

MEAN TEMPERATURE AND MEAN CONCENTRATION DISTRIBUTIONS OVER A PHYSICALLY MODELLED THREE-DIMENSIONAL HEAT ISLAND FOR DIFFERENT STABILITY CONDITIONS

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Abstract. Results of flow visualization, and the mean temperature measurements over a physically modelled three-dimensional heat island in a wind tunnel capable of simulating stratified atmospheric boundary layers are presented. Concentration measurements of Kr85 released from an upwind two-dimensional continuous line source show good correlation with flow visualization and mean temperature distributions. The results indicate the unique features of three-dimensional flow over a heat island – lateral low-level convergence, upward vertical motions, and upper-level horizontal divergence.

1. Introduction

Warmth of a city as compared with its surrounding rural areas, known as the urban heat-island effect, has been investigated by several field and theoretical studies – Landsberg (1961), Hilst and Bowne (1966), Bornstein (1968), Clarke (1969), Tag (1969), Myrup (1969), Vukovich (1971), Ackerman (1974), Braham (1974) and others. One of the problems associated with the field studies is the practical difficulty of setting up an extensive micro- and mesoscale meteorological measurement system that would help in understanding the kinematics of air flow in and around a city. The project METROMEX presently under way at St. Louis (Lowry, 1974) is probably more comprehensive than previous urban heat-island studies. In the absence of knowledge of basic flow behaviour, it becomes all the more difficult to evolve numerical models and to verify them. Another approach that may be used to reach at least a better qualitative understanding of heat-island dynamics is the physical modelling in a wind tunnel capable of simulating stratified atmospheric boundary layers. Such a study was undertaken at Colorado State University in the large meteorological wind-tunnel facility shown in Figure 1, where the three-dimensional flow and diffusion of air over an idealized heat island were examined for a variety of approach flow stability conditions and surface boundary conditions of the heat island (SethuRaman, 1973). This paper treats primarily the mean temperature and mean concentration distributions over the heat island.

2. Modelling Criteria

A description of the experimental arrangement and the modelling criteria have been

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given elsewhere (SethuRaman and Cermak, 1974). In essence, the similarity of approach flows was achieved with the equality of gross Richardson numbers based on the relationship

$$R_g = \frac{g \Delta\theta z}{\bar{\theta} \bar{u}^2}, \quad (1)$$

where g is the gravitational acceleration, $\bar{\theta}$ is the average potential temperature and \bar{u} is the mean wind speed at height z . This parameter is different from the gradient Richardson number in that it represents the average characteristics of flow over the height considered, usually the depth of the atmospheric surface layer.

A Richardson number typical of a rural area upwind of an urban region was selected on the basis of available data from field studies. A gross Richardson number of 0.18 was considered to be representative for the upwind rural area during night-time inversion conditions. One of the important factors for boundary-condition similarity over the heat island is simulation of the heat source which acts as the prime driving force for the flow perturbations. Equality of Monin-Obukhov similarity parameters was adopted to model the heat source so that

$$\left(\frac{z}{L}\right)_p = \left(\frac{z}{L}\right)_m, \quad (2)$$

where L is the Monin-Obukhov length, and p and m denote the prototype and model conditions respectively. The Monin-Obukhov length is defined as

$$L = -\frac{u_*^3 C_p \rho \bar{\theta}}{kgH}, \quad (3)$$

where u_* is the friction velocity, k is the Kármán constant, $\bar{\theta}$ is the average potential temperature of air, ρ is the density of air, C_p is the specific heat of air at constant pressure, and H is the heat flux. The heat flux from a city has a diurnal and seasonal variation and also depends on various other factors such as the size, population, etc. For the purposes of modelling, a representative average value from a medium-sized city was assumed. The model features for different approach flows are given below:

Surface-based inversion approach flow –

R_g for approach flow	= 0.18
Surface temperature outside the heat island	= 4 °C
Ambient air temperature	= 43 °C

Elevated inversion approach flow –

Height of the upwind elevated inversion	= 4 cm
R_g for approach flow	= -0.03
Surface temperature immediately upwind (This was necessary to produce elevated inversion.)	= 43 °C
Surface temperature outside the heat island	= 4 °C
Ambient air temperature	= 43 °C

Near neutral approach flow –

- R_g for approach flow = 0
- Surface temperature outside the heat island = 26 °C

For all approach flows –

- Ambient mean wind speed = 1.25 m s⁻¹
- Average surface temperature over the heat island = 121 °C

From an analysis of the urban boundary layer observed at various cities and its counterpart over the model, the appropriate scale length was inferred to be 1:1300. Based on this scale ratio, the model roughness length, z_0 , was estimated to represent a prototype value of 169 cm. Detailed comparison of the model results to typical prototype observations is given in another paper (SethuRaman and Cermak, 1974). In general, the agreement is good.

