The use of Mesoscale Models on Air-Pollution Studies in Industrial Installations

G. Kallos

Department of Applied Physics, Meteorology Laboratory, University of Athens, Ippocratous 33, Athens 10680, Greece

ABSTRACT

This paper discusses the combined use of a mesoscale numerical model and a Lagrangian particle dispersion model in order to derive useful conclusions on the possible environmental impacts in the area around the site of a new industrial installation or in larger areas. This procedure is recommended for cases with complicated flow patterns over irregular terrain or for areas near coastlines. In such cases the dispersion and transport of pollutants could not be achieved with the classical Gaussian models because they are not able to handle important local features accurately. Local circulations such as sea-land breezes or slope flows can influence the dispersion and transport of pollutants in different ways. The results presented in this paper are part of a detailed study for the possible environmental impacts in the Eastern Corinthian Gulf in Greece where an alumina plant will be built. Experimental data, a synoptic classification scheme, and model simulations will help to take all the appropriate measurements during the design of the plant in order to minimize the environmental impacts during its operation.

KEYWORDS: Air pollution, Gaussian model, Mesoscale model, Lagrangian particle dispersion model, Dispersion, Diffusion, Transport

SOFTWARE AVAILABILITY

Colorado State University Mesoscale Model and Lagrangian Particle Dispersion Model original codes are available from Professor R. A. Pielke, Colorado State University, Department of Atmospheric Science, Fort Collins, CO 80523, USA. Modifications for these codes as well as the plotting routines for CALCOMP plotting packages and plotters are available from the author of this paper.

INTRODUCTION

Having advance knowledge of the microclimate, other specific characteristics and the flow behaviour which would lead in pollution episodes of the area where a new plant will be erected, will assist us to take all the appropriate measurements to avoid significant environmental damage from the released air pollutants. In almost all cases, an environmental study for the plant design employs Gaussian type models to study the dispersion of pollutants. The shortcomings however of such models are well known, and in several cases the results are considered unreliable. The reliability of such methods is even lower in cases where the site is characterized by a highly varying topography or is near the coast. In such cases the wind fields in the area are very complicated and the spatial and temporal variations are significant. In these cases accurate description of the wind fields and detailed description of the dispersion of pollutants is necessary. Following this apporach, Pielke, McNider and their collaborators have carried out a number of studies for different areas in U.S.A.. Arritt and Pielke [1] had investigated the role of topographically induced mesoscale circulations in pollutant transport in Shenandoah Valley. Yu and Pielke [2] had studied the layered haze phenomenon in the Lake Powel area, Segal et al [3] have studied the impacts of the air pollution from the urban areas of South Florida to the neighboring National Parks, Physick [4] had studied the dispersion characteristics in the Grand Canyon region under various wind and stability regimes while Pielke et al [5] discussed various tools which can be applied on emergency cases, such as accidental toxic or radioactive releases as well as nowcasting air pollution episodes.

In this study some preliminary results from a numerical investigation of the mesoscale circulation and pollutant transport in the area of the Eastern Corinthian Gulf in Greece are presented. The pollutant source is in the area of Thisvi near the northern coast of the Gulf from the proposed alumina plant. The pollutants, mostly sulfur dioxide, result from petroleum combustion. The combusted quantity is estimated to 150 - 170 tons per day. The initial estimate of the stack height is about 100m above the ground level and 130m above the sea level. The topography around this area is very complex and the site is about 1.5Km from the coast. To the North of the site, there is a small valley of an elliptical shape with the smaller axis of about 3Km and the larger of about 6Km. Further to the North there is Mount Elikon with its peak at approximately 1500m. There are also three small populated areas in a distance of 3-5Km from the site in the northern end of the small valley. Some other populated areas

are located from 5-20Km away. The southern coastline of the Corinthian Gulf is also populated, with the largest city of Corinth. The possible transport of pollutants toward south or north when the sea-breeze is the dominant mechanism in the area during the summer is examined. The sea-breeze circulation dominates in this area for a considerable number of days during the summer months. As seen in Figure 1, the coastline has an East-West orientation thus the sea-breeze circulation is expected to have a significant component perpendicular to the coastline.

