REAL-TIME MODELLING OF COMPLEX ATMOSPHERIC RELEASES IN URBAN AREAS

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Abstract

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If a nuclear installation in or near an urban area has a venting, fire, or explosion, airborne radioactivity becomes the major concern. Dispersion models are the immediate tool for estimating the dose and contamination. Responses in urban areas depend on knowledge of the amount of the release, representative meteorological data, and the ability of the dispersion model to simulate the complex flows as modified by terrain or local wind conditions. A centralised dispersion modelling system can produce realistic assessments of radiological accidents anywhere in a country within several minutes if it is computer-automated. The system requires source-term, terrain, mapping and dose-factor databases, real-time meteorological data acquisition, three-dimensional atmospheric transport and dispersion models, and experienced staff. Experience with past responses in urban areas by the Atmospheric Release Advisory Capability (ARAC) program at Lawrence Livermore National Laboratory illustrate the challenges for three-dimensional dispersion models.

1. INTRODUCTION

The first step in responding to a radiological release to the atmosphere involves using computer models to determine the extent of contamination. Dispersion models can help during the initial response in two key ways. First, emergency managers can use dispersion models results to advise the public to stay indoors or evacuate if necessary. Second, models can estimate the amount of nuclear material which has been deposited on the surface of buildings or the ground. Monitoring teams can use the modelled deposition pattern to initiate radiological field surveys which will in turn be used to determine initial exposures and health impacts, identify areas for contamination control and ultimately plan the accident clean-up. In addition, if the source is gaseous or if it is diluted below instrument detection limits, models will likely be the only method to quantify health concerns.

Potential sources of large radiological releases include nuclear power plants, and nuclear fuel processing and storage facilities. Other lessor risks include nuclear-powered ships or submarines or nuclear-powered satellite re-entry and burn-up. Smaller sources include transportation of nuclear fuels, industrial and university research reactors, other research facilities, and hospitals. Emergency preparedness requires the careful consideration of source inventories, possible pathways to the air, the nuclides involved, and their combined dose via inhalation, immersion, ingestion, and groundshine pathways.

In the mid-1970s the U.S. Atomic Energy Commission, now the U.S. Department of Energy, decided that a national center would be a cost-effective way to provide advisories for significant accidental releases of nuclear material anywhere in the country. For two decades, the ARAC program has evolved with that purpose and has been integrated with several federal organizations including the Federal Radiological Monitoring and Assessment Center (FRMAC). Some notable ARAC responses include Three Mile Island, Chernobyl, the oil fires in Kuwait, and the eruption of Mt. Pinatubo in the Philippines (Sullivan et al. 1993).

2. THREE-DIMENSIONAL DIAGNOSTIC DISPERSION MODEL

The ARAC emergency response center in Livermore, California produces timely and credible calculations by employing several dispersion models integrated with real-time world-wide meteorological data links, on-line source-term, topographic, geographic, and dose databases. ARAC's core mesoscale models are the three-dimensional, diagnostic, finite-difference computer codes shown in Figure 1. The typical model run takes about 10 min of Digital Equipment Corporation (DEC) VAX 6610 CPU time at 35 million instructions per second (Mips) to complete, including the automated preparation of the input files.

