92-86.10

# Overview of The Variable-Grid Urban Airshed Model (UAM-V)

**Ralph E. Morris**
**Mark A. Yocke**
**Thomas C. Myers**
Systems Applications International
San Rafael, California

**Vince Mirabella**
Southern California Edison
Rosemead, California

Air & Waste Management Association
Since 1907

For Presentation at the
85th Annual Meeting & Exhibition
Kansas City, Missouri
June 21-26, 1992

## INTRODUCTION

The Urban Airshed Model (UAM), developed and maintained by Systems Applications International (SAI), is the most widely used photochemical air quality model in the world today. Its roots extend back to SAI's pioneering efforts in photochemical air quality modeling in the early 1970s. In the intervening years the model has undergone a nearly continuous process of application, comprehensive performance evaluation, update, extension, and improvement. Other photochemical models have been developed during this long period of UAM usage, but no contemporary model has proven to be more reliable or technically superior.

UAM has been applied to and evaluated in over 34 cities—26 in the United States and eight abroad, including Athens, Turin, Taipei, Kaohsiung, Tokyo, Mexico City, and Melbourne. It has been successfully applied and evaluated in areas with meteorological conditions that range from simple to complex, coastal and inland locations, mild to severe ozone problems, emissions configurations ranging from low to high spatial variability, and measured data that range from sparse to rich. According to a 1991 National Academy of Sciences report, no other model has enjoyed such wide usage and complete documentation.[1] Indeed, UAM is the only photochemical grid model recommended by the U.S. EPA for urban and regional ozone modeling.[2]

The most current operational version of the model, UAM-V, contains more technical features and capabilities than even other research-grade models. For example, UAM-V has two-way grid nesting allowing regional precursor transport and several imbedded urban areas to be treated in a single modeling domain. In addition, UAM-V allows variation in the number and spacing of vertical layers, specification of three-dimensional meteorological variables, and explicit treatment of subgrid-scale photochemical plumes (i.e., plume-in-grid). The UAM-V software has been completely rewritten to be modular in form, and includes updated deposition, plume rise, solar flux, and chemical kinetics modules. UAM-V has been chosen for use by federal, state, and local government agencies for regional and urban-scale air quality planning in Michigan, Illinois, Indiana, Wisconsin, Texas, Louisiana, and California. Technically advanced and compatible input processing packages are also operational and available for UAM-V, including a prognostic meteorological model with four-dimensional data assimilation and a complete gridded emission inventory preparation system.

## CONCEPTUAL OVERVIEW OF THE MODEL

UAM-V is a three-dimensional photochemical grid model designed to calculate the concentrations of both inert and chemically reactive pollutants by simulating the physical and chemical processes in the atmosphere that affect pollutant concentrations. The basis for the UAM-V is the atmospheric diffusion or species continuity equation. This equation represents a mass balance in which all of the relevant emissions, transport, diffusion, chemical reactions, and removal processes are expressed in mathematical terms. The model is usually applied to a 48- to 120-hour period during which adverse meteorological conditions result in elevated pollutant concentrations of the chemical species of interest.

The major factors that affect photochemical air quality include the spatial and temporal distribution of emissions of $NO_x$ and volatile organic compound (VOC) (both anthropogenic and biogenic); the composition of the emitted VOC and $NO_x$; the spatial and temporal variations in the wind fields; the dynamics of the boundary layer, including stability and the level of mixing; the chemical reactions involving VOC, $NO_x$, and other important species; the diurnal variations of solar insolation and temperature; the loss of ozone and ozone precursors by dry and wet deposition; and the ambient background of VOC, $NO_x$, and other species in, immediately upwind, and above the region





of study. The UAM-V simulates these processes when it is used to calculate ozone concentrations. It can also be used to simulate carbon monoxide concentrations in an urban area, a simulation that involves no chemical reactions.

Because the UAM-V accounts for spatial and temporal variations as well as differences in the reactivity (hydrocarbon speciation) of emissions, it is ideally suited for evaluating the effects of different emission control scenarios on urban air quality. This is accomplished by first replicating an historical ozone episode to establish a base case simulation. Model inputs are prepared from observed meteorological, emission, and air quality data for a particular day or days using prognostic meteorological modeling and/or diagnostic and interpolative modeling techniques. The model is then applied with these inputs and the results are evaluated to determine its performance. Once the model results have been evaluated and it has been determined that the model performs within prescribed levels, the same meteorological inputs and a projected emission inventory can be used to simulate possible future emission scenarios. That is, the model will calculate hourly ozone patterns likely to occur under the same meteorological conditions as the base case.

