Air Pollution Transport Studies in a Coastal Zone Using Kinematic Diagnostic Analysis

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ABSTRACT

Data from a mesoscale wind analysis of a vigorous lake/land breeze circulation on 4 September 1974 along the western shoreline of Lake Michigan are available. A computer program takes subjectively analyzed observed and estimated u and v components of the wind for a 24 h period, calculates vertical motions, and then estimates the trajectory of any particle(s) released within the coastal zone. The computed three-dimensional trajectories are presented using computer graphics displays. They reveal highly complex transport processes for aerosols released from typical line and multistack point sources. Aerosol recirculation and size sorting can be found within the lake breeze cell.

1. Introduction

A considerable body of literature is developing concerning diffusion over water and in coastal zones (Lyons, 1975) but there is less known about transport mechanisms in complex coastal flows. For distances greater than several kilometers, transport may often be of paramount importance in estimating total pollutant dispersion. An understanding of transport processes is vital in such areas as deposition of heavy metal aerosols to lake surfaces (Lyons and Keen, 1975). Likewise predicting the impact zones of photochemical oxidants or accidentally released hazardous materials requires a detailed knowledge of coastal zone transport mechanisms (Lyons and Cole, 1976). While tracer studies (Sandberg *et al.*, 1970) can yield valuable information regarding resultant concentrations and dosages, the details of the actual transport often remain obscure. Direct computation of trajectories can be accomplished if a sufficiently detailed wind field is available, either from observations or numerical simulation.

Numerical modeling techniques for mesoscale flow have made steady advances over the past two decades. Estoque (1962) was able to study nonlinear phenomena, as well as account for the effect of the prevailing synoptic flow. McPherson (1970) developed a three-dimensional simulation of the effect of coastal irregularities (Galveston Bay) on sea breezes. Moroz (1967) and Neumann and Mahrer (1975) specifically modeled lake breezes *per se.* Pielke (1974) produced a three-dimensional, multilevel primitive equation model for the Florida peninsula. This code has been consistently updated with improved boundary-layer parameterizations and an ability to handle topographic variability. While several of the models being developed are increasingly capable of resolving the details of mesoscale coastal winds, as a group they tend to have some deficiencies. These mainly derive from the relatively large horizontal grid spacings (rarely less than 5 km), which make it difficult to resolve the intense convergence zones associated with frontal wind shifts, which are frequently on the order 2.0 km or less in width. Consequently, peak vertical motions are generally underestimated. Observations by tetroons, gliders and other indirect means suggest that organized convergence zone updrafts often approach or exceed 100 cm s^{-1} (Lyons and Olsson, 1973; Simpson, 1964; Wallington, 1959). These updraft zones can have profound effects on the transport of pollutants.

On the whole, modelers have made few detailed studies of pollution transport, although Pielke (1975), Dieterle and Tingle (1976), Warner and Anthes (1977), among others, have recently begun to explore these possibilities.

The goal of this paper is to use analyses of observed data to provide an illustration of the complex three-dimensional nature of the transport characteristics of land and lake breeze flows. Of special interest are the center line paths of parcels released at any point in time of space, particularly their behavior near the updraft zones. Also noted are apparent recirculation of pollutants and size sorting of aerosols within the lake breeze cell. A field program in the Milwaukee area (Lyons, 1977) gathered extensive lake/land breeze data, and

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that from one particularly good example (4 September 1974) will be used herein. Complete details and data analyses are available in Keen (1975), Lyons (1975, 1977) and Keen and Lyons (1978). The case is summarized below, stressing the observations near Milwaukee on the lake's western shore.

2. Data sources and preparation

The lake breeze of 4 September 1974 was typical in many regards. After a clear, cool night, produced by an anticyclone centered over Illinois, a land breeze was present at dawn beneath an intense 100–200 m deep nocturnal radiation inversion. Smoke was seen drifting southeast over the lake. By 0850 CDT, however, observations of surface wave patterns made from an aircraft found a lake breeze front had formed offshore. By 1000 CDT, the front had moved onshore, penetrating to about 30 km inland by 1900 CDT. Inflow depths varied from 500 to 700 m, with a peak velocity of about 4 m s^{-1} 150 m above the shoreline at 1400 CDT. The Coriolis acceleration caused a clear shift in surface inflow winds from northeast to south-southeast as the day progressed. Tetroons, of which three were tracked by double theodolite, showed convergence zone updrafts in excess of 40 cm s^{-1} during late morning. A well-defined return flow layer of about 1100 m depth was present with a southwesterly direction prevailing. Numerous surface anemometers defined the low-level wind field throughout the period. Four serial pibal stations operated between 0800 and 1600 CDT at the shoreline, and 8, 14, and 24 km inland.

Fig. 1 displays the techniques used to prepare the subjective hand analyses of pibal and surface wind data for the trajectory calculations. All data were decomposed into u (east–west) and v (north–south) components, which in this locale are normal and parallel to the lakeshore. They were then hand-plotted on charts which represent an east–west vertical section through Milwaukee from 35 km inland to 15 km offshore, and from the surface to 2200 m AGL (above ground level). Most studies of lake breezes suggest the lake's perturbations generally are not significant above 2000 m AGL. For those times and areas where specific data are not available, particularly at night and over the water, the isotach analyses were drawn using judgment guided by the author's familiarity with Lake Michigan wind patterns as well as general characteristics of such flows as described in the literature. A v component wind chart was prepared every hour from midnight to midnight. Since the u component contained the strong gradients producing the intense wind shift zone convergence (typically $100\text{–}300\times10^{-5}$ s^{-1}), these were drawn at up to 15 min intervals during the day. These frequent analyses were necessary during the forenoon hours, when the wind shift moved inland at 8 km h^{-1}. A total of 89 hand-drawn wind component analyses were made. A high degree of confidence exists for the overland convergence zone analyses, with a far smaller degree for the extrapolation over water.

