VELOCITY AND TEMPERATURE SPECTRA AND COSPECTRA IN AN UNSTABLE SUBURBAN ATMOSPHERE

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Abstract. Boundary-layer flow over very rough surfaces is poorly understood so the applicability of standard micrometeorological theory is uncertain. This study presents observations of the turbulent fluctuations of meteorological parameters over a suburban area. Even though the height of measurement is considered to be close to the junction between the inertial and roughness sub-layers, the wind and temperature spectra and the momentum and sensible heat flux cospectra are in good agreement with reference data from smoother surfaces. Recommendations are made concerning site requirements, height of measurement and averaging times for the study of turbulence and turbulent fluxes over suburban terrain.

1. Introduction

Several experimental results (e.g., Thom *et al.*, 1975; Garratt, 1978 and 1980) show that conventional flux-profile relationships and the validity of the non-dimensional Monin–Obukhov functions for momentum and heat transfer must be questioned over horizontally uniform but very rough natural surfaces such as tall crops and forests. This reinforces the idea that the surface layer over a very rough surface must be considered in two parts: usually referred to as the inertial sub-layer (Tennekes, 1973) and the roughness sub-layer (Raupach, 1979). In the former, under adiabatic conditions, height above the effective surface is the only controlling length scale and the semi-logarithmic profile laws are obeyed. On the other hand, in the roughness sub-layer which is adjacent to the surface itself, the flow is affected by wake motions introduced by individual roughness elements. In this region, length scales defined by the surface characteristics become important.

In order to measure variances and covariances of meteorological variables that are consistent with Monin–Obukhov similarity theory (MOST), it is essential to avoid the roughness sub-layer and to work in the surface layer (inertial sub-layer) wherein the vertical fluxes of entities are assumed to be approximately constant with height, as long as horizontal advection due to changes in surface character in the upwind zone is absent. In this layer, turbulent fluxes can be evaluated using standard micrometeorological approaches such as the aerodynamic, Bowen ratio-energy balance and eddy correlation methods.

Boundary-layer flow over very rough terrain has been investigated mainly for surfaces covered by tall crops or trees with some additional understanding gained from wind tunnel work. Based on such observations, a range of values for the

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lower height limit, z_* (measured from zero-displacement, d, upwards) for the validity of the Monin–Obukhov functions above large roughness elements is reported. Raupach *et al.* (1980), based on a wind tunnel study under neutral conditions, suggest that (for wind), $(z_* + d) = h + 1.5D$, where h is the height of the roughness elements and D is the inter-element spacing. Under unstable conditions over a forest, Garratt (1980) concludes that (for wind), $z_*/z_0 = 100$ (where z_0 is the surface roughness length) is a useful generalization and the ratio probably decreases (down to 10) with increasing density of roughness elements. For temperature, he finds $z_*/z_0 = 100$ for sparse and about 65 for denser forests.

Much less effort has been spent understanding boundary-layer flow over urbanized areas. This is disappointing considering that an ever increasing number of The World's population is exposed to urban atmospheres. Without doubt, it would be of considerable interest and value to know if and where standard micrometeorologidal theories are applicable in the urban system. Both energy balance and atmospheric diffusion studies would benefit from a better understanding of the structure of turbulence in the urban boundary layer. There are a number of reasons for this lack of understanding. One is the set of practical problems associated with the selection and location of an observation site ensuring the unobstructed exposure of the sensors. Another is the lack of a recognized methodological framework within which the information is to be analysed, although recent attempts have been made to overcome this.

Based on the literature already mentioned, Oke (1984) suggested a possible framework for the complex and high roughness environment of urban terrain. He divided the urban atmosphere into an urban canopy layer (UCL) which is dominated by microscale features associated with individual roughness elements and an overlying urban boundary layer (UBL). The transition between the UCL and UBL is not characterized by a sharp discontinuity; rather, the microscale features of the UCL meld into local or meso-scale ones in the roughness layer (called the 'roughness sub-layer' by Raupach, 1979). The integrated effects of the urban 'surface' thereby form an horizontally-homogeneous turbulent surface layer and the mixed layer of the UBL. In a more recent study, Schmid (1988) develops a model to estimate the two-dimensional surface area contributing to a turbulent flux measurement and hence provides a possible way of assessing if a flux measurement taken at a specific height is representative of the area under investigation. Oke *et al.* (1989) investigate the applicability of standard boundary-layer theory and observation methods to the urban system and conclude that 'despite the physical problems presented by the nature of the 'surface', it is possible to obtain valid areally-averaged fluxes from fixed-point observations provided that careful site selection, height of measurement and temporal sampling procedures are followed'. Analyses to estimate the value of z_* as performed for forests, are not available for urban surfaces; therefore, estimations for 'proper' (within the surface layer) measuring heights rely on the already cited recommendations from other systems.

