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Field Evaluation of an Urban Canyon Airflow and Scalar Dispersion Model, Part I: Description of Field Experiments and Airflow Regimes

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Summary The design and execution of two field experiments which measured airflow and scalar dispersion in model urban canyons placed in the atmospheric boundary layer are described. These data were acquired to evaluate SCAM, a three dimensional, steady state airflow and scalar dispersion model. Continuous, parallel rows of single storey buildings were used to simulate an urban canyon, with each experiment having different canyon lengths and aspect (height:width) ratios. A scalar (nitrous oxide) was emitted from a semi-continuous line source which ran along the ground for the full length of the canyon. The three dimensional flow field and scalar concentrations were measured using a spatial array of sensors throughout the canyon air volume. SCAM could thus be evaluated for varying canyon geometries and approach flows in a natural boundary layer. Results of the field evaluation are described in two companion papers. Part I describes the field program, the measured scalar concentrations and airflow regimes.

1. INTRODUCTION

1.1 Context and Rationale

The urban environment is home to an increasingly large proportion of the human population. By 2000, over half of the world's people will live in cities. Understanding the physical urban environment and its effect on atmospheric processes is imperative if we are to intelligently plan cities that demand fewer resources and reduce environmental costs.

Urban climates result from the exchange of heat, mass and momentum between the urban surface and the atmosphere. The methodological problems posed by the complexity of the urban environment are resolved by recognising, following Oke (1976), that cities and their climate are characterised by two distinct spatial scales: the mesoscale influence of the whole city which leads to the development of an *urban* boundary layer (UBL) and the microscale influence of buildings and city blocks which make up the urban canopy layer (UCL). The urban canyon is the fundamental building block of the UCL, comprising two parallel rows of buildings (height, H) separated by an alley or street (width, W). The canyon aspect ratio (A=H/W) is considered to be a primary influence on the microclimate of the UCL.

Several intensive measurement and modelling studies (see reviews by Oke, 1988a; Grimmond and Oke, 1995; Cleugh, 1995 and Changnon, 1981) have shown the typical magnitude and variation of heat and energy fluxes in the UBL. There have been a few detailed measurement studies in the complex UCL showing the nature of radiation exchanges, energy balances and airflow (Nunez and Oke, 1977; Mills and Arnfield, 1993) in urban canyons. However the sheer complexity of the UCL, and the logistical difficulties of mounting experiments there, means that modelling is the primary means by which further insight into urban canopy atmospheric processes will be gained.

Such modelling requires not only the development of physically-based models but also obtaining high quality measurement data sets for model evaluation. The research described in Parts I and II of this paper is the third step in our development of a full energy budget model for a dry urban canyon which began with the development of a canyon radiation exchange model (Johnson *et al.*, 1991). A steady state, numerical model for flow around buildings was then modified to simulate airflow in urban canyons (Hunter, 1989; Hunter *et al.*, 1991, 1992). A scalar dispersion model was subsequently linked to the airflow model (Hunter, 1993). The combined airflow and scalar dispersion model is known as SCAM. SCAM was initially evaluated using CO concentrations obtained from a US study (Johnson *et al.*, 1971), however a more rigorous evaluation of SCAM was required before it could be linked with the radiative exchange model to achieve a full energy balance model. This further evaluation of SCAM, using airflow and scalar concentrations measured in model urban canyons placed in an atmospheric boundary layer, is the subject of the research described.

1.2 Objectives

The objectives of this paper, and its companion (Part II: Johnson *et al.*, this volume) are to:

(1) describe the design and execution of two field experiments conducted to obtain an evaluation data set for SCAM (Part I);
(2) describe the mean airflow regime in the urban canyon and the resultant scalar concentration distribution (Part I);
(3) describe the implementation of SCAM for the experimental urban canyons and compare SCAM's predictions of the airflow and scalar concentration distributions with those measured (Part II).

