Invited Paper

The applications of new technologies to modeling mesoscale dispersion in coastal zones and complex terrain


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ABSTRACT

Over the past two decades, especially in the regulatory and emergency response arenas, dispersion modelers have tended to use the Gaussian plume approach, or its various segmented plume and puff advection progeny. Such codes often fail in the complex wind and turbulence patterns found in coastal zones and complex terrain. Concurrently, other, more sophisticated approaches were being developed and tested, such as prognostic mesoscale numerical models (MNMs) for simulating complex, three-dimensional, time-dependent meteorological fields. The MNMs can in turn drive Lagrangian particle dispersion models (LPDM). The MNM and LPDM codes, however, require substantial computational resources. Until recently their application typically required access to a mainframe supercomputer. High performance workstations have emerged which can now provide throughput rivaling that of a supercomputer, but at a fraction of the cost. The combination of MNMs, LPDMs and workstations are beginning to change the way in which air quality professionals approach dispersion modeling. This paper will review several applications of these new technologies, including RAMS, the Regional Atmospheric Modeling System.

Examples included in this review will address (1) plume dispersion near both straight and complex coastlines, (2) the generation of meteorological input to photochemical grid models of multi-day ozone episodes in the Lake Michigan basin, (3) model performance evaluation against an SF6 tracer release into a lake breeze front, (4) design and testing prototypes for real-time emergency response systems for use in coastal zones, and (5) predicting the convective boundary layer (CBL) and dispersion over complex terrain. A central theme in all the simulations is the critical role of regions of organized mesoscale vertical motions in determining plume transport. The mesoscale vertical motion (w) field is extremely difficult to measure. If model horizontal mesh sizes are properly specified, computed w fields using RAMS appear to provide realistic results.
INTRODUCTION

For over two decades, the simple Gaussian straight-line plume (GSLP) model and its numerous segmented plume and puff-advection derivatives have been widely applied by the air quality modeling and emergency response communities. In its simplest formulation, GSLP use implies the assumption of (1) a steady-state atmosphere, (2) instantaneous transport of the plume through the domain, (3) purely horizontal transport and (4) a horizontally homogeneous environment defined by a single (often surface layer) meteorological measurement site. More sophisticated approaches include vertical displacement of the plume center line due to mechanical disturbance of the flow by complex terrain (Hanna and Strimaitis, 1990). Other dispersion codes use diagnostic wind field models, usually derived from sparse networks of surface wind and stability measurements, sometimes augmented by minimal upper air input (Lange, 1978). Such diagnostic codes can partially account for vertical displacement of the plume due to flow over terrain obstacles, but can not properly resolve complex, thermally-driven, three-dimensional mesoscale regimes. These produce vertical shear, recirculation and regions of strong vertical motion formed by flow discontinuities which markedly influence plume behavior. The inappropriateness of applying GSLP codes uniformly to all meteorological regimes and terrain types has been noted (Lyons, 1975).

Military, nuclear power and chemical facilities worldwide continue to install new emergency response dispersion prediction systems. While often representing significant improvements over earlier, pure-GSLP approaches, these systems generally share at least two common limitations for use in emergency response: (1) the use of primarily near-surface wind data which cannot define three-dimensional recirculating mesoscale flows such as associated with sea/land breezes, and (2) the use of non-time dependent wind data. Even if a perfect 3-D description of the transport winds were initially available over the entire domain, the rapidly evolving flow field associated with many mesoscale weather regimes mandates using predicted winds to forecast source impacts upon receptors.

While noting some recent exceptions (Stauffer and Seaman, 1990; Williams and Yamada, 1990), most air quality modelers and emergency response planners continue to be heavily reliant upon GSLP-based methodologies. The reasons for this are complex, and include (1) the code's modest computational requirements, (2) their conceptual simplicity and ease of interpretation, (3) their ability to be initialized with on-site or easily available meteorological data, (4) a long history of application and a large cadre of trained practitioners, (5) available model calibrations from numerous field monitoring and tracer programs, (6) regulatory agency inertia and (7) for emergency response, the ability to generate results quickly, typically within 15 minutes.

There have been important developments over the past few years in mesoscale prognostic and dispersion modeling (Pielke 1992, 1991) in parallel with increasingly affordable and accessible high performance computing (Grubb and Borchers, 1991) and effective visualization of model output (Lincoln et al, 1990). These developments, combined with a growing realization that mesoscale dispersion problems require new approaches, are beginning to alter the methods employed by air quality and emergency response professionals. As affordable workstations [effectively desk top
supercomputers] become widely available, computational limitations will no longer be a significant impediment to the use of mesoscale prognostic models to drive full-featured dispersion codes. This paper will illustrate some of the capabilities of these new technologies. It will also highlight an area which has received relatively little attention in dispersion studies - the impact of organized, thermally-driven mesoscale vertical motions upon 3-D plume transport. Since routine measurements of mesoscale vertical motion are virtually non-existent, their influence on dispersion has been only minimally investigated for transport in the 10 km to 100 km range. The prognostic model's ability to predict the vertical (w) component of the wind field is shedding new insights into this aspect of dispersion processes.

THE NEW TECHNOLOGIES

The dispersion simulations in this paper utilize RAMS, the Regional Atmospheric Modeling System, which in turn provides input for Lagrangian Particle Dispersion Models (LPDM). The codes were executed on an IBM RS/6000-series workstation with onboard visualization software. A brief description of these components follows.

RAMS is a non-hydrostatic, primitive equation, prognostic mesoscale modeling system which has evolved from codes developed by Pielke (1974) and Tripoli and Cotton (1982) and which continues to be developed at Colorado State University. Any number of vertical levels can be selected, with a few dozen being typical. The vertical levels telescope from the surface, starting several meters above the ground. This provides for a detailed resolution of planetary boundary layer structure. Surface heat and moisture fluxes are computed as a function of variable land use, albedo, roughness, soil type, soil moisture and topography. There is full treatment of long and shortwave radiative fluxes. Clouds and precipitation microphysics can be included when required. The horizontal domain and grid sizes are arbitrary. However, since computational requirements increase markedly with the inverse of the grid spacing for a given domain size, determining the size of the horizontal grid becomes a critical decision. The development of multiple nested, two-way interactive grids greatly increases the utility of the code. Large portions of the domain can be covered at coarse resolution, with finer mesh grids nested inside the larger ones and centered over the area of concern.

RAMS may also be nested within global or hemispheric models when temporal variability in the outer boundary conditions is needed. The model can be initialized using only a single, local rawinsonde. If significant horizontal and temporal atmospheric variability exists, options for non-homogeneous initialization and four-dimensional data assimilation (4DDA) are available through an isentropic analysis preprocessor (ISAN). The model outputs include the basic state variables (u,v,w wind components; potential temperature; specific humidity; pressure) at each model grid point and selected time step. In addition, a wide variety of derived variables can be produced, including friction velocity, surface heat flux, Monin-Obukhov length, mixing depth, surface heat flux and Pasquill-Gifford stability class.

The RAMS code is modular, written in standard FORTRAN 77 and runs on a variety of platforms. RAMS and its predecessors have been used by researchers in many institutions to simulate a wide range of atmospheric
phenomena, including land/sea breezes, orographic cloud systems, mountain/valley flows, large eddies, boundary layer development in complex terrain, and the impact of terrain variability upon mesoscale atmospheric structure (Lyons, 1973).

