Comparison of Lake-Breeze Model Simulations with Tracer Data

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ABSTRACT

During the 1980s there were numerous occurrences of ozone exceedances of federal standards in the Lake Michigan area. An intensive field program was undertaken in order to gain insight into the dispersion patterns in the area. A field experiment, which included a tracer release, was conducted on 16 July 1991 and provided the data used to test the skill of a meteorological and dispersion modeling system. Specifically, the Regional Atmospheric Modeling System (RAMS) provided meteorological input to a Lagrangian Particle Dispersion Model.

The RAMS model was run at a variety of grid spacings and configurations, and the output was compared to observations for each simulation. It was found that a minimum ∆x of 4 km and a 3D setup were needed to accurately simulate the meteorology of 16 July 1991. The dispersion model was then run for each meteorological simulation and compared to aircraft data. Again the 3D simulations produced the best correlations to tracer data. It was also found in the 2D simulations that the highest correlation to meteorological variables was derived from the finest-resolution meteorological simulation. Finally, a commonly used Gaussian plume model, the Industrial Source Complex Model, was run using the best RAMS produced meteorology. It was clear from the results that this model is not applicable to this case day and, in fact, failed to produce a nonzero correlation to the aircraft data.

1. Introduction

The Lake Michigan Ozone Study (LMOS) is a multistate effort of Wisconsin, Illinois, Indiana, and Michigan, as well as the United States Environmental Protection Agency (EPA). One of the goals is to develop a photochemical model capable of predicting the transport and formation of ozone and its precursors (Gerritson 1992). This effort was a response to the exceedingly high number of days in that area that were in violation of the 12-h maximum ozone level set by the National Ambient Air Quality Standard (NAAQS).

During the 1980s there were 213 days in which at least one monitoring station experienced ozone levels greater than 120 ppb (Lyons et al. 1992). Many of the highest levels were confined to a narrow band running roughly parallel to the Lake Michigan shoreline. Many ozone precursors, such as volatile organic compounds (VOCs) and nitrogen oxides (NOx), originate from highly industrialized sources near the shoreline regions of northern Illinois and Indiana and southern Wisconsin.

LMOS was coordinated to assist in developing modeling efforts. It is hoped that the model used here will help in assessing the impact of different sources on other areas within the LMOS domain. Besides the Regional Atmospheric Modeling System (RAMS) and the Lagrangian Particle Dispersion Model (LPDM), other models used for assessment include the Urban Airshed Model (UAM, Morris et al. 1992) and the Empirical Kinetics Modeling Approach (EKMA, Dodge 1977). Indeed, much of the preliminary design of the tracer study was accomplished through the RAMS–LPDM couplet (Lyons et al. 1992).

2. Model description

a. The RAMS model

The model used to predict the meteorological fields for 16 July 1991 was the RAMS model. The RAMS model is a primitive equation prognostic model. The model was run in a nonhydrostatic compressible mode for all simulations. The basic model equations can be found in Pielke et al. (1992). The model was run in both 2D and 3D modes. In the 2D mode there is no variation in north–south direction, and the solution is computed in an east–west-oriented vertical plane, while the 3D solution is computed in all spatial directions.
The model was set up for each run with the following characteristics:

- topography with a terrain-following \( \sigma \) coordinate system;
- 30 vertical levels with a minimum grid spacing of 10 m at the surface, stretched to 800 m at the model top;
- horizontal domain—a stereographic tangent plane;
- Arakawa C grid;
- second-order leapfrog time differencing with time splitting (Tripoli and Cotton 1982);
- Smagorinsky deformation \( K \) turbulence closure with a Richardson number enhancement (Tremback et al. 1987);
- Louis (1979) surface-layer parameterization;
- multilayer soil model based on Tremback and Kessler (1985);
- vegetation based on Lee (1992);
- spatially varying vegetation;
- rigid lid for the upper boundary;
- radiative lateral boundary based on Klemp and Wilhelmson (1978a,b); and
- water vapor treated as passive tracer.

b. Four-dimensional data assimilation (4DDA) and nudging

In an inhomogeneously initialized simulation an isentropic analysis package is used. First the National Meteorological Center (NMC) 2.5° analyzed field data is fed into a pressure analysis stage where it is put on a user-defined grid that more than encompasses the area to be modeled. Next this pressure data is used as input to an isentropic analysis stage that interpolates the pressure data onto an isentropic grid. In addition, rawinsondes are objectively analyzed to the isentropic grid. Finally, surface data is objectively analyzed to a horizontal grid.