This study presents the results of a project designed to measure and analyse the turbulent fluctuations of the longitudinal wind component u, the vertical wind component w, air temperature T and the covariances of momentum uw and sensible heat flux wT at one height over an urbanized area. The turbulence measurements are presented in a form so as to arrive at conclusions concerning the appropriateness of the observation height involved and the averaging times used. Thereby the analysis should provide information regarding the suitability of this site for turbulence measurements and their use in energy balance computations.

The approach taken is to compute the energy spectra and cospectra of the turbulence fluctuations and so yield information about the dominant eddy sizes involved in the turbulent transfer through the analysis of the spectral shapes. The question of the proper averaging time to be used (an increase in measuring height requires a longer averaging time) is approached by inspecting the low frequency end of the spectra (cospectra) to see if they conform with MOST. This theory has been shown to apply over surfaces exhibiting the required low roughness and homogeneous fetch requirements. In this respect, the empirical results from the Kansas 'ideal' boundary-layer experiment (Kaimal *et al.*, 1972) will be used as a standard for comparing the results presented in this study. The Kansas results will be referred hereinafter as the 'reference' or 'Kaimal' spectra and data.

If, as suggested by the studies cited earlier, an extra length scale due to the influence of individual roughness elements is introduced, deviations from the shape of 'ideal' reference spectra (cospectra) should be observed. If present, they might indicate that the sensors are at too low a height so that results relate to processes in the roughness layer.

2. Experimental

The data for this study were gathered at the Sunset suburban site in Vancouver, British Columbia, Canada as part of a surface and boundary-layer research programme during the summer of 1986. The general requirements leading to the selection of this particular site are described and discussed in Kalanda *et al.* (1980) and Steyn (1980) and include as a prime criterion, the fetch required for the atmospheric layer of interest to adjust to a change in surface properties upstream.

The aerodynamic roughness of the site is assessed to be 0.5 m, using Lettau's (1969) land-use/roughness element analysis. Based on estimations from land-use analysis, the zero-plane displacement length d is about 3.5 m. Instruments to probe the surface layer were mounted on the top of a triangular-section, steel lattice, free-standing tower.

Using the dimensions of the Sunset tower site (building height $h = 8.5$ m, building spacing $D = 23$ m) and the formulae of Garratt (1980) and Raupach *et al.* (1980), the top of the roughness sub-layer, z_*, is calculated to be located between 39 and 50 m for the momentum flux and between 32 and 50 m for the sensible heat flux. However, these values depend on the density of the surface roughness elements and may be lower. Nevertheless, in this study with measurement heights, z', (above d) of only 19 m for sensible heat and 22 m for momentum, there is reason to suspect that the observations may be influenced by wake effects.

Wyngaard (1973) addressed the problem of averaging time. For a sensor height of about 20 m and an uncertainty of 15%, his analysis yields an averaging time of 19 min for the second moments of vertical wind and temperature, 543 min for the momentum flux and 56 min for the sensible heat flux during unstable conditions ($z'/L = -1$). In this study, the averaging time was pre-selected to be 60 min for all components.

The turbulent fluctuations of the longitudinal (u) and vertical (w) wind velocities, the covariance of the kinematic momentum flux (uw) and the mean wind direction were measured with a modified Gill twin propeller-vane anemometer (GTVA) (Pond and Large, 1978). The modifications included a tilt of 60 deg from the horizontal plane for the sensor measuring the vertical wind. Rotation increases the frequency response and introduces about one half of the horizontal wind component into the tilted sensor. The turbulent fluctuations of the vertical velocity (w) and the temperature (T) and hence the covariance of the kinematic heat flux (wT) were measured with a sonic anemometer and fine-wire thermocouple (SAT) (Campbell Scientific, Model CA27T).