3. Experimental Observations

The experimental arrangement shown in Figure 2 consisted of three electrical heaters, each 0.60 m square, providing a total heated area of 0.60 × 1.80 m located approximately 20 m from the beginning of the wind-tunnel test section (SethuRaman, 1973). The capability of this wind tunnel to simulate stratified atmospheric boundary layers has been discussed by Cermak (1971). About half of the experimental observations were made for a smooth heat island and the other half for flow over a rough heat island. The roughness elements consisted of aluminum blocks, 2.5 cm square and 0.6 cm thick, arranged in a street-block pattern with a spacing of 1.25 cm. The observations consisted of flow visualization with a passive smoke source and the measurement of mean and fluctuating temperatures in a three-dimensional flow field. The surface temperatures were measured with an infrared pyrometer. Twenty-five similar copper-constantan thermocouples mounted on a rack and controlled by

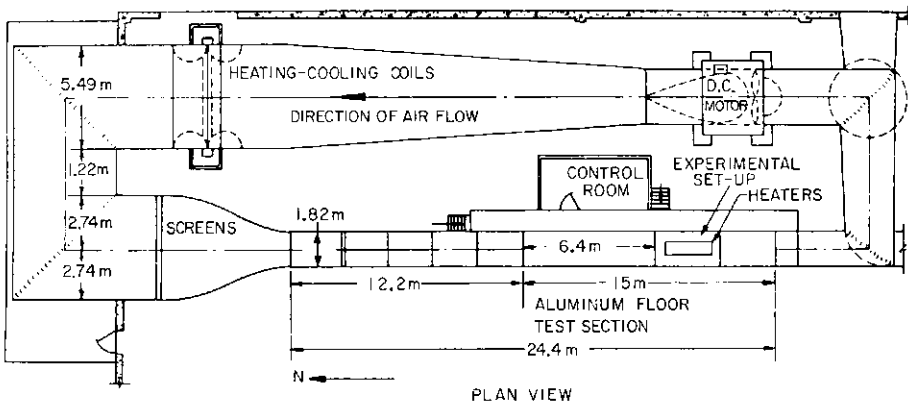


Fig. 1. Meteorological wind tunnel – Fluid Dynamics and Diffusion Laboratory, Colorado State University.

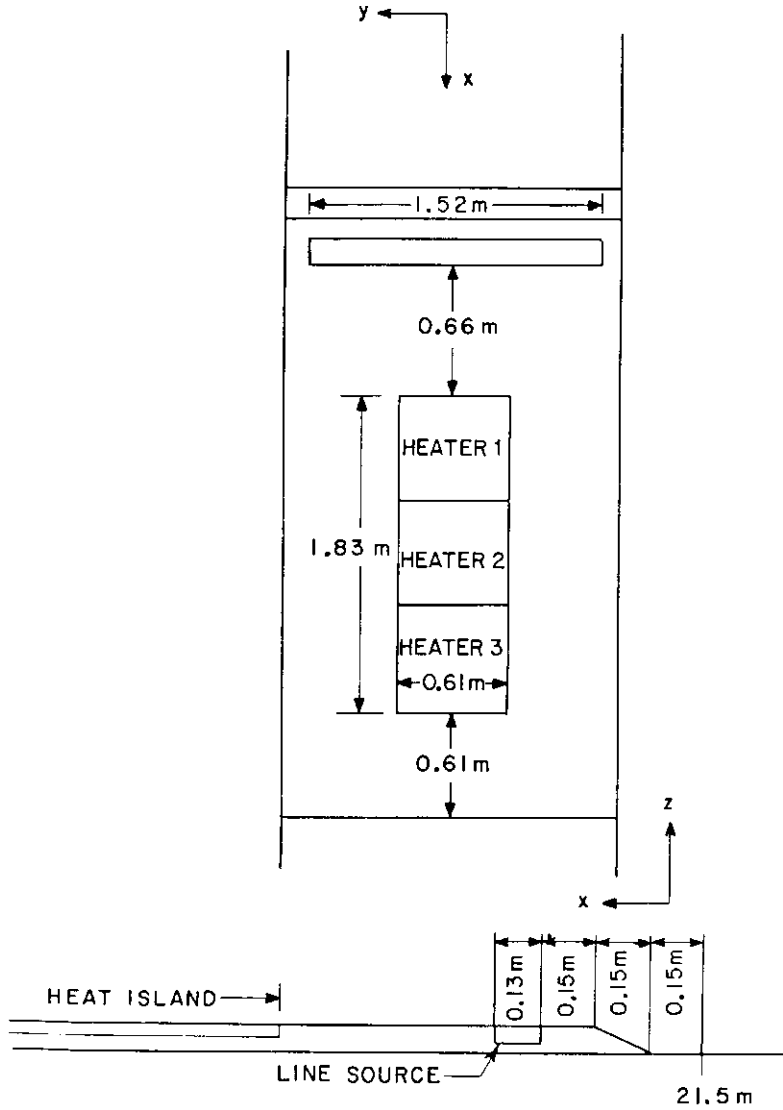


Fig. 2. Experimental arrangement for the idealized heat island.

a multiple switch were used to measure the mean temperatures with the reference junction maintained at 0°C . Care was taken to allow for the response time of the thermocouples before taking measurements. The emf output was integrated over a sufficiently long time if it showed large fluctuations due to the unstable nature of the flow over the heat island.