RAMS uses the files created by the isentropic analysis package to nudge the RAMS solution to the observations near the lateral boundaries. The equation used is a tendency equation described by Wang and Warner (1988). The nudging is nonzero and weighted the most at the five outermost grid points. Given the duration of the simulations (12 h) and the near homogeneous nature of the synoptic forcing, it is probable that the variable initialization combined with nudging will have little impact on the solution obtained but was used nevertheless to provide the most realistic synoptic forcing possible.

c. LPDM

The LPDM used in this study was modified to account for the observed shallow thermal internal boundary layer (TIBL). The main equations of the LPDM can be found in McNider et al. (1988) and Moran (1992). The LPDM incorporates RAMS-generated mean flow fields as well as turbulent components parameterized from RAMS data. The particles then are advected using this information.

The LPDM accounts for effects of the TIBL by diagnosing boundary layer heights based on the Richardson number and the vertical profile of the momentum exchange coefficients. The Richardson number-based height aids in defining the TIBL. The TIBL is characterized by extremely stable temperature profiles and subsequently produces nearly no dispersion of an air mass contained within it.

The LPDM allows the user to pick multiple sources of point, line, area, or volume types. The LPDM also can take 2D meteorology and be run in a 3D mode for particle modeling. This feature was employed for the various 2D runs.

d. ISCST

The Industrial Source Complex Short Term (ISCST) Model (Bowers et al. 1979) is an EPA-approved Gaussian plume model. It can be run in a long-term (LT) mode (multiple years) or a short-term (ST) mode (days). For this particular application the ISCST was run in a short-term mode. As Gaussian plume models generally do, ISCST uses a steady-state synoptic background as forcing for dispersion. The model uses stability class and wind information from a meteorological tower, as well as morning and afternoon soundings, to supplement mixing-depth information. Other features of the ISCST are

- specification of multiple sources and source types;
- deposition calculations;
- user specification of the vertical temperature gradients and their subsequent assignment to Pasquill–Gifford classes;
- user input topography and/or flagpole receptor heights;
- choice of a default EPA standard run or customized parameters; and
- rural or urban modes.

A rigorous derivation of the Gaussian plume equation can be found in Pielke (1984). In addition, he points out several well-known difficulties of these models when applied to complex mesoscale circulations. They are

- oversimplification of fundamental conservation relationships;
- inability to represent recirculation, that is, wind profiles are unidirectional in the vertical;
- the use of a constant stability class, although the terrain may be heterogeneous.
These limitations will be shown to be significant in the situation modeled in this study.

3. Meteorological simulations

a. Initial conditions

There were a total of six simulations performed in hopes of ascertaining the effects of mesh size, dimensionality, and the lake on the meteorology and dispersion. A summary of configurations are presented in Table 1. Detailed discussions of initialization procedures aids in understanding the differences that developed between the simulations.

All the homogeneous simulations were initialized using a sounding taken from the 3DV simulation at 0600 LST 16 July from a cell located 32 km west of the Zion Nuclear Power Plant. The homogeneously initialized runs were then integrated forward 12 h. It should be noted that the 3DV simulation was started at 0000 UTC 14 July, thus it had been integrated for 36 h already. This was done because the simulation was used for a 3-day episode in other work and to eliminate numerical noise present during the initial hours of integration in an inhomogeneously initialized simulation. The homogeneous simulations used the sounding altered in the following manner. An estimated planetary boundary layer (PBL) height was calculated from the 3DV run by examining the vertical change of lapse rates of the sounding location. The winds below this height were turned roughly 30° clockwise in the 2D runs. This was necessary because 2D simulations tend to turn more to lower pressure than in the 3D runs.

The homogeneous simulations were initialized using the sounding shown in Fig. 1. The sounding has a negative area of roughly 5600 J kg⁻¹, with a heating of

![Fig. 1. Sounding taken from the 3DV simulation.](image-url)
396 J kg\(^{-1}\) required to reach a convective temperature of 32\(^\circ\)C. The convective condensation level was found to be 820 mb, the lifting condensation level 410 mb, and the K index was calculated to be 35. Total precipitable water was calculated as 2.14 cm. The sounding also possesses a mean directional wind shear of 23\(^\circ\) km\(^{-1}\) and a wind shear in magnitude of 4.1 m s\(^{-1}\) km\(^{-1}\) in the lowest 3 km.

The presence of the nocturnal jet is evident in the sounding, as exemplified by the low-level winds in excess of 10 m s\(^{-1}\). The sounding displays dryness all the way up to the last level recorded by the sonde. This was the justification for treating water vapor as a passive tracer in the model.

