a Northern Hemisphere modeling system was activated using the 381-km resolution AFGWC gridded analysis data at standard pressure levels. ARAC had developed this hemispheric version of ADPIC during the 1986 Chernobyl accident (Gudiksen et al. 1989). Using this modeling system, ARAC evaluated the hemispheric transport, dispersion, and deposition of fire-generated soot particles. Although coarse in horizontal resolution, these calculations retained the same vertical resolution as the regional calculations and also included terrain. The results showed the persistent northwest-to-southeast flow out of the gulf region, followed by complex transport and mixing

[1]Optical depth is a dimensionless number representing the total attenuation (sum of absorption and scattering) of light in a vertical column of air. It is determined by the specific extinction (extinction cross section per unit mass) times the mass concentration integrated over the vertical column.

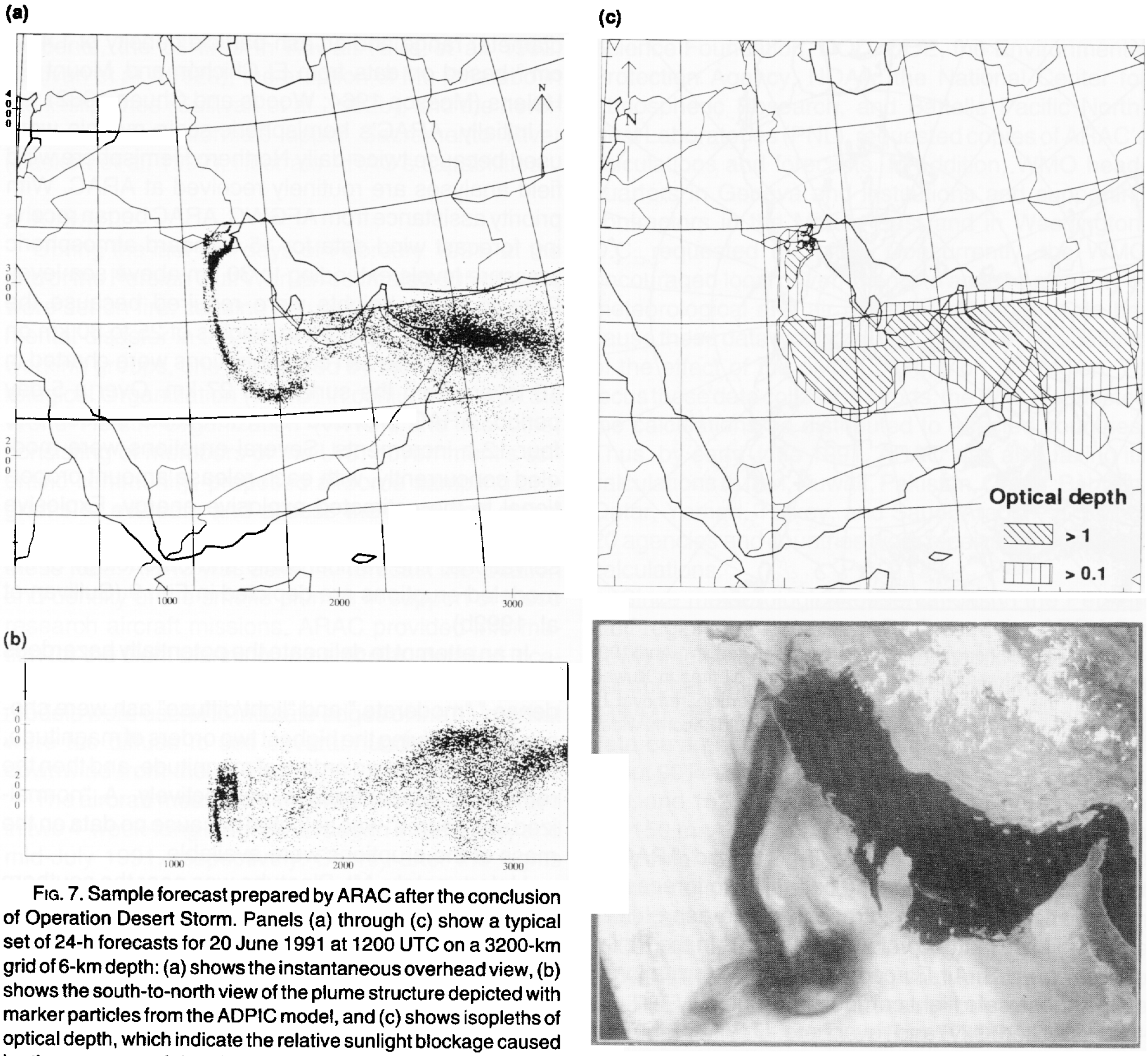

FIG. 7. Sample forecast prepared by ARAC after the conclusion of Operation Desert Storm. Panels (a) through (c) show a typical set of 24-h forecasts for 20 June 1991 at 1200 UTC on a 3200-km grid of 6-km depth: (a) shows the instantaneous overhead view, (b) shows the south-to-north view of the plume structure depicted with marker particles from the ADPIC model, and (c) shows isopleths of optical depth, which indicate the relative sunlight blockage caused by the presence of the plumes. Panel (d) shows the plumes as detected by the visible-wavelength scanner aboard a U.S. Air Force Defense Meteorological Satellite Program satellite taken at 0503 UTC.

patterns as the diluted plume interacted with the seasonal monsoon flow over Ethiopia, Somalia, the Arabian Sea, India, and Southeast Asia (Fig. 8).