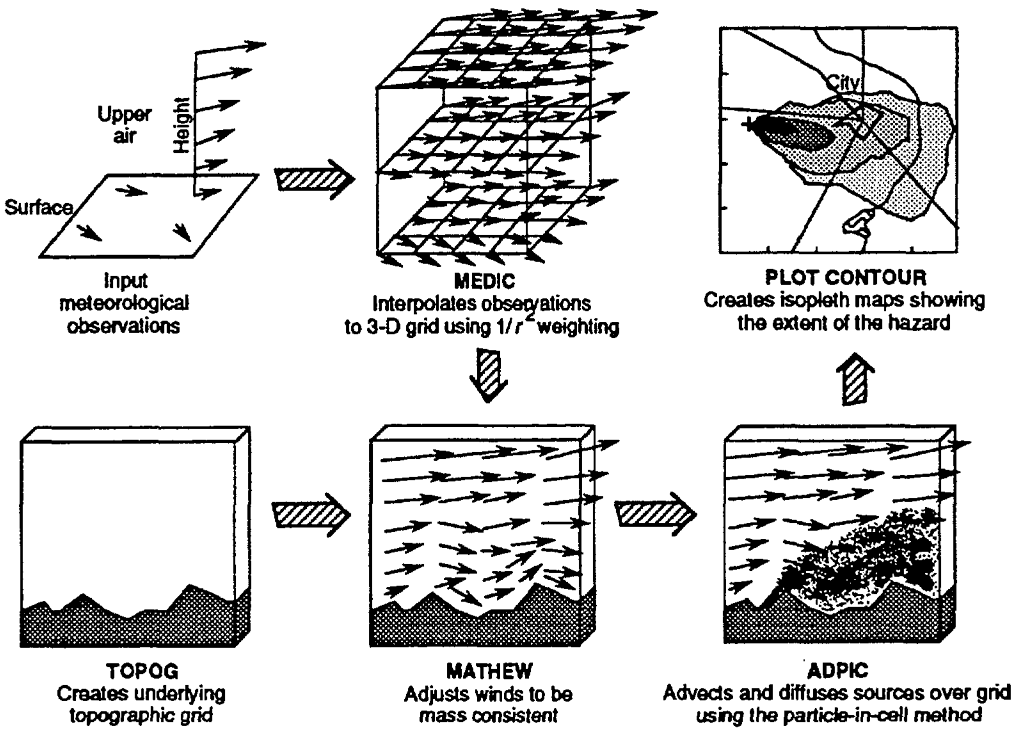


Figure 1. ARAC's primary diagnostic emergency response dispersion model run stream

For a response a grid is chosen and the underlying block-cell terrain is built from an on-line database with 0.5 km resolution using the TOPOG code. The system automatically acquires meteorological data surrounding the accident location anywhere in the world via a dedicated link to the U.S. Air Force Global Weather Center. These wind-speed and direction observations are first interpolated over the chosen grid by the Meteorological Data Interpolation (MEDIC) code using an inverse-distance-squared ($1/r^2$) weighting of the data and wind-profile laws. The effects of terrain and atmospheric stability on the wind field are determined by the Mass-adjusted the Winds (MATHEW) code which creates a mass-consistent, nondivergent flow field over the grid. 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.

MATHEW provides the mean winds for Atmospheric Dispersion by Particle–in–Cell (ADPIC), a nested-grid dispersion model. Tens of thousands of marker particles are available to represent as many different sources or nuclides as necessary in a single model run. Dispersion of the marker particles can be described by two basic processes: transport by the mean wind and diffusion by turbulence. Rates of horizontal and vertical diffusion, which vary in space and time, are computed using empirical equations.

Primary accidental release mechanisms for nuclear accidents include ventings, fires and explosions. Fires or explosions can eject material vertically from several hundred meters to several kilometres. Time-dependent 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. Radioactive decay, particle-size-dependent gravitational settling, dry deposition, and precipitation scavenging are computed as the material is transported and diffused. A uniform inversion height and atmospheric stability are specified over the model domain but can be changed as a function of time.

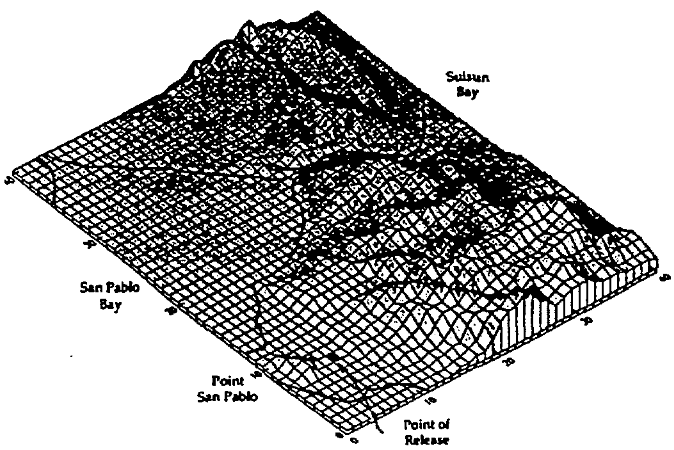
3. MODEL LIMITATIONS AND IMPROVEMENTS

ARAC has conducted over a dozen studies comparing the model calculations with tracer field measurements on the 10 to 100 km scale. Results show that the diagnostic codes compare to within a factor of 2 of the measurements about 20 to 50% of the time and to within a factor of 5 about 35 to 85% of the time depending on the complexity of the flow. Clearly there is room for improvement in model accuracy.