The u and v component isotach analyses were then converted into computer compatible form (cards then tape) using a Bendix Datagrid precision digitizer. The process of interpolating wind components onto a grid utilized graphics routines available at the University of Wisconsin Computer Science-Statistics Center. The u and v components were first interpolated onto a 51 by 23 grid (1.0 km horizontal, 100 m vertical) using a modified inversion-weighted-distance technique, followed by a smoothing of the interpolated matrix to exclude any abnormally high or low values. A bilinear interpolation routine further refined the horizontal grid to 201 points at 0.25 intervals. A simple linear interpolation then produced u and v component matrices for every 15 min over the 24 h period. A total of 887 616 wind components were entered onto the data tape.

3. Kinematic diagnostic analysis

A Fortran IV mainline program was written for a Univac 1106 computer with the objective of being able to release a particle at any point in space or time within the data domain and trace its position at all subsequent times. It has the capability of simulating releases from

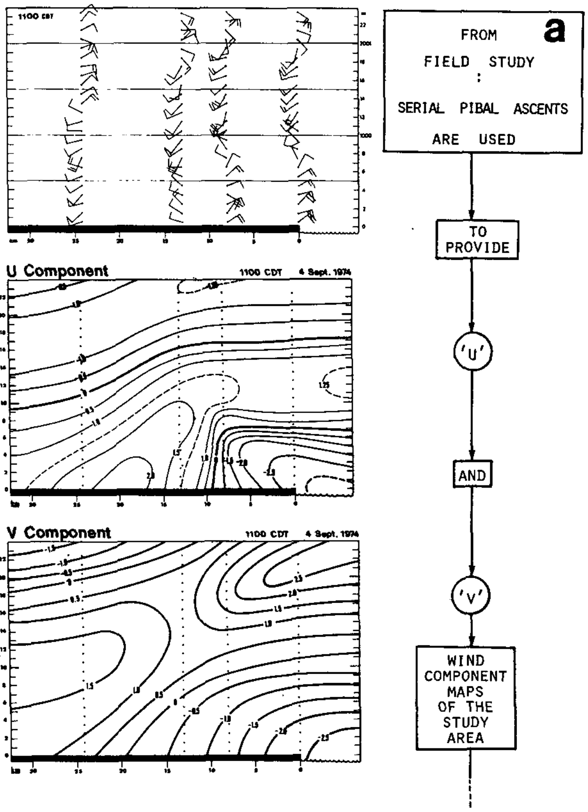

Fig. 1. Graphical summary of kinematic diagnostic analysis producing three-dimensional trajectories in complex coastal wind fields given measured u and v wind components.

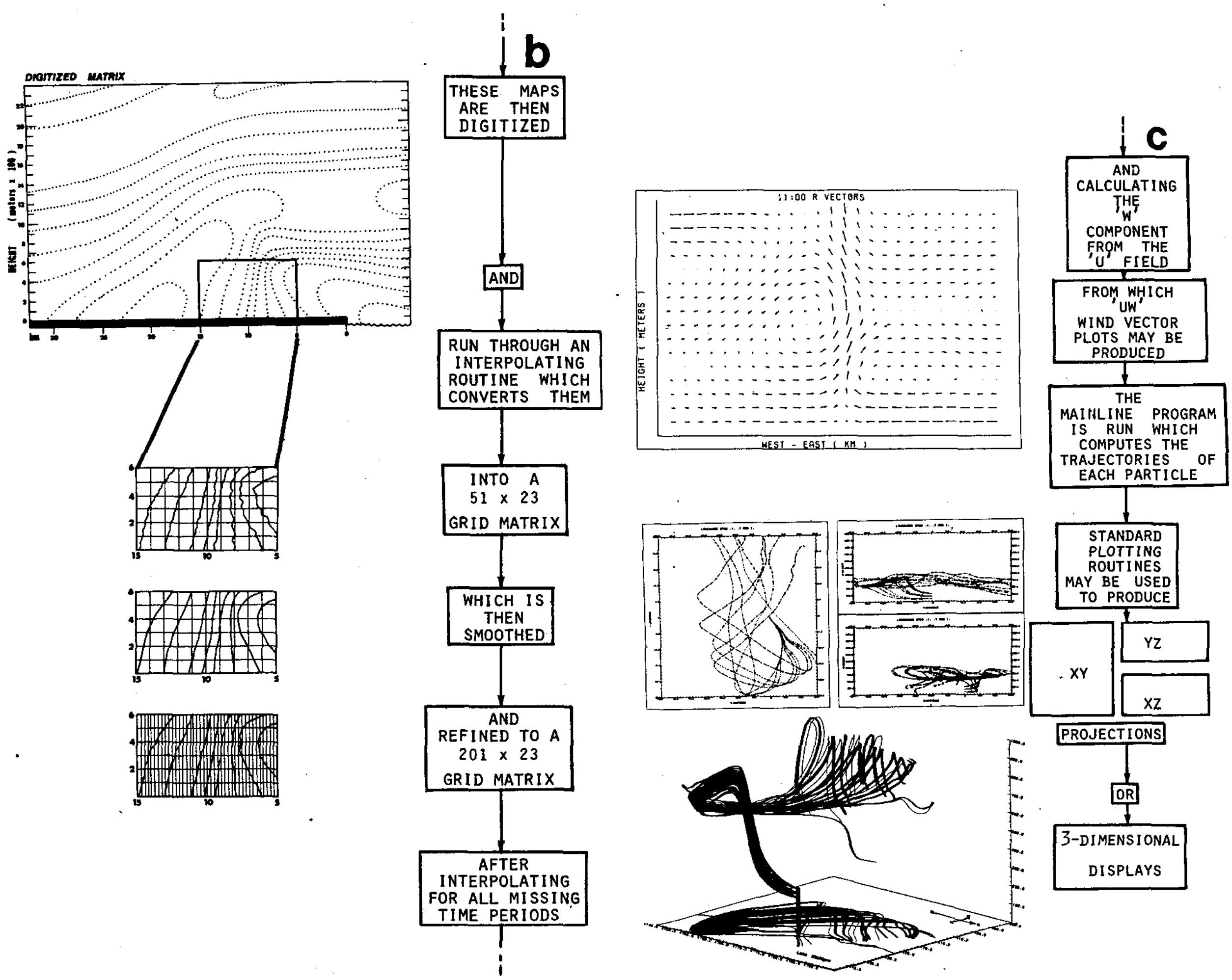

FIG. 1. *Continued*

point, multi-stack point, line, area and volume sources, as well as "aerial bursts." Calculations are made at 60 s intervals. UTM coordinates are employed. It is assumed that the north–south coastline is straight. It is further assumed that the flow is uniform in the y (north–south) direction. Thus, vertical motion w can be computed from the one-dimensional divergence equation