Samples taken during the research flights showed that the particles were mostly hygroscopic. Consequently, a large fraction could be removed from the atmosphere by precipitation within and beyond the gulf region. Therefore, although the soot particles probably would not be transported as far as depicted in the hemispheric model, the calculations did indicate the potential for long-range effects from these fires.

During the period that ARAC was making calculations, several events were observed that suggest a possible correlation between precipitation anomalies and the presence of soot from the oil fires; these include a large negative monsoon season precipitation anomaly in Pakistan and northwestern India and a positive precipitation anomaly on India's southwestern coast. ARAC's hemispheric calculations also show that the historic Bangladesh cyclone in late April 1991 and severe floods in China during late May 1991 and the first week of July 1991 are potentially correlated with the local presence of modeled soot particles.

ARAC completed its calculations for the oil well fires on 1 November 1991, a few days before the last fire was extinguished. All meteorological data and contour plots for both the 3200-km and the long-range Northern Hemisphere grids have been archived for possible future research studies.

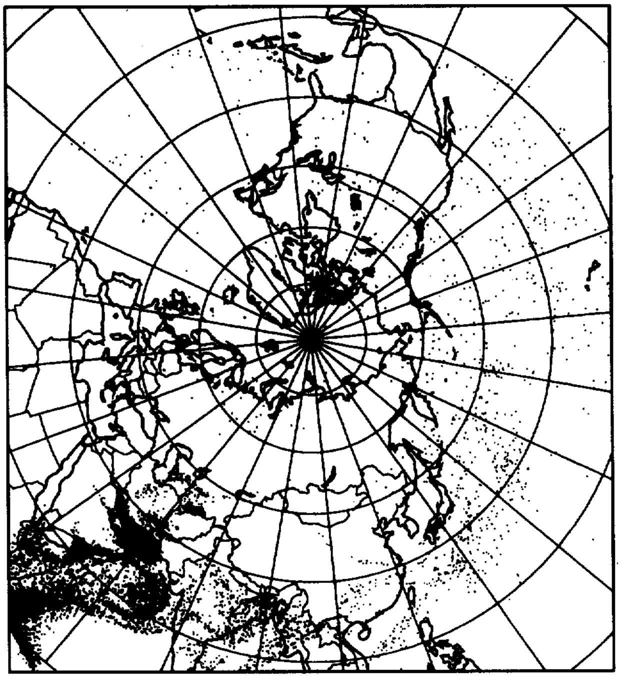

FIG. 8. Hemispheric particle dispersal calculated on 1 April 1991 after 39 days of continuous release from the oil fires in Kuwait. Although this calculation did not allow for particle removal by condensation, it was clear that soot particles could become widely dispersed.

b. Mt. Pinatubo

On 14 June 1991, the AFGWC asked ARAC to adapt its computer modeling capability to forecasting the locations and concentrations of the ash plumes from the Mt. Pinatubo volcanic eruptions in the Philippines. The U.S. Air Force needed this information to help choose safe flight corridors through the ash-filled sky and evacuate U.S. citizens from areas endangered by the volcano (Subic Bay Naval Base and Clark Air Base). Pilots need to avoid these plumes because ash sucked into the jet engines melts and recondenses on the jet turbines, potentially causing engine failure. Except for an internal experimental attempt to model one of the Mt. Redoubt, Alaska, eruptions in December 1989, this was the first time that ARAC had been asked to do real-time modeling of hazardous plumes of volcanic ash.

The AFGWC provided observations of the location, time, duration, and height of the eruptions. To serve as the basic geometry for release of the ADPIC marker particles, the ash cloud injections were modeled as large cylindrical volumes of several kilometers radius and vertical extent. ARAC selected a lognormal particle-size distribution spanning the 10- to 200-μm-diameter range and an ash-particle density of 1.45 g cm^{-3} based on data from El Chichón and Mount St. Helens (Mossop 1964; Woods and Chuan 1982).