This research has an important contribution beyond just providing a test data set for model evaluation. It provides an excellent temporal and (albeit more limited) spatial description of the mean and turbulent airflow and scalar concentrations in the air volume of a very simple urban canyon. In particular, the controlled release of the scalar from a line source with a known emission rate means that the information can also be used to better understand airflow and transport processes in urban canyons. For example, much has been written about the importance of the aspect ratio (A) as a dimensionless criteria determining airflow, turbulence and thus microclimates in urban canyons. Oke (1988b) developed criteria for determining airflow regimes (isolated roughness, wake interference and skimming) within urban canyons using only A. However, as Hunter *et al.* (1991) show, this is only valid for infinitely long, 2D canyons. In realistic 3D canyons, the ends become important. A consideration of basic fluid mechanics also suggests that the upwind roughness (which determines the turbulence in the approach flow); the wind shear at roof height and the width of the upwind and downwind buildings will also be important. Criteria such as those of Oke's do not consider these other factors. The data obtained provide us with the opportunity to evaluate some of these issues. Thus, we examine the measurement data for evidence of particular flow regimes and confirm that SCAM can indeed replicate these.

2. SCAM: A SCALAR CANYON AIRFLOW MODEL

2.1 Brief Model Description

SCAM has three components: a GRID file which defines the urban canyon geometry, the position of the scalar source and its emission rate; an airflow model (CITY); and a 3D atmospheric diffusion model which uses the output from CITY to predict scalar dispersion (via. advection and turbulent diffusion) in the urban canyon specified in the GRID file. Part II describes these components in detail.

At the core of SCAM is CITY, a modified form of Paterson's (1986) 3D model of flow around buildings. CITY is a steady state, k-ε, 1.5 order closure model. Thus there are three prognostic equations for the mean velocities and turbulent kinetic energy (TKE) and a highly parameterised equation for the dissipation, ε. CITY is initiated with an upwind, equilibrium wind profile. SCALAR solves the atmospheric diffusion equation for this airflow and a known scalar emission rate. Details of the numerical methods; model implementation *etc.* are given in Hunter (1989; 1993).

2.2 Sensitivity Analyses

A model such as SCAM predicts a steady state flow regime on the assumption that the approach flow is constant in time. A scalar is then emitted into this flow and its within-canyon concentration calculated. Thus the output of SCAM is characterised by detailed spatial resolution, but no temporal variation. Field measurements, on the other hand, will always be limited spatially because of sensor availability and the need to minimise interference with the existing flow. They are, however, characterised by a detailed time record, at a limited number of locations.

A number of conditions must therefore be met if we are to succeed in our aim of evaluating a steady state model with field data. The first is that the modelled flow field and scalar distribution not be overly sensitive to small changes in upwind wind direction. A second requirement is that the time taken for the scalar concentrations to reach steady state be less that the time over which the upwind wind conditions change. Limited availability of sensors means that they must be optimally positioned. To this end, we undertook a series of sensitivity analyses to determine the sensitivity of the model to upwind wind direction; times typically taken to reach steady state and typical scalar distributions across the canyon. The latter was used to identify locations to place sensors in the field experiment. For example, although sensors should be sited at the canyon ends to sample maximum concentrations, the position of these "peaks" is sensitive to wind direction. Concentration measurements are therefore better taken in the mid-canyon position at varying heights and include sites 2-3 m from the lee wall. Results from these and further sensitivity analyses conducted as part of the preliminary model evaluation, are described in Part II.

3. FIELD EXPERIMENT

3.1 Why Field Measurements?

The data needed to evaluate a model such as this could be obtained in three ways: direct numerical simulations (*eg.* using large eddy simulation); wind tunnel modelling and field measurements in a "natural" atmospheric boundary layer (ABL). The advantage of the first two approaches are that they are compatible with SCAM, *ie.* they produce steady state solutions with a large degree of spatial resolution. Unfortunately, they are also both models so one is always faced with the question of whether they are correct.

Wind tunnel simulations are a widely used, and valid, evaluation technique, however they are not without their flaws. For example, for this research we require airflow data around roughness elements with heights (H) of order 10 m. The ratio of H to ABL depth is *ca.* 0.01. In boundary layer wind tunnels, the boundary layer may only be 1 m deep and so the modelled roughness element height would need to be 0.01 m to maintain similitude. However, Reynold's number similarity must also be maintained. Given that ABL flows around buildings have Reynolds numbers of $\approx 10^6$, velocities in wind tunnels would need to be of order 10^3 ms^{-1} to maintain dynamical similarity. Normally, larger roughness elements would be used to achieve Reynolds number similarity but then the ratio of H to boundary layer depth will be large, *ca.* 0.1 for wind tunnels compared to 0.01 for ABL flows. This does not invalidate the use of wind tunnels, it simply highlights the disadvantages of using wind tunnels as the main source of data to evaluate a numerical model. Indeed, wind tunnel data are often compared to ABL data as a reality check.

