TURBULENCE CLOSE TO A ROUGH URBAN SURFACE
PART II: VARIANCES AND GRADIENTS

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Abstract. Measurements of the turbulent wind and temperature fluctuations were carried out in the vicinity of the roof level, over an urban surface at a site where mean gradients of wind speed and temperature were also available. The measurement heights were about 23 and 28 m above ground, the local roof level being 18 m. Measurements were taken on top of a building (at $z = 23$ and 28 m) and over a street canyon (at $z = 23$ m), i.e., fully within the urban roughness sublayer.

The scaled variances of temperature and wind velocity, as well as the non-dimensional gradients of wind speed and temperature, are presented and discussed in terms of departures from Monin–Obukhov similarity theory. Local scaling is found to be a useful concept for the description of turbulence within a roughness sublayer. Expressions for the scaled velocity variances are presented that are valid for all measurement positions; they compare well with results from other urban studies. The non-dimensional gradient of mean wind speed is found to be well represented by the semi-empirical functions for the inertial sublayer if locally scaled. At 5 m above roof level, however, the variability due to horizontal inhomogeneity becomes very large. The non-dimensional temperature gradient, on the other hand, is height dependent and not well defined over the present rough urban surface.

1. Introduction

The present paper describes the results concerning some general turbulence characteristics from an experimental study conducted in the city of Zürich, Switzerland. In a companion paper (Rotach, 1993a; henceforth referred to as I), the behaviour of Reynolds stress at the same site is described. The Reynolds stress is found to vary with height at the present site. Scaling considerations, taking this into account, will be discussed in some detail here.

The lowest part of the urban boundary layer, the surface layer, will be considered in two parts: the roughness sublayer (RS), where the flow is three-dimensional due to the influence of individual roughness elements, and the inertial sublayer (*IS*), where surface layer scaling (i.e., Monin–Obukhov similarity theory, MOST) may be expected to hold (see Figure 1 in I). The existence of a roughness sublayer is not specific to urban surfaces but, unlike the case of smoother terrain, it can have a substantial vertical extension of several tens of meters. Because sources of pollutants are often situated within or close to the RS in urban environments, knowledge of the structure of turbulence in the roughness sublayer is essential for improving urban dispersion models. Due to the lack of better knowledge, the semi-empirical relationships according to MOST are used in many urban diffusion (and/or flow) models even within the roughness sublayer (e.g., Beniston, 1987; Eichhorn *et al.*, 1988; Gross, 1989). One approach to studying RS turbulence

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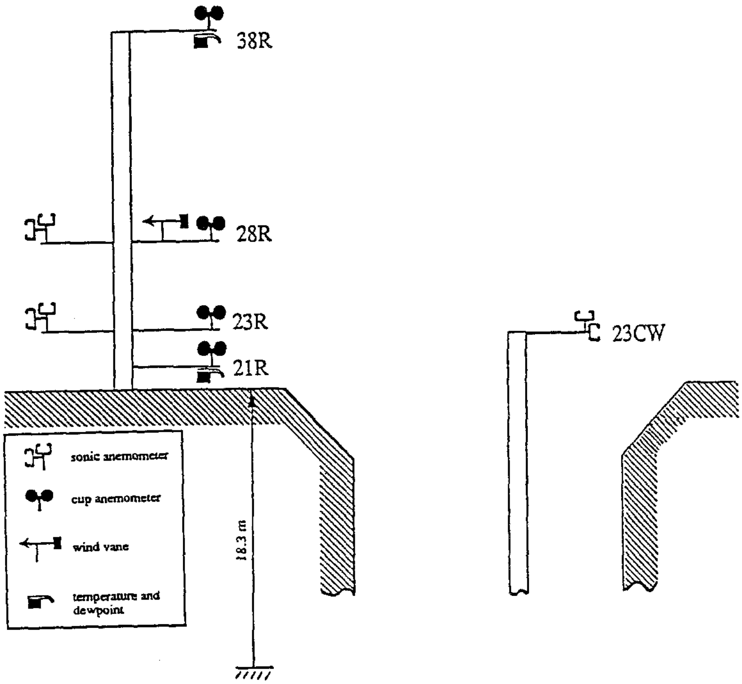

Fig. 1. Schematic view of the measurement site. The labels at the various positions refer to the height above ground (e.g., 28R denotes the measurement position about 28 m above the ground on the roof (*R*) profile). On the canyon tower, only the measurements used in this study are displayed. The symbol for 'sonic anemometer' denotes all (but not simultaneously) realized measurement positions.

is thus to look at the departures from inertial sublayer predictions (knowing that the latter cannot be expected to hold in principle). It has been followed in much of the work on flow modification of rough vegetated surfaces, and will be adopted here.

If the turbulent fluxes are not constant with height, as observed at the present site and discussed in detail in I, we are left with the problem of how to scale flow variables in the RS. Two approaches have been followed: the first is to use the state of the inertial sublayer as a reference and thus to introduce the IS turbulent fluxes together with one (or more) length scale as scaling variables. This can be convenient if these length scales are available (from measurements or model predictions) and has often been used in wind tunnel experiments (e.g., Perry *et al.*, 1969; Raupach *et al.*, 1980; Raupach, 1981). On the other hand, Högström *et al.* (1982) have suggested that local scaling may be appropriate for the urban RS. Some support for this concept will be presented concerning various non-dimensional variables. In addition, possible modifications with respect to *IS* formulations are discussed in the case of the vertical velocity variance.

