EVALUATION OF A TURBULENT FLOW AND DISPERSION MODEL IN A TYPICAL STREET CANYON IN YORK, U.K.

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INTRODUCTION

The use of micro-scale CFD models of urban streets has become increasingly popular because of their ability to predict the distribution of pollutants within irregular street layouts and thus allow the identification of hotspots. For operational purposes however, the models often employ simplified representations of the street geometry, inflow conditions, turbulence closure, or employ a low resolution grid in order to produce simulations within computing constraints. Hence, there is a pressing need to evaluate predictions from such CFD models for a variety of geometries of relevance to the urban environment. While previous studies have compared concentration predictions from CFD models with field data and flow predictions with wind tunnel data, this work presents comparisons of model predictions with measurements of turbulent flows *and* concentrations of a traffic related tracer at a field site. The flow model employed is the k-epsilon model MISKAM (Eichhorn 1996) where a Lagrangian stochastic model was used for dispersion in order to minimise artificial diffusion. The model's sensitivity to grid resolution and inflow velocity profile is tested, as well as the influence of traffic conditions on the emissions model used.

EXPERIMENTAL SITE

Figure 1 shows the street layout around the measurement site on Gillygate in York, U.K. Details of the full experiment are given in Boddy et al. (2005). Sonic anemometers measured the in-street winds at 20 Hz at the lighting columns G3 and G4 and also on a nearby mast. The mast anemometer (sampled at 10 Hz) was at a height of 19.5 m and situated clear of most surrounding obstacles so that it was sampling the above roof-level winds. [CO] measurements were made in the street using electrochemical sensors. Because CO in street canyons is primarily produced by petrol engines and is practically inert on short timescales, it acts as a tracer for the dispersion of traffic-related pollutants. Traffic data was collected using SCOOT (Split Cycle and Offset Optimisation Technique) sensors at both ends of Gillygate (only inbound sensor shown in Figure 1). This study uses traffic flow and congestion measures derived from the detector occupancy operating at 4 Hz. All measurements used are 15-minute averages of the raw data. Gillygate is a narrow street canyon (width $W \sim 15$ m) flanked by two and three storey buildings on either side (typical height H of 10-12 m) with pitched roofs. Typically 15-16,000 vehicles pass along Gillygate on weekdays with slightly more traffic (53%) in the inbound lane. Congestion is common and traffic queuing can occur in the inbound lane stretching back from the traffic signal 200 m from the measurement site. There is no significant gradient on Gillygate or in the surrounding area. Discussion here is limited to anemometers on columns G3 and G4 (Figure 1) at heights of 5.5 m and 5.7 m, respectively i.e. roughly mid-canyon height. The streetbox on G3 was at 3.5m. The anemometer on column G3 was situated roughly 2 m from the side of the canyon, while that on G4 was 1 m from the opposite wall. Field work took place over 30 days during Oct.-Nov. 2003.

MODEL

The model used is a combination of a CFD model describing the mean flow and a Lagrangian stochastic particle model to predict the dispersion of pollutants. The flow model (MISKAM 4.2.1, Eichhorn, 1996) uses a k-ε turbulence closure. The Lagrangian stochastic model is based on the formulation of Thomson (1987) for inhomogeneous Gaussian turbulence. Full details are given in Dixon et al. (2005). The model domain is 270m wide by 400m long by 50m high and includes all buildings within approximately 100m of the measurement site (see Figure 1). The grid is non-uniform with the highest resolution of 1m by 2m by 1m at the measurement site. A logarithmic wind profile is assumed at the inflow boundaries with a roughness length z_0 of 10cm. The roughness lengths within the domain are set to 10cm at the ground and 1cm on the buildings. The buildings are idealised as rectangular blocks. The pollutant source is specified as a box within which the particles are initially randomly located and given a random velocity assuming a Gaussian distribution about the mean wind. The source extends for 100m along Gillygate from the junction with Lord Mayor's Walk and is 9m wide and 1m deep. For each run, 50,000 particles are tracked through the domain.

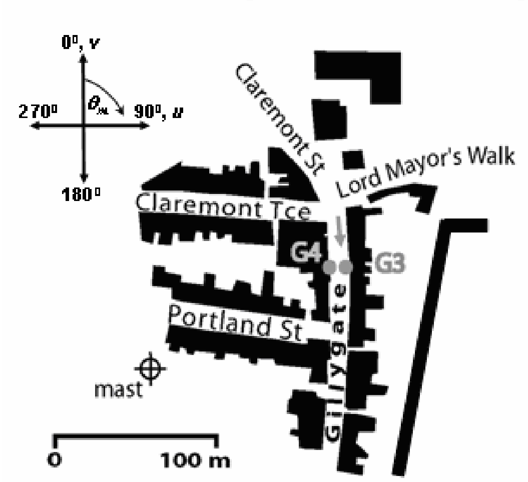


Fig.1. Street layout around experimental site. Arrow denotes traffic sensor in inbound lane.