For these reasons, as well as the difficulty of accessing a wind tunnel or an LES model, we decided to conduct our measurements in the ABL using urban canyons whose height was of the same order as typical urban canyons.

3.2 Site Selection Criteria

The need for strong, steady winds dictated the timing of the experiment. Vortex driven flows are most likely when roof-level windspeeds exceed 2 ms^{-1} (DePaul and Shieh, 1986). Furthermore, neutral flows are required both upwind and within the urban canyon. Finally, steady winds are required to achieve conditions compatible with a steady state model. In Sydney, such winds are most frequent either in the winter/spring when westerly flows dominate or in the seabreezes that occur from spring through to autumn.

These predominant wind directions meant that a north-south oriented canyon would have approach flow angles roughly normal to the canyon's long axis and would minimise jetting flow parallel to the canyon. The largest concentrations and maximum vortex circulation would be achieved under these conditions, making it a more interesting regime to model. The canyon roof, walls and floor also needed to be smooth as SCAM cannot simulate the turbulence generated by wall irregularities.

A controlled scalar release was required, using a line source stretching the full length of the canyon, at the canyon midpoint. In pollution studies, such a line source would simulate a line of traffic (although this is not necessary for this experiment). Nitric oxide (NO) was selected as the scalar because it can be detected at very low concentrations, thus reducing the amounts of gas used and costs.

Meeting these criteria was simplified by using a "model" urban canyon rather than an existing street flanked by buildings. Two sites were selected for each field experiment: one in Western Sydney for the winter study and one at the coast in Northern Sydney for the autumn study.

3.3 Field Program 1 (FP1)

Two parallel rows of storage units, aligned north-south, at "Allsafe Storage" in Blacktown (Western Sydney) were selected for FP1. The canyon dimensions (L=68 m; W=7.5 m and H=3 m) yield an aspect ratio of 0.42. The large L:H ratio (>20) effectively makes this canyon two dimensional. A grass paddock extended 500 m to the west of the canyon. The surrounding land-use was a mix of farms and light industries.

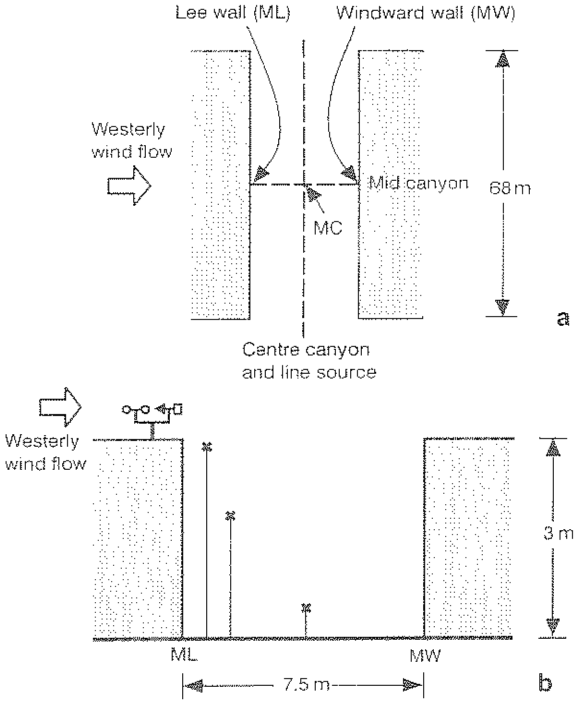


Figure 1: Model urban canyon experimental layout in FP1: (a) plan view showing mid-canyon, centre canyon, lee and windward walls; (b) cross section at mid-canyon showing location of Gill propeller anemometers (x) and rooftop anemometer. Note that the basic layout for FP2 was identical.