Turbulence close to rough urban surfaces has been investigated in some detail in the past. In particular, the (scaled) velocity variances have often been studied (Bowne and Ball, 1970; Ramsdell, 1975; Coppin, 1979; Clarke *et al.*, 1982; Högström *et al.*, 1982) as they are required as input in many pollution models. It is common to all these studies that only small deviations from IS predictions (with increased scatter, though) are reported. However, these results are not conclusive in terms of whether local scaling may be appropriate or not, for two reasons. First, there is often only one level of measurement (with a large range of (non-dimensional) observation heights among the various studies). Second, the assumptions concerning the relation between fluxes and gradients (constant flux assumption vs. direct measurement of fluxes) differ substantially between the studies. Concerning the non-dimensional gradients of wind speed or a scalar close to a rough urban surface, on the other hand, there is no information in the literature. The present results will therefore have to be compared to other types of rough surfaces such as forests or artificially constructed surfaces in wind tunnel experiments.

2. Site and Instrumentation

The data presented in this study were obtained at a site close to the center of Zürich (Switzerland) between March 1987 and May 1988. The site is characterized by a fairly regular distribution of buildings (approximately 20 m high) within a radius of about 300 m. Nevertheless, the zero plane displacement, d, was found to vary with wind direction. The zero plane displacement was determined using two independent methods (Rotach, 1993b), leading to d/h between 0.5 and 0.88 if h is the local roof height (18.3 m). The setup consisted of a 20 m high tower located on the roof-top of a five-story building and a second tower within the neighbouring street canyon, each having four instrumented levels (Figure 1). The experimental arrangement is described in more detail in I and a full description is given in Rotach (1991). For present purposes, only measurements carried out fully within the RS, i.e., above roof level, are included. These are at positions 28R, 23R and 23CW of Figure 1.

Mean wind speed and temperature were measured at positions 21R, 23R, 28R and 38R, i.e., approximately 3, 5, 10 and 20 m above roof level, respectively. Gradients of mean variables were calculated by fitting a second-order polynomial in ln z' ($z' = z - d$) to the data and taking the derivative with respect to z' at the required height.

Two sonic anemometers provided the turbulence data (recorded with a frequency of 1 s^{-1}). One was a three-dimensional Kaijo Denki (probe TR-61C) and the other a combination of two two-dimensional Kaijo Denki probes (TJ-51). Both instruments have been carefully tested and calibrated in a wind tunnel. Details on data handling including stationarity checks and error estimates can be found in I.

TABLE I

Parameters for the determination of $\sigma_w/u_* = C_1'(1 - C_2'z'/L)^{1/3}$ and $\sigma_w^3 = C_1u_*^3 + C_2u_f^3$, respectively, from various sites

Study	C_1'	C_2'	C_1	C_2	C_1/C_2	Site
Panofsky *et al.* (1977)	1.3	3	2.20	2.64	0.83	'ideal'
Clarke *et al.* (1982)	1.16	2.95	1.56	1.84	0.85	Rural reference site*, $z'/L \geqslant -5$
Clarke *et al.* (1982)	1.13	1.56	1.44	0.90	1.60	Four urban sites average values*
Present study	0.94	1.94	0.84	0.65	1.29	Urban site $0 \geqslant z'/L \geqslant -1$

* Averaged over values for the summer and fall data sets, evaluated separately.

Only two additional minor points have to be mentioned here. Firstly, from one of the sonic anemometers (the 'combined probe', at position 23R) no temperature reading was available. The local Obukhov length L at the position of the 'combined probe' was therefore computed using $\overline{w'T'}$ from the other instrument. As the turbulent flux of sensible heat can vary by up to 30% between either positions 23R and 28R or 23R and 23CW (Rotach, 1991), the estimate of local stability may be in error by the same percentage at the combined sonic anemometers position (23R). During a short period of time, however, the three-dimensional probe was also at position 23R (see Table I in I). Thus all the data points from position 23R could be checked for the originating instrument. Excluding the data from the 'combined sonic' from the analysis did not change any of the qualitative or quantitative results to be presented in the following.

Spectral estimates have been calculated using a standard FFT routine, with a parzen window applied to the data first. No spectral results will be presented here, but the wavelength corresponding to the spectral peak will be required. For this purpose, the spectral estimates were first block-averaged into 32 frequency bands approximately equidistant in the frequency domain (Kaimal and Gaynor, 1983). Finally a simple function of the form

$$nS_i = \frac{An}{1 + Bn^{5/3}}, \tag{1}$$

was fitted to the block-averaged spectral estimates S_i, where n is the natural frequency and A and B are parameters. The frequency of the spectral peak was then determined by differentiating Equation (1). The spectral peak was only calculated if the data of the respective run were reasonably well represented by (1) (visual inspection).

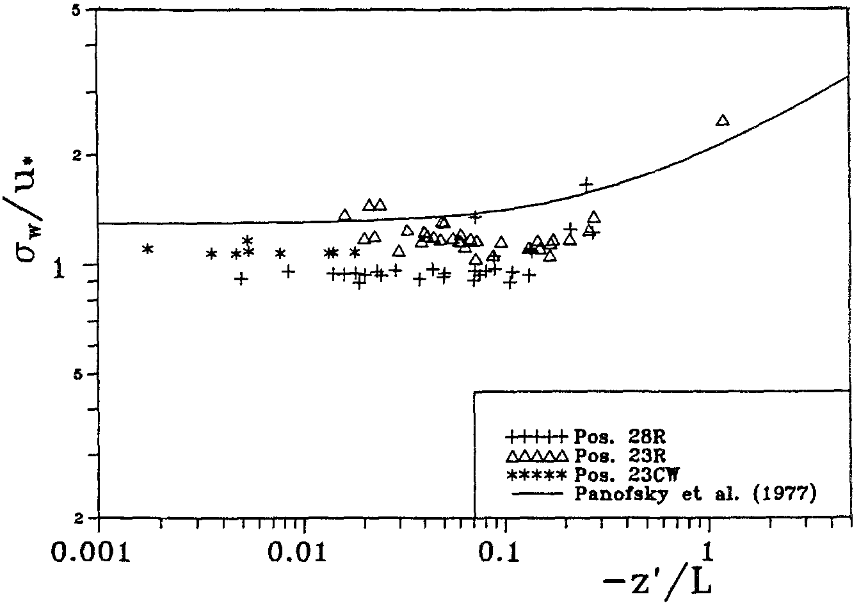

Fig. 2. Scaled standard deviation of vertical velocity at three different positions. Symbols as indicated in the inset.