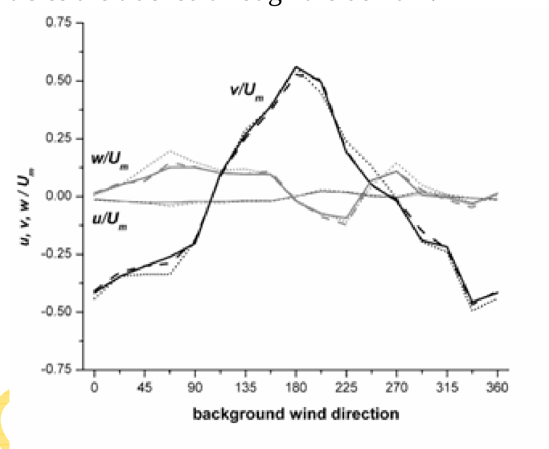


Fig. 2. Sensitivity of normalised velocity at G3 for base run A (solid lines), run B (dashed lines) and run C (dotted lines)

RESULTS

Model sensitivity

The effects of changing the inflow profile and the grid resolution in the model were studied. Three model setups were used: run *A* used the model as described above, run *B* was identical to run *A* with the resolution of the model doubled in each direction over the modelled measurement area in the domain, and run *C* was the same as run *A* where the inflow z_0 was 50 cm. Figure 2 shows minimal differences in the mean flow components normalised by the wind speed at the mast U_m at G3 for the three runs. Graphs of t.k.e. and concentration (not shown) also show only minor differences between runs. Hence the model setup is not overly sensitive to small changes in the inflow profile or model resolution.

Mean flow

The experimental data in Figure 3 shows evidence of a single vortex spanning the street for background wind direction θ_m from 30^0 to 135^0 with positive vertical velocities at G3 and negative at G4. The mean flow within the canyon is helical in this regime when there is significant along street flow. The model reproduces this mean flow well, although the vertical velocity is generally underestimated. Along street flow is negative when θ_m is perpendicular to the street from 90^0 in both model and field data. Analysis of the model wind field (not shown) shows this is due to the channelling of the wind from Lord Mayor's Walk into Gillygate. For θ_m between 180^0 and 270^0, Figure 3 shows a large increase in the standard deviation of the wind components. This is thought to be primarily caused by the effects of eddy shedding from a tree near the mast which may also be retarding the flow at the mast leading to anomalously high normalised experimental data in this sector. Consequently, caution should be applied when analysing this section of data. For θ_m between 195^0 and 240^0, the field data shows a vortex in the reverse direction with positive vertical velocity at G4 and negative at G3. Around 270^0, the anemometers at both G3 and G4 show upward flow. The model also captures this feature and study of the model flow field (not shown) shows that flow from the side streets Claremont Terrace and Portland Street is converging at the measurement sites, leading to positive vertical velocities here. While the model has reproduced the measured mean flow quite well, some discrepancies remain, notably the model overestimates the along street flow for θ_m from 100^0 to 180^0. This was improved by extending the domain further down Gillygate but raises the question of how far and how well an urban area needs to be defined within the model to capture the flow field correctly.