The concept of a Lagrangian dispersion model is not of recent vintage, but its widespread application has been limited by (1) lack of available 3-D input data and (2) considerable computational requirements. Models such as RAMS can provide appropriate input to an LPDM. The LPDM code used here is based on ideas presented in McNider et al. (1988) and Pielke et al. (1991). The LPDM simulates the ensemble dispersion of up to tens of thousands of particles from a user-specified source. Once emitted, the particles are subjected to a velocity field which advects them through space. The subsequent position of each particle is computed according to the following:

\[
\begin{align*}
X(t + \Delta t) &= X(t) + (u + u') \Delta t \\
Y(t + \Delta t) &= Y(t) + (v + v') \Delta t \\
Z(t + \Delta t) &= Z(t) + (w + w' + w_p) \Delta t
\end{align*}
\]

where \(u, v\) and \(w\) are the resolvable scale wind components obtained directly from the meteorological model. The \(u', v'\) and \(w'\) turbulent wind components are also derived from the meteorological model as normally-distributed, random numbers whose standard deviation is determined from local turbulence conditions at the particle location. The term \(w_p\) in Equation (3) is an additional vertical velocity resulting from external forces such as gravitational settling.

The emissions can be configured to represent point, volume, area and vertical and horizontal line sources with instantaneous, continuous or variable emission rates. The particles can represent gases or aerosols. Each particle is assigned attributes, including its source, time of release and the quantity of chemical mass or radiation it represents. Half lives for chemicals and radionuclides may be assigned. Gravitational settling and impaction can be treated, as can dry deposition (Arritt, 1991). The LPDM can derive the most likely individual particle trajectory by nulling the turbulent wind fluctuation terms. The ensemble particle cloud, representing a streakline from a continuous release, is ideal for visualizing transport and diffusion mechanisms.

Workstations approach performance levels recently reserved for mainframe supercomputers only. This is particularly true if the workstation is dedicated to a task. Most mainframe systems operate in a multi-user environment, with turn-around times often many times slower than actual run times. Our group has utilized primarily the IBM RS/6000 series machines (single processors rated at 7 to 35+ megaflops, with 32 to 512 megabyte memories). Other vendors have introduced machines with similar capabilities. It is expected that prices will continue to drop and performance will continue to rise in these product lines for the foreseeable future. Even with current platforms, prognostic 3-D runs with relatively fine mesh sizes (\(\Delta x<10\) km) can certainly be made for air quality investigations and even some emergency response applications (Lyons et al., 1991).

Onboard high resolution graphics (1280 x 1024 pixel, 24 bit color) and visualization software reduces tedious post-processing of the large output files, which can often approach a gigabyte in size. Animated, color, 3-D
visualizations and image manipulation features dramatically increase the meteorologist’s ability to interact with and comprehend the model output, which is inherently three-dimensional and time dependent.

THE COASTAL ZONE

The following examples illustrate some of the influences of coastal zone phenomena upon mesoscale plume dispersion as simulated using RAMS and an LPDM. We will progress from simple meteorological regimes and source configurations to those with greater complexity.

Fumigation during Gradient Onshore Flow

A frequent dispersion regime found on all coastlines during the warm season (land temperature greater than the adjacent water) concerns fumigation of elevated plumes from shoreline sources released into an inland-flowing air mass accompanied by strong insolation (Lyons and Cole, 1973). RAMS generated a 24-hour, two-dimensional simulation of the lower troposphere (<7000 m) over the central Lake Michigan region using a 1000 m horizontal mesh size. The clear skies and 5 m/sec easterly gradient flow over a relatively cold lake surface are typical of mid-May, and ideal for fumigation of elevated plumes released in the downwind shoreline region. A source, such as a power plant, is here represented by a single stack, located on the western shoreline, with a constant effective stack height of 219 meters AGL. Four thousand particles were released over a four hour period beginning at 0800 LST. Figure 1a,b shows plan and side views of the plume at 1200 LST after the thermal internal boundary layer (TIBL) had become well developed. The plume, initially very stable, drifted inland about 8 km before downward mixing began upon intersection by the deepening TIBL. Plume matter was mixed both downwards and upwards by the deepening turbulent layer as it advected further inland. The horizontal dispersion showed some asymmetry due to boundary layer shear. Figure 1c shows the peak normalized instantaneous concentrations received at the surface during the fumigation episode as a function of range downwind from the source. Note the increase from negligible levels at <8 km to the peak value at 10 km and the gradual decline further inland.

These results appear similar to previous GSLP modeling results. The use of a prognostic model, however, revealed an additional aspect of fumigation previously unrecognized. While the gradient onshore synoptic flow was not associated with a lake breeze frontal zone, the acceleration of the wind field through the downwind coastal zone pressure gradient did result in a zone of slight subsidence extending several tens of kilometers inland. Although mid-day subsidence values were only in the 3 to 5 cm/sec range, the plume was significantly impacted. Close inspection of the plume in Figure 2a shows that before being intersected by the upward developing TIBL, the plume centerline had a distinct downward slope. The regional subsidence caused the plume centerline to descend from its initial 219 m AGL height to 150 m AGL at the onset of fumigation. This newly recognized aspect of the fumigation process resulted in the calculated "hot spot" moving several kilometers closer to the shoreline and producing higher ground level concentrations.

Models such as RAMS, when exercised with suitably fine horizontal and vertical meshes, can simulate the life cycle of the TIBL. The numerous empirical TIBL equations currently in use with GSLP codes are generally
constrained to using homogeneous initial temperature lapse rates, uniform wind fields and spatially invariant fluxes of heat, moisture and momentum fluxes over both land and water (Garratt, 1990). Moreover, none of the empirical formulae can account for the impact of shoreline subsidence or upward motion. Prognostic models, even in a 2-D mode, would appear to provide for a far more realistic assessment of the fumigation mechanism.

**Plume Transport in the Lake Breeze Frontal Zone**

Complete, 3-D RAMS simulations of the Lake Michigan land/lake breeze system have been conducted for a day with a weak lake breeze (Lyons et al. 1990). The prognostic model horizontal grid cell size used in the shoreline zone was 1000 meters. Figure 2 portrays modeled conditions in an east-west plane through Lake Michigan. An LPDM-generated plume representing dispersion from a continuous release lasting three hours (beginning 1200 LST) from a 50 m elevated source on the western shore at the Wisconsin-Illinois border is shown in Figure 3. The plume initially moved north-northwest inland with minimal vertical mixing beneath the inversion within the shallow, 250 m deep inflow layer. The predicted lake breeze front had pushed inland about 6 km along the western shore by early afternoon. As the plume moved inland, it intersected the frontal convergence zone, which had computed upward motions in the 100 - 150 cm/sec range. At that point the plume was largely translocated aloft into the return flow layer. The peak normalized surface layer concentrations as the plume advected away from the source are shown as a function of range (Figure 4a). Peak surface concentrations dropped only slowly during the first 20 km of travel from the source, but then fell rapidly by over five orders of magnitude in the next 20 km downwind. This was not solely the result of diffusion. Rather, the plume as a whole was vertically translocated aloft in the lake breeze frontal updrafts.

Figure 4b shows two trajectories derived from the surface layer and full 3-D RAMS wind fields, respectively. If one were to compute a trajectory using only surface layer winds, the particles would appear to continue to move north-northwest, then north. Yet, when the full, 3-D wind information available from the model is employed, the reason for the rapid decrease in surface concentrations is readily apparent. Many individual particles did describe along-shore, quasi-helical trajectories as they became entrapped within the lake breeze cell's circulation, as suggested in previous studies (Kaleel et al., 1983; Lyons and Olsson, 1973). However, in this case, only about 30% of the plume particles completed the helical trajectory and were re-entrained back into the inflow layer. After several hours of transport time, much of the material was found encapsulated aloft over the lake to the northeast of the source. Many of these particles later were fumigated to the surface over the eastern shoreline of Lake Michigan.

