UCRL-JRNL-211678

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

The National Atmospheric Release Advisory Center (NARAC) Modeling and Decision Support System for Radiological and Nuclear Emergency Preparedness and Response

John S. Nasstrom, Gayle Sugiyama, Ron Baskett,
Shawn Larsen, Michael Bradley

April 25, 2005

International Journal of Risk Assessment and Management
Special Issue: Nuclear and Radiological Emergency
Preparedness — The Role of Monitoring and Modeling in an
Emergency Situation

Disclaimer

Article accepted for publication in the International Journal of Risk Assessment and Management
Special Issue: Nuclear and Radiological Emergency Preparedness — The role of monitoring and modeling in an emergency situation

The National Atmospheric Release Advisory Center (NARAC) Modeling and Decision Support System for Radiological and Nuclear Emergency Preparedness and Response

John S. Nasstrom[*], Gayle Sugiyama, Ronald L. Baskett,
Shawn C. Larsen, and Michael M. Bradley

Lawrence Livermore National Laboratory
P.O. Box 808, L-103
Livermore, CA, 94551, USA
E-mail: jnasstrom@llnl.gov, sugiyama@llnl.gov, rbaskett@llnl.gov,
larsen8@llnl.gov, mbradley@llnl.gov

Biographical Notes

John Nasstrom is the Lawrence Livermore National Laboratory (LLNL) Program Manager for the Department of Energy's Atmospheric Release Advisory Capability (ARAC) Program. He received his B.S., M.S. and Ph.D. degrees in Atmospheric Science from the University of California, Davis. He has over 20 years experience in atmospheric dispersion modeling research, and operational emergency response systems for airborne hazards while working at the National Atmospheric Release Advisor Center.

Gayle Sugiyama is the Program Leader for the LLNL Energy and Environment Directorate's NARAC and IMAAC Program, and manages LLNL work for the National Atmospheric Release Advisory Center (NARAC) and the Inter-Agency Modeling and Atmospheric Assessment Center (IMAAC). She holds a Ph.D. in Physics from the California Institute of Technology. Her thesis and early career research focused on methods for simulating quantum many-body systems. For over a decade she has worked in the NARAC to develop models that simulate the flow and dispersion of hazardous materials. Her research interests include boundary-layer meteorology, atmospheric dispersion, data-driven simulation for event reconstruction, and high-performance computing for scientific applications.

---

[*] Corresponding author

Ron Baskett is a team leader for NARAC and IMAAC operations at LLNL. He has worked as an air quality consultant and a satellite meteorologist. Since starting with NARAC in 1983, he has played a key role in helping managing operations and development of the emergency response modeling system. He holds B.S. and M.S. degrees in atmospheric science from the University of California, Davis.

Shawn Larsen obtained his B.S. in geophysics at the California Institute of Technology in 1982, his M.S. in geophysics at Cornell University in 1984, and his Ph.D. in geophysics at the California Institute of Technology in 1990. He has been a geophysicist and computer scientist at Lawrence Livermore National Laboratory since 1991 and a visiting research geophysicist at the University of California at Berkeley since 1996. He joined the NARAC program as the hardware and software systems manager in 2004. His research interests include earthquake seismology, wave propagation, numerical modeling, high performance computing, and the application of advanced computer-based technologies to scientific problems.

Michael Bradley leads the International Emergency Management and Cooperation projects for the National Atmospheric Release Advisory Center (NARAC) at Lawrence Livermore National Laboratory (LLNL). He holds a B.S. in physics from Purdue University, an M.S. in meteorology from the South Dakota School of Mines and Technology, and a Ph.D. in atmospheric science from the University of Illinois, where he developed a numerical model of orographic storms. For over 20 years at LLNL he has worked in NARAC operations, and also has conducted and led numerical modeling research in cloud dynamics, cloud microphysics, aerosol physics, general circulation model cloud- and sub-grid-scale parameterizations, and wildfire behavior prediction.

Abstract

This paper describes the tools and services provided by the National Atmospheric Release Advisory Center (NARAC) at Lawrence Livermore National Laboratory (LLNL) for modeling the impacts of airborne hazardous materials. NARAC provides atmospheric plume modeling tools and services for chemical, biological, radiological, and nuclear airborne hazards. NARAC can simulate downwind effects from a variety of scenarios, including fires, industrial and transportation accidents, radiation dispersal device explosions, hazardous material spills, sprayers, nuclear power plant accidents, and nuclear detonations. NARAC collaborates with several government agencies and laboratories in order to accomplish its mission.

The NARAC suite of software tools include simple stand-alone, local-scale plume modeling tools for end-user's computers, and Web- and Internet-based software to access advanced modeling tools and expert analyses from the national center at LLNL. Initial automated, 3-D predictions of plume exposure limits and protective action guidelines for emergency responders and managers are available from the center in 5-10 minutes. These can be followed immediately by quality-assured, refined analyses by 24 x 7 on-duty or on-call NARAC staff. NARAC continues to refine calculations using updated on-scene information, including measurements, until all airborne releases have stopped and the hazardous threats are mapped and impacts assessed.

Model predictions include the 3-D spatial and time-varying effects of weather, land use, and terrain, on scales from the local to regional to global. Real-time meteorological data and forecasts are provided by redundant communications links to the U.S. National Oceanic and Atmospheric Administration (NOAA), U.S. Navy, and U.S. Air Force, as well as an in-house mesoscale numerical weather prediction model. NARAC provides an easy-to-use Geographical Information System (GIS) for display of plume predictions with affected population counts and detailed maps, and the ability to export plume predictions to other standard GIS capabilities. Data collection and product distribution is provided through a variety of communication methods, including dial-up, satellite, and wired and wireless networks.

Keywords
Atmospheric dispersion modeling, decision support system, measurement data assimilation

1 Introduction

The dispersion of radiological material in the atmosphere poses potential risks to human health. Releases may occur from accidents involving nuclear power plants, nuclear material processing and transportation, or nuclear weapons. The post-cold-war proliferation of nuclear material has increased the potential for threats from radiological dispersal devices and nuclear weapons. In order to prepare for airborne releases and mitigate the resulting impacts, tools are needed that can accurately and quickly predict the environmental contamination and health effects.

A wide variety of tools are needed in order to characterize the airborne source, atmospheric transport and diffusion, surface deposition, resuspension, and dose to humans from multiple pathways (air immersion, ground exposure, inhalation and ingestion). Equally important is to translate the assessment of dose into easily comprehensible guidance for critical decisions, such as evacuation, sheltering-in-place, and relocation (NCRP, 2001), and to provide relevant decision-support information (such as affected population and other geographical data) needed by emergency responders and decision makers. Finally, in order to facilitate timely decisions and protect lives, it is essential to quickly and simultaneously distribute common situational awareness products to decision makers in multiple, collaborating agencies at different levels of government.

The National Atmospheric Release Advisory Center (NARAC) addresses these needs by providing tools and services that predict and map the probable spread of hazardous material accidentally or intentionally released into the atmosphere. Located at the University of California's Lawrence Livermore National Laboratory (LLNL), NARAC is a national support and resource center for planning, real-time response, detailed studies, and research into airborne hazards, involving nuclear, radiological, chemical, biological or natural emissions.

NARAC's origins date to the early 1970s, when the U.S Atomic Energy Commission (AEC) supported LLNL to develop an advanced modeling capability to assess impacts from airborne releases of radiological contamination. Sullivan, *et al*. (1993) and Ellis, *et al*. (1997) provide a description of NARAC's models, software systems, scientific validation and operations during its first two decades of existence. During this period, NARAC provided assessments of the consequences of the Three Mile Island and Chernobyl nuclear power plant accidents.

NARAC provides its operational tools and services to users under the sponsorship of several agencies. The primary sponsors of NARAC operation are the Office of Emergency Response in the U.S. Department of Energy's (DOE) National Nuclear Security Administration (NNSA); the Interagency Modeling and Atmospheric Assessment Center (IMAAC) of the U.S. Department of Homeland Security (DHS); and the U.S. Naval Reactor program. NARAC is an integral part of the DOE's contribution to the Federal Radiological Monitoring and Assessment Center (FRMAC) (Wilber *et al.*, 2006). NARAC provides support to over 40 individual DOE and U.S. Department of Defense (DOD) facilities. NARAC also supports DOE's International Emergency Management and Cooperation (IEMC) Program to help strengthen worldwide emergency preparedness and to develop capabilities to respond to international nuclear events through collaborative projects with other governments and international organizations. The DHS Science and Technology Directorate has supported the research and development of emergency response modeling systems, including atmospheric flow and dispersion modeling in urban areas. Under the auspices of the DOE, DHS and DOD, NARAC works with over 100 collaborating state and federal organizations involved in emergency preparedness activities.

According to the new U.S. National Response Plan (DHS, 2004), the DHS-led IMAAC generates the single Federal prediction of atmospheric dispersions and their consequences utilizing the best available resources from the Federal Government and "provides a single point for the coordination and dissemination of Federal dispersion modeling and hazard prediction products that represent the Federal position during an Incident of National Significance". Current collaborating agencies include the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA), the Department of Defense (DOD), the Department of Energy (DOE), the Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), and the Nuclear

Regulatory Commission (NRC). The IMAAC was created under the auspices of the Homeland Security Council on April 15, 2004. NARAC is the designated primary initial provider of IMAAC capabilities.

This paper describes current capabilities, operational applications, recent advances, and ongoing research within NARAC. Section 2 describes the meteorological, geographical, hazardous material property, and other databases used by NARAC. An overview of the computer models used to simulate atmospheric flows, airborne dispersion, and surface deposition is provided in Section 3. Decision-support products, including dose to humans, protective action guides, and geographical information displays, are covered in Section 4. The software systems used to collect data, automatically execute computer models, and disseminate decision-support products in real-time are described in Section 5. The multi-disciplinary staff, facilities, and operations are summarized in Section 6. Testing, evaluation, and applications of the NARAC models and other operational capabilities are reviewed in Section 7. The integration of measurement data with model predictions to produce refined and improved simulations is included in Section 8. Future research and development directions are described in Section 9.

2 Supporting Databases

The NARAC mission — to provide near-real-time predictions of atmospheric dispersion anywhere in the world — requires access to large volumes of current and forecast weather data, and to extensive databases of population density, hazardous material source characteristics, radiological, chemical, and biological material properties, dose factors, dose limits, and protective action guides.

