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A FIELD STUDY INTO THE ROLE OF LARGE GUSTS AND COHERENT TURBULENT STRUCTURES IN MOMENTUM, HEAT AND PARTICLE TRANSPORT IN AN URBAN STREET CANYON

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SUMMARY

Ultrasonic anemometers have been deployed to measure turbulence in a downtown street canyon with busy traffic in Manchester, UK. Data has been recorded at a height of 5 m at the canyon mid-length. The data was recorded as part of an eddy correlation system, providing synchronised measurements of fine aerosol number concentration. In this study conditional sampling and quadrant analysis are applied to identify the contribution of large gusts and coherent turbulent structures (ejections and sweeps) to the transport of momentum, sensible heat and particles within the canyon. It was found that larger than average gusts were infrequent, but transported more than half the flux of momentum, heat and particles. Sweeps and ejections were found to dominate heat and particle fluxes. An approach flow greater than 40 ° to the canyon sometimes led to a recirculating flow within the canyon, during which large sweeps were found to transport particles downwards towards the canyon floor.

1. INTRODUCTION

There has been a growth in the scientific attention paid to air flow and dispersion processes in street canyons in recent years. Until very recently, however, most of this scientific activity has been applied to modelling studies. Most modelling studies aim to provide steady-state descriptions of mean flow in highly idealised canyons. There has been much less progress in describing and understanding transient processes in real canyons where there is no reason to expect that there is any steady state. Similarly, it is unclear how the flow in idealised (typically symmetrical, empty and isolated) model canyons relates to that in the highly complex situation in real streets.

2. ACTIVITIES

The data presented in this paper are a subset of the data from the Street Canyon Aerosol Research study (SCAR). The experimental design, together with a general description of the mean flow and turbulent intensity in the canyon were presented in Longley *et al.* (2004a, c).

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The section of Princess Street in Manchester chosen for the study contains two lanes of traffic carrying up to 1100 vehicles h^{-1} in one direction only. The canyon is 17 m wide and asymmetrical with building heights of 22 - 28 m on the south-west side and 10 – 18 m on the north-east side.

The data described in this paper were recorded using an ultrasonic anemometer (RM Young Model 81000) that was deployed at a height of 5 m at the mid-length of the canyon in a car parking bay between the road and the sidewalk. The data was recorded as part of an eddy correlation system, providing synchronised measurements of fine aerosol number concentration (0.1 µm < D_p < 3.0 µm) measured using an optical particle counter (PMS ASASP-X). A general description of particle fluxes is presented in Longley *et al.* (2004b).

The data was averaged into 10-minute sections. Within each 10-minute period the velocity time series clearly indicated the presence of transient excursions. Many previous studies in less complex environments have identified the important role of coherent turbulent structures embedded within the general randomness of turbulence. In particular, structures such as horseshoe or hairpin vortices have been described in turbulent boundary layer flows, arising from instabilities in velocity profiles. The vigourous lee eddy at the head of the horseshoe leads to 'ejections' of low-momentum air into the flow above, which are also associated (by mass conservation) with 'sweeps' of high momentum air.

Due to the prevalence of channelling in the street canyon (see below), a co-ordinate frame of reference based upon the canyon was adopted, so that the velocity vectors u, v and w were longitudinal, lateral and vertical with respect to the canyon.

20 Hz measurements of u, v, w, T and N (particle number concentration) were decomposed into the mean and fluctuation (e.g. $u = \overline{u} + u'$) in 10-minute blocks. Each measurement was then assigned to one of four quadrants denoted by i: outward interaction ($+u'$,$+w'$, i = 1), ejection ($-u'$, $+w'$, i = 2), inward interaction ($+u'$, $-w'$, i = 3) and sweep ($-u'$, $-w'$, i = 4). As noted above, ejections and sweeps are typically considered to be indicative of coherent events, whereas interactions represent randomness.

The contribution of large gusts was investigated by conditional sampling using a hyperbolic 'hole'. The hole size, H, can be varied so that only those lines of data in which $u_{xy}'w' > H\overline{|u_{xy}'w'|}$ is considered ($u_{xy}' = (u'^2 + v'^2)^{0.5}$).

The time fraction for each quadrant and any given hole size, $T_{i,H}$, is the proportion of the total averaging period, T, during which the instantaneous co-variance is in that quadrant, i.e.

$$T_{i,H} = \frac{1}{T}\int_0^T I_{i,H}(t)dt$$

where $I_{i,H}$ = 1 if ($w'u'$, or $w'T'$, etc.) is in quadrant *i*, and $\left|u_{xy}' w'\right| \geq H\overline{|u_{xy}'w'|}$, or $I_{i,H}$ = 0 otherwise.