For FP1, the line source for scalar emissions was a simple, pressurised garden soaker hose running the full canyon length at the canyon centre (Figure 1a). NO and air were mixed at mid-canyon and pumped into the hose. NO was thus released along the full length of hose through holes spaced at *ca.* 0.05 m intervals.

A 9 m mast placed upwind, and instrumented with a Met One cup anemometer and wind vane, recorded the approach wind speeds and directions needed for model initialisation.

To evaluate SCAM, airflow and scalar concentrations measurements were needed at varying locations within the urban canyon airspace, focussing on the mid-canyon area where the vortex is centred.

Three 3D (Gill) propeller anemometers were deployed to measure the across-canyon, along-canyon and vertical wind velocities at three locations. Figure 1b shows these inital locations: z=0.75 m in the canyon centre at the mid-canyon point (MC); lee wall at z=1.5 m (ML); lee wall at z=2.9 m (also ML and rooftop Gill), but they varied between experimental runs. An R.M. Young Wind Sentry anemometer and wind vane were placed on the upwind roof (50 cm above the roof). Signals from these sensors were sampled and stored at 5Hz using a 21X Campbell Scientific micrologger and PC. Upwind winds were sampled every ten seconds and one minute statistics recorded.

Gas intakes were arranged in two vertical profiles at mid-canyon (Figure 2). Each profile had an intake at 0.75 m. 1.5 m and 2.9 m. One profile was located adjacent to the canyon lee wall (ML) and the other at mid-canyon (MC).

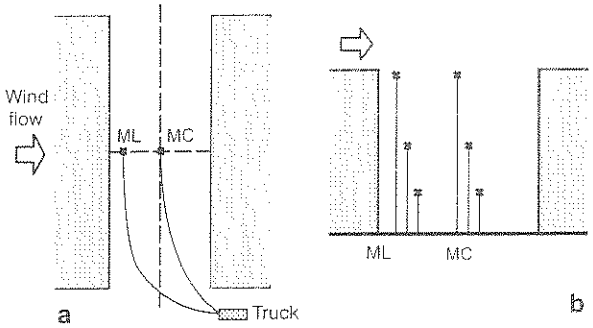


Figure 2: (a) Plan view of FP1 canyon with location of gas intakes and PVC tubing back to truck and mobile laboratory; (b) cross section showing vertical profile of gas intakes (x).

Two gas sampling units (Monitor Labs NOx Analysers) were housed in CSIRO's mobile laboratory. Air from each of the intakes was bought back along separate PVC tubes to the two NOx analysers. These were switched such that two pairs of PVC lines could be sampled, consecutively, by each analyser, enabling a total of four sites to be monitored. These data were sampled at 0.1 Hz and stored on a PC.

Measurements were obtained over a sequence of 8 non-consecutive days from August - November, 1993. Only 2 days with gas sampling and airflow measurements were obtained. The remaining 6 days recorded airflow alone.

3.2 Field Program 2 (FP2)

Basically the same array was used in FP2, however significant improvements were made to the line source and gas sampling procedures.

Four demountables were assembled into a north-south oriented canyon (H=3 m; L=18 m; W=3 m) on a large paddock adjacent to sports fields in Curl Curl, Northern Sydney. This canyon has an aspect ratio of unity and a L:H ratio of six - making it a truly 3D canyon. The fetch surrounding the canyon comprised grass paddocks and sports fields extending for over 500 m to the east and west. Thus both easterly and westerly winds could be used.

The line source was replaced by an elevated (0.1 m), 0.03 m diameter PVC tube with 0.5 mm holes drilled every 0.05 m. This rigid line source ensured an even pressure distribution, and hence flow rate, along its full length (18 m).

The same anemometers (cup and propeller) were used as in FP1, however the upwind anemometer and windvane were mounted at a height of 2 m. The sampling scheme and instruments were otherwise identical to FP1.

An extra NOx analyser was hired, enabling 6 sites to be sampled in a single experimental run. As in FP1, PVC tubing was used to bring air from the gas intakes back to the NOx analysers which were housed inside one of the demountables. The two profiles were used in a similar configuration to FP1.