The fate of a plume from a four-hour release emanating at the same location but beginning at 0530 LST is illustrated in Figure 5. After two hours, the plume was steadily moving northeastward in the synoptic flow over the lake, showing relatively little horizontal or vertical mixing over the cold water. At the end of four hours (0930 LST), the leading edge of the plume had almost reached the eastern shore. At the same time, a weak lake breeze developing along the western shore began to re-entrain part of the plume back to the west. By 1330 LST, much of the western portion of the plume was involved with the helical circulation patterns of the west shore lake breeze. The eastern edge of
the plume was mixing upward in the developing TEBL while the remainder of
the plume over the lake remained within 200 m of the surface in the intense
conduction inversion over the cold water. Considering that there are literally
thousands of point and area sources in this region, each of which undergo
different but equally complex dispersion during land and lake breeze events,
the enormity of the task of modeling regional air quality for photoreactive
pollutants becomes apparent.

**Meteorological Modeling for Regional Photochemical Simulations**

During the 1980s, the Lake Michigan area experienced 213 days when
one or more monitors recorded ozone in excess of 120 PPB (Koerber et al.
1991). During the 1987-1988 summers the number of exceedance days (>120
PPB hourly average ozone) at individual monitors varied from zero to 26 days.
Sites within 20 km of the lake shore experienced exceedances 4.5 times more
frequently than inland sites, and also higher ozone maxima. Analyses show that
high ozone episodes in the LMAQR typically occur when a slow moving
anticyclone is located south and east of the region and a very warm, humid,
stagnant, maritime, tropical air mass dominates the region (Haney et al. 1987;
Lyons and Cole, 1976). These are also favored conditions for lake breeze
development. In 1976, Lyons and Cole (1976) demonstrated that there was a
strong association between high ozone and lake breezes in southeastern
Wisconsin. Monitoring data suggested that the highest surface concentrations
occurred in a relatively narrow band, perhaps 10-20 km wide, running parallel
to but slightly inland from the lake shore. Aircraft measurements have
indicated elevated "pools" of ozone over the lake, typically in the 300 to 1500
m AGL layer. Previous air pollution field studies along the western shore of
the lake noted the tendency of tetroons released into lake breeze inflows to
travel in broad, quasi-helical vortices roughly parallel to the shoreline in the
direction of the mean gradient wind V component. This suggests that a portion
of the pollutants ejected into the elevated return flow layer at the front were
subsequently re-entrained into the inflow layer. Given that quasi-helical
trajectories do occur, how significant are they in the ozone enhancement
process?

During the 1990-1993 period, the Lake Michigan Ozone Study (LMOS)
is charged with quantifying regional source/receptor relationships during high
ozone episodes. A comprehensive modeling system will use emission and
advanced photochemical grid models (PCGM) developed for the region.
Meteorological input to the PCGM will be obtained from a version of RAMS.

**Model Evaluation**

Given that the LMOS modeling system is being developed to provide
quantitative guidance in formulating regional emission control strategies, the
evaluation and validation of the various modeling components is of
considerable importance. The large observational data base collected during the
1991 LMOS field program will serve as the basis of ongoing evaluation studies
which will be reported in the literature over the next several years. A few
preliminary findings are summarized below.

**Evaluation of Meteorological Predictions**
Since RAMS is a suite of modeling components with hundreds, if not thousands of potential configurations, the design of the RAMS version used is of critical importance. Once an optimal configuration is determined, its actual performance can be measured against data. The election of the domain size, the horizontal mesh size ($\Delta x$) and the number and spacing ($\Delta z$) of vertical levels is among the more important design decisions.

As a general rule, the finer the $\Delta x$, the better refined will be mesoscale features. A series of sensitivity tests were conducted to assess the impact of RAMS model $\Delta x$ upon resolving the lake breeze and its resultant impact upon pollutant transport. RAMS was run in a 2-D mode in an east-west plane across the lake using $\Delta x$ values of 27, 9, 3, 1.0 and 0.33 km (Lyons et al., 1991). As shown in Figure 6, the lake breeze developed in all cases, but was increasingly better defined with smaller $\Delta x$. These results were in turn used to drive an LPDM to simulate the dispersion of a plume from a continuous surface layer (3 m) source located on the western shoreline (Figure 7). The predicted plume showed broadly similar behavior at all mesh sizes, but did appear to "converge" to a similar pattern for $\Delta x < 3000$ meters. As shown in Table I, there is a strong dependence of maximum, RAMS-predicted, vertical motions and $\Delta x$, reaching almost 150 cm/sec at 0.33 km mesh size (not shown). All other factors being equal, the finer $\Delta x$ mesh would appear to more realistically portray the lake breeze and its resultant dispersion. But as illustrated in Table II, for a given domain size the model run time increases dramatically as $\Delta x$ becomes smaller. A domain having $\Delta x=1000$ meters would require approximately three orders of magnitude more computer time than a configuration using a $\Delta x =10$ km.

The size of the domain is also of importance. Since the LMOS episodes can extend for many days, it is required that the influence of migrating synoptic scale pressure systems and fronts be properly treated. Thus, a model domain on the order of 5000 km is required. RAMS' ability to provide multiple, two-way nested grids partially resolves the conflicting requirements between a large domain and very fine $\Delta x$, at least in the area of primary interest. Figure 8 shows the three domains, using 80 km, 16 km and 4 km, selected for the LMOS production runs.

Extensive evaluation of the RAMS model performance is underway. A number of graphical and statistical measures comparing model output to observations have developed in conjunction with Thomas Tesche (Tesche, 1991).

Figure 9a shows a graphical presentation of the RAMS-predicted surface layer (10 m) wind field overplotted with one-hour averaged wind vectors from the LMOS observation network. The conformance between modeled and predicted flow fields appears to be close. Measured temperatures compared to RAMS predictions (Figure 9b) also show close correspondence.

A variety of statistical measures are also being applied. These will be discussed in detail in future papers, but Figure 10 provides an example. The modeled and observed temperatures at the vessel stationed in mid-lake derived from the 16 km and 4 km grids show that the coarser $\Delta x$ mesh performs comparatively poorly. Further analysis suggests that selection of the vertical spacing is also important in such cases. RAMS has the ability to nest in the vertical. In this case the lowest level in the 4 km grid centered on Lake
Michigan is at 10 m, versus the 50 m for the 16 km grid. Previously Lyons et al. (1983) discussed the very shallow (<100 m) conduction inversion often found over the lake during summer. In order to resolve this important feature, a number of model levels with approximately 10 m spacing are required, as evidenced by the improved performance of the model in the 4 km grid.

The domain-averaged wind speed and directions (10 m) for the 4 km grid are shown in Figure 11a. Wind speeds track quite closely, as do wind directions, although a slight but persistent bias of about $15^\circ$ is noted in the model winds (Figure 11b). Additional statistical measures including root mean square errors (systematic and unsystematic), index of agreement, standard deviations, maximum deviations, normalized bias and variance ratio skill are being computed as additional evaluation tools.

Initial results suggest that the RAMS-generated meteorology does provide a close similitude to the observed wind, mixing depth and turbulence fields during the several LMOS episodes. For a straight shoreline such as Lake Michigan, the $\Delta x$ used in the model determines how well the frontal zone and its associated updrafts are resolved. Generally, as long as the model $\Delta x$ is less than 20 km, with 3 to 4 km needed to produce reasonable vertical motion intensities, the simulated lake breezes are qualitatively similar. This result does not hold for a complex coastline, such as discussed below.

**Evaluation of Mesoscale Dispersion**

The ability of RAMS to characterize mesoscale dispersion in the lake breeze was evaluated using SF$_6$ tracers. RAMS and an LPDM were used to design a field tracer measurement program conducted by North American Weather Consultants using surface sampling networks, aircraft and a mobile van. The goal was to sample a tracer plume released into a lake breeze inflow from 5 m AGL at the shoreline (along the Wisconsin-Illinois border). SF$_6$ is an inert, non-toxic tracer which is colorless and odorless. It has a global background around 2 PPT. Scientech TGA-4000 real-time SF$_6$ analyzers with a response time of $<1$ sec and a threshold $<10$ PPT were mounted in both a twin engine Cessna 340 aircraft and a mobile van. Both were equipped with additional meteorological and pollution measuring equipment and either Loran or GPS navigation systems. These were ready to be deployed within 30 minutes of the passage of a lake breeze front at a point about 3 km inland from the shoreline and to continue plume mapping for at least four hours. Up to 18 syringe samplers were to be deployed in arcs or east-west traverses up to 60 km downwind of the release point. Nine one-hour averages were to be obtained between 0900 and 1800 LST on test days.