Observations were taken during a period of good weather, on eight days at the end of August and the beginning of September 1986. Atmospheric stabilities encountered were $-2.4 < z'/L < 0.06$ with an arithmetic mean value of -0.75. All measurements were recorded with a Campbell Scientific (Model CR21X) data logger. The sampling frequency was 10 Hz for the GTVA and the SAT components and 0.3 Hz for the Gill-vane. The GTVA signals were low-pass filtered at a frequency of 10 Hz to remove commutator noise.

3. Results

3.1. VELOCITY AND TEMPERATURE SPECTRA

The spectra and cospectra presented here are normalized by the respective variances and covariances and hence are a function of non-dimensional frequency ($f = nz'/U$) and stability (z'/L) only. No attempt was made to classify the normalized spectra (cospectra) according to stability, although some stability dependence could be observed.

In Figure 1, the composite w spectrum from the SAT and GTVA systems are presented and compared with the spectrum of Steyn (1982) measured at the same site and with a model spectrum suggested by Højstrup (1981). The agreement between the SAT and the GTVA spectra is excellent; however, it should be

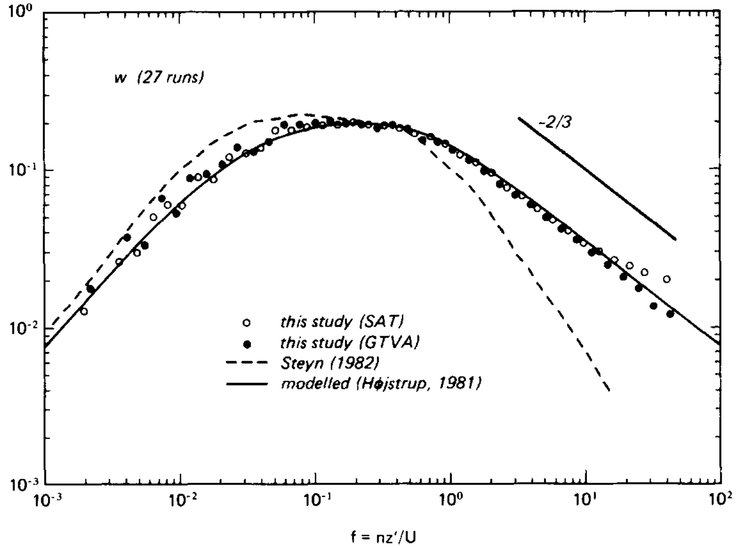

Fig. 1. Composite spectrum of vertical velocity normalized by the variance. Also indicated are spectra from other authors.

noted that the Gill measurements were extended with an artificial −2/3 slope in the inertial sub-range. Nevertheless, the fact that the two composite spectra measured with two different systems, follow each other so closely is very promising and gives confidence in the use of the GTVA.

Comparison between the results from this study and that of Steyn (1982) reveals two obvious differences. Firstly, the faster roll-off in Steyn's spectrum is due to the fact that he did not apply a frequency correction to the propellor measurements. On the low frequency side, the composite spectrum of Steyn shows higher energy content than that from this study. However, this 'increase' is relative since the position of the vertical spectrum depends on the stratification of the atmosphere and shifts to lower frequencies with increasing instability (Steyn's observations are from very unstable conditions, z'/L up to −100).

The comparison with the model spectrum (which is based on observations from smoother surfaces and evaluated at $z/L = -0.75$), is very good with only one minor difference: the peak in the measured spectrum from this study is less well defined and at non-dimensional frequencies of $0.05 < f < 0.1$, a 'flat' region with slightly higher energies than the model can be observed. This makes it difficult to decide upon a specific peak frequency. Taking the spectral density with the largest magnitude, the peak frequency (f_m) is at 0.2 with a possible range of $0.08 < f_m < 0.3$. Since $f = nz'/U = z/l_m$, where l_m is the peak wavelength, with $f_m = 0.2$ the dominant eddy scale is computed to be $l_m = 5z'$ or about 100 m.