3. Variances

3.1. VERTICAL VELOCITY VARIANCES

In the inertial sublayer over homogeneous terrain and in neutral conditions, σ_w is expected to obey the simple relation

$$\sigma_w = A_w u_* \tag{2}$$

where A_w is a constant found to be approximately 1.25 over a wide range of different sites (Panofsky and Dutton, 1984). For non-neutral conditions, σ_w scales with observation height according to Monin–Obukhov scaling:

$$\frac{\sigma_w}{u_*} = \Phi_w(z'/L)\,. \tag{3}$$

Panofsky *et al.* (1977) suggest for Φ_w

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

but other authors find slightly different formulations. Figure 2 shows the present urban roughness sublayer data together with relation (4). Note that both the stability as well as u_* are local values (in Figure 2 and throughout the following if not noted differently). The locally scaled vertical velocity variances appear to

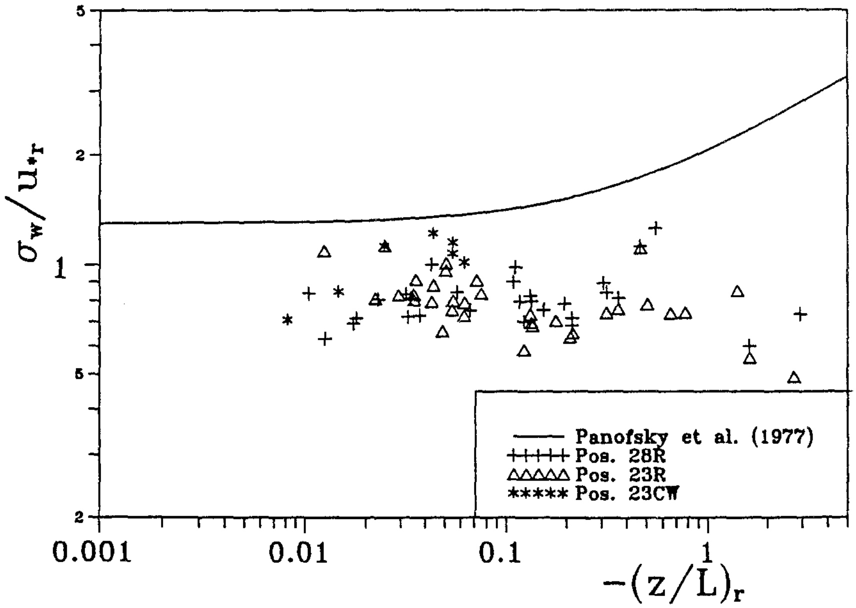

Fig. 3. As Figure 2, but with non-local scaling. The friction velocity and stability are calculated at the reference level (subscript 'r'), i.e., 20 m above roof level.

be somewhat smaller than predicted by (4), with a neutral limit ($|z'/L| \leq 0.05$) of 1.0. Due to the small range of stabilities covered by the present observations, these results are not conclusive in terms of the 1/3 power for strong convection. There is, however, no contradiction either. The observed neutral limit lies at the lower end of other values for A_w reported from urban areas ranging from 1.1 (Coppin, 1979) to 1.5 (Ramsdell, 1975). Hanna and Chang (1992) recommend a value of 1.2. Figure 2 suggests that there might be a difference beween the scaled vertical velocity variance at the three measurement positions. In particular, the data from position 28R are low with respect to (4) over a wide range of stabilities.

When scaled with the friction velocity of the above-lying inertial sublayer, σ_w/u_*^{IS} would be even smaller by 15–30% due to the increase of Reynolds stress with height (see I). A reference friction velocity u_{*r} that is derived from the profile data at position 28R (20 m above roof level) may be used as an estimate for u_*^{IS} as outlined in I. Figure 3 shows that this type of non-local scaling considerably increases the scatter. This must partly be attributed to the uncertainty introduced by using u_{*r} instead of u_*^{IS}. However, a comparison of Figures 2 and 3 indicates that the locally scaled σ_w is much better defined than σ_w/u_*^{IS}.

An alternative approach for the vertical velocity variance can be obtained by considering the budget for the turbulence kinetic energy in stationary and horizontally homogeneous conditions:

$$\epsilon = u_*^2 \frac{d\bar{u}}{dz} + \frac{g}{\bar{T}} \overline{w'T'} - \frac{1}{2} \frac{d\overline{w'q^2}}{dz} - \frac{1}{\bar{\rho}} \frac{d\overline{p'w'}}{dz} , \tag{5}$$

where $q^2 = u'^2 + v'^2 + w'^2$. Neglecting the last two terms on the rhs of equation (5), and letting $\epsilon = \sigma_w^3/L_\epsilon(w)$, where $L_\epsilon(w)$ is a dissipation length scale, Clarke *et al.* (1982) found

$$\sigma_w^3 = u_*^3 \frac{L_\epsilon(w)}{kz} + \frac{g}{\bar{T}} \overline{w'T'} L_\epsilon(w) , \tag{6}$$

where the neutral formulation for the gradient of mean wind speed has been used. Equation (6) can be expressed as

$$\sigma_w = \left(\frac{L_\epsilon(w)}{kz} \right)^{1/3} (u_*^3 + k u_f^3)^{1/3} , \tag{7}$$

with u_f being a convective velocity scale:

$$u_f = \left(\frac{g}{\bar{T}} \overline{w'T'} z \right)^{1/3} . \tag{8}$$

Rotach (1990) shows that the assumption $L_\epsilon(w)/kz$ = const. ($\approx$1.1) is justified for the present data, and σ_w is well represented by the rhs of Equation (7). This is in agreement with the results of Clarke *et al.* (1982) who found a slightly different factor, $L_\epsilon(w)/kz \approx 1.2$, for their urban sites.