$$w(z)=W_0-\int_{z=0}^{z}\left(\frac{\partial u}{\partial x}\right)dz,$$

where $w=0$ at the ground ($z=0$). Winds outside the 51 km by 2200 m data domain were set equal to those at the boundaries, so that a particle traveling beyond could return if a wind shift occurred.

The flow is considered "laminar" at all points, that is, the path prescribed for a particle is simply due to the mean transport wind. No account is taken for diffusion from mechanical or thermal causes. A particle is started at a given x, y, z position and time and advects for a specified number of hours—or until it leaves the computational domain (optional) or "impacts" at the surface. Each particle is assigned a nominal settling velocity, which is derived from Stoke's law, assuming spherical particles of a given size with a mean density of 2.0 g cm^{-3}. This allows for a very crude approximation to deposition at the surface. The settling velocity w_s is everywhere added to the computed w to arrive at the particle vertical motion $w_p=w+w_s$. For gases, w_s is assumed zero and thus no surface deposition is accounted for.

The main program requires 27 K words of core, with an additional 21 K needed if 1000 particles are released. The data produced over 24 h includes 1 331 424 values of u, v and w. The computed x, y, z positions for 273 particles requires 4 700 000 bytes of disk storage or 800 ft of tape at 1600 bpi. Experimentation has shown that plotting particles at 6 min intervals was generally adequate to properly resolve the details of the trajectories.

A Calcomp plotter was used for data presentation. Several formats are available. As seen in the examples in Fig. 1, an "XY" plot is a plan view of the particle

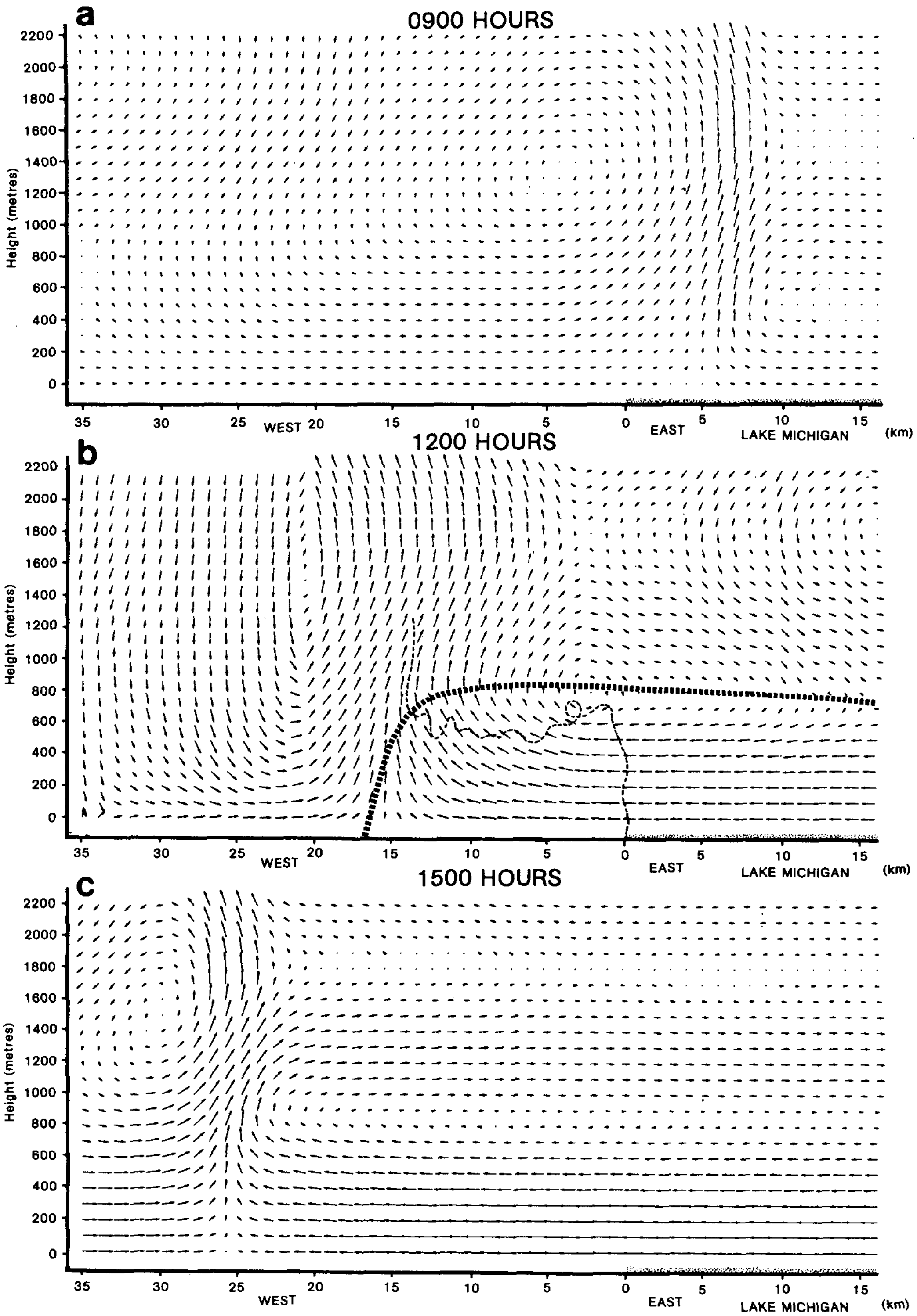

FIG. 2. Wind streamlines in the XY plane normal to the shoreline using u and computed w values, in the lowest 2200 m, from 35 km inland to 15 km offshore (a) at 0900 CDT, with convergence zone forming offshore; (b) at 1200 CDT, showing the measured boundary of the lake breeze inflow (heavy dotted line), and the observed trajectory of a tetroon released from the shoreline at 1048 CDT; and (c) at 1500 CDT, with the convergence zone approaching its maximum inland penetration.