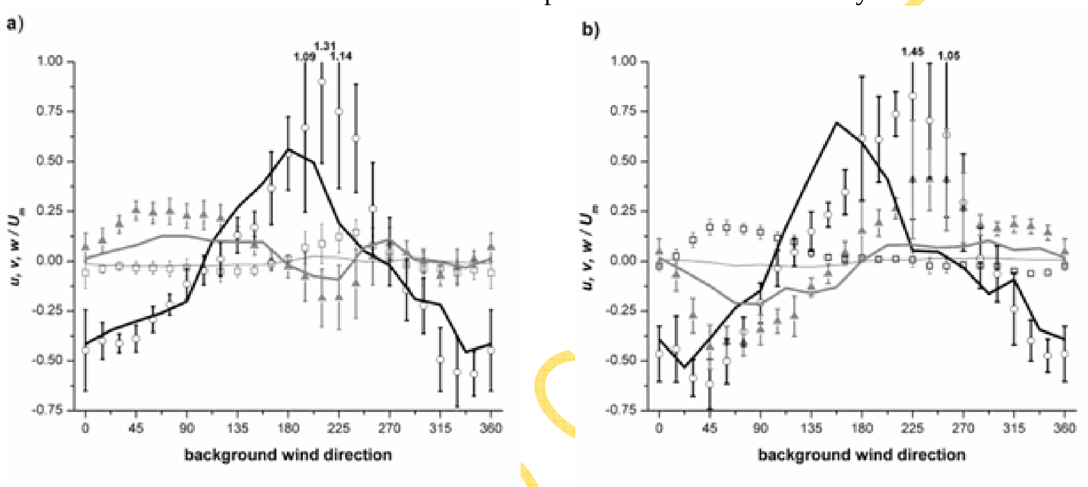
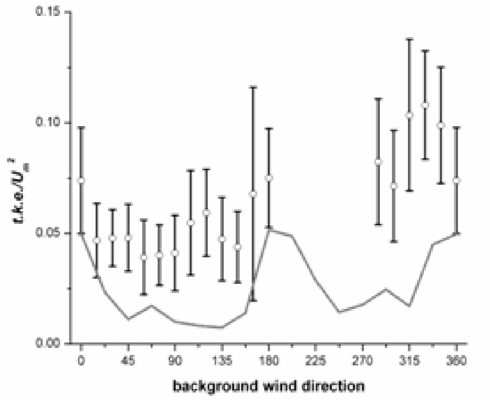


Fig. 3. Normalised velocity components against background wind direction from experimental and model data for a) G3 and b) G4. Experimental data: ∀ u component, − v component, 7 w component. Model data: □u component, □v component, □w component. Experimental data show standard deviations of data as error bars.

Turbulent kinetic energy

Figure 4 shows the t.k.e. measured at G3 in the canyon and normalised by U_m^2. Experimental values between θ_m 195^0 and 270^0 are excluded because of the effect of the tree at the mast. The model generally underestimates the t.k.e. measured in the canyon. The model shows marked peaks for background flow parallel to the street, but even these values are less than the field values. This contrasts with the findings of Sahm et al. (2002) in their comparison of CFD models with wind tunnel data of flow in a street canyon. They found that MISKAM and other CFD codes tend to exaggerate the t.k.e. in the canyon, particularly on the windward side. The discrepancy arises because the normalised values recorded in the wind tunnel are an order of magnitude smaller than those measured in the street in this study while the model values are similar in both cases. A possible explanation lies in the difference in the background flows between wind tunnels and field experiments. A 15-minute average of wind from a particular direction in the field is comprised of a range of flows from different directions. An analysis of the mast data in this study showed that the standard deviation of the wind direction σ_θ in a 15-minute period was approximately 20^0 and so the in-street t.k.e. will reflect this extra variability in the background wind which is not always present in wind tunnels. This extra level of turbulence in the real canyon may have a direct impact on the dispersion of pollutants.



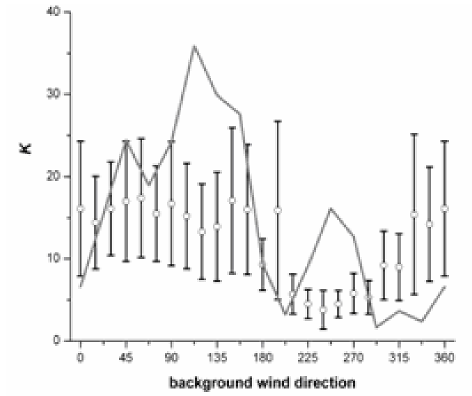


Fig. 4 Normalised t.k.e. at G3:
– experimental data, □ model data.

Fig. 5 Normalised concentration K at G3:
– experimental data, □ model data.