A similar form for σ_w as Equation (7), but consistent with (4), can be obtained by fitting $\sigma_w^3 = C_1 u_*^3 + C_2 u_f^3$, thus allowing one to investigate the relative importance of mechanical and thermal production, respectively. Table I lists the parameters C_1 and C_2 for the present data set, together with those corresponding to (4), and the results reported from another urban site (Clarke *et al.*, 1982). Mechanical production of vertical velocity fluctuations dominates at both urban sites ($C_1/C_2 \geqslant 1$), while the thermal production is more important over smoother terrain. The results of Clarke *et al.* (1982) are from a much larger stability range ($0 \geqslant z'/L \geqslant -5$) than the present urban data. The non-dimensional heights were furthermore considerably different: $z/h \approx 4$ or greater in the case of the St. Louis data of Clarke et al. (1982) and $1.27 \leqslant z/h \leqslant 1.55$ for the present observations. The comparable coefficients obtained at two distinctly different urban sites suggest that the enhanced mechanical production has to be taken into account when applying an equation like (4) over a very rough surface. Averaging the coefficients from the two urban sites (Table I), yields

$$\frac{\sigma_w}{u_*} = 1.04(1 - 1.75 z'/L)^{1/3} . \tag{9}$$

Note that the results of Clarke *et al.* (1982) were obtained by using measurements of fluxes and variances at the same height. Even if they do not require local scaling explicitly, they are thus consistent with this concept; averaging of the coefficients leading to (9) therefore seems to be justified. Equation (9) is, if applied in an urban RS as in the case of the present measurements, valid for local values of the friction velocity.

Although not analyzed explicitly in favour of a formulation corresponding to (9), the data presented by Roth (1991) from a suburban site in Vancouver (z/h being about 2.6 and 1.7, for the measurement heights 18.9 and 11 m, respectively) agree well with the parameters C_1' and C_2' (Table I) given by Clarke *et al.* (1982) and thus with Equation (9). Data on the scaled velocity variances presented by Högström *et al.* (1982) from an urban RS (z/h being about 1.3) are limited to a very small stability range ($|z'/L| \leq 0.2$) and thus do not provide very conclusive results on the ratio of mechanical to thermal production. More data from urban areas at various non-dimensional heights and stabilities are required to establish the enhanced mechanical production of vertical velocity fluctuations over rough urban surfaces as expressed in Equation (9).

3.2. HORIZONTAL VELOCITY VARIANCES

Mixed-layer scaling rather than surface-layer scaling has been found to apply for the horizontal velocity variances (Panofsky *et al.*, 1977). Nevertheless, some authors report a certain dependence of $\sigma_{u,v}/u_*$ on stability over urban surfaces too (e.g., Ramsdell, 1975; Clarke *et al.*, 1982; Roth, 1991). In general, the scatter of $\sigma_{u,v}/u_*$ increases considerably with larger $-z_i/L$.

The data from the present urban roughness sublayer do not show any dependence on stability. Values of σ_u/u_* range from 1.7 to 3.2 with a near neutral average ($|z'/L| \leq 0.05$) of 2.2 (note, however, that the average over the whole stability range yields almost the same value and scatter). The scaled standard deviation of lateral velocity ranges from 1.2 to 2.5 with a near neutral average of 1.5. Here, the average over the whole stability range is slightly higher (about 1.7), but a well defined stability dependence again cannot be observed. These near neutral limits lie at the lower end of the range reported in the literature for other urban sites (σ_u/u_*: 2.4 (Clarke *et al.*, 1982) to 2.8 (Högström *et al.*, 1982); σ_v/u_*: 1.5 (Bowne and Ball, 1970) to 2.8 (Högström *et al.*, 1982)). Although the measurements were taken rather close to the top of the buildings, no systematic variation of $\sigma_{u,v}/u_*$ with wind direction could be detected. It is concluded that, in accordance with observations at various other urban sites (Ramsdell, 1975; Coppin, 1979; Högström *et al.*, 1982), there is only a weak (if any) variation of the horizontal velocity fluctuations over the stability range covered ($-1 \leq z'/L \leq 0$). Most likely this dependence is masked by processes of larger scales (mixed-layer scaling).

