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REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE October 27, 2004	3. REPORT TYPE AND DATES COVERED Final Report, period covering 10/01/00 to 06/30/04

4. TITLE AND SUBTITLE: Effects of Roughness and Thermal Inhomogeneities on Urban Flows	5. FUNDING NUMBERS: ~~Proposal P-39091-EV; Agreement~~ DAAD19-00-1-0562
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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING / MONITORING AGENCY REPORT NUMBER 39091.3 - EV

11. SUPPLEMENTARY NOTES

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12 a. DISTRIBUTION / AVAILABILITY STATEMENT	12 b. DISTRIBUTION CODE
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13. ABSTRACT (Maximum 200 words)

Theoretical analyses, laboratory experiments, numerical modeling and field studies were conducted to investigate the effects of topographic and thermal inhomogeneities on urban flows. The laboratory studies employed idealized urban flow geometries of general applicability, and the resulting flow, turbulence and dispersion were studied using state-of-the-art flow diagnostic techniques. The field observational test beds have been a mock urban experiment conducted at the US Army Dugway Proving grounds and large scale experiments conducted at the Phoenix and Salt Lake City airsheds. Simple analytical models were developed, which were tested using laboratory and field experiments. Such modeling helped identify and parameterize processes occurring in sub-grid scales of urban models. The new parameterizations were implemented in community modeling systems, and their efficacy was evaluated by comparing modeling results with field observations. A three-dimensional micro-scale model was also developed to study flow through street canyons. The latter model was nested to a meso-scale model, and the efficacy of this multi-scale nested modeling system was investigated by comparing their predictions with field results.

14. SUBJECT TERMS: Flow Past Buildings, Computational Fluid Dynamics Modeling, Urban Modeling, Dispersion, Multi-Scale Flow Analysis	15. NUMBER OF PAGES 38
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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1. Forward

The world is in the middle of a surge of urbanization, with some twenty megacities having arrived by the end of twentieth century. The population influx into cities has necessitated providing clean air and water, food, housing, healthcare and infrastructure for communication, governance, transportation and security. Of these, the quality of air is a factor of paramount importance, given that it is the medium of living and constituents of air are intimately related to human health and safety. Anthropogenic stressing of environment through pollutant emissions and land-use change as well as the threat of biological and chemical terrorism are of particular concern at present times.

The Environmental Fluid Dynamics group at Arizona State University has been involved in research related to the studies of urban airsheds, from the standpoint of a multi-scale flow transport and analysis from regional to personal scales. The project described herein was supported by the Army Research Office in support of those efforts, especially to study the effects of topographic and thermal inhomogeneities on urban scale flows. The emphasis was on the dispersion of pollutants in and from urban basins, effects of urban heat islands and flow though urban canyons.

Theoretical analyses, laboratory experiments, numerical modeling and field studies were the approaches used in the study. Laboratory studies were conducted using idealized flow geometries by employing state-of-the-art flow diagnostic techniques. These studies provide information on relevant flow processes and principal dynamical balances. The observational test beds have been a mock urban experiment conducted at the US Army Dugway Proving Grounds and large scale experiments conducted in the Phoenix and Salt Lake City airsheds. Our participation in these experiments was leveraged by the funding received from other agencies such as the National Science Foundation, the Department of Energy and the Arizona Department of Environmental Quality. Simple analytical models were developed and tested using laboratory and field experiments to identify and parameterize processes occurring in sub-grid scales. These parameterizations were implemented in community modeling systems, and their efficacy was evaluated by comparing the modeling results with field observations. A three-dimensional micro-scale model was also developed to study flow through street canyons, which was nested to the meso-scale modeling system.

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3. Statement of the Problem Studied and Research Performed

Thermal and topographic inhomogenities are *sine-quo-non* of urban flows. Topographic inhomogenities cover a multitude of scales, from the scales of natural orography of tens to hundreds of km to building scales of a few meters. Thermal inhomogeneities arise from a variety of sources, for example, as a result of uneven distribution of solar insolation owing to local topographic factors and land-use variability in urban areas. The *goal* of our research program was to study the influence of topographic and thermal inhomogeneities on urban scale flows. A schematic of space-time scales involved in studying urban flows are shown in Figure 1. The main reason for the complexity of urban air quality and dispersion problems is the diversity of these spatio-temporal scales. These include 'urban' scales of a few tens of km (normal city size, where large amounts of pollutants are emitted), meso-scales of a few hundred km (where secondary pollutants are formed and dispersed) and neighborhood scales (tens of meters) where groups of individuals are exposed to contaminants. In the last few years, major efforts have been directed at understanding processes of such different scales and at developing urban parameterizations [see Brown (2000) for a review]. One of the least understood aspects of all is the flow, dispersion and turbulence at 'building cluster' scales, where turbulence generated by the wakes of built elements efficiently mixes and diffuses momentum, heat, moisture and other substances.

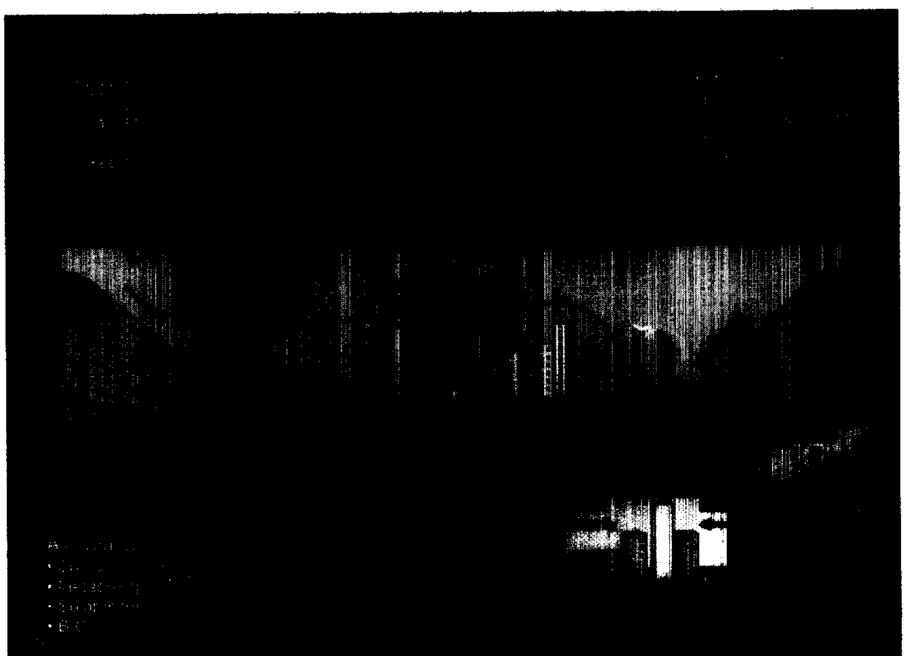

Figure 1: Multiple scales involved in an urban flow system.

The *long-term goal* of our research program is to provide scientific knowledge necessary for the prediction of small-scale motions (e.g. urban street canyon scales or the personal scales), starting from regional (synoptic scale) flows predicted by community models (i.e. multi-scale flow prediction and analysis). In such a modeling system, synoptic scale flow provides boundary conditions for meso-scale flow models. Mesoscale flow is modified by large urban features to produce urban scale flow, which is again perturbed by the land use inhomogeneities to produce neighborhood scale flow patterns; it is in this scale that typical meteorological and air quality predictions are made and mitigation strategies are negotiated. Mesoscale models can be used down to the higher end of the neighborhood scales, below which the utility of mesoscale models is questionable. Computational fluid dynamics models can be nested with mesoscale models to predict the smaller central business district (CBD) scale and personal scale flows. In order to contribute to the flow modeling in such complex systems, the present work was focused on topographic and thermal inhomogeneities of urban and smaller scales. To this end a number of research sub-tasks were undertaken: (i) urban heat island flows (which encompasses thermal inhomogeneities); (ii) thermal circulation in complex terrain (thermal and topographic inhomogeneities); and (iii) flow through an array of buildings (topographic inhomogeneities). A multi-pronged approach consisting of laboratory experiments, theoretical modeling, field experiments and numerical modeling was used. These approaches and the results of the studies are described in the following sections.

The original purpose of the project was to study dynamical aspects of urban- and building-scale flows using laboratory experiments and theory. In the first year, the work on urban heat islands was completed and the emphasis of the second year was on the purging of contaminants from urban valleys. In the latter project, a series of laboratory experiments was conducted to study transport and dispersion of negatively buoyant contaminants released in a cavity by an overlying turbulent flow. The aim was to understand the concentration distribution downstream of the cavity as well as the evolution of the velocity field following the distortion by the cavity (Strang & Fernando 2004). During the course of the project, however, the PI's group was invited to partake in a much larger-scale experiment known as the Mock Urban Setting Test (MUST) conducted at the U.S. Army Dugway Proving Ground, Utah, during the period September 2–27, 2001. This was an excellent complement to the laboratory experiments that were being conducted, as it allowed detailed measurements at considerably higher Reynolds numbers that are more amenable for scaling up to real building scales (using the principles of Reynolds number similarity). In parallel to MUST activities, during the second and third year, laboratory experiments on roughness discontinuities in urban flows were also conducted and a neighborhood-scale, three-dimensional computational fluid dynamics (CFD) model for flow in street canyons surrounded by an arbitrary array of buildings was developed (Baik et al. 2003). The model was applied to the MUST experimental configuration with the aim of evaluating the model. In addition, the model was configured and applied to the flow of the Central Building District (CBD) of Oklahoma City, in support of the URBAN-3 experiments. Our group was a key participant in the latter field study.