For this study a two stage procedure was employed: In the first stage the two-dimensional version of the Colorado State University Mesoscale Model (CSUMM) was used to predict the meteorological fields for the vertical cross-section along the axis shown in Figure 1 by the thick line. In the second stage, a Lagrangian particle dispersion model described by McNider [6] and Pielke et al [7] was used. A brief description of the two models is given below while the capability of this procedure to describe such complex phenomena is briefly discussed.
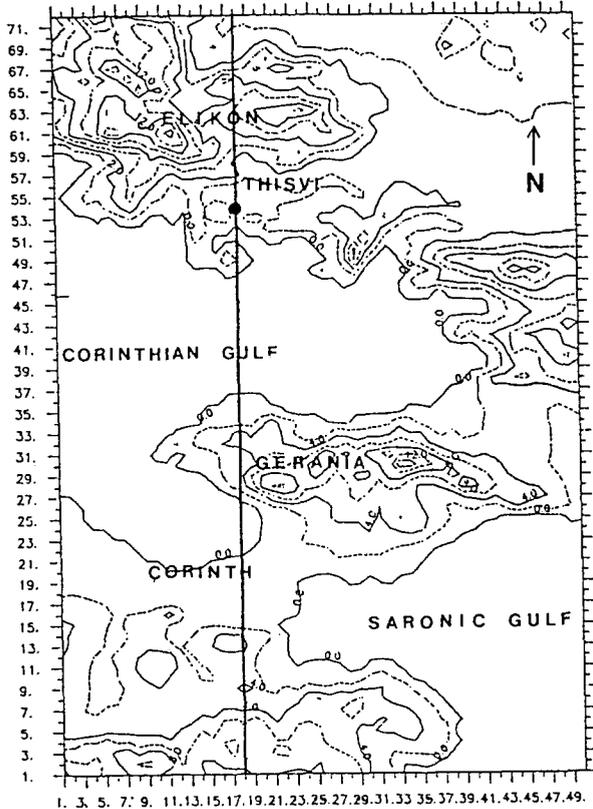

Figure 1. Map of the simulation area. Contour interval is 200 m (400 m between solid lines). The cross section is along the heavy line running north-south through Corinthian Gulf. The site of the plant is shown by a thick dot.

MODEL DESCRIPTIONS

a. *Mesoscale Model*

The mesoscale model used in this study was originally developed by Pielke [8] and modified later by Mahrer and Pielke [9]. The CSUMM is a hydrostatic, prognostic model based on the primitive equations of motion, energy, continuity, and water content. It uses the terrain-following coordinate system and exchange coefficients for parameterization of the turbulence exchange processes. For the Planetary Boundary Layer (PBL) a detailed parameterization is used where short and long-wave radiative contributions are included in the surface energy balance calculations. The depth of the convective boundary layer is computed from Deardorff's [10] prognostic equation with Businger's [11] similarity theory used for the surface layer. The exchange coefficient profile in the PBL was specified by O'Brien's [12] cubic polynomials. For the case of stable stratifica-

tion, the local exchange coefficient scheme based on local gradient Richardson number calculations is used. At the uppermost four levels of the model, an absorbing layer is applied to avoid reflections of the generated gravity waves.

b. *Lagrangian Particle Dispersion Model (LPDM)*

This model uses as input the predicted fields from the mesoscale model described previously. It is a Lagrangian type dispersion model on which the motions of discrete mass elements (which represent the pollutants) are tracked inside the model domain. The position of each particle at time t is given by $X_i (t)$, i = 1, 2, 3, while at time t+Δt is given by

$$X_i (t+\Delta t) = X_i (t) + (u_{oi} + u_i' + u_i'') \Delta t ,$$

where

Δt   is the time step

X_i are the spatial coordinates of each particle

u_{oi} are synoptic-scale wind components

u_i' are mesoscale wind components

u_i'' are microscale velocity components (turbulent)