Clarke *et al.* (1982) suggest using the wavelength corresponding to the maximum energy in the u- and v-spectra, $\lambda_{\max,u}$ and $\lambda_{\max,v}$ respectively, as a substitute for the mixed-layer height z_i if the latter is not available. Starting with an equation similar to (6) they find, e.g., for the longitudinal velocity component

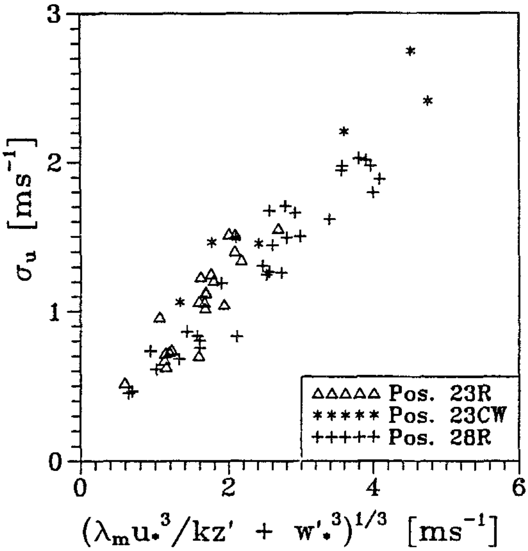

Fig. 4. The standard deviation of horizontal velocity fluctuations as a function of the rhs of Equation (10). Symbols as indicated in the inlet.

$$\sigma_u = C_u\left(\frac{u_*^3\lambda_{\max,u}}{kz} + w'^3\right)^{1/3}, \tag{10}$$

where

$$w'_* = \left(\frac{g}{\bar{T}}\overline{w'T'}\lambda_{\max}\right)^{1/3} \tag{11}$$

is a modified free convection velocity scale. For smooth terrain, Panofsky *et al.* (1977) proposed

$$\frac{\sigma_u}{u_*} = 2.29(1 - 0.042z_i/L)^{1/3}, \tag{12}$$

This is consistent with equation (10) if $\lambda_{\max,u}/kz$ (or $\lambda_{\max,v}/kz$, respectively) is assumed to be constant, and $\lambda_{\max,u} \approx 1.5z_i$ (Kaimal, 1978).

Figure 4 shows the standard deviation of the longitudinal velocity component against the rhs of equation (10). The factor of proportionality is $C_u = 0.58$, appropriate for the data at all measurement positions. Equation (10) is a fair predictor for σ_u with a rms difference between measurement and prediction of 0.22. Note again that to achieve this result, all variables have to be considered as local. A similar analysis for the lateral velocity fluctuations yields $C_v = 0.52$ and, with a somewhat larger scatter, a rms difference of 0.32.

Clarke *et al.* (1982) find similar values for C_u (Equation 10) for their urban sites

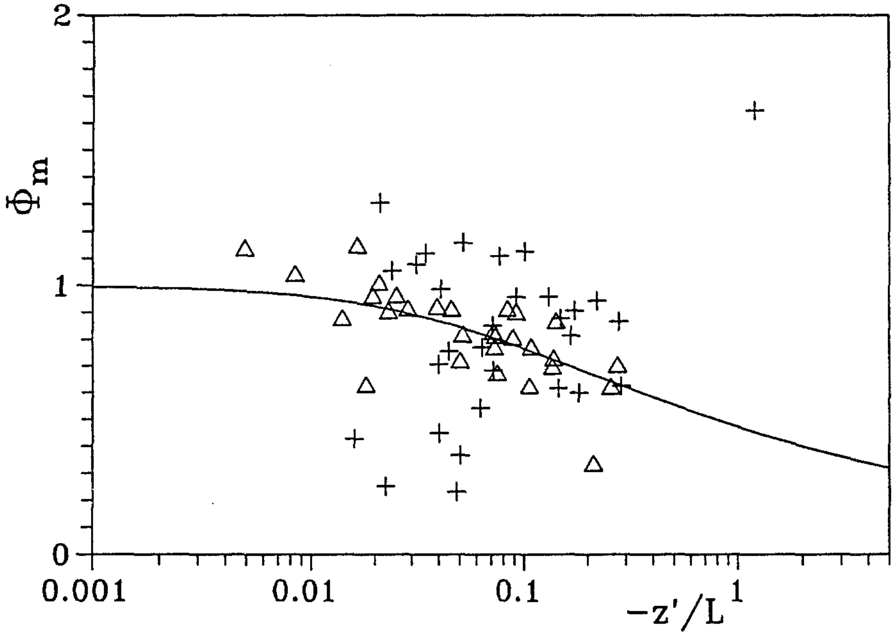

Fig. 5. The non-dimensional wind shear Φ_m for different stabilities at positions 28R (Δ) and 23R (+).

(at $z/h \geqslant 4$). Their factor of proportionality varies from 0.43 to 0.56 depending on site and stability range. This indicates that (10) may be of general use for flows over urban (dynamically rough) surfaces with the coefficient C_u being (weakly) dependent on the geometry of the roughness elements. However, if the maximum wavelength of the energy spectrum is known for a particular situation, it is very likely that σ_u or σ_v are directly available. Relations between $\lambda_{\max}$ and other, more easily available length scales must therefore be found in order to use equation (10).

4. Dimensionless Gradients of Mean Variables

4.1. THE DIMENSIONLESS WIND SHEAR

The dimensionless gradient of mean wind speed

$$\Phi_m(z'/L) = \frac{d\bar{u}}{dz'}\frac{kz'}{u_*} \tag{13}$$

for the measurement positions 28R and 23R is shown in Figure 5 in comparison with the semi-empirical formulation of Businger *et al.* (1971), modified after Högström (1988). Two features are apparent at first glance:

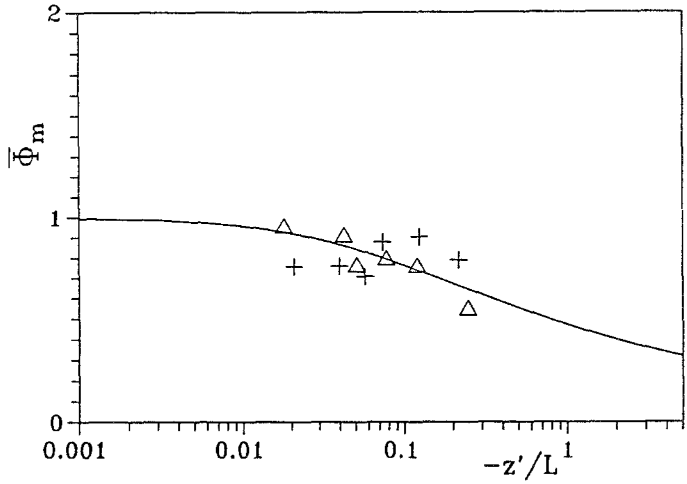

Fig. 6. As Figure 5, but averaged over intervals of stability.

