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Turbulent transfer relationships over an urban surface. II: Integral statistics

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SUMMARY

A comprehensive study of atmospheric turbulence over an urban surface has been carried out. Part II presents the normalized standard deviations of all important atmospheric variables from unstable conditions measured at $z'/z_0 = 37$ and analysed within the Monin–Obukhov similarity framework. They differ from the rural reference data in the following ways.

(1) The normalized standard deviation of vertical velocity is systematically smaller.
(2) The efficiency of urban transfer of heat and especially momentum are larger.
(3) The humidity statistics cannot be described within the similarity framework.

It is suggested that the roughness sublayer effects and large-scale space and time inhomogeneities of the motions in the suburban atmosphere are responsible for the observed dissimilarities.

1. INTRODUCTION

This paper explores the integral properties of atmospheric turbulence over an urban surface and complements the spectral results discussed in Part I (Roth and Oke 1993). Unfortunately research such as this has received little attention in the past although observations from other rough surfaces such as those for crops and forests have demonstrated differences from measurements taken within the homogeneous surface layer. The main objective is to investigate the applicability of the Monin–Obukhov similarity (MOS) framework in the urban roughness sublayer. The integral statistics of all important variables (including humidity for the first time) are covered, and the linear correlation coefficients are used to analyse the turbulent transfer mechanism.

The measurements representing unstable conditions ($-0.05 > z'/L_v > -1.80$) were made at a tower site in suburban Vancouver, B.C., Canada for $z' = z - d = 19$ m and $z'/z_0 = 37$, where z, d and z_0 are heights above ground, zero-plane displacement height and roughness length, respectively. The research context, site and observational program are discussed in part I (sections 1 and 2). The observations that we shall be discussing are the average readings from two sensor combinations mounted at the same height (horizontal separation about 2 m). Further details regarding the instrumentation can be found in Part I (section 4 and Table 1).

The standard deviation, σ, (and the variance) of a turbulence measurement represents one of its basic characteristics. Often the variance is computed without consideration as to which scales contribute to the transfer. Steyn (1982) argued that the most appropriate averaging band for the determination of the integrals should cover the full range of micrometeorological fluctuations, i.e. from the low-frequency end of the spectrum defined by the spectral gap (if present) up to the inertial subrange. McBean (1971), however, pointed out that for u and v, and to a lesser extent T and q, the computed variance depended on the length of the record, which can be seen from the spectra of these measurements that still contain some energy at low frequencies (especially q; Part I, Fig. 4(b)).

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Here the integral statistics have been evaluated over the entire frequency range available ($0.0003 < n \leqslant 10$, where n is the natural frequency in Hz). Considering the long averaging time (60 min), this will introduce some uncertainty and scatter into the results.

2. INTEGRAL STATISTICS

(*a*) *Standard deviations of velocity*

Rough surfaces are a cause of drag on the atmosphere and create intense turbulence. The ratio of the friction velocity, u_*, to the mean wind speed, U, is related to the drag coefficient, C_D, through the expression

$$C_D = (u_*/U)^2 \tag{1}$$

and is therefore a measure of the surface roughness. The literature suggests a wide range of values for the u_*/U ratio for 'ideal' (low roughness, homogeneous fetch) surfaces but generally less than 0.1 for $z_0 < 0.01$ (Counihan 1975, for $z = 30$ m). Here the more general definition of the friction velocity has been adopted, viz. $u_* = (\overline{u'w'}^2 + \overline{v'w'}^2)^{1/4}$, which takes into account the possibility that the stress tensor may not be aligned with the mean wind. A plot of u_* vs. U from all stability conditions encountered here is given in Fig. 1. The slope is greater than 0.1 and agrees well with the slope (0.13) of an estimated linear fit obtained by Clarke *et al.* (1982) (dashed line in Fig. 1) for their measurements under near-neutral conditions at an urban site ($z' = 25$ m: the surroundings, mainly two-storey dwellings) and 0.13 from Högström *et al.* (1982) for their central city site (6 m above the roof of a 21 m-high building).

(*i*) *Turbulence intensity*. Turbulence intensity, I, is defined as the ratio of the standard deviation of the respective wind component to the mean wind speed, viz.

$$I_i = \sigma_i/U \quad (i = u, v, w). \tag{2}$$

These are important variables for diffusion modelling and depend on the height of

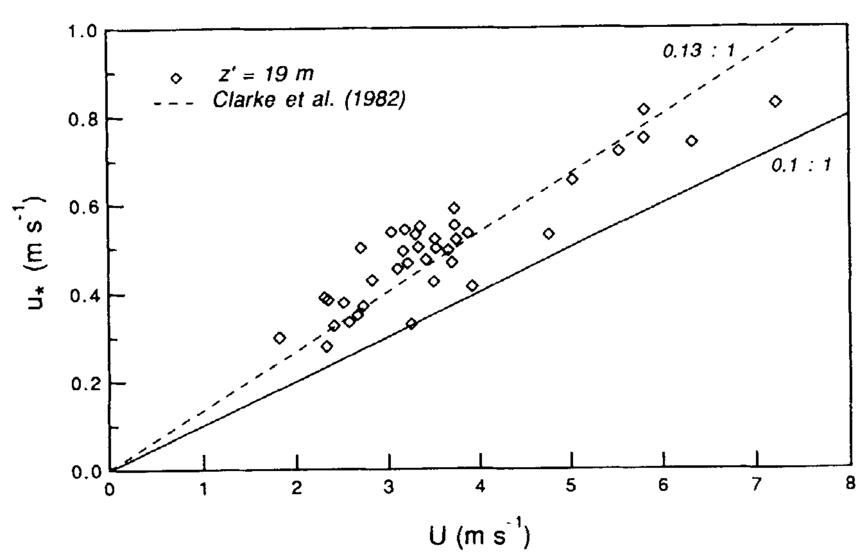


Figure 1. Plot of u_* vs. U. The dashed line is a linear fit from Clarke *et al.* (1982) for their suburban site ($z' = 25$ m).

observation, the surface roughness and the stability. It appears that the horizontal components (Fig. 2(a)) and the vertical component (Fig. 2(b)) are functions of z'/L_v. The scatter is considerable for the horizontal components and excludes the fitting of empirical curves. The general behaviour, however, agrees well for both v and w with other urban observations from Clarke *et al.* (1982). In particular, this study and that by Clarke *et al.* both reported higher turbulence intensities for the horizontal components which also increase faster with increasing instability compared to the vertical components.

Over rural areas the turbulence intensities are about twice as low and, for the u component, σ_u/U lies approximately between 0.1 and 0.15 under near-neutral conditions measured at $z = 30$ m (Counihan 1975). The increased turbulence intensities over the urban surface are probably due to form-drag and associated mechanical shear production near the roughness elements, which results in a decrease in wind speed.

