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INITIAL GUIDANCE TO OBTAIN REPRESENTATIVE METEOROLOGICAL OBSERVATIONS AT URBAN SITES

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NOTE

FOREWORD

The Thirteenth Session of the Commission for Instruments and Methods of Observation (CIMO) recognized the need to include in the WMO Guide to Instruments and Methods of Observation, WMO-No.8 (CIMO Guide) a new chapter on Urban Observations. Professor Tim Oke, University of British Columbia, Canada, transformed his long-time experience in this field into a new chapter of the CIMO Guide, scheduled for publication in the beginning of 2006. This IOM Report is therefore an important tool for early dissemination of CIMO guidance to Members on the observation of meteorological elements in urban areas. I would like to express my appreciation to Professor Oke for this excellent publication and his ongoing contribution to the work of CIMO.

The IOM Report stresses the need to fully appreciate the scales of urban climates (micro-, local- and meso-scale) as they impact phenomena and measurement methods. In particular, the presence of the Urban Canopy Layer (UCL) defines a micro-scale dominated layer beneath roof-level and a layer above roof level and the Roughness Sub-layer (RSL), which responds to the local scale. The above roof layer represents a blended influence that brings with it questions on the rate of internal boundary layer growth and the location of the source areas (‘footprints’) for meteorological sensors.

The essential first step in selecting urban station sites is to evaluate the physical nature of the urban terrain. This will reveal areas of ‘homogeneity’ and conversely areas of transition and inhomogeneity. A new site classification system has been devised to describe any urban site. It is based on measures of the urban structure, land cover, building fabric and metabolism (anthropogenic heat, water and pollution), rather than land-use zones which only relate to function, which is not necessarily climatically significant. The suggested classes are called *Urban Climate Zones* (UCZ).

The IOM Report deals with the realities for those faced with the establishment of a meteorological station at an urban site where application of standard siting is often either impossible or nonsensical. The overall objective is to obtain observations of those elements that are representative of the UCZ. For measurements involving a station located in the UCL the suggestion is to centre the sensors in a representative space. For measurements in the blended layer special attention is paid to the height of measurement because of the need to avoid unwanted advective influences so that the source areas are fully representative of the UCZ.

A section of the IOM Report is devoted to the special requirements for documenting metadata in urban environments. Because the environment of urban stations changes frequently as development proceeds, metadata (and their frequent update) are as important as the meteorological data gathered.

In preparation of the IOM Report, information on the results of the Questionnaire to NMHSs were taken into account as well as the feedback received following presentations made at various conferences, Casablanca (Morocco), Nice (France), Sydney (Australia), Ottawa (Canada), Lodz (Poland) and Albuquerque (United States); and circulation to several experts in urban meteorology. It was also made available for comments to members of the International Association for Urban Climate.

I wish to extend my sincerest thanks to Professor Tim Oke for the remarkable work done in preparing this Initial *Guidance to Obtain Representative Meteorological Observations at Urban Sites*. I also wish to thank Mr Eric Leinberger, cartographer, Department of Geography, University of British Columbia, for preparing the figures appearing in this publication.

(Dr. R.P. Canterford)

Acting President
Commission for Instruments and
Methods of Observation

INITIAL GUIDANCE TO OBTAIN REPRESENTATIVE METEOROLOGICAL OBSERVATIONS AT URBAN SITES

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1 General

There is a growing need for meteorological observations conducted in urban areas. Urban populations continue to expand and meteorological services are increasingly required to supply meteorological data in support of detailed forecasts for citizens, building and urban design, energy conservation, transport and communications, air quality and health, storm water and wind engineering, insurance and emergency measures. At the same time meteorological services have difficulty in taking urban observations that are not severely compromised. This is because most developed sites make it impossible to conform to the standard guidelines for site selection and instrument exposure given in the *Guide to Meteorological Instruments and Methods of Observation* (WMO 1996) [hereinafter referred to as the *Guide*] due to obstruction of airflow and radiation exchange by buildings and trees, unnatural surface cover and waste heat and water vapour from human activities.

