

EVALUATION OF SPATIALLY-AVERAGED FLUXES OF HEAT, MASS AND MOMENTUM IN THE URBAN BOUNDARY LAYER

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ABSTRACT

This paper investigates the applicability of standard boundary layer theory and observational methods to the urban system. It considers the spatial and temporal sampling problems posed by the large size of the roughness elements and the considerable horizontal spatial variability of the sources and sinks.

The discussion is illustrated by reference to a series of studies conducted over suburban terrain in Vancouver, B.C., Canada. Special attention is paid to the validity of micrometeorological theory and method utilizing eddy correlation or profile methods to evaluate turbulent exchanges. It is concluded 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.

INTRODUCTION

Insight into the physical basis of urban climate is a necessary prerequisite to proper interpretation of climatic observations, the development of valid models and intelligent application in urban design. At the core of this physical base is an understanding of the exchanges of heat, mass and momentum between the urban 'surface' and the atmospheric boundary layer. This must include knowledge of the numerical magnitude of the fluxes and their associated budgets or balances.

Evaluation of these quantities using micrometeorological techniques is well developed over simple, extensive surfaces (e.g. Haugen 1973; Brutsaert 1982; Oke 1987). The extension of these approaches to obtain spatially-averaged fluxes in the urban boundary layer requires considerable care and highlights questions of methodology which are commonly (and usually justifiably) ignored over more

simple surfaces. Most of the problems centre on the reality that the surface of a city is a complex array of different surface patches (such as buildings, streets, lawns etc.). It is thus characterized by large roughness elements and by great spatial variability in the source and sink distributions of water vapour and heat. Since most micrometeorological techniques utilize observations from a single site (usually instruments on a tower) this raises basic questions of how to sample the environmental signals so as to obtain statistically-valid and spatially-representative averages.

Our group has gained experience in these questions as the result of a field programme in Vancouver, B.C., Canada. In this paper we present some of the concepts developed in order to ensure that fluxes and budgets are evaluated in a rigorous fashion, given the constraints of the urban environment.

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OBSERVATION IN AN 'IDEAL' BOUNDARY LAYER

Over extensive, flat and uniform surfaces with small roughness, tower-observations are commonly conducted in the 'constant flux layer' in the lowest part of the atmosphere, up to about 100 m in height. The name 'constant flux layer' arises from the observation that turbulent fluxes vary by only about 10% within this layer (see e.g. Panofsky, 1973). Since instrument height is large relative to the height and horizontal spacing of the surface elements, their contribution can be assumed to be effectively combined into an integrated signal. If there is a large homogeneous fetch in the upwind direction, the atmospheric properties and fluxes can therefore be assumed invariant in the horizontal and a one-dimensional approach, using concentration and diffusivity profiles, can be adopted. In such conditions the observation site and instruments can be placed anywhere, as long as they are in the constant flux layer. The time required to obtain a suitable average of turbulent states depends on the instrument height and the atmospheric stability, but the range of temporal scales contributed to the transport of entities is well defined and sampling guidelines are available (Wynngaard 1973).

Under these conditions micrometeorological techniques are known to yield fluxes that are consistent with the principles of Monin-Obukhov Similarity Theory (MOST), a scaling scheme which ties surface turbulent fluxes and profiles together in one-dimensional, semi-empirical scaling relations (e.g. Stull, 1988, p. 357ff.). In MOST, the only relevant external length-scale is the height, and scale relations are independent of the surface character, except for the surface roughness length which enters as a lower integration limit.

In practice, the radiative, and sub-surface conductive, fluxes are typically measured directly with radiometers and flux plates respectively. The turbulent fluxes are measured directly via eddy correlation, or indirectly, using profile methods such as the aerodynamic or Bowen ratio-energy balance approaches. These latter methods depend upon the assumed similarity of diffusivities for different entities, some of which are known to be approximations of restricted validity.