Only a few studies deal with the subject of the stability dependence of turbulence intensity. Brook (1972) (between 7 and 18 m on top of an 18 m-high building), Ramsdell (1975) (for $-2.5 < z/L < 0.17$; $1 < z < 50$ m in an urban residential area), Högström *et al.* (1982) (for $-0.2 < z'/L < 0.2$) and Rotach (1991) (for $-0.3 < z'/L < 0.004$; 5 and

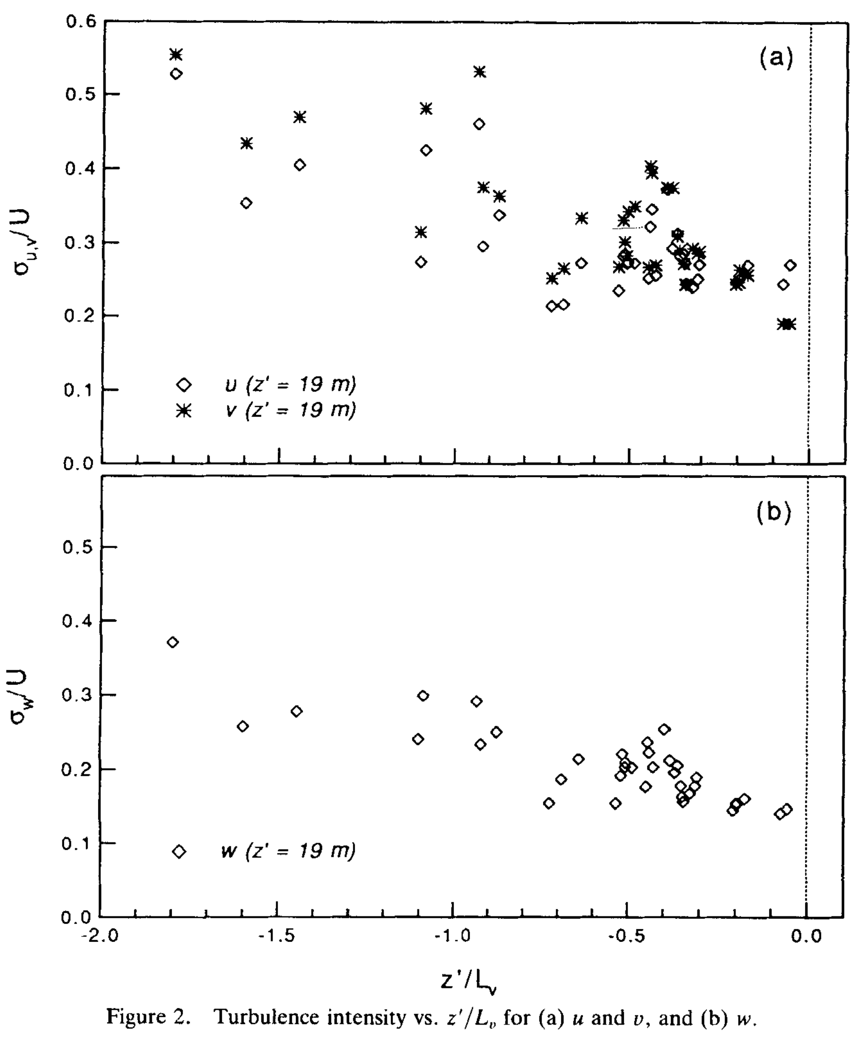


Figure 2. Turbulence intensity vs. z'/L_v for (a) u and v, and (b) w.

10 m above an 18 m-deep urban canyon) could not observe any relationship. Apart from Ramsdell (1975), however, these studies encompass a limited stability range only close to neutral. Similar to the data in Fig. 2, are those of Clarke *et al.* (1982) who also observed that values increased with increasing instability (for $-1.6 < z'/L < 0.8$); they also noted increasing values with increasing surface roughness.

(*ii*) *Normalized standard deviations.* The normalized horizontal velocity standard deviations $\sigma_{u,v}/u_*$ are plotted in Fig. 3(a) and compared against the estimated fit from Clarke *et al.* (1982) for their industrial site, expressed in the form:

$$\sigma_v/u_* = 2.5(-z'/L_v)^{1/3} \quad (z'/L_v < -1). \tag{3}$$

(Note that, based on an inspection of the Clarke *et al.* data, the empirical fit in Fig. 3(a) has been extended beyond the region of its validity to $z'/L_v = -0.5$). The values given here for the σ_v/u_* ratios are slightly higher than those found by Clarke *et al.*, however,

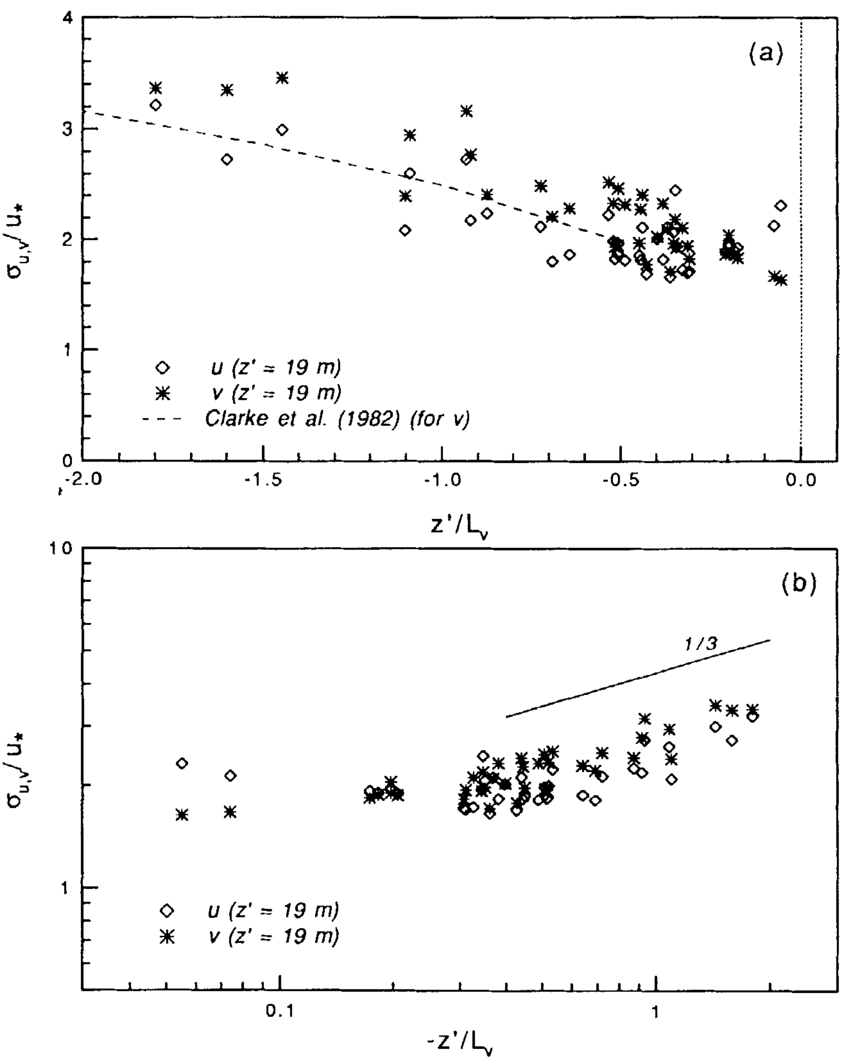


Figure 3. Normalized standard deviations of u and v vs. z'/L_v. (a) Compared with an empirical fit by Clarke *et al.* (1982) (dashed line) for their industrial site; (b) on a log–log plot.