## HISTORY OF THE DEVELOPMENT OF THE MODEL

The UAM has been under continual development for over 20 years, involving more than 100 person-years of technical effort. It has been supported by many organizations; public and private organizations have contributed to the substantial effort of demonstrating the utility of the UAM to investigate complex ozone air quality management issues.

The history and development of mathematical photochemical models, particularly the UAM, has kept paced with advances along three fronts:

> The scientific front, which is governed by the scientific community's acceptance of a suitable formulation, of supporting algorithms that represent pertinent physical and chemical processes, and of measurement methods and data bases that support parameter estimation and model performance evaluations;
>
> The regulatory front, which is governed by the relevance and practicality of the UAM to evolving regulatory programs and by acceptance of decision makers; and
>
> The computing technology front, which is governed by the availability (to air quality modelers) of computing systems capable of large-scale numerical modeling, and facilitated by the transportability of the UAM to those systems, and the UAM's "user friendliness."

Since 1969, when the UAM was first conceived, substantial changes across all three fronts have occurred. Some of these changes were anticipated, some were completely outside the control of the developers even when they were anticipated, and some were not anticipated.

In the 1950s and 1960s many urban areas of the country became aware of periods of elevated photochemical oxidants consisting mainly of ozone (also called "smog"), although the problem of urban ozone was first recognized in the Los Angeles area in the 1940s. The 1963 Clean Air Act provided limited federal power to abate air pollution endangering health and welfare. It also instructed the Department of Health, Education, and Welfare to develop criteria on the effects of air pollution and its control. The 1967 Air Quality Act required states to establish air quality standards consistent with federal criteria, and established the National Air Pollution Control Administration

(NAPC), EPA's predecessor. In 1969 the NAPC contracted with SAI for the development of a model to simulate ozone formation, eventually to be called the Urban Airshed Model (UAM).

The initial model development and evaluation phase, from 1969 through 1973, culminated with the judgement by the EPA and its peer reviewers that the UAM approach was feasible and practical. This led to further development and evaluation.

The period from 1973 through 1977, also heavily supported by the EPA, emphasized algorithm development and evaluation. During this period the Carbon Bond Mechanism (CBM-1)--a method for condensing and simplifying complex explicit mechanisms describing photochemical oxidant formation--was developed and tested; methods for treating the effects of temperature and UV scattering by airborne particles on reaction rate constants were identified, evaluated, and selected; a computationally efficient approach for treating nighttime ozone chemistry was selected; alternative, improved methods of numerical integration were examined, and the SHASTA (Sharp and Smooth Transport Algorithm)[3] procedure selected; improved representations of vertical diffusivity, plume rise, and surface removal were evaluated and incorporated in the UAM; a module was developed for treating the influence of subgrid-scale $NO_x$ emissions from point and line sources on the grid-average ozone concentrations output by the model; and the computer code was modified to enable the input of a fully three-dimensional wind field.

The period 1977 to 1978 was devoted to improving the software and documentation and to systematic evaluation of UAM performance using measurements obtained in the St. Louis area as part of the EPA's Regional Air Pollution Study (RAPS). In designing the software, consideration was given to those computer systems to which the air pollution modeling community would likely have access in the 1979 to 1982 period. To overcome the memory restrictions, special features such as "overlay" and "grid segmentation" were adopted. The UAM was judged by the EPA's Office of Research and Development and Office of Air Quality Planning and Standards to perform successfully for the 20-plus days chosen for examination from the St. Louis data base. After further tests by EPA's staff, this version of the code was made available to the public in 1980.

Since 1980 work has continued on improving chemical mechanisms for daylight and nighttime conditions and for gaseous and liquid media, removal processes, numerical methods for integrating parabolic equations, methods for improving gas-to-particle conversion and particle dynamics, and improved methods for prescribing UAM inputs and for evaluating UAM performance.

In 1984 the EPA's Office of Air Quality Planning and Standard proposed that the UAM be a "recommended" (preferred) model for "photochemical pollutant modeling applications involving entire urban areas." In finalizing its recommendation in 1986 the EPA noted that the UAM "is the most widely applied and evaluated photochemical dispersion model in existence."[2]

The 1980 public version of the model contained version II of the Carbon-Bond Mechanism, the chemical kinetics model that calculates the chemical transformations of emissions to pollutant species. On the basis of experience with many different applications of the UAM and recent technical advances, this version of the model was updated in 1988. The two main improvements were the incorporation of version IV of the Carbon Bond Mechanism (CB-IV)[4] and the use of the Smolarkiewicz numerical integration scheme to solve the advection equation.[5] This improved version of the UAM (with CB-IV) was released to the public in June 1990.[6]