NARAC continuously receives up-to-date surface and upper-air meteorological observations from the worldwide meteorological network via redundant communication links to the U.S. Air Force Weather Agency and the U.S. National Weather Service. Additional meteorological observations are supplied by NARAC-supported sites and several regional mesoscale networks (mesonets) in, and near, the U.S. (including the western U.S. MESOWEST network and NOAA Wind Profiler networks). Global and regional numerical weather prediction forecasts from the U.S. Navy Fleet Numerical Oceanographic and Meteorological Center (FNMOC) and the National Weather service are obtained several times daily. NARAC also utilizes an in-house version of the U.S. Navy's COAMPS mesoscale numerical weather prediction model.

NARAC maintains extensive geographical databases of terrain elevation and land-use classifications to specify the lower boundary conditions for its three-dimensional atmospheric flow and dispersion models. Global-coverage terrain elevation is provided by databases with 10 km horizontal resolution obtained from NOAA's National Geophysical Data Center (NGDC), the U.S. Geological Survey (USGS) data with 1 km resolution, and the National Geospatial-Intelligence

Agency's (NGA) Digital Terrain Elevation Data (DTED) with 1 km, 100 m, and 30 m resolution and approximately 60% coverage of the world. U.S. terrain elevation is provided by the USGS Digital Elevation Model (DEM) database with 30 m resolution. Urban building elevation and morphology data, needed for specialized building-scale flow and dispersion model simulations, are obtained from a variety of sources.

Urban and rural land-use characteristic data are provided by the Global Land Cover Characteristics (GLCC) and Oak Ridge National Laboratory's (ORNL) LandScan database (1 km horizontal resolution, 24 land-use categories). U.S. coverage is provided by the USGS Land Use Land Cover (LULC) 200-m resolution database and the USGS National Land Cover Database (NLCD) with 21 categories, 30 m resolution, and 48 U.S. state coverage.

NARAC uses population density data to estimate the number of people potentially affected by a particular contamination or dose level. Global population coverage is provided by ORNL LandScan data (30 min, or approximately 1 km, resolution, day-night average). U.S. coverage for residential populations is provided by U.S. Census Bureau data. A database from Los Alamos National Laboratory (McPherson and Brown, 2003) uses U.S. Census Bureau residential data and augments it with business population (from the State Business Directory) and estimates of day-night worker migration, providing a population density database that accounts for time-of-day population variation for the entire U.S. on a 250-m resolution grid. For special events, NARAC's population databases can be manually adjusted to account for the additional people present (e.g., at a stadium or a convention for a special event).

NGA VMAP and ADRG databases provide global base maps for displays of geographical data. U.S. maps and aerial imagery are provided by Geographic Data Technology, Inc., Census Bureau TIGER, USGS DRG, USGS DOQ and GlobeXplorer.

A specialized residential building leakiness database (for calculating the infiltration of exterior air into residential buildings) has been developed in collaboration with Lawrence Berkeley National Laboratory (Chan *et al.*, 2004). This database is derived from U.S. Census data and studies of U.S. building leakiness. A commercial building air infiltration modeling capability is currently in development.

3 Models

NARAC utilizes a range of numerical modeling capabilities to support different types of release events, distance scales (local, regional, continental and global), and response times. Simpler, fast-running deployable models are used to perform screening calculations and fast initial response, and can be used in the field when connections to the NARAC facility are not available. More detailed three-dimensional dispersion models, coupled to real-time observational data and numerical weather prediction model output, are used by scientific specialists for both near-real-time response and detailed assessments. Urban canopy parameterizations, empirical urban dispersion models, and building infiltration models provide enhanced understanding of urban effects. Computational fluid dynamics models that explicitly resolve urban structures are used for high-fidelity applications including vulnerability analyses and planning studies.

3.1 Grids

NARAC's central system models (ADAPT and LODI) use the same type of grid system to store terrain elevations, land characteristics, meteorological fields, airborne hazardous material concentrations, and surface deposition data. The grid system uses a continuous representation of the ground surface based on a piece-wise bilinear interpolation of grid-point terrain elevation data. The system supports run-time selection of both the number of grid points and grid resolution, and can include variable resolution in both the vertical and horizontal coordinates. Variable vertical resolution provides appropriate representation of the meteorological fields, including higher resolution in the critical near-surface region. Variable horizontal resolution is used when warranted by topographical variation, meteorological data density, plume dimensions, or source location/geometry. Nested grids also can be used for modeling problems involving several spatial scales. NARAC software supports a variety of map projections required for a range of spatial scales from local to global.

3.2 Meteorological models

NARAC uses both diagnostic and prognostic (forecast) meteorological models. Forecast or numerical weather prediction (NWP) models predict the time evolution of the atmospheric flow field by solving the conservation equations for mass, momentum and thermodynamic energy. The models incorporate relevant physical processes for moisture, cumulus convection, and radiation, as well as parameterizations of sub-grid-scale turbulent mixing.

The primary internal NARAC source of prognostic mesoscale model data is an in-house version of the Naval Research Laboratory's Coupled Oceanographic and Atmospheric Mesoscale Prediction System (COAMPS) model (Hodur, 1997), which can be relocated to produce forecasts for any location in the world. NARAC has developed an urban canopy parameterization for COAMPS which has been shown to improve the representation of urban flow fields (Chin et al, 2005).

Forecast meteorological data are continuously obtained from outside agencies. Specifically, NARAC regularly receives data from (a) the National Weather Service GFS model (1.0 degree horizontal resolution, 3-hourly data out to 180 hrs from model initializations at 0000, 0600, 1200 and 1800 UTC, and also 0.5 degree horizontal resolution, 3-hourly data out to 84 hrs from model initializations at 0000, 0600, 1200 and 1800 UTC), (b) the U.S. Navy NOGAPS model (1.0 degree horizontal resolution, 3-hourly data out to 72 hrs from 0000 and 1200 UTC initializations), (c) the National Weather Service ETA model (40 km and 12 km horizontal resolution, 3-hourly data out to 84 hours for initializations at 0000, 0600, 1200 and 1800 UTC), and (d) the National Weather Service (NWS) RUC model (20 km horizontal resolution, 1 to 3 hourly data from hourly initializations, continuing with 3-hourly data from 4 to 12 hrs for initializations at 0000, 0300, 0600, 0900, 1200, 1500, 1800, 2100 UTC). For special applications, data can be obtained from regional simulations made by the FNMOC using the NRL COAMPS mesoscale model, or by the U.S. Air Force Weather Agency (AFWA) using the MM5 model.

The ADAPT model (Sugiyama and Chan, 1998) assimilates data from observations (e.g., from surface stations, rawinsondes, profilers) and/or weather forecast models, as well as land-surface data, for use in the NARAC dispersion model, LODI. ADAPT constructs meteorological fields (mean winds, pressure, precipitation, temperature, turbulence quantities, etc.) based on a variety of interpolation methods and atmospheric parameterizations (Chan and Sugiyama, 1997; Sugiyama and Chan, 1998). ADAPT produces non-divergent wind fields using an adjustment procedure based on the variational principle and a finite-element discretization. A finite-element representation is used for spatial discretization because of its effectiveness in treating complex terrain and its flexibility in dealing with variable resolution grids. The solution is obtained via a choice of conjugate gradient solvers, using a stabilization matrix to improve computational efficiency.

In emergency response mode, ADAPT is typically run by ingesting real-time observational data. Terrain and atmospheric stability effects are introduced through the variational mass-conservation adjustment process. Land-surface characteristics and surface heat and momentum fluxes can be used to diagnose horizontally-averaged properties of the mean wind and turbulence, using similarity theory relationships. ADAPT diagnostic simulations typically require under a minute to execute.

ADAPT can estimate turbulence quantities required by the dispersion model, LODI, using similarity-theory scaling relationships. The methods summarized by van Ulden and Holtslag (1985) are used to estimate surface heat and momentum fluxes and turbulence scaling parameters (e.g., friction velocity, u_*; Obukhov length, L; convective velocity scale, w_*; and boundary layer depth, h) from near-surface meteorological observations and land-use data. The turbulent diffusivities, K_x, K_y, and K_z, are calculated as a function of height and horizontal location using these scaling parameters and similarity-theory relationships described by Nasstrom *et al.* (2000).

3.3 Source characteristics

Atmospheric dispersion models require a source term that describes characteristics such the mass or activity released to the atmosphere, the emission rate, height, spatial distribution, and particle size distribution. For nuclear power plant accidents, NARAC relies on the Nuclear Regulatory Commission's (NRC) RASCAL model (Sjoreen, 2001) for source term estimates based on plant conditions. In collaboration with the NRC, NARAC has developed an interface to quickly import nuclear power plant accident source terms from RASCAL into the NARAC dispersion model. For radiological dispersal devices (such as explosives and sprayers), NARAC uses source characteristics from Sandia National Laboratories (Harper *et al.*, this issue). The gross activity, spatial distribution, and particle size distribution of the stabilized nuclear debris cloud for nuclear detonation sources are derived from an approach used by Harvey and Serduke (1979). Buoyancy-driven and/or momentum-driven plume rise from continuous sources such as fires or stack emissions is computed inside the NARAC dispersion model, LODI, as described below. The CAMEO/ALOHA software and associated databases (EPA, 1999a and 1999b) are used for chemical material properties and toxic industrial chemical releases mechanisms (such as leaking tanks).

3.4 Gaussian plume and puff models

Fast-running Gaussian plume and puff dispersion models are valuable tools for local-scale predictions, rapid initial response to an incident, and quick screening calculations to assess the magnitude of a hazard. Gaussian plume models are attractive for their relative simplicity of mathematical formulation (analytic expressions), limited input parameter requirements, and computational speed. Gaussian plume models typically use only a single constant wind velocity and general categories of turbulent mixing (using a stability class) to parameterize turbulence diffusion (derived semi-empirically from experiments using near-surface releases). These models are therefore valid only for near-surface dispersion over short distance and time scales for which these assumptions are valid. However, they can be reasonably reliable in situations involving simple flows, such as unidirectional steady-state flow over relatively flat terrain.