OBSERVATION IN THE URBAN BOUNDARY LAYER

Spatial Averaging

The large physical dimensions of urban roughness elements and the spatial inhomogeneity of the surface create practical difficulties in the use of 'constant flux layer' approaches. Every surface facet of the urban-atmosphere interface has its own exchange of heat, mass and momentum with the atmosphere and these sources and sinks are arranged at different levels and in different geometric configurations. The micro-scale flux fields within, and just above the urban canopy, are therefore highly variable in space and time. The magnitude of the spatial variability of the various fluxes in the present study area in Vancouver is demonstrated by Schmid *et al* (1989). In the case of sensible heat flux comparisons at two spatially separated sites, differences up to 25% are possible within the same land-use zone in certain conditions. The action of turbulent mixing 'smears' these differences in the roughness sublayer above the roughness elements so that at some height (z^*) the horizontal variability disappears (in the time average) and a constant flux layer is present (see Fig. 1. for a schematic illustration of the case of sensible heat). As a result the turbulence field below z^* is not horizontally uniform, even in a time average, and must be considered three-dimensional, whereas the flow above z^* may be treated as horizontally uniform in a time average. Thus, spatial averaging is closely linked to temporal averaging of turbulence: the probability that a large surface area can contribute to the turbulence at a point increases both with the time interval over which the statistical properties of turbulence are determined and the height of the measurement (see also Mulhearn and Finnigan, 1978).

It follows that all measurement systems for turbulent fluxes must be located above z^* to be considered fully spatially representative of the underlying terrain. On the other hand the top of the constant flux layer in an urban area is usually set by the existence of internal boundary layers responding to changes of upwind surface character (i.e. local or meso-scale land-use). In unstable conditions, and with large roughness elements and surface patches, typical of an urban area, it is possible that the roughness sublayer exceeds the vertical range of the constant flux layer concept,

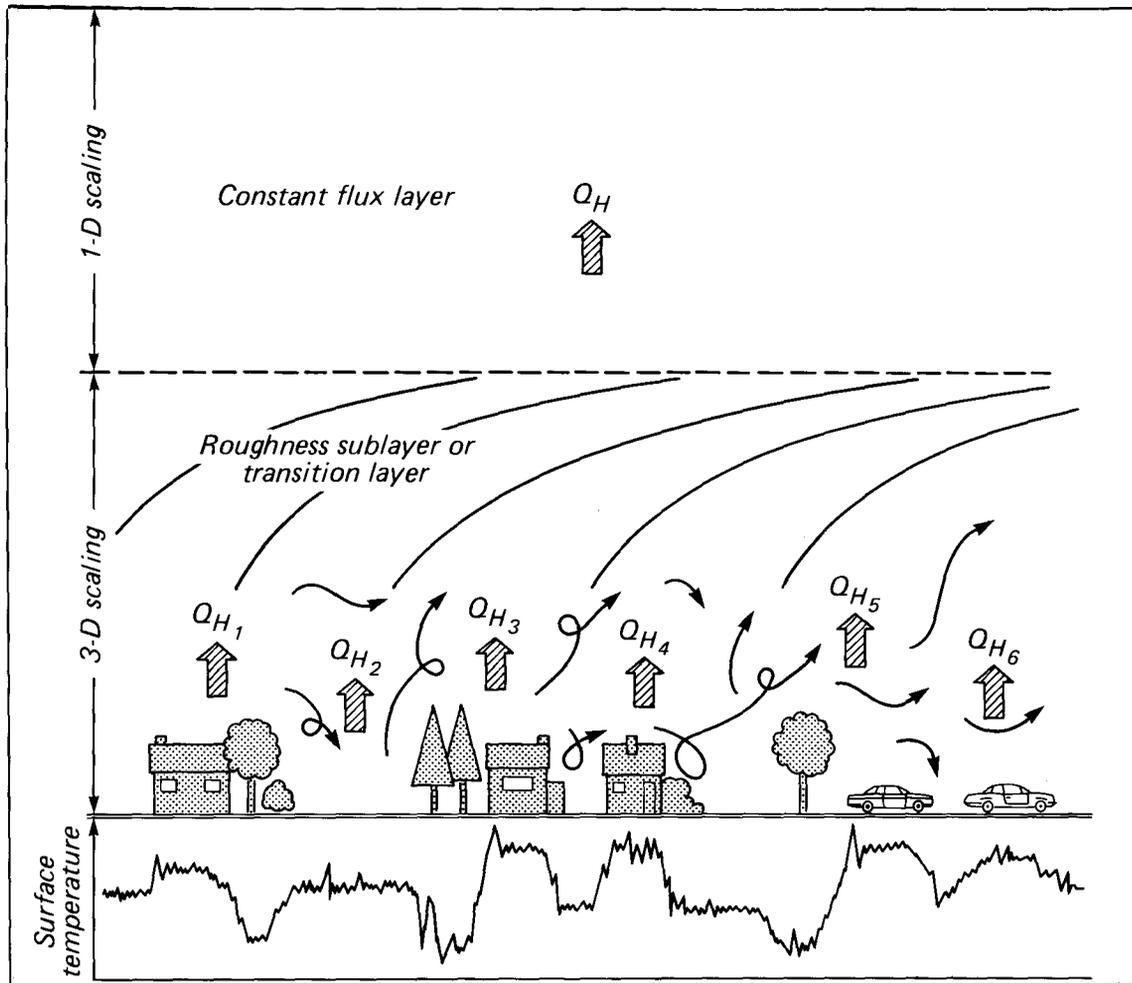


Fig. 1: The vertical structure of the surface turbulent layer over an urban surface for the case of sensible heat.

so that one-dimensional surface layer scaling becomes inappropriate.