Although the CB-IV version of the UAM has been the most widely used and evaluated air quality simulation model in the world, until recently the structure of the model's computer code was based on 1970-1980 computing architecture and was not able to take advantage of the speed enhancements available in the current and future generation of computer systems. Thus, in 1989-1991 SAI embarked on a massive effort to rewrite the computer code for the UAM. The UAM was refined and enhanced through the update of the computer code and inclusion of the new capabilities, algorithms, modules, and features. The result was the UAM-V. This newest version has the following additional features over the previous version: (1) structured modular computer code; (2) more flexible vertical grid structure; (3) three-dimensional temperature, water vapor, horizontal and vertical diffusivities, and pressure inputs; (4) variable-grid resolution for chemical kinetic calculations; (5) two-way nested grid; (6) update of the CB-IV chemical mechanism; (7) new dry deposition algorithm; (8) advanced prognostic meteorological model for inputs; (9) true mass balance; and (10) plume-in-grid subgrid-scale treatment.

## TECHNICAL FORMULATION

The UAM is a three-dimensional grid (Eulerian) model designed to calculate the concentrations of both inert and chemically reactive pollutants by simulating the physical and chemical processes in the atmosphere that affect pollutant concentrations. The basis for the UAM is the atmospheric diffusion equation (also called the species continuity or advection/diffusion equation). This equation represents a mass balance in which all of the relevant emissions, transport, diffusion, chemical reactions, and removal processes are expressed in mathematical terms as follows:

$$\underbrace{\frac{\partial c_i}{\partial t}}_{\text{Time Dependence}} + \underbrace{\frac{\partial (u c_i)}{\partial x} + \frac{\partial (v c_i)}{\partial y} + \frac{\partial (w c_i)}{\partial z}}_{\text{Advection}} = \underbrace{\frac{\partial}{\partial x}\left(K_X \frac{\partial c_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_Y \frac{\partial c_i}{\partial y}\right) + \left(K_V \frac{\partial c_i}{\partial z}\right)}_{\text{TurbulentDiffusion}}$$

$$+ \underbrace{R_i}_{\text{Chemical Reaction}} + \underbrace{S_i}_{\text{Emissions}} + \underbrace{D_i}_{\text{Dry Deposition}} + \underbrace{W_i}_{\text{Wet Deposition}}$$

where

$c_i$ = the concentration of pollutant i, a function of space $(x,y,z)$ and time $(t)$

$u,v,w$ = horizontal and vertical wind speed components

$K_X$, $K_Y$ = horizontal turbulent diffusion coefficients

$K_V$ = vertical turbulent exchange coefficients

$R_i$ = net rate of production of pollutant $i$ by chemical reactions

$S_i$ = emission rate of pollutant $i$

$D_i$ = net rate of change of pollutant $i$ due to surface uptake processes

$W_i$ = net rate of change of pollutant $i$ due to wet deposition processes

The species continuity equation is solved using the method of fractional steps in which the atmospheric diffusion equation is solved separately in the following order: emissions are injected; horizontal advection/diffusion is solved; vertical advection/diffusion and deposition is solved; and chemical transformations are performed for reactive pollutants. The UAM-V performs this four-step solution procedure during each time step. The maximum time step is a function of the grid size and the maximum wind velocity and diffusion coefficient. Typical time steps for coarse grid spacing (10-20 km) is 10-15 minutes, whereas those for fine grid spacing (1-2 km) are on the order of minutes.

## OVERVIEW OF MODEL CONCEPTS

The UAM-V employs finite differencing numerical techniques to solve the advection/diffusion equation. The region to be simulated is divided into several three-dimensional grids covering the region of interest. The grid system for the UAM-V is defined with a base coarse grid covering the entire domain, within which finer grids are defined for subregions in which more refined analysis is deemed necessary. Fine grids can be "nested" in the horizontal and vertical, and many levels of nesting can be defined if desired. For example, in the Lake Michigan Ozone Study the UAM-V is configured with a coarse 16 km grid to cover a large region of interest; within this region is an 8 km grid for the mesoscale Lake Michigan region, and within this subregion a 4 km grid is embedded for fine-scale simulation of the complex lake-breeze circulations on the western shore of Lake Michigan (Figure 1).