NARAC software tools incorporate and/or interface with several Gaussian plume and puff models. NARAC software allows users to run the Hotspot Gaussian plume model (Homann, 1994), which provides emergency response personnel and emergency planners with a fast, field-portable set of software tools for evaluating incidents involving radioactive material. Hotspot predicts dispersion and deposition using the Gaussian plume equation, and provides a fast and usually conservative means for estimating the radiation effects associated with the short-term (less than 24 hours) atmospheric release of radioactive materials. It includes options for dispersion of continuous plumes, explosions, fires, and ground resuspension (area contamination). Interfaces to share chemical information between NARAC software tools and the NOAA/EPA CAMEO/ALOHA (EPA, 1999b) toxic industrial chemical database and Gaussian plume modeling system have been developed.

Gaussian puff models can incorporate temporal, horizontal, and vertical variations in meteorological conditions. Such models can therefore be used over larger range of distances and scales. We are developing the ability to run the urban-scale Urban Dispersion Model (UDM) Gaussian puff model (Griffiths, 2002) within the NARAC software system. The UDM is an empirical urban model, which includes the time- and space-averaged effects of buildings and building complexes on transport and diffusion.

3.5 Explosive prompt effects models

Conventional or nuclear explosions produce potentially harmful, prompt effects from blast overpressure, thermal radiation or ionizing radiation. NARAC software predicts conventional high explosive blast overpressure effects using the Sandia National Laboratories BLAST model, which utilizes overpressure relationships published by Caltagirone (1986). Prompt effects from nuclear detonation associated with direct blast injury, tumbling/impact, thermal injury, and prompt radiation are predicted using the Sandia NUKE model, which utilizes relationships published by Glasstone and Dolan (1977). A Nuclear Explosion program in Hotspot software provides a simple, PC-based deployable tool for predicting the effects of a surface-burst nuclear weapon, including prompt effects (from neutron and gamma radiation, blast, and thermal radiation), and fallout information (Homann, 1994).

3.6 Lagrangian Monte Carlo dispersion and deposition modeling

For regional to global scale atmospheric dispersion, NARAC uses a 3-D Lagrangian stochastic, Monte Carlo atmospheric dispersion model that is coupled to the meteorological models, described above. Numerical methods based on the Lagrangian approach have several advantages because they are meshless. The accuracy of an individual particle trajectory calculation using a Lagrangian stochastic method is not dependent on grid resolution or the number of trajectories computed. Lagrangian methods can resolve point sources without additional computational cost or an approximate sub-grid parameterization, unlike Eulerian methods or hybrid Eulerian-Lagrangian, particle-in-cell methods.

The NARAC 3-D dispersion model, the Lagrangian Operational Dispersion Integrator (LODI), simulates the processes of mean wind advection, turbulent diffusion, radioactive decay, first-order chemical reactions, wet deposition, gravitational settling, dry deposition, and buoyant/momentum plume rise. This model solves the 3-D advection-diffusion equation:

$$\begin{aligned}\frac{\partial C}{\partial t} &= -\bar{u}\frac{\partial C}{\partial x} - \bar{v}\frac{\partial C}{\partial y} - \bar{w}\frac{\partial C}{\partial z} \\ &\quad + \frac{\partial}{\partial x}\left(K_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right) \\ &\quad + w_s\frac{\partial C}{\partial z} - \Lambda C - \lambda C + Q \end{aligned} \qquad (1)$$

where C is the mean air concentration of a species; $\bar{u}$, $\bar{v}$, and $\bar{w}$ are the mean wind components in the *x*, *y*, and *z* directions, respectively; *t* is time; K_X, K_Y, and K_Z are the eddy diffusivities for the three coordinate directions; w_s is the absolute value of the gravitational settling velocity; Λ is the precipitation scavenging coefficient; λ is the decay constant for radioactive decay (or the rate constant for first-order chemical reaction); and *Q* is the source term. Additional terms (not shown) are used to calculate the production of radionuclides due to the decay of other radionuclides in a decay chain.

Equation (1) is solved using the Lagrangian stochastic, Monte Carlo method, in which deterministic particle displacements due to the mean wind are calculated using the Runge-Kutta methods described by (Leone *et al.*, 1997). The displacement of a particle due to turbulent diffusion is performed using the method developed by Ermak and Nasstrom (2000) based on a skewed, non-Gaussian particle position probability density function, necessary for the efficient simulation of diffusion in inhomogeneous turbulence (especially near the ground surface).

The source term, *Q*, in Eq. (1) is specified using input parameters for the initial spatial distribution of source material (options are provided for point, line, 3-D Gaussian, and uniform spherical distributions) and the total source mass (or activity) emission rate, *q*. Both the spatial distribution and emission rate may change in time, in order to simulate moving and time-varying sources. For an aerosol source, the mass (or activity) distribution (i.e., the mass of the species of interest as a function of particle size) can be specified via input parameters specifying a lognormal distribution or from tabular input.

The LODI dispersion model includes parameterizations for the vertical rise of bent-over plumes from continuous sources due to initial vertical momentum and/or buoyancy. Analytic expressions reviewed by Weil (1988) are used for the mean height and radius of the plume as a function of time. The final rise of a plume is limited by several factors, including the intensity of the ambient turbulence and the presence and strength of stable layers at or above the source. The model uses the minimum rise found from separate calculations of the rise due to each of these effects. During the initial plume rise phase of a particle trajectory, an additional mean vertical velocity due to plume rise is added to the mean vertical velocity of the particle due to other processes (mean wind, gravitational settling). Diffusion during the plume rise phase is calculated using an effective diffusivity, assuming that the standard deviation of the spatial distribution of material in the plume is proportional to the plume radius. In the absence of modeled or observed temperature data, the ambient potential temperature gradient is assumed to be zero in the neutral and unstable atmospheric boundary layer (ABL), and a similarity theory temperature profile is used in the stable ABL. The standard atmosphere temperature gradient (–0.0065 deg m^{-1}) is used above the ABL.

The terminal settling velocity, w_s, for aerosol particles is calculated using the particle diameter, particle density, air density, and air viscosity derived from methods described by Hinds (1982). Different methods are used based on the Reynolds number of the flow around the falling particle. For particle Reynolds number, Re < 1, Stokes' Law is valid and is used to calculate the terminal settling velocity. For Re > 1, Stokes' Law is not valid and we use the table-based method described by Hinds (1982).

Dry and wet deposition of contaminants are simulated by LODI. A deposition velocity, v_d, is used to parameterize the effects of all near-surface dry deposition processes below a reference height, including turbulent and molecular diffusion to the surface, inertial impaction on the surface, absorption by the surface, as well as gravitational settling. The deposition velocity for gases ($w_s = 0$) is $v_d = 1/r_T$, where r_T is the total deposition resistance (e.g., Wesely and Hicks, 1977). For particulate matter ($w_s > 0$), the deposition velocity is calculated according to

$$v_d = \frac{w_s}{1 - e^{-w_s r_T}} \tag{2}$$

(Sehmel and Hodgson, 1978).

Dry deposition of material onto the surface is calculated by depleting the mass of computational particles near the surface, so that the flux of material to the surface is consistent with this deposition velocity (Leone, *et al.*, 2005). By depleting mass from all particles near the surface, instead of entirely removing a fraction of the particles, the statistical significance of both the deposition and air concentration calculations is greatly improved (by maintaining a larger computational particle count for both calculations). Precipitation scavenging and wet deposition is calculated using the size distributions of both the precipitation and the contaminant particles, and the fall velocities of both, as described by Loosmore and Cederwall (2004).

3.7 Building-scale computational fluid dynamics models

For detailed studies of flow and dispersion of airborne material around buildings and in the urban environment, NARAC uses a Computational Fluid Dynamics (CFD) model. While CFD models are computationally expensive compared to simpler modeling approaches, they are capable of simulating the dynamics of turbulent flows and can capture high-resolution features, such as flow jetting between obstacles, impingement and separation regions, wake vortices, and recirculation zones caused by obstacles or terrain features. One of the important phenomena that CFD models capture is the lingering of contaminant material in recirculation zones behind buildings, after most of the material has transported downwind. CFD models using Large Eddy Simulation (LES) are able to capture turbulent fluctuations and peak concentrations.

The FEM3MP CFD model (Chan and Stevens, 2000), is based on solving the three-dimensional, time-dependent, incompressible Navier-Stokes equations on massively parallel computer platforms. The numerical algorithm uses a finite-element representation for accurate representation of complex building shapes and variable terrain, together with a semi-implicit projection method and modern iterative solvers for efficient time integration. Physical processes treated in FEM3MP include turbulence modeling via the RANS (Reynolds Averaged Navier-Stokes) and LES (Large Eddy Simulation) approaches, atmospheric stability, aerosols, UV radiation decay of biological agents, surface energy budget, and vegetative canopies. A next-generation version of FEM3MP, the Adaptive Urban Dispersion Integration Model (AUDIM) is currently under development.

3.8 Parallelization

Key numerical models are parallelized to take advantage of the shared and distributed memory run-time environments that are available in NARAC's computer systems. Parallelization of the models improves computational performance and is particularly important for high-resolution simulations or complex source applications. NARAC models utilize a parallel implementation based on a combination of Message Passing Interface (MPI) and OpenMP, in order to support both multi-processor and massively-parallel computing platforms.

The LODI model has been parallelized by taking advantage of the inherently parallel nature of Lagrangian random-walk dispersion models (Larson and Nasstrom, 2002). A parallel version of the COAMPS model, based on horizontal domain decomposition, was developed in a joint LLNL and Naval Research Laboratory collaboration (Mirin *et al.*, 2001). This version is being used operationally by the Navy and is being integrated into the NARAC system. FEM3MP and AUDIM are built on constructs which allow optimal performance on high performance computing platforms.

4 Dose, Health Effects and Decision-Support Products

Atmospheric dispersion and deposition models predict quantities such as time-integrated or time-averaged air concentration, peak air concentration experienced at any interval during the total exposure time, and accumulated surface deposition. These quantities are converted into products that are useful to a wide range of users, including emergency responders, support scientists, emergency managers, and decision makers.

NARAC products include maps showing areas in which dose limits are exceeded, areas in which protective action (sheltering, evacuation, relocation) limits are reached, estimated counts of the affected population, and geographic reference data (e.g., roads, political boundaries, terrain, water bodies, aerial photography, critical facilities such as schools and hospitals). Other potentially valuable information included in NARAC products are map displays of meteorological observations and model wind fields.