Initially, ARAC's hemispheric-scale models were used because twice-daily Northern Hemisphere wind field analyses are routinely received at ARAC. With priority assistance from AFGWC, ARAC began receiving forecast wind data for 15 standard atmospheric pressure levels extending to 30 km above sea level. Data to these heights were required because the eruptions were reported to heights of 25 to 30 km on 14–15 June. The ash concentrations were charted in 10 layers from the surface to 27 km. Over a 5-day period, ARAC provided 48-h forecasts divided into four 12-h increments. Several eruptions were modeled concurrently, with each release amount proportional to the estimated explosive energy. Explosive energy was estimated from the cloud-top height observations. The vertical scale and chronology of the modeled eruptions are depicted in Fig. 9 (Sullivan et al. 1992b).

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 highest two orders of magnitude, and then the remaining concentrations, respectively. A "normalized unit source" was selected because no data on the mass of the eruptions were available.

Unfortunately, Mt. Pinatubo was near the southern boundary for the Northern Hemisphere model grid. Consequently, these calculations were of limited usefulness for the area south and southwest of the Philippines. They did, however, cover the primary evacuation route from Cebu, Philippines, to Guam, which remained ash-free, as Fig. 10 indicates.

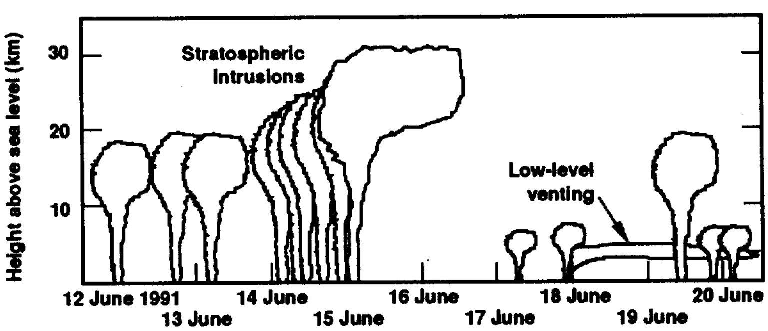

FIG. 9. Time sequence and relative heights of the initial ash plumes from the Mt. Pinatubo eruptions used for ARAC's ash-cloud model calculations for 12–20 June 1991.

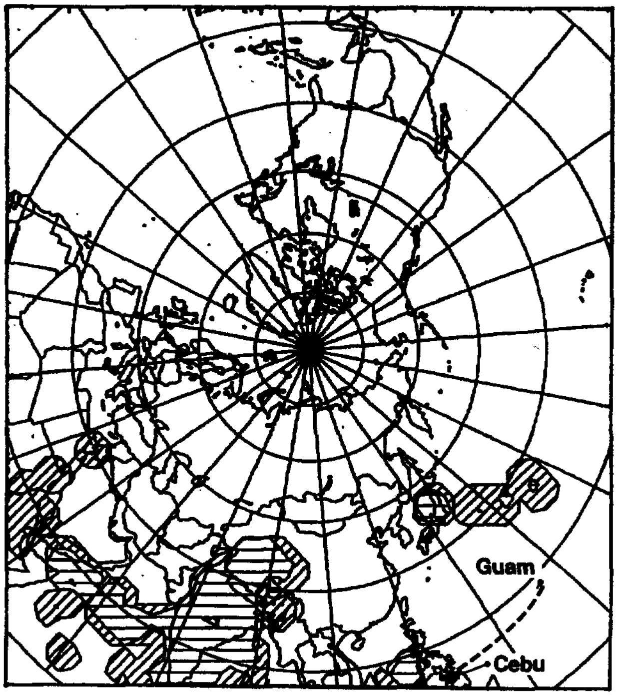

FIG. 10. One of the first Mt. Pinatubo ash-cloud advisory maps prepared for the U.S. Air Force on a hemispheric scale. This plot was for the 6- to 9-km layer at 0000 GMT on 20 June 1991.