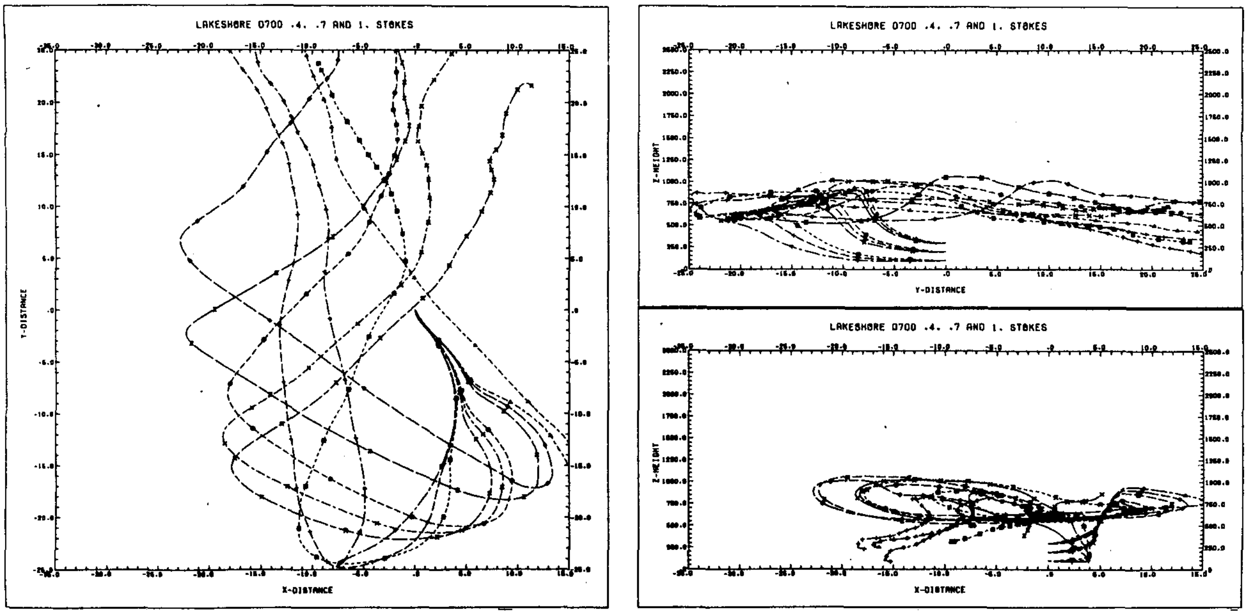

FIG. 3. Trajectories of particles with settling velocities of 0.4 cm s^{-1} (dotted line), 0.7 cm s^{-1} (dashed line) and 1.0 cm s^{-1} (dash-dot line) released from 100, 200 and 300 m above ground at the shoreline; released at 0700 CDT. Time hacks every 60 min.

trajectories in a square 50 km×50 km. A "YZ" plot is a vertical section running north–south along the shoreline, with trajectories projected onto that plane, with the view toward the west. An "XZ" plot is a vertical section running east–west looking to the north (lake on the right). Also available are three-dimensional perspective displays of particle paths with ground plane projections. The program has the capability to generate streak lines (emulating plumes as seen at a given time).

4. Some results

Fig. 2 shows computed UW streamlines, in an "XZ" plane, computed at three different times. At 0900 CDT (Fig. 2a), the newly forming convergence zone is still offshore, with a weak land breeze still present at the surface. By 1200 CDT (Fig. 2b), the updrafts associated with the wind-shift line have penetrated about 17 km inland. The top of the inflow layer and the frontal surface are marked with the heavy dotted line. The thin