Surface characteristics were initialized using a variety of datasets. For topography in the homogeneous simulations a 30-s topographical dataset was used for all mesh sizes. The coarsest mesh in the 3DV run covered an area that was outside the areal coverage of the 30-s dataset at some points; consequently, at those locations a 10-min topographical dataset was used.

The land percentage and vegetation for the simulations were derived from 30-s data supplied by the United States Geological Survey (USGS). Again, the coarse mesh for 3DV was initialized using a 10-min dataset. The USGS data contains 176 different vegetation classes. These classes were reduced to 18 total classes, consistent with the Biosphere–Atmosphere Transfer Scheme (BATS) (Dickenson et al. 1986), which are then used by RAMS. The variability, which increases with decreasing mesh size, in vegetation can produce solenoids in both the north–south and east–west directions, much like the quasi-north–south orientation of the lake breeze. For transport on longer timescales this would invariably have an impact on dispersion (Lee 1992; Moran 1992; Pielke et al. 1991). The variable land percentages along the coast will have similar effects. In 2D the coastal variation in land percentage is not realized since the land percentage is constant as one goes poleward or equatorward. The magnitude of these differences on the resultant dispersion will be ascertained in the next section.

One more surface characteristic, which was set differently for 3DV versus the other simulations, was sea surface temperature (SST). In the 3DV simulation the SST varied over the lake area, while in the other runs it was set to a constant. It was shown in Xian (1991) that the use of spatially varying SST versus an averaged SST has little impact on the meteorology of the lake breeze as long as the lake is colder than the air above.

As mentioned earlier, the 3DV run employed files that were used to nudge the entire domain toward an observed pattern. These files were spaced at 6-h intervals and created separately for each grid. This allowed finer details to be assimilated for finer mesh size. Previously it was mentioned that the synoptic forcing on the day was near constant, and that this could minimize the effects of nudging on the final solutions.

Soil moisture was initialized using the U.S. Department of Agriculture’s soil moisture survey. For 3DV this information was digitized to the coarsest mesh then interpolated to the finer grids. An average of the 16-km 3DV grid values, at all soil grid levels, was computed and that value was used to initialize the homogeneous runs at each corresponding level.

b. 2D and 3D comparisons of X–Z sections

A series of meteorological plots in an east–west vertical (X–Z) plane are shown, through the Zion data plane, to demonstrate the differences between simulations. All output plots of meteorology that follow will be in the same format. Starting in the upper left and proceeding clockwise the first plot is 2D2, followed by 2D4, 2D16, NL, 3DV, and 3DH. In all plots the contours limits and intervals have been kept constant and are listed in the captions.

The initial fields of U, the east–west component of velocity, and \(\theta\), the potential temperature, are shown in Figs. 2 and 3. The differences in the initial states are minimal except in the 3DV case. This case exhibits lighter winds and a slope to the \(\theta\) isolines. In the heterogeneous case the variable initialization, and the fact the simulation has been integrated for the 36 hours of model time, has resulted in the inhomogeneities present.

Figure 4, taken at 1300 LST shows that all simulations with a land water contrast have developed a lake breeze of varying degrees. The 2D2 and 2D4 runs show remarkable similarities. Both have an inflow depth of roughly 200 m and have penetrated inland about 4 km. In contrast, the 3DH and 2D16 runs exhibit shallow inflows of about 125 m. While 3DV has an inflow depth of around 200 m, it still possesses a unique structure to the solenoid. The vertical motion displayed in Fig. 5 increases as \(\Delta x\), the horizontal grid spacing, decreases, which is expected. Of course the increase has bounds, as several 500-m simulations showed the lake-breeze updraft magnitude was nearly equivalent to that obtained in the 2D2 simulation. Yet 2D16 still does not register vertical motion of a magnitude greater than \(\pm 2.5\) cm s\(^{-1}\) and does not reach this value until 1400 LST.

By 1600 LST the lake-breeze circulations are near or have peaked in the intensity of upward vertical motion. In the 3D simulations peak updrafts were not in excess of 15 cm s\(^{-1}\), while 2D2 had peak updrafts of 35 cm s\(^{-1}\). The 2D4 simulation had nearly the same updraft velocity as the 2D2 simulation (nearly 30 cm s\(^{-1}\)), indicating that the lake breeze is resolved properly with a 4-km mesh size. This is an important result since the 3D finest mesh sizes also used a 4-km \(\Delta x\). This is important in terms of computational time since the computational time roughly increases inversely proportional to the square of the mesh size.