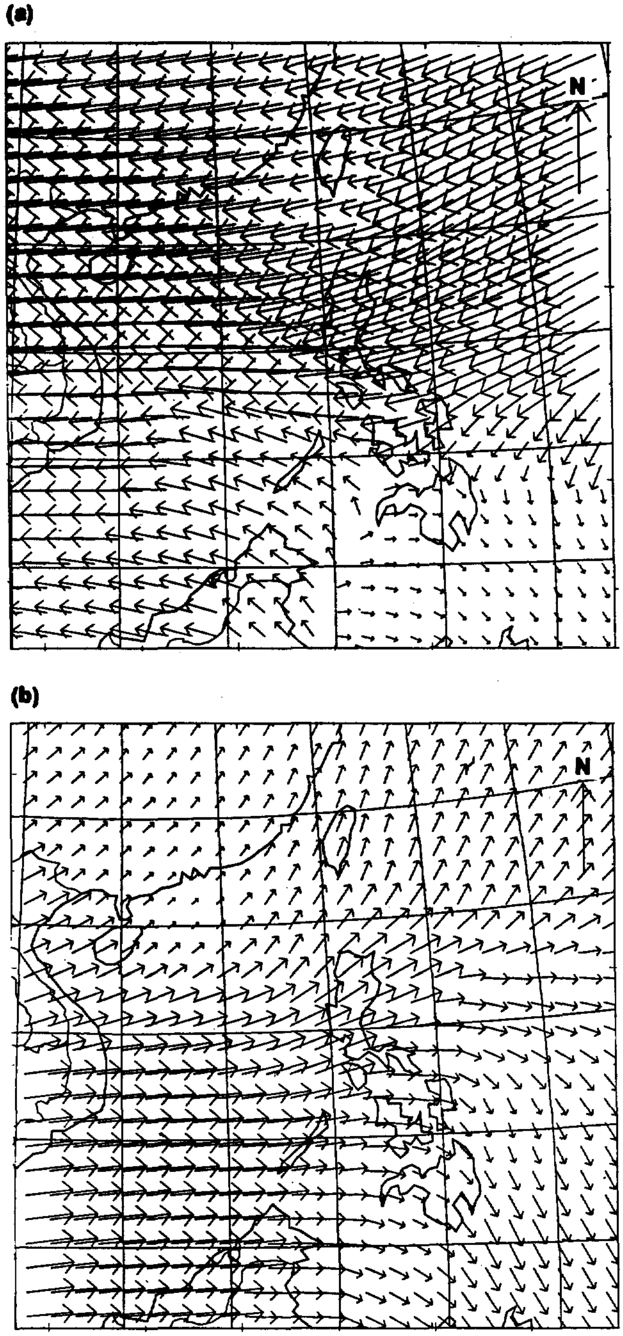

FIG. 11. Regional-scale wind fields for the 19 June 1991 Mt. Pinatubo eruption: (a) upper-atmosphere winds (~15 km) and (b) lower-atmosphere winds (~2 km).

Shortly after transmission of the first calculations, the U.S. Air Force requested comparable advisories for a more detailed subregion of a few thousand kilometers that was centered on the Philippines. Figures 11a,b delineate this new subdomain and also reveal the complex, sheared wind flow regimes at 2.5 and 15 km on 19 June 1991. To prepare these calculations for this subregion, ARAC extracted gridpoint profiles from the hemispheric data grids and merged them with available regional rawinsonde data. At the time of the eruptions, this was a manual process; now, this merging of data is substantially automated.

For the cataclysmic Mt. Pinatubo eruptions, the complex three-dimensional atmospheric structure of the region produced dramatically divergent ash-cloud patterns (Fig. 12). The large eruptions, including stratospheric intrusions with ash reaching 10 to 30 km above sea level, created ash clouds with strong westward transport over the South China Sea, Southeast Asia, India, and beyond. These enormous eruptions resulted in numerous aircraft encounters with ash and subsequent engine damage. The low-level eruptions (ash less than 10 km above sea level) and quasi-steady-state venting produced plumes that generally dispersed to the north and east throughout the support period, 12–20 June 1991.

Although the initial ARAC approach proved viable, further refinement is possible. A distinct need exists to quantify eruptions consistently so 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 data or eruption height. Particle sizes, density, and other relevant characteristics should be refined. Finally, databases of all known or potentially active volcanoes

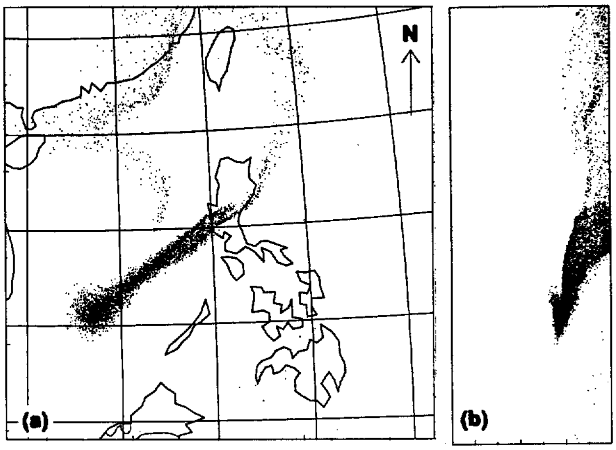

FIG. 12. Regional-scale particle dispersion modeled for the ash plume from the 19 June 1991 Mt. Pinatubo eruption: (a) overhead view, and (b) east-to-west view.

with their locations and characteristics could be prepared, and links to volcanologists' alerting networks could be established.

c. Upper Sacramento River

On 15 July 1991, the California Office of Emergency Services (OES) through the DOE asked ARAC to estimate the air concentrations from a spill of metam sodium herbicide into California's Lake Shasta. About 70 000 liters (L) of metam sodium were spilled into the upper Sacramento River 5 km north of Dunsmuir, California, when a Southern Pacific Railroad tank car derailed on the night of 14 July 1991 (see Fig. 13).