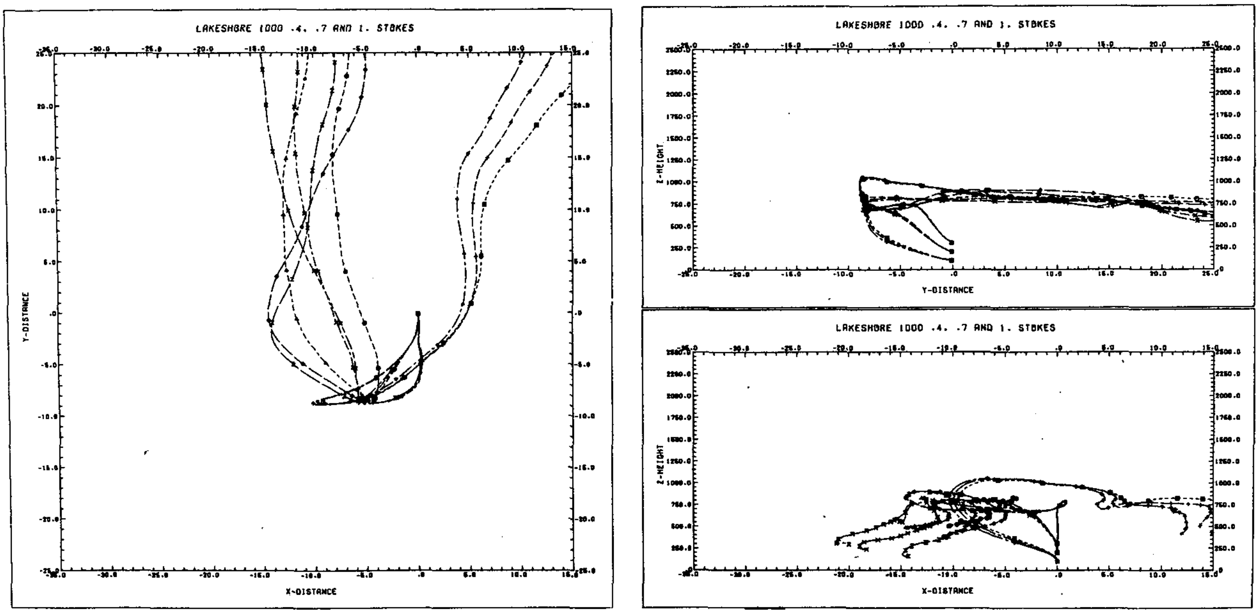

FIG. 4. As in Fig. 3 except for releases at 1000 CDT.

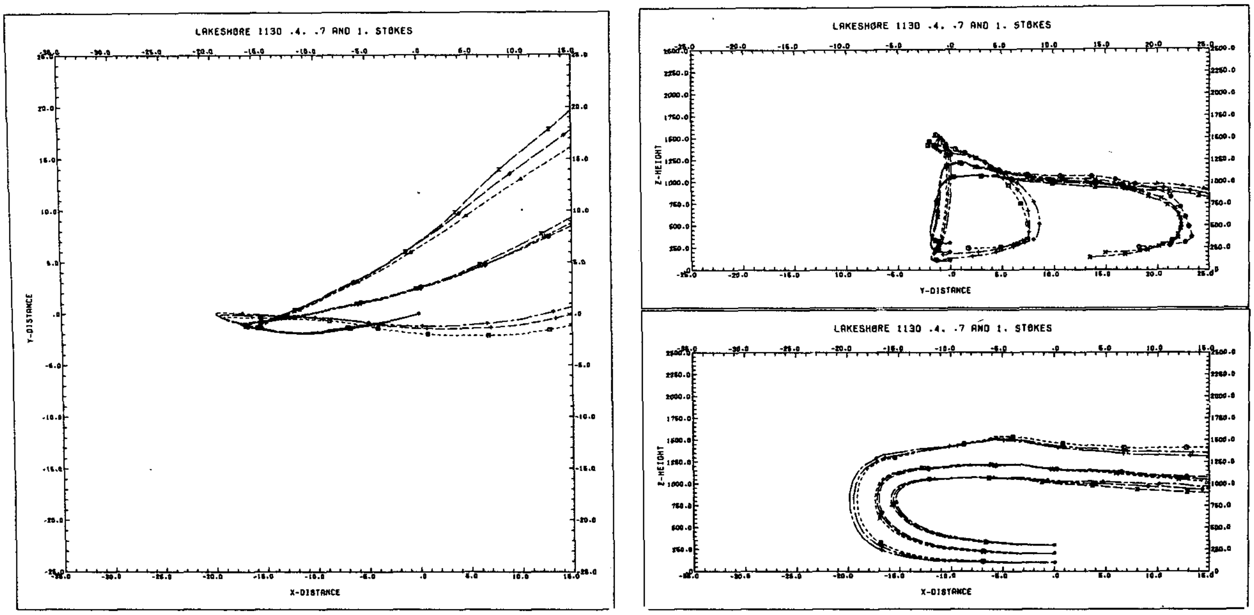

FIG. 5. As in Fig. 3 except for releases at 1130 CDT.

dotted line is the "XZ" projection of the trajectory of a tetroon launched from the shoreline at 1048 CDT. The tetroon drifted inland near the top of the inflow and about 1115 CDT, executed a small cycloidal loop. This could be imagined from the computed flow field but more likely represented the effect of shear waves forming at the interface between onshore and offshore flowing airstreams. By 1500 CDT (Fig. 2c), the convergence zone had penetrated about 25 km inland and was beginning to weaken.

Figs. 3, 4 and 5 represent trajectory plots of various-sized particles released from shoreline point sources. Specifically, they represent the paths taken by large aerosols (5–9 μm size range) with normal settling velocities of 0.4, 0.7 and 1.0 cm s^{-1}, each launched from "stacks" at release heights H of 100, 200 and 300 m. This range of H values is not dissimilar to the range of effective plume heights from a multi-stack coal burning power plant located at that position. Fig. 3 displays the paths of particles released at 0700 CDT (during land breeze outflow period) and tracked for 18 h. All particles first drifted southeast, but the directional shear caused considerable horizontal spreading. This phenomenon frequently was encountered during aircraft plume monitoring programs. After 0900 CDT, all particles were forced aloft by the undercutting lake breeze inflow. Before noon, they had all subsided into the upper portion of the inflow zone and moved inland at around 600 m. Vigorous fumigation was occurring this day, and in reality much of this material would have been rapidly mixed earthward more than 10 km inland. In either case, however, all material would then have risen at the updraft zone between 18 and 22 km inland, to begin drifting slowly north and northeast in the weak return flow. By evening, most of the particles began floating earthward well north of their release point but in a zone