The summer of 1991 was characterized by very warm lake water temperatures, frequent frontal passages and rather strong surface layer winds. Thus lake breezes were less numerous than normal, especially when coincident with weak southerly flow and ozone rich air masses. On 16 July 1991, strong southwesterly surface flow (6-12 m/sec) was present as an anticyclone moved eastwards (Figure 12). Ozone values were relatively low over Wisconsin and Illinois, except for a very narrow strip along Lake Michigan were they peaked as high as 130 PPB. Over the lake and western lower Michigan the higher values were in the 110 to 123 PPB range (Figure 13). A Doppler sodar on the western shore just near the state border (Zion, IL) noted a sharp shift from southwest to southeast flow at 1100 LST. The lake breeze inflow was very
shallow, however, not exceeding 210 m in depth (Figure 14). Surface anemometers in an east-west line extending inland from the sodar showed a shift to onshore by 1245 LST at the 3 km site. The front did not reach the 8 km anemometer. Ozonesonde and rawinsonde observations taken from ships in the lake confirmed a layer of higher ozone (80-120 PPB) from just above the surface to the base of the synoptic inversion at 1700 m MSL (Fig. 15). An inversion in the lower 200 m over the lake strengthened during the day. The cool dome over the lake was not found more than 500 m above the water. The southeast inflow layer extended offshore but was not greater than 200 m in depth. This lake breeze is about as minimal a lake breeze event as can be observed. Yet even this modest circulation had significant impact on plumes. The SF₆ was released from the shoreline starting at 1248 LST. The release rate was carefully monitored and held constant for four hours. The aircraft and van were deployed shortly after the release started. The aircraft made 17 east-west traverses of the shoreline at approximately 13 and 50 km downwind of the release. Eleven altitudes were flown ranging from 370 to 1650 m MSL. Figure 16 shows a segment of the flight track approximately 10-15 km north of the release. The results are projected onto an east-west plane. The region in which SF₆ was detected (shaded) is a narrow column extending almost vertically to over 1600 m MSL, tilting slightly lakeward. This marks the SF₆ plume being convected upwards in the strong updrafts associated with the lake breeze front. The van found relatively high concentrations near the surface within a few kilometers of the shoreline to about 10 km of the release with only residual values, again only within the marine air mass, for another 35 km northward (Figure 17). When the van left the lake-influenced air, SF₆ values quickly fell to zero. These measurements are entirely consistent with the predicted plume behavior in test simulations.

The aircraft SF₆ measurements were re-mapped into the same space as used for the RAMS and LPDM simulations of this plume. Figure 18a,b shows the particle model simulation of the SF₆ release in both plan (XY) and vertical east-west plane (XZ)views. RAMS in this case used a Δx= 2 km. This resolved the lake breeze frontal zone along the west shore quite sharply. The LPDM-simulated SF₆ plume replicated the basic features observed in the aircraft measurements. The predicted plume rose aloft in a concentrated column around 10 km north of the release, reaching as high as 1600 m MSL. Widespread plume descent was found over the lake. The comparatively modest downdrafts with this very weak lake breeze limited the number of particles that were re-entrained back into the inflow, although some did undergo helical trajectories. Correlation coefficients between the aircraft measured and LPDM-predicted tracer were made using a sampling volume 500 x 500 m and 200 m deep, averaged along about 3 seconds of flight path. Values of R averaged 0.36 from 3000 to 7200 seconds after the start of the release, although values above 0.80 were noted for extended segments of the flight. The flight path averaged value of the predicted tracer during this time frame was 7 PPT, versus an observed value of 21 PPT. Given that the model was attempting to replicate a spatially contorted, three-dimensional plume, these initial results are encouraging.

**Meteorological Modeling of Complex Coastlines**

While the western shoreline of Lake Michigan is relatively straight, the complex of islands and estuaries upon which the Kennedy Space Center (KSC) is located presents a more complicated modeling challenge.
RAMS was used to simulate complex mesoscale circulations over the KSC region (Lyons et al., 1990). On 7 November 1988, there were clear skies as a weak high pressure system drifted eastward through the eastern Gulf of Mexico. At daybreak there were moderate (5 m/sec) northwest surface winds. Minimum temperatures over land were approximately 10°C-13°C as compared to 22°C-26°C water surface temperatures offshore. Solar insolation was near the maximum possible for the date, yet inland maximum temperatures rose to only about 3°C warmer than those over the ocean. This temperature difference was sufficient, however, to allow development of an Atlantic Sea Breeze (ASB). It was first detected, as is common, along the west shore of the Indian River at 1000 LST. It pushed inland very slowly, reaching a position 9 km west of the river shore by 1600 LST. Even with the proximity to the winter solstice, surface heating over the adjacent Merritt Island and Cape Canaveral land masses resulted in distinct convergence zones onto these "heated islands". This was accompanied by strongly divergent flows off the Indian and Banana Rivers, sometimes referred to locally as "river breezes". Figure 19 shows the complexity of the observed surface winds at 1200 LST. The ASB frontal position and the island convergence zones were shown to persist for most of the day (Figure 20). These perturbations in the wind field were located near major Space Shuttle and missile launch complexes, as well as near storage and handling facilities for highly toxic oxidizers and other chemicals.

The RAMS modeling domain used three nested grids with mesh sizes of 9 km, 3 km and 1000 meters, respectively. The innermost, fine mesh grid (1000 m) covered a region of 40 x 34 kilometers. RAMS-predicted wind fields are found to be strongly dependent upon the model horizontal mesh size. Figure 21 shows the surface wind streamlines at 1200 LST as they were resolved using only the coarse 9 km Florida-sized grid. While the general flow pattern and the main ASB convergence was evident, none of the fine scale structure over Merritt Island or Cape Canaveral was resolved. A much greater level of detail emerged when the innermost 1000 m grid, centered over the CCAFS/KSC region, was utilized (Figure 22). In addition to the ASB front, the convergence zones over southern Merritt Island and the Cape were evident. Figure 23 shows the maximum predicted boundary layer vertical motions associated with the wind field discontinuities at 1200 LST. In addition to the 150+ cm/sec updrafts associated with the main ASB, organized upward ascent of 30 to 45 cm/sec was associated with the convergence zones over Merritt Island and Cape Canaveral.

Examination of the wind fields in the vertical east-west sections through the center of the domain shows the impact of model horizontal mesh size (Figure 24). At the coarse, 9 km grid size only the single ASB circulation cell was evident in the UW streamline field. At the 1000 m grid size three distinct circulations associated with the ASB, Merritt Island and Cape Canaveral convergence zones became resolved. The selection of the horizontal mesh size resulted in both quantitative and qualitative differences when resolving features in the mesoscale flow field which were on the order of 1-2 kilometers in horizontal scale.

The predicted maximum vertical motions are quite sensitive to the horizontal grid size used. The maximum predicted updrafts in the ASB frontal zone were 30 cm/sec using a 9 km grid. This is comparable to many other coarser grid, mesoscale modeling results. Recent Doppler sodar field
observations, however, suggest that sustained vertical motions in the 1 to 2 m/sec range are present during coastal wind field discontinuities in the KSC area (Taylor et al., 1989). We note that the 1 km RAMS configuration produced a peak updraft of 170 cm/sec during mid-day. Companion zones of strong subsidence (>30 cm/sec) were associated with diffluence over the Indian and Banana River estuaries.