The herbicide moved in the river toward the northernmost finger of Lake Shasta, California's largest reservoir and a popular summer recreation area, 75 km to the south. As it flowed down the deep canyon toward the lake, some of the water-soluble metam sodium decomposed into hydrogen sulfide, methylamine, and methylisothiocyanate (MITC) gases, which were released into the air. As a result, residents along the river were advised to evacuate the area, and an 80-km stretch of Interstate 5 was temporarily closed. The major impact from the spill occurred along the Sacramento River. Nearly all the fish were killed and MITC gas concentrations were sufficient to deleteriously affect health, especially in Dunsmuir. However, state emergency response officials were also concerned that when the spill poured into the still water of Lake Shasta on 16 July, the rate of evaporation and photodissociation would rapidly increase as the slick's enlarged surface area was exposed to the strong and extended summer sunlight.

For this response, ARAC created a 20-km × 20-km × 700-m grid centered on the northern tip of the Sacramento River arm of Lake Shasta. This grid used the maximum resolution of the on-line topographic database with each grid cell representing 0.5 km × 0.5 km (Fig. 14).

The OES provided ARAC with the Material Safety Data Sheet (MSDS) and estimated that at most half, or 35 000 L, of the metam sodium could realistically be expected to reach the northern tip of Lake Shasta. Using this information, ARAC personnel derived a release rate of 126 g s^{-1} for the hydrogen sulfide. A similar calculation gave 25 g s^{-1} for the methylamine release. A 1.6-km-diameter circular area source was used for the models. When the spill arrived in the lake early Wednesday morning, it was 3 km long and was estimated to contain between 41 600 and 45 000 L of metam sodium; this compared reasonably well to the 35 000 L estimated by the OES.

As with many real-world events, representative meteorological data for this accident were in short supply. In this case, ARAC used a forecast by the National Weather Service (NWS) for southwesterly winds at 5 m s^{-1} over the Lake Shasta area for Tuesday morning, 16 July. This forecast proved to be reasonably accurate, since the actual winds at 0800 PDT on Tuesday morning were from 200° at 3 m s^{-1}.

Figure 15 shows the horizontal wind field produced by MATHEW for 50 m above ground level and with terrain features taken into account. Wind vectors are displayed for every other grid cell, or every 1 km. The map is centered on the source of the metam sodium pool. The Sacramento River arm of Lake Shasta is in the center of the map; Interstate 5 is the solid line

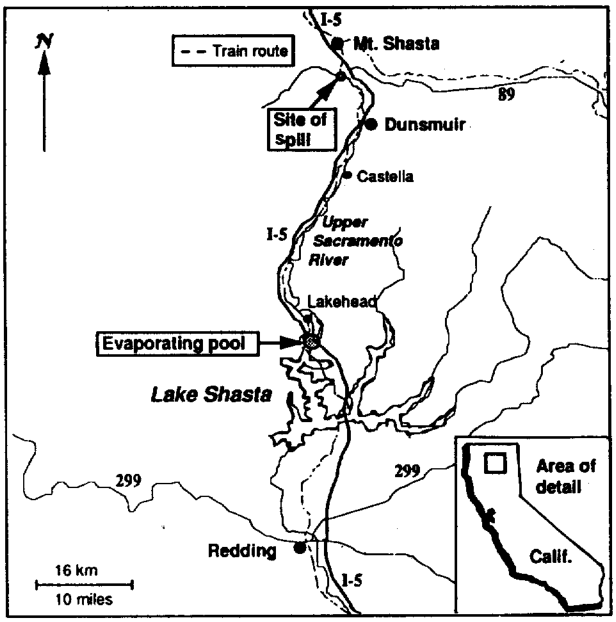

FIG. 13. The upper Sacramento River and Lake Shasta region affected by the metam sodium spill.

winding from south to north across Lake Shasta. The numbers on the perimeter of the map refer to universal transverse mercator coordinates in kilometers.

ARAC estimated that the atmospheric stability would be neutral all day for 16 July. Figures 16a,b show instantaneous cross-section and overhead views of the particle locations at 1000 PDT, or 4 h after the release began. Figure 17 is a three-dimensional visualization of the ADPIC marker particles displayed over the color-shaded relief. Real-time perspective views such as this help assessors assure the consistency of the model results in accordance with the forecast meteorology, complex terrain, and source release mechanism. The figures show how the predicted gas cloud spread across the tip of the lake and moved up the western-facing slopes of the ridge north of the lake. After 5 km of travel, the gas cloud rose to 600 m above ground level. This moderate upslope flow readily diluted the cloud. The assumptions of high daytime evaporation and photodissociation rates resulted in significantly larger source rates than would occur at night. Consequently, ARAC modeled only the daytime case near the lake.