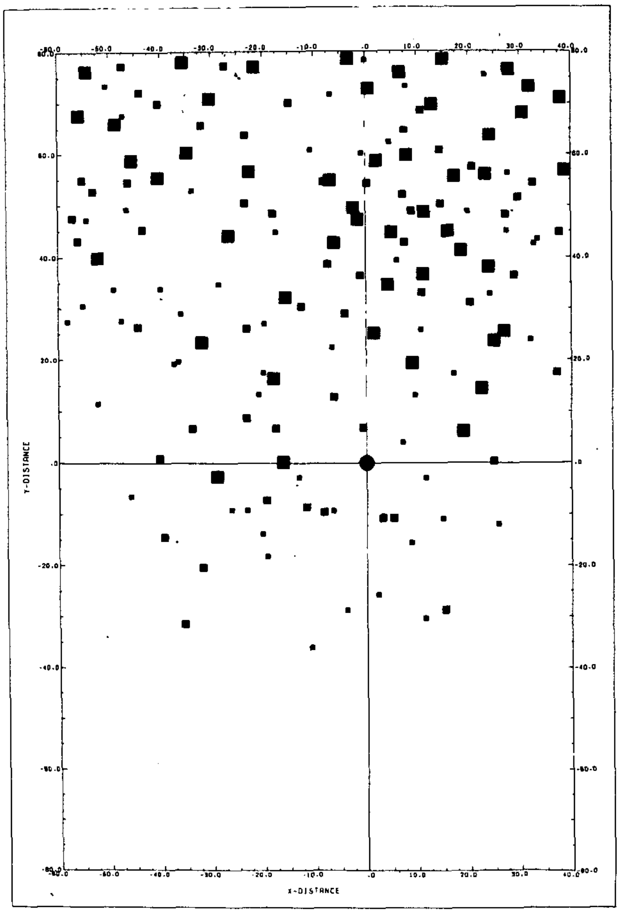

FIG. 6. The XY projections at 1800 CDT of a series of 180 particles released between 0700 and 1500 CDT from a shoreline source (circle) with emission heights of 20, 50, 100, 150, 200 and 300 m. The large squares are class A particles; medium squares class B; and smallest squares, class C. Area shown is 160 km by 100 km.

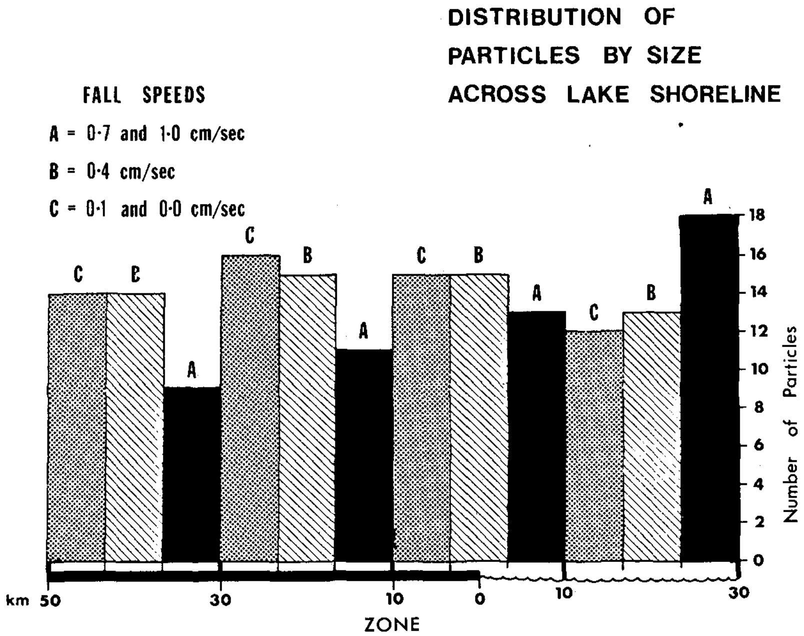

FIG. 7. Histograms of distribution of particles of various sizes across the shoreline, at 1800 CDT (based on data from Fig. 6).

over 30 km wide. Thus, the lake breeze does apparently recirculate particulates. Also demonstrated is the fact that for a cluster released at somewhat different altitudes, wind shear causes considerable lateral plume spread.

Fig. 4 shows some notably different results for releases at 1000 CDT. First, the highest plume (300 m) is emitted initially above the inflow layer, even drifting slightly offshore for the first hour. The lowest plume material reaches the updraft zone first and is quickly shot into the return flow layer at around 900 m. It then slowly subsides back into the remnant inflow layer over the lake by 2000 CDT. The two higher releases likewise enter into the return flow, but somewhat later, and drift more northerly, with particulate fallout mostly over land areas. For 1130 CDT releases, Fig. 5 shows the effect of a much stronger and deeper inflow. The plume moves inland in a cohesive manner, and after 2 h is ejected into the return flow through the updraft zone, with fallout over the lake occurring during the subsequent evening hours.

Lyons and Olsson (1973) proposed that a size sorting of aerosols occurs within lake breeze cells with the larger sizes possibly depositing onto the lake surface after one trip through the return flow layer, while the smaller aerosols and gases may potentially recirculate several times. Fig. 6 shows the result of an experiment in which 180 various sized particles were released from above a given shoreline location at 20, 50, 100, 150, 200 and 300 m at 0700, 0900, 1100, 1300 and 1500 CDT, and tracked until 1800 CDT. Class A particles had settling speeds of 1.0 and 0.7 cm s^{-1}, class B, 0.4 and 0.5 cm s^{-1}; and class C, 0.0 and 0.1 cm s^{-1}. Fig. 8 shows the XY position of each of the particles projected onto the surface at 1800 CDT. Most apparent is the tremendous spatial distribution of the particle whereabouts over an area of more than 10 000 km^2. Some organization to the pattern is evident in Fig. 7, a histogram of the location of the three size classes in 20 km wide zones. There would be a clear preference for the larger particles to be found over the lake, and thus presumably impact in the water some time thereafter.

Fig. 8 represents the trajectories of an "aerial burst," the release of 52 particles simultaneously at 0700 CDT, at 200 m above the shoreline, and tracked for 12 h. Particle sizes imply 0.0–1.0 cm s^{-1} settling speed. The "cloud" first drifted southeast over the lake, presumably away from the Milwaukee population center, lessening any "threat" that may have existed. Soon, however, it was forced aloft into the return flow over the lake, and then gradually sank back into the upper part of the inflow, and spread northwestward, crossing over the Milwaukee area during midafternoon. Active fumigation would have mixed the material to the surface over the western portion of the city in a band more than 20 km wide.