Clarke *et al.* also found an inverse relationship with z_0 in all three velocity components and that their results varied slightly from site to site. Here the data are close to the $(-z'/L_v)^{1/3}$ similarity prediction (with some scatter) for $-z'/L_v > 0.6$ (determined from the log–log plot in Fig. 3(b)). No stability dependence was observed by Ramsdell (1975) and for the ratio σ_u/u_* by Coppin (1979) (for $-1.04 < z/L < -0.27$; $z = 34$ m, average building height, 10 m). Steyn (1982), at the same site as was in use here, measured an increase of the normalized standard deviations with increasing instability (up to $z'/L = -70$), however, he could not choose between z or z_i (height of the planetary boundary layer) as the better scaling variable.

Experimental data from the homogeneous surface layer for the horizontal wind components are usually less supportive of the similarity prediction and it is often argued and observed that u and v scale better with mixed-layer variables (apart from z'/L_v). However, Arya and Sundararajan (1976) found a definite increase of $\sigma_{u,v}/u_*$ with increasing instability with the Kansas data, which is similar to what McBean (1971) observed in another rural study.

Much attention has been paid to the neutral limits within which $\overline{w'T'_v} \rightarrow 0$ and similarity theory predicts the normalized velocity standard deviations to be constant. Extrapolation of existing data to neutral would be a dubious procedure, however; the data closest to $z'/L_v = 0$ have values of 2.3 and 1.7 for u and v, respectively, and agree well with other observations from studies of both rural (e.g. Counihan 1975 recommends values of 2.5 and 1.9 for u and v) and other urban surfaces, with the possible exceptions of the studies by Jackson (1978) ($10 < z < 70$ m, with surroundings consisting of 7 to 50 m-high buildings), Steyn (1982) and Rotach (1991) who, for u, reported finding values which were more than 10% below the reference values (Table 1). The neutral data for v are generally marked by a lot of scatter (for both rural and urban surfaces) and Rotach (1991) again reported lower values compared to the reference. It should be noted that his data represent turbulent processes in the urban roughness sublayer, as is clearly demonstrated by Rotach (1991).

The normalized standard deviations of the vertical velocity component are shown in Fig. 4. The solid line in Fig. 4(a) represents the empirical fit by Panofsky *et al.* (1977)

TABLE 1. COMPARISON OF STANDARD DEVIATIONS OF WIND VELOCITY NORMALIZED BY THE FRICTION VELOCITY FOR NEUTRAL STABILITY FROM THE PRESENT AND OTHER URBAN STUDIES

Study	σ_u/u_*	σ_v/u_*	σ_w/u_*	Comments
Bowne and Ball (1970)	2.5	1.5	1.3	Slightly unstable; $z = 53.3$ m
Ramsdell (1975)	2.5	2.0	1.5	Urban residential; $0.6 < z < 48.2$ m
Jackson (1978)	2.1	1.7	1.7	Averages; $10 < z < 70$ m
Coppin (1979)	2.5	—	1.1	w extrapolated to neutrality; $z' = 23.8$ m
Steyn (1982)	2.2	1.8	1.4	Near neutral; $z' = 20$ m
Clarke *et al.* (1982)	2.3	1.7	1.2	Averages from 2 suburban sites; $z' = 25$ m
Högström *et al.* (1982)	2.5	2.2	1.5	Uplandia; $\hat{z} = 6$ m
	2.6	2.3	1.4	Gränby; $z = 50$ m
Yersel and Goble (1986)	2.7	2.2	1.2	Averages from various upwind surface conditions; $z' = 24$ m
Rotach (1991)	2.2	1.2/2.0†	1.0	Near neutral; $\hat{z} = 5$ and 10 m
Hanna and Chang (1992)	—	—	1.2	Suburban site; $z = 10$ m
Present study	2.3	1.7	1.2	Near neutral; $z' = 18.9$ m
Counihan (1975)	2.5	1.9	1.3	Rural reference

z, height above surface; z', effective height; $\hat{z}$, height above top of buildings.
† Values represent two different wind direction sectors which, however, have similar surface characteristics.