(i) at the higher level (10 m above roof level, position 28R), the correspondence to the inertial sublayer prediction is fairly good but there is considerable scatter (not dependent on stability).

(ii) At the lower level on the other hand (position 23R), large deviations from the Businger *et al.* (1971) formulation are observed over the whole (though small) stability range.

Regarding the first feature, it can be concluded that the gradient of wind speed is in equilibrium with the local turbulent flux of momentum at this height well above mean roof level but well within the roughness sublayer. If scaled with the proper u_* from the inertial sublayer (see I), Φ_m can be expected to be biased by some 15% below its IS prediction (for that particular height). At only 5 m (or $\approx$0.25 h) closer to roof level, this equilibrium between the local flux of momentum and gradient of mean wind speed is completely absent. Deviations from the inertial sublayer prediction, $\Delta\Phi_m = \Phi_m - \Phi_m^{IS}$, are very large, positive or negative.

Averaging the data in Figure 5 over ranges of stability, in order to obtain an estimate of horizontal averages for Φ_m (see Section 3.1. in I), shows that the average $\overline{\Phi}_m$ are reasonably well represented by the inertial sublayer formulation of Businger *et al.* (1971) at position 28R (Figure 6). This is even true for the measurement position closer to the roof level in the sense that deviations from the ideal site formulation are small on average. However, the data at this level do not show the characteristic $-1/4$ power stability dependence predicted by the *IS* formulation. The run-to-run variability (i.e., the variance about the values shown in Figure 6) increases by a factor up to 5 between positions 28R and 23R (Table II).

An error analysis for equation (13) leads to an uncertainty of Φ_m of about 30

TABLE II

Average $\overline{\Phi}_m$ and the variance about these averages for different stability ranges at the two measurement positions 28R and 23R

	Position 28R			Position 23R		
$-z'/L$	$\overline{\Phi}_m$	$\delta\Phi_m$	%	$\overline{\Phi}_m$	$\delta\Phi_m$	%
≤0.03	0.96	0.140	15	0.76	0.433	57
0.03–0.05	0.92	0.050	5	0.76	0.307	40
0.05–0.07	0.77	0.048	6	0.71	0.296	42
0.07–0.09	0.80	0.072	9	0.88	0.175	20
0.09–0.15	0.77	0.095	12	0.91	0.166	18
≥0.15	0.55	0.143	26	0.71*	0.133	17

* One run excluded from average, see Figure 5.

to 35% (at positions 28R and 23R, respectively) directly due to measurement uncertainties in $d\bar{u}/dz'$, u_* and z' (determination of d). While the measurements at position 28R correspond within this range to the *IS* prediction even for the single runs (Figure 5), the departure can be substantially larger at position 23R. It is thus concluded that horizontal inhomogeneity plays a minor role at $z/h =$ 1.55 at the present site. Raupach *et al.* (1980) give as a characteristic height z_h up to which horizontal inhomogeneity is non-negligible, $z_h = z + D$, where D is the inter-element spacing (for their artificial roughness elements in a wind tunnel, center to center). Although D is less well defined for a real urban structure than in a wind tunnel, z_h is significantly smaller than $h + D$, even if the width of the street canyon (15 m) is used as the smallest possible estimate for D at the present site.

In summary, it is found that Φ_m in the present urban RS is well represented on average by the inertial sublayer prediction if local values for u_* (and stability) are used for its derivation. At $z/h = 1.55$, even the individual runs lie within the measurement uncertainty around the *IS* prediction. At $z/h = 1.27$, or only 5 m closer to the roof level, however, horizontal inhomogeneity leads to a large scatter of the data. These results can be compared to those obtained over other types of rough surfaces such as forests or tall vegetation. In much of the early work on this subject, $\Delta\Phi_m$ was reported to be smaller than zero (e.g., Thom *et al.*, 1975; Garratt, 1978a, 1978b, 1980). This would correspond to the present results if u_* from the *IS* had been used to scale the profile of mean wind speed. On the other hand, Raupach (1979) does not find systematic differences from the ideal site formulation of Φ_m at $z/h = 1.2$, 1.4 and 1.8 over a forest. These differences may at least partly be attributed to the different methods and assumptions (constant flux assumption) used to derive the relevant turbulent fluxes. However, in a more recent study, Högström *et al.* (1989) show that $\Delta\Phi_m$ is also related to the density of the roughness elements (they also use a constant flux assumption that is shown to hold for $z/h \geqslant 1.45$). When comparing the results from flows over vegetated