Figs. 9, 10 and 11 shows the behavior of a "line" source comprised of six release points, at 2 m above ground, located in a northeast–southwest line from 2 km inland to 13 km inland. The particles, with nominal settling velocities of 0.1 cm s^{-1} were followed for 12 h. In Fig. 9, the releases are made into the land breeze outflow at 0700 CDT. The pollutants travel near the ground to just several kilometers offshore, where they are entrained into the advancing lake breeze. They then push back inland, rising aloft in the updraft zone and spread

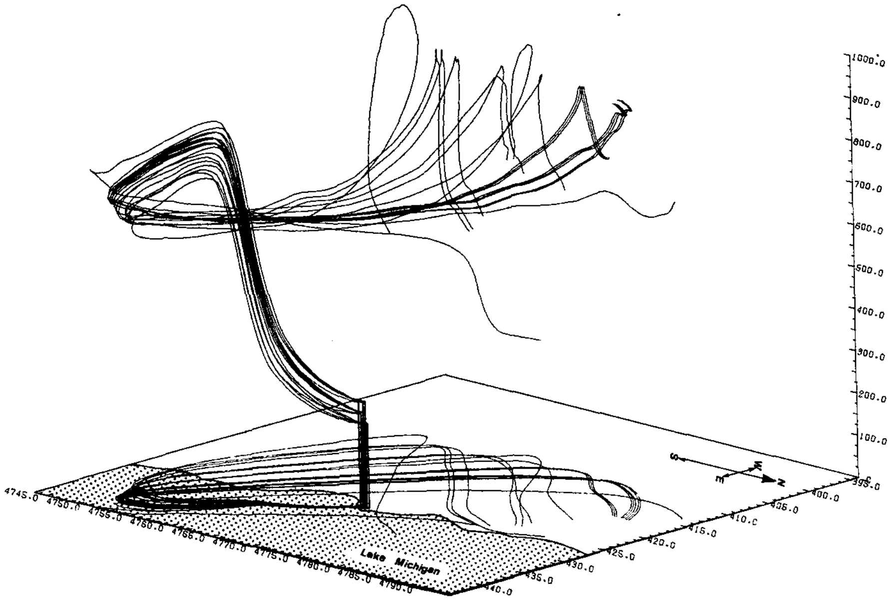

FIG. 8. A three-dimensional plot of a simulated aerial "burst" of 52 particles at 200 m height at 0700 CDT, with surface projection included, computational period of 12 h. Area is 50 km by 50 km.

out laterally in the return flow over the lake above 800 m. The 1500 CDT releases (Fig. 10) move rapidly inland, reach the updraft zone at 25 km west of the shore, where they are injected fountain-like into the winds at higher levels. By 2000 CDT that evening (Fig. 11) weak southwesterly surface flow had reestablished itself over the city. Some of the particles impacted on the ground. Those that did not gradually drifted toward the lakeshore in the developing land breeze and were then swept into the inflow of the next day's lake breeze.

5. Summary and conclusions

The kinematic diagnostic analysis of available data appears to be a useful technique for gaining insights into the extreme complexity of coastal zone transport processes. The results did approximate reasonably well the general pollution patterns observed this day as described by Keen and Lyons (1978). Aircraft observations strongly suggested that large aerosol particles were indeed falling into the inflow layer east of the shoreline

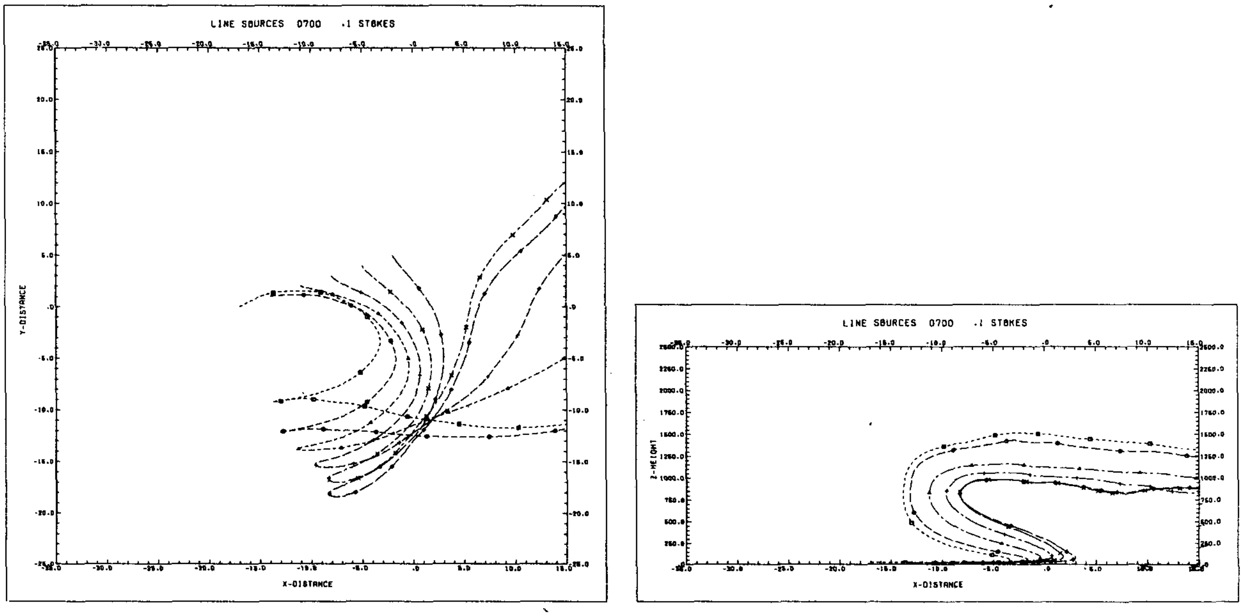

FIG. 9. Trajectories of particles of 0.1 cm s^{-1} settling velocity, released from six points (2 m) in a southwest–northeast line (from 2 to 13 km inland) at 0700 CDT. Time hacks every 60 min.