The vertical layer structure of the UAM-V can be defined without constraints imposed by model formulation. When a prognostic meteorological model is used to define the UAM-V meteorological inputs, the vertical layers of the UAM-V are defined to match the vertical layer structure of the meteorological model. Note that this makes the UAM-V much more flexible than its predecessor, in which the vertical layers were defined with respect to the diffusion break (mixing height) established by the user. The UAM-V grid nesting in the vertical allows for the use of high resolution in regions where it is needed. For example, in Figure 1 five vertical layers could be specified to resolve synoptic transport and any other important features (e.g., a nocturnal jet) in the outer region (the coarse, 16 km grid), whereas 8-12 vertical layers could be defined in the innermost (fine) grid, where high vertical resolution is needed to resolve the lake-breeze convergence zone.

### Treatment of Atmospheric Chemistry

The UAM-V employs version IV of the Carbon Bond Mechanism (CB-IV), with some extensions, for solving chemical kinetics.[4,6] As implemented in the UAM-V, the CB-IV contains over 80 reactions and over 30 species. Two significant updates to the CB-IV mechanism in the UAM-V have been made at the suggestion of Dodge[7] and others: an update to the PAN temperature effects and inclusion of a radical-radical reaction that acts as a radical sink under low $NO_x$ concentration conditions.

The differential equations that describe the CB-IV are a "stiff" system, that is, the equations contain wide variations in time (reaction rate) constants. Solving these equations with a "stiff" numerical integration scheme, such as the one developed by Gear,[8] would result in prohibitively expensive computer time. Thus the solution of the CB-IV in the UAM uses quasi-steady-state assumptions for the low-mass fast-reacting species (i.e., the "stiff" species) and the more computationally efficient Crank-Nicholson algorithm for the remainder of the state species.

Photochemical models require information on solar radiation in order to calculate photolysis rates for the photochemical reactions which drive the formation of ozone. The CB-IV chemical mechanism





implemented in the UAM-V requires photochemical reaction rates, or $J$ values, for five processes: $J_{NO2}$, $J_{HCHOr}$, $J_{HCHOs}$, $J_{O1D}$ and $J_{ALD2r}$. Photolysis rates for several other photochemical reactions are derived from these $J$ values by using scaling factors.[4]

In the UAM-V, $J$ values are calculated on a cell-by-cell basis using a photolysis rate preprocessor[9,10] that is part of the UAM-V modeling system. The preprocessor generates a look-up table of photolysis rates for the five $J$ values for varying solar zenith angles and altitudes as a function of solar flux, albedo, turbidity, and ozone column density using wavelength-resolved absorption cross-section and quantum yield data for each photolysis reaction. Given a grid cell location (latitude/longitude), the time and date, the average height of the grid cell above mean sea level, the total ozone column, the albedo, and the turbidity (haziness), the UAM-V interpolates the photolysis rates from the look-up table. The interpolated photolysis rates are reduced by UAM-V if cloud data indicate an attenuation of solar radiation.

Inputs for the UAM-V photolysis rate preprocessor are: (1) the extraterrestrial solar flux—a parameterization of the brightness of the sun at the top of the atmosphere[42]; (2) gridded surface UV-albedo over the modeling domain—the fraction of ultraviolet light reflected from the earth's surface, which is land-use dependent and typically 0.05 over land for wavelengths from 290 to 400 nm[11]; (3) gridded turbidity over the modeling domain—the optical scattering due to both aerosols and gas molecules. Aerosol loadings representative of suburban air are currently utilized; (4) gridded total $O_3$ column density over the modeling domain—in Dobson units; (5) the wavelength resolved absorption cross-section, $\sigma(\lambda)$, for each species undergoing photolysis (current data: $NO_2$,[12] HCHO,[43] $O_3$,[14] ALD2[15]); and (6) the wavelength-resolved quantum yield, $\phi(\lambda)$, for each photolysis process (current data: $NO_2$,[16] HCHOr,[17] HCHOs,[17] $O_3$[13], and ALD2r[15]).

The first three inputs listed above are combined to calculate the wavelength resolved actinic flux, $I(\lambda)$, as a function of the solar zenith angle and altitude.[8,9] The photolysis rates are then obtained by performing an integration over the triple product $I \cdot \sigma \cdot \phi$ at 1 nm wavelength intervals:

$$J_n = \int_{\lambda_{min}}^{\lambda_{max}} I_n(\lambda) \cdot \sigma_n(\lambda) \cdot \phi_n(\lambda)\ d\lambda$$

The result is a look-up table of photolysis rates for the five $J$ values, 10 solar zenith angles, 11 heights above sea level, 5 albedos, 3 turbidities, and 5 ozone column densities. The photolysis rates are interpolated from the look-up table using the gridded ozone column, albedo, and turbidity input and are reduced when clouds are present.