Dispersion from a Simple Source

Contaminants released within this domain and advecting into the organized updraft zones could be expected to undergo substantial vertical translocation. Any resultant dispersion is likely to be at considerable variance with that indicated by a two-dimensional, diagnostic wind field model driven by surface layer anemometers. The LPDM simulated the continuous release of a neutrally buoyant gas from a near ground (2 m) source. Beginning at 1100 LST, it emulated the plume from a hypothetical train derailment on a bridge over the Indian River. The plume is visualized in Figure 25a,b at six hours after the start of the accident. In the plan view (Figure 25a) the plume initially drifted towards the ASB front but then bifurcated into two distinct branches. An elevated, perspective view from the southwest began to clarify the processes involved (Figure 25b). The plume initially advected inland to the southwest in the ASB inflow layer. Upon reaching the strong updrafts in the ASB front it was translocated aloft in the narrow (1-2 km) chimney of updrafts. Part of the plume was then re-entrained back into the ASB inflow by strong subsidence over the Indian River. It underwent "second trip fumigation" over the shoreline area some 20 km south of the source. The other branch of the plume was injected sufficiently far aloft to enter the return flow-enhanced gradient wind and headed east-southeast. Figure 26 summarizes these features.

Dispersion from Complex Source

The LPDM can also predict the transport of particulate aerosols with a spectrum of terminal velocities. Size sorting due to differences in particle settling speeds in a sea/lake breeze was initially inferred from airborne measurements within the Chicago urban plume (Lyons and Olsson, 1973). Simulated trajectories for several aerosol sizes released from an elevated source into a diagnostic lake breeze wind field model suggested that substantial "size sorting" was possible (Keen et al., 1979). The following examples look at the dispersion from an instantaneous release of a cloud of particles with a large range in terminal velocities.

Using the same RAMS-generated meteorology for KSC as above, the consequences of a Space Shuttle launch accident was simulated. Of concern is the fate of a myriad of toxic particulates resulting from the explosive destruction of an onboard satellite's nuclear power supply. Table III shows the hypothesized fractionation of the payload's plutonium oxide fuel into a spectrum of particulate sizes. Each size class is represented by 4000 particles. The settling velocities (wp in Equation 3) were specified in the accident design scenario to range from 118 cm/sec (63 µm diameter) to 0.06 cm/sec for submicron sized particles. The deposition to the surface is a priori represented simply as a size-dependent percentage of those particles reaching within a predetermined distance (25 m) of the surface.
The accident occurred at 1345 LST during the model predicted, 7 November 1988 sea breeze. Two accident scenarios were simulated, explosions at 300 m and 1000 m above the launch pad. Each initial cloud was specified as a cube 100 meters on a side. Figure 27 shows both the airborne debris cloud and the deposited particulate matter from the 1000 m accident about an hour after the event. The odd horseshoe shape of the particulate debris cloud resulted from the size sorting of the aerosols in the complex updrafts and downdrafts of the sea breeze/heated island circulations. The heaviest particulates were deposited within a few kilometers of the source sub-point. The finest particulates remained suspended aloft. The intermediate size particles were variously falling through, being suspended in, or ascending back aloft within the updrafts.

As shown in Figure 28, the maximum surface deposition integrated over all particle sizes as a function of range from the accident subpoint often varied by an order of magnitude or more between the two scenarios. If one compares the deposition as a function of particle size, even more complex patterns emerge. Figure 29, for the 300 m accident, shows the total surface deposition as well as the contribution of the largest (63 μm) and the smallest (0.79 μm) particles. The former are all found within approximately 5 km of the accident sub-point whereas the latter, representative of respirable particles, are not mixed into the surface layer until more than 10 km downwind.

The airborne concentrations of the particles resident in the surface layer show similarly complex patterns both as a function of release height and particle size. The smaller, respirable size particle concentrations were especially affected by the explosion height. As shown in Figure 30a, submicron particles from the 1000 m explosion did not penetrate into the surface layer until more than 50 km downwind. For the 300 m scenario (Figure 30b), 0.79μm particles were found in significant numbers in the surface layer air, in part the effect of sea breeze recirculation.

While the above treatment of heavy particles dispersion is oversimplified, the example serves to illustrate in a graphic manner the potential need to account for the size sorting of aerosols. This is especially true for transport over mesoscale distances in which organized upward motions are equal to or larger than the settling velocities of the larger aerosols, resulting in the suspension and accumulation of particles of certain sizes.

Emergency Response

Large quantities of potential air contaminants are handled during routine and launch operations at the Kennedy Space Center/Cape Canaveral Air Force Station (KSC/CCAFS). An extensive network of surface layer wind monitors has been established, in part, to serve as input into real-time emergency response dose assessment systems. While a considerable improvement over those used in many other facilities, there are deficiencies in the techniques currently employed at KSC/CCAFS. The three-dimensional wind fields can not be adequately resolved using surface layer data even when supported by limited upper air information.

A system called ERDAS - the Emergency Response Dose Assessment System - will be tested for its operational suitability at KSC in 1993. The
ERDAS includes two major software systems, RAMS and the advanced HYPACT (hybrid particle and concentration transport) dispersion model based in part on concepts reported by Uliasz and Pielke (1991). HYPACT will simulate releases from a variety of source types, ranging from chemical spills to launch vehicle exhaust plumes. Dry deposition and differential transport of a spectrum of aerosol sizes due to gravitational settling are treated. The prognostic model can also provide meteorological forecasts suitable for ingest into other existing dispersion systems, such as the MARSS system (Taylor and Schumann, 1986). The ERDAS and its interactive display will be resident on an IBM RS/6000-550 with 64 megabyte RAM and over 1 gigabyte disk. The workstation's onboard graphics capability will be controlled by a customized Graphical User Interface (GUI) tailored to allow efficient operation of the system and rapid interpretation of the dispersion model.

Current practice at KSC has undergone review by the Air Resources Laboratory, National Oceanic and Atmospheric Administration (NOAA) (Hosker et al. 1992). It was noted that the Meteorological and Range Safety Support System (MARSS) is one of the more sophisticated emergency response systems in use today. On the other hand, it employs the venerable Ocean Breeze/Dry Gulch (OB/DG) algorithm driven by the surface layer wind field and stability measurements as observed by the WINDS mesonetwork. A spatially variable, two-dimensional wind field is derived from the WINDS network, but the impact of vertical motion fields is not addressed. Other candidates for use include the AFTOX Gaussian plume code developed by the U.S. Air Force (Kunkel, 1991). Driven by point surface layer meteorological measurements it estimates mixing depth and continuously variable dispersion categories. It assumes uniform terrain and wind fields.

ERDAS is being designed and developed with a number of general criteria in mind. Most importantly, it strives to provide the foundation for a general purpose solution to forecasting the local meteorological environment at KSC over the next 24 hours and in turn being able to assess dispersion potentials for ranges from several hundred meters to 100 km or more for a wide variety of contaminants and source types. The software systems are highly modular. Thus, once the base ERDAS system is initially configured, future enhancements can be added with relative ease.

The general characteristics of the ERDAS are outlined schematically in Figure 31. Figure 32 shows the three grids proposed for use in ERDAS. A 60 km mesh covers the southeastern U.S. Florida will be resolved using a 15 km mesh. A 110 x 110 km region covering the KSC area will use a 3 km mesh. This represents the coarsest mesh felt adequate to resolve both the sea breeze and island/estuary perturbations. As work station processors become even more powerful, spawning an ever finer mesh grid (approximately 1000 meters) directly over KSC is readily accomplished.

RAMS will be initialized twice daily, taking approximately six hours to produce a 24-hour forecast. A RAMS forecast will always be resident in the machine for immediate use by the dispersion code. The model can be initialized with as little as a single, local rawinsonde. For extended runs over areas of this size, RAMS preferably is nested within global or hemispheric model output from NMC. ERDAS will utilize non-homogeneous initialization with non-stationary boundary conditions. As additional data resources such as
When profiler data become available at KSC, these can be incorporated into the initial analysis using four-dimensional data assimilation (4DDA) options.