The six gas intakes were consecutively sampled (again using a switching arrangement) at 1 Hz using a Campbell Scientific 21X micrologger. The data were transferred to a PC at the end of each experimental run which, because of storage limitations on the 21X, had to be shortened to 30-45 mins.

A total of 15 experimental runs were acquired over 6 days in March and April, 1994. All but one (March 31) comprised both gas and airflow measurements.

4. RESULTS: AIRFLOW REGIMES

All data were averaged into one minute blocks for the initial analysis of the flow regimes. This is because the vortex circulation is believed to be driven by the mean, rather than the turbulent, flow. Periods when the upwind flow was fairly constant for periods of 10 mins were selected for model evaluation.

Although the primary goal of the research was to evaluate SCAM, we firstly used the measured data to "describe" the airflow regime present in each canyon, for varying approach flows. Three questions were of particular interest: (i) is there a cross-canyon vortex?; (ii) is the flow skimming, wake interference or isolated roughness (using the definitions of Oke, 1988b)?; (iii) what is the effect of oblique flow and canyon ends on (i) and (ii), especially in the FP2 canyon?

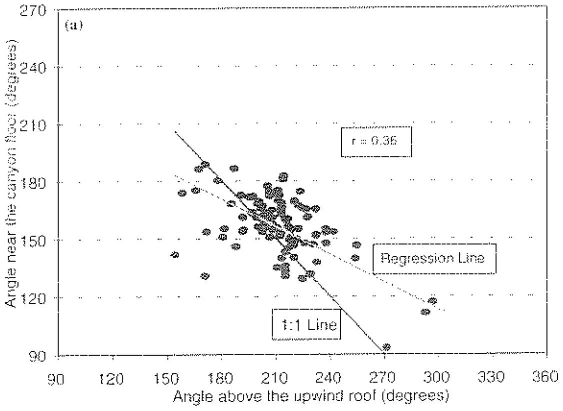
This approach is adopted for two reasons. Firstly, the modelled gas concentrations will be incorrect if the predicted flow regime is incorrect, so an evaluation of the airflow predictions is crucial to the evaluation of SCAM. Secondly, despite our best efforts, the airflow *is* temporally variable which makes a direct comparison between wind velocities (measured and modelled) difficult. Rather, it is better to use the measured data to describe the airflow regime and then compare this with the predictions from SCAM. Each canyon is treated separately in the following description because quite different features were observed in each.

4.1 Airflow Regimes in FP1

4.1.1 The Vortex

A mean cross-canyon vortex will be characterised by a reversal in flow direction at the floor of the urban canyon. Thus for normal flow, the airflow at the canyon floor will be reversed and directed *back* towards the lee wall. Nakamura and Oke (1988) identified such a flow feature in their wind measurements in an urban canyon (A=1) by comparing the wind direction at the upwind roof and the canyon floor (mid and centre canyon position). They found that the within-canyon wind direction (θ_{canyon}) was almost a "mirror reflection" of the flow at rooftop ($\theta_{rooftop}$). At intermediate approach angles (>0°), Nakamura and Oke observed that the angle of incidence was greater than the angle of "reflection", indicating a "cushioning" of the flow.

Plotting θ_{canyon} vs $\theta_{rooftop}$ for FP1 (Figure 3a) reveals a similar relationship, but the data is very scattered. A much stronger relationship is found between the mean wind direction measured at the rooftop just inside the lee wall (θ_{roof}) and θ_{canyon} (Figure 3b). Similar relationships were found for the other runs in FP1, and illustrate the same features described by Nakamura and Oke.



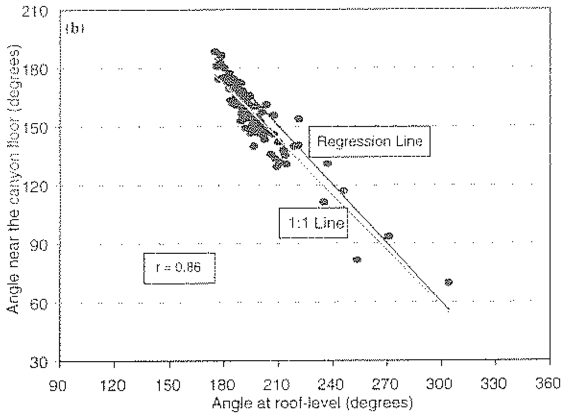


Figure 3: Scatterplots showing relationships between θ_{canyon} (y-axis) and (a) $\theta_{rooftop}$; (b) θ_{roof}. Runs 2 and 3, 21/09/93.