The final set of X–Z figures show the lake breeze in a varying state of decay. Shown in Fig. 6 is the U ve-
Fig. 2. East-west horizontal cross section (X-Z) of east-west component of velocity \( u \) (m s\(^{-1}\)) contoured from -5 to 15 in 1 m s\(^{-1}\) intervals at 0600 LST. Solid lines are positive values and dashed lines are negative values.

Velocity component at 1800 LST. The 3D simulations show that the lake breeze has nearly collapsed, while the 2D runs exhibit a slight weakening from the previous hour plots. This is clearly related to the extra degree of freedom inherent in the 3D simulations. The weakening lake breeze shows up in the reduced potential temperature gradient plotted in Fig. 7. The 2D simulations still display a TIBL, while in the 3D simulations the TIBL is eliminated. At this time the vertical motion has also weakened considerably in the 3D simulations, while the 2D simulations still exhibit fairly strong vertical motions. This is shown in the contours of vertical motion in Fig. 8.

c. 3D comparisons of X-Y sections

All horizontal cross section (X-Y) plots in this section will be in the same format. The
top two plots will be from NL, the middle two plots from 3DH, and the bottom two plots are from 3DV. Variables plotted, contour intervals, and limits are listed in the captions below the figures.

The lake breeze is fairly well developed by 1300 LST. Figure 9 shows that the 3DH lake breeze has penetrated farther inland than the 3DV counterpart, as indicated by the dashed line on the U plot. An interesting feature unique to the 3D lake simulations is observable near Milwaukee, where the land–water boundary forms a peninsula. There is an obvious splitting of the magnitude of the lake breeze at this point, where it is weakened by the lake breeze north and south of the convergence, as well as the orientation of the direction of the prevailing wind to the shore.

d. Model comparison to meteorological observations

The Zion 10-m tower data were used to compare the output from the RAMS model. A synthetic tower
was created from the RAMS data by linearly interpolating between grid points to the corresponding location of the towers near Zion. This was done only in the horizontal direction since the 10-m level was simulated in the RAMS model. This comparison provides information about model performance and bias by performing correlations to wind speed and temperature at each of the four meteorological towers located onshore, 3, 8, and 24 km inland from Zion.

Figure 10 shows plots of time series for wind direction. The 180° line has been darkened to indicate lake-breeze onset. The upper-left panel is the time series at the Zion shoreline site. The diagram shows that the observed wind begins to turn around slightly after 11 LST. The 2D2 runs is the only simulation that predicts the turnaround closest to its occurrence. The other simulations have the lake breeze coming ashore between 1000 and 1100 LST. These results are all acceptable since the temporal resolution of the observations is only 1 h. The other sites are valuable for comparing the total inland penetration of the lake breeze. The upper-right panel shows that all simulations
except 3DH predict that the front reached the 3-km site, which agrees with the observations. Notice that the 3DV simulation barely reaches the 3-km site. Farther inland, at the 8-km location, the data implies that the 2D2, 2D4, and 2D16 simulations all have reached the tower. This is in disagreement with the observations, which show wind directions from 200° to 240°. None of the 3D simulations reach the 8-km tower. (Of course, the NL run would not reach because it never produces a lake breeze; it was done to study the impact of the lake on dispersion. Again this is related to stronger convergence generally predicted in the 2D simulations. This does have an impact on the dispersion results, as will be explained in the next section. The temperature curves displayed in Fig. 11 bear out what was seen in the previous meteorological cross sections in that the temperature was generally a couple of degrees warmer in 3DV. At the Zion site, shown in

![Graph](image-url)
the upper left, the drop in temperature as the front passes is fairly evident in all cases except NL and 3DV, although the 3DV curve does level off. The temperature drop shows the same trends in each model run except none of the runs predict the temperature increase when the front moves back offshore. The 8-km site shows fairly good agreement except the 2D2 and 2D4 runs that penetrated too far inland, bringing in the cooler air. Finally, the 24-km site shows similar curves for all simulations. The 3DV simulation appears to perform the best, and this could be a benefit of the added information from the nudging.

In order to quantify this information in a more detailed manner, correlation coefficients, \( r \), were computed at the selected sites for wind speed and temperature. The results are contained in Fig. 12. The site locations are identified as before. Moving to the upper panel, correlations for total wind speed
in the 3DV simulation show the best correlation. The effects of the frontal boundary passing, or being in close proximity to the 8-km site, seems to degrade the correlations for the other simulations that form a lake breeze. The nudging is again the most plausible explanation for the superior 3DV results. Finally, the lower panel shows correlations for temperature. The results are quite similar in all cases. The most difficult temperature prediction should occur where frontal boundaries are observed, and this is confirmed by the results. Notice the correlations all increase as one proceeds inland, farther away from the convergence zone.