The microscale velocity component u_i'' is computed from the Markov process

$$u_i''(t+\Delta t) = R_{Li} u_i''(t) + (1-R_{Li}^2)^{1/2} u_i'''(t) +$$
$$\delta_{i3}(1-R_{L3}(\Delta t))W_d$$

with

$$R_{Li} (\Delta t) = exp(-\Delta t/T_{Li})$$

$$u_i'''(t) = r\sigma_i$$

$$W_d = T_{L3} \partial/\partial x_3 (\sigma_3^2)$$

R_{Li} is the Lagrangian velocity autocorrelation in the i-th direction

T_{Li} is the Lagrangian integral time scale for each direction

$u_i'''(t)$ is a random velocity component

δ_{i3} is the Kronecker delta

W_d is the drift velocity correction

r   is a normal random variate (with 0 mean and 1 variance)

σ_i is the standard deviation of the i-th microscale velocity component

Synoptic and mesoscale wind components are these calculated directly from the mesoscale model while the turbulent components are deduced from the mesoscale model closure scheme. A more detailed description of this technique is presented in McNider [6], Arritt [13], and Pielke et al [14].

DATA USED

During the period from July 31 to August 3, 1987 a program of extensive measurements in the surface as well as in height was performed in the area near the site of the plant. Model simulations were performed for August 3. During this day the synoptic conditions were favorable for the formation of sea-land breeze circulation in the area. The data used for the initialization of the model were local tethered balloon observations at 02:00 LST for the lowest 1000m and above this level, the radiosonde observations from Athens airport (located approximately 40Km ESE from the site) at 02:00 LST. These profiles were interpolated to obtain the appropriate data at the model levels. Initial profiles and additional data used for this simulation are shown in Table I. For more details about the experimental data for this day see Helmis et al [15]. The simulation starts at 02:00 LST and the first three hours were used for dynamic initializa-

tion, allowing the initial fields to adjust to the terrain before sunrise where the heating of the surface begins. The model coordinates were rotated 90 degrees counterclockwise, therefore in the following figures the left corner corresponds to the South while the right to the North. Terrain data were obtained from maps 1:50000 and were smoothed appropriately.

Table I. Model input data used for simulation of August 3, 1987 case.

Initial profile

Height(m)	Potential Temp.(K)	Specific Humid.(g/Kg)
5.	295.20	0.0137
10.	295.21	0.0136
50.	295.40	0.0104
150.	297.00	0.0099
300.	297.90	0.0089
500.	298.52	0.0085
700.	299.50	0.0084
900.	300.50	0.0073
1100.	301.45	0.0070
1300.	302.20	0.0061
1500.	302.78	0.0059
1800.	304.10	0.0057
2100.	305.90	0.0053
2500.	308.25	0.0045
3000.	310.84	0.0029
3500.	314.75	0.0027
4000.	317.10	0.0024
4500.	320.05	0.0022
5000.	322.96	0.0019
6000.	326.94	0.0009
7000.	328.99	0.0008
8000.	331.89	0.0007
9000.	332.99	0.0007

Additional data

Albedo	0.20
Roughness length	15. cm
Surface pressure	1012. mb
Sea-surface temperature	298. K
Initial PBL height	350. m
Horizontal grid interval	1000. m
Time step	10. sec
Geostrophic wind speed	3. m/s
Geostrophic wind direction	335. deg.
Soil density	1.5 g/cm3
Soil specific heat	0.3 cal/gK
Wetness of the soil	0.05
Soil thermal conductivity	0.003 cal/cmKs
Time start	02:00 LST
Grid points horizontal	80
Grid points vertical	23