4.1.2 Airflow Regime

Wind tunnel studies by Hussain and Lee (1980) and the numerical simulations of Hunter *et al.* (1992) suggested that a simple cross-canyon vortex within a skimming flow regime only occurs in canyons where A>0.65. Given that the aspect ratio in FP1 was only 0.42, are these observed flow reversals actually a recirculating flow in the wake of an isolated building? Further insight was obtained by analysing the data collected from the three Gill anemometers mounted at a height of 0.75 m in the centre of the canyon (MC) and at the lee (ML) and windward walls (MW).

Strong easterly flow is recorded at MC, a reversal of the above canyon flow. There is also a strong relationship between the updraft velocities (w_{up}) at the lee wall and the downdraft velocities (w_{down}) at the windward wall (w_{up}=0.4w_{down}). This close link is maintained even as the approach flow changes, suggesting that these are parts of a single flow feature, a cross-canyon vortex. Interestingly, DePaul and Shieh (1986) report typical downdraft velocities of 0.6 w_{up} for the vortex flow found in their canyon.

These features suggest that isolated roughness flow is not present, which is reasonable given the heights and spacing of these buildings. Wake interference flow, which is more likely, would be indicated by turbulent, mostly westerly flow at MC. In fact the flow at MC is always easterly and the vertical velocities are always positive (ie. showing updrafts) and less turbulent than at the base of the lee wall (ML).

In summary (see Figure 4), all the ground level flow is directed back towards the lee wall, with the strongest velocities occurring at centre canyon (MC). Strong downdrafts are present at the windward wall (MW) and slightly weaker updrafts at the lee wall (ML). All of these features point to a skimming flow regime.

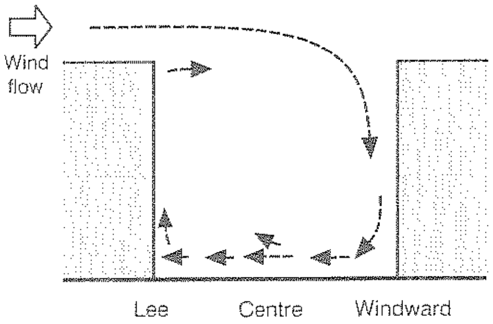


Figure 4: 2D schematic of wind vectors showing the cross-canyon vortex, driven by skimming flow, as determined by Gill uvw anemometers. FP1 canyon (mid-canyon position).

A windspeed threshold for the onset of vorticular flow was also apparent in FP1. $\theta_{rooftop}$ and θ_{canyon} were better correlated (required for vortex flow) when the above roof windspeeds exceed 2 ms^{-1}, in accordance with DePaul and Shieh (1986) and providing further evidence of skimming flow.

The limited concentration data are in accord with this skimming flow regime. The highest concentrations are found near the ground (and thus in proximity to the source) and at the lee wall (ML0.75). Here there are weaker updrafts, and the airflow (the lower arm of the cross-canyon vortex) has moved over the line source. This leads to a "build-up" of scalar at the base of the lee wall.

4.2 Airflow Regimes in FP2

4.2.1 The Vortex

The canyon used in FP2 had an aspect ratio of unity. Previous work (*eg.* Hunter *et al.*, 1992; Nakamura and Oke, 1988) suggests that such a canyon would also be characterised by a cross-canyon vortex as a component of a skimming flow regime. It was on this basis that we sited the anemometers and gas intakes for FP2.

Correlations between $\theta_{roof,\ rooftop}$ and θ_{canyon} failed to reveal any consistent patterns that would suggest this regime. One experimental run observed flow towards the lee wall at ground level, however this is overwhelmed by the influence of lateral flow which seems to break down this structure. This influence of lateral flow is responsible for the failure to identify a cross- canyon vortex using these methods.