The size and shape of the surface source area contributing to a measured flux at a point depends upon the flux being measured, the methods employed and the meteorological conditions prevailing. This is not widely appreciated. We will illustrate the situation by reference to net all-wave radiation and the turbulent sensible heat fluxes.

The source area of net radiation is determined by the area 'seen' by the net

pyrradiometer. The view from a tower tends to be a circle centred on the measurement tower. The size of the area remains constant with meteorological conditions but is dependent on the instrument used and the height at which it is mounted. It can be demonstrated that net radiation is spatially conservative in urban areas (Grimmond 1983; Cleugh 1989). The surface characteristics of albedo and emissivity can also be shown to be relatively conservative in urban areas (Arnfield 1982; Oke 1988). Therefore as long as the instrument height is sufficient to view a reasonably large

array of surface elements its placement is not critical.

The area influencing the measurement of turbulent fluxes at a point, lies upwind in the direction of the prevailing wind. The upwind, downwind and lateral boundaries of the source area are dependent on the characteristics of the flow and on the boundary layer development in the atmospheric layer between the surface and the sensor level (Pasquill, 1972; Schmid and Oke, 1989). The area tends towards an elliptical shape. It is possible to determine the dimensions of the turbulent source area using the Source Area Model (SAM) by Schmid (1988). SAM is based on a reverse plume diffusion model which provides an Eulerian approach to identify the source area and is described in detail by Schmid and Oke (1989). Naturally the location and shape of this area is continually shifting with the wind and stability. It is also relevant to note that the SAM together with an analysis of spatial characteristics (see Schmid, 1988) can be used to calculate the height of the transition layer (z^*).

The existence of different source areas for radiative and turbulent fluxes raises problems for budget closure. The comparison of flux components with different source areas in a balance equation is methodologically incorrect, since the system is inconsistent in itself; each component of the balance refers to a different system. Over highly complex surfaces the balance of measured instantaneous fluxes cannot be expected to close due to the spatial incompatibility of turbulence and radiation measurements (Grimmond *et al.*, 1989). The same is true for time averages, if the source areas are small, since the measurements can be strongly biased by individual surface elements. With larger source areas, the spatial averaging of the flux contributions increases and thus the measurements become more spatially representative. In urban areas, which are large enough to be considered spatially homogeneous above a certain scale, it is possible that the source areas of all balance components are spatially representative. In this case, the different source areas are at least statistically compatible and closure of the energy balance should be possible. A method to estimate the spatial representativeness of flux measurements is presented in Schmid (1988).

To complete the procedure it is necessary to ensure the other components of the urban energy balance are evaluated in a manner consistent with the radiative and turbulent terms, i.e. the anthropogenic heat flux and sub-surface heat storage. In our work the former is calculated from inventories of fuel use and population, and the latter from a parameterization involving net radiation and land cover. Both therefore involve the preparation of a spatial inventory in the area surrounding the tower site. Since the net radiation is spatially conservative a consistent energy balance is achieved by using the turbulent source areas calculated from SAM to access the corresponding areas in the fuel use and land cover inventories, and thence to evaluate the anthropogenic and storage heat fluxes (Grimmond 1988). This procedure is not necessary if the fuel use and land cover fields are spatially homogeneous at scales of the same order as the turbulent source areas (Grimmond *et al.*, 1989).

An inconsistency which remains is the mixture of calculated anthropogenic heat fluxes with measured radiative fluxes (which therefore include some effects of anthropogenic heating). This means that the energy source terms are not completely separate, but the error is thought to be acceptably small.

Temporal Averaging

The strong link between temporal and spatial averaging of turbulent fluxes has been noted in the previous section: due to turbulent mixing and the random nature of diffusion, the temporal averaging contained in a point-measurement implies an integration of surface contributions over a 'source area'.