The model outputs are highly flexible. Output files include the basic state variables (u, v, w wind components; potential temperature; specific humidity, pressure) as well as a large variety of derived quantities (mixing depth, turbulent kinetic energy, Pasquill-Gifford class, friction velocity, etc.). The model output can be configured to emulate any number of observation systems as "synthetic data". Therefore it will be possible to use RAMS to produce animations of forecasted wind fields in the same format as appearing on the MARSS display or predictions of profiler or rawinsonde observations. Output can be formatted to be used directly in other codes such as AFTOX, which provides it with a forecast capability not previously available.

RAMS output will be the prime input into the HYPACT dispersion code. For approximately the first hour, the available observations will also be incorporated into the HYPACT input files, using the RAMS output as a template for the initial objective analyses.

Even with their impressive performance, work stations have limitations. As mesh size diminishes, run times increase dramatically. Certain RAMS options such as explicit cloud microphysics also require substantial computational resources. For these reasons, the RAMS configuration in the initial ERDAS will be limited to a 3 km inner mesh size and will not treat convective cloud formation.

Thunderstorms produce large perturbations in wind and turbulence fields. Lyons et al. (1986) present examples illustrating how a mesoscale convective system can inject large amounts of convective boundary layer pollutants into the upper troposphere while also transporting relatively clean, mid-tropospheric air into the surface layers. Thunderstorms occur with the large majority of Florida east coast sea breezes (Lyons and Fisher, 1988). RAMS is capable of modeling convective storms explicitly. Considerable success was achieved in simulating the Merritt Island thunderstorm and Atlantic sea breeze convection in a recently completed project (Lyons et al., 1992c). Before this option is installed in ERDAS, two advances are required. Since the inclusion of the microphysical module currently slows RAMS down by a factor of four over its "dry" implementation, either more efficient microphysics and/or faster processors must be employed. Work is proceeding on a faster microphysics package (factor of two speed-up). With workstation performance doubling every 12 to 18 months, it is simply a matter of time before ERDAS can treat convective cloud impacts upon local dispersion. The results of the 1991 CaPE (Convection and Precipitation/Electrification) field measurement program will provide data for evaluating RAMS' performance.

Since a 24 hour dispersion forecast not accounting in some way for the potential for convective disturbances in the boundary layer is potentially misleading, we propose an interim solution. Thunderstorm forecasting experiments at KSC demonstrated that relatively simple diagnostics applied to a "dry" prognostic model showed skill at predicting the initiation of sea breeze storms during the upcoming day (Lyons et al., 1987; 1992b). Various candidate storm diagnostics will be examined, including the K index, the KLIW index, convective available potential energy and the output of 1-D diagnostic cloud models. As part of the ERDAS display, the spatial and temporal evolution of
the convective storm potential diagnostic will be available to the forecaster. This will help flag those upcoming periods in which the dispersion estimates may be disrupted by deep convective clouds.

COMPLEX TERRAIN

In addition to accounting for differences in surface fluxes between land and water and the resulting mesoscale circulations, RAMS also can assess the impacts of spatial heterogeneity in land use characteristics and soil moisture. The effects of surface heterogeneity upon dispersion has been summarized by Pielke et al. (1991). Regions of cropland surrounded by desert, irrigated versus non-irrigated fields, variations in soil moisture due to antecedent precipitation and other similar landscape features can produce mesoscale circulations of comparable strength to lake and sea breezes. The "inland sea breezes" become less pronounced as large scale wind speeds increase and/or the spatial scale of the discontinuities decrease.

Even over flat terrain, the impacts of surface characteristics upon plume dispersion can be significant. When significant orography exists, especially when accompanied by large land use variability, dispersion processes becomes highly complex. RAMS has been used in a variety of studies of CBL structure in complex terrain and the resulting transport. Stocker and Pielke (1990) report on simulations of hypothetical plume transport over the Grand Canyon area. Even using a relatively coarse grid (10 km), substantial horizontal and vertical distortion of the plumes was predicted (Figure 33a,b). Stocker et al. (1991) modeled the combined effects of the sea breeze and mountain/valley flows upon the transport of multiple sulfur dioxide plumes during a period of air stagnation in eastern Virginia. Figure 34 illustrates the resultant plume patterns revealed by application of an LPDM. Plume dispersion from a tall stack in the southwestern U.S. is currently being evaluated using RAMS run on a simulated operational basis for an entire year period.

While the above referenced 3-D simulations are being run with relatively coarse mesh sizes (=10 km), RAMS has the capability to model the impact of complex terrain on phenomena such as the nocturnal drainage flows and the development of the convective boundary layer. When RAMS is implemented in a large eddy simulation (LES) mode, considerable detail about atmospheric turbulent structure begins to emerge (Cotton et al., 1991). Figures 35-38 presents the results of a nested, 2-D simulation in an east-west plane showing the interaction between large scale, terrain-forced flows and boundary layer circulations along the foothills of the Rocky Mountains. The mesh sizes used in the three grids used are 3060, 760 and 190 m. The broad area of upslope (easterly) surface flow into the heated, mountainous terrain is evident in the 760 m grid (Figure 35). The detailed structure of the CBL in terms of potential temperature, mixing ratio (which acts as a passive tracer) and turbulent kinetic energy are revealed in the 190 m grid portion of the domain over the plains (Figures 36-38). While the predicted eddies are similar in structure to those observed, they are several times too wide. This discrepancy is expected to be resolved as full 3-D LES simulations are conducted. The potential for using models such as RAMS for dispersion modeling in even the most complex terrain is evident from such simulations.
In 1990, a field SF6 tracer measurement program was conducted in complex terrain in northern Spain at the Guardo power plant (Ibarra, 1991). The plant is located at the mouth of the steep, north-south canyon of the Carrion River. Tracer was released both from the stack and a site on the canyon floor. Currently RAMS is being configured with a 5 level nest to simulate the complicated flows observed in this region, which include mountain waves, barrier eddies, nocturnal drainage flows and daytime upslope winds. The model will use mesh sizes of 32 km, 8 km, 2 km, 500 m and 125 m in order to resolve the interactions between the synoptic and topographically controlled flows. Figure 39a,b shows the resolved airflow for one of the experiments on the outer grid (covering all of Spain) and over 80 x 80 km area at Δx= 2 km. Final results including extensive evaluation of HYPACT tracer simulations will be presented during 1993. As a result of such model evaluation efforts, we anticipate growing levels of confidence in the utility of such meteorological and particle modeling systems for complex terrain dispersion studies.

Given adequate computing resources, RAMS can be applied to even smaller scales, such as flow over large buildings (Nicholls et al., 1992). Figure 40 presents an example of the non-steady state eddy structure resulting from flow over a 50 m tall rectangular shaped building. Such simulations could provide additional insight into building wake effects upon pollutant dispersion.

SUMMARY AND CONCLUSIONS

Increases in computational power now allow for "desk top" simulation of an ever growing class of mesoscale phenomena. Until recently, these simulations required access to a mainframe supercomputer. The ability to perform such computations for real-time forecasting is already or soon will be at hand for a number of problems.

The impact of organized mesoscale vertical motions upon plume transport has only begun to be appreciated. The fumigation of elevated plumes may be substantially impacted by shoreline subsidence. In some sea breezes, vertical motions are of the same order of magnitude as the horizontal wind components. In sea breeze frontal zones, entire plumes can be vertically translocated aloft en masse. Once in the return flow layer, while individual trajectories in a sea breeze may undergo helical recirculation, plumes may often split into several branches, with large amounts remaining pooled aloft. The potential impacts of aerosol size sorting requires further detailed study. Future coastal zone tracer tests aimed at evaluating the performance of various modeling systems including the RAMS/LPDM, should be cognizant of the role played by vertical motion in mesoscale dispersion, which in some cases may dominate dispersion processes.