4.2.2 The Effect of Lateral Flows and Canyon Ends

Analyses of each of the flow components, similar to those for FP1 (but note that the approach flow is now easterly - not westerly), were conducted to determine the general flow regime in FP2. The importance of the canyon ends and lateral flows was also assessed.

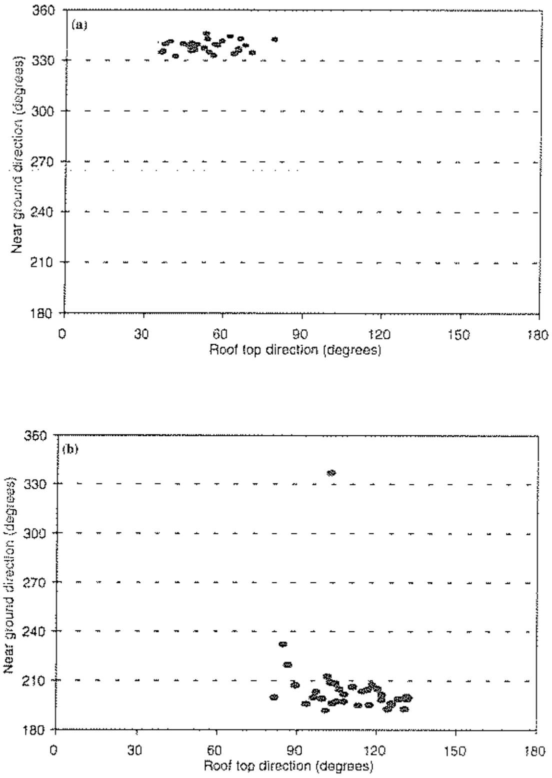


Figure 5: Relationship between direction of approach flow (Roof top direction) and wind direction at canyon floor, midcanyon: (a) for E-NE and (b) for E-SE approach flows

For normal approach flows, downdrafts observed at the base of the windward wall (MW) were correlated with updrafts at the base of the leeward wall (ML), although the relative strengths did not follow the pattern found in FP1. The cross-canyon velocities at MW and MC were consistently westerly (ie. reverse flow). This cross-canyon flow was correlated with the updrafts observed at the lee wall (ML) and the downdrafts at the windward wall (MW). These findings are similar to FP1 and suggest a skimming flow regime.

The negligible cross-canyon flow observed at the lee wall (ML) may indicate a "quiet" recirculation zone, a feature observed at this position in the field program of Johnson *et al.* (1971) and the simulations of Johnson and Hunter (1995).

Of considerable interest is the increased importance of lateral flows, and canyon ends for this short canyon. For approach flows that varied from 30 to 90° (Figure 5a) the within-canyon (MC) direction is constant at *ca.* 340°. Approach flows varying from 80 and 130° likewise are matched by fairly constant within-canyon flows of around 200° (Figure 5b). Once established, it appears that the lateral component within the canyon is maintained until overcome by an opposing flow from the opposite direction. In short, flow parallel to the canyon walls is *not* needed to maintain lateral flow within the canyon.

An experimental run with the Gill anemometers placed at the canyon ends revealed the importance of lateral flows. As the northerly flow component increased, stronger updrafts at the base of the northern lee wall were observed, and *vice versa* for the southern end (Figures 6a and b). Thus the momentum from the flow penetrating the canyon is transferred into the lateral flow and the vertical flow via the vortex.

The combination of these flow characteristics, plus the presence of updrafts throughout, suggests a spiralling vortex flow moving downstream with the flow penetrating the canyon. This vortex decreases in strength with downstream distance in the canyon.

The scalar concentration measurements show, as in FP1, decreasing concentrations with height at the lee wall and at the canyon midpoint. A surprising feature, however, is the reversal of this pattern at the windward wall where concentrations at 0.75 m are slightly *less* than at 1.35 m. This suggests a transport mechanism at levels halfway up the canyon not seen in the airflow measurements, *ie.* a non-reversing flow at a height of 1.4 m that moves over the source (at canyon centre), carrying the scalar towards the windward wall. At each height, concentrations were always greatest at the lee wall, followed by those at the canyon centre which, in turn, were greater than concentrations at the windward wall. This is in accord with a vortex circulation.