In Figure 2, the observations of the u component (from the GTVA in this study) are compared with the composite spectrum from Steyn (1982) measured at

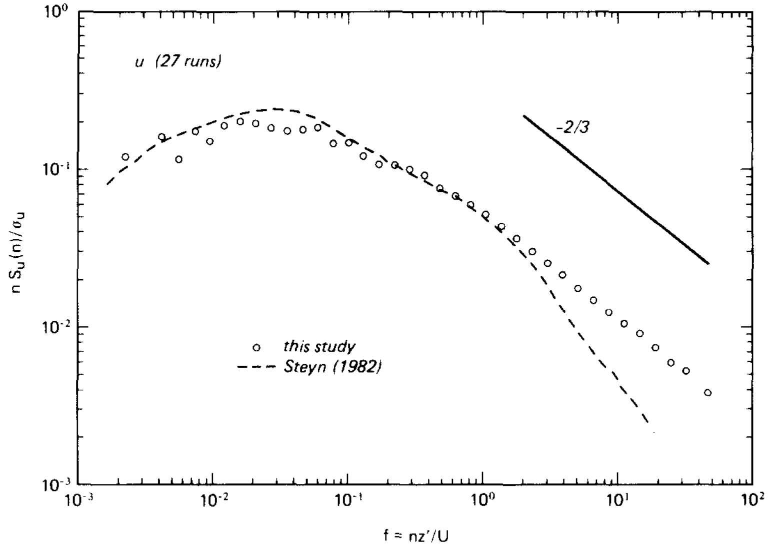

Fig. 2. Composite spectrum of along-wind velocity normalized by the variance and comparison with that of Steyn (1982).

the same site. The results are quite similar, the differences at the higher frequencies again originating in the frequency response deficiencies of the Gill anemometer used by Steyn whereas the GTVA measurements were corrected for the frequency response, therefore exhibiting the required $-2/3$ slope. The main differences between the observations from this field programme and those of Steyn are a prominent dip at about $f = 0.03$ and a smaller dip at $f = 0.2$ in the results from this study.

In general, the observed composite along-wind spectrum exhibits a maximum at low frequencies and a weak inflexion point at higher frequencies (the small dip mentioned above). These features are shown by Kaimal (1978) to be typical for unstable spectra in the surface layer over relatively smooth surfaces. The determination of a peak frequency is made difficult because of the prominent dip at the low frequencies. The highest spectral value can be found at about $f_m = 0.017$ ($l_m = 60z' = 1320\,\mathrm{m}$) with a possible range of $0.01 < f_m < 0.03$. For both velocity components analysed here, the agreement between the results from this study and other urban observations as well as reference data is good.

The composite temperature spectrum in Figure 3 very closely follows the $-2/3$ slope in the inertial subrange. The T spectrum is different from the w spectrum but similar to the u spectrum in that it shows one broad peak and only a slight roll-off at the low frequency end. The peak frequency (as determined from the largest spectral density) is at about $f_m = 0.023$ ($l_m = 43z' = 817$ m). However, it is more realistic to give a range of f_m's as $0.01 < f_m < 0.06$.

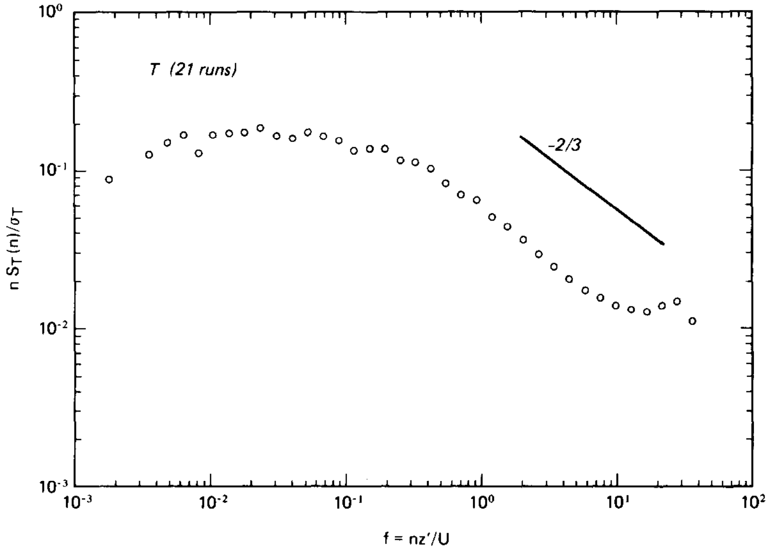

Fig. 3. Composite spectrum of temperature normalized with the variance.