DISCUSSION

As highlighted above, the modeling area is characterized by a complex terrain and frequent changes from land to sea. In Figure 1 the coastline is oriented along the E-W axis in both sides of the Gulf, so the main features of the sea-breeze mechanism could be represented in two-dimensional runs along a N-S axis. In sea-breeze cases, it is possible to have recirculation of the air-pollutants (Lalas et al [16], Christidis [17], Pielke et al [7]). The synoptic flow in this run was 3m/s from NNW which is blocked by Mount Elikon in the North. During the morning hours, the sea-breeze starts to develop with a northward orientation near the ground in the northern coast and a southern in the South. In the center of the domain a shallow convergence zone is formed over the mount Gerania, because of the sea-breeze cells developing in both sides of the mount. The sea-breeze cell in the northern side is intensified by the slope flow developed at Mount Elikon because of its orientation. This is the main reason why the vertical development of this cell is extended up to 2Km in this region during the afternoon hours. The return flow is merged with the synoptic circula-

tion, and an intensification in the upper levels is observed. Figures 2a-c display the horizontal wind field component through the N-S axis with positive direction toward North, the vertical velocity field, and the potential temperature field respectively for 14:00 LST, when the sea-breeze mechanism is at its peak, are shown. During the night, when the sea-breeze ceases, a slope flow is developed in the slopes of the mountains. In Figures 3a-c the flow and potential temperature fields at 01:00 LST are shown.

The LPDM was used to simulate the movement of 500 particles released at the alumina plant stack. The release was at a fixed time once from a height of 150m above the ground level. The particles serve as tracers for the illustration of the combined effects of advection by the wind field resolved from the mesoscale model and the subgrid-scale turbulence. After the release, the positions of these particles were plotted at fixed time intervals. Several simulations for releases at different day and night hours were performed. For releases during the morning hours, when the sea-breeze is developing, the particles moved toward North, where a portion impacted onto the slopes of the mountain while the rest of them moved toward South with the return flow. Figures 4a and 4b show the position of the particles one and five hours respectively after the release at 08:00 LST. Because the release occured at a time where the sea-breeze started to develop, and the flow in the lower levels is relatively weak with small vertical extend, the particles moved initially toward the slopes of the Mount Elikon. Later they moved southward because the return flow from the sea-breeze circulation and the synoptic wind component are from North. During the day, in the northern slopes of Gerania, the sea-breeze circulation in the lower levels is from North while in the southern is from the South. In the coast of Northern Peloponnese the sea- breeze is from North. A convergence zone developed over Gerania. Over the sea a stable layer is forming during the day hours. (see Figure 2). Therefore the particles released from the site of the plant and moved in this area followed a complicated path. A portion of them moved toward Peloponnese while the others, trapped within the stable layer over the sea, moved later toward North with the aid of the sea-breeze (Figure 4b). Particles released later during the day moved quickly northward over the slopes of Elikon and later southward with the return flow, reaching the heights of 2-3Km (not shown here). Particles released a few hours before sunset moved initially toward the slopes of the Mount Elikon. Later when the sea-breeze weakens, these particles remain near the slopes of the mountain and start moving downslope toward their release point at a small distance from the ground (see Figure 4c). This is because of the downslope flow developed near the ground during the night hours. For releases during the night hours when the atmosphere becomes more stable over the land, the transport and dispersion of the particles occur in a smaller scale than during the day. The particles remain for longer time around the area of release and moved slowly toward South over the sea. Figure 4d shows the dispersion around the source three hours after the release of the particles at 21:00 LST, while Figure 4e shows the condition for the same release after seven hours. In this figure we can see a significant amount of particles remaining in the vicinity of release for several hours during the night while others are transported toward South over the sea in a height of about 700 m above the sea level. This is due to the light winds near the surface and the stronger winds aloft. The land-breeze mechanism is not strong enough to maintain its classical configuration and the northern flow dominates in the area. During the morning hours of the next day, the particles remaining near the sea-surface move northward after the sea-breeze mechanism starts again.

