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Project Summary

Flow and Dispersion of Pollutants Over Two-Dimensional Hills: Summary Report on Joint Soviet-American Study

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Wind tunnel experiments and theoretical models concerning the flow structure and pollutant diffusion over two-dimensional hills of varying aspect ratio are described and compared. Three hills were used, having small, medium, and steep slopes. Measurements were made of mean and turbulent velocity fields upwind, over, and downwind each of the hills. Concentration distributions were measured downwind of tracer sources placed at the upwind base, at the crest, and at the downwind base of each hill. These data were compared with the results of two mathematical models developed in the U.S.S.R. for treating flow and dispersion over two-dimensional hills. Measured concentration fields were reasonably well predicted by the models for a hill of small slope. The models were less successful for hills of steeper slopes, because of flow separation from the lee side of the steepest hill and high turbulence and much-reduced mean velocity downwind of the hill of medium slope.

This Project Summary was developed by EPA's Environmental Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

This report presents preliminary results of the Joint Soviet-American Work Program for studying air flows and dispersion of pollutants in hilly terrain. The work was conducted in the Fluid Modeling Facility of the U.S. Environmental Protection Agency (EPA), Research Triangle Park, NC.

Investigations of pollutant transport and dispersion in the atmosphere over complex relief are critical for the protection of air quality, since industrial enterprises and other sources of air pollution frequently locate within such terrain. Although much effort has been expended in elucidating this problem and in establishing guidelines for industry and control organizations to use in predicting air pollution, the problem is far from solved. Presently, three main approaches are used to study the problem:

Theoretical Modeling

To calculate pollutant dispersion, it is necessary to know how irregularities of the ground surface distort the mean and turbulent structure of the incident flow. Some investigations of peculiarities of turbulent dispersion in distorted flows, even separated flows, have been made. Practically speaking, however, those results can be used only if the distorted mean flow field, i.e., mean streamline pattern, is known. Since mathematical modeling of flow structure is quite difficult, these diffusion theories have been applied only with highly simplified assumptions about the mean flow, e.g., potential flow. The most realistic models of flows, some which include diffusion calculations over irregular terrain, have been obtained through solution of simplified equations of viscous flow with additional simplifying assumptions on turbulence structure. In spite of differences between these models, underlying assumptions limit their applicability to gentle relief. Most of these theories are also too complicated for use in the daily practice of air pollution prediction. Hence, simpler models that assume potential (or "quasi-potential") flow over irregular terrain have become widespread. In the U.S., models are used that neglect, even for neutral flow, the convergence of streamlines over obstacles as in the EPA Valley Model. More recently, attempts have been made to describe the flow structure over steeper obstacles where flow separation may occur. But these attempts deal only with laminar flows which involve numerical solutions of Navier-Stokes equations at small to moderate Reynolds numbers.

Field Experiments

Full-scale experiments, while important, are expensive and time-consuming, especially in complex terrain. Extensive measurements and analyses are required of wind, temperature, and concentration distributions to gain sufficient understanding of the fundamental physics. Generalization from field data is difficult because of peculiarities of specific sites and meteorological conditions. Controlled variation of independent variables is generally not possible, and complicating factors are abundant. However, all models must ultimately be tested by comparison with real-world data. Significant field experiments in complex terrain are now being conducted by the Department of Energy, the Electric Power Research Institute, and the EPA.

Wind Tunnel Modeling

The difficulties of mathematical and field investigations of atmospheric flows and pollutant dispersion in complex cases such as hilly terrain have stimulated the development of wind tunnel modeling, where the atmospheric boundary layer and diffusion processes are stimulated. This method's advantages are the simplicity of fixing and controlling the governing parameters and the reproducibility of conditions, among others. While it is still technically impossible to satisfy simultaneously all similarity criteria, most investigators now have a consensus opinion of how to approximate atmospheric processes of different scales in wind tunnels. Two basic approaches exist. The first is the investigation of specific topographic sites. Such "specific" studies are usually requested by an industrial company or by a controlling air-protection organization. The second category, "generic" studies, focuses on idealized situations to obtain fundamental understanding of the principal governing parameters and the physical processes involved. Such investigations have been developing in recent years in EPA's Fluid Modeling Facility and the U.S.S.R. To simplify the investigation, one frequently considers two-dimensional relief and neutral stratification of the flow. Inroads have also been made on three-dimensional relief and non-neutral stratification.