### Treatment of Advective Pollutant Transport

Pollutants are transported primarily by advection, that is by the mean or bulk motion of the air. Advection in the UAM is treated by specifying horizontal wind fields (i.e., $u$ and $v$ wind components in each grid cell) for each vertical layer and each nested-grid. The vertical wind velocity in the UAM-V terrain-following coordinate system is then calculated from the conservation of mass equation. Proper specification of the hourly and three-dimensional varying winds is one of the key steps to successful application of the UAM-V. The winds influence how different emissions are mixed together, advected downwind, and diluted. To date, wind fields for most UAM-V applications have been calculated by a prognostic meteorological model,[18,19,20] although objective analysis of upper-air and surface meteorological observations has also been used to generate wind fields.[21]

Previous versions of the UAM used the Sharp and Smooth Transport Algorithm (SHASTA)[3] to solve the advection/diffusion equation. When the SHASTA method was originally implemented in the UAM it was found to be the best compromise between accuracy and computational efficiency compared to other numerical schemes. Prior to its public release, it was more accurate than other methods available.[22] Since then, however, studies of several other advection schemes have indicated that SHASTA may compute excessive numerical diffusion.[5,23,24,25] Thus an improved numerical advection scheme[5] has been implemented in the UAM-V. Current research is underway to implement additional advection algorithms as options in the UAM-V. In some idealized tests several other algorithms have exhibited less numerical diffusion than the Smolarkiewicz algorithm; however, the computation time is greater.[26] It remains to be seen whether under typical real-world flow conditions these other algorithms produce any noticeable differences from the Smolarkiewicz algorithm and thus whether the increased computational burden is warranted. An alternative advection algorithm is currently being implemented in the UAM-V as an option so that users can select the advection algorithm that best meets the needs of their application.

**Treatment of Grid Nesting**

The UAM-V contains provisions for two-way interactive nesting of fine grids within coarser mesh grids in both the horizontal and the vertical. The fine grids must be nested completely within the coarse grid; the edges of the fine grid must correspond to a coarse grid cell boundary and, currently, the fine grids must be rectangular in shape (or trapezoidal if a latitude/longitude coordinate system is being used). The horizontal spacing of a fine grid may be any integral subdivision of the coarse grid within which it is embedded, but fine grids cannot overlap each other.

Data for the fine grids may either be input separately or the UAM-V will interpolate the data from the coarse grid to the fine grid. For example, the user may specify a finer resolution of winds and emissions for a fine grid but let the UAM-V interpolate the temperature, water vapor concentrations, and other meteorological inputs from the coarse grid data.

The species continuity equation using nested grids in the UAM-V is solved as follows. Transport/diffusion/deposition is solved on the coarse grid for one coarse-grid time step. As necessary, the coarse-grid data are interpolated to the fine grid(s). A time step is defined for the fine grid(s) that is an integral multiple of the coarse-grid time step, and transport/diffusion/deposition and chemistry are performed for the fine grid. These two steps are repeated until a time period equal to the coarse-grid time step is completed. Finally, chemistry is performed in those coarse grid cells not covered by a fine grid. The UAM-V nested-grid approach was tested to assure accuracy and mass consistency.[18,19,20]

**Treatment of Turbulent Diffusion**

Dispersion of pollutants in the UAM-V is assumed to be proportional to the rate of change of concentration in space (i.e., the concentration gradient or K theory first-order closure approach). The proportionality factor is termed the eddy diffusivity coefficient ($K_x$, $K_y$, and $K_z$ in the advection/diffusion equation). In most applications of UAM-V, the horizontal eddy diffusivities and vertical turbulent exchange coefficients are obtained from the output of prognostic meteorological models. When such data are not available, algorithms using control theory techniques are employed in conjunction with the results of a planetary boundary layer model to generate optimal diffusivity coefficients.[27,28,29,30]





**Treatment of Surface Removal Processes**

The dry deposition algorithm in the UAM-V is based on the scheme in the RADM model described by Wesley.[31] The approach in UAM-V is described in detail elsewhere.[32] The UAM-V dry deposition algorithm was subjected to independent peer review, and several minor updates were suggested and made.[33]

**Aqueous-Phase Chemistry and Wet Deposition**

As an option, the UAM-V also contains aqueous-phase chemistry and wet deposition algorithms that are consistent with the formulation of the CB-IV gas-phase chemical mechanism. Aqueous-phase chemistry usually does not influence ozone formation during ozone episodes, and the solution of aqueous-phase chemistry is time consuming; thus, for most ozone applications the UAM-V aqueous-phase chemistry and wet deposition options are not used. The UAM-V aqueous-phase chemistry and wet deposition algorithms are based on the work of Gery and co-workers[33] and have been updated to include metal chemistry and ionic strength correction effects as well as the latest information on aqueous chemical kinetic rates and Henry's law coefficients.[35,36,37]