The modeling methodologies discussed above also can be applied to transport in complex terrain. Thermally-driven systems, including drainage flows, anabatic winds and convection over heated mountain slopes, can produce a range of vertical transport phenomena not unlike those found in coastal zones.

Additional experience is still required to ascertain how best to apply these new tools. The cases selected here for demonstration all represent flat coastal or complex terrain mesoscale circulations during fair weather. Other weather systems, especially those in which convective precipitation is involved, will
require more advanced model initialization techniques. On the other hand, fair weather land and sea breezes represent a significant fraction of the mesoscale events at many coastal sites.

The specification of the horizontal mesh size is one of several important prognostic model design factors. In order to resolve a topographic feature, it should be represented by at least four grid cells. Thus, actual model "resolution" can be stated as four times the horizontal mesh size for that portion of the domain covered by the finest grid. In areas of complex coastlines such as KSC it would appear that Δx values approaching 1000 m are desirable.

The larger challenges to taking advantage of these new tools are not necessarily technological issues. Rather, the major questions may well involve changing long entrenched regulatory practices, as well as providing user training and access to the technologies in question. In addition, extensive validation of the new models with tracer tests and field measurements is mandated so that managers can quantify the degree of reliability and accuracy inherent in these new techniques. A series of papers to advance these goals is planned.

ACKNOWLEDGMENTS

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Figure 1a. (top left) Perspective view, looking north along the western shore of southern Lake Michigan, showing an LPDM simulation of a fumigating elevated plume from a shoreline source located near the Illinois-Wisconsin border, about 1200 LST, during a period of stable onshore flow from the lake over the heated land during mid-May. Figure 1b (top right). Plan view showing the increased horizontal dispersion occurring after the thermal internal boundary layer (TIBL) intersects the base of the elevated plume beginning about 7 km inland. Figure 1c. Maximum computed normalized surface layer concentrations along the plume centerline as a function of distance inland.
Figure 2. Four views from the RAMS two-dimensional model run for a typical July lake breeze in a 2-D plane across Lake Michigan at 1400 LST. Domain extends from surface to 2500 m AGL. The horizontal section extends from 35 km inland to 15 km offshore. Shown are (a) the streamlines, (b) the u (east-west) wind component (m/sec), (c) the potential temperature (°K) and (d) the vertical motion (20 cm/sec contours). The land portion of the domain is shown as a heavy line along the bottom of the graphs.
Figure 3. (left) Plan view of a simulated plume released from a 50 m high shoreline source into a weak lake breeze along the Lake Michigan shoreline. Figure 3. (right) Perspective view of the plume from the southwest showing large quantities of the plume being translocated vertically due to the strong updrafts in the lake breeze frontal zone.

Figure 4a. (left) Modeled normalized surface layer concentrations at the center line of the plume shown above, demonstrating a dramatic decrease as the plume intersects the lake breeze frontal updrafts. Figure 4b (right). Typical trajectories, calculated utilizing only surface winds (trajectory a) and the complete 3-D RAMS wind field (trajectory b).
Figure 5. (top) RAMS/LPDM simulated plume from shoreline source released into southwesterly synoptic flow over Lake Michigan, at 2 hours after 0530 LST start. Figure 5. (middle) Plume at the end of the four hour release, 0930 LST. Figure 5. (top) Plume at 1130 LST. Particles on west shore extend to about 1500 m AGL.
Figure 6. Five 2-D realizations of a lake breeze in a 3000 m deep east-west plane across southern Lake Michigan using the RAMS model at 27, 9, 3, 1 and 0.33 km horizontal mesh. All frames at 1500 LST. Shown are the U wind component, m/sec (left) and the W vertical motion, cm/sec (right). The lake surface is shown as a darkened line. The top of the lake breeze inflow is indicated by a darkened line, with negative values shown as dashed lines.
Figure 7. Five realizations at 1400 LST of a continuous plume of particles released from a shoreline, 3 m AGL, beginning at 1630Z and continuing until 2030Z, using the Lagrangian Particle Dispersion Model driven by the RAMS prognostic meteorological model. The RMS model was run with five different horizontal mesh sizes. The XY (plan) view of the plume is shown (left) and the XZ view looking north (right). The XZ section is 1500 m high and the horizontal width of both views is 189 km.
Figure 8. RAMS-predicted surface layer wind streamlines at the three mesh sizes (80, 16, 4 km) used for the LMOS domain simulations of the 16-19 July 1991 ozone episode. A weak lake breeze front is present along the western shoreline, penetrating only a few kilometers by late afternoon. The inflow layer was no more than 200 m deep.
### Maximum vertical motions (cm/s)

2-D non-hydrostatic mode

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Table I. Maximum upward vertical motions (cm/sec) in a lake breeze frontal zone as a function of time and model mesh size (Δx).

### ESTIMATED RAMS MODEL EXECUTION TIME

PROCESSORS: IBM RS/6000-550 and CRAY X/MP

WITHOUT NESTING, MICROPHYSICS

Generic domain size: 50 x 50 km • Vertical levels: 40 • Duration: 12 hrs

(multiply run times by 1.44 for typical 4-level nest)

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Table II. Estimated 3-D and 2-D RAMS model run times on available computer systems for the indicated domain as a function of the size of the innermost mesh of a nested grid, prognostic model. The figures are extrapolated from test runs using an IBM RS/6000-550 and a single processor Cray X/MP.
Figure 9a. (left) RAMS model evaluation using graphical display of predicted surface layer (10 m) winds versus observed hourly average wind vectors. Figure 9b. (right) RAMS-predicted, 10 m isotherms (°C) and observed temperatures.
Figure 10a. (top) Model predicted temperatures versus those observed at 2 m above the surface for a three day period for a vessel anchored in south central Lake Michigan, from the lowest (50 m) layer on the 16 km grid. Figure 10b. (bottom) The same, except for the 10 m model level on the 4 km grid.
Figure 11a. (top) Domain-averaged model wind speed at 10 m in the 4 km grid compared to all available observations for a three day period. Figure 11b. (bottom) The same, except for wind direction.
Figure 12. The surface synoptic pattern at 1200 UTC, 16 July 1991, the date of LMOS Tracer Test #2. The domain coverage of the nested 16, 4 and 1.33 km (not used) RAMS grids over Lake Michigan are shown.

Figure 13. The maximum observed hourly ozone values (PPB) in the LMOS domain on 16 July 1991. Values in excess of 120 PPB on the western shore were confined to a narrow band less than 10 km wide.
Figure 14. Doppler sodar wind time-height section on the shoreline at Zion, IL, near the Wisconsin-Illinois border, at the point of tracer release for 16 July 1991 (times LST). The heavy line indicates the lake breeze inflow (defined as $u < 0$ wind components).

Figure 15. Ozonesonde (left) and rawinsonde (right) observations made over Lake Michigan in mid-afternoon, 16 July 1991. Note the deep ozone layer extending to the base of the synoptic inversion, the shallow surface inversion over the water and the 200 m layer of onshore winds.
Figure 16. NAWC SF₆ sampling aircraft flight tracks within 30 km of the release point and within the first three hours after the start of the release. The flight track is projected onto an east-west plane. The shaded area shows the region in which SF₆ tracer was detected in a several kilometer wide column extending almost vertically to above 1600 m MSL. This corresponds closely to the lake breeze front updrafts.