Until recently, most generic studies of flow and dispersion in complex terrain have been concerned with hills of either small or large slopes. Separation on the lee slope was not expected to occur for hills of small slopes but was definitely expected for hills of large slopes. A few hills with moderate slopes have been investigated, but these have been conducted in short wind tunnels where the boundary layer was relatively thin and external turbulence was generated by a grid. The work reported here concerns hills with slopes ranging from small to large. This work attempts to generate new experimental information and to compare the results of the wind tunnel measurements with calculations based on previous mathematical models.

Computer programs that calculate pollutant concentrations using the above mentioned mathematical models were constructed for specific ground surface shapes. These shapes were single two-dimensional hills or valleys generated from a set of parametric equations.

The shapes of hills studied in the wind tunnel are shown in Figure 1 with aspect ratios of n = 3, 5 and 8 (maximum slope angles of 26°, 16°, and 10°, respectively). The working program consisted of:

a. Wind tunnel measurements of mean and fluctuating velocities of the neutrally stable flow in the presence of rough hills as well as pollutant concentrations from elevated point sources located in different positions relative to the hills;

b. wind tunnel measurements of concentrations from an elevated point source located over the rough flat floor; and

c. numerical calculations of surface concentrations in the presence of the hills as well as for the flat ground surface on the basis of the theoretical models, and comparisons of these results with the experimental data.

Results and Discussion

Wind and concentration measurements within the artificially-thickened, rough-wall boundary layer showed that the latter is a reasonable simulation of the neutral atmospheric boundary layer. The following points of agreement were demonstrated:

1. When a particular value of the Lagrangian integral scale was assumed, lateral plume growth rates agreed with Taylor statistical theory.

2. Vertical growth rates for ground-level sources agreed with Lagrangian similarity theory.

3. Rate of decay of ground-level concentration at large downwind distances agreed with gradient diffusion theory ($C \propto x^{-3/2}$).

Comparisons of numerical models with experimental data generally agreed within 10 to 15% in predicting the locations and values of maximum surface concentrations as the stack height was varied; further improvements may be expected when values of lateral and vertical diffusivities more precisely corresponding to the wind tunnel boundary layer are put into the model.

The flow over the steepest hill (n = 3) separated on the lee slope and formed a recirculation zone or cavity (see Figure 2). This cavity extended to 6.5 hill heights downwind of the crest. Within the cavity, the mean speed of the reversed mean flow was 20% of the free-stream velocity. The flows over hills 8 and 5 did not separate, but the