**Plume Rise Algorithm**

The UAM-V incorporates the TUPOS approach to calculating plume rise.[38] TUPOS initially calculates stability-dependent plume rise based on either buoyancy or momentum flux for the layer containing the stack, whichever is larger. If the plume rise is sufficient to take it into the next UAM-V vertical layer, then local stability is recalculated along with a residual buoyancy flux into that layer (momentum flux applies in the stack layer only) and plume rise is again calculated using the appropriate stability-dependent equations with the local stability. If wind speeds are higher than two-thirds of the stack exit velocity, the final plume rise is modified by Froude-number-dependent stack tip downwash.

**Subgrid-Scale Treatment of Point Source Plumes**

Most photochemical grid models inject emissions from point sources in a grid cell at a height defined by a plume rise algorithm. Thus, emissions from a point source, which are initially very compact in a plume, are instantaneously spread out across a grid cell. One measure of the ozone formation potential of an air parcel is the VOC-to-$NO_x$ ratio. At a low VOC-to-$NO_x$ ratio ozone formation is inhibited by the high $NO_x$ concentrations, whereas at high ratios the ozone formation is limited by the amount of $NO_x$ present. When a photochemical grid model instantaneously disperses point source $NO_x$ emissions across a grid cell, which usually contains significant quantities of VOCs, then a more optimal VOC-to-$NO_x$ ratio for ozone formation is obtained. However, in reality, the point source $NO_x$ emissions are contained within a compact plume where ozone is depleted, not formed. Thus, to better treat such emissions from major point sources, the UAM-V contains a subgrid-scale Lagrangian module that treats point source emissions using a Reactive Plume Model (RPM) until the plume size is commensurate with the size of the grid cell, at which point the mass in the plume is added to the grid cell in which the plume is located and further calculations are performed by the grid model.

Based on a detailed analysis of different approaches,[39] we chose the Reactive Plume Model (RPM)[40] for implementation of plume-in-grid modeling in the UAM-V. The RPM was selected because it is able to treat near-source chemistry and plume entrainment/detainment processes. It has also been successfully used in the past to treat plume-in-grid in the PARIS model.[41] Uncertainty over whether other approaches could be implemented successfully was one of the biggest factors in the selection of the RPM. However, the treatment of plume advection and plume-grid mass transfer in

PARIS[41] needed significant improvement. The UAM-V plume-in-grid treatment includes: (1) Use of the elliptical form of the RPM, in which the reactive plume is represented by a series of four to six concentric ellipses as "reactor cells". (The RPM usually represents a plume by several rectangular grid cells of equal height but differing widths arranged side by side.) Concentrations from the grid model are entrained into the outer ellipse and allowed to diffuse into the inner concentric ellipses based on the plume expansion rate and gradient transfer theory. (2) When the plume size (area of the ellipse) is commensurate with the size of a grid cell (area of a cell face, i.e., horizontal times vertical grid spacings), the pollutant mass in the outer ellipse is added to concentrations in the grid model. This process is repeated until the puff is eliminated. (3) Other factors can also affect the RPM pollutant mass release time, including the relationship between the plume location and the coarse/fine grid structure. If the plume size is not commensurate with the coarse grid size but the plume is about to enter a fine grid in which the plume size is commensurate with the fine grid size, the pollutant mass will be released to the grid model. The use of the elliptical form of RPM for treatment of point source emissions in a grid model is illustrated in Figure 2.

## CURRENT STATUS

The UAM-V is currently being used in the Lake Michigan Ozone Study (LMOS), the Gulf of Mexico Air Quality Study (GMAQS), and southern California. The LMOS application will become part of the State Implementation Plans (SIPs) for the states of Illinois, Indiana, Michigan, and Wisconsin. The GMAQS application is being performed for the Minerals Management Service (MMS), with heavy involvement from the states of Louisiana and Texas. The LMOS will also produce documentation in early 1993 for the UAM-V and the model will be used by the four states in the region to evaluate alternative emission control strategies.

## REFERENCES


1. Rethinking the Ozone Problem in Urban and Regional Air Pollution, National Research Council, National Academy Press, 1991.

2. Guidelines on Air Quality Model (Revised), EPA-450/2-78-027R, U.S. Environmental Protection Agency, 1986.

3. J. P. Boris and D. L. Book, Flux-corrected transport: I. SHASTA, a fluid transport algorithm that works. J. Comp. Phys., 11:38-69 (1973).