Radioactive dose is calculated from model-computed air- and ground contamination values, using dose conversion factor databases provided by Oak Ridge National Laboratory. For internal 50-year committed dose from inhalation, these factors were published by the EPA (1988) and are a function of radionuclide, chemical form, and particle size. The factors are derived from the International Commission on Radiological Protections (ICRP) Publication 30 lung model and methodologies for internal dose. Optionally, inhalation dose conversion factors, based on the ICRP-66 lung model and ICRP 60/70 series methodologies (published by the EPA, 1999c), can be used. For external dose from both ground and air immersion exposure, dose conversion factors published by EPA (1993) are used. In addition, acute (24-hour) dose factors from Eckerman (2001) are used for estimating non-stochastic effects, from high acute radiation doses for applicable target organs (the lung, small intestine wall, and red bone marrow).

Radiological dose limits from the U.S. Environmental Protection Agency (EPA, 1992) for guiding protective actions (sheltering, evacuation, and relocation) and for emergency workers engaged in property protection and life saving activities are automatically displayed as plume model contour areas on NARAC map products. Population data, dose-response models, and risk factors are used to estimate the number of casualties from acute dose exposures and the number of latent cancer incidents from chronic doses using methodologies described by EPA (1992) and NCRP (1993).

For toxic chemical exposure, NARAC uses airborne exposure limits from the EPA's Acute Exposure Guideline Levels (AEGL), the American Industrial Hygiene Association's Emergency Response Planning Guides (EPRG), and the U.S. Department of Energy's Temporary Emergency Exposure Limits (TEEL). Up to three exposure levels are shown: (1) notable discomfort, (2) serious/long-lasting effects, and (3) life-threatening effects. For chemical and biological warfare agents, lethal dosage levels are shown if those levels are attained.

NARAC report generator software developed in collaboration with Sandia National Laboratories is used to reliably and accurately assemble a detailed effects and consequences report, which combines effects contour maps, tables of plume centerline values, and the assumptions, background, and explanatory text relevant to the calculations.

5 Software Systems

The current third-generation NARAC software system became operational in 2000. It is a fully automated client-server system with internet-oriented technologies, and can handle multiple simultaneous users and events. The complete system allows automated 3-D predictions of atmospheric plumes and their consequences to be delivered in less than 15 minutes. The software is deployed in a heterogeneous hardware environment that currently includes UNIX, Linux, and Windows servers.

NARAC's software system utilizes a multi-tiered distributed software architecture that provides real-time access to the global meteorological and geographical databases and atmospheric modeling tools. The software infrastructure is composed of two primary components: (1) the NARAC Central System (NCS) and (2) the NARAC Enterprise System (NES). The Central System integrates a sophisticated modeling environment with data warehousing capabilities, and contains tools to generate end-user products. In-house NARAC staff has direct access to the Central System. The NES provides user-friendly web and other internet-based tools that allow registered users to remotely access advanced NARAC services and to share products with other users. In addition, the NES has a stand-alone capability that allows remote users to run simple plume models when internet and other communication channels to the Central System are not available.

The NARAC Central System combines three major subsystems (the meteorological data, geospatial data, and model execution subsystems) with an environment for advanced scientific analysis and visualization. The meteorological data, or metdata, subsystem manages the acquisition, archival, and processing of meteorological observations from over 20,000 instrument sites. It also handles gridded forecast data from external sources (e.g., NWS, AFWA, and FNMOC) and NARAC's in-house version of the COAMPS mesoscale model. The metdata subsystem allows temporally and geographically relevant data to be extracted for use in the model execution subsystem.

The geospatial or geodata subsystem manages the registration, archival, and processing of multiple geographic data sets for use by the models, and in the analysis of model output and visualization products. The geodata subsystem allows topically and geographically relevant data to be extracted for use in a specific region.

The model execution subsystem manages the lifecycle, parameters, and supporting databases used by the suite of model input data pre-processing tools, atmospheric models, and post-processing utilities. The generation of products and the analysis of model results are also handled by the model execution subsystem.

The NARAC Central System utilizes a distributed client-server framework employing the Common Object Request Broker Architecture (CORBA). CORBA is a vendor-independent open architecture used for application networking. The current Central System was designed and developed using an object-oriented approach. The core services are written in C++, while Java is used for user-interface clients and servers that support remote access. Key atmospheric models such as LODI and ADAPT are written in Fortran 90. An object-oriented database system is utilized for modest-sized data and metadata storage for very large data sets. Large data sets are stored in their native format or as NetCDF files.

The core Central System services run on Unix/Linux platforms, with the software and hardware architecture permitting multiple events to be run in parallel. Future advances of the NARAC system will include the integration of new models being developed via on-going R&D efforts (e.g., CFD models and sensor-data-driven event reconstruction models). These models are computationally intensive and hence utilization of high performance computing resources will be necessary.

Development of the NARAC Enterprise System (NES) began in 2000. The NES allows remote users to “reach back” to the NARAC Central System, share results and information with other users, and operate in a stand-alone mode if reach-back connectivity is not available. The NES consists of three components: the Enterprise or Middle Tier, the NARAC Web, and the NARAC iClient. Information exchange between the Central System, Enterprise Tier, and the iClient and NARAC Web end-user tools is handled via Extensible Markup Language (XML) and Hyper Text Markup Language (HTML).

The Enterprise Tier handles all external user connections to NARAC, processes requests for calculations and forwards them to the Central System, stores and processes the results of calculation requests, delivers these results in the form of data files or web pages, and handles user access and data security issues.

The NARAC Web and iClient are end-user tools that allow remote access to the NARAC Central System via the Enterprise Tier. The NARAC Web is a secure web site that permits remote users to input simple release scenarios, automatically run NARAC models, and view and manage the results of model runs. The iClient is a more sophisticated desktop application that provides NARAC reach-back capability and stand-alone operation using local models on a user’s remote system. It was designed using Java and web-based technology to provide a platform independent tool for deployed emergency management analysts. The iClient is designed for subject matter experts, whereas the NARAC Web is targeted at a wider audience. Currently, there are approximately 100 iClient and 1200 NARAC Web external users.

6 Staff, Facilities and Operations

In 1996, the Department of Energy (DOE) funded the construction of a new emergency operations center, computer center and staff offices for NARAC at LLNL. NARAC's operations center has uninterruptible power supplies, backup power generators, and computer systems that support the models and software systems described above. The same building houses a modern training facility for hands-on classroom training of users and the offices of the multi-disciplinary NARAC staff.

Locating the entire multi-disciplinary NARAC team together in the same building provides a unique and ideal environment for developing and maintaining a state-of-the-science atmospheric dispersion prediction capability. The NARAC team, comprised of research, development and operational personnel, has substantial collective subject matter expertise in operational meteorology, atmospheric science, chemistry, numerical modeling, geographical information systems, health physics, industrial hygiene, computer science, engineering and computer system administration.

In order to respond rapidly to emergency situations, NARAC maintains a 24-hour-per-day on-call staff. When an emergency occurs, NARAC operational staff members immediately begin providing technical and scientific support, including quality assurance of model input data and predictions. This support continues until all airborne releases are terminated, the hazardous areas are defined and mapped, measurement data have been used to update model predictions, and the long-term impacts are assessed. In addition to its regular services, the staff can also use NARAC's advanced modeling and visualization tools to provide specialized products needed by users. The staff also provides support and training on NARAC tools and services.

NARAC's professional staff is primarily a centralized resource. A minimum team is comprised of an event operations manager, one or more operational support scientists, and a customer support assistant. Depending on the event, the team also may include a health physicist, industrial hygienist, chemist, administrative assistant, and computer technician. In-house software and model developers can support rapid customization of tools to meet the needs of a particular incident response.

NARAC personnel are available for deployment to an incident location. The need for deployment is determined by the requirements for extensive NARAC support. Deploying a NARAC liaison at a FRMAC, has proven to be invaluable for facilitating information flow between on-scene emergency managers and NARAC, and for fostering full utilization of NARAC tools and services. The deployed team usually consists of one operational support scientist per shift.

7 Testing and Applications

Emergency response modeling systems must be extensively validated in order to verify that they have been implemented properly, produce realistic predictions, and are reliable in emergency conditions. NARAC models and software systems have been rigorously tested and evaluated in multiple ways. Before being used operationally, software quality is assured by testing in separate computer systems before moving to the operational system.

Evaluation of models includes the use of analytic solutions (known, exact mathematical solutions to the model equations) to verify that the numerical methods used are sufficiently accurate. Comparisons against tracer field experiment data are used to test and evaluate models for a range of real-world terrain and meteorological conditions. After-action reviews following actual atmospheric release events evaluate model usability, efficiency, and reliability of models for real-world operations. Since the NARAC modeling system is designed to simulate cases involving both simple and complex terrain, and multiple space and time scales (microscale, to mesoscale, to continental scale), it must be tested under all these conditions. A few examples are presented in the remainder of this section.

The meteorological data assimilation and interpolation algorithms in ADAPT have been successfully tested by comparison to observational data (Sugiyama and Chan, 1998). The non-divergence adjustment algorithm is verified against potential flow solutions and wind tunnel data (Chan and Sugiyama, 1997).

A series of tests using analytic solutions have been performed to verify that the LODI dispersion model accurately solves the advection-diffusion equation. Results for solutions to the 1-D diffusion equation for linear and quadratic $K_z(z)$ have been given previously by Ermak and Nasstrom (2000). Comparisons have been made against analytic solutions for the following cases: (1) 3-D advection and diffusion from a instantaneous Gaussian source with constant mean wind, constant diffusivities, and an impermeable lower boundary; (2) 1-D vertical diffusion of a well-mixed, uniform spatial distribution with similarity-theory $K_z(z)$ and impermeable upper and lower boundaries; (3) 3-D advection and diffusion from a continuous point source with linear $K_z(z)$, constant wind, no downwind diffusion, travel-time-dependent K_y, and impermeable lower boundary; (4) 1-D settling, surface deposition, radioactive decay, and integrated ground exposure due to a uniform vertical concentration distribution of aerosol with zero wind and zero diffusivity; and (5) 2-D advection and diffusion from a continuous point source with power law $\overline{u}(z)$, linear $K_z(z)$, zero downwind diffusion, and an impermeable lower boundary. These tests have been used to develop automatic time step restrictions (based on grid spacing, magnitude of the diffusivity and its gradient, magnitude of the wind speed components, boundary layer depth, and decay time constant) that ensure accurate numerical solutions (less than 5% error in the computed quantities, air concentration and/or deposition, for each solution).