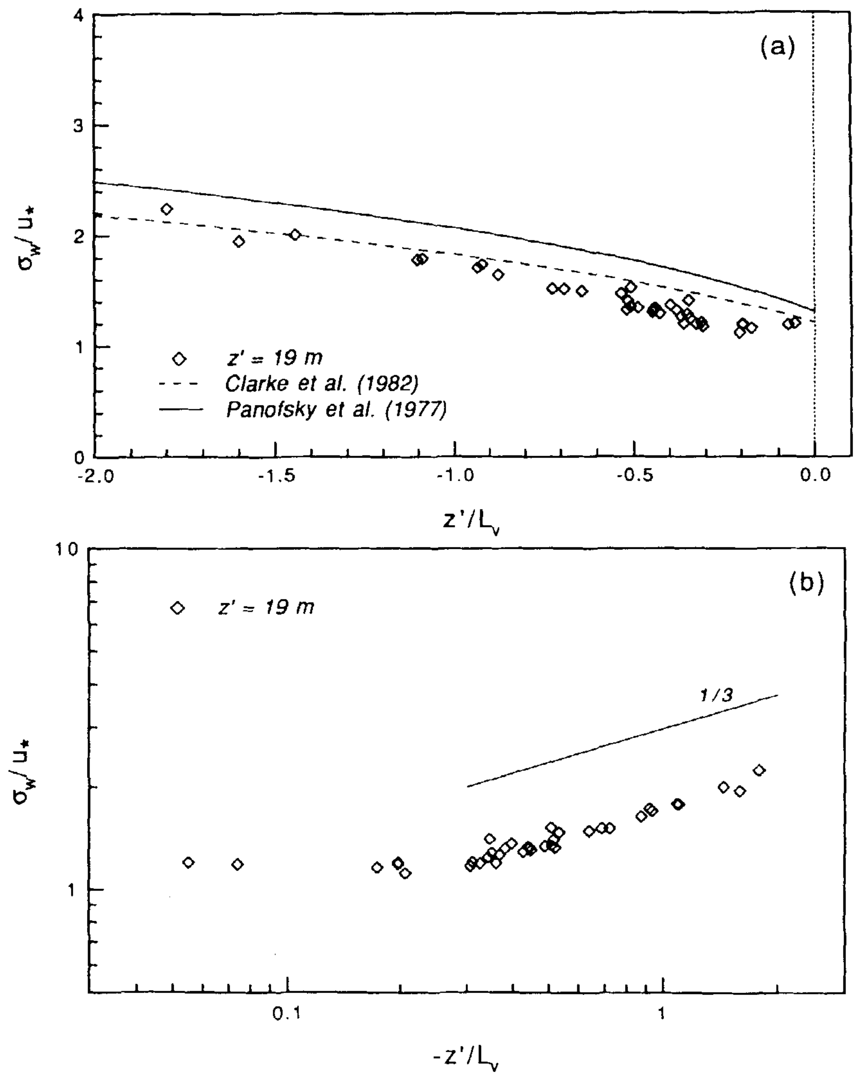


Figure 4. As for Fig. 3 but for w and for the solid and dashed lines in (a) which are empirical fits to rural data by Panofsky *et al.* (1977) and suburban data by Clarke *et al.* (1982).

to data from a tower and aircraft, over rural terrain, using the formula

$$\sigma_w/u_* = 1.3(1 - 3z'/L_v)^{1/3}. \tag{4}$$

The data here follow the trend of the reference curve (i.e. display the same power-law dependence) but are generally lower in value. Agreement with the urban results of Clarke *et al.* (1982) (dashed line in Fig. 4(a)) for their urban site represented by the expression

$$\sigma_w/u_* = 1.2(1 - 2.5z'/L_v)^{1/3} \tag{5}$$

is good at large instabilities but for small values of $-z'/L_v$ the present observations lie below their curve. Variability between sites, however, was quite considerable and observations from another urban site in St. Louis (not shown) compare well with the lower values observed under slightly unstable conditions from the present site. In another study the urban near-neutral observations by Rotach (1991) are also lower than those by Panofsky *et al.* (1977) and those from the present data. Hanna and Chang (1992) reported measuring turbulence from 10 m towers at three sites in Indianapolis, USA. Compared to the reference curve, the Indianapolis values, unlike the present results, are higher at their urban site (which is actually a grassy field along a river adjacent to the built-up urban area), close to at their surburban site and generally slightly lower at their rural site.

The MOS free-convection prediction of a 1/3 slope is followed for $-z'/L_v > 0.4$ (Fig. 4(b)), which is the same as was observed with the rural data from Wyngaard *et al.* (1971). In other urban studies Ramsdell (1975) could not discern a trend with stability, whereas Coppin (1979) and Steyn (1982) did observe increasing values with increasing instability. In the data from Hanna and Chang (1992) only the observations from the suburban site follow the 1/3 power-law prediction.

In the neutral limit, again taking the ratios from the least unstable cases, σ_w/u_* has a value of about 1.2, which is in agreement with other rural (e.g. Counihan 1975 recommends 1.3) and most urban observations (Table 1). The largest deviations from the reference were measured by Jackson (1978) and Rotach (1991) who reported values of 1.7 and 1.0, respectively.

The relatively small σ_w/u_* ratios resemble the lower non-dimensional dissipation values for turbulent kinetic energy (TKE) appearing in Part I (Fig. 8(a)). It was suggested (Part I, subsection 7(a)) that at suburban sites the local production of TKE is larger than its dissipation owing to the increased importance of the transport processes. The data shown in Fig. 4(a) indicate that transfer of momentum is indeed very efficient and it will be shown below (Fig. 9(a)) that the relevant suburban transfer correlation coefficients are also very high.

Since z'/L_v contains u_*^3 in the demoninator a pseudo-correlation may be introduced in the free-convection similarity prediction because σ_w is normalized by u_*. Besides u_*, the free convection velocity scale, viz.

$$u_f = (g/T_v\, \overline{w'T_v'}\, z')^{1/3} \tag{6}$$

has been suggested as an important factor in conditions of strong upward heat flux and light winds. Based on a derivation from the turbulent kinetic energy budget, Clarke *et al.* (1982) formulated the following functional dependence of σ_w on both u_* and u_f:

$$\sigma_w = C w_m \qquad \text{with } w_m = (u_*^3 + 0.4 u_f^3)^{1/3} \tag{7}$$

where C is an empirical parameter. Agreement between the present results and the fit to the Clarke *et al.* data for $-1 < z'/L_v < 0$ obtained for their industrial and urban sites ($C = 1.18$) is fair (Fig. 5) and a better linear fit could have been obtained if it had not been necessary to include the origin. However, the emphasis here is on the comparison of different data-sets. Rotach (1991) evaluates the same functional dependence of σ_w on w_m, and his data are well represented by a straight line with $C = 1.12$.

(*b*) *Standard deviations of scalars*

In the free-convection regime dimensional considerations show that the normalized standard deviations of scalars are a function of $(-z'/L_v)^{-1/3}$ (e.g. Hill 1989). The variation of σ_T/T_* ($T_* = -\overline{w'T'}/u_*$) with stability is shown in Fig. 6. The solid line in Fig. 6(a)

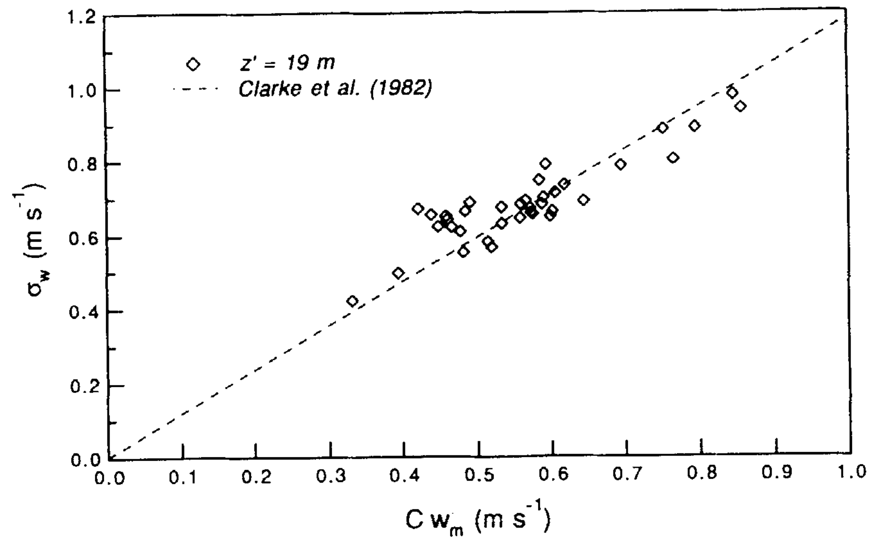


Figure 5. Normalized standard deviations of w vs. w_m compared with a linear fit by Clarke *et al.* (1982) (dashed line) for their industrial and suburban sites (using $C = 1.18$).