The work performed during the project is of direct relevance to the DOD's mission, in that it directly deals with prediction of flow and dispersion (obscurants, toxins) in urban areas. For example, with the specter of biological and chemical warfare in sight, it has become necessary to understand how a release of airborne material into an urban canyon or to an entire urban basin is dispersed and diluted downstream by an existing mean flow, so that estimates can be made on the safe tactical perimeter for emergency evacuations. In addition, urban canyons (streets flanked by tall buildings) are areas of high pedestrian traffic, and winds therein determine the pedestrian comfort, energy utilization, exposure levels to toxins, seepage of pollutants into nearby buildings, wind damage and the flushing of pollutants by background flow.

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5. Summary of the Results

Sub-tasks involved in the project, the approach used in research and the results are described in this section.

5.1 Purging of Pollutants from a Cavity

A simple two-dimensional cavity containing a buoyant contaminant, subjected to an overlying mean flow, was used in this study. A schematic of the flow configuration is shown in Figure 2, where purging of heavy fluid from a cavity of dimensions (W x H) filled with a dense contaminant is shown. The background flow is a turbulent channel flow of depth D with a free stream velocity U_o. The governing parameters for the problem are U_o, W, H, D, the buoyancy jump across the interface between the cavity and free stream fluids Δb_o and the molecular parameters κ (molecular diffusivity of the contaminant) and ν (kinematic viscosity of the fluid). It has been determined that any independent parameter Π^* at a given location can be expressed as

$$\Pi^* = \Pi^*(W/H, Ri), \qquad (1)$$

where $A=W/H$ is the cavity aspect ratio and $Ri=\Delta b_o H/U_o^2$ is the Richardson number.

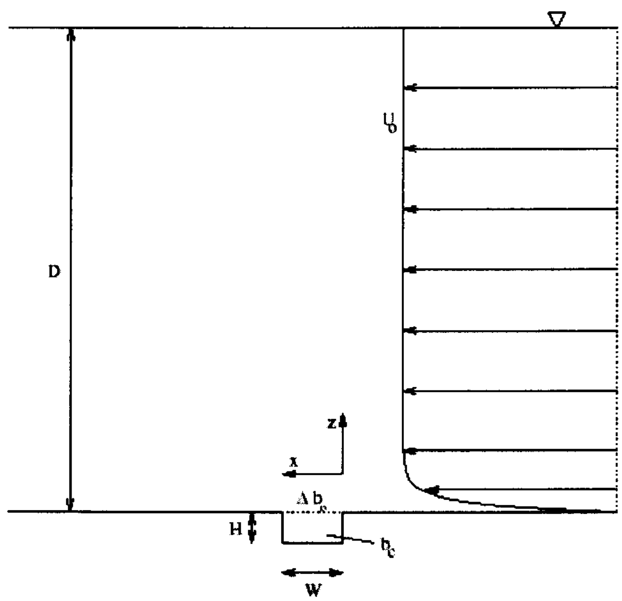


Figure 2: A schematic of the channel flow over a transverse, rectangular cavity containing a heavy fluid.

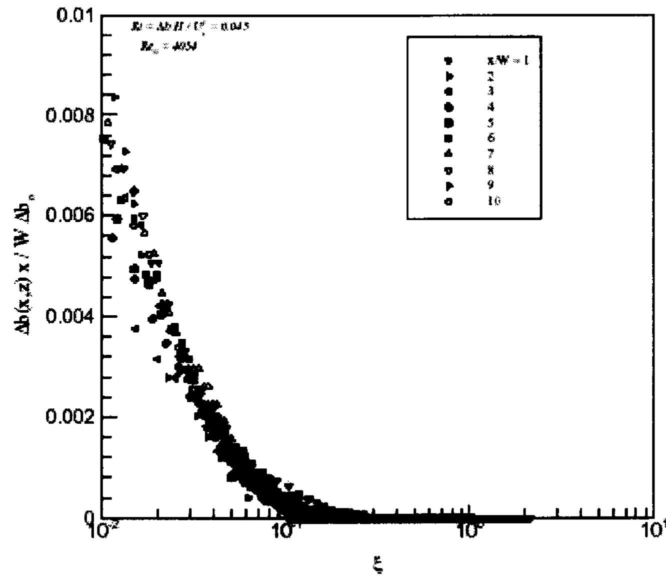
Concentration and velocity field measurements were performed proximate to the rectangular cavity underlying the turbulent channel flow boundary layer (shown in Figure 1) using laser-induced fluorescence (LIF) and laser-Doppler velocimetry (LDV) techniques, respectively. The channel flow was established in a closed-loop water channel facility, similar in design to that of Odell & Kovasznay (1971). Given the above set of parameters, experiments were performed for an aspect ratio of A = 1 and 2, and a Richardson number Ri range of 0.05 to 1. During the experiments, the Reynolds number based on the fluid depth ranged from 1.5×10^4 to 4×10^4 (or the related parameter, the Reynolds number based upon the momentum thickness, $2500 < Re_\theta < 4000$).

At low Ri, in particular for $Ri \sim 0.05$, and at a sufficiently large cavity aspect ratio (i.e. $A \sim 2$), the contaminant transport was found to be the greatest, as evident from the measurements of normalized contaminant concentration and root-mean-square (*rms*) buoyancy fluctuations immediately downstream of the cavity. Furthermore, it was found that cavity fluid ejection at large aspect ratios was driven by low frequency motions excited by the flow-cavity interaction. During these ejections, contaminants were periodically expelled from the cavity. This low frequency phenomenon was observed using LIF photos (Figure 3) and later quantified using concentration spectra at the trailing edge of the cavity. The frequency of such ejection events was found to be on the order of 1 Hz.

Figure 3: Instantaneous concentration image of cavity contaminant ejection and downstream dispersion for Ri = 0.17 and A = 2.

Furthermore, calibrated LIF data facilitated the measurement of the vertical distribution of concentration (represented as a buoyancy difference between the local buoyancy and the buoyancy of the ambient fluid far from the boundary layer) at equally spaced streamwise locations downstream from the cavity trailing edge. As evident from Figure 4, it was determined that the concentration profiles were collapsible when re-scaled as $\Delta b^* = (W\Delta b_o/x)f_1(Ri, A)$ and plotted as a function of $\xi = z/x$; here f_1 is a function. Additionally, the power law dependence of Δb^* on the Richardson number and aspect ratio was investigated. The corresponding exponents were found to be -0.86 and -0.64, respectively.

As described above, measurements of the velocity field local to the cavity and downstream of the trailing edge were performed. Interestingly, the friction velocity downstream of the cavity (or the related skin friction coefficient) was negligibly affected for an aspect ratio of A = 1; see Figure 5 (dashed lines). This observation is consistent



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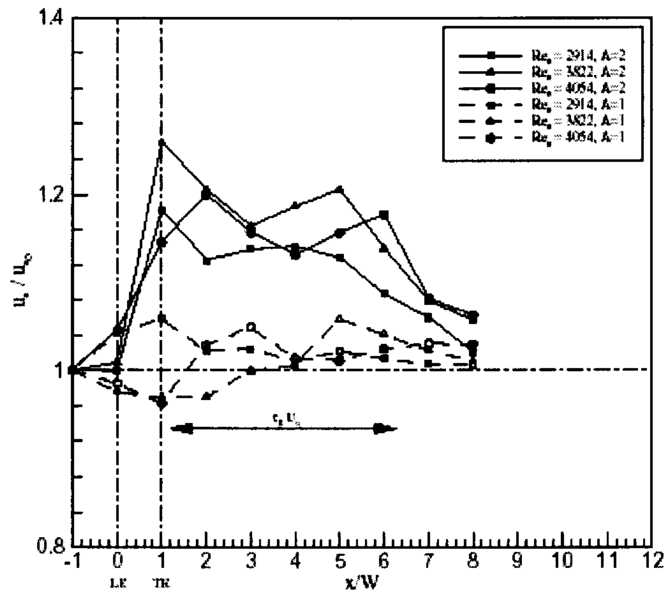


Figure 5: The variation of normalized friction velocity downstream of cavity. LE – leading edge; TE – trailing edge. The displacement of a fluid parcel in the freestream corresponding to an eddy turnover time is shown.

with other previous observations, such as those reported by Pearson et al. (1997) except that they noted oscillations of the skin friction coefficient. Alternatively, the downstream boundary layer tended to respond to the larger aspect ratio cavity ($A = 2$) with a moderate increase (20 %) in the friction velocity immediately downstream of the trailing edge and a slow recovery to the nominal value (i.e. upstream of the leading edge) within an eddy turnover scale; see Figure 5 (solid lines). Therefore, it appears that the relaxation of perturbations induced by the cavity are taking place over a large eddy turnover time scale downstream, which is the same time scale over which the turbulent kinetic energy spectrum relaxes in response to perturbations occurring at larger scales. The measurements also revealed that, above the cavity, there is a reduction of the mean velocity gradient but an increase of turbulent kinetic energy. Apparently, the interaction between mean shear and Reynolds stresses is strong enough that the increase of Reynolds stress overshadows the reduction of the velocity gradient.