4. Comparison of LPDM simulations

a. Characteristics of the LPDM simulations

The tracer SF6 was released at 1241 LST 16 July 1992. A total of 600 kg were released in 4 h, corre-
Fig. 8. East–west vertical cross section (X–Z) of vertical component of velocity $W$ (m s$^{-1}$) contoured from −0.525 to 0.975 in 0.05 m s$^{-1}$ intervals at 1800 LST. Solid lines are positive values and dashed lines are negative values.

A blower with a 15-ft PVC pipe of 1-in. diameter was deployed to vent the SF$_6$ from the release site, Waukegan Harbor (Wilkerson 1991), corresponding to a 5-m effective release from a point source. Roughly 1 h after the release began, aircraft flights started. The aircraft made multiple transects at a variety of heights, ranging from 100 to 1600 m AGL. The aircraft also varied in distance from the release site, reaching a maximum distance of 50 km from the harbor (Bowne et al. 1991).

The LPDM was run off the meteorology of the six simulations. Based on the release data, the LPDM was configured to use an effective release height of 5 m AGL. The release was started at 1241 LST and continued for 4 h. Locations of the particles were tabulated every 15 min of simulation time. A total of 20 000 particles were released at a rate of 1.33 particles per second. The 20 000 figure was arrived at after several sensitivity runs were completed. It was found that results improved steadily as the number of particles was
increased from 1000 to 20,000 particles, at which point the improvement was no longer perceptible. Up to 100,000 particles were released for this sensitivity comparison, and no appreciable difference was noted above 20,000.

Figure 13 shows an X–Y cross section of the simulated particle plume after 1-h simulation time. The order of the plots is as follows. Moving clockwise and starting in the upper-left panel is the 2D2, followed by 2D4, 2D16, NL, 3DV, and 3DH. Only the 2D2 and
2D4 plumes show similarity. Inspection of the plots close to the source shows that the plume in these two runs moves inland farther than any of the other simulations. Notice the narrowness of the plume as it moves inland in the extremely stable lake air. The air changed from a Pasquill–Gifford (determined from vertical gradients in theta, between the 10- and 50-m model levels) class of A to an F when the front passed. In the case of the 2D2 and 2D4 simulations the front has moved farther inland. The 3D plumes are quite different. The 3DH plume appears to reach the front boundary rather quickly. Once the plume reaches the front it is quickly injected upward by the updraft into the return flow aloft. In the 3DV simulation it appears that the plume slides up the coast more before it is transported aloft. The NL plume appears to be Gaussian in shape, as it should be when minimal shear is present.

An X–Z cross section of the particles is shown in Fig. 14. The time and order is the same as the previous figure. The base of the plumes show considerable divergence from one another. The 2D2 and 2D4 plumes are the widest because there is greater inland transport in these simulations. The 3DV plume is the narrowest, probably a result of more southerly flow in this simulation. The LPDM parameterization appears to have reasonable results, even in the 2D16 run where vertical motions were less than 2.5 cm s⁻¹. Despite the weakness of the updraft the particles still get transported aloft.

Particle positions in an X–Y plane after 5 h of simulation exhibit several similarities in spatial extent for the lake-breeze simulations, as displayed in Fig. 15. Notice the NL plume has no similarity to the others. The 3DH, and to a lesser degree the 3DV, simulations show the 3D nature of the coastline, while the 2D runs
exhibit a straight line to the left edge of the plume. Because of more southerly flow in the 3DV case, the 3DV plume is farther north than any of the other plumes, while the homogeneous simulations show more particles to the east northeast of the release site.

Overall, it appears that the homogeneous runs produced quite similar results. All homogeneous plumes appear to have the same spatial extent in the horizontal direction.

The NL simulation was performed to ascertain the impact of the lake on dispersion. One way to quantify the lake effect was to calculate the percent of particles recirculated from the beginning of the release. A recirculation is defined as a particle first moving west, then
east, and then back to the west. This was computed over a long enough interval to remove the counting of false recirculations due to turbulence. The percent of particles recirculated is defined as the number of particles that undergo one or more recirculations, divided by the total number of particles. Table 2 provides a summary of this data. The second column from the left lists the ratio of particle recirculations to total particles released, followed by percent of particles undergoing recirculation. The impact of the lake is obvious. From 70% to 80% of the particles are transported in a solenoidal circulation. This behavior of pollutant parcels along the west shore of Lake Michigan was originally suggested by Lyons and Cole (1976). This num-

![Diagram showing wind direction and speed correlation coefficients](image-url)
of flight the plane detected no SF$_6$, at which point it made a low transect just north of the harbor. The first part of the flight concentrated on measurements near the release point at a variety of heights, while the last couple of hours were flown at distances of 20–50 km to the north and east of Waukegan Harbor.