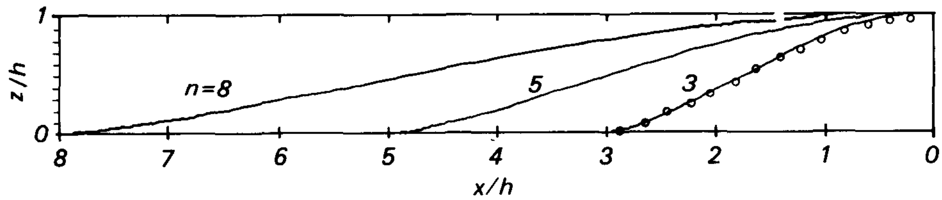
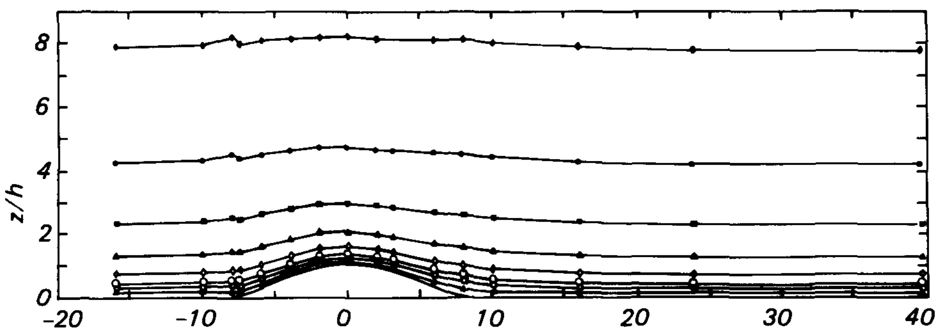
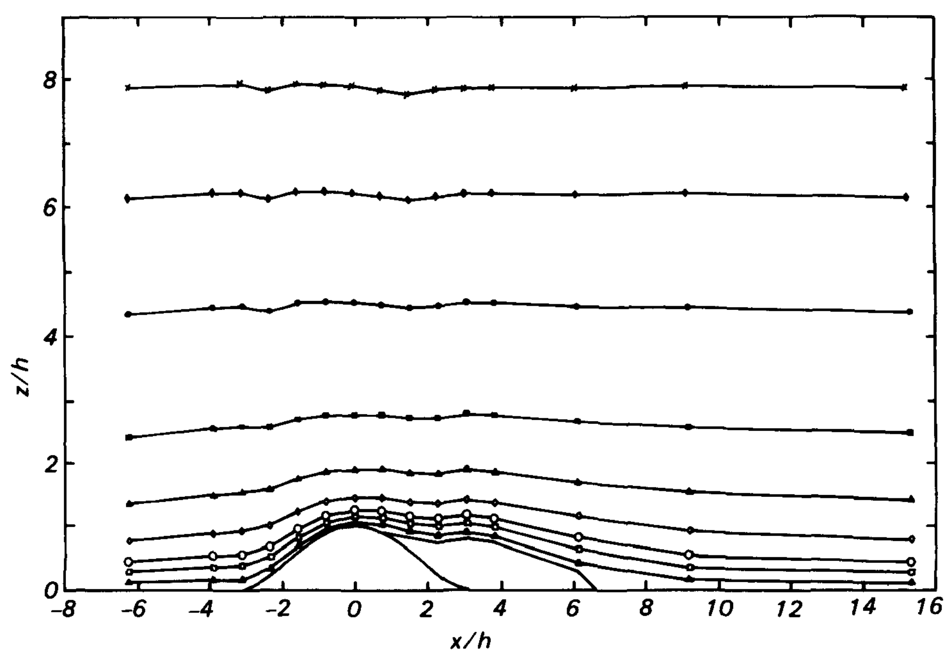


Figure 1. *Shapes of model hills (to scale).*



a) *hill n = 8*

Figure 2. ***Streamlines over hill 3 computed from experimental data.***



b) *hill n = 3*

Figure 3. ***Streamlines over hill 8 computed from experimental data.***

mean streamline patterns were noticeably asymmetric in contrast with potential theory (see Figure 3). The horizontal mean wind velocity near the downwind base of hill 5 was very small: 10% of the velocity in the absence of the hill at a height of $0.2h_o$. The longitudinal turbulence intensity, however, was extremely large — twice the mean velocity at $0.2h_o$. Even though the flow was not observed to separate *in the mean,* instantaneous flow reversals were frequently observed through smoke visualization. Probability density distributions measured with a pulsed-wire anemometer showed that the flow was negative up to 40% of the time, and that the mean was small but positive. Changes in the turbulence structure due to the presence of hill 8 were not highly significant, whereas changes over hills 3 and 5 were quite strong. The speed-up of the flow over the tops and the slow-down on the lee sides were larger over the steeper hills.

The dispersion characteristics were obviously also changed by the presence of the hills. The existence of a cavity region drastically influenced the shapes of the vertical concentration profiles and the values of the surface concentrations within the cavity. Concentrations within the cavity region were essentially uniform with height. Surface concentrations were sometimes greatly increased, sometimes somewhat decreased when compared with values over flat terrain. These variations depended upon the stack height and location with respect to the hill center. Instead of being smoothly varying functions of downwind distance, some surface concentration profiles contained characteristic dips that identified the beginning and end of the cavity region.