CONCLUSIONS

This paper briefly discusses the combined use of a mesoscale atmospheric model with a Lagrangian particle transport and dispersion model to study some of the dispersion and diffusion characteristics of pollutants released from the stack of a large industrial installation. In such complex terrain the flow fields show temporal and spatial variations and therefore the dispersion characteristics are varying significantly. These variations cannot be described accurately with simple numerical models such as the Gaussian or the mass consistent ones. With the aid of mesoscale models and Lagrangian trajectory models we are able to describe the complicated flow fields as well as the dispersion and diffusion of pollutants on an accurate manner. This strategy with the aid of synoptic classification and
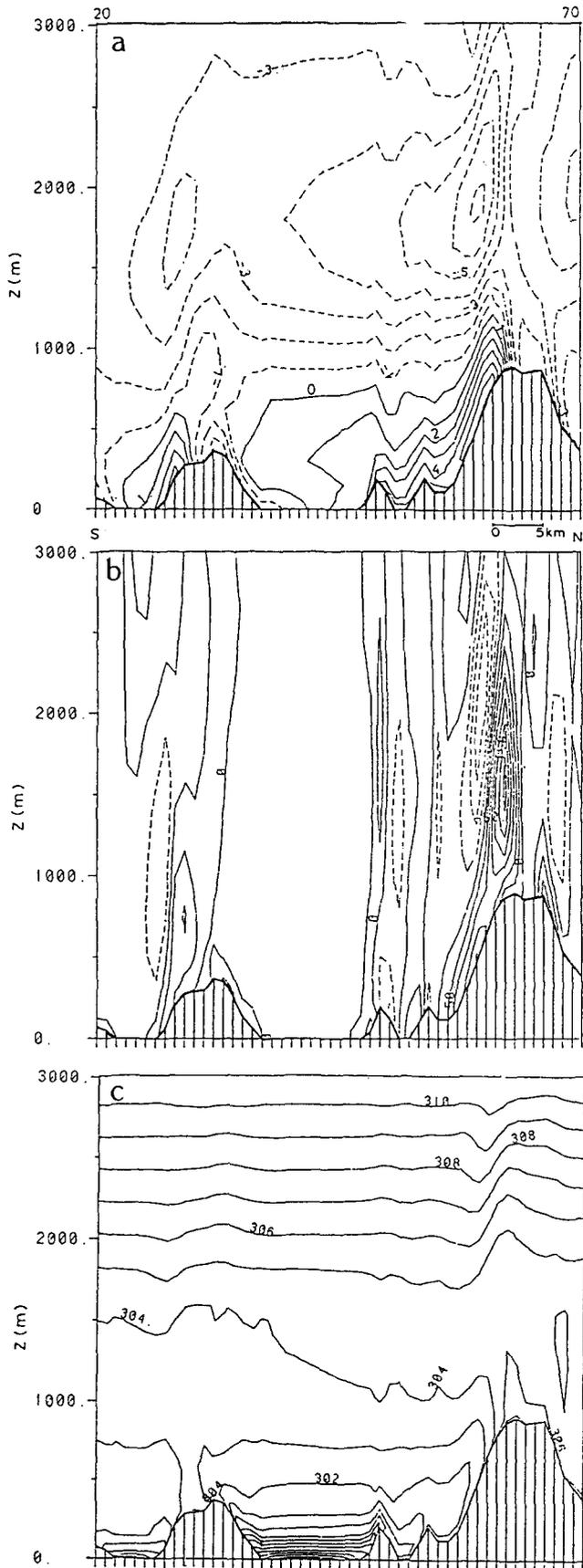