represents the Wyngaard *et al.* (1971) fit to the Kansas data given by

$$\sigma_T/T_* = 0.95(-z'/L_v)^{-1/3} \qquad (z'/L_v < -0.03). \tag{8}$$

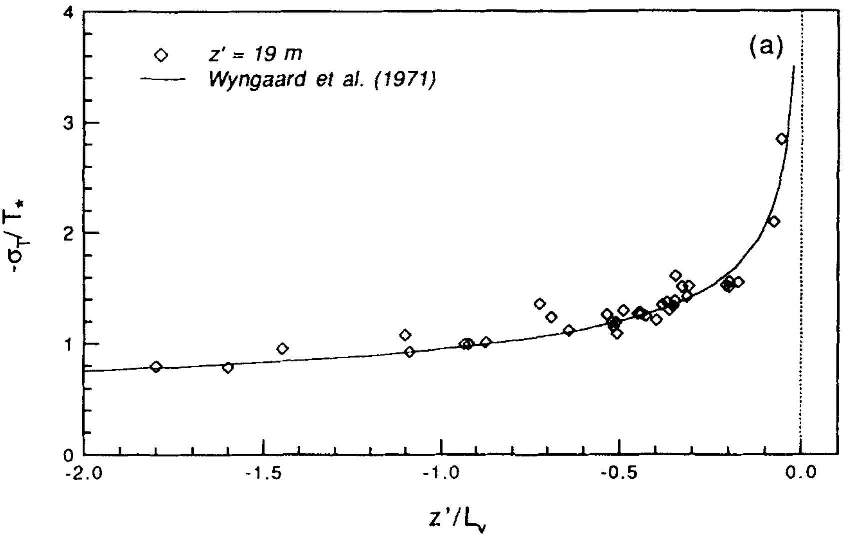
The urban data here agree well with the rural reference. Very close to neutral the ratios become large owing to the fact that although the heat flux (and hence T_*) is close to zero, some temperature fluctuations caused by horizontal inhomogeneities (which in the ideal case are zero) will be present. The observations from the present study also agree well with the urban data of Clarke *et al.* (1982). The predicted slope of $-1/3$ is followed for $-z'/L_v > 0.3$ (Fig. 6(b)), which is similar to observations over rural surfaces (e.g. Wyngaard *et al.* 1971; Smedman-Högström 1973).

The variation of σ_q/q_* ($q_* = -\overline{w'q'}/u_*$) with stability compared with a curve based on rural data from Högström and Smedman-Högström (1974) of the form

$$\sigma_q/q_* = 1.04(-z'/L_v)^{-1/3} \tag{9}$$

(solid line) is plotted in Fig. 7(a). The scatter is large, especially for slightly unstable conditions. The trend of the reference curve (Fig. 7(a)) and the homogeneous surface layer's $-1/3$ dependence on stability (Fig. 7(b)) are not followed. By rewriting Eq. 14 of section 3 (to have σ_q/q_* on the left-hand side) it follows that the relatively large values observed for slightly unstable conditions result from a combination of generally low transfer efficiency of moisture (Fig. 10(a)) and low σ_w/u_* values (Fig. 4), the latter being caused by large frictional velocities.

Rural observations by McBean (1971) show a similar amount of variability when plotted against z'/L_v. McBean concludes that to scale humidity with a stability parameter is better done based on moisture flux than on heat flux, and that this also reduces the variability. McBean further suggests that for every passive scalar (a passive scalar is a scalar, such as humidity, whose variations do not significantly affect the buoyancy of an air parcel) a new stability parameter may be necessary, unless the scalar is highly correlated with temperature. It will be shown below (Fig. 10(b)) that at the present site this latter condition is not met.



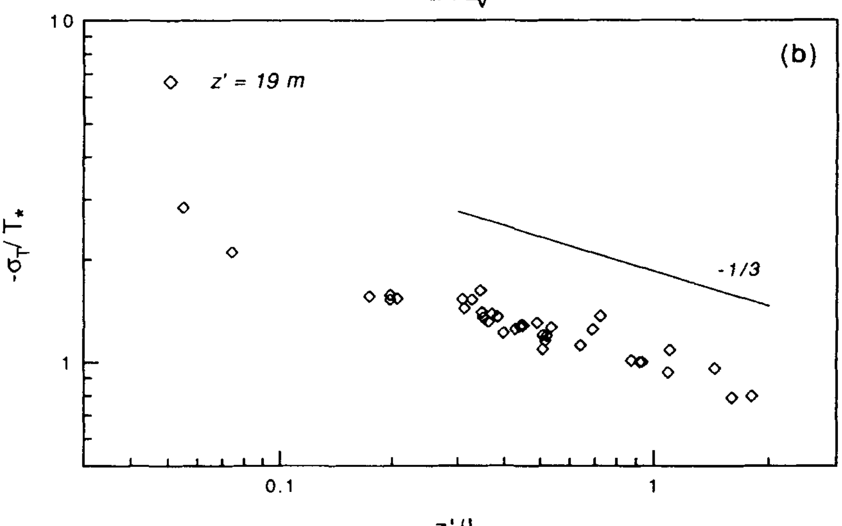


Figure 6. As for Fig. 3 but for T and for the solid line in (a) which is an empirical fit to rural data by Wyngaard *et al.* (1971).