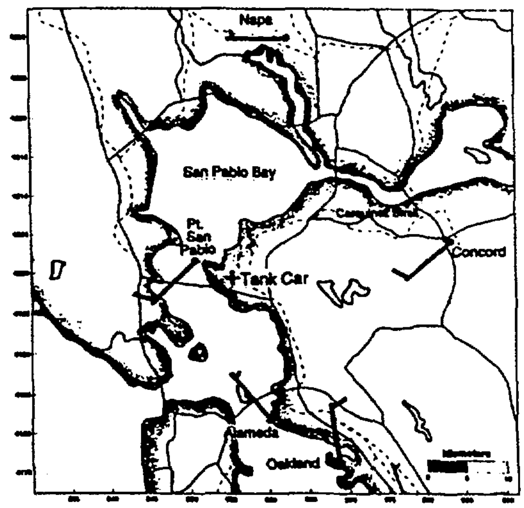
Accurately locating the plume is the most important goal of an emergency response model. The effect of turbulent spread is usually secondary except for light wind conditions or very near the source. For diagnostic models, thermally driven flows such as sea breezes, slope flows, or convective motion are not created in the calculation. Resolving these features relies primarily on the representation of input wind observations. For urban-scale diagnostic models the greatest single improvement can be accomplished with more representative meteorological observations (Lange 1984), especially vertical wind profiles (Baskett et al. 1990). Even if wind data exists at several urban airports, diagnostic models suffer from the lack of sufficient real-time observations to describe complex flow fields near an accidental release. This is especially true during stable nocturnal conditions such as the 1984 Bophal accident (Singh and Ghosh 1987).

The recent ARAC response to a large oleum tank car release in the San Francisco Bay Area of California (Baskett et al. 1994) demonstrates some limitations of diagnostic models in a complex setting. Early on the morning of July 26, 1993 in the city of Richmond, while a railroad tank car was being heated, a pressure relief valve failed. Over 7000 kg of sulphur trioxide gas was released to the atmosphere before the valve could be capped 3.75 hours later. The gas quickly condensed into a dense sulphuric acid mist which was observed to spread about 10 km downwind. Figure 2a shows the terrain setting and Figure 2b shows the surface wind observations available at the time of the release. The tank car was located between three airports (Napa, Concord and Alameda). Fortunately the local air quality management district operated a tower at Pt. San Pablo which was only about 5 km from the accident. Figure 2c shows the wind field and Figure 2d shows the plume location using the nearby tower. Without that tower's real-time data, the diagnostic wind model would have placed the plume 60 degrees more clockwise than occurred.

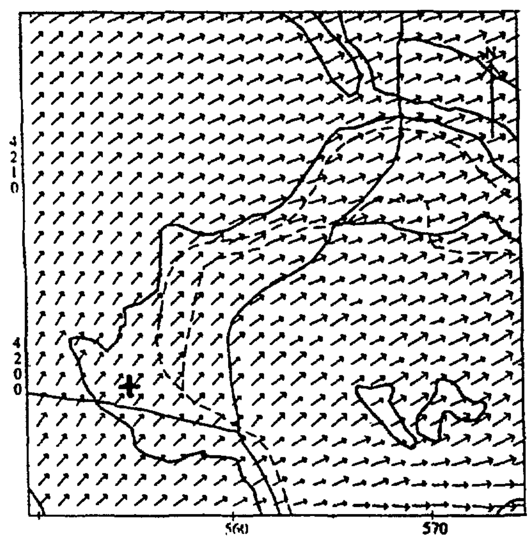
Furthermore, in a post-accident analysis, wind data from a refinery 1.5 km north of the release showed that more variable winds and more turbulence occurred at the accident than were observed at Pt. San Pablo. The Pt. San Pablo tower was influenced by flow over the Bay while the sulphuric acid plume experienced flow over a small ridge and an industrialised urban area. Allowing for a variable range of influence by individual observations is the next improvement planned with a new wind field generator, WINDGEN. In addition, the new model will use a terrain-following co-ordinate system to eliminate cell-face errors from block terrain. Future improvements will focus on detailed effects of spatially-varying mixing heights, land use, and surface roughness, including local features such as small hills, lake and ocean shorelines.