The heat and particle flux fractions are the contributions of gusts larger than $H\overline{|u_{xy}'w'|}$ to the total mean flux, i.e.

$$HF_H = \frac{\langle w'T' \rangle_H}{\overline{w'T'}} \quad \text{and} \quad PF_H = \frac{\langle w'N' \rangle_H}{\overline{w'N'}}$$

where the angle brackets $\langle ... \rangle$ indicate conditional averages.

3. RESULTS

A key observation made during this study was that the mean flow within the canyon was largely channelled along the canyon axis. When the wind direction above the canyon was within 40 ° of the canyon axis the wind direction within the canyon averaged over 10 minutes was always within 30 ° of the canyon axis. When the approaching flow was greater than 40 ° from the canyon axis two different flow behaviours were observed within the canyon: either channelled flow as above, or a more complex and fluctuating situation characterised by flow across the canyon width, albeit still dominated by eddies in the horizontal plane. Within the experimental period these two behaviours occurred with roughly equal frequency. There was limited evidence of a canyon-filling vortex, as suggested by many modelling studies, but overall it seemed that horizontal flows were dominant. For each 10-minute period of data these differing behaviours were clearly delineated into two groups by the standard deviation of wind direction measured within the canyon (Figure 1), and hence these two groups of data are labelled ‘channelled’ and ‘recirculating’.

In this study two periods of channelled flow and one period of recirculating flow, within which wind and traffic conditions varied little, have been isolated and studied.

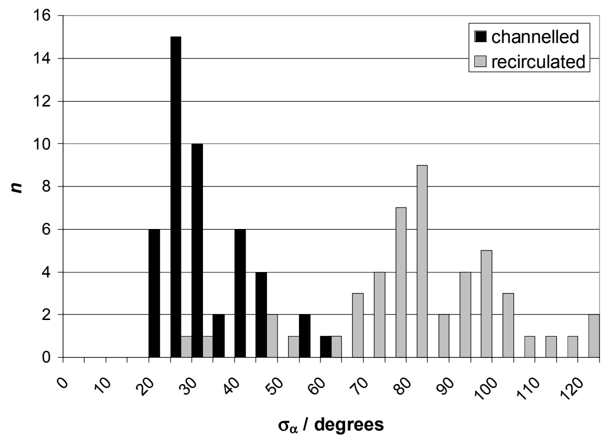

Figure 1: Frequency distribution of standard deviation of wind direction, illustrating the two flow regimes.

3.1. Channelled flow

Two periods are considered. Period 1 was during the daytime and consists of 9 periods of 10 minutes between 11:00 and 17:20 on 23rd October 2001. Period 2 was an evening period of 20 periods of 10 minutes between 17:40 and 21:30 on the 24th October 2001. Compared to Period 1, traffic flow rates during Period 2 were similar, but the wind speed was approximately half.

When all data is considered, the time fractions for each quadrant were 0.2 – 0.3, with ‘coherent’ quadrants, i.e. sweeps and ejections, being slightly more frequent (51 – 57 % in total). These fractions only varied by up to a few percent depending upon the flow regime. However, when considering large gusts, inward interactions became less frequent while outward interactions became more frequent.

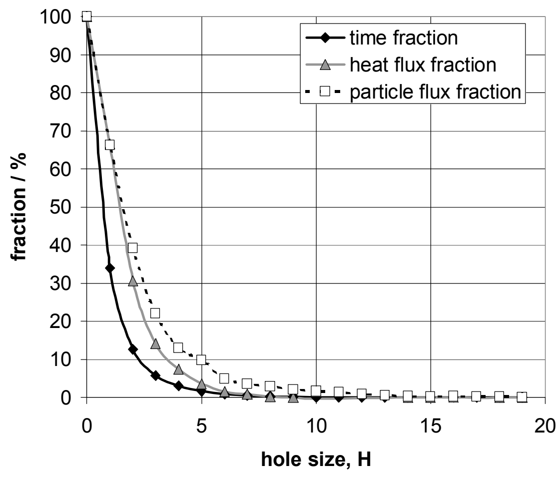

Figure 2: Time, heat flux and particle flux fractions versus hole size in channelled flow, Period 1.