Variations over a wide range of temporal scales (frequencies) contribute to the turbulent fluxes over urban terrain. At periods longer than about one hour synoptic, and meso-scale process, and the thermal effects of the daily solar cycle affect all turbulent fluxes. These influences have to be considered when time series of surface layer turbulence are examined using techniques such as spectrum analysis. Especially when the effects of a complex surface on the spectral structure of turbulence are of interest, these external trends introduce non-stationarity into the signal. This can be avoided by limiting the maximum sampling period to one hour and/or removing any remaining trends.

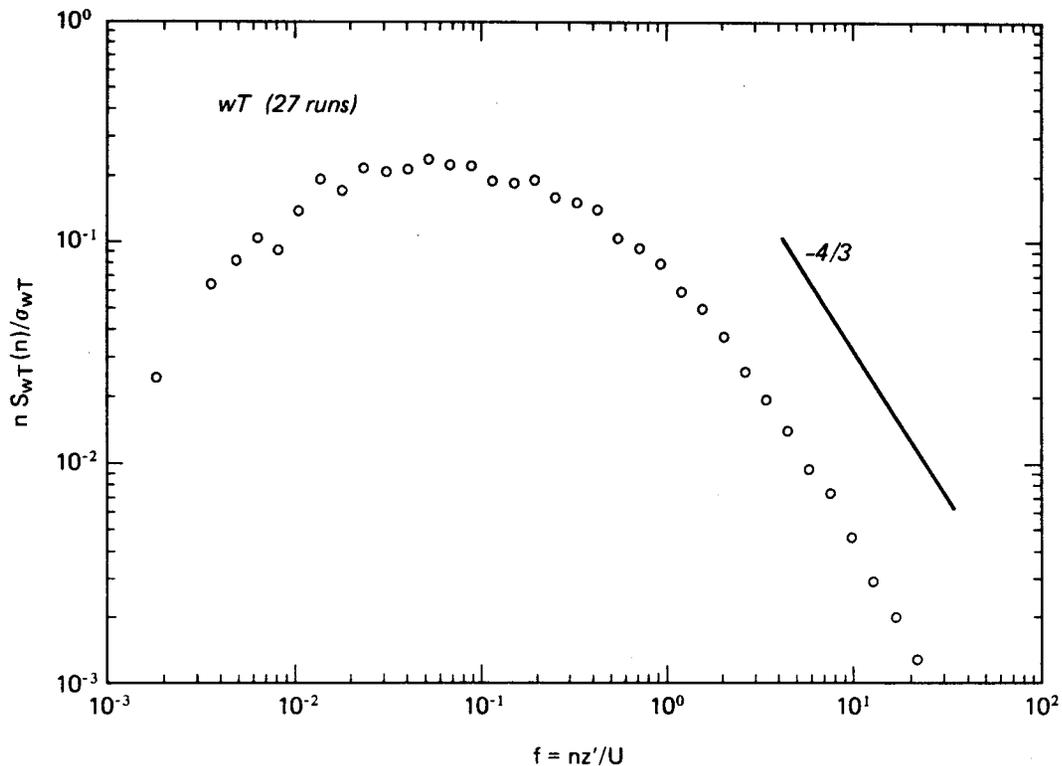


Fig. 2: Composite cospectrum of sensible heat flux, based on many runs in unstable conditions. The power spectral density normalized with the covariance (vertical) vs. the natural frequency (n) normalized with the height of measurement and the mean wind speed. The line with $-4/3$ slope corresponds to the inertial subrange form required by theory (after Roth et al., 1989).

Conspectra of sensible heat flux exhibit a peak at frequencies corresponding to periods of about one minute, and decrease again toward higher frequencies (periods of seconds or less, where energy production gives way to dissipation (Fig. 2). The analysis of such cospectra in the Monin-Obukhov framework show that in the 'ideal' constant flux layer the position of the peak frequency is strongly dependent on the height of measurement. Over complex surfaces such as the suburban area in Vancouver, where instrument towers extending a few tens of metres above the surface may still not be above z^* , the energy-carrying eddies will be influenced by wakes and plumes shed from individual surface elements. It has been suggested (e.g. Raupach et al., 1980) that over very rough surfaces length scales related to the dimensions of the dominant elements (e.g. buildings) may become important, thereby introducing a dependence of turbulence on the specific configuration and

geometry of the surface. As already noted, this is in contrast to MOST, where height is the only relevant external scaling length. This effect is expected to be most prominent for the momentum flux but more work is needed to demonstrate this over an urban surface.