Temperature spectra from other studies utilizing measurements over rough urban surfaces agree quite well with the observations from this study. Clarke *et al.* (1982) report a broad peak at about $f_m = 0.02$, and Coppin (1979) at approximately $f_m = 0.04$. The composite spectrum is also in relatively good agreement with the Kaimal data.

3.2. FLUX COSPECTRA

Figure 4 shows the composite heat flux cospectrum. It shows one broad peak bordered by a sharp roll-off at the low frequency end and another at higher frequencies. At non-dimensional frequencies $2 < f < 8$, hence within the inertial sub-range, the spectrum exhibits a $-4/3$ slope (as required by theory) which is followed by a faster roll-off at the highest frequencies. Theoretically, at very high frequencies, cospectra should become zero because the increasing isotropy of the flow field results in a correlation approaching zero. The increasingly faster roll-off in this composite spectrum confirms this feature (in fact the last two points, not plotted, were slightly negative). The peak frequency, at $f_m = 0.05$ ($l_m = 20z' = 380$ m), has a range of about $0.04 < f_m < 0.1$. Coppin (1979) is the only other author to report heat flux cospectra measured over an urban surface (however, it was not presented in logarithmic co-ordinates). He found the peak to occur at about $0.06 < f_m < 0.1$ for unstable stratification, which is in good agreement with the results from the present study.

Figure 5 displays the composite cospectrum of the momentum flux. It is similar to the heat flux cospectrum (Figure 4) with a fast roll-off at the low frequency end

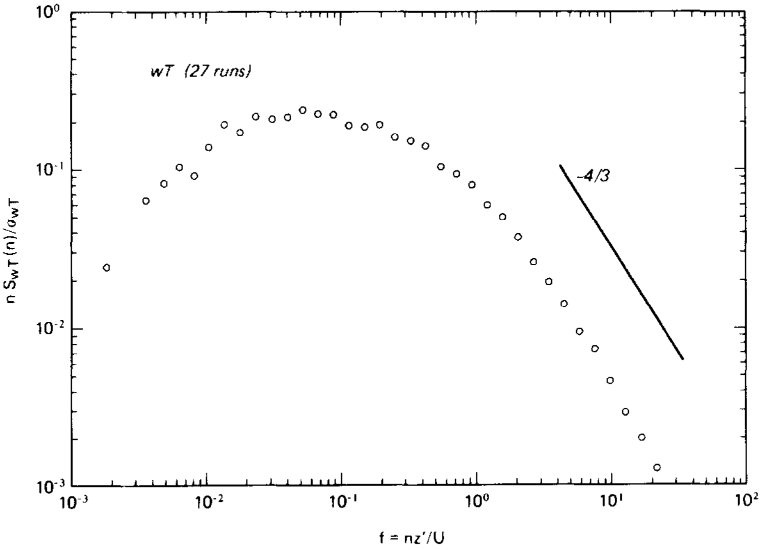

Fig. 4. Composite cospectrum of sensible heat flux normalized by the covariance.

but the peak is not as broad. The peak frequency, based on the highest cospectral estimate, is at $f_m = 0.04$ ($l_m = 25z' = 550$ m) with a possible range of $0.02 < f_m < 0.06$. Kaimal *et al.* (1972) report that cospectral estimates for the momentum flux at very low frequencies ($f < 0.01$) show a tendency to reverse sign and become negative. Under unstable conditions in particular, the low frequency cospectral estimates fluctuate between large positive and negative values. This is observed