An example simulation result from the 2-D (downwind distance, *x*, versus height, *z*) case of a continuous point source at $z = 15$ m, a power law $\bar{u}(z) = 5z^{0.2}$ m s^{-1}, and a linear $K_z(z) = 0.1z$ m^2 s^{-1} (both typical of the neutral surface layer) is shown in Fig. 1. In this simulation, a graded vertical wind grid was used with a minimum grid spacing of 0.25 m for the first three grid points near the surface, and each succeeding vertical level having twice the spacing of the next lower level. A total of 10^5 particle trajectories were calculated. Concentrations were calculated by sampling particles on a grid with 3 m vertical resolution near the surface. Agreement between the numerical and analytic solutions for the mean air concentration is very good, verifying that the LODI model accurately simulates advection and diffusion in vertically inhomogeneous mean wind and turbulence.

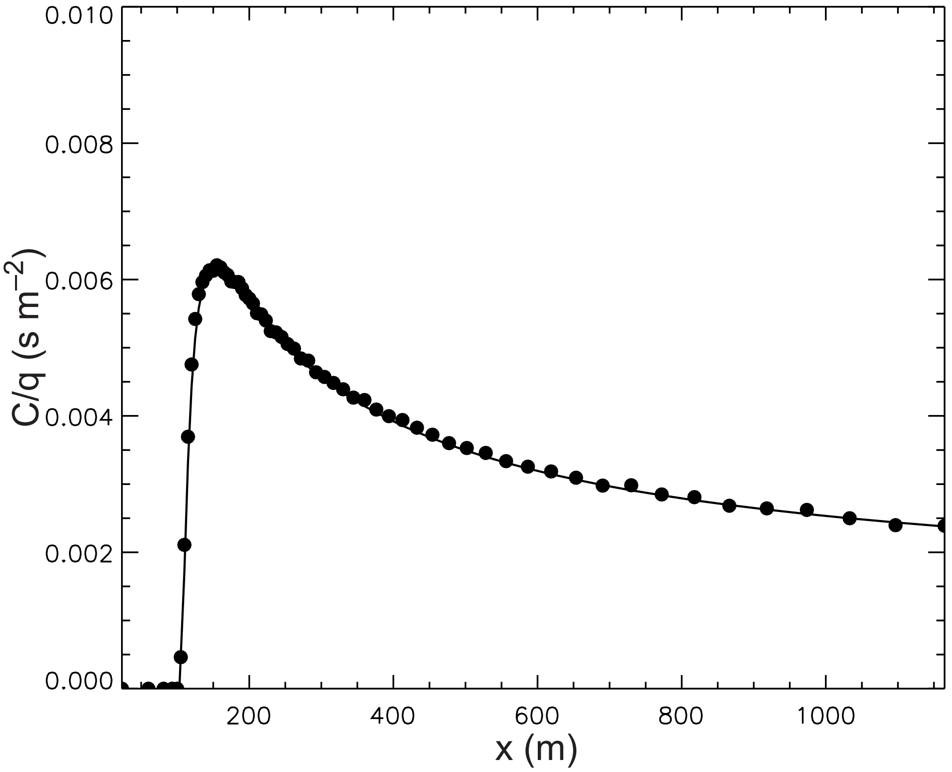

Fig. 1. Concentration (per unit source strength) versus downwind distance from analytic solution (curved line) and numerical model solution (circles) at 19.5 m above the surface for the 2-D case of a power law wind speed and linear diffusivity.

Historically, NARAC has used a variety of tracer experiments for model testing and evaluation (Sullivan et al, 1993; Nasstrom and Pace, 1998; Foster *et al.*, 2000). An example is the Project Prairie Grass experiment (Barad, 1958) which was used to test the ability of the ADAPT/LODI modeling system to simulate microscale dispersion. Continuous 10-min releases of SO_2 gas at a height of 0.46 m were conducted in an area of flat, arid grassland. Time-average concentrations were measured at z = 1.5 m on arcs 50, 100, 200, 400, and 800 m from the source and at heights of 0.5, 1.0, 1.5, 2.5, 4.5, 7.5, 10.5, 13.5, and 17.5 m on six towers located on the 100-m arc. The 20-min average wind and temperature were measured at a multi-level tower instrumented at 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, and 16.0 m. A rawinsonde provided upper level wind and temperature data.

These observations were used by ADAPT to generate a wind field on a grid with 26 vertical levels which resolve the tower observation levels (grid levels at $z = 0, 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, \ldots$ meters). A zero-slip speed was imposed at the surface. The 10-min average cross-wind velocity variance from a 2-m tower observation nearest the source location and closest to the gas release time was used to scale the horizontal velocity variance parameterization. For the LODI dispersion simulation, 10^5 particle trajectories were computed and concentrations were calculated by sampling particles in a graded vertical grid with a 0.25 m vertical spacing at the surface and succeeding higher grid volumes spaced so that they were centered at the heights of the vertical tower concentration observations.

Two-dimensional (downwind distance versus height) simulations were made to compare model results to the crosswind-integrated 100-m arc-observed concentrations computed by Wilson *et al.* (1981). We used values of L and u_* calculated by Wilson *et al.* from observed wind and temperature profiles assuming a surface roughness height of 0.005 m. Deposition velocity values were calculated using the method of Weseley and Hicks (1977) for estimating the total SO_2 deposition resistance. For the SO_2 canopy resistance, we also used their value for vegetation subject to water stress, 200 s m^{-1}. For stable conditions, values of h were set to the height of the nocturnal surface-based inversion, determined from the rawinsonde temperature soundings. For unstable conditions, h was set to the height of base of the elevated inversion layer in the observed temperature sounding.

Fig. 2 shows comparisons of predicted and observed crosswind-integrated concentration profiles for the Prairie Grass experiments with a range of atmospheric stability: #50 (unstable), #45 (near neutral), and #59 (stable). These model results show good agreement with the observations for all three stability conditions, and demonstrate the ability of the models to simulate dispersion in the vertically inhomogeneous mean wind and turbulence conditions found close to the ground.

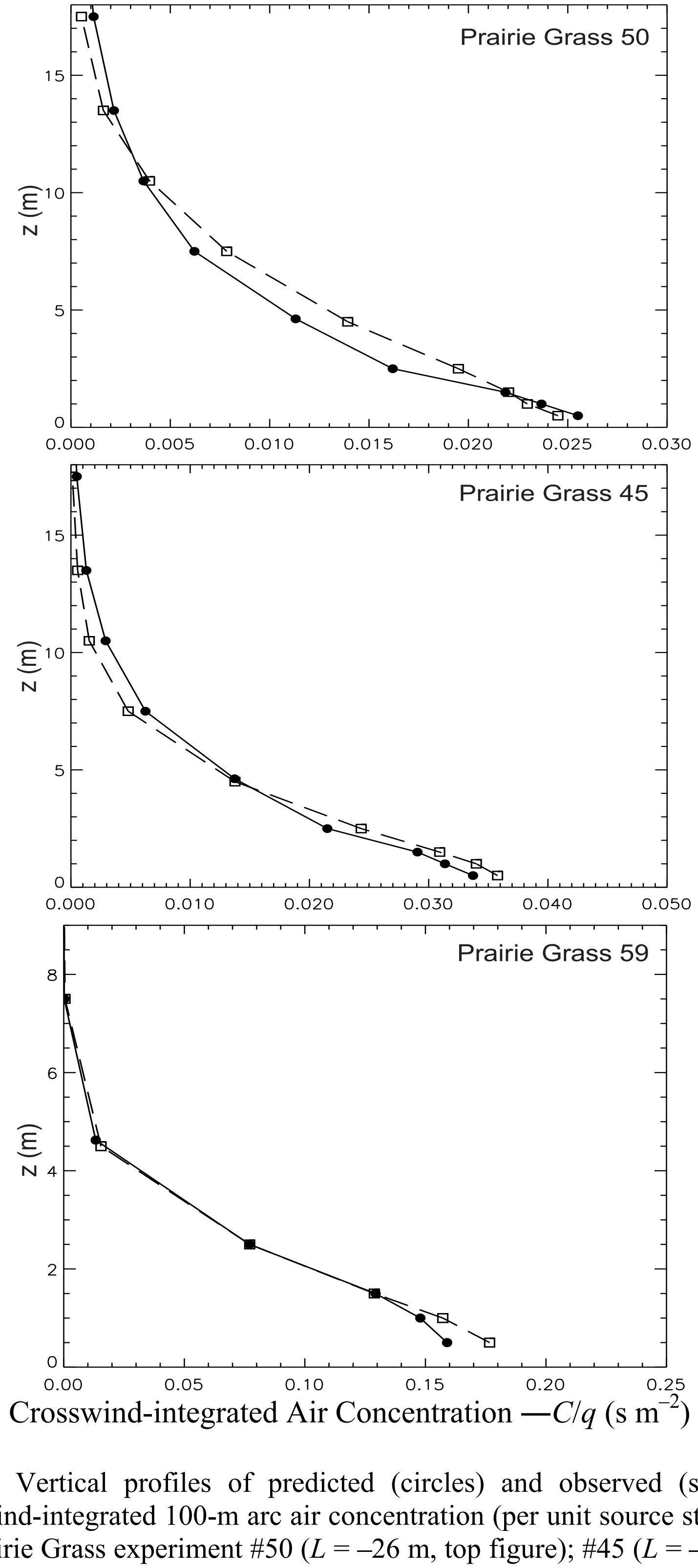

Fig. 2. Vertical profiles of predicted (circles) and observed (squares) crosswind-integrated 100-m arc air concentration (per unit source strength) for Prairie Grass experiment #50 (*L* = –26 m, top figure); #45 (*L* = –110 m, middle) and #59 (*L* = 7.3 m, bottom).

Figure 3 shows a comparison of air concentrations predicted using the ADAPT/LODI models compared to measurements from the Diablo Canyon tracer experiment (DOPPTEX) conducted along the central coast of California (Thuillier, 1988). This simulation is for SF_6 gas released at the site of the Diablo Canyon nuclear power plant. Fig. 3 shows shaded contours of the simulated 1-hr averaged surface concentration from 1900 to 2000 UTC, overlaid on terrain contours and coastline. Also plotted are representative observed values of SF_6 air concentration (numerical values next to "+" symbols, which indicated sampler locations). The simulated plume concentrations match the complex pattern of the measured values well, with a few minor outliers.