In addition, mean concentration measurements were made of Krypton-85 released from an upwind continuous line source and several point sources at different locations in and around the heaters. The purpose of using the point sources was to follow

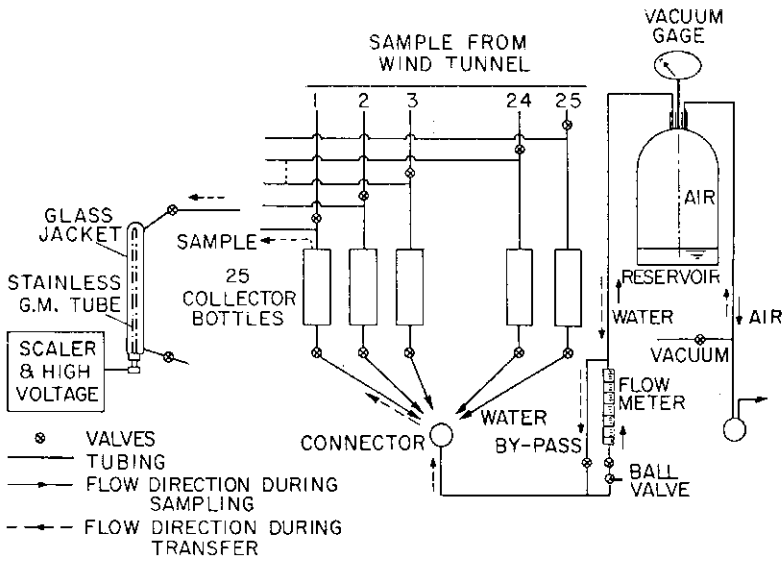


Fig. 3. Line diagram of the sampling system for diffusion experiments.

quantitatively the movement of air in, above and around the heaters and to verify the results obtained by flow visualization. Air in the wind tunnel was replaced after each run to reduce the background concentrations to a minimum. Sampling racks were set up at the required locations over the model and samples were drawn by vacuum pressure from the wind tunnel through flexible tubing and collected in glass bottles by the displacement of water. The details of the sampling system are shown in Figure 3. This arrangement enabled simultaneous collection of twenty-five samples. Each sample was then analyzed for radioactivity with the help of a Geiger-Mueller tube and an electronic scaler.

4. Discussion and Results

Visualization with a passive smoke source (TiCl_4) at positions of interest yielded valuable qualitative information about the flow pattern over and around the heat island. Quantitative measurements of mean temperatures and mean concentrations reproduced the effects observed by flow visualization and provided further insight. Coordinates are chosen such that x is along the length of the heaters, y along the width with the origin at the center of the upwind edge of the heater and z in the vertical direction.

4.1. MEAN TEMPERATURE DISTRIBUTIONS

Two large circulating cells were observed for a surface-based-inversion approach flow – a downward motion near the upwind edge of the heat island shown in Figure 4 and another cell downwind of the heat island, as shown in Figure 5, with a heat plume extending upward. The downwind cell extended over the heat island for a distance of

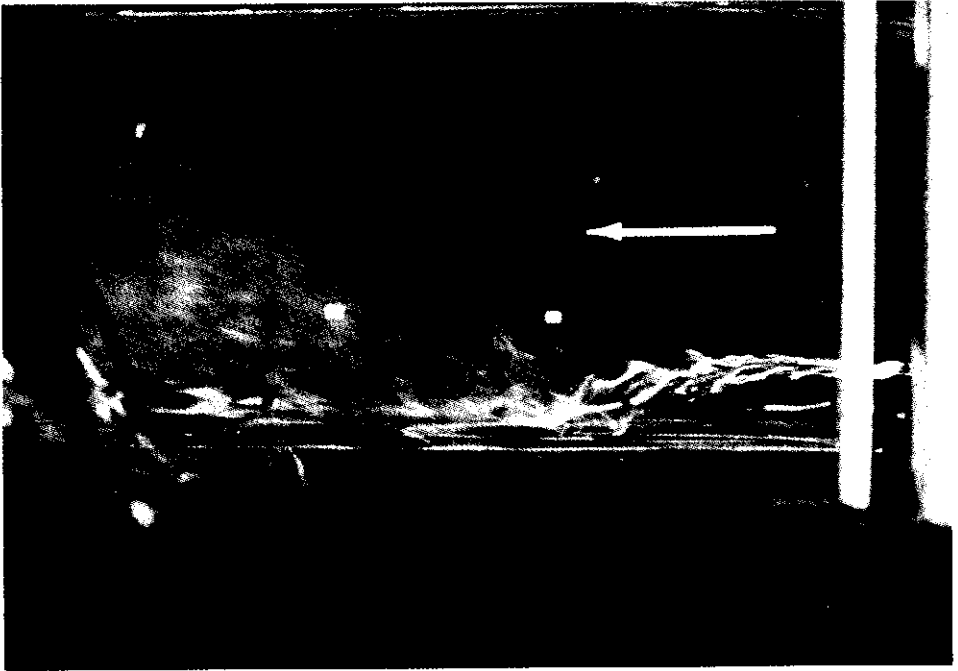


Fig. 4. Surface-based inversion approach flow over a smooth heat island – Elevated smoke source upwind of the heat island.