5.2 The Mock Urban Setting Test (MUST)

The MUST campaign, a multinational collaborative effort sponsored by DTRA and coordinated by the U.S. Army Dugway Proving Ground (DPG), took place at the West Desert Test Center, Utah, in September 2001. A uniform array (12 x 10) of large shipping containers (semi-trailer size, dimensions 12.2 x 2.42 x 2.54m) was placed on a test grid in the Utah desert to represent a uniform neighborhood of buildings. The dimension of the array was 180 x 176m, with a Plan Index Area of 0.12; thus the flow regime was near the boundary between isolated roughness and wake interference regimes. The site was instrumented by various participating groups with a host of instruments, such as sonic anemometers, meteorological balloons, thermistors, photo ionization detectors; and their placements in the region of interest for our analysis is shown in Figure 6. Here the red diamonds represent Los Alamos National Laboratory (LANL) 2D sonic anemometers at height 2.0-2.1 m (frequency 0.5 Hz); blue ellipses and circles, the University of Utah (UofU) 3D sonic anemometers (20 Hz) placed on a 5-meter tower at heights 0.6, 1.0, 1.8, 2.6 and 3.7 m; green rectangles, the 3D LANL sonic anemometers (Metek, 20 Hz) placed at distances 0.17, 0.95 and 3.96 m from the southern (expected upstream) edge of the containers, at heights 3.80, 2.37 and 1.70 m, respectively. The tower was placed at $2H$ ($H = 2.54$ m is the building height) from the downstream edge of the first container row. Incoming wind speed and direction were obtained from our (ASU) sonic anemometer located 33 m upstream (for expected winds from the southeast direction). Balloons carrying tethersondes were vertically traversed at a site 420-m northeast of the center of the building cluster, providing background profiles of important meteorological quantities. As mentioned, the objective was to create meteorological and dispersion data in support of the development and evaluation of urban dispersion models and to ascertain the transferability of laboratory results to real urban canopies. The test also provided an opportunity to investigate the effects of background atmospheric stability on the flow, turbulence and dispersion in urban settings.

The focus of our research is the first urban canyon of MUST. Flow patterns therein were analyzed for different angles of incoming wind. Velocity and temperature fields around the obstacle were mapped for several vertical and horizontal planes.

Profiles of such important quantities as the turbulent kinetic energy (TKE), *rms* velocities, Reynolds stresses and Richardson number were calculated and analyzed for the tower location of two building heights downstream of the first row of obstacles.

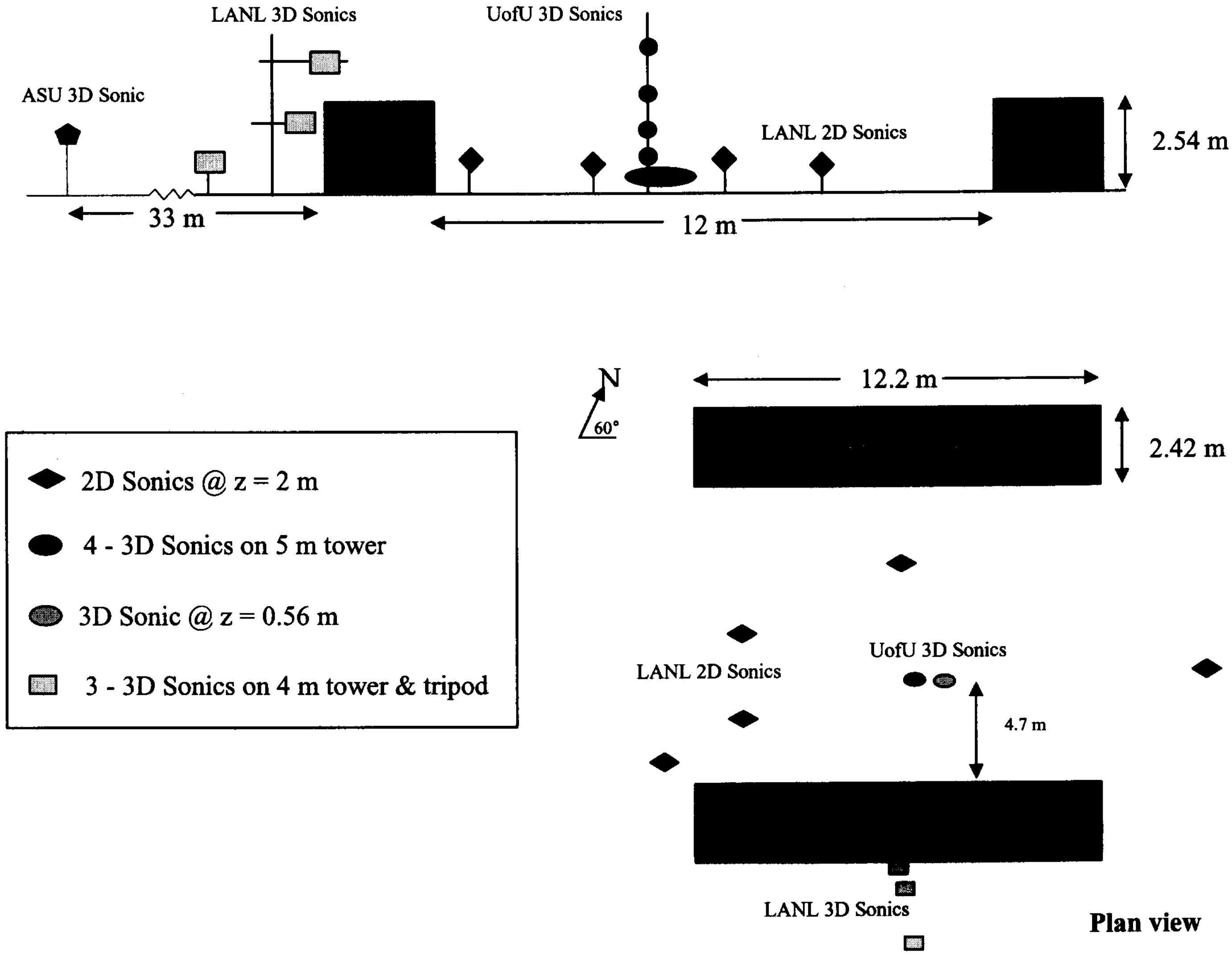


Figure 6. Siting of equipment surrounding the first urban canyon during MUST.

Three types of flow were observed, depending on the orientation of the incoming wind. The first type was characteristic of the case where winds approach normal to the longer side of the container (building), $\alpha = 90^{\circ}$. Similar to that observed in previous laboratory experiments with element arrays (e.g. Lee & Park 1994), a recirculation zone was detected here at the center plane, with negligible lateral (along canyon) velocity. Figure 7a shows an example for this case, where the flow field at 00:45 (LST) on 09/25/2001 is shown in plan view. A streamwise vertical section through the center of a building in the first row is shown in Figure 7b. Previous research indicates that the important parameter in this case is the building height to street width ratio A. Accordingly, for low A, a single primary vortex is formed, and for $1.5 < A < 2.7$ two vortices are expected. These previous findings are in general agreement with the present observations made with $A = 0.21$, where a single vortex was found to form.

Figure 8(a,b,c) show spectra taken upstream and in the first urban canyon at heights $1H$ and $1.5H$, respectively, in which several interesting features can be identified. Within the urban canyon, a dominant frequency appears at $f \approx 0.1$ Hz, corresponding to a Strouhl number of $fH/U \approx 0.2$, where U is the approach velocity. This is the typical value corresponding to vortex shedding behind bluff bodies at high Reynolds number Re (in this case $Re = UH/\nu = 3\text{x}10^5$, ν being the kinematic viscosity). The second dominant frequency appearing at ~ 1 Hz corresponds to the shear layer instability frequency for $Re \approx 10^5$ (Kim & Durbin 1988). In general, Kolmogorov inertial subrange is evident in all spectra, indicating the fully turbulent nature of the flow, and the results shown are typical of all experimental periods. The vertical distribution of kinetic energy (normalized by the mean flow velocity) for cases $\alpha < 5°$ is shown in Figure 9. The data do not collapse well, and it appears that the kinetic energy distribution is sensitively dependent on other parameters such as the stability of the flow and kinetic energy of the incoming flow.

A second type of flow pattern was noted when $5° < \alpha < 20°$. In this case also a recirculation region appears behind the building, but with a significant lateral component of velocity. The third flow type was a significant variant from the above cases in that when $\alpha > 45°$, recirculation at 2H disappeared (but occurred close to the building) and the flow simply channeled between the buildings. Wind above H has almost the same direction as the wind upstream, but it changed with height. Wind direction at 0.2H is 20 degrees rotated with respect to the direction at $1.4H$. Horizontal wind speed changes almost linearly between $0.2H$ and $1.4H$, while profiles of Reynolds stresses and TKE showed the same qualitative behavior as in the case of $\alpha = 0$.

Profiles of wind velocity components, TKE, turbulent intensity, as well as Reynolds stresses inside the urban canyon were studied as a function of incoming wind speed and direction. The velocity U_H at the building height H correlated well with the wind speed U_r at the reference height $h_r = 16$ m (measured 33 m upwind of the first row of containers) according to a power-law profile

$$\frac{U_H}{U_r} = \left(\frac{H}{h_r}\right)^{0.53}. \qquad (2)$$

When $\alpha < 20°$, horizontal wind speed was found to increase from the ground to $0.7H$ and then starts to decrease. The lateral component of wind speed was larger at $0.2H$

and 0.4*H*, which is due to formation of large vortices in the plan view, at the lower part of the urban canyon. In most cases the vertical component of velocity was negative, indicating downward flow. Turbulent intensities increase with height inside the canyon and reaches maximum at the building top and decreases. *Rms* of the lateral component is larger in the lower part of urban canyon. Reynolds stresses and turbulent kinetic energy generally increase with height and reach a maximum at the canopy top level where they start to decrease with height.