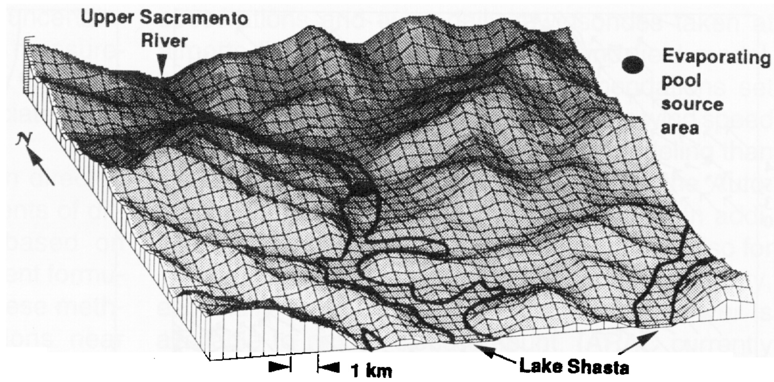

FIG. 14. Perspective view created by TOPOG of the model grid terrain surrounding the metam sodium pool on the upper Sacramento River arm of Lake Shasta.

In accordance with the OES request, ARAC predicted the instantaneous and 8-h-average air concentrations of toxic gas by-products over upper Lake Shasta. The calculation showed that the gases would be well below any health hazard. ARAC's modeled maximum values were compared (Table 3) with the American Conference of Governmental Industrial Hygienists threshold limit values for exposure to a toxic substance. The higher emission rate for H_2S was the primary concern during the incident. However, hindsight shows that MITC was more toxic. Since the source rate of MITC was not known during the response, it was not included in the modeling of the Lake Shasta area.

TABLE 3. Modeled concentrations associated with the metam sodium spill on the upper Sacramento River compared with threshold limit values.

	Methylamine (ppm)	H_2S (ppm)
Short-term exposure limit	—	15
Maximum instantaneous modeled concentration	2.4	9
Time-weighted average limit	10	10
Maximum 8-h average modeled concentration	0.12	0.6

Figure 16c is a contour plot for the 8-h average air concentration of H_2S. The instantaneous H_2S and methylamine plots showed a similar pattern, with contours extending northeastward. The maximum values were all located on the lake. The decision not to evacuate the area was based on these calculations. Southern Pacific Railroad officials began aerating the metam sodium pool early Sunday morning, 20 July. News reports indicated that the maximum air concentration measured within the water curtain surrounding the aerator was 4 to 5 ppm. Although this concentration was measured over an aerated lake surface, it compared favorably with the model's maximum instantaneous concentration of 9 ppm by quiescent evaporation.

The Sacramento River incident shows that rail car spills can be quite complex and adversely affect both the environment and public health. Emergency response plans should include detailed consideration of the atmospheric source term. In this response, it was assumed that daytime (light) reactions of metam sodium in warm water produced the maximum by-products. At the time, little was known about the photodissociation rate. Also, decomposition at night (dark reaction) in the water was not understood during the response. Moreover, release rates for by-products, such as MITC in this case, need to be quantified in emergency response plans.

6. Future directions

The Sacramento River spill response demonstrates that the framework for developing a toxic-chemical

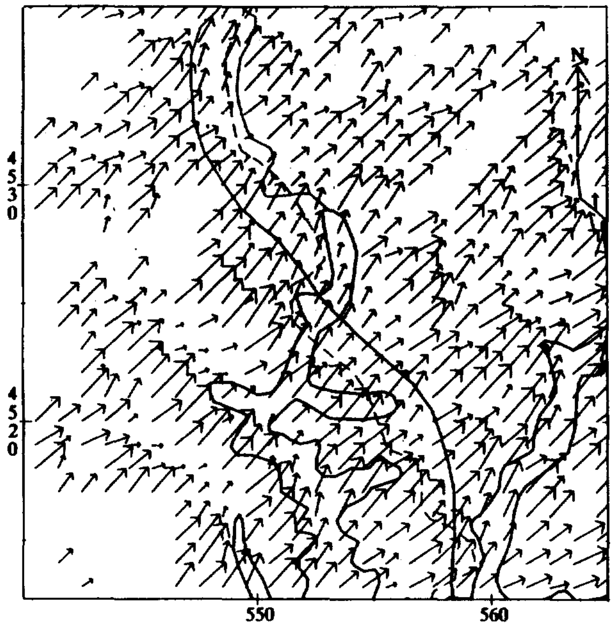

FIG. 15. MATHEW horizontal wind field for Tuesday, 16 July 1991, for the area around the metam sodium pool on the upper Sacramento River arm of Lake Shasta at 50 m above terrain.