This chapter provides information to enable the selection of sites, installation of a meteorological station and interpretation of the data from an urban area. In particular it deals with the case of what is commonly called a ‘standard’ climate station. Despite the complexity and inhomogeneity of urban environments, useful and repeatable observations can be obtained. Every site presents a unique challenge. To ensure meaningful observations requires careful attention to certain principles and concepts that are virtually unique to urban areas. It also requires the person establishing and running the station to apply those principles and concepts in an intelligent and flexible way that is sensitive to the realities of the specific environment involved. Rigid ‘rules’ have little utility. The need for flexibility runs slightly counter to the general notion of standardization that is promoted as WMO observing practice. In urban areas it is sometimes necessary to accept exposure over non-standard surfaces at non-standard heights, to split observations between two or more locations, or to be closer than usual to buildings or waste heat exhausts.

The units of measurement, and the instruments used in urban areas are the same as those for other environments. Therefore only those aspects that are unique to urban areas, or are made difficult to handle because of the nature of cities, such as the choice of site, the exposure of the instruments and the documentation of metadata are covered in this chapter.

Timing and frequency of observations, and coding of reports should follow appropriate standards (WMO, 1995, 1998, 2002).

For automated stations and the requirements for message coding and transmission, quality control, maintenance (noting any special demands of the urban environment) and calibration, the recommendations of Chapter I, Part II of the *Guide* (WMO 1996) should be followed.

1.1 Definitions and concepts

1.1.1 STATION RATIONALE

The clarity of the reason for establishing an urban station is essential to its success. Two of the most usual reasons are, the wish to represent the meteorological environment at a place for general climatological purposes; and the wish to provide data in support of the needs of a particular user. In both cases the spatial and temporal scales of interest must be defined and, as outlined below, the siting of the station and the exposure of the instruments in each case may have to be very different.

1.1.2 HORIZONTAL SCALES

There is no more important input to the success of an urban station than an appreciation of the concept of scale. There are three scales of interest (Oke, 1984, Figure 1):

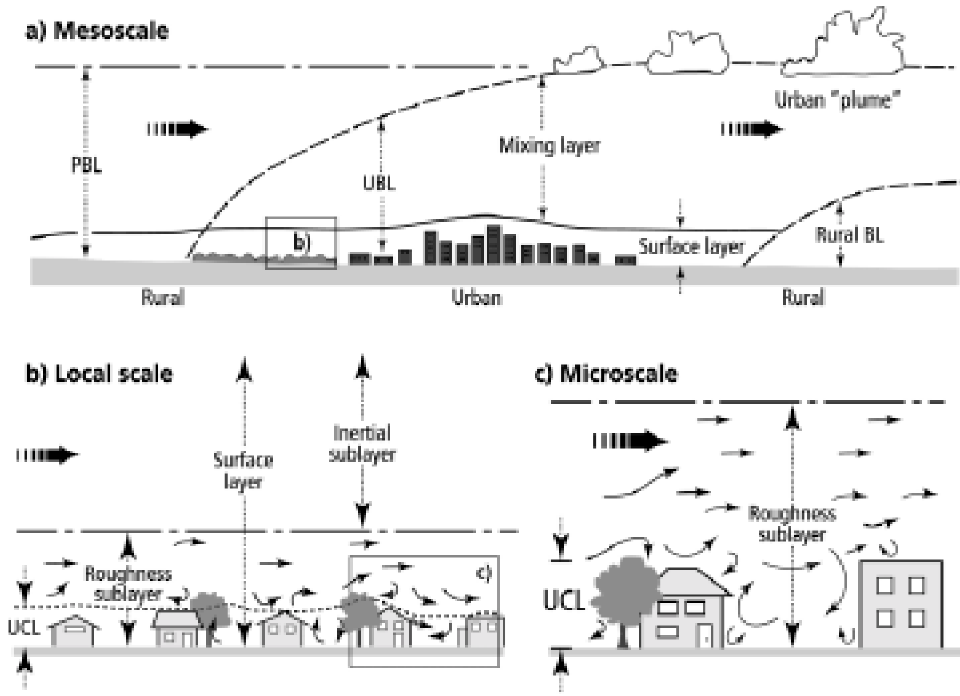


Figure 1 — Schematic of climatic scales and vertical layers found in urban areas. PBL – planetary boundary layer, UBL – urban boundary layer, UCL – urban canopy layer [modified from Oke, 1997]