The measurements taken at night showed some interesting features of the temperature distribution. As expected, the approach flow at the ASU site was stably stratified near the ground, but the perturbations at the first building cluster caused mixing and recirculation, clearly showing an unstable stratification (Figure 10) and overturning within the canyon (thus affecting the kinetic energy budget!). The flow above the buildings again returned to the stable stratification. This clearly points to the importance of accounting for the stratification in dealing with urban building clusters, as they can significantly change the turbulent intensity distribution within the canyon.

Changes of a wind field due to its interaction with the MUST roughness canopy were calculated by employing the model developed by Belcher et al. (2003). This model identifies three stages of flow adjustment upon introduction of a roughness change to a flow. In the *impact* region, located upwind of the roughness change, the drag and the finite volume of roughness elements decelerate the flow, thus generating an adverse pressure gradient. In the *adjustment* region, downwind of the leading edge of the roughness canopy, the flow decelerates until it comes to a local balance between downward momentum transport by turbulent stresses and removal of momentum by the drag of canopy elements. After this equilibrium is established, an internal boundary layer develops, and the canopy affects the overlying mean flow as if it is responding to a change of roughness. This is called the *roughness-change* region. The length of the adjustment region is a function of the canopy geometry, specified by the roughness density (frontal area density) and the drag coefficient of individual canopy elements.

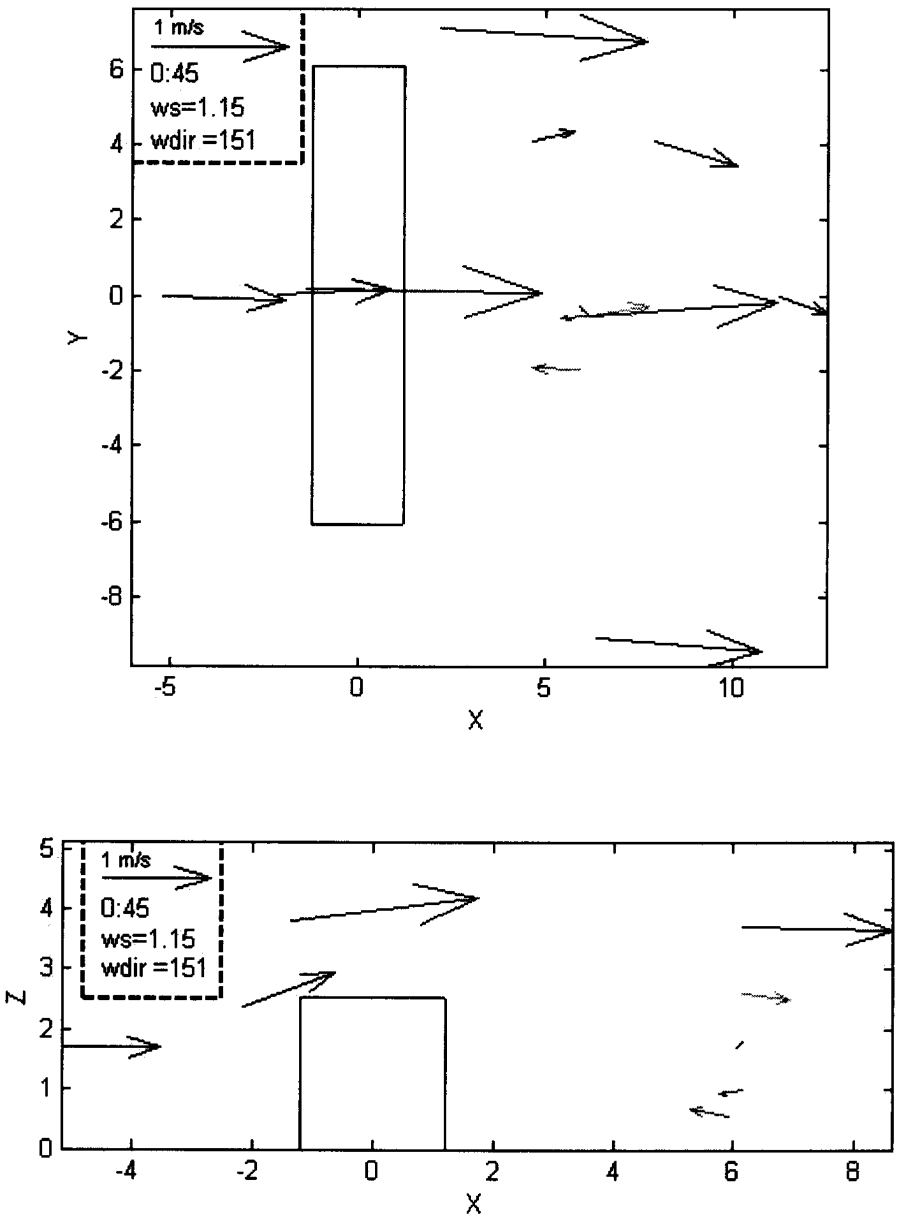
The model assumes that the fraction of the canopy that is occupied by obstacles is small, *i.e.* the distance between elements is large compared to the breadth. In this case, the obstacle drag can be represented as a point force, located at the center of each roughness element. Spatial averaging renders point forces into a continuous body force that extends throughout the canopy volume. The equations describing the mean flow are:

$$U_j \frac{\partial U_i}{\partial x_j} + \frac{\partial P}{\partial x_i} = \frac{\partial \tau_{ij}}{\partial x_j} - f_i, \quad \frac{\partial U_i}{\partial x_i} = 0 \qquad (3)$$

where t_{ij} is spatially averaged turbulent stress and f_i is the drag per unit volume.

Each quantity is decomposed into that corresponding to the incident profile and a perturbation induced by the canopy. Equations are then linearized by assuming small perturbations and neglecting products of perturbation quantities. Over much of the flow, the shear stresses are smaller than the inertial terms so that the shear stress term can be neglected. Also, the curvature of the incoming profile is neglected, since it is small away from the surface. Boundary conditions include no-slip at the surface and the decay of perturbations with the distance from the canopy.

The above model was used to predict velocity perturbations with respect to the mean flow as a result of flow distortion due to the simulated city. The incoming flow was obtained using sonic anemometers located at three different heights of the 16m tall tower, approximately 35m south from the edge of array. A sonic tower in the center of the array provided velocity profile above the canopy. The frontal area density of the array was 0.12. It was assumed that the lateral velocity gradients near the centerline were negligible, so that the centerline flow can be calculated using a two-dimensional model. Since the model did not include any influence of the density stratification on the flow, the experimental result used for comparisons were taken during the periods where the atmosphere was neutrally stratified (around 18:30 local time). Figure 11 shows a comparison of predicted perturbations in the middle of the array with experimental results. It also includes calculated profiles at the upwind and downwind edge of the array. The model correctly estimates the height where perturbations decay, while change of velocity perturbations with height seems to be less steep compared to experimental results.



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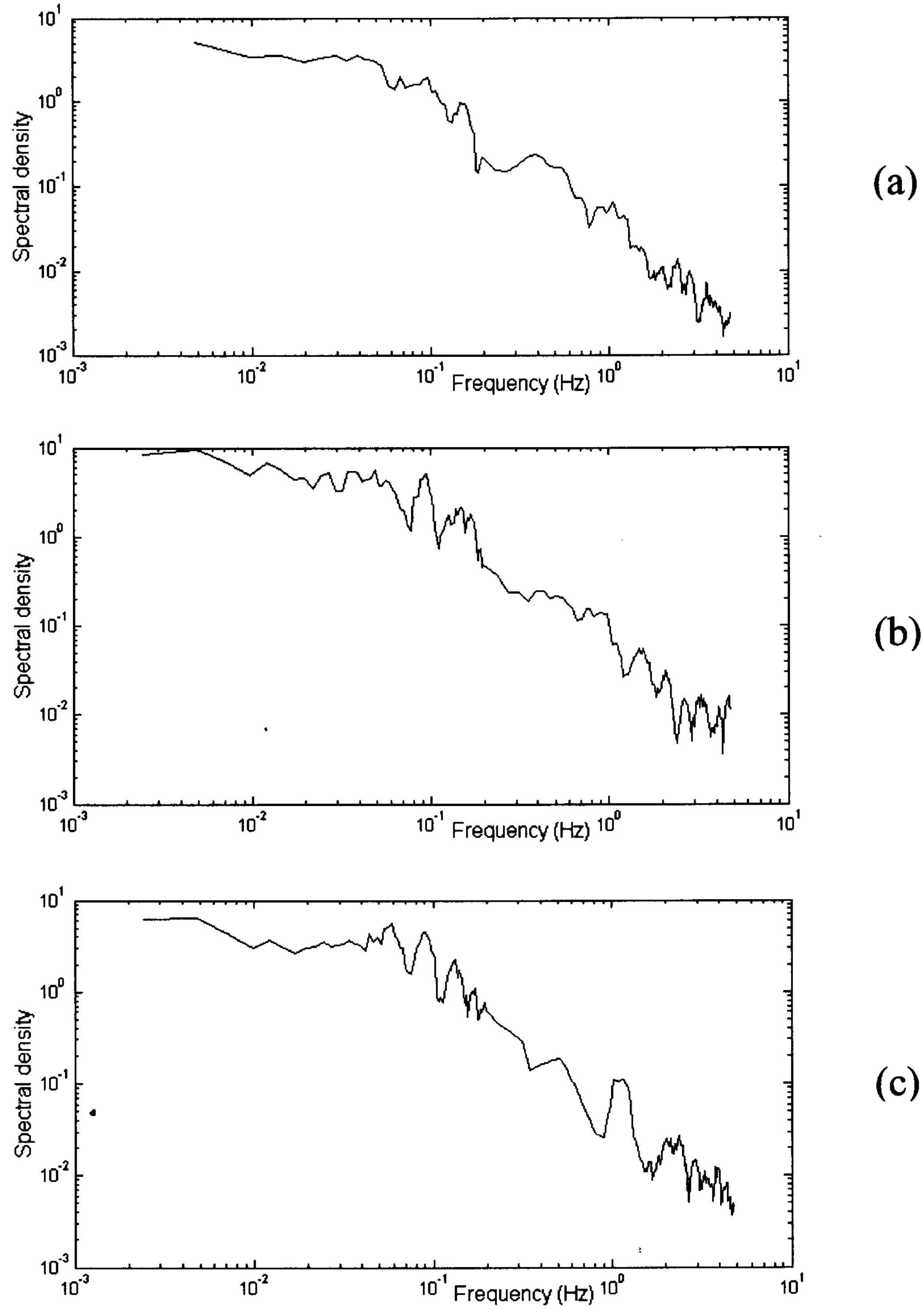