(c) *Covariances*

In the following, another test for the applicability of similarity theory to an urban data-set is described. Wyngaard *et al.* (1971) show that $-\overline{u'T'}/\overline{w'T'}$ can be interpreted as the ratio of the buoyant production rates of stress and energy. Modifying the free-convection scaling (to account for the fact that $-\overline{u'T'}$ must vanish in free convection) they obtain an expression of the form

$$-\overline{u'T'}/\overline{w'T'} = a\phi_m\phi_h \tag{10}$$

where $\phi_m = (1 - 15z'/L_v)^{-1/4}$ and $\phi_h = 0.74(1 - 9z'/L_v)^{-1/2}$. The urban results compare favourably with this prediction (solid line) based on the Kansas data (using $a = 5$) (Fig. 8). On the unstable side the ratio drops toward zero, which can be expected

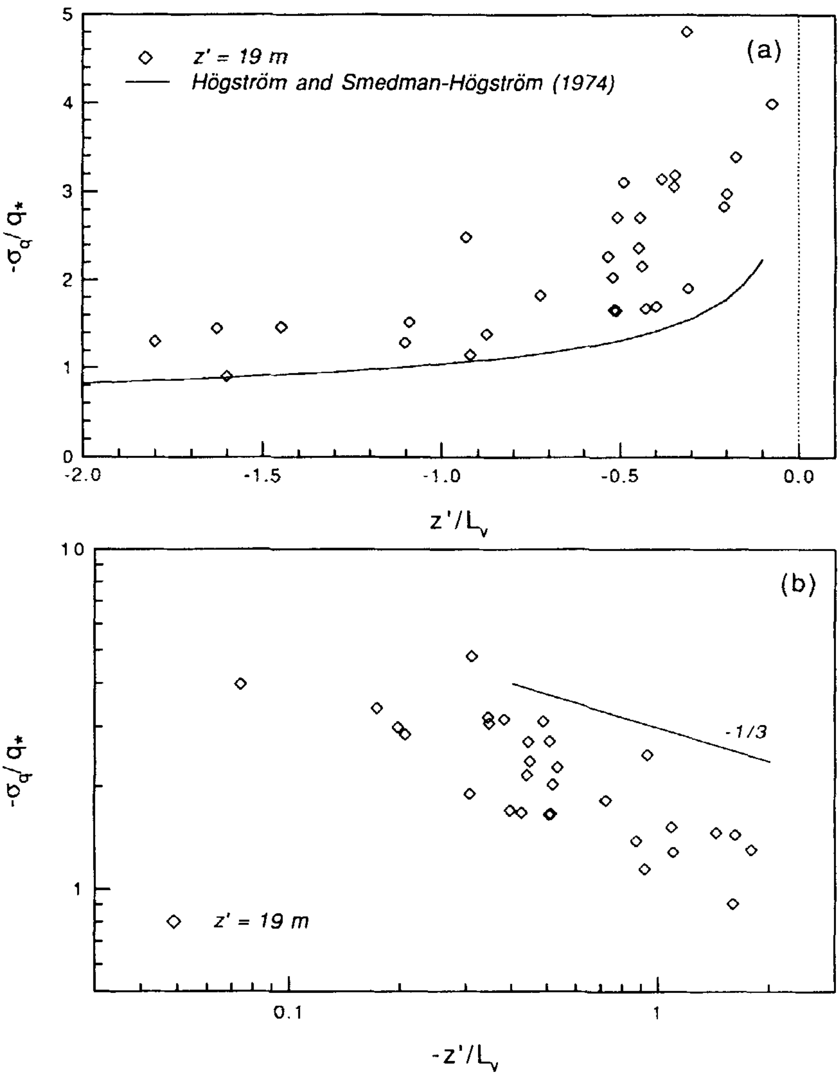


Figure 7. As for Fig. 3 but for q and for the solid line in (a) which is an empirical fit to rural data by Högström and Smedman-Högström (1974).

intuitively, because in the free convection limit there should be no preferred horizontal direction, and therefore no correlation between the fluctuations of u and T.

Considering the rough and inhomogeneous nature of the urban surface the agreement between the two data-sets plotted in Fig. 8 is surprising. One would expect that the horizontal temperature gradients introduced by the inhomogeneity of the surface would result in an anomalously high horizontal heat flux (if u' and T' are correlated). This could be due either to small-scale advection of sensible heat from warmer surface patches or to large-scale structures related to the urban heat island circulation. However, it is also observed that the vertical heat flux over an urban surface is influenced by local scale advection which, at the present site, usually results in heat flux convergence (Schmid *et al.* 1991). It follows that both covariances on the left-hand side of Eq. (10) are 'too high',

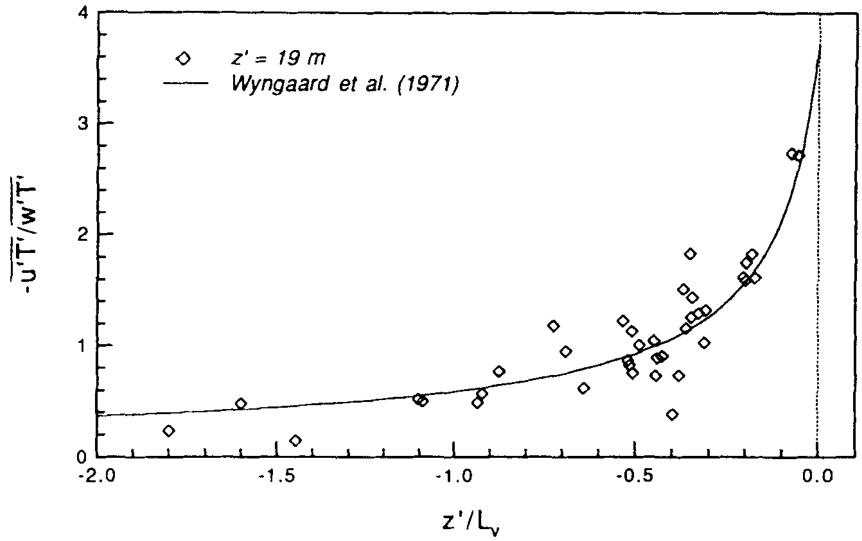


Figure 8. Ratios of horizontal and vertical components of heat flux compared with an empirical fit by Wyngaard *et al.* (1971) (solid line).

but not necessarily their ratio. Clarke *et al.* (1982) measure ratios of the two heat fluxes which are considerably higher than the Kansas curve and therefore higher than the observations from the present study (e.g. the ratio is about 1 for $z'/L_v \approx -2$). They attribute their result to horizontal temperature gradients associated with the inhomogeneous nature of the urban surface.

3. Correlation coefficients

The spectral correlation coefficients were discussed in Part I (sections 6 and 8). It is also useful to compare the overall transfer mechanisms, regardless of scale. In this respect the linear correlation coefficients (normalized covariances) are defined as

$$r_{ij} = \overline{i'j'}/(\sigma_i \sigma_j) \tag{11}$$

where i and j stand for any combination of u, w, T and q. This variable ranges between +1 (two variables are perfectly positively correlated) and −1 (two variables are perfectly negatively correlated) by definition.

The momentum transfer correlation coefficient, $-r_{uw}$, decreases from relatively large values near neutral (0.4) to less than 0.2 at large instabilities (Fig. 9(a)). Thus the efficiency of momentum transfer is decreasing with increasing instability. The solid line in Fig. 9(a) represents an empirical fit to rural data of the form

$$r_{uw} = -0.31(1 - 0.66|z'/L_v|) \qquad (-0.7 < z'/L_v < 0) \tag{12}$$

from McBean (1970). Close to neutral and in slightly unstable conditions the present observations are considerably larger than the reference providing direct observational evidence that urban momentum transfer is more efficient.