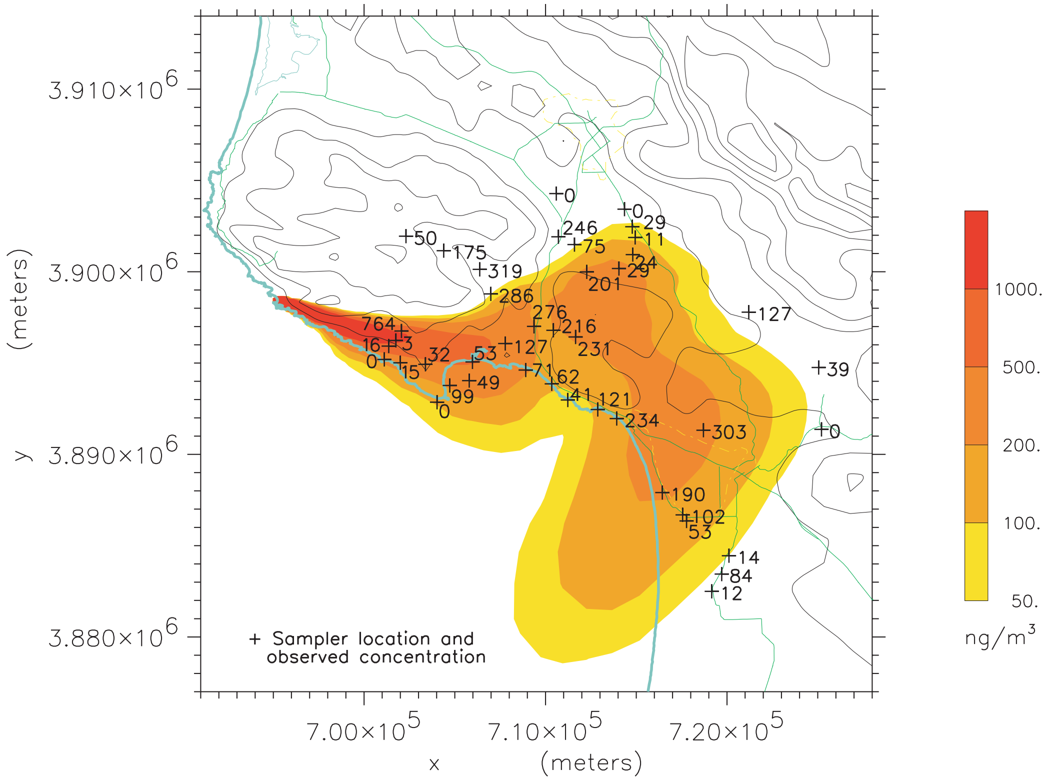

Fig. 3. Air concentration (in ng m^{-3}) predicted using the ADAPT/LODI models (shaded contours) compared to measured 1-hr averaged air concentrations (numerical values next to "+" symbols, which indicated sampler locations from 1900 to 2000 UTC on August 31, 1986 from the Diablo Canyon tracer experiment. Contour lines represent terrain elevation in intervals of 100 m.

Predictions from FEM3MP are verified and validated against data from wind tunnel (Chan and Stevens, 2000) and field experiments (Chan, *et al.*, 2004). An example described by Chan (2004) using data from an URBAN 2000 field experiment

(Allwine, *et al.*, 2002) is shown in Fig. 4. The simulated dispersion experiment, Release 1 of Intensive Observation Period 7 (IOP7), was conducted under very light wind and highly variable wind direction. The source location is indicated by the horizontal line with approximate coordinates (500, -625). The small color-coded squares plot the corresponding field measurement data (colors are chosen consistent with the contour level colors). Excellent agreement is obtained between the predicted concentration patterns and the observed data.

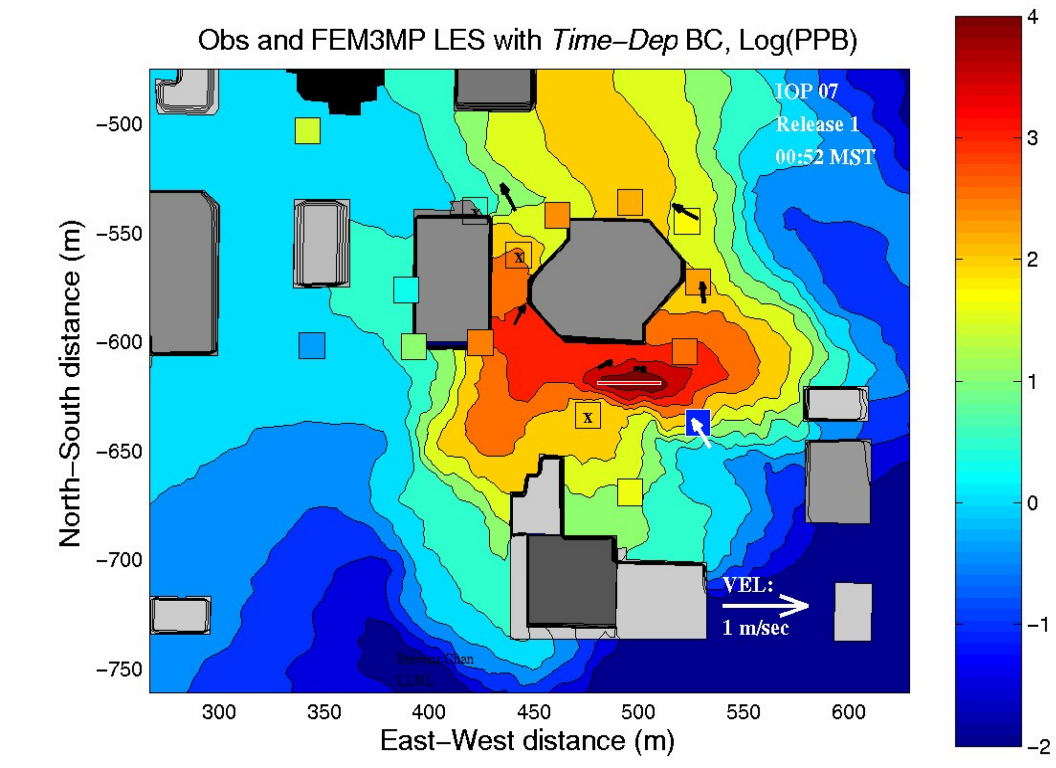

Fig. 4. FEM3MP predicted time-averaged (for t = 50-55 min) concentration patterns on z = 1 m plane from a Large Eddy Simulation (LES) using time-dependent boundary conditions constructed from 1-sec sonic anemometer data collected on the rooftop of City Center building. The gas sampler concentration observations are superimposed as small squares with the same color scheme as the model concentration contours (from Chan, 2004).

8 Integration of Measurement Data with Model Predictions

Because of limitations and uncertainties in input data (e.g., source term estimates) and other modeling assumptions, it is important to incorporate field measurements into predictions and assessments of dose as soon as possible during an incident or accident. For terrorist scenarios (e.g., an RDD) little may be known about the characteristics of the dispersed and airborne material. In this case, an idealized gas or aerosol source with a unit amount of material can be used to initially predict the downwind area in which to focus air- or ground monitoring activities. For nuclear power plant accidents, estimates of the source term may be available from plant conditions or data from a monitored stack. However, refinement of these estimates requires additional data.

Integration of measurements of radioactive contamination, airborne or on the ground, is especially valuable in the early and intermediate phases of an event. Even if only sparse measurement data are available, they can be used to calibrate initial model predictions to more accurately predict areas potentially needing protective actions (such as sheltering, evacuation or relocation). NARAC predictions, in turn, can help guide field teams to potentially contaminated areas that need monitoring. Models can then be used to interpolate between measurements and extrapolate beyond areas that have been monitored by measurement teams. By using this approach to the problem, low levels of contamination that are difficult to measure can be simulated more accurately. This methodology also can aid in helping guide crop and food field sampling teams to areas in which contamination might result in an ingestion-pathway dose that exceeds regulatory limits.

Since its inception, NARAC has included the use of measurement data to update model predictions. Today, NARAC routinely participates in emergency response drills with organizations that collect air concentration, ground deposition, and radiation exposure measurements. NARAC provides modeling support and works closely with regional and national measurement and dose assessment teams, including those at supported DOE and DOD sites and the Department of Energy (DOE) National Nuclear Security Administration (NNSA) Office of Emergency Operations' regional Radiological Assessment Program (RAP), Accident Response Group (ARG), and Aerial Measurement System (AMS), as well as the Federal Radiological Monitoring and Assessment Center (FRMAC).

NARAC works as part of the FRMAC to utilize measurement data for updating model predictions. Data are collected, assessed, and stored in FRMAC databases, and then electronically transmitted to NARAC. An Extensible Markup Language, or XML, file is being developed in a collaboration with the Remote Sensing Laboratory and Sandia National Laboratories to electronically transfer measurement data from FRMAC databases to the NARAC modeling system. XML has proven to be a simple, flexible, self-describing text format for this use. Data are stored with necessary metadata, such as units of measure, time of measurement, type of instrument, type of radiation or isotope.

NARAC scientists visually and statistically compare measured and computed values for each monitoring location point. A useful statistic is the average ratio of measured and computed values. These ratios provide good statistical measures for values that can vary over many orders of magnitude, and can be used to scale the airborne source amount assumed in the model. A range of values for uncertain model input data (in particular wind data from several possible sources, particle size distributions and release heights for buoyant releases) are analyzed to determine the input data that result in the best-fit model predictions, as measured by the measured-computed ratios.

Examples of NARAC's use of field measurements to update model predictions and estimate source terms include the Uranium Criticality accident at Tokaimura, Japan, in 1999, and the accidental melting of a Cesium source at a steel-processing facility in Algeciras, Spain in 1998 (Vogt *et al.*, 1999).

9 Future Research and Development

In order to meet the challenges of future threats, an expanded set of capabilities may be required. An improved understanding of the atmospheric boundary layer flows for stable, nocturnal, transitional, urban, and coastal conditions is needed. Significant improvements in fidelity will result from a deeper understanding and new models of key physical processes, such as precipitation scavenging, resuspension, multiphase chemical kinetics, explosive releases, and fires. For example, advanced approaches to simulating the time-dependent resuspension flux of deposited contamination (Loosmore, 2002) show promise for more realistic simulation of material re-suspended after deposition onto ground surfaces.