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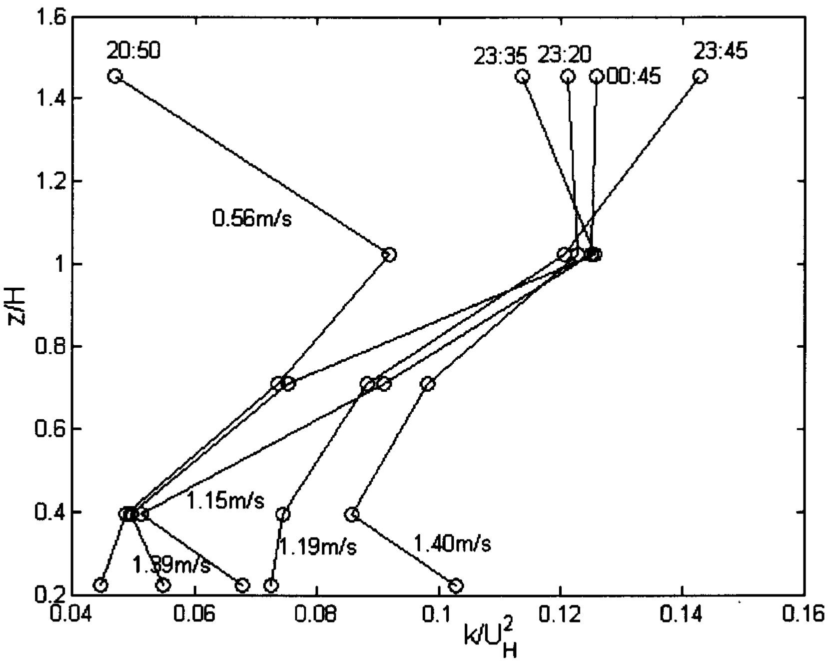

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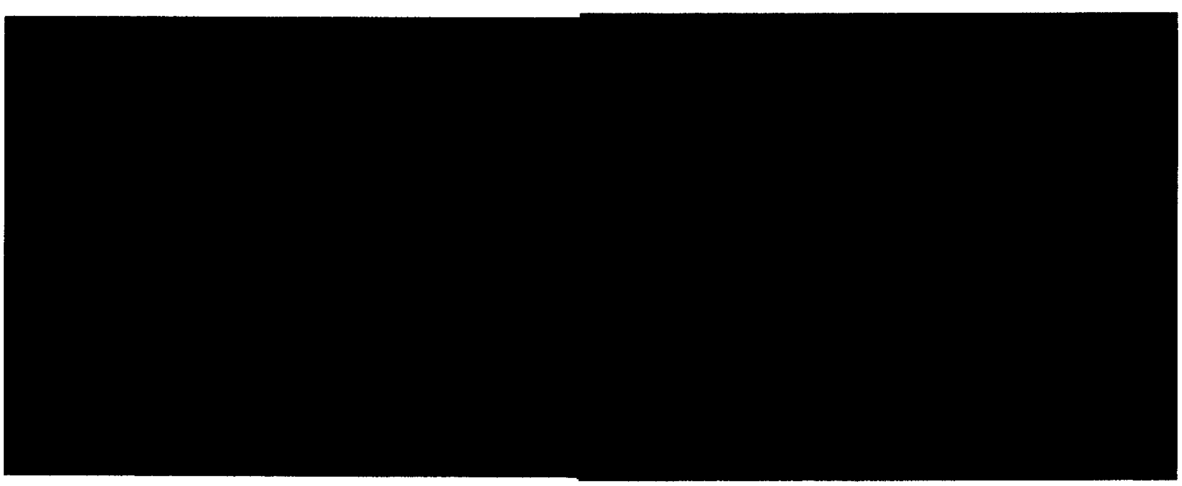

(a) (b)

Figure 10. Comparison of temperature (Θ) profiles (5 minute averages) outside (a) and inside (b) the urban canyon for different LST during 09/24/2001 (the times of profiling are given).

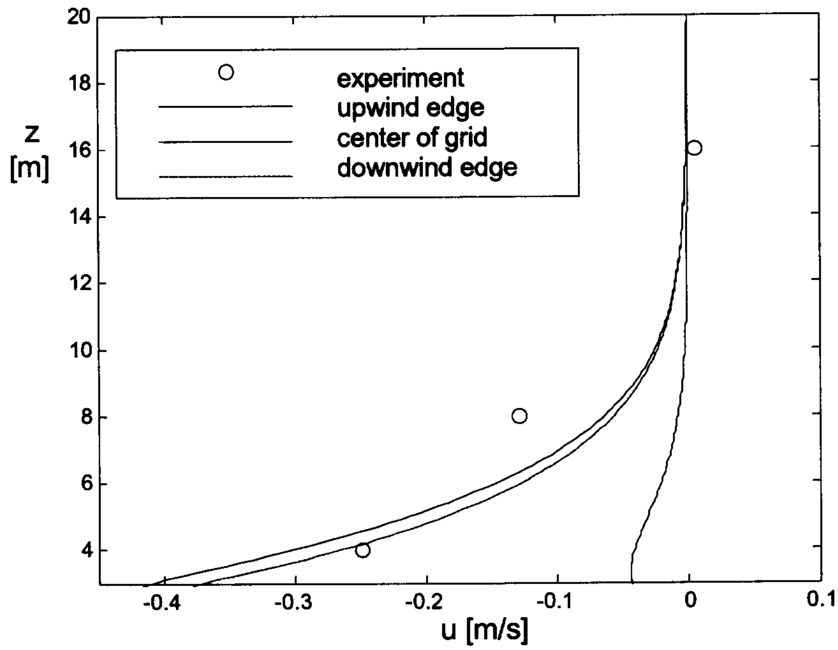

Figure 11. A comparison of calculations and MUST measurements with regard to flow through a mock building cluster.

5.3 Development of a Computational Fluid Dynamics (CFD) Model

A three-dimensional CFD model was developed to simulate flow around building clusters, and it was applied to the MUST building configuration (Baik et al. 2003). In this code, the primitive governing equations, namely, the Reynolds-averaged equations of momentum (with Boussinesq approximation) as well as conservation equations for heat, mass and scalars are solved, with closure realized by 'eddy diffusivity' modeling of Reynolds stresses and turbulent heat and mass fluxes. Eddy diffusivities, in turn, are calculated using prognostic equations for TKE and the dissipation rate. The governing set of equations is solved numerically on a staggered, non-uniform grid system using a finite volume method. A semi-implicit method is used for the pressure linked equation (SIMPLE) algorithm. Simulations were performed for different incoming wind angles α (defined as the angle between the incoming winds and the normal to the long axis of the first set of trailers), and the predictions were compared with measurements. The computational domain encircled the tower and the six closest buildings (Baik et al. 2003).

Figure 12 compares the predicted TKE, horizontal wind speed and vertical velocity with the experimental values for the case $\alpha = 0$ for the MUST array. A reasonable qualitative agreement was observed for all three quantities, but glaring quantitative differences arose with regard to the TKE, where it was over-predicted. The best prediction was realized for the horizontal wind speed, but the vertical velocity component was somewhat over-predicted at larger heights. The distribution of TKE for a model calculation involving a set of six buildings is shown in Figure 13 for the cases $\alpha = 45°$ and 0°, where the TKE distributions for two buildings in tandem are shown. We expect the predicted dissipation rate to underestimate the measurements, given the over-prediction of TKE by the CFD model. A simulation of a puff release into the CBD of Oklahoma City is shown in Figure 14, and such simulations were conducted prior to the URBAN-2 (Summer 2003) experiments, in support of field trials and to further evaluate the model. The comparisons of the predictions with observations are being conducted as a part of the on-going work.