Correlation coefficients between the aircraft data and the concentrations predicted by each simulation were calculated. There is a question when calculating the correlation values. Since the LPDM output is produced at a frequency of 15 min, and the aircraft data is at 1–2-s intervals, what averaging time should be used for determining the correlations? Instead of trying to answer this question, the correlations were calculated over a spectrum of averaging times, ranging from 60 to 900 s. The results are displayed in Fig. 16. It is clear that the 3DH shows acceptable correlations. The values range from 0.6 at 60 s to roughly 0.9 at 900 s. Notice that the 3DH line does not have the same amount of variability as the other plots. The 3DV results have the next best correlations, followed by 2D2 and 2D4. The similarity of 2D2 and 2D4 curves further supports the assertion that a 4-km mesh is suitable for the 3D grids, and a 2-km mesh is not necessary. The NL and 2D16 show the least amount of correlation to the data, as expected. The order of agreement was quantified by integrating the area under the curves.

number appears to be fairly consistent throughout the entire set of lake-breeze simulations. If this number were realized for the entire urban corridor along the west side of the lake, the potential impact to Wisconsin could be substantial in terms of its photochemical effects. Of course, this number is meaningless unless the tracer data verifies the LPDM results.

b. Observational LPDM evaluation

The tracer data collected 16 July 1991 was used to verify the results of the LPDM simulations. The spatial position, observed concentration, and time of day were recorded for later analysis. Software was developed to use this information by flying a hypothetical, numerical aircraft through the LPDM created plume and calculating an LPDM concentration. Each particle in the LPDM represents a certain mass of SF$_6$. By counting the number of particles in a volume along the flight path, the concentration was ascertained. Considerable testing went into the determination of a grid volume to use for the calculation. It was found that the results were optimized when the volume used was 250 m ($\Delta x$) and 100 m ($\Delta z$) perpendicular to the flight path. The third dimension was the distance between consecutive measurements, typically 100–150 m.

One hour after the initiation of the 4-h tracer release the plane took off at 1341 LST. For the first half hour
c. A comparison of the ISCST and LPDM models

One of the purposes of this study was to compare a Gaussian plume model to the LPDM. For this comparison the ISCST was run in an enhanced mode, where the meteorology from the 3DV run was used to drive the ISCST model. The 3DV results were used because the surface values were in excellent agreement with the observations. Normally the ISCST uses meteorological towers to supplement the nearest sounding. The information from the sounding is used to diagnose a probable PBL height. In this ISCST run the PBL height was supplied by the model, which varied from 1200 m at the time of the release to 1550 m by midafternoon. As mentioned in section 1d, there are some inherent weaknesses of Gaussian-based models. As stated in section 2d, they are

- oversimplification of fundamental conservation relationships;
- inability to represent recirculation, that is, wind profiles are unidirectional in the vertical;
- the use of a constant stability class, although the terrain may be heterogeneous.

Reviewing Table 2, it is apparent that the second difficulty listed above should be clearly visible in any comparison. With the confirmation that the 3DH LPDM simulation is in agreement with the observations, at least 70% of the material should recirculate. In addition, a probable transport pattern scenario would be that the material is first advected to the frontal boundary, then it is carried aloft by the frontal updraft, at which point it may either recirculate in proximity to the frontal zone or be injected into the return flow aloft. Since the wind aloft is southwesterly and the surface winds are southeasterly, the ISCST will not predict either one of these situations correctly.

Figure 17 shows surface isopleths for an ISCST run and surface isopleths for the 3DH LPDM simulation and concentrations recorded by a mobile van. The top of Fig. 17 is a perspective view of observed surface isopleths. The van's path is indicated by the dark solid

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**Table 2. Summary of LPDM recirculation data.**

<table>
<thead>
<tr>
<th>Run name</th>
<th>Ratio of recirculations to total particles</th>
<th>Percent of particles undergoing recirculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D16</td>
<td>0.88</td>
<td>70</td>
</tr>
<tr>
<td>2D4</td>
<td>1.0</td>
<td>80</td>
</tr>
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<tr>
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<td>67</td>
</tr>
<tr>
<td>NL</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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**Fig. 16. Correlation of measured SF₆ concentrations and LPDM concentrations; correlation versus interval averaging time.**
LMOS TRACER STUDY 2-July 16, 1991 14:00-21:00 CDT
DRIVE TRACK/SF6 PLUME LOCATION -<500 ppt- WEST VIEW