Dispersion

To compare the experimental and modelled [CO], the data was normalised by $K=CU_mHL/Q$, where U_m is the mast wind speed, H the canyon height and Q/L the emission rate per unit length. Background [CO] was subtracted from the streetbox data. A linear relationship is assumed between the total traffic flow and emission rate, using an average emission factor of 7.81 mg m^{-1} veh^{-1} for peak-time traffic. Data was excluded when the traffic flow fell below 100 vehicles hr^{-1} because the low [CO] values were near the limit of the sensor, and also when the mast wind speed fell below 2 ms^{-1} due to the increased effect of traffic produced turbulence. This removed roughly 50% of the data. Fig. 5 shows the comparison of field and modelled K at G3. Both show generally higher values when G3 is on the leeward side of the canyon compared to the windward side reflecting the presence of a cross canyon vortex flow for many wind directions. The model in general overestimates the concentration in the street when the streetbox is on the leeward side of the street. This can perhaps be explained by the lower levels of t.k.e. shown in the model compared to field data and also the model's smaller vertical velocities. The convergent flow in the wind data has led to significant peak in the model concentration at 270^0, but this is not shown in the field data. The modelled K's show some sharp changes between adjacent wind directions whereas the field values are more smoothly changing. This may be another result of the fluctuating direction of the background wind in the field. In addition, despite the restriction of the dataset to conditions where the normalisation should apply, the variability of the data is still high. The intermittency in the flow is one possible cause of variability. Another cause could be the variability in traffic emissions which in reality are governed by many factors including vehicle type, acceleration, engine/ambient temperatures and levels of congestion, in addition to the traffic flow. Fig. 6 investigates the impact of congestion by separating the field data into 3 different traffic regimes: free-flowing, occupancy ≤12 %, congested, occupancy > 62 % and unstable for occupancy levels between 12 % and 62 % when the traffic switched between these two states. Normalised concentrations for the congested regime are significantly higher than those for the unstable and free-flowing regimes. Estimating pollutant emissions using only the traffic flow and excluding congestion has therefore added to the variability of the normalised concentrations. It follows that a better parameterisation for the emission of pollutants including the effects of congestion is required, if comparison with model output is to be correctly made. In addition, Fig. 7 demonstrates the possible influence of spatial variability in traffic emissions during congested conditions as predicted by an integrated traffic microsimulation and instantaneous emission model. The figure shows that using a microsimulation model, the emissions are predicted to be higher close to the traffic signals at either end of Gillygate compared to the link averaged emissions profile. Including such effects within the dispersion model demonstrates that the use of link averaged profiles leads to higher predicted concentrations at the measurement site when compared to using the spatially varying emissions profile. This is a result of the emissions being concentrated around the inbound traffic signal under congested conditions, which could lead to an overestimation of normalised concentrations at the measurement site when using link averaged emissions.

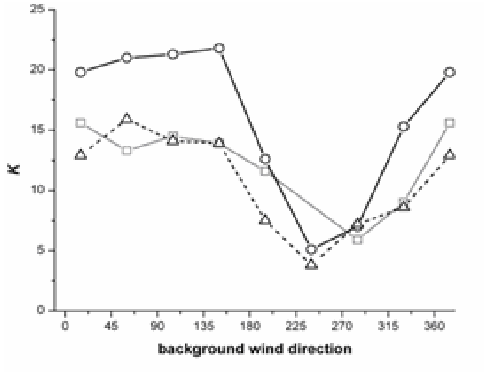


Fig. 6 K vs. θ_m at G3 split by traffic occupancy at inbound sensor: —□— occupancy ≤ 12 %, ---Δ--- 12% < occupancy ≤ 62%, —○— occupancy > 62 %.

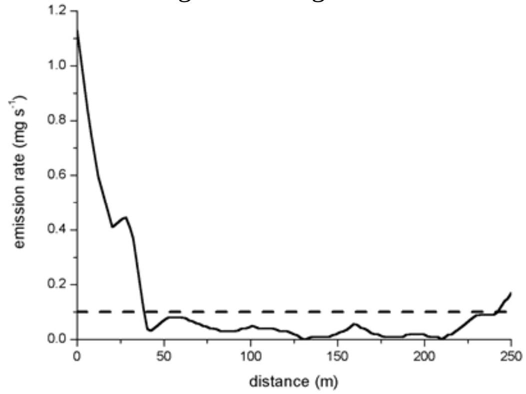


Fig 7 Spatial variation in emissions of CO along Gillygate between 08:30 – 08:45: —variable emissions; — — mean emissions (Tate et al, 2005).

CONCLUSIONS

The *k-ε* flow model MISKAM has reproduced the mean flow features observed in a complex street canyon quite well, including channelling, vortex, helical and convergent flows. The model tended to underestimate the vertical velocity and t.k.e. in the canyon and perhaps contributed to the dispersion model overestimating the maximum concentrations. The fluctuating direction of the background flow may have been a major reason for the model underestimating the dispersion in the canyon, as well as the use of link averaged emissions profiles. The model was shown to be insensitive to small changes in grid resolution and the roughness length used within the inflow profile.

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