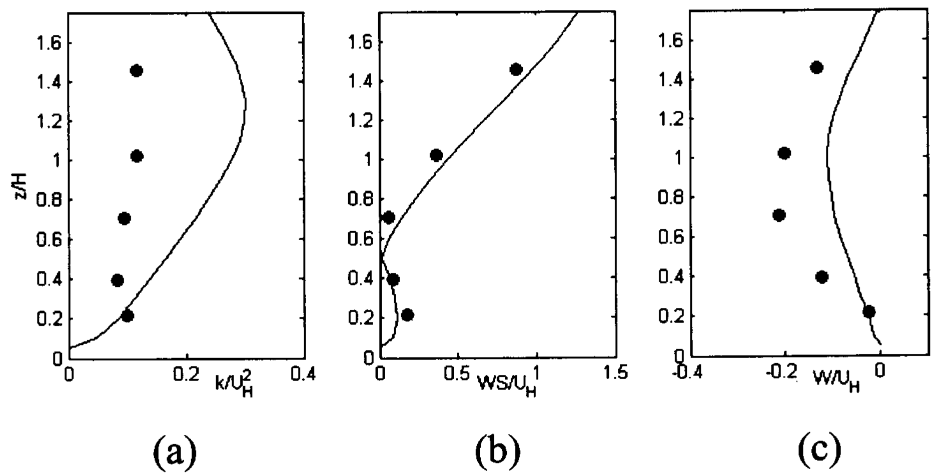

Figure 12. Comparison of modeling and experimental results for 09/24/2001 at 23:15, for normalized (a) turbulent kinetic energy, (b) horizontal wind speed $WS = \sqrt{U^2 + V^2}$ and (c) vertical velocity (W).

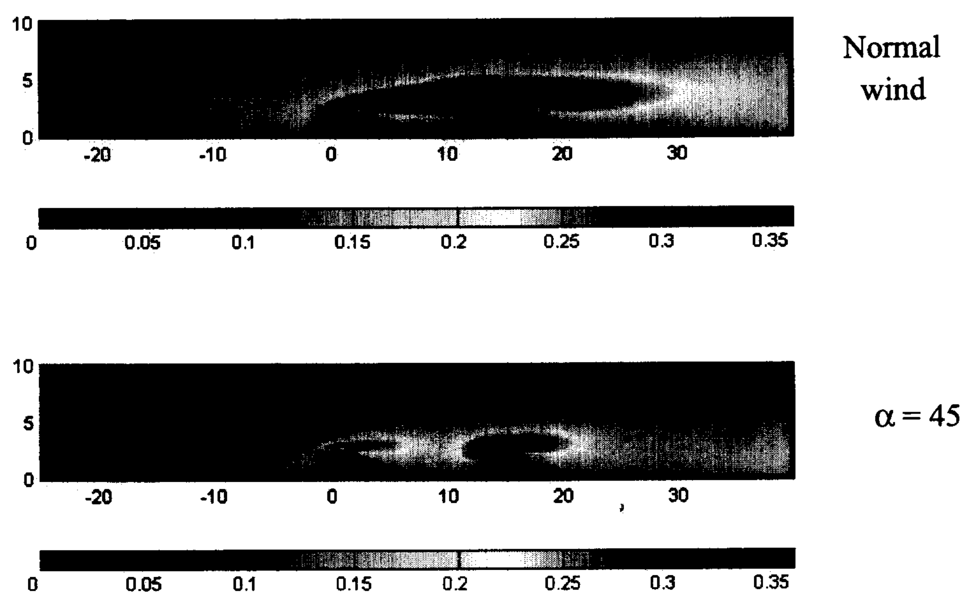

Figure 13. The distribution of TKE in the central vertical plane of two buildings in tandem calculated using the model for the cases of approaching wind angles of 0° (normal) and 45°.

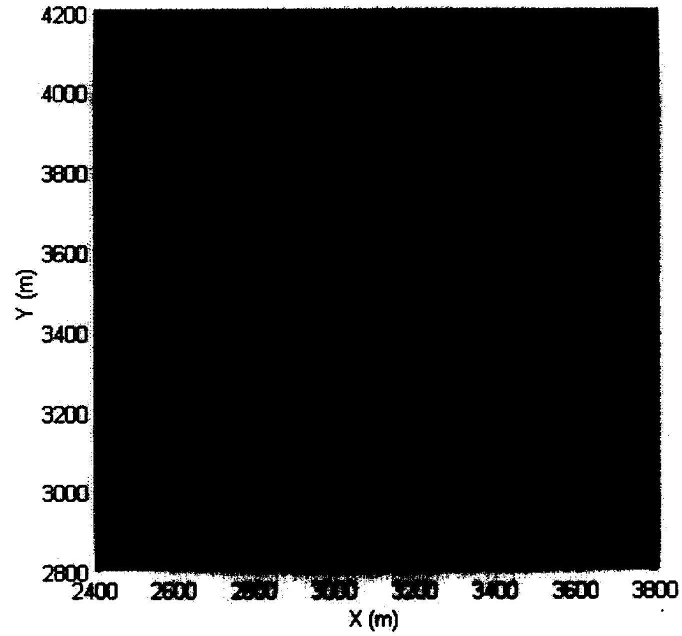

Figure 14. Visualization of pollutant concentration and wind velocity field at 1m height for Oklahoma City for the wind coming from the west. The wind speed was 2.5 m/s. The pollutant was released at (x = 2400m, y = 3500m, z = 5m) and visualization was done at time 51 minutes since the start of 30 minutes long release.

5.4 Surface Energy Budget Estimates Using JU-2003 Data

The purpose of the JU 2003 field campaign was to gather data that help better understand flow, heat transfer and dispersion of contaminants in urban environments. Knowledge gained from this study is expected to be used to improve, refine and validate computer models that simulate flow and dispersion in urban areas. The JU-2003 was conducted in a real urban area, and the data were collected in different parts of the urban domain, including in the Central Business District (CBD), in commercial/industrial areas as well as in suburbs. This wide distribution of measurements sites enabled a comprehensive understanding of flow and its stability and their local variations.

A part of the work undertaken by our group during JU-2003 dealt with studies on often-used surface energy budget schemes for mesoscale meteorological models. The surface energy budget is central to the driving and modification of urban flows, and it has been argued that energy-budget parameterizations employed in the popular mesoscale meteorological model MM5 needs improvement (Zehnder 2002). During JU-2003, we fielded a suite of instruments to measure the dominant components of the surface energy budget in a grassy city park located in a suburban area. Two days in mid-July (16 and 17) were chosen for analysis, considering relatively cloud-free skies on those days. Various components of the surface energy budget (see Figure 15) are expected to be in balance.

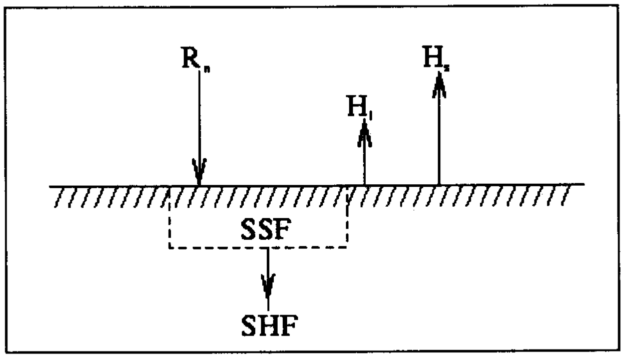

Figure 15. A schematic of the components of the surface energy budget: Net Radiation R_n, sensible heat flux (H_S), latent heat flux (H_l), soil heat flux (SHF) and soil storage flux (SSF).

Instruments were located in three separate locations: the LiDAR location, Energy station location and an urban canyon (sonics) location (see Figure 16). The instrumentation consisted of a Coherent Technologies, Inc. Doppler LiDAR (Light Detection And Ranging), 3-D sonic anemometers, radiation sensors, infrared temperature sensors, thermistors, soil heat flux plate and soil water content sensor. The LiDAR was located approximately four kilometers to the south-southeast from the CBD on the southwest corner of 25th Street and Amin Drive (N 35°26.330', W 97°29.533', and altitude 384m above MSL). The LiDAR operated during the Intensive Observational Periods (IOPs) as well as during non IOPs. Most of the scanning strategies were coordinated with the Army Research Laboratory (ARL) LiDAR group to capitalize on the opportunity for Dual Doppler scanning strategies. The first (sonic instrumented) tower was located in the CBD on the northwest end of the Park Avenue, close to the Broadway Avenue. It was equipped with three sonic anemometers (sampling rate 10Hz): Applied Tech. at 2.5m above ground level (agl), Young at 5m agl, and Metek at 8.5m agl. Besides sonic anemometers, an IR sensor (sampling rate 8Hz) was mounted on the same tower to measure street surface temperature. Raw data from three velocity components and temperature were stored. One minute averages and rms of the surface IR temperature were stored. The Young sonic and the IR thermometer were working 24/7 during the whole campaign period. During the first part of the campaign, the two other sonics were working only during the IOPs. Starting with the IOP 6, all three sonics operated continuously. Second ("Energy") tower was located on the grassy field with a slope angle 1.3 deg near the intersection of N Walker Avenue and NW 11th Street. Energy Tower was located at N 35°28.764', W 97°31.202', and 378m MSL and was instrumented with: Kipp and Zonen Net Radiometer at 9.2 m agl, one cup anemometer at 8.9m agl and the other at 1.5m agl, one thermistor at 8.3 m agl and the other at 1.1 m agl, IR thermometer, upward facing pyranometer and downward facing pyrgeometer at 3.5m agl, 3D Sonic anemometer (Campbell Sci.) and Krypton Hydrometer at 2.5m agl. A soil heat flux plate (6.5cm below the ground level), six thermistors (2 x 2cm, 3cm, 4cm, 5cm and 8cm below the ground level) and a soil water content reflectometer were added on July 13. Data from the net radiometer, cup anemometers, thermistors, pyranometer, pyrgeometer and soil heat flux plate were stored as five-minute averages. Data from IR thermometer, sonic anemometer, Krypton Hydrometer and soil water content reflectometer were stored as one minute averages. For both IR sensors, emissivity of the surface was assumed as unity.