Enhanced transfer can be explained qualitatively through wake diffusion and horizontal inhomogeneity of the flow. Thom *et al.* (1975) show that the wake diffusion effect results in a flow with enhanced diffusivity in the roughness sublayer by the superposition upon the shear flow of turbulent wakes generated by individual roughness elements.

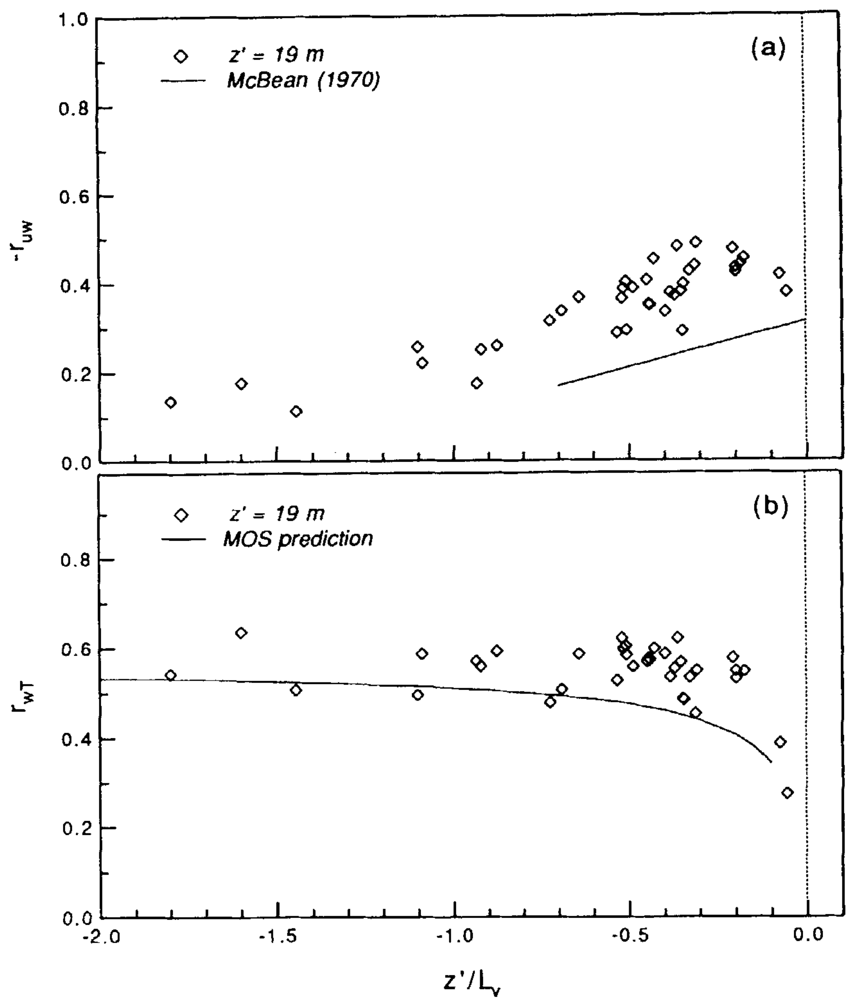


Figure 9. Correlation coefficients vs. z'/L_v for (a) momentum transfer and (b) heat transfer. The solid lines in (a) and (b) are empirical fits to rural data by McBean (1970) and the MOS prediction (see text), respectively.

Dynamically, the enhanced vertical diffusivity for momentum may be associated with the 'horse-shoe vortex' which surrounds, and extends downstream from, buildings immersed in shear flow, creating a region of interacting wakes (Raupach *et al.* 1980). These wake regions are characterized by small eddies which are efficient in transporting momentum across the mean stream lines.

The variation of the heat transfer correlation coefficients, r_{wT}, as a function of z'/L_v is shown in Fig. 9(b). The solid line is the MOS prediction derived by rewriting the correlation coefficient as

$$r_{wT} = (u_*/\sigma_w)(T_*/\sigma_T) \tag{13}$$

and replacing the normalized standard deviations in Eq. (13) with Eqs. (4) and (8). In general the observations from the present study are higher than those predicted by the similarity law and the values observed by McBean (1970) (not shown). The data indicate that a small stability change close to neutral is sufficient for the correlation coefficients to increase sharply. For $z'/L_v < -0.5$ the magnitudes level off at $r_{wT} \approx 0.6$.

Like momentum, the transfer efficiency of heat is slightly larger compared to that of the reference. Although wake diffusion can contribute to an enhancement of the diffusion of heat, it may be the buoyant convective effects that are largely responsible for the enhancement of r_{wT}. Free convection from three-dimensional buildings (e.g. off vertical walls) which can be maintained by discrete heat sources or sinks (rather abundant in urban areas) can effectively enhance heat transfer—even in near-neutral conditions.

The correlation coefficients of moisture transfer, r_{wq}, and its variation with stability are given in Fig. 10(a). The solid curve has been obtained from the equation

$$r_{wq} = (u_*/\sigma_w)(q_*/\sigma_q) \tag{14}$$

and from using Eqs. (4) and (9) to represent the normalized standard deviations. It is seen that the present measurements are generally lower than the similarity prediction