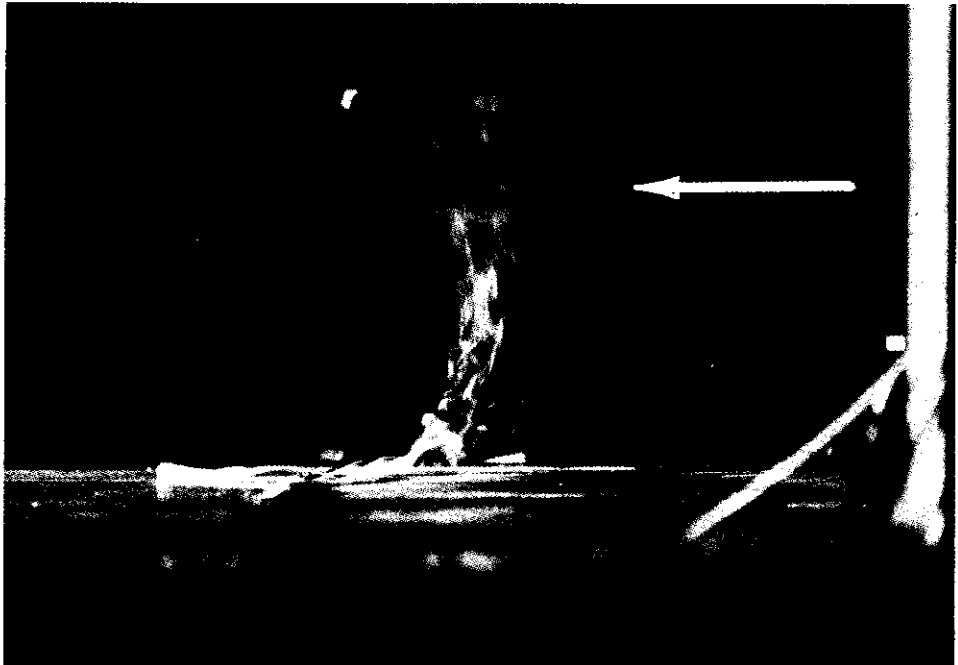


Fig. 5. Surface-based inversion approach flow over a smooth heat island – Ground smoke source downwind.

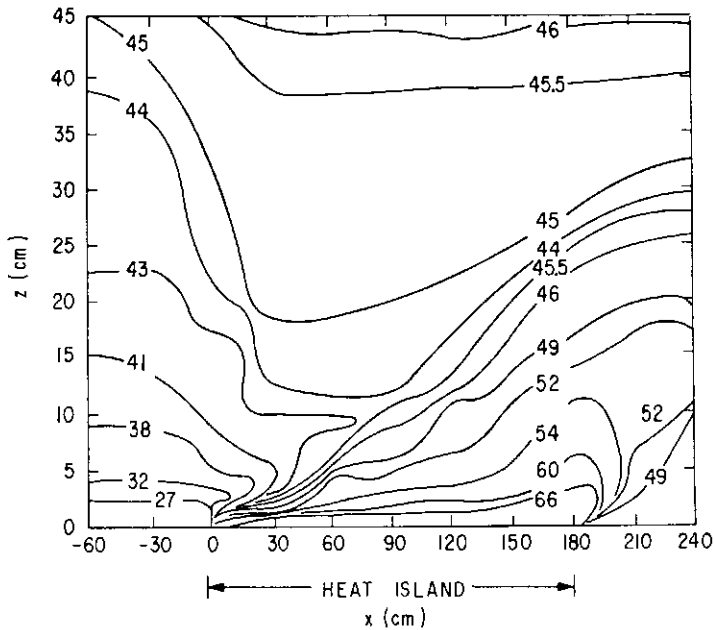


Fig. 6. Mean temperature contours for a surface-based inversion approach flow over an unstable, rough heat island along the centerline. (Temperatures are in °C.)

about 1/5th of its length and was not symmetrical about the downwind edge. In the absence of any ambient flow, one would expect these two cells to be symmetrical about the center of the heat island. Mean temperature contours in a vertical plane along the centerline shown in Figure 6 indicate essentially the same features. The existence of urban heat plumes has been observed by Clarke (1969), Auer and Dirks (1974) and several other investigators. Dungey and Morris (1972) found during their studies at St. Louis that the precipitation initiation in the area was predominantly through drop coalescence in the urban plume and that the frequency of precipitation initiation over and downwind of the city was about 2.4 times the corresponding value over upwind rural areas.