4. M. W. Gery, G. Z. Whitten, and J. P. Killus, "Development and Testing of the CBM-IV for Urban and regional Modeling." EPA-???/, U.S. Environmental Protection Agency, 1988.

5. P. K. Smolarkiewicz, A simple positive definite advection scheme with small implicit diffusion. Monthly Weather Review, 111:479-486 (1983).

6. R. E. Morris and T. C. Myers, User's Guide for the Urban Airshed Model -- Volume I: User's Manual for UAM(CB-IV), EPA-450/4-90-007a, U.S. Environmental Protection Agency, 1990.

7. M. C. Dodge, A comparison of three photochemical oxidant mechanisms. J. Geophys. Res., 94:(D4):5121-5136 (1989).







8. C. W. Gear, Numerical Initial Value Problems in Ordinary Differential Equations. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1971.

9. P. F. Schippnick and A. E. S. Green, Analytical characterization of spectral actinic flux and spectral irradiance in the middle ultraviolet. Photochem. Photobiol., 35:89-101 (1982).

10. A.E.S. Green., K. R. Cross, and L. A. Smith, Improved analytic characterization of ultraviolet skylight. Photochem. Photobiol., 31:59-65 (1980).

11. K. L. Demerjian, K. L. Schere, and J. T. Peterson, Theoretical estimates of actinic (spherically integrated) flux and photolytic rate constants of atmospheric species in the lower atmosphere. Adv. Environ. Sci. Technol., 10:369-460 (1980).

12. W. B. DeMore, M. J. Molina, and R. T. Watson, et al., Chemical Kinetics and Photochemical Data for Use in Stratospheric Modeling, (83-62) Evaluation Number 6, Jet Propulsion Laboratory, Pasadena, California (1983).

13. W. B. DeMore, S. P. Sander, and D. M. Golden, et al., Chemical Kinetics and Photochemical Data for Use in Stratospheric Modeling, (90-1) Evaluation Number 9, Jet Propulsion Laboratory, Pasadena, California (1990).

14. L. T. Molina and M. J. Molina, Absolute absorption cross-sections of ozone in the 185 to 300 nm wavelength range. J. Geophys. Res., 91:14,501-14,508 (1986).

15. D. L. Baulch, R. A. Cox, and R. F. Hampson, et al., Evaluated kinetic and photochemical data for atmospheric chemistry, J. Phys. Chem. Ref. Data, 13:1259 (1984).

16. E. P. Gardner, P. D. Sperry, and J. G. Calvert, Primary quantum yields of $NO_2$ photodissociation, J. Geophys. Res., 92:6642-6652 (1987).

17. J. G. Calvert, "The Homogeneous Chemistry of Formaldehyde Generation," in Proceedings of the NATO Advanced Study Institute on Atmospheric Ozone, U.S. Department of Transportation, Washington DC, 1980.

18. R. E. Morris, T. C. Myers, and S. G. Douglas, et al., "Development of a Nested-Grid Urban Airshed Model and Application to Southern California," 84th annual Air and Waste Management Association meeting, Vancouver, 1991.

19. R. E. Morris, M. A. Yocke, T. C. Myers, et al., "Development and Testing of a Nested-Grid Version of the Urban Airshed Model," Air and Waste Management Association Specialty Conference: Tropospheric Ozone and the Environment II, 1991.

20. T. C. Myers, S. G. Douglas, R. E. Morris, et al., "Technical Achievements and Progress on SCE Technical Services Purchase Orders C1030011, C1030010, and C1030915," Systems Applications International, San Rafael, California, 1991.


92023.03

21. R. E. Morris, T. C. Myers, and M. A. Yocke, "Effects of Grid Resolution in the UAM on Evaluation of Emissions Control Strategies," Air and Waste Management Association Specialty Conference: Tropospheric Ozone and the Environment II, 1991.

22. J. P. Killus, J. P. Myer, D. R. Durran, et al., Continued Research in Mesoscale Air Pollution Simulation Modeling, Vol. V: Refinements in Numerical Analysis, Transport, Chemistry, and Pollutant Removal, EPA-600/3-84-095a, U.S. Environmental Protection Agency, 1984.

23. K. Schere, An evaluation of several numerical advection schemes. Atmos. Environ., 17:1897-1907 (1983).

24. D. P. Chock and A. M. Dunker, A comparison of numerical methods for solving the advection equation. Atmos. Environ., 17:11-24 (1983).

25. D. P. Chock, A comparison of numerical methods for solving the advection equation--II. Atmos. Environ., 19:571-586 (1985).