The accuracy of predictions of the consequences of airborne hazardous material release events can be significantly improved by incorporating higher resolution, more representative meteorological data from local observational networks (mesonets), radar-derived precipitation, and satellite analyses of winds, temperatures, and clouds. Remote sensing data from lidars, wind profilers, radar, and/or sodar systems can provide more realistic detailed meteorological data field for important quantities such 3-D wind field, turbulence, and mixing layer depth. Numerical weather prediction models can make use of additional meteorological observations to improve forecasts using data assimilation algorithms.

An emerging aspect of emergency response is the importance of methods for incorporating measurement data into predictions and analyses. Sensor data networks and real-time data feeds are needed to supply new meteorological and contaminant concentration measurement and new simulation tools are need to interpret and assimilate this data.

Automated techniques for optimizing model simulations using air and ground contamination measurements hold promise for faster refinement of uncertain model input variables, such as the source term. The development and operational use of event reconstruction tools is now becoming feasible due to the convergence of numerical modeling approaches, remote and deployable sensor technologies, high performance computing, and operational deployments of detector networks. These technologies are at the forefront of a revolutionary new paradigm for treating dynamic complex problems, which involve mutual optimization of sensor data and models (the use of data to steer models and of models to guide data collection). A variety of approaches are being pursued, including heuristic methods (backward trajectories, ensemble simulations), Bayesian-inference stochastic sampling algorithms, and non-linear optimization. A LLNL approach couples data and predictive models with Bayesian inference and stochastic sampling to provide backward analyses to determine unknown source characteristics, optimal forward predictions for consequence assessment, and dynamic reduction in uncertainty as additional data become available (Kosovic, et al., 2005). These techniques can greatly aid an effective response to an unexpected radiological event that requires rapid quantitative estimation of the source term(s) based upon the available data, in order to provide the best possible predictions of transport and the resulting health risks to the exposed population and emergency responders. For practical application in real-time, sensor-driven modeling techniques must be integrated into information systems the combine automated data acquisition, analysis, display and distribution of predictions and decision-support products.

Uncertainty estimation is urgently needed for proper interpretation of simulation results. Ensemble weather forecasts can provide estimates of natural variability and forecast errors. A full uncertainty analysis of a release event would take into account the uncertainties in all input parameters (e.g., the meteorological fields and source attributes), incorporate the sensitivity of the model outcomes to those parameters, and produce quantitative uncertainty ranges for output results of interest. Monte Carlo analysis builds a probability distribution for predictions from a suite of model runs, generated from a randomly sampled set of input variables. Response surface methodology (RSM) is an alternate approach which constructs uncertainties from a suite of runs, but utilizes classical experimental design theory to generate the inputs for the event simulations. Sensitivity analysis decouples input uncertainty from model processes algorithms to provide an understanding of the sensitivities of model outcomes to the input parameters. Computed sensitivities then can be re-coupled with input uncertainties to quantify prediction uncertainty. Methods must also be developed for interpreting and presenting uncertainty estimate and guidance to users and responders.

In order to more accurately characterize dispersion, deposition and dose, source properties — such as particle size distribution, isotope inventories, buoyant rise — for gas and aerosol released from nuclear and conventional explosives need to be better characterized, and need to account for different types of source material and different urban and rural land characteristics. Continued advances in the prediction of gas and aerosol infiltration into buildings, and the coupling of indoor and outdoor transport models, is needed in order to better predict dose and effects for indoor population.

10 Summary

This paper has described the current capabilities of the National Atmospheric Release Advisory Center (NARAC) for hazardous airborne material dispersion predictions. In order to accomplish NARAC's mission of providing real-time atmospheric hazard predictions and detailed assessment, a wide range of supporting databases, computer models, software systems, and services have been integrated together. These include the following:

- Methods of calculating source term data for nuclear weapons, nuclear power plant accidents, explosive sources, and non-explosive sources (e.g., liquid dispersion and fires)
- Automated, real-time, global meteorological observation acquisition (including global observation network, regional networks, and local networks)
- Automated collection and storage of continental-scale and global-scale gridded meteorological analyses and forecasts from several U.S. agencies
- Global terrain and geographical information (including land use/cover and maps) databases
- Meteorological models for three-dimensional, regional-scale flows with terrain effects
- Computation of prompt effects. including conventional explosive blast effects and the prompt effects of nuclear detonation associated with direct blast injury, tumbling/impact, thermal injury, and prompt radiation (effects are quantified in terms of injury and fatality counts)
- Three-dimensional dispersion models with time-varying source properties and meteorological conditions from local-, regional-, and global-scale meteorological models, including spatially-varying, aerosol-size-dependent, and rain-rate-dependent precipitation scavenging
- Computational fluid dynamics models capable of simulating the details of building-scale flow and dispersion for detailed planning and consequence assessments
- Continuous stack emission (momentum- and/or buoyancy-driven) and fire (buoyancy-driven) plume rise source models
- Dispersion models that simulate the decay and in-growth of radionuclides in decay chains before release, during atmospheric transport, and after deposition.
- Dose factor databases for inhalation, ground exposure, and air immersion exposure modes (function of radionuclide, chemical form, and particle size).
- Affected population estimates using time-dependent population density databases
- Tool to reliably and accurately assemble final consequence reports that include contour maps, graphs, tables, and assumptions and background material relevant to calculations.
- Software tools for remote access (via secure network, internet, wireless or dial-up) to NARAC central system automated model predictions, with user interfaces for both specialists and non-specialists to control models and display geographical information

- Fast-running steady-state, local-scale, Gaussian-plume dispersion modeling tools for deployed use
- Web site for distribution of model products, consequence reports and background information to multiple, authorized agencies and users over network, wireless, or dial-up communications links
- Semi-automated software tools for entering field measurement data, graphically and statistically comparing measurements and model predictions, and refining model predictions to fit measured data
- 24 × 7 on-duty or on-call technical and scientific support staff.

NARAC's numerical models and software systems are continuously tested to evaluate their performance, and assure they are ready to respond. Testing using analytic mathematical solutions, field experiments and actual accidents has shown that the NARAC modeling system can simulate airborne dispersion over scales ranging from local to regional to continental scales. Integration of measurement data to update and refine model predictions is a key aspect of NARAC's capabilities.

Real-world incidents have proven the value of NARAC tools and services over a 26 year history. This history has shown that success in meeting operational challenges depends on (1) a multi-disciplinary staff to provide expertise in the broad range of disciplines needed for analyzing the consequences of airborne hazards (from sources to effects), (2) maintaining a real-time computer system with a comprehensive set of modeling tools and supporting meteorological, geographical and hazardous material databases, (3) continuous integration of the results of a research and development program that is driven by operational needs, (4) the integration of measurement data and model simulations, and (5) rigorous testing and evaluation of both modeling system components and the operations as a whole. Research and development is ongoing today, and includes work on sensor data assimilation into model predictions, urban effects on flow and transport, deposition and resuspension, high performance computing, model uncertainty estimation, source characteristics, indoor exposure prediction, and geographical information systems.

11 Acknowledgements

The models, software system and operational applications described in this paper have significantly benefited from the contributions of an outstanding multi-disciplinary team, including F. Aluzzi, E. Arnold, R. Belles, D. Bonner, E. Bush, L. Carroll, S. Chan, S. Chin, E. Davis, M. Dillon, B. Eme, D. Ermak, K. Fischer, C. Foster, K. Foster, J. Gash, C. Gellner, L. Glascoe, J. Greenfield, J. Guensche, T. Harvey, S. Homann, B. Kosovic, D. Larson, M. Leach, R. Lee, J. Leone, G. Loosmore, J. Lundquist, B. Pobanz, R. Shectman, J. Shinn, T. Sullivan, S. Taylor, W. Thomas, P. Vogt, H. Walker, J. Welch, and V. Weseloh. We thank our colleagues at Sandia National Laboratories—John Fulton, Fred Harper, Bill

Marshall, Art Shanks, and Will Wente—for their active collaboration to integrate prompt effects models, radiological dispersal device source terms and consequence reports into NARAC software. The authors would like to express their appreciation to John Wilson (U. Alberta) for generously providing his analysis of the Prairie Grass crosswind-integrated concentrations. We thank Steve Chan for providing the example CFD model results. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

12 References

Allwine, K., J. Shinn, G. Streit, K. Clawson, and M. Brown, 2002: Overview of Urban 2000, *Bulletin of the American Meteorological Society,* **83** (4), 521-536.

Barad, M.L., 1958: *Project Prairie Grass, A Field Program in Diffusion* (three volumes), Geophysical Research Papers No. 59, AFCRC-TR-58-235, Air Force Cambridge Research Center, U.S. Air Force, Bedford, MA.

Caltagirone, J., 1986: *Contents of Structures to Resist the Effects of Accidental Explosions* (TM 5-1300, NAVFAC P-397, AFM 22), Army Belvoir Research Development and Engineering Center, Fort Belvoir, VA.

Chan, S.T. and G. Sugiyama, 1997: A New Model for Generating Mass-Consistent Wind Fields over Continuous Terrain, Preprint, *ANS Sixth Topical Meeting on Emergency Preparedness and Response*, San Francisco, CA (April, 1997), 375-378.

Chan, S.T., 2004: Large Eddy Simulation of Turbulent Flow and Dispersion in Urban Areas and Forest Canopies, Preprint, *Workshop on Mesoscale and CFD Modeling for Military Applications*, Jackson State University, Jackson, MS, May 25-26, 2004.

Chan, S.T. and D. Stevens, 2000: An Evaluation of Two Advanced Turbulence Models for Simulating the Flow and Dispersion Around Buildings, *The Millennium NATO/CCMS Int. Tech. Meeting on Air Pollution Modeling and its Application*, Boulder, CO, May 2000, 355-362.

Chan, S.T., Humphreys, and R. Lee, 2004: A Simplified CFD Approach for Modeling Urban Dispersion, *American Meteorological Society Annual Meeting*, Seattle, WA, Jan. 11-15, 2004, American Meteorological Society, Boston, MA.

Chan, W., P. Price, A. Gadgil, W. Nazaroff, G. Loosmore, and G. Sugiyama, 2004: Evaluate Shelter-in-Place as Part of an Emergency Operation Plan, *AMS Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone*, AMS 84th Annual Meeting, 2004 January 11-14, American Meteorological Society, Boston, MA.