Low-level horizontal convergence, vertical (upward) motions and upper-level horizontal divergence as shown in Figures 7 and 8 characterized flow over the heat island. Lateral horizontal convergence superimposed on the ambient flow produced longitudinal roll vortices along the periphery of the heat island. The relative magnitudes of the drift of cold air over the heat island for near-neutral, surface-based inversion, and elevated-inversion approach flows for a rough heat island are shown in Figures 9, 10 and 11, respectively, as mean temperature distributions in a vertical plane along the width at 75 cm downwind. A lateral horizontal cross-over distance ratio λ/w may be defined, where λ is the lateral distance that characterizes the low-level convergence and w is the half width of the heat island. This ratio had the follow-

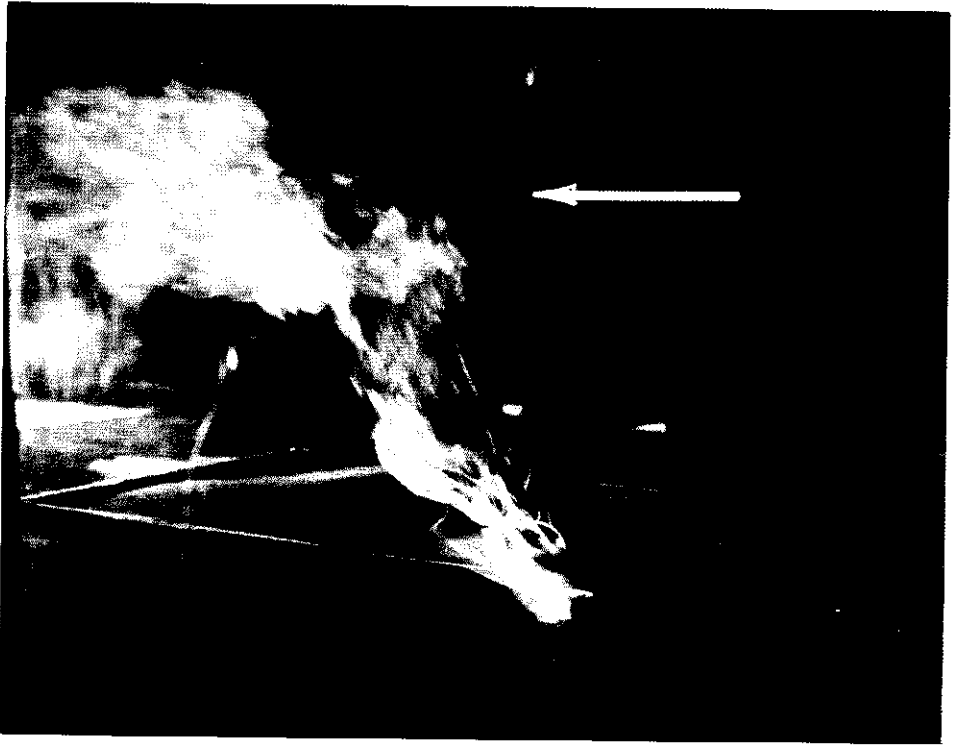


Fig. 7. Surface-based inversion approach flow over a smooth heat island – Ground smoke source at left side. (White tape marks the edges of the rectangular heat island.)

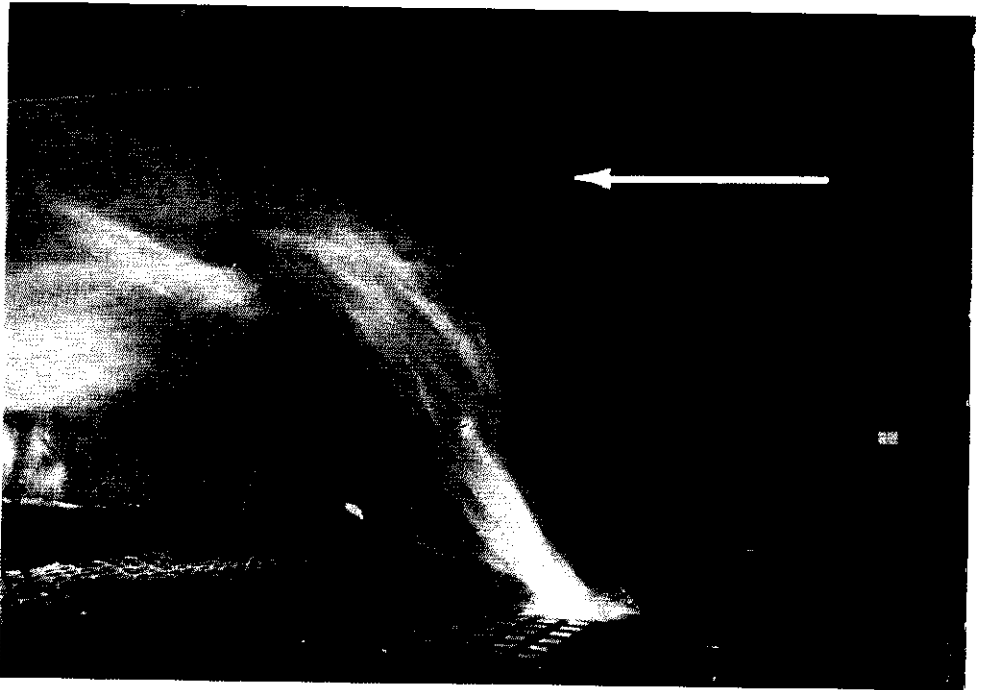


Fig. 8. Surface-based inversion approach flow over a rough heat island – Ground smoke source at the center. (White tape and roughness discontinuity mark the edges of the heat island.)