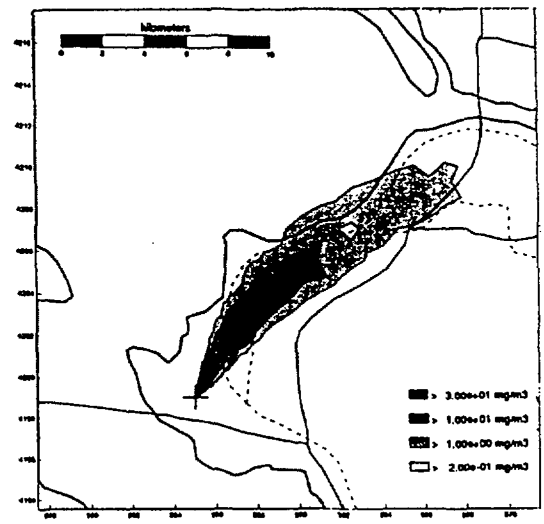
(a) Model grid and terrain



(b) Surface wind observations at beginning of release



(c) Surface wind field at beginning of release



(d) Second hour sulfuric acid air concentration

Figure 2. Example urban-scale dispersion model calculation for the July 26, 1993 Richmond, California toxic spill

Improvements are also planned to use spatially-varying precipitation measurements. As with wind data, the realism of the model is strongly tied to the ability of the measurements to resolve variations in the precipitation field, especially during convective (thunderstorm) conditions.

4. PROGNOSTIC MODELING

The advent of more powerful computers has created the opportunity to implement more sophisticated mesoscale prognostic models which will reduce the dependence on meteorological observations. Prognostic models require supercomputers to solve the primitive set of atmospheric equations and produce results faster than real-time. Mesoscale prognostic models are initialised by multi-layer gritted synoptic scale forecast models such as the U.S. National Weather Service Nested Grid Model (NGM). The NGM produces forecast datasets every 6 hours on a 90 km horizontal grid spacing. Features smaller than 90 km on a side are resolved by the mesoscale model. Mesoscale models include boundary layer dispersion physics driven by radioactive transfer, soil processes and the surface energy balance. In addition aerosol and cloud microphysics are parameterized to estimate localised cumulus convection, and aerosol and water mass budgets.

High-end workstations which compute forecasted wind fields up to 48 hours in the future are being used to run prognostic models continuously at a single location (Nappo et al. 1993, Yamada 1993, Tremback et al. 1994, Fast and O'Steen 1994). Operating prognostic models at an arbitrary location provides different challenges with different design considerations. To demonstrate the feasibility of using prognostic models for a national system, we successfully simulated the atmospheric flow field for the 1993 Richmond oleum spill. Next year we will begin implementing a mesoscale model for the ARAC system.

5. CONCLUSIONS

Determining the extent of contamination from computationally fast three-dimensional diagnostic models is the first step in responding to an accidental atmospheric release in or around a city. Improved physics which account for spatially-varying phenomena will increase model accuracy. These improvements will benefit from real-time access to more automated surface and upper air (sodar and wind profiler) meteorological systems, such as from air quality management districts and industry. After the initial diagnostic run, new prognostic models offer promise in simulating releases which extend more than a few hours and in locations with sparse meteorological observations.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the Department of Energy by Lawrence Livermore National Laboratory under Contract W–7405–Eng–48 and by EG&G Energy Measurements, Inc. under Contract DE–AC08–93–NV11265.

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