Figure 2. Predicted fields of (a) u component in m/s (interval 1 m/s), (b) w component in cm/s (interval 25 cm/s), (c) potential temperature in degrees K (interval 1 deg.K) at 14:00 LST for 3 August 1987. Only the domain between the grid points 20 and 70 is shown. Broken lines show negative velocities.
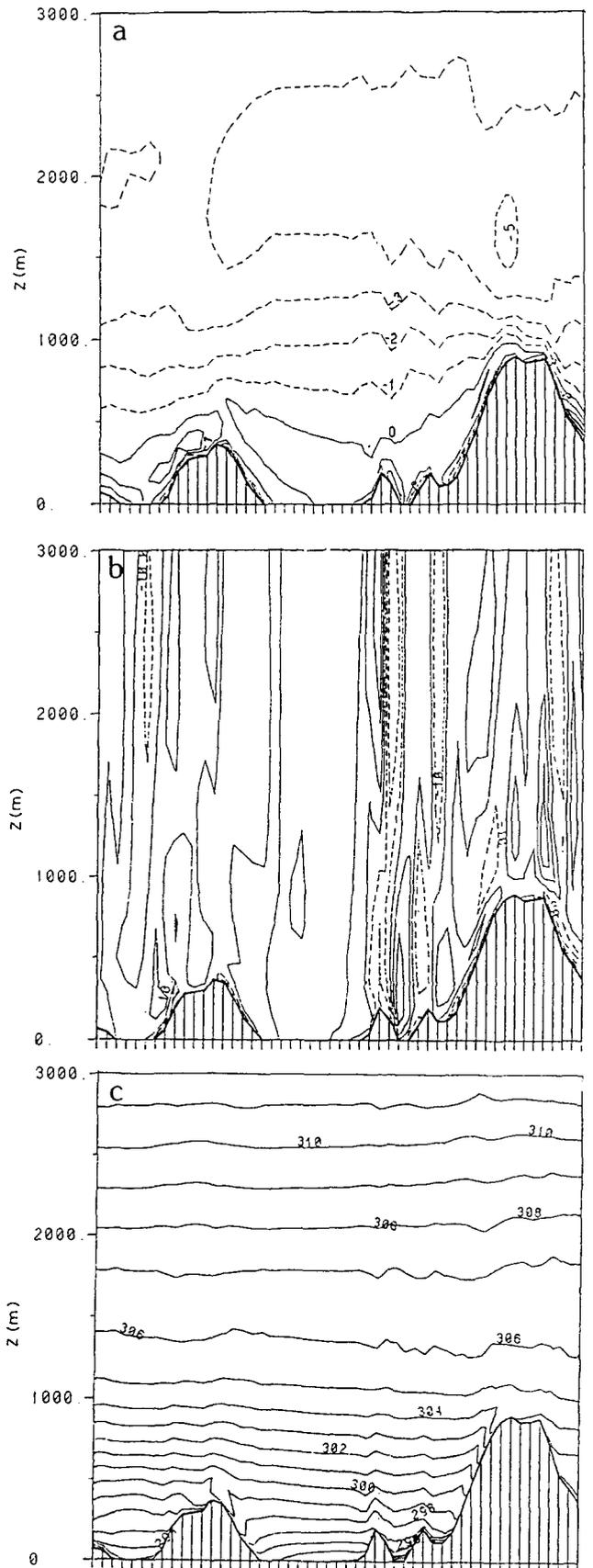
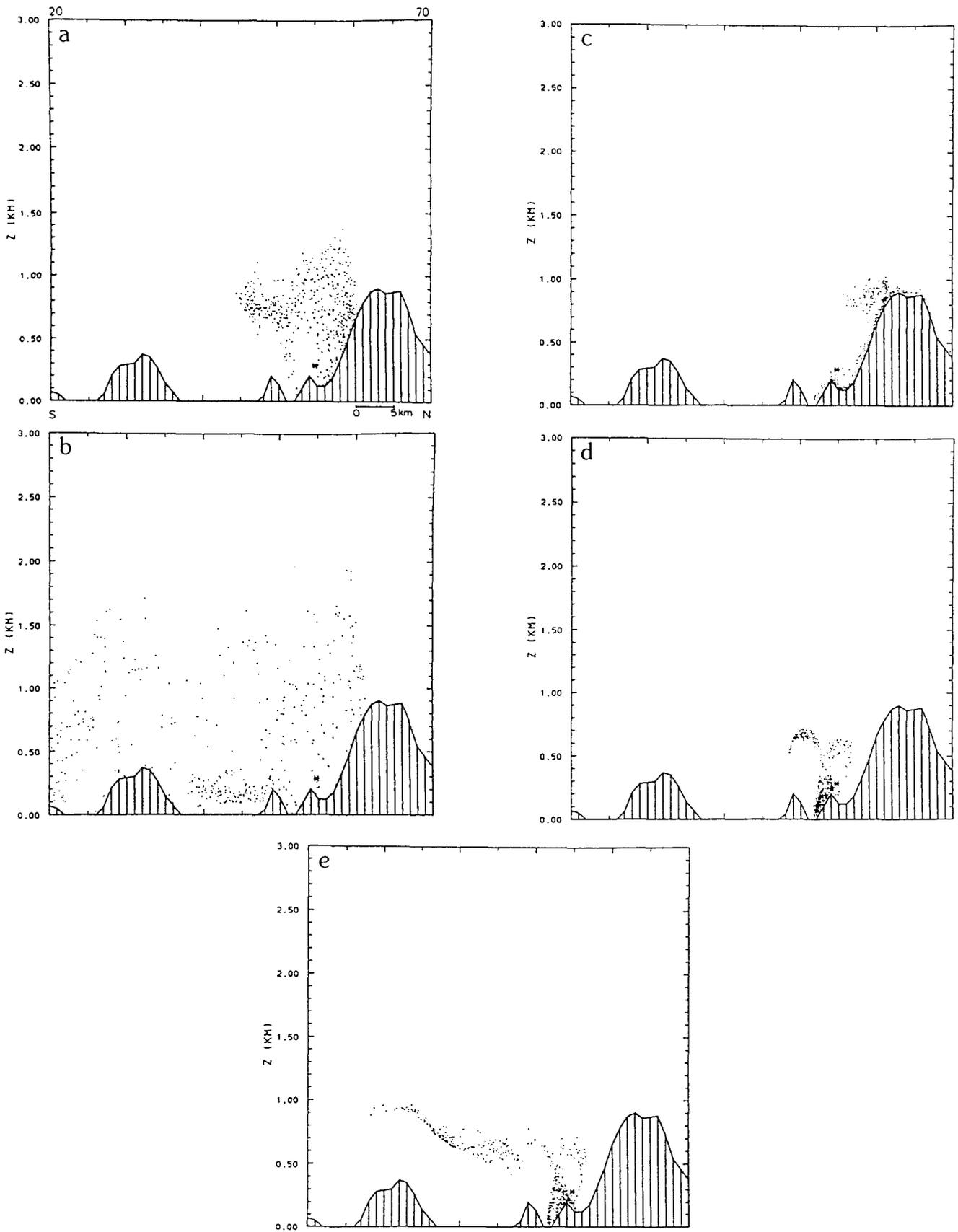Figure 3. As in Figure 2 but for 01:00 LST at 4 August 1987. Contour interval for w is 10 cm/sec.