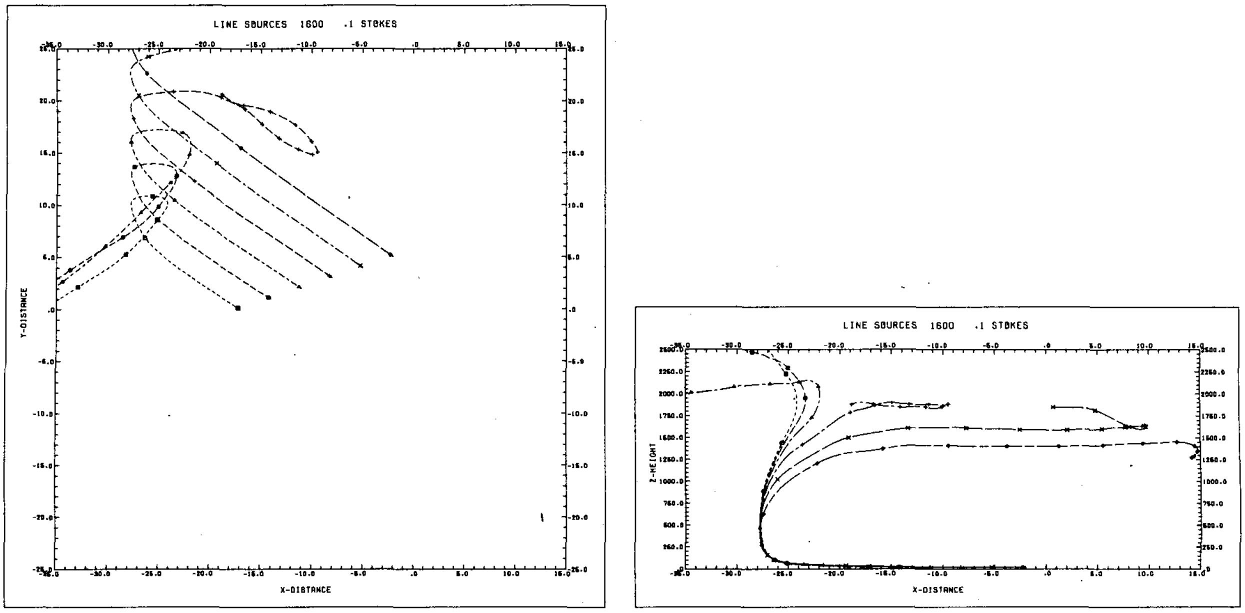

FIG. 10. As in Fig. 9, except for releases at 1600 CDT.

during the late afternoon. Widespread elevated layers of "smoke" (small aerosols and NO_x gases) were found distributed throughout the upper portion of the inflow, as well as in the return flow layer, over a wide area east and north of Milwaukee.

It is suspected, however, due to the lack of overwater data, that the hand-analyzed wind fields failed to result in sufficiently strong subsidence lakeward of the convergence zone. It is felt, especially for smaller size aerosols, that the particles should have been reentrained into the lake breeze inflow more readily than seen here. It would thus appear that for determining air motions over offshore areas the improving numerical models may begin to demonstrate superiority over conventional wind observations.

At this time, an experiment is underway by the authors to compare in detail the measured u, v, w wind components presented here to those produced by the University of Virginia Mesoscale Model (UVMM) adapted for Lake Michigan. If sufficient agreement between the two wind fields can be found, it is hoped that this model can then be used as a "front end" to this

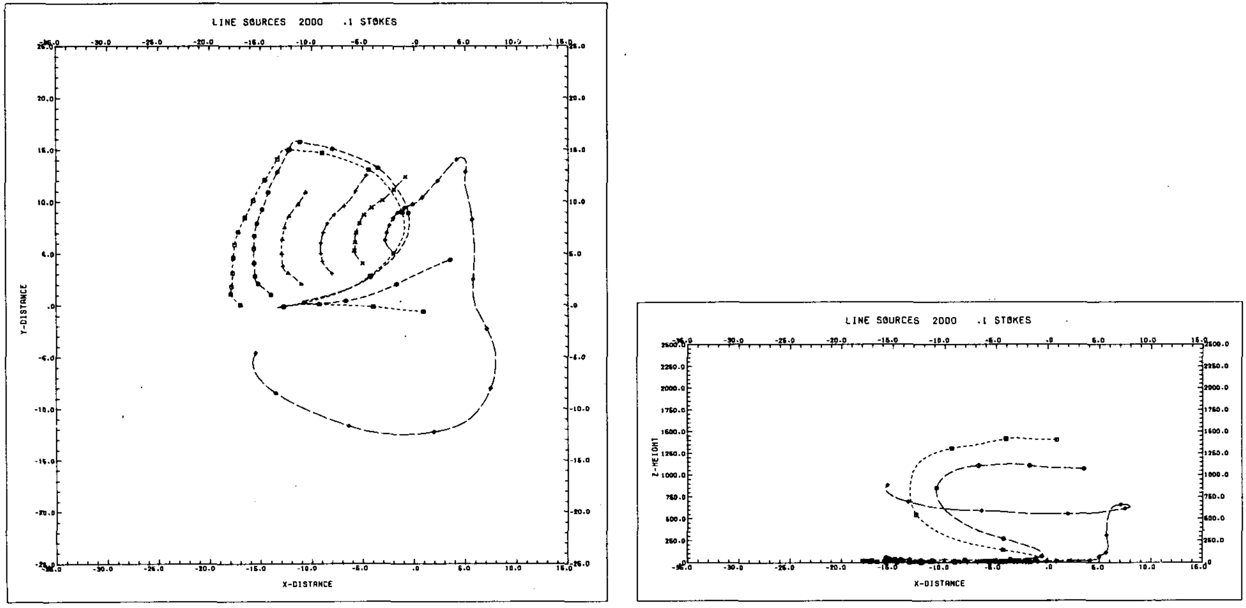

FIG. 11. As in Fig. 9 except for releases at 2000 CDT.

analysis routine to generate *u*, *v*, *w* wind sets representative of other synoptic situations.

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