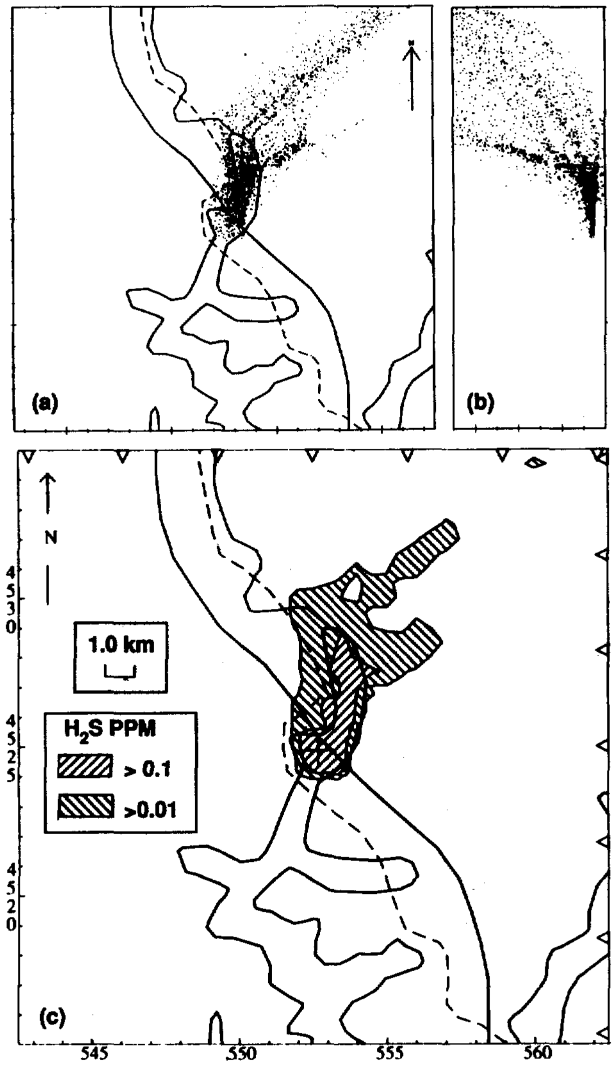

FIG. 16. Results of ARAC's simulation of the metam sodium evaporating pool on the Sacramento River on 16 July 199.. (a) instantaneous overhead view of ADPIC marker particles 4 h after the release of metam sodium began; (b) instantaneous east-to-west view, also 4 h after the release; and (c) contour plot of an 8-h, ground-level H_2S integrated air concentration on 16 July 1991. These calculations indicated that an evacuation of the Lake Shasta area was unnecessary.

emergency response modeling capability exists at ARAC. Responses to atmospheric releases during major transportation accidents rely on quick access to meteorological data and models to accurately simulate winds where observations are sparse. However, significant new developments with default source terms, release mechanisms, toxic chemical property databases, and exposure indices would have to be added at ARAC to establish a real-time operational capability for responding to releases of toxic chemicals. In addition, new tools such as the dense-gas models developed by Ermak (1992) would need to be engineered into the operational environment. Industrial hygienists and chemists would have to be added to the ARAC operations staff, and training would have to be extended to include the assessment of toxic chemical accidents.

Federal funding for this and other new expansion is being considered for the latter half of the 1990s. In preparation for these developments, ARAC has invested several months in restructuring the 1980s version of the MATHEW/ADPIC codes. First to be implemented in late 1993 will be a "hybrid-particle" extension of ADPIC. This improvement will allow ADPIC to model an unlimited number of nuclides and the ingrowth and decay of daughter products. Consequently, sources of mixed fission products, such as those from nuclear reactor accidents, will be treated in their full complexity.

Another new development will be the "predictor corrector" addition to MATHEW/ADPIC (Edwards et al. 1993), which will automate the integration of model calculations and field measurements. Often, the accurate source rate or amount is not known during an accident, but concentration measurements in the field are readily available. The predictor-corrector code performs an automated, nonlinear, least-squares regression analysis to optimize the agreement between a set of paired measured and modeled concentrations. The objective scheme can iterate on several model-input parameters (such as the source rate, the source release geometry, the deposition velocity, or the wind field) within reasonable ranges of uncertainties and find the best fit to the concentration measurements. In real-time accident situations, it is the usual case that the greatest uncertainty is associated with the source term information.

In addition, research at LLNL has been directed toward developing state-of-the-art treatments of diffusion using Monte Carlo techniques based on Langevin equation and random displacement formulations in ADPIC (Rodean et al. 1992). These methods can (a) improve diffusion calculations near sources, (b) use direct measures of atmospheric turbulence, (c) eliminate grid-based numerical errors, and (d) improve diffusion calculations in unstable boundary layers.