Uncertainties regarding the height of the roughness sublayer, the lengths governing the appropriate scaling laws and the dominant time scales create concerns with regard to the use of the eddy correlation technique over urban surfaces. This method involves the correlation of atmospheric variables over the range of frequencies contributing to the flux. The low frequency end is set by the averaging period chosen and the high frequency end is determined by the sampling interval. Given fast response instruments the high limit is easily satisfied but the choice of the low limit is important and not readily apparent for the urban atmosphere. On one hand the averaging

time has to be long enough to encompass all frequencies contributing to the flux, but on the other hand it must be short enough to avoid non-stationarity, otherwise Monin-Obukhov arguments are invalid.

Studies over extensive, low roughness terrain find the cospectral peak at time scales of less than 100 s and exhibit fairly sharp roll-off at lower frequencies (e.g. Kaimal *et al.* (1972) Anderson and Verma, 1985). Roth *et al.* (1989) measured the sensible heat and momentum fluxes over the suburban site in Vancouver. They used an effective measurement height of 20 m and an averaging time of 60 min. The spectra and cospectra behave in a fashion consistent with the applicability of Monin-Obukhov theory and indirectly imply that this

scaling method may be valid even over non-ideal conditions. The cospectral peaks occur at times scales of less than 180 s and there is a clear drop-off at lower frequencies with a slope corresponding to results over 'ideal' surfaces (Fig. 2).

To address the problem of limited stationarity, sensible heat flux covariances averaged over 60 min were compared with estimates from within the corresponding record but averaged over only 15 min, i.e. four 15-minute periods were analyzed, added and averaged. Roth *et al.* (1989) show that shortening the averaging time creates no significant under- or overestimation over a large range of fluxes (Fig. 3).

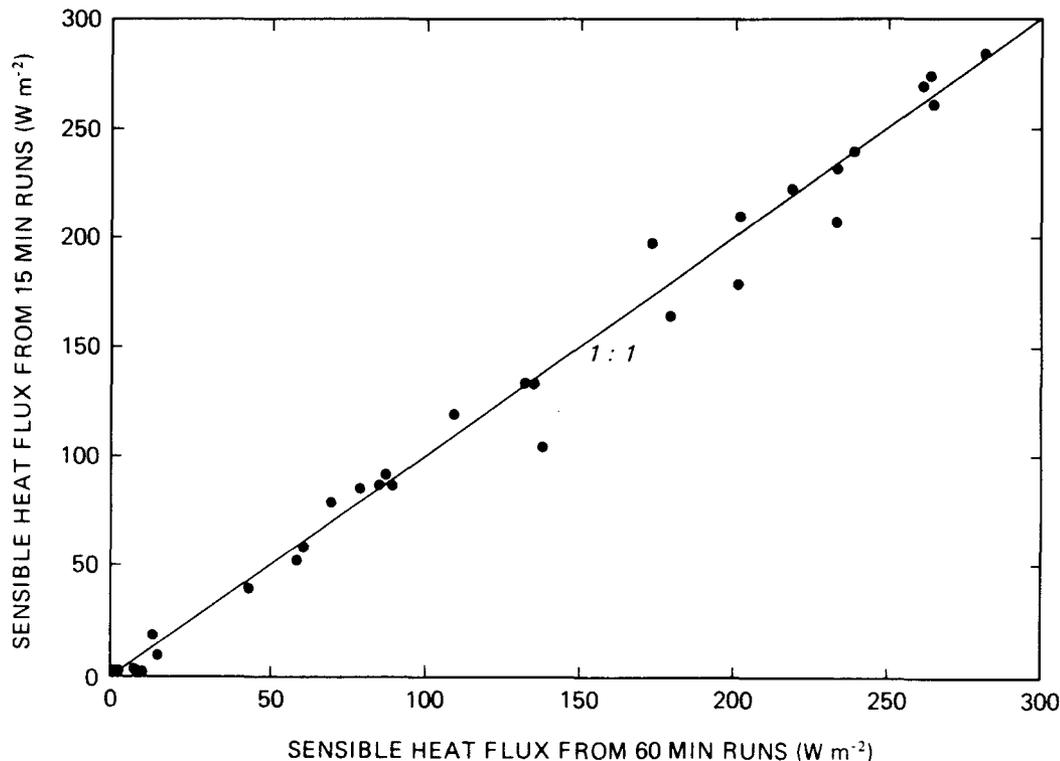


Fig. 3: Comparison of sensible heat flux densities ($W m^{-2}$) averaged over 60 and 15 min, respectively. The solid line is 1:1 (after Roth *et al.*, 1989).