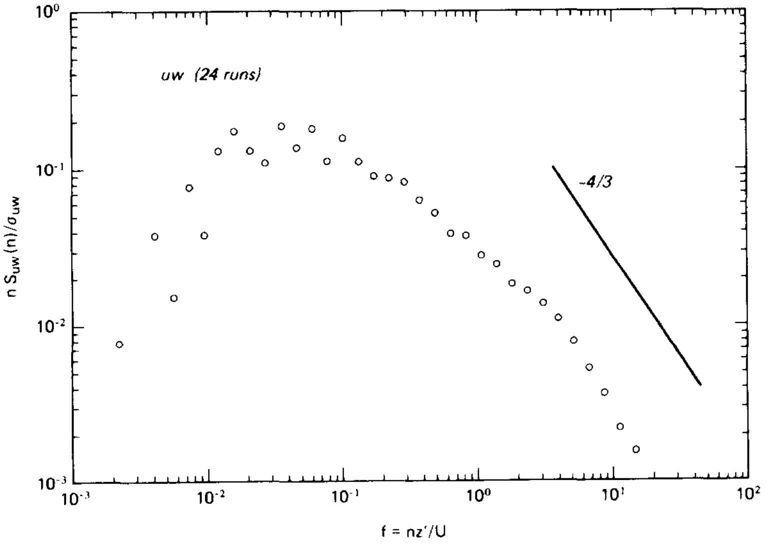

Fig. 5. Composite cospectrum of momentum flux normalized by the covariance.

in this study; however, the sign reversal occurs up to slightly higher frequencies than for the reference case. In the inertial sub-range, the *uw* cospectra are required (by theory) to follow a −4/3 slope. An examination of this behaviour is not possible here because the high frequency estimates are contaminated by noise, and the observations at $0.2 < f < 1.5$ were probably introduced by movements of the tower.

3.3. AVERAGING TIMES

To obtain valid estimates of turbulent variances and covariances, the chosen averaging time has to be long enough to enable measurement of the low frequency contributions by the variables of interest. The recommendations of Wyngaard (1973) are outlined in Section 2. In practice the averaging time should be chosen so that the low frequency energy cut-off is negligible.

Converting the recommended averaging time for w and T to a non-dimensional frequency, by using a typical wind speed of 3 m s^{-1} and a height (z') of 20 m, the frequency cut-off is $f_c = 0.006$. Inspecting the low frequency end of the vertical wind (Figure 1) and temperature (Figure 3) spectra shows that about 20 min (or $f_c = 0.006$) might be sufficient to obtain a reasonable estimate for the w variance, but the temperature spectrum still shows a considerable amount of energy at non-dimensional frequencies below 0.006. The low frequency shape of the u spectrum (Figure 2) is similar to that of temperature, suggesting that a longer averaging time (about 60 min; $f_c = 0.002$) would be more appropriate for both. However, the specification of a low frequency cut-off for these two spectra is made difficult since they tend to develop a low frequency peak related to

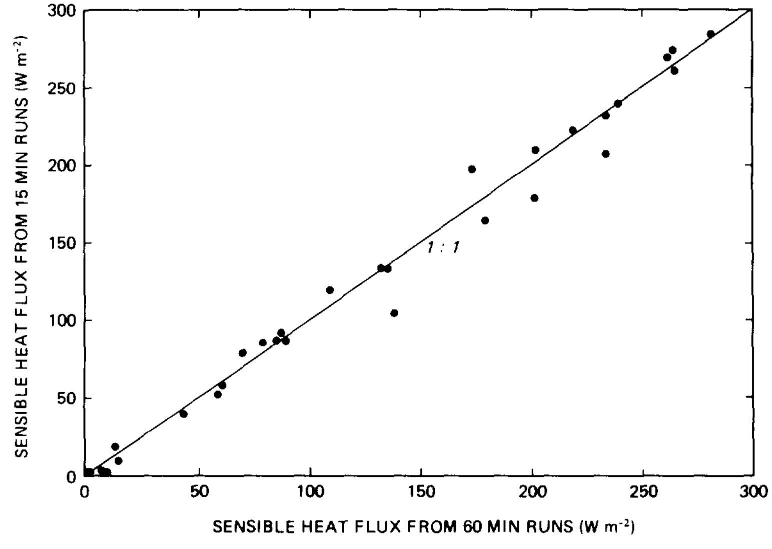

Fig. 6. Comparison of sensible heat fluxes averaged over 60 and 15 min, respectively.

mesoscale phenomena under certain stability conditions. Hence, it is necessary to decide which frequency limits can be regarded as being due to truly microscale turbulence.

The cospectra of heat (Figure 4) and momentum (Figure 5) both show a relatively sharp roll-off on the low frequency side. For the momentum cospectra, an averaging time of between 30 and 40 min ($f_c = 0.004$ and 0.003) might be sufficient, particularly when considering the large statistical variation in the cospectral densities at that end. For the cospectra of heat flux, Wyngaard's suggested averaging time of 56 min seems long enough to include all low frequency contributions. Indeed, the sharp roll-off in Figure 4 suggests that an even shorter averaging time in the order of 30 min or less ($f_c = 0.004$) could be justified here.