Figure 4. Particle locations at (a) 1 hour, (b) 5 hours after the relelease at 08:00 LST, (c) 3 hours after the release at 19:00 LST, (d) 3 hours, (e) 7 hours after the release at 21:00 LST. The release point is marked by an asterisk.

micrometeorological observations can be used to study the dispersion characteristics in order to guide the design of the factory. The conclusions will be used to minimize the environmental impact from the industrial operations. It is obvious that three - dimensional simulations are more appropriate in such cases but even the two -dimensional ones provide useful informations. For the present study, based on these results, several three - dimensional simulations will follow in the near future. Such a procedure can be obviously applied also in the case of accidental toxic releases.

ACKNOWLEDGEMENTS

REFERENCES

[1] Arritt, R. and R.A. Pielke (1984), Numerical investigations of terrain induced mesoscale circulations and pollutant transport in the Shenandoah Valley. Third Conference on Mountain Meteorology, Oct.15-19 1984, Portland, Oregon, 4 pp.

[2] Yu, C.-H. and R.A. Pielke (1986), Mesoscale air quality under stagnant synoptic cold season conditions in the Lake Powell area. Atmos. Environ., Vol. 20, pp. 1751-1762.

[3]   Segal, M., R.A. Pielke, R.W. Arritt, M.D. Moran, C.-H. Yu and D. Henderson (1986), Southern Florida air pollution climatology study and selected episodic impacts. Prepared for the Air Quality Division, National Park Service, Department of the Interior, Denver, Colorado, Contract No. NA81RAH00001, Amendment 17, Item 15, 237 pp.

[4]   Physick, W.L. (1986), Application of a mesoscale flow model in the irregular terrain of the Grand Canyon National Park. Prepared for the Air Quality Division, National Park Service, Department of the Interior, Denver, Colorado, Contract No. NA85RAH05045, Amendment 17, Item 15, 98 pp.

[5] Pielke, R.A., R.W. Arritt, M. Segal, M.D. Moran, and R.T. McNider (1987), Mesoscale numerical modelling of pollutant transport in complex terrain. Boundary-Layer Meteor.,Vol. 41, pp. 59-74.

[6]   McNider, R.T. (1981), Investigation of the impact of topographic circulations on the the transport and dispersion of air pollutants. Ph.D. Dissertation, University of Virginia, Charlottesville, Virginia, 210 pp.

[7] Pielke, R.A., R.T. McNider, M. Segal, and Y. Mahrer (1983), The use of a mesoscale numerical model for evaluations of pollutant transport and diffusion in coastal regions and over irregular terrain. Bull. American Meteor. Soc.,Vol. 64, pp. 243-249.

[8] Pielke, R.A. (1974), A three-dimensional numerical model of the sea breezes over South Florida. Mon. Wea. Rev.,Vol. 102, pp. 115-139.

[9] Mahrer, Y. and R.A. Pielke (1977), A numerical study of the airflow over irregular terrain. Beit. zur Phys der Atm., Vol. 50, pp. 98-113.

[10] Deardorff, J. (1974). Three dimensional numerical study of the height and mean structure of a heated planetary boundary layer. Boundary-Layer Meteor., Vol. 7, pp. 81-106.

[11] Businger, J.A. (1973), Turbulent transfer in the atmosphere surface layer. Workshop in Micrometeorology, Amer. Meteor. Soc., Chap.2.

[12] O'Brien, J.J. (1970), A note on the vertical structure of the eddy exchange coefficient in the planetary boundary layer. J. Atmos. Sci. Vol. 27, pp. 1213-1215.

[13] Arritt, R.W. (1985), Numerical studies of the thermally and mechanically forced circulations over complex terrain. Ph.D. Dissertation, Dept. of Atmospheric Science, Colorado State University, Fort Collins, Colorado, 193 pp.

[14] Pielke, R.A., M.D. Moran, M. Segal, D.A. Wesley and T.B. McKee (1987) Opportunities for Nowcasting air pollution episodes and accidental toxic and radioactive releases. Proc. Symp. Mesoscale Analysis & Forecasting, Vancouver, Canada, 17-19 Aug. 1987, ESA SP-282, pp. 463-470.

[15] Helmis, C., D. Asimacopoulos, D. Deligiorgi, K. Varotsos, and G. Kallos (1987), Micrometeorological study of the area of Thisvi, Viotia. First intermediate report prepared for the Hellenic Alumina Industry Inc. 111 pp. (in Greek)

[16] Lalas, D.P., V.R. Veirs, G. Karras and G. Kallos (1982), An analysis of the SO2 concentration levels in Athens, Greece. Atmospheric Environment, Vol. 16, No. 3, pp. 531-544.

[17] Christidis, Z.D. (1986), Hydrodynamic mesoscale modelling of atmospheric transport and pollutant deposition in the vicinity of a lake. Ph.D. Dissertation, Dept. of Atmospheric Science, University of Michigan, Ann Arbor, Michigan. 353 pp.