SF6 CONCENTRATION (ppt)

KILOMETERS FROM SF6 RELEASE (NORTH-SOUTH)

SF6 PLUME

DRIVE TRACK

Surface Concentration (log(ppt))

Surface Concentration (log(ppt))

Fig. 17. Perspective view of (a) Observations from a mobile van from 1300 to 2000 LST. Values are in ppt (Wilkenon 1991). (b) Surface isopleths in log(ppt). Left-ISCST; right-LPDM. The two panels taken at 1600 LST. Domain size is 37.5 km × 37.5 km.

line. Peak concentrations were less than 320 ppt. There were no values recorded west of 5 km inland, and those 10 km to the north of the source are sparse and all less than 50 ppt. In the bottom of Fig. 17 is the surface concentrations predicted by the ISCST model on the left and the LPDM on the right at 1630 LST. The ISCST and LPDM isopleths were produced using a logarithmic scale, with the contours in terms of the log
of the concentration in parts per trillion. The domain size in each panel is 37.5 km × 37.5 km. The differences between the ISCST and LPDM are apparent. As expected, difficulty arises for the ISCST when the particles reach the frontal boundary and are transported aloft. Clearly the ISCST cannot handle this situation. Although the ISCST model is intended to predict maximum ground-level concentrations a few kilometers from the source, it still shows values two orders of magnitude too large. In addition, the use of an atypical stability class further complicates the situation. Notice how quickly the ISCST plume widens; this is not what was observed. It is apparent that the ISCST model also has a tendency to overpredict the concentration values. Many of the isopleths were on the order of 10 000 ppt close to the source and 1000 ppt to the edge of the domain; while at the same time the LPDM predictions were on the order of 1000 ppt near the source and dropped off to roughly 100 ppt away from the source. The pattern of the observations and the LPDM are similar. Clearly the ISCST model should not be applied to areas dominated by mesoscale circulations.

5. Summary

The introduction discusses some of the general air quality trends in the Lake Michigan basin where a high number of days exceeded the federal ozone standards. The complex circulations and photochemistry associated with land–lake interactions and the urban buildup along the coastline are felt to be important causes of the large number of exceedances. A field program (LMOS) was developed to understand the source–receptor relationships in this region.

The meteorological simulations were performed for a case day at a variety of grid spacings in order to ascertain the effect of Δx on the meteorological simulations and dispersion modeling. It was found that simulations with 4 km or less grid spacing simulated the event realistically. The NL and 2D16 simulations were not representative of the lake breeze of 16 July 1991. The 2D2 and 2D4 simulations showed a stronger convergence and inland penetration, while the 3D runs exhibited a realistic penetration according to observations. A set of statistics were run to quantitatively verify the model results. Wind speed, direction, temperature, and dewpoint measured at the meteorological towers positioned around the Zion Nuclear Power Plant were correlated to meteorological towers extracted from the RAMS dataset for the entire suite of simulations. The highest correlation was calculated using the 3DV dataset, with the rest of the simulations showing similar results.

In section 3 the RAMS meteorological output was used by the LPDM to mimic the SF6 release of 16 July 1991. The release, from Waukegan Harbor, Illinois, was 4 h in duration. The results from the LPDM demonstrated an impact of the lake-breeze circulation on dispersion. It was found that upward of 65% of the particles released by the LPDM underwent at least one recirculation.

A simulated aircraft was flown through the resultant plume and a variety of correlations were computed with the actual aircraft data. This was found to be necessary because of the fine temporal and spatial resolution of the aircraft data versus the fixed temporal resolution of the LPDM-derived fields. The LPDM results were somewhat different in terms of model accuracy as found from the results of the meteorological simulations. It was expected that the most highly correlated meteorological simulations would produce the best dispersion results. Contrary to this assumption, the 3DH correlations were, on average, the highest, followed by 3DV, 2D2, 2D4, 2D16, and finally NL. Overall, the LPDM showed skill in predicting the spatial and temporal distribution of the–concentration fields.

Near the end of section 3, a brief comparison of the ISCST model and the LPDM was performed. A side-by-side comparison of the surface concentrations derived from the two models showed differences in structure and magnitude. The ISCST not only overpredicted the magnitudes, it also produced the typical Gaussian shape, with concentrations predicted to reach far inland. The LPDM concentrations were as large as those of ISCST only in close proximity to the release.