To substantiate the fact that for the sensible heat flux an averaging time of less than 60 min is sufficient, the heat flux covariances computed over 60 min were compared with those from within the same record but averaged over only 15 min ($f_c = 0.007$), i.e., four 15 min periods were added and averaged and then compared with the flux estimate of the corresponding 60 min record. According to McBean (1972), a cut-off at $f_c = 0.007$ might result in a flux underestimation of about 16%. However, as seen in Figure 6, there is no significant under- or overestimation over a large range of heat fluxes from about 5 to 300 W m^{-2}.

4. Summary and Conclusions

The results from this study add to the sparse number of observations of turbulence over rough urban surfaces and provide some insight regarding the nature of the turbulent fluxes. The selected runs (about 70% of the entire data set) are found capable of providing some general conclusions and a basis for comparison with other studies.

Considering that the sensors were operated at a height of only about 20 m above zero-plane displacement, which is below the recommended height for this site (between about 32 and 50 m), the results show remarkably good agreement with reference data and with studies from other urban turbulence programmes.

More specifically, on the high frequency side, in the inertial sub-layer, the spectra of w and T follow the theoretically required $-2/3$ slope very closely. No conclusions can be made concerning the high frequency shape of the u spectra, since the signals were corrected for inadequate frequency response by the propellor system on the basis of adjusting the roll-off to a $-2/3$ slope. In the case of the wT cospectra, the required $-4/3$ slope in the inertial subrange is matched very well and is followed by an increasingly steeper roll-off which is in agreement with theory and results from smoother surfaces. Because of the noise problem described earlier, the uw cospectral densities at the high frequency end cannot be analysed. Compared to the momentum cospectra, the inertial sub-range of the heat flux cospectra start at higher non-dimensional frequencies (>2 vs. about 1).

On the low frequency side, the spectra from this study show the same behaviour as the observations from smoother surfaces. The w spectra exhibit a rapid roll-off whereas the spectra of u and T are characterized by considerable scatter and only drop slightly with decreasing frequency. Large scatter and frequent sign reversal are noticeable at the low frequency end of the two cospectra investigated. Compared to the reference cospectra from smoother sites, the cospectra from this study seem to roll-off slightly faster.

The analysis of the peak frequency, as an indication of the dominant eddy scale involved in the energy transfer, deserves special attention. Comparing the f_m values from this study with the reference data, no differences can be observed. The peak frequencies of all components either coincide with the reference value or are within the range given. The agreement with other urban studies is also good. The only difference is in the temperature spectrum, where Coppin (1979) reports a slightly higher value than observed here.

Minor deviations from the reference spectra observed over smoother surfaces include the flatter appearance of the peak regions in the w and u spectra, the slightly faster roll-off at the low frequency end of the cospectra and a relatively flat region in the momentum cospectra between the peak and the inertial subrange. However, more careful investigation is needed before it can be concluded that these differences are true urban anomalies.

Regarding the objectives of this study, the following conclusions can be drawn:

- The Sunset site, which has been used in several previous micrometeorological studies, seems suitable for turbulence and energy-balance measurements representing suburban terrain.
- To obtain useful estimates of variances and covariances for this site using a z' of about 20 m, the averaging-time recommendations suggested by Wyngaard (1973) seem to be appropriate for the w component (20 min), but should be longer in the case of the u and T components (45 min) and can be relaxed for the heat and momentum fluxes (to 30 min or less).
- The fact that measurements over a rough surface, at a height that is less than is normally assumed to be required, exhibit more concurrence than difference with reference data is somewhat puzzling. It raises the possibilities that either the measurement height constraints over a rough urban surface can be relaxed or (assuming the sensors are placed in the roughness sublayer) that the effects of individual roughness elements is not strong enough to be observed in spectral analyses.

In addition it should be pointed out that this study provides the first cospectra of the fluxes of heat and momentum over a suburban surface that are based on an extended data set. It is also the first evidence that heat flux cospectra over a suburban surface agree well with observations from smoother surfaces.

Acknowledgements

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