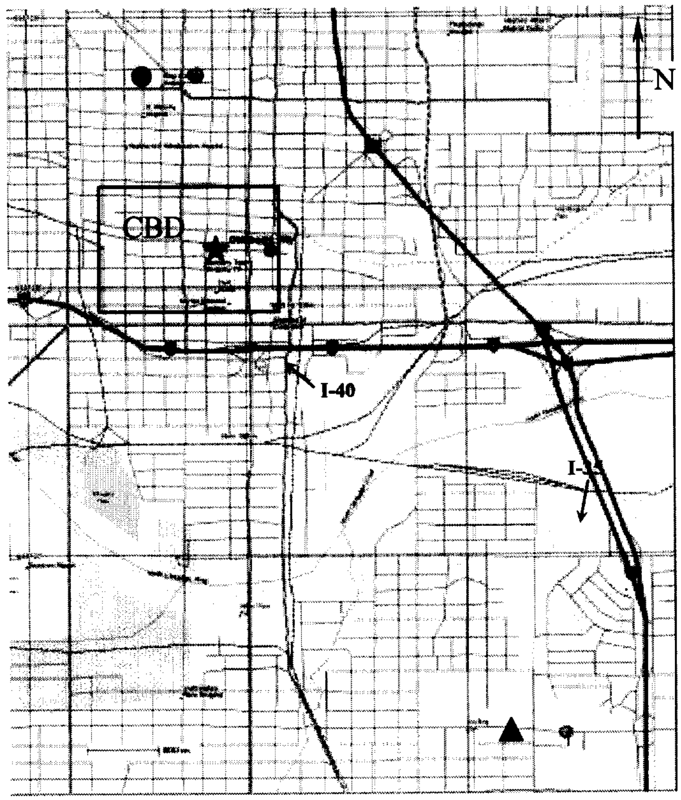

Figure 16. Locations of the ASU experimental sites during the JU2003 experiment. Interstate highways I-40 (West-east) and I-35 (235) (North-south) are visible. Location of the sonic tower in the CBD is marked with a star (north of I-40); energy tower is marked by circle (further north from I-40) and LiDAR location is marked with triangle (far south, west of I-35).

At the energy budget station, a net radiometer was used to measure the shortwave (R_s) and longwave radiation (R_l), both facing up and down. The net radiation present at the Earth's surface is $R_n = R_{s\downarrow} + R_{l\downarrow} - R_{l\uparrow} - R_{s\uparrow}$ (Figure 15). The part of R_n transferred to the atmosphere does so by one of the two processes: the sensible heat and through the evaporation of water into the air, the latent heat. These were measured by turbulent flux instruments near the ground (Figure 17). The sonic anemometer and fine wire thermocouple were used to measure the covariance between vertical velocity w and temperature T fluctuations $\overline{w'T'}$, where primes quantities indicate fluctuations based on one minute averages. The sensible heat flux is given by $H_s = c_p \rho \overline{w'T'}$, where c_p and ρ are the specific heat at constant pressure and density, respectively, of dry air. The sonic anemometer was used with a Krypton hygrometer to measure the covariance between vertical velocity and water vapor density q, $\overline{w'q'}$. The latent heat flux is $H_L = L_v \overline{w'q'}$, where L_v is the latent heat of vaporization.

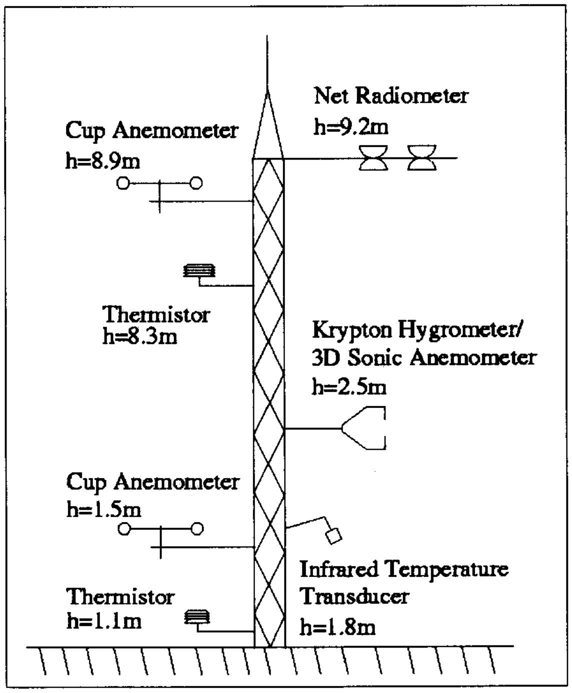

Figure 17. Meteorological tower used to measure the surface energy budget.

In order to close the energy budget, it is necessary to measure the heat flux through the bottom of the control surface for the soil layer (SHF) as well as the storage in the control volume (SSF). SHF was measured by a heat flux plate located at a depth of 6.5cm. Integration of the vertical temperature profile within soil yields energy storage per unit area. Differentiating this with respect to time produces the net flux required to heat or cool the upper soil layer, i.e. the Soil Storage Flux, *viz.*

$$SSF = \frac{d}{dt} \int_{depth}^{0} c \rho_S T(z) dz,$$

where c is the specific heat of the soil, ρ_S the soil density and $T(z)$ the temperature profile (Grimmond & Oke, 2002).

Skin temperature was measured at two sites, the downtown (street canyon) site and the energy tower site (open grassy field) are presented in Figure 18 for a five day period (190 to 195 Day of Year[1]; July 10 to July 15). A warming trend throughout these five days can be noted. A sharp increase in temperature above the open grassy field occurs several hours after sunrise. Sunrise time was around 6:30 AM local time and the skin temperature began rising around 8:30 AM. Morning heating in the urban canyon is retarded due to the shading effects of the buildings. As the solar input started penetrating into the urban canyon, the skin temperature started growing quickly around 10:30 AM. During the daytime, the skin temperature in the urban canyon is slightly lower, again due to the shading effects of buildings and trees located on the sidewalk. The temperature began to drop rapidly around 4:00 PM at both sites. However, after one hour the temperature drop in urban canyon slowed down, but continued to cool steadily through the night until warming took place in the morning. On the other hand, skin temperature in the open field kept a very rapid cooling rate (~ 9 °C/hour) until it reached a state with a very low cooling rate (~ 0.17 °C/hour) that lasted until morning.

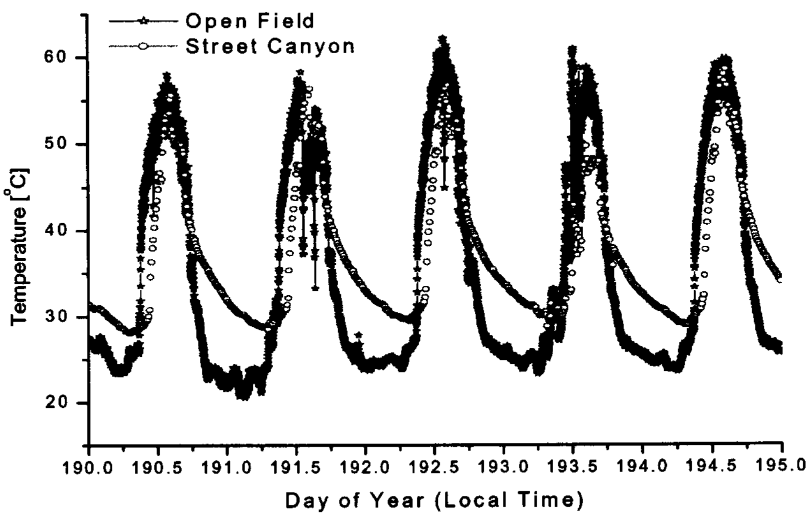

Figure 18. Surface ("skin") temperatures measured in street canyon and in open grassy field.

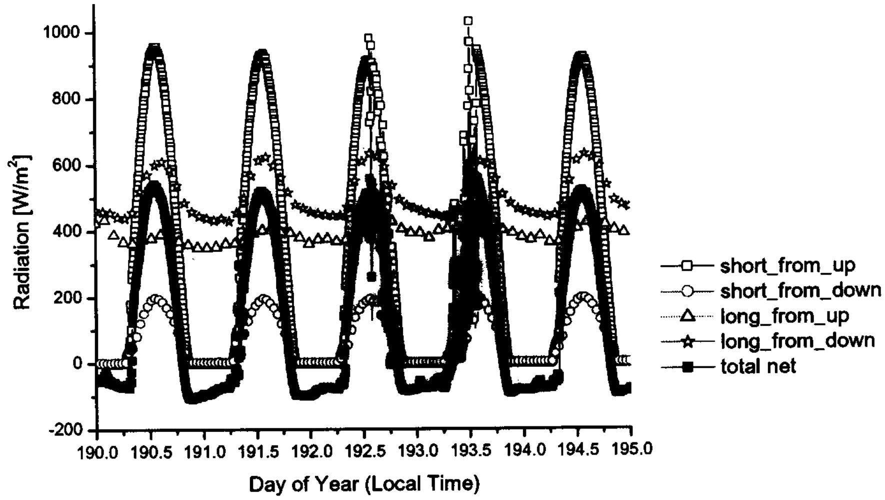

Figure 19. Incoming and outgoing short (0.3 to 3 μm) and long (5 to 50 μm) wave radiation components and total net radiation measured at the Energy Tower site.

Note the nighttime temperature difference between two sites, which is 7 °C on the average. Given that the two sites were only 1.3 kilometers apart, this significant temperature difference points to the urban heat island effect introduced by the high heat capacity land use material in the CBD. Figure 19 presents radiation measurements taken at the Energy Tower's site for the same period as in Figure 18. Daytime incoming radiation excess (positive net radiation) produces soil heating, sensitive and latent heat flux. Nighttime radiation deficit (negative net radiation) cools the ground and eventually can produce negative sensitive and latent heat flux.