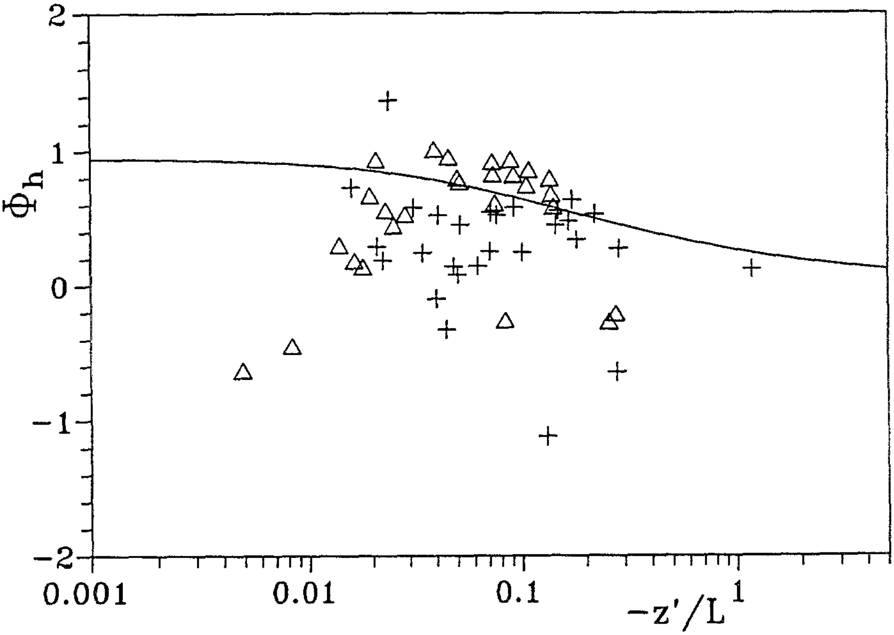

Fig. 7. As Figure 5, but for the non-dimensional potential temperature gradient.

(rough) surfaces with the present urban results, the difference not only in the density but also in the nature of the roughness elements (i.e., their stiffness) will have to be taken into account.

4.2. THE DIMENSIONLESS POTENTIAL TEMPERATURE GRADIENT

The dimensionless gradient of potential temperature is shown in Figure 7 as compared to the inertial sublayer prediction Φ_h^{IS} (Businger *et al.*, 1971, modified after Högström, 1988). Disregarding the large deviations of Φ_h close to neutral due to very small heat fluxes and temperature gradients, much larger scatter than for the dimensionless wind shear is observed (note the different axes). The measured Φ_h is generally higher at position 28R than at the lower position. The few negative values of Φ_h indicate that counter-gradient flux (in a local sense) may occur. For all these runs, the heat flux remains positive while the temperature gradient changes sign. These 'distorted' profiles cannot be attributed to measurement errors since i) the observed differences in potential temperature between two neighbouring levels are typically an order of magnitude larger than the relative accuracy of the instruments and ii) the situation can persist substantially longer than one averaging period.

The same averaging procedure over ranges of stability, as in the previous section for Φ_m, can be applied to the temperature gradients. At position 23R, the average Φ_h is is substatially smaller ($\overline{\Phi_h} \approx 0{,}2$) than its *IS* prediction (not shown). At the upper level, on the other hand, the locally scaled and averaged RS measurements are comparable in magnitude (and even trend with stability) with the *IS* prediction. Thus even local equilibrium seems to be completely absent in the case of the non-dimensional temperature gradient when approaching a very rough surface. Due to the complicated source distribution (see below), $\overline{\Phi}_h$ does not follow the *IS* prediction, neither in trend nor in magnitude in the immediate vicinity of a rough surface. This is observed even if local scaling is applied and is in clear contrast to the situation for Φ_m.

The behaviour of the eddy diffusivity for heat (K_h, proportional to u_*/Φ_h) close to a rough surface is much more complicated than that for momentum. Coppin *et al.* (1986) point out that K_h is not only dependent on the wind field but also on the source distribution (of heat). For their 'ideal' experimental setup in a wind tunnel, they show that the thermal structure consists of two regions, an inner layer (within and just above the canopy, not necessarily corresponding to canopy and RS), where the length scales are dependent on the canopy geometry, and an outer layer (which would correspond to the internal boundary layer due to the urban heat island effect in the present case). The exchange of heat at a given height is dependent in a complex manner on the two competing influences of enhanced diffusivity close to the rough surface and the near-field effect that tends to reduce the eddy diffusivity (Coppin *et al.*, 1986). Over the present urban structure, the situation is even more complicated, as a whole series of thermal internal boundary layers over heated (or cooled) roofs alternating with cooler (warmer) street canyons will develop. Thus, a steady state and an equilibrium description of heat exchange is not suited for an urban RS as stated many times before (e.g., Coppin *et al.*, 1986).

In a phenomenological approach, the departure of Φ_h from the *IS* prediction can be described as a function of surface properties such as 'material' (vegetation, building materials), density of roughness elements and their mechanical behaviour (stiffness). For forests, a strong reduction of Φ_h seems to be generally observed (Högström *et al.*, 1989). The same behaviour is reported from an artificial rough surface in a wind tunnel (Coppin *et al.*, 1986). Qualitatively, the present data agree with these observations. However, a series of additional experimental efforts will be necessary at various urban sites to examine to what extent such a phenomenological description of the Φ_h departure is useful and consistent over urban surfaces.

4.3 The Richardson number

According to Monin–Obukhov similarity theory, the gradient Richardson number *Ri* can be expressed in the *IS* as a function of z'/L. Using the same explicit semi-empirical expressions as in foregoing sections, we have in the unstable case