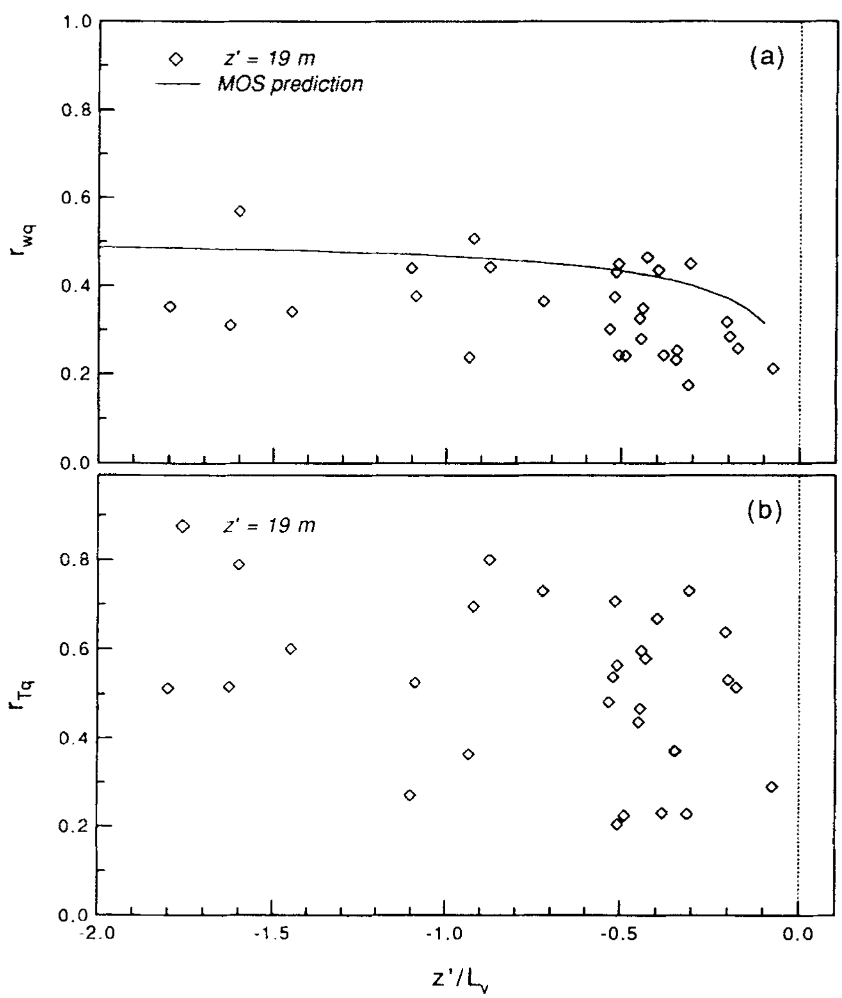


Figure 10. As for Fig. 9 but for (a) wq and (b) Tq. The solid line in (a) represents the MOS prediction (see text).

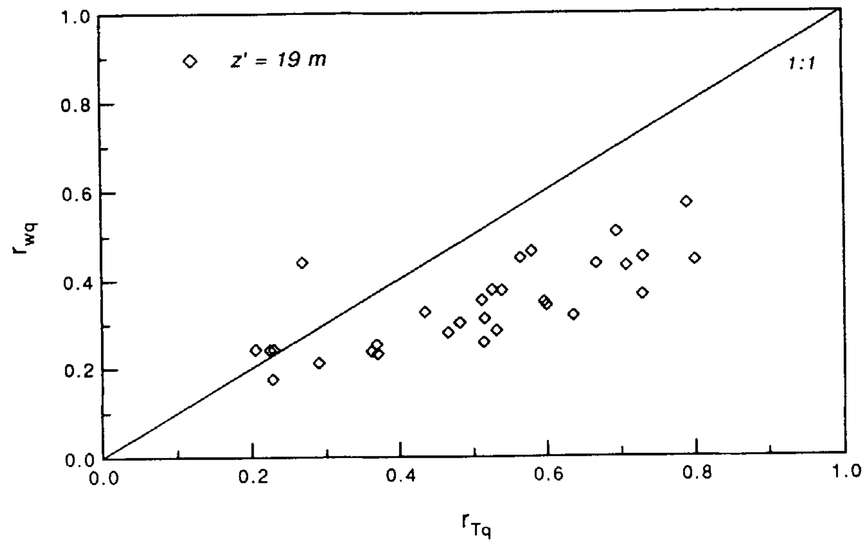


Figure 11. Comparison of wq and Tq correlation coefficients.

over the entire stability range observed and, as has been noted for other humidity statistics, that the variability is large.

Hill (1989) showed that, for MOS to apply, the temperature and humidity fluctuations have to be proportional to each other in the surface layer, i.e. the Tq correlation coefficients have to be of unit magnitude. Such 'ideal' behaviour has been observed in a few rural studies (e.g. Swinbank and Dyer 1967) at the present site, however, the magnitudes are distributed at random between 0.2 and 0.8 with no systematic variation with stability (Fig. 10(b)).

The dependence of r_{wq} on r_{Tq} is shown in Fig. 11 in which a clear positive relationship between the two can be seen. At the low end both r_{Tq} and r_{wq} have roughly the same magnitude, namely 0.2, but the one-to-one relationship breaks down when the correlation coefficients are larger.

4. Summary and conclusions

The principal objective in this exercise has been to investigate experimentally the applicability of MOS to observations of turbulence integral statistics made in an urban atmosphere; the following conclusions may be drawn.

The turbulence intensities of all three velocity components show a dependence on z'/L_v and increase with increasing instability. The normalized standard deviations of velocity and temperature follow the predicted slopes when presented within the similarity framework. For the horizontal wind components this is somewhat unexpected because, for them, surface layer similarity is generally only weakly supported by observations, even over rural surfaces. The magnitudes of the normalized velocity standard deviations for near-neutral conditions agree well with the neutral reference data and with observations from other urban studies. Differences from the rural reference data include the following:

(1) σ_w/u_* is systematically smaller at all stabilities.
(2) σ_q/q_* is generally larger, in particular under near-neutral and slightly unstable conditions, and does not exhibit a free-convection behaviour ($-1/3$ slope).

The linear correlation coefficients generally follow the trend observed in rural reference data or as predicted by similarity theory (i.e. they display the same power-law behaviour); their magnitudes, however, are different.

(3) $-r_{uw}$ is larger for near neutral and slightly unstable conditions.
(4) r_{wT} is slightly larger for all stability conditions.
(5) r_{wq} is smaller for most stability conditions.

It is hypothesized that the observed increase in the efficiency of urban momentum transfer is caused by wake diffusion effects, which was also the explanation given by Raupach *et al.* (1980) for the increase in vertical diffusivity of momentum over a rough surface. Therefore, as McBean (1987) pointed out, much of the momentum transfer in cities is due to pressure perturbations associated with the form-drag of structures rather than to the viscous forces associated with skin friction. There is no analogous process for heat and moisture, which must be transferred through turbulent mixing alone.

The scatter observed in the humidity statistics is largely related to the considerable amount of low-frequency energy observed in the corresponding spectra (Part I, Fig. 4(b)). It follows that similarity theory might not be applicable because similarity variables are based locally, whereas an experimental site would be affected also by the large-scale space and time inhomogeneities of the atmospheric motions (McBean 1971). This is especially true in the urban case because of the unusually well-developed interaction between the rough surface and the upper part of the boundary layer. In particular it is suggested that the poor correlation between T and q is caused by spatial inhomogeneity or, for unstable conditions, by the downward advection of air from the mixed layer above (Roth 1991).

The results from this study show that the observations reflect the inhomogeneous nature of the surface. This has implications for measurements, made in similar environments, and for which techniques are used whose purpose is to evaluate the turbulent momentum, energy and mass fluxes on the basis of a profile approach which assumes that the profiles are logarithmic and that there is some knowledge of eddy diffusivities. For instance, it can be seen from an examination of the linear correlation coefficients of the present study that the transfers of the various fluxes are not similar. This topic has been explored further by Roth (1991). The questions of horizontal inhomogeneity and generality in the present results have already been broached in Part I (section 9); the comments made there also apply to the integral statistic results presented here.

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