In late 1993, ARAC will upgrade its VAX cluster with two 125-Mips VAX 7000-620 computers. This improvement begins to make possible implementing more sophisticated real-time models. A number of DOE-sponsored research programs such as ASCOT have recently developed several new codes (Yamada et al. 1990). Near-future plans include engineering a prognostic, regional-scale emergency response model, such as the hydrostatic simulator of the atmospheric boundary layer (SABLE) model (Zhong et al. 1991), into the ARAC system. Prognostic models can simulate and forecast flows dominated by local forcing (e.g., nocturnal drainage flows and sea-breeze circulations). In the future, more powerful computers may allow even more sophisticated, nonhydrostatic meteorological models (e.g., Leone and Lee 1989) and dense-gas dispersion models (e.g., Chan 1992) to be used for very complex emergency response problems.

Emergency response programs like ARAC also stand to benefit from better real-time meteorological data in the future, such as from the modernization of the National Weather Service. ARAC's model evaluation studies have revealed that routine hourly surface observations and twice-daily rawinsondes taken at airports limit the accuracy of the wind field model. ARAC strongly supports the recommendations set forth in Powell (1993) that 10-min average wind speed and direction are better for dispersion modeling than the 2-min averages currently planned for the Automated Surface Observing System (ASOS). In addition, the standard deviation of wind direction, also for 10 min, is needed to estimate atmospheric stability, especially at ASOS stations where no observer is available to record cloud amount. (ARAC currently uses cloud amount to determine Pasquill stability class.) Possibly the greatest improvement for initializing regional-scale dispersion models could be realized with hourly profiler data such as from NOAA's Wind Profiler Demonstration Network. The extra spatial and temporal detail has already been shown to improve mesoscale forecasts, especially on days with significant weather systems (Smith and Benjamin 1993).

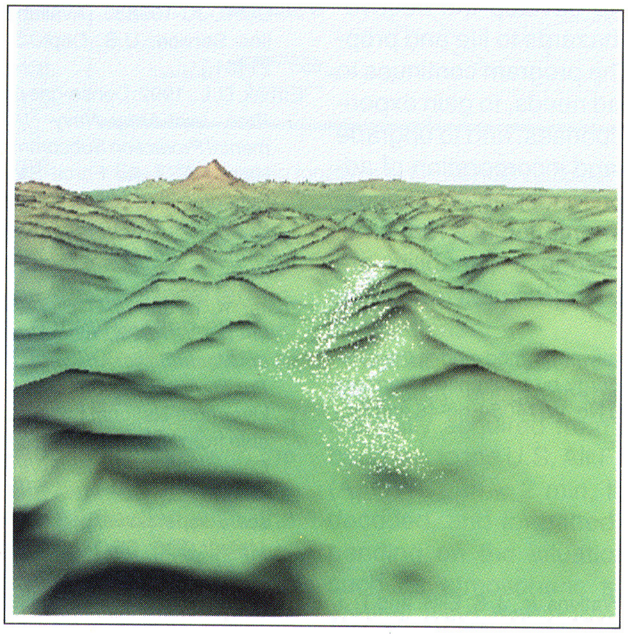

Fig. 17. Model-generated visualization of the gas cloud (shown here by marker particles) due to evaporation of the metam sodium pool on the Sacramento River arm of Lake Shasta. The cloud is being carried toward the north-northwest and is channeled by the complex terrain. Mount Shasta is on the horizon, and the Sacramento River gorge is to the left of the cloud.

7. Summary

Our ability to monitor and predict the environmental and health impact of natural and man-made hazardous phenomena is becoming ever more important as our world increasingly depends on sophisticated technologies. Over the past 18 years, ARAC has developed and evolved a computer-based, real-time, radiological dose-assessment service for the U.S. Department of Energy and Department of Defense. This service is built on the integrated components of computer-acquired, real-time meteorological data, extensive computer databases, numerical atmospheric dispersion models, dose-effect models, graphical presentation codes, and the extensive expertise of an operational assessment staff. The focus of ARAC is on the off-site problem (i.e., a few kilometers and beyond) where regional meteorology and topography are the dominant influences on the transport and diffusion of hazardous material. Numerous model evaluation studies have confirmed the practicality of this modeling system for point-source accident/event release on local to regional to continental scales. Many past real-time applications of this system have resulted in significant enhancements of the ARAC emergency response system. Recent applications to a toxic spill in the upper Sacramento River, to oil fires in Kuwait, and to Mt. Pinatubo's volcanic eruptions have shown the program's utility and flexibility.

The ARAC modeling system provides a means for quickly determining the probable scope of an atmospheric emergency. Emergency managers can use ARAC's graphical products to develop the best response strategy to minimize hazards to life and property in the affected regions. The program continues to evolve in response to identified needs, to gain experience from actual accident responses, and to upgrade data sources. Development and incorporation of advanced atmospheric dispersion models, both diagnostic and prognostic, and implementation of a real-time, toxic-chemical emergency response capability are major goals for the program during the next few years.

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