Figure 17. NAWC SF₆ sampling van track (dark line) and observed tracer concentrations (vertical lines). The SF₆ release point is indicated. High values are noted for the first 10 km north-northwest of the site, but only lakewards of the lake breeze front. Very low values are detectable in the marine air for another 35 km north along the shoreline.
Figure 18a. (top) LPDM simulation of tracer plume, 2 hours after start of release, showing all particles projected onto an east-west plane, and a 6 minute portion of the sampling aircraft flight. Figure 18b. (bottom) The same, but for a plan (XY) view.
Air Pollution

Figure 19. Analysis of the surface wind streamlines at 1200 LST, 7 November 1988. Wind data were compiled from approximately 60 KSC mesonetwork, National Weather Service and FAA stations. The dashed line indicates the persistent convergence zone features.

Figure 20. Analysis of the location of the observed major convergence zones associated with the sea/island breezes of 7 November 1988. Times are UTC (Z), which are 5 hours ahead of the local standard time (LST). Note the persistent convergence onto southern Merritt Island and, to a lesser extent, the Cape Canaveral area. The Atlantic sea breeze front moved steadily inland all day.
Figure 21. RAMS surface wind streamlines at 1200 LST, 7 November 1988, for most of Florida, but only using the 9 km coarse mesh. Note that while the Atlantic sea breeze is well defined, the fine structure induced by the complex coast line in the KSC region is not resolved.

Figure 22. RAMS surface layer wind streamlines at 1200 LST, 7 November 1988, showing the innermost 1000 m nest. TIX is the Titusville Airport on the mainland, X68 the Shuttle Landing Strip on Merritt Island, and 003 is an anemometer site on Cape Canaveral.
Figure 23. Maximum upward vertical motions in the lowest 2000 m over the KSC area, 5 cm/sec contour intervals, at 1200 LST, showing updrafts greater than 130 cm/sec in the Atlantic sea breeze frontal zone south of TIX as well as 45 cm/sec updrafts over the southern Merritt Island convergence zone.
Figure 24. The effect of model mesh size on resolving airflow over the complex coastline. Shown are east-west vertical planes, 2000 m deep, through KSC, portraying the UW wind streamlines for the 9 km and 1000 m grids. Land areas indicated by a heavy underline.
Figure 25a. (left) Plan view at 1700 LST, 7 November 1988, of an LPDM-predicted particle plume from a continuous release, beginning at 1100 LST from a 2 meter source located over the Indian River. Figure 25b. (right) The same plume, but seen from a southwesterly perspective, revealing the vertical translocation and bifurcation of the plume induced by the regions of organized mesoscale vertical motion.

Figure 26. Schematic of the bifurcating plume shown in the previous figure. The plume from the low-level source initially moves inland in the Atlantic sea breeze inflow. It rises rapidly in the strong updrafts in the sea breeze front over the Florida mainland. Some of the plume matter subsides back into the sea breeze inflow due to strong subsidence over the Indian River and then undergoes "second trip" fumigation as it moves inland again some 20 km south of the source. The other branch of the plume, ejected higher into the gradient flow, drifts almost due eastward as it exits the region.
Table III. Distribution of radionuclide aerosols resulting from a Space Shuttle launch explosion. The ten aerosol size classes are each represented by 4000 particles. The fall speed (cm/sec) and the surface deposition probability once within 25 m of the surface are indicated.

<table>
<thead>
<tr>
<th>Particle Diameter (micron)</th>
<th>Fall speed (cm/sec)</th>
<th>Activity/Particle (Curie)</th>
<th>Deposition probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.60</td>
<td>118.40</td>
<td>7.025x10^{-2}</td>
<td>1.00</td>
</tr>
<tr>
<td>38.30</td>
<td>44.30</td>
<td>5.475x10^{-2}</td>
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<td>26.00</td>
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<td>4.910x10^{-2}</td>
<td>1.00</td>
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<tr>
<td>16.50</td>
<td>8.20</td>
<td>4.286x10^{-2}</td>
<td>1.00</td>
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<tr>
<td>8.53</td>
<td>2.20</td>
<td>1.765x10^{-2}</td>
<td>1.00</td>
</tr>
<tr>
<td>5.55</td>
<td>0.93</td>
<td>6.500x10^{-2}</td>
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</tr>
<tr>
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</tr>
<tr>
<td>2.60</td>
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<td>1.850x10^{-2}</td>
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</tr>
<tr>
<td>1.65</td>
<td>0.15</td>
<td>1.775x10^{-2}</td>
<td>0.15</td>
</tr>
<tr>
<td>0.79</td>
<td>0.06</td>
<td>3.025x10^{-2}</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Figure 27. Simulated drifting debris cloud of toxic particles about one hour after the explosive destruction of the Space Shuttle at 1000 m over the KSC launch site. Wind and turbulence fields are derived from the 7 November 1988 RAMS simulation. Most of the heaviest particles (D>10 μm) are already deposited on the surface, while the lightest ones continue suspended aloft. The horseshoe shaped cloud results from the medium sized particles being entrained into the band of upward motion extending southward from Cape Canaveral.
Figure 28. Calculated maximum surface deposition as a function of distance from the accident sub-point for all sizes of plutonium oxide particulates for explosions centered at both 300 and 1000 m AGL.

Figure 29. Calculated maximum surface deposition of plutonium oxide particulates as a function of range from the 300 m AGL accident subpoint for (1) all particle sizes, (2) only 63 μm diameter particles and (3) only 0.79 μm diameter particles.
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Centerline Air Concentration of Plutonium Oxide Particulate in the lowest 10 meters from a 300 meter release

- All Particles
- Diam = 0.79 micron
  Vdep = 0.00057 m/sec

Distance from Release (km)

Centerline Air Concentration of Plutonium Oxide Particulate in the lowest 10 meters from a 1000 meter release

- All Particles
- Diam = 0.79 micron
  Vdep = 0.00057 m/sec

Distance from Release (km)

Figure 30a. (top) Calculated maximum atmospheric concentrations of plutonium oxide particulate in the 10 m layer as a function of range for all sizes of particulates and only for those of 0.79 |im size for accidents occurring at 1000 m AGL. Figure 30b (bottom) Same but for 300 m AGL.
Figure 31. Schematic of the Emergency Response Dose Assessment System (ERDAS) planned for operational testing at the Kennedy Space Center in 1993.
Figure 32. The approximate domains of the three grids (60, 15 and 3 km) planned for use in the ERDAS at KSC and examples of wind fields resolved on the 15 and 3 km grid (showing wind vectors for every second point).
Figure 33a. (left) Smoothed topography over part of the Grand Canyon region, with 10 decameter isopleths. Figure 33b. (right) Complicated plume patterns resulting from application of RAMS and the LPDM (Stocker and Pielke, 1990).

Figure 34. LPDM-simulated plumes from multiple sources of SO₂ in Virginia. This image represents a single scene from a multi-day animation sequence of the plume dispersion under the influence of sea breezes and topographically controlled flows. Courtesy of M. Uliasz.
Figure 35. Predicted u wind component (easterly values dashed), 2 m/sec isotachs, over the Colorado Rockies and adjacent plains, grid 2 (Δx=760 m) of a 3-grid 2-D LES simulation, during the late morning (Cotton et al, 1991).

Figure 36. Potential temperature (°K) over grid 3 (Δx=190 m) of the 2-D nested grid LES run showing the convective boundary layer structure from the Front Range east into the plains (Cotton et al. 1991).
Figure 37. Same as previous figure, but showing RAMS-simulated turbulent kinetic energy associated with large eddies in the CBL.

Figure 38. Same as previous figure, except showing water vapor mixing ratio (gm/kgm) associated with CBL eddies.
Figure 39a. (left) RAMS-simulated, large scale, surface layer wind flow over Spain, 40x40 points, using Δx = 32 km. Figure 39b. (right) Grid 3, 40x40 points, with Δx = 2 km, centered in the mountainous terrain near the Guardo power plant.

Figure 40. Example of RAMS-predicted turbulent eddy flow over a large rectangular building, after 180 seconds run time, using Δx = 2 m (Nicholls et al., 1992)