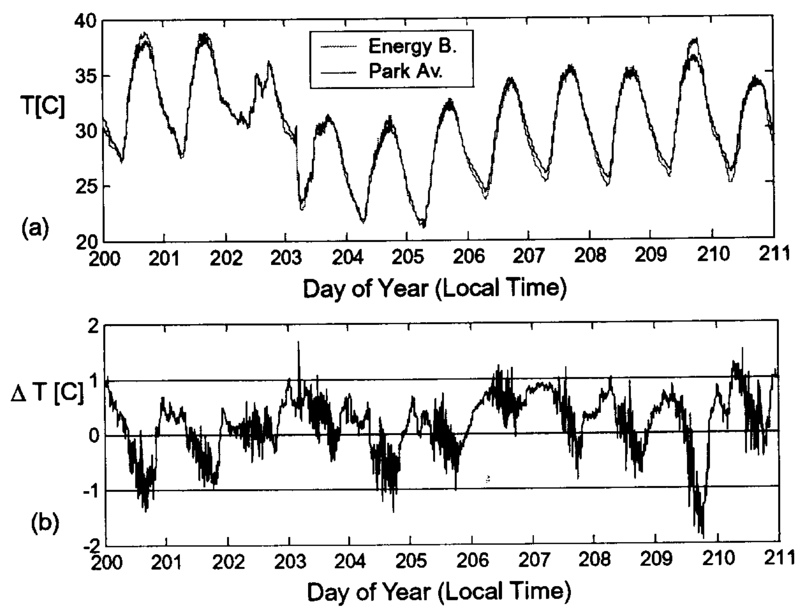

Figure 20. (a) Air temperatures at 8.5m measured in the street canyon and in an open grassy field. (b) The temperature difference between the two locations.

The sum $H_S + H_l + SHF + SSF$ is expected to balance the net radiation R_n (Figure 15). Comparing these quantities as in Figure 21, we see consistency between the two curves. This is an indication that the measured quantities indeed do a good job of characterizing the surface energy budget in this suburban park. Further, it appears that the assumption of a vertical, one dimensional system may be adequate to describe the surface energy budget at this experiment site. The largest deviation from the one-dimensional model occurred during afternoon, which can be on the order 50 W/m^2. Currently we are in the process of evaluating, in component form, various energy budget parameterizations used for several meso-scale meteorological models.

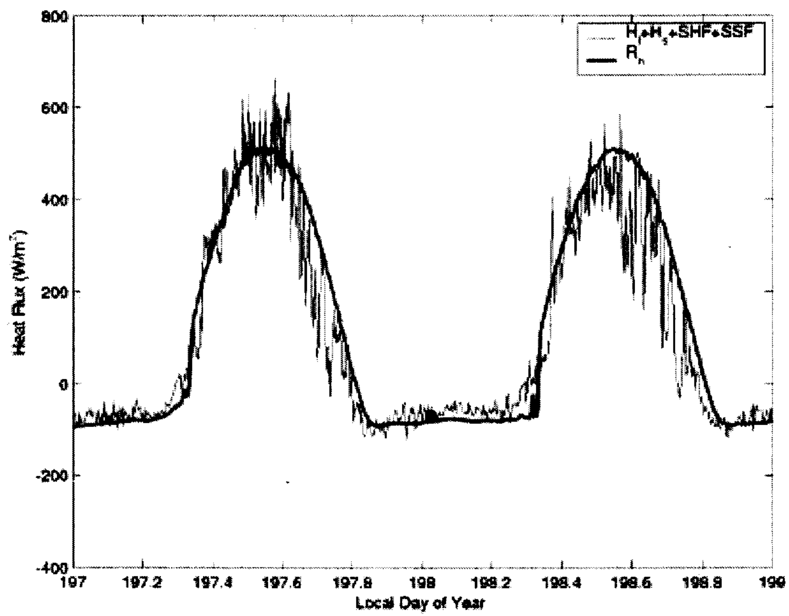

Figure 21. The one dimensional energy balance, evaluated using the measurements of various flux components involved.

Figure 22 shows a time series of 30-min. averaged wind direction for a two day period. In most afternoons, the winds inside the canyon were westerly while during the other periods the winds were coming from the east. There were periods where the wind direction was persistently from the west or east for a period of 48 hours or more. This behavior can be attributed to the slow change of large-scale wind forcing and the constrained nature of the flow due to the east-west oriented urban canyon. Also, wind direction fluctuations were much stronger for winds coming from the east than from the west, which is a consequence of the tower location. The west end of the urban canyon was approximately 130m away from the tower and the flow in between is smoothly channeled, but for easterly winds the flow arrived at the tower upon traveling only 20m from a street intersection. A sudden shift of wind direction at the lowest sonic at 198.3 occurs at the same time as a significant drop in wind speed. Due to the low speed of the incoming wind at this time, local perturbations caused by traffic might have dominated air motion and corresponding directional shift during this period.

Wind speed profiles show that the wind speed in the middle sonic (located 5m agl) was often lower than the other two sonics, which can be explained as an influence of a tree canopy located very close to the tower at this level. The wind speed was characterized by large fluctuations (Figure 23), which are expected to be due to traffic and the presence of buildings and vegetation. Analysis of 5, 30 and 60 minutes average velocity profiles shows that wind speed at the highest sonic is not necessarily higher than at the lowest ones, and especially during the evening the wind speed at the lowest sonic recorded a higher speed than the highest sonic. Nonetheless, the highest sonic measured the highest turbulent kinetic energy most of the time. Smaller wind speeds at higher levels were also observed in the middle of the urban canyon for certain periods (Oklahoma University tower, see Brown et. al. 2004). Some interesting flow features were detected on the southern side in the middle of the urban canyon during 15.00-16.30 (local time), where it was observed a shift of wind direction by 180 degrees slightly above 8 m, wherein the wind speed is close to zero. All these observations point to the immense complexity of flow field inside a typical urban canyon. To obtain a better picture of the flow field in the Park Avenue urban canyon, it will be necessary to simultaneously consider wind speed and direction from all sensors located therein.

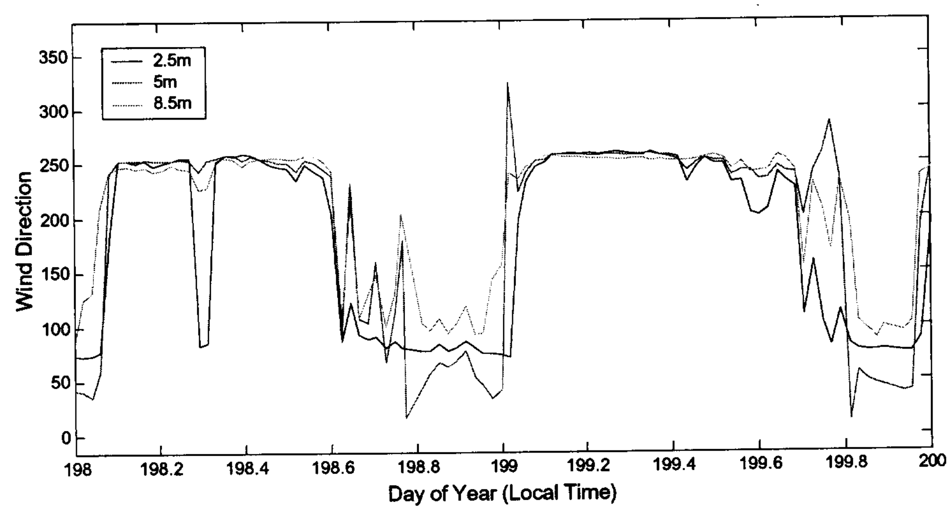

Figure 22. Time series of wind direction measured in street canyon

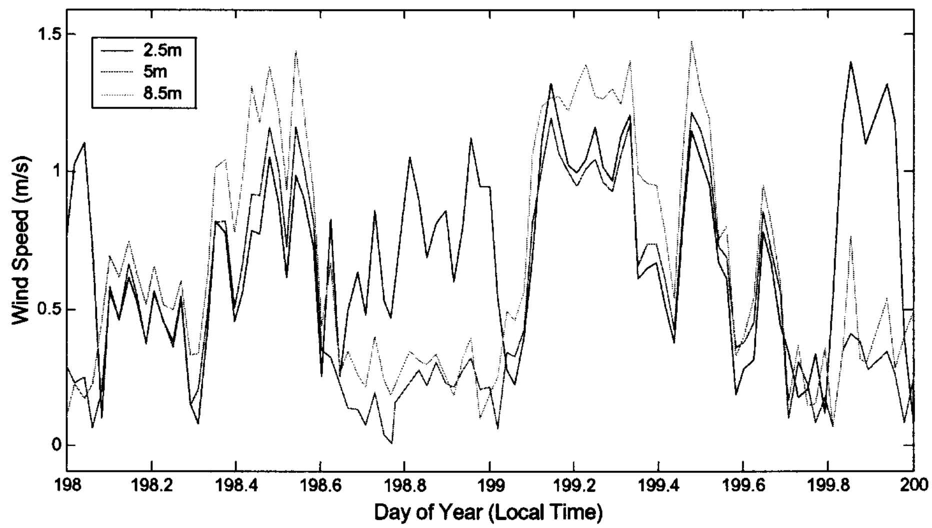

Figure 23. Time series of wind speed measured in the street canyon

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7. List of All Participating Personnel

H.J.S. Fernando, Principal Investigator
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8. Report of Inventions

No inventions to be reported.