Net sensible heat fluxes were positive (upwards) for all hole sizes. Sensible heat fluxes were mostly transported by ejections and sweeps (127 % in Period

1 and 98 % in Period 2). In both periods a heat flux fraction of 0.5 was associated with a hole size of 1.5 and a time fraction of 0.2 (see Figure 2), meaning that 50 % of the heat flux was transported by gusts larger than 1.5 times the mean, which occurred 20 % of the time.

Mean particle fluxes were positive (upwards) for all hole sizes. Particle fluxes were also dominated by ejections and sweeps (126 % in Period 1 and 180 % in Period 2). A particle flux fraction of 0.5 was associated with hole sizes of 1.6 (Period 1, Figure 2) and 2.3 (Period 2) and time fractions of 0.18 (Period 1, Figure 2) and 0.1 (Period 2), meaning that 50 % of the particle flux was transported by gusts larger than 1.6 – 2.3 times the mean, which occurred 18 - 10 % of the time. The difference between Periods 1 and 2 was largely due to the different contribution of large outward interactions (+*u*'+*w*'). In Period 1 these motions were relatively more common and they contributed to a negative particle flux representing updraughts of relatively clean air. In Period 2 outward interactions below hole size 3 were similarly associated with a negative particle flux. In larger gusts, however, *N*' was positive indicating the updraught of relatively polluted air. Above hole size 6 outward interactions dominated particle flux. Also, inward interactions (-*u*'-*w*') transported almost no flux in Period 1, but a significant negative flux (downdraught of clean air) in Period 2. It is intriguing that this occurred in Period 2 only, which was a period of light winds. The net result was that in Period 2 large gusts carried a greater share of the total net flux.

3.2. Recirculating flow

During the recirculating period the time fractions were similar to the channelled period, although sweeps, rather than outward interactions, dominated large gusts. Sensible heat fluxes were positive at all hole sizes and dominated by sweeps. As with channelled flow, 50 % of the heat flux was transported by gusts larger than 1.5 times the mean, which occurred 20 % of the time (Figure 3).

Particle flux was dominated by frequent sweeps of clean air, and less frequent ejections of polluted air. In contrast to the channelled periods, however, particle flux was only positive (upwards) below hole size 3, corresponding to a time fraction of 0.06 (Figure 3). I.e. In the 6 % of time during which gusts were larger than 3 times the mean, net particle fluxes were negative. This was largely due to sweeps transporting negative flux, i.e. a downdraught of polluted air. It seems reasonable to attribute this to the recirculation of air within the canyon space or the entrainment of particles from above the canyon. Outward interactions made a minimal contribution to particle flux.

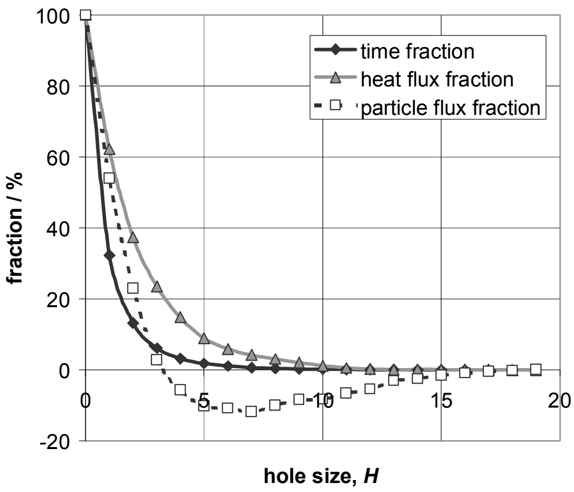

Figure 3: Time, heat flux and particle flux fractions versus hole size in recirculating flow.

4. CONCLUSIONS

Some temporal variation in the turbulent transport of momentum, sensible heat and fine particles has been illustrated and quantified in a real, complex urban street canyon. Flow within the canyon tended to be channelled along the canyon axis, although when winds approached the canyon at greater than 40 °, a more complex recirculating flow was observed. It was shown that one half of the sensible heat flux was transported by large gusts which occurred around 20 % of the time, largely by sweeps and ejections. Particle fluxes were even more acutely related to large but infrequent sweeps and ejections. In recirculating flow large sweeps transported particles back down towards the canyon floor.

These results must be considered carefully and cannot be considered general due to large run-to-run variability, limited data coverage and the complexity of the topography. Further investigation is required to identify general features of turbulence in street canyons.

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