ing values for different approach-flow stability conditions at $x=75$ cm downwind:

Near neutral	0
Surface-based inversion.....	0.25
Elevated inversion	0.15

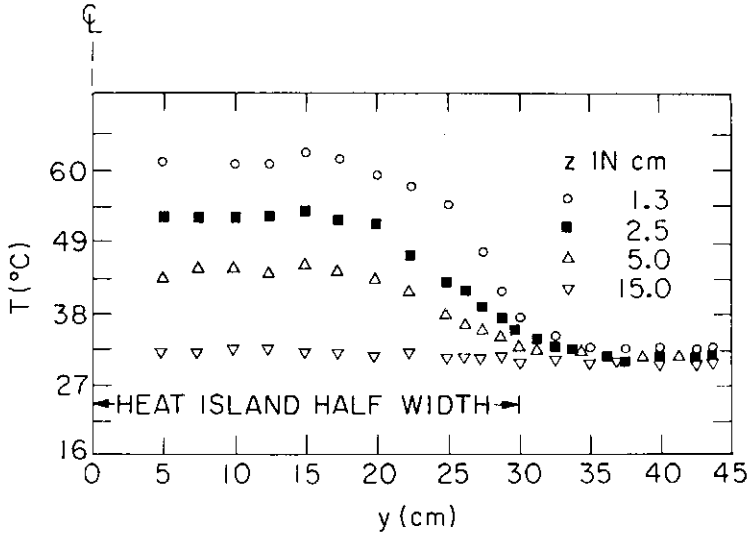


Fig. 9. Mean temperature distribution in a vertical plane along the width for neutral approach flow over a rough heat island at $x=75$ cm.

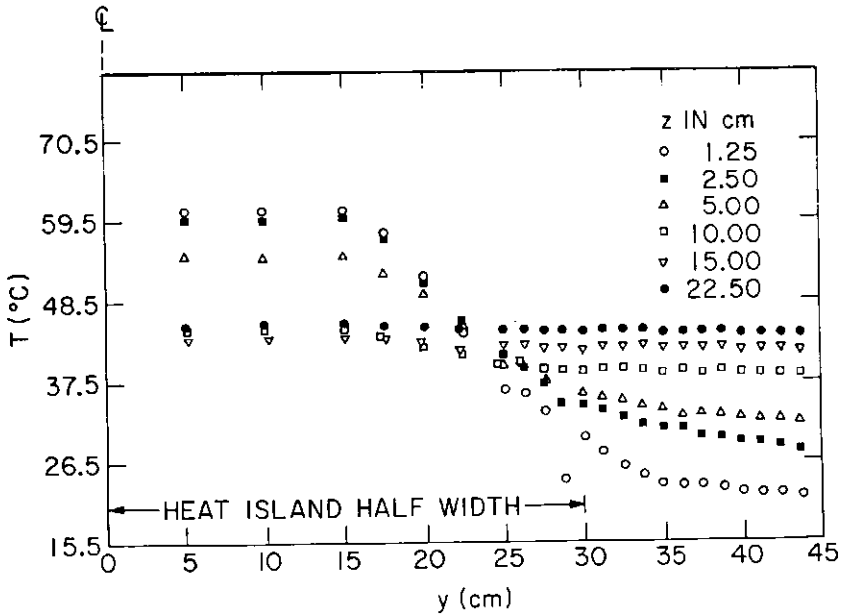


Fig. 10. Mean temperature distribution in a vertical plane along the width for surface-based inversion approach flow over a rough heat island at $x=75$ cm.

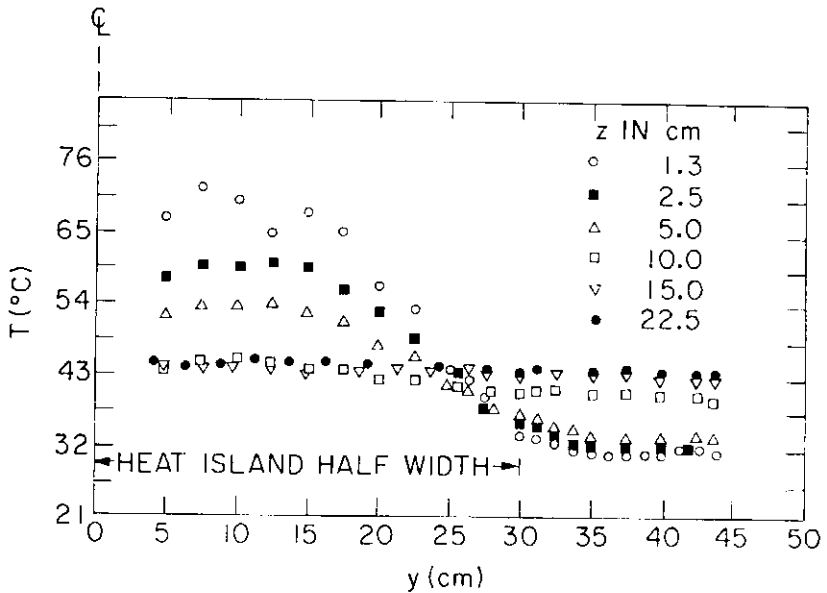


Fig. 11. Mean temperature distribution in a vertical plane along the width for elevated inversion approach flow over a rough heat island at $x=75$ cm.