(a) Microscale – every surface and object has its own microclimate on it and in its immediate vicinity. Surface and air temperatures may vary by several degrees in very short distances, even millimetres, and airflow can be greatly perturbed by even small objects. Typical scales of urban microclimates relate to the dimensions of individual buildings, trees, roads, streets, courtyards, gardens, etc. Typical scales extend from less than one metre to hundreds of metres. The formulation of the guidelines in Part I of the *Guide* specifically aims to avoid microclimatic effects. The climate station recommendations are designed to standardize all sites, as far as practical. Hence the use of a standard height of measurement, a single surface cover, minimum distances to obstacles and little horizon obstruction. The aim is to achieve climate observations that are free of extraneous microclimate signals and hence they characterize local climates. With even more stringent standards at first order stations they may be able to represent conditions at synoptic space and time scales. The data may be used to assess climate trends at even larger scales.

Unless the objectives are very specialized, urban stations should also avoid microclimate influences, but this is hard to achieve.

(b) *Local scale* – this is the scale that standard climate stations are designed to monitor. It includes landscape features such as topography but excludes microscale effects. In urban areas this translates to mean the climate of neighbourhoods with similar types of urban development (surface cover, size and spacing of buildings, activity). The signal is the integration of a characteristic mix of microclimatic effects arising from the source area in the vicinity of the site. The source area is the portion of the surface upstream that contributes the main properties of the flux or meteorological concentration being measured (Schmid, 2002). Typical scales are one to several kilometres.

(c) *Mesoscale* – a city influences weather and climate at the scale of the whole city, typically tens of kilometres in extent. A single station is not able to represent this scale.

1.1.3 **VERTICAL SCALES**

An essential difference between the climate of urban areas and that of rural or airport locations is that in cities the vertical exchanges of momentum, heat and moisture does not occur at a (nearly) plane surface, but in a layer of significant thickness called the urban canopy layer (UCL) (Figure 1). The height of the UCL is approximately equivalent to that of the mean height of the main roughness elements (buildings and trees), z_H (see Figure 4 for parameter definitions). The microclimatic effects of individual surfaces and obstacles persist for a short distance away from their source but are then mixed and muted by the action of turbulent eddies. The distance before the effect is obliterated depends on the magnitude of the effect, the wind speed and the stability (i.e. stable, neutral or unstable). This blending occurs both in the horizontal and the vertical. As noted, horizontal effects may persist up to a few hundred metres. In the vertical, the effects of individual features are discernable in the roughness sublayer (RSL), that extends from ground level to the blending height z_r, where the blending action is complete. Rule-of-thumb estimates and field measurements indicate z_r can be as low as $1.5z_H$ at densely built (closely spaced) and homogeneous sites but greater than $4z_H$ in low density areas (Grimmond and Oke, 1999; Rotach, 1999; Christen, 2003). An instrument placed below z_r may register microclimate anomalies but above that it 'sees' a blended, spatially-averaged signal that is representative of the local scale.

There is another height restriction to consider. This arises because each local scale surface type generates an internal boundary layer, in which the flow structure and thermodynamic properties are adapted to that surface type. The height of the layer grows with increasing fetch (the distance upwind to the edge where the transition to a distinctly different surface type occurs). The rate at which the internal boundary layer grows with fetch distance depends on the roughness and the stability. In rural conditions height:fetch ratios might vary from as small as 1:10 in unstable conditions to as large as 1:500 in stable cases and the ratio decreases as the roughness increases (Garratt, 1992; Wieringa, 1993). Urban areas tend towards neutral stability due to enhanced thermal and mechanical turbulence associated with the heat island and their large roughness, therefore, a height:fetch ratio of about 1:100 is considered typical. The