For hill 8, the deviations of the diffusion patterns from those over flat terrain were much less significant. Changes in the concentration fields were apparently not influenced as much by changes in turbulence structure as by changes in the mean flow field.

A simple way to evaluate the effects of terrain on concentration is to calculate a terrain correction factor, which is defined as the ratio of the maximum surface concentration occurring in the presence of the complex terrain to the maximum that would occur from the same source located in flat terrain.

The terrain correction factors for the values and locations of maximum surface concentration obtained from the wind-tunnel measurements were compared with factors calculated using a quasi-potential model. The results are tabulated in Table 1. Satisfactory agreement between theory and experiment was obtained: 80% of the calculated values were within 25% of the measured values when the stack was located at the upwind base or top of hill 8. When the stack was located at the downwind base, the theory significantly underpredicted the experimentally observed concentration values. This disparity is apparently related to the inability of the quasi-potential model to account for the asymmetry of the flow over the hill.

For hills 3 and 5, there was, as expected, a large disparity between calculated and experimental values when the stack was located at the downwind base of the hills caused by the presence of the recirculation zone and the zone of extremely low wind velocity. Streamwise diffusion may not be neglected in these zones. Nevertheless, there was a certain amount of agreement when the stack was located at the top or upwind base: 70% of the calculated values were within 25% of the measured values.

A comparison was also made between results of a numerical model and experimental measurements for values and locations of maximum surface concentration. Input to the numerical model were wind-tunnel data on the mean and turbulent flow fields over hill 8. The comparisons of maximum surface concentrations showed relatively good agreement; all calculations were within 30% of measurements when the stack was located at the upwind base or top of the hill; there was satisfactory agreement, all within 40%, when the stack was at the downwind base.

Table 1. *Terrain Correction Factors for Maximum Surface Concentration.*

Stack Height / Hill Height	Source at Upwind Base: From Measur.	Source at Upwind Base: Calcul.	Source at Hill Top: From Measur.	Source at Hill Top: Calcul.	Source at Downwind Base: From Measur.	Source at Downwind Base: Calcul.
			HILL, n = 8			
0.25	1.45	1.42	0.91	0.66	3.43	1.42
0.50	1.12	1.37	0.56	0.67	2.99	1.37
1.00	1.47	1.24	0.78	0.74	2.39	1.24
1.50	1.16	1.20	0.82	0.75	1.68	1.20
			HILL, n = 5			
0.25	1.96	1.70	0.54	0.53	15.00	1.70
0.50	2.04	1.59	0.63	0.54	8.12	1.59
1.00	1.74	1.35	0.86	0.65	5.63	1.35
1.50	1.20	1.28	1.04	0.67	2.90	1.28
			HILL, n = 3			
0.25	2.81	2.29	0.34	0.38	7.50	2.29
0.50	2.47	2.02	0.69	0.41	6.42	2.02
1.00	1.78	1.52	0.91	0.55	10.80	1.52
1.50	1.87	1.39	0.94	0.59	7.77	1.39

Recommendations

Further refinement of the technique used for producing the wind field and the application of more appropriate models for eddy diffusivities should improve the agreement with experimental data.

Additional tests showed that the flow structure and separation is insensitive to the Reynolds number over a limited range, but it is not known for certain that the relatively low-Reynolds-number wind-tunnel flow simulates the very large-Reynolds-number flow in the atmosphere. Nevertheless, it is important that theoretical models be developed to predict separated flows such as this wind tunnel flow, since separation definitely occurs on the lee sides of steep-enough full scale hills.

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The complete report, entitled "Flow and Dispersion of Pollutants Over Two-Dimensional Hills: Summary Report on Joint Soviet-American Study," (Order No. PB 82-121 179; Cost: $13.50, subject to change) will be available only from:

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