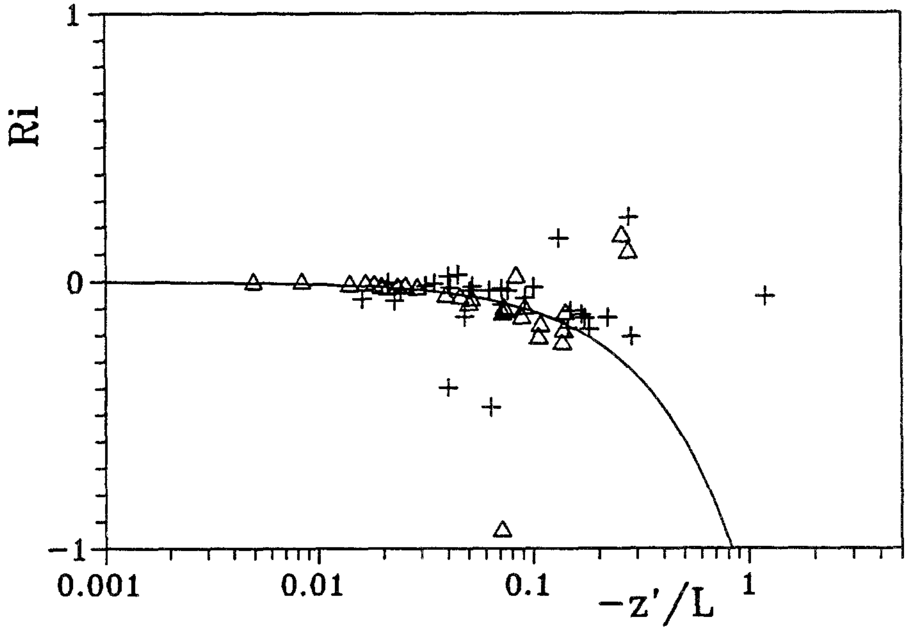

Fig. 8. As Figure 5, but for the gradient Richardson number Ri. Positive values of Ri refer to cases of counter-gradient flux of temperature.

$$Ri = \frac{z'}{L}\frac{\Phi_h}{\Phi_m^2} = \frac{0.95\frac{z'}{L}\left(1 - 19.3\frac{z'}{L}\right)^{1/2}}{\left(1 - 11.6\frac{z'}{L}\right)^{1/2}}. \tag{14}$$

The Richardson number, as calculated according to its definition from the gradients, is compared to the *IS* prediction (14) in Figure 8. Apart from a few erratic exceptions (often due to counter-gradient fluxes), the correspondence is found to be fair at both positions, $z/h = 1.27$ and 1.55. This is particularly noteworthy in the near neutral range where Φ_m and Φ_h behave distinctly differently (Figures 5 and 7, respectively). This leads to the interesting observation that, although flux-gradient relations, and in particular Φ_h, may not be preserved in the roughness sublayer, a 'gradient-gradient' relation such as *Ri* still holds approximately. Note, however, that z'/L in Figure 8 refers to local stability as in the previous sections.

5. Summary and Discussion

The description of turbulence close to a rough surface suffers from two main weaknesses: first there is no consistent theory except higher order closure approaches which require the explicit resolution of single roughness elements if, e.g., wake effects (among others) are to be modelled realistically. This is not very practical with regard to applications and moreover, information on the higher order moments for the closure is not available either. Second, due to this lack of theory, inertial sublayer scaling (i.e., Monin–Obukhov similarity theory) is often applied for convenience in flow or dispersion models over rough surfaces. Thus, departures from *IS* behaviour have often been studied over vegetated (e.g., Thom *et al.*, 1975, Högström *et al.*, 1989) or artificial (e.g., Raupach *et al.*, 1986) rough surfaces. The same approach has been followed in the present study. As there are no other studies available from the literature on many aspects of RS turbulence over urban surfaces as described here, the results are primarily characteristic of the present site. However, the observations are found to be qualitatively similar to what has been reported from roughness sublayers over vegetated or artificial surfaces. This indicates that they could be of general validity.

The observations at the present site can be summarized as follows:

1. considering the complicated flow structure around one single building, a clear reduction in complexity of the turbulence characteristics over a surface consisting of many buildings (roughness elements) is observed.
2. horizontal averages are often required for a comprehensive description in particular of turbulence-gradient relations (such as Φ_m). Horizontal inhomogeneity becomes negligible (i.e., smaller than the measurement uncertainty) at a height that is smaller than $z/h = 1.5$.
3. local scaling is found to be successful for the description of turbulence. Provided that local turbulent fluxes, and thus stability measures, are used, the *IS* semi-empirical functions (and often even the numerical constants) can be retained within the roughness sublayer. Thus, the description of turbulence within the RS requires knowledge of the vertical profile of Reynolds stress (see I) and also of the turbulent heat flux. An alternative scaling approach, with an estimate of the inertial sublayer friction velocity, increases the scatter and reduces the predictability.
4. the vertical velocity variance is generated by mechanical production to a larger extent than is predicted by the *IS* semi-empirical function. This leads to a less pronounced dependence on stability. Similar results have been reported from other urban sites.
5. the horizontal velocity variances cannot be predicted by local scaling. Using the maximum wavelength of the respective energy spectrum, on the other hand, gives satisfactory results.
6. the eddy diffusivity for heat is, in accordance with observations over vegetated or artificial surfaces, found to be much less well-defined than that of momentum. If this is also true for other scalars (such as pollutants), as is suggested because of a similar source distribution, this would imply that Lagrangian dispersion models might be better suited

> for urban dispersion modelling than Eulerian ones. Similar suggestions have been made for other rough surfaces (e.g., Legg and Raupach, 1983).

Concerning point three above, it has to be noted that the concept of local scaling as originally proposed by Högström *et al.* (1982) and found to be appropriate at the present site, is used in a different sense than originally proposed by Nieuwstadt (1984) for the stable (nocturnal) boundary layer. Nieuwstadt's analysis shows that turbulence under certain (stable) conditions is determined by a local stability measure. The measurements in the present urban RS indicate that even the proper inertial sublayer relations often apply (including numerical parameters), provided that all variables have been determined at the same height. This reflects a limiting behaviour with respect to the inertial sublayer when the turbulent fluxes become height dependent (see I), rather than constituting a completely new scaling regime.

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