Chin, H.-N.S., M.J. Leach, G. Sugiyama, J.M. Leone Jr., H. Walker, J.S. Nasstrom, M. J. Brown, 2005: Evaluation of an Urban Canopy Parameterization in a Mesoscale Model Using VTMX and URBAN 2000 Data, *Monthly Weather Rev.*, **133**, 2043-2068.

DHS, 2004: *National Response Plan*, December 2004, Department of Homeland Security, Washington, DC.

Eckerman, K., 2001, Dose Coefficients for Acute Health Effects, Oak Ridge National Laboratory, Oak Ridge, TN.

Ellis, J.S., R. Lee, D. Sumikawa, and T.J. Sullivan, 1997: ARAC and its Modernization, *Radiation Protection Dosimetry*, **73**, 241-245.

EPA, 1988, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*. Federal Guidance Report No. 11, Document No. EPA 520/1-88-020, U.S. Environmental Protection Agency, 1988.

EPA, 1992: *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents*, Office of Radiation Programs, U.S. Environmental Protection Agency, Washington, DC 20460

EPA, 1993, *External Exposure to Radionuclides in Air, Water, and Soil. Federal Guidance* Report No. 12, Document No. EPA-402-R-93-081, U.S. Environmental Protection Agency, 1993.

EPA, 1999a: *CAMEO: Computer Aided Management of Emergency Operation User Manual*, Environmental Protection Agency, Chemical Emergency Preparedness Office, Washington, DC 20460.

EPA, 1999b: *ALOHA: Areal Locations of Hazardous Atmospheres User Manual*, Environmental Protection Agency, Chemical Emergency Preparedness Office, Washington, DC 20460.

EPA, 1999c, *Cancer Risk Coefficients for Environmental Exposure to Radionuclides*. Federal Guidance Report No. 13, Document No. EPA-402-R-99-001, U.S. Environmental Protection Agency, 1999

Ermak, D.L., and J.S. Nasstrom, 2000: A Lagrangian Stochastic Diffusion Method for Inhomogeneous Turbulence, *Atmos. Environ.,* **34**, 7, 1059-1068.

Foster, K.T., G. Sugiyama, J.S. Nasstrom, J.M. Leone, Jr., S.T. Chan, and B.M. Bowen, 2000: The use of an operational model evaluation system for model intercomparison, *Int. J. Environment and Pollution*, **14**, 77-88.

Glasstone, S. J., and P. J. Dolan, 1977: *The Effects of Nuclear Weapons*, U. S. Department of Defense and U. S. Department of Energy, (3rd edition).

Griffiths, I.H., D.R. Brook, D.J. Hall, A. Berry, R.D. Kingdon, K. Clawson, C. Biltoft, J.M. Hargrave, D. C. Strickland, and A. M. Spanton, 2002: Urban Dispersion Model (UDM) Validation, *AMS 4th Symposium on the Urban Environment*, Norfolk VA, 20-24 May 2002, American Meteorol. Soc., Boston MA.

Harper, F.T., S. Musolino and W.B. Wente, 2006: Realistic Radiological Dispersal Device Hazard Boundaries and Ramifications for Early Consequence Management Decisions, *Int. J. of Risk Assessment and Management*, this issue.

Harvey, T.F., and F.J.D. Serduke, 1979: *Fallout Model for System Studies*, Report UCRL-52858, Lawrence Livermore National Laboratory, Livermore, CA.

Hinds, W.C., 1982: Aerosol Technology, John Wiley and Sons, New York, 424 pp.

Hodur, R. M. 1997: The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), *Mon. Wea. Rev.*, **125**, 1414-1430.

Homann, S.G.,1994: *HOTSPOT Health Physics Codes for the PC*. Report UCRL-MA-106315, Lawrence Livermore National Laboratory, Livermore, CA.

Kosovic, B., G. Sugiyama, S. Chan, F. Chow, K. Dyer, R. Glaser, W. Hanley, G. Johannesson, S. Larsen, G. Loosmore, J. Lundquist, A. Mirin, J. Nitao, R. Serban, and C. Tong, 2005: Stochastic Source Inversion Methodology and Optimal Sensor Network Design, 9th Annual George Mason University Conference on Atmospheric Transport and Dispersion Modeling, July 2005.

Larson, D.J., and J.S. Nasstrom, 2002: Shared and Distributed Memory Parallelization of a Lagrangian Atmospheric Dispersion Model, *Atmos. Environ*., **36**, 1559-1564

Leone, Jr., J.M, J.S Nasstrom, and D. Maddix, 1997: A First Look at the New ARAC Dispersion Model, Preprint, *American Nuclear Society's Sixth Topical Meeting on Emergency Preparedness and Response*, San Francisco, CA, April 1997, American Nuclear Society, Inc., La Grange Park, IL.

Leone Jr., J.M., J.S. Nasstrom, D.M. Maddix, D.J. Larson, G. Sugiyama and D.L. Ermak, 2005: *Lagrangian Operational Dispersion Integrator (LODI) User's Guide*, Report UCRL-AM-212798, Lawrence Livermore National Laboratory, Livermore, CA

Loosmore, G., 2002: Resuspension Modeling for Real-Time Emergency Response, 12th *Joint Conference on the Applications of Air Pollution Meteorology*, Norfolk VA, Amer. Meteorol. Soc., Boston, MA.

Loosmore, G.A. and R.T. Cederwall, 2004: Precipitation scavenging of atmospheric aerosols for emergency response applications: testing an updated model with new real-time data, *Atmos. Environ*., **38**, 993–1003

McPherson, T.N. and Brown M.J. 2003: *U.S. Day and Night Population Database (Revision 2.0) - Description of Methodology*, Report LA-UR-03-8389, Los Alamos National Laboratory, Los Alamos, NM.

Mirin, A., G. Sugiyama, S. Chen, R. M. Hodur, T. Holt, J. Schmidt, 2001: Development and Performance of a Scalable Version of a Nonhydrostatic Atmospheric Model, *DOD HPC Modernization Program User's Group Conference*, Biloxi, MI

Nasstrom, J.S. and J.C. Pace, 1998: Evaluation of the Effect of Meteorological Data Resolution on Lagrangian Particle Dispersion Simulations using ETEX Experiment, *Atmospheric Environment,* **32**, 4187-4194.

Nasstrom, J.S., G. Sugiyama, J.M. Leone, Jr., and D.L. Ermak, 2000: A real-time atmospheric dispersion modeling system, *Eleventh Joint Conference on the*

Applications of Air Pollution Meteorology, Long Beach, CA, Jan. 9-14, 2000. American Meteorological Society, Boston, MA, 84-89

NCRP, 1993, *Limitation of Exposure to Ionizing Radiation*, Report No, 116, National Council on Radiation Protection, March 31, 1993

NCRP, 2001: *Management of Terrorist Events Involving Radioactive Material*, NCRP Report No. 138, National Council on Radiation Protection and Measurement, 7910 Woodmont Ave., Bethesda, Maryland, 20814-3095.

Sehmel, G.A., and W.H. Hodgson, 1978: *A Model for Predicting Dry Deposition of Particles and Gases to Environmental Surfaces*, Report PNL-SA-6721, Battele Pacific Northwest Laboratories, Richland, WA.

Sjoreen, A. L.. J. V. Ramsdell, Jr., T. J. McKenna, S. A. McGuire, C. Fosmire, and G. F. Athey, 2001: *RASCAL 3.0: Description of Model and Methods*, NUREG-1741, US NRC.

Sugiyama, G. and S. T. Chan, 1998: A New Meteorological Data Assimilation Model for Real-Time Emergency Response, Preprint, *10th Joint Conference on the Applications of Air Pollution Meteorology*, Phoenix, AZ (11-16 January, 1998), Am. Met. Soc., Boston, MA. 285-289

Sullivan, T.J., J.S. Ellis, C.S. Foster, K.T. Foster, R.L. Baskett, J.S. Nasstrom, and W.W. Schalk III, 1993: Atmospheric Release Advisory Capability: Real-time Modeling of Airborne Hazardous Material, *Bulletin of the Amer. Meteorol. Soc.*, **74**, 2343-2361.

Thuillier, R.H., 1988: Tracer Experiments and Model Evaluation at Diablo Canyon Nuclear Power Plant, *Proc. of the ANS Topical Meeting on Emergency Response—Planning, Technologies and Implementation*, CONF-880913, Amer. Nuc. Soc., LaGrange, IL.

van Ulden, A.P. and A.A.M. Holtslag, 1985: Estimation of atmospheric boundary layer parameters for diffusion applications, *J. Climate Appl. Meteor.*, **24**, 1196-1207.

Vogt, P.J., B. M. Pobanz, F. J. Aluzzi, R. L. Baskett, T. J. Sullivan, 1999: ARAC Modeling of the Algeciras, Spain Steel Mill Cs-137 Release, *Proceedings American Nuclear Society 7th Topical Meeting on Emergency Preparedness and Response*, Santa Fe, NM, September 14-17, 1999, American Nuclear Society, Inc., La Grange Park, IL. Also: Report UCRL-JC-131330, Lawrence Livermore National Laboratory, Livermore, CA.

Weil, J.C., 1988: Plume Rise. In *Lectures on Air Pollution Meteorology*, A. Venkatram and J.C. Wyngaard (eds.). Am. Meteorol. Soc., Boston, 390 pp.

Wesely, M.L. and B.B. Hicks, 1977: Some factors that affect the deposition rates of sulfur dioxide and similar gases to vegetation, *J. Air Poll. Control Assoc.*, **27**, 1110-1116.

Wilber, D., D. Daigler, E.C. Nielsen, S.R. Riedhauser, A. Shanks, R.C. Thompson, and J.S. Nasstrom., 2006: Nuclear/Radiological Emergency Response in the United States, *Int. J. of Risk Assessment and Management*, this issue.

Wilson, J.D., G.W. Thurtell, and G.E. Kidd, 1981: Numerical simulation of particle trajectories in inhomogeneous turbulence, III: Comparison of predictions with experimental data for the atmospheric surface layer, *Bound.-Layer Meteorol.*, **21**, 443-463

University of California
Lawrence Livermore National Laboratory
Technical Information Department
Livermore, CA 94551