26. D. P. Chock, A comparison of numerical methods for solving the advection equation--III. Atmos. Environ., 25A:853-871 (1991).

27. R. G. Lamb, Continued Research in Mesoscale Air Pollution Simulation Modeling, Volume III: Modeling of Microscale Phenomena, EPA-600/4-76-016c, U.S. Environmental Protection Agency (1976).

28. R. G. Lamb, W. R. Shu, D. R. Durran, et al., Continued Research in Mesoscale Air Pollution Simulation Modeling, Vol. VI: Further Studies in the Modeling of Microscale Phenomena, EPA-600/3-84-095B, U.S. Environmental Protection Agency, 1984.

29. M. K. Liu and D. R. Durran, "On the Prescription of the Vertical Dispersion Coefficient Over Complex Terrain," Joint Conference on Applications of Air Pollution Meteorology, American Meteorological Society and Air Pollution Control Association, 1977.

30. J. Smagorinsky, General circulation experiments with the primitive equations: I. The basic experiment. Mon. Wea. Rev., 91:99-164 (1963).

31. M. L. Wesely, Parameterization of surface resistances to gaseous dry deposition in regional-scale numerical models, Atmos. Environ., 23(6):1293-1304 (1989).

32. H. A. Gray, M. P. Ligocki, G. E. Moore, et al., "Deterministic Modeling in the Navajo Generating Station Visibility Study," SYSAPP-91/045, Systems Applications International, San Rafael, California, 1991.

33. J. S. Scire, "A Review of the UAM-V Dry Deposition Algorithm and Recommendations for Dry Deposition Modeling in the LMOS Study Region," Document A195-100, Sigma Research Corporation, Westford, Massachusetts, 1991.





34. M. W. Gery, R. E. Morris, S. M. Greenfield, et al., "Development of a Comprehensive Chemistry Acid Deposition Model (CCADM)," SYSAPP-87/061, Systems Applications, Inc., San Rafael, California, 1987.

35. D. J. Jacob, E. W. Gottlieb, and M. J. Prather, Chemistry of a polluted boundary layer. J. Geophys. Res., 94(D10):12,975-13,002 (1989).

36. G. V. Buxton, C. L. Greenstock, W. P. Helman, and A. B. Ross, Critical review of rate constants for reactions of hydrated electrons, hydrogen atoms and hydroxyl radicals (OH/O-) in aqueous solution. J. Phys. Chem. Ref. Data, 17(2):513-886 (1988).

37. P. Neta, R. E. Huie, and A. B. Ross, Rate constants for the reactions of inorganic radicals in aqueous solution. J. Phys. Chem. Ref. Data, 17(3):1027-1284 (1988).

38. D. B. Turner, T. Chico, and J. A. Catalano, TUPOS -- A Multiple Source Gaussian Dispersion Algorithm Using On-Site Turbulence Data, EPA-600/8-86/010, U.S. Environmental Protection Agency, 1986.

39. T. C. Myers, R. E. Morris, and M. A. Yocke, "Plume-in-Grid Treatment for UAM-V", memorandum to Mike Koerber of the Lake Michigan Air Directors Consortium, Systems Applications International, San Rafael, California, 1991.

40. R. E. Morris, E. C. Chang, S. B. Shepard, and M. P. Ligocki, "Users Guide to Version IV of the Reactive Plume Model (RPM-IV)," SYSAPP-91/118, Systems Applications International, San Rafael, California, 1991.

41. C. Seigneur, T. W. Tesche, P. M. Roth, and M. K. Liu, On the treatment of point source emissions in urban air quality modeling. Atmos. Environ., 17:1655-1676 (1983).

42. C. Fröhlich and C. Wehrli, "Spectral Distribution of Solar Irradiance from 25000 nm to 250 nm," in An Introduction to Solar Radiation, M. Iqbal, Academic Press, 1983.

43. C. A. Cantrell, J. A. Davidson, A. H. McDaniel, R. E. Shetter, and J. G. Calvert, Temperature-dependent formaldehyde cross sections in the near-ultraviolet spectral region. J. Physical Chemistry, 94 (1990); J. D. Rogers, Ultraviolet absorption cross sections and atmospheric photodissociation rate constants of formaldehyde. J. Phys. Chemi., 94 (1990).

**NOTE TO EDITORS**

FIGURE 1. UAM-V nested-grid structure used in the application to the Lake Michigan region.




FIGURE 2. Schematic representation of the UAM-V subgrid-scale point source treatment; the elliptical form of the Reactive Plume Model is used to simulate the point source plume, outer ellipsis are "peeled off" the plume when the plume size is commensurate with a grid cell size.