PRESENT PRACTICE

For work over suburban terrain we utilize and recommend use of micrometeorological techniques to evaluate spatially-averaged fluxes. However care must be exercised to choose: a site with sufficient fetch to avoid obvious meso-scale advection; a measurement height that is above the roughness sublayer; and, an averaging time that is dictated by the energy spectra or cospectra.

We prefer the eddy correlation approach over profile methods. The latter require a greater depth of constant flux layer in which to work and the small size of the gradients over this very rough surface places great pressure on measurement accuracy to avoid large errors in computed fluxes. Of the profile

methods we prefer the Bowen ratio-energy balance over the aerodynamic. The latter requires similarity of the diffusivity for momentum with that of the entity of interest. Even over ideal terrain this is not fully valid and over rough urban areas it is likely to break down further due to the bluff-body effects of buildings where much of the momentum transfer is via pressure fluctuations, a process not utilized by heat or mass. Despite these shortcomings, reasonable agreement between eddy correlation and Bowen ratio-energy balance estimates of turbulent heat fluxes can be achieved (Fig. 4). We also use eddy correlation values of sensible heat flux density together with measured Bowen ratios to calculate the latent heat flux density.

Energy budget closure is not assured in a one-dimensional approach over complex ter-

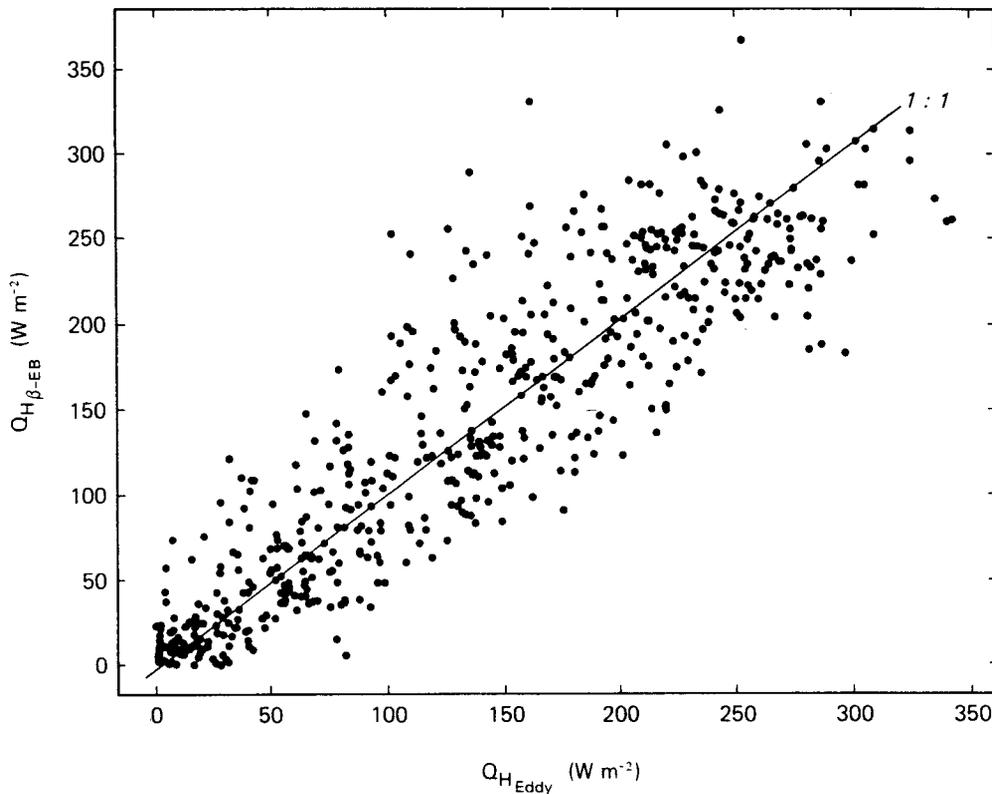


Fig. 4: Comparison of sensible heat flux densities determined using eddy correlation and Bowen ratio-energy balance systems. Q_H^{Bowen} values include net radiation measured from the same tower and parameterized values of sub-surface storage using the scheme of Cleugh (1989).

rain but the use of a turbulent flux source area concept can provide a rational means to minimize the problem: if the flux measurements incorporate spatial averages over a large enough area, the values are spatially representative and budget closure is achieved statistically.

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