6. Conclusions and recommendations

There are several major and minor conclusions that can be drawn from the results of the study.

- The RAMS model showed skill simulating the lake breeze of 16 July 1991.

As previously mentioned, it was believed that the most highly correlated meteorology would translate into the best dispersion results. However, the correlations of the meteorological observations and the simulations were surface based. All tower observations used were taken at 10 m or less. The winds that effect the plume are those aloft, above the depth of the inflow, which was roughly 200 m in depth. The surface information was used because of the temporal and spatial sparseness of the upper-air data.

- The RAMS–LPDM coupled model system results demonstrate an ability to accurately predict the observed tracer concentration fields.

The 3DH LPDM simulation results were highly correlated to those observed by the aircraft. The fact that it had a higher correlation than the 3DV simulation is not surprising since, as mentioned in the preceding paragraph, the meteorological validation was biased to near-surface observations. The LPDM results point to a possible weakness in the system using nudging and data assimilation. The spatial sparseness of the upper-air data and the NMC analysis could actually be the cause of this weakness. The NMC analysis is performed.
on a 2.5° × 2.5° grid, which represents roughly 300 km × 300 km. The rawinsonde stations are generally farther apart than this. Thus, any information used in nudging is obtained by interpolating between data points separated by distances much larger than the mesh size. If there is a strong localized ageostrophic component to the flow, the solutions obtained by nudging will tend to diverge from the proper solution since the information aloft is smoothed in the 2.5° × 2.5° analysis.

- The lake plays a profound role in altering the wind patterns associated with the Lake Michigan basin.

The results presented in section 3 demonstrate this rather dramatically. Ageostrophic wind components developed throughout the periphery of the entire lake. On both shores, the lake breeze developed with a complex variety of magnitudes depending on the highly irregular shape of the coastline. In addition, a mesohigh developed over the southeastern portion of the lake. This in turn lead to a convergence zone southeast of the lake. Inspection of the surface winds leads to the conclusion that parcel trajectories originating from the mesohigh area could cover a full 360° of motion.

The particle-modeling results were equally dramatic. Table 2 displays the lake influence with clarity. With no lake present, there were no particle recirculations, while the rest of the simulations showed that particle recirculations were undertaken by more than 65% of the particles. The no-lake simulation showed a plume advecting to the northeast, while the other simulations indicate particles dispersing in directions ranging from the west to the east-northeast.

- The ISCST model does not produce realistic tracer concentration fields for this coastal regime.

This was expected based on the weaknesses outlined in sections 1 and 3. It would be surprising if a Gaussian plume model would be more successful than the RAMS-LPDM coupled anywhere where surface heterogeneities, wind shear, or any other mechanisms that lead to vertical transport or heterogeneous stability class are present. It is inherent in the derivation of the Gaussian plume model equations that these situations are not represented realistically.

- The 3D RAMS-LPDM system demonstrated more ability in predicting the evolution of the tracer field than the 2D RAMS-LPDM system, despite one of the 2D simulations employing a ΔX one-half the size of the finest ΔX used by the 3D simulations.

This was a result of the strong convergence and inland penetration predicted by the 2D system. Considering that the plane is sampling the plume at roughly 1-s intervals, it would be expected that the precise prediction of the location of the lake-breeze front is crucial to the predictions produced by the LPDM simulations. As noted in section 2, the 2D simulations reached the 8-km tower location, and thus went past this location to some degree, while the 3D simulations did not penetrate past this point. Assume, for instance, that the 2D frontal position prediction was 1 km too far inland (actually it was more than this). With respect to the motion of the plane, which was traveling at roughly 70 m s⁻¹, this is over 14 sampling periods. Clearly, this will decrease the magnitude of any correlation calculated.

- A grid spacing around 4 km in the horizontal direction is necessary to correctly model the lake breeze of 16 July 1991.

This conclusion, of course, is more general than an application to this particular day. This comes from experience in modeling land–lake breezes and a suite of sensitivity studies used to decide on the configuration of the various meteorological simulations performed in this study. The suggestion that at least 4ΔX is needed to resolve a feature (Pielke 1984) implies that the characteristic length of the lake breeze for this day was 16 km during the earlier hours of its development. During the first 2 h of lake-breeze onset the horizontal size of the inflow is roughly 16 km in magnitude. The horizontal extent of the feature does increase in magnitude as the simulation time approaches mid afternoon, as indicated by the late onshore arrival of the 2D16 lake-breeze front.

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