The lateral horizontal cross-over distance also signifies the relatively rapid decrease of the elevated-inversion height along the heat-island width and the consequent reduction of turbulence intensity.

4.2. MEAN CONCENTRATION PROFILES

4.2.1. Line Source Release

The mean concentration measurements of the Krypton-85 released from a two-dimensional, ground-level continuous line source, 60 cm upwind of the heaters, indicated the nature of the flow and the amount of mixing for different cases studied. Vertical growth of the plume from the line source along the centerline for different conditions of the approach flow and the heat island is given in Figure 12. The upper boundary of the plume shown corresponds to points at which the local concentration was 10% of the maximum concentration. Ground-based inversion flow over a smooth surface created a gravity wave phenomenon with minimum dispersion. Most of the material remained within 3 cm of the surface. On the contrary, flow over the heat island produced dispersion several times more than that over an unheated surface. The plume boundaries also indicated the nature of development of heat-island plumes. The steepest gradient was observed for the surface-based-inversion approach flow over a rough heat island.

Mean concentration profiles along the centerline for neutral and surface-based inversion approach flows over a smooth surface are shown in Figure 13. The profiles

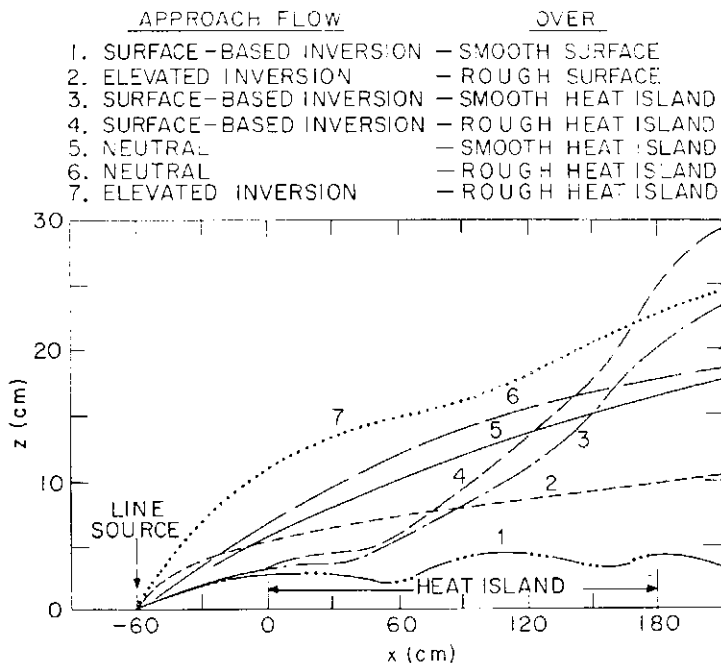


Fig. 12. Growth of the Kr-85 plume in the downwind direction based on 10% of the maximum concentration for different cases - Line source upwind of the heat island.

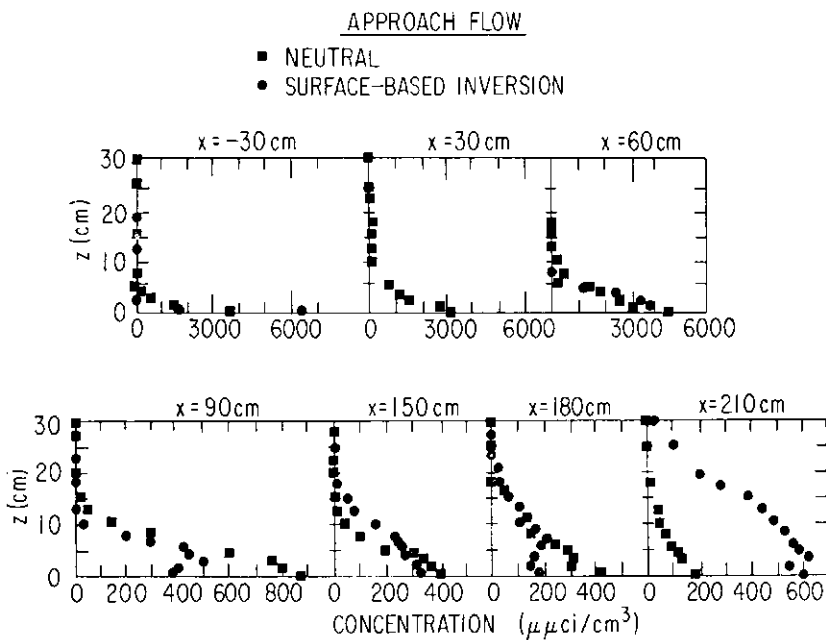


Fig. 13. Vertical mean concentration profiles of Kr-85 along the centerline for neutral and surface-based inversion approach flow over a smooth surface - Line source upwind of the 180-cm heat island.

for the neutral approach flow indicate a continuously decreasing ground-level concentration with downwind distance. The modified concentration profiles for the same source strength observed for a surface-based inversion approach flow show an increase in mean concentration values upwind. A sudden decrease in concentration over the heat island due to increased mixing and dispersion as compared with the undisturbed flow measurements was also observed. The decrease in ground-level concentrations varied from about 90% at $x=60$ cm to 20% at $x=150$ cm. Concentrations increased almost threefold downwind of the heat island due to the convergence of air flowing along both sides.

4.2.2. Point-Source Release

Point-source releases of Krypton-85 were made essentially to complement the flow-visualization results with quantitative data obtained by measurement of mean concentrations. Two locations of the sources – one on the heater and the other to one side of the heat island – are discussed here. Vertical profiles of mean concentrations at three downwind distances for the material released from a continuous ground-level point source at $x=82$ cm located over the heat island are shown in Figure 14. The ground-level concentrations decreased appreciably downwind – a 90% decrease in a distance of 53 cm. Mean concentrations continued to decrease downwind of the heat island, contrary to the results shown in Figure 13 and discussed in the previous section for an upwind line source. This effect is probably due to the plume, generated by the heat island, as shown in Figure 7.

The location of the ground-level continuous point source was then moved 2.5 cm to one side of the heaters with $x=82$ cm and $y=32.5$ cm. Lateral profiles of the ground-level mean concentrations at two downwind distances are shown in Figure 15. Concentrations at 30 and 45 cm downwind of the source decreased with distance outside the heat island whereas those inside showed a definite increase. The peaks that occurred at both locations were at the same lateral distance from the centerline. Occurrence of the peaks inside the heat island and a general increase in the concentration with distance downwind indicated the low-level convergence of cold air across the periphery towards the core of the heat island as was shown in Figure 7.

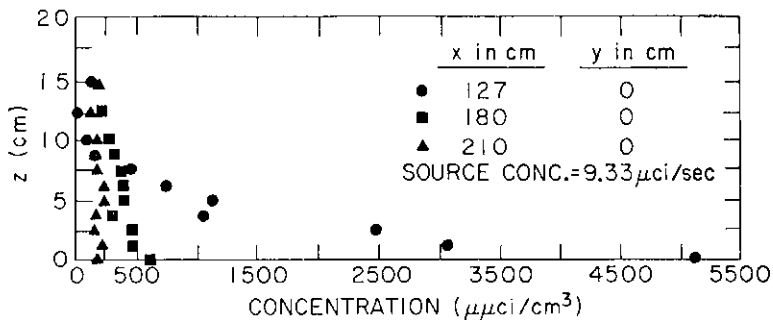


Fig. 14. Vertical mean concentration profiles of Kr-85 released from a ground-level continuous point source at $x=82$ cm and $y=0$ for a surface-based inversion approach flow over a rough heat island.

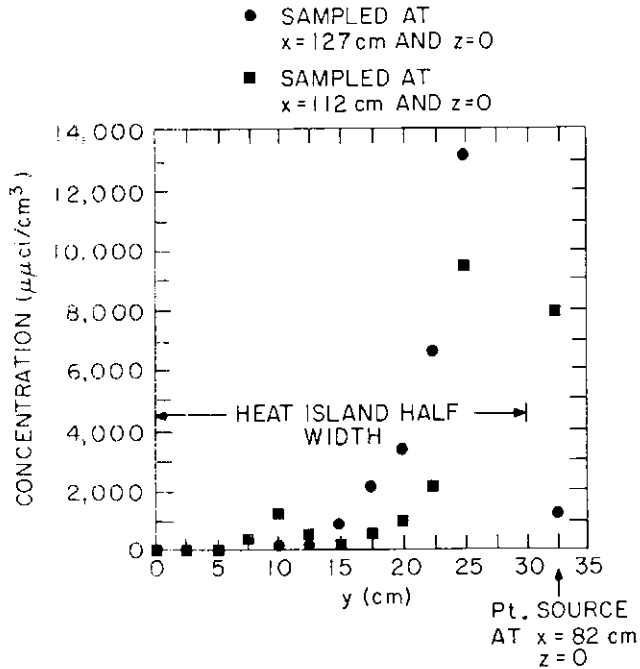


Fig. 15. Lateral ground-level mean concentration profiles of Kr-85 released from a ground-level continuous point source at $x=82$ cm and $y=32.5$ cm for a surface-based inversion approach flow over a smooth heat island.

5. Conclusions

Mean temperature and mean concentration measurements made over a physically modelled heat island based on equality of Richardson number for approach flow and equal Monin-Obukhov parameter for surface boundary conditions revealed the existence of two large circulation cells, one upwind and one downwind. The heat island was characterized by low-level horizontal convergence, upward vertical motions, and upper-level horizontal divergence. The region surrounding the heat island demonstrated horizontal divergence at lower layers, downward vertical motion, and upper-level horizontal convergence. An elevated heat plume was observed to exist downwind of the heat island. Lateral convergence also produced longitudinal roll vortices along the edges. The model results showed several features representative of the three-dimensional flow. These may have to be taken into consideration to achieve a better understanding of flow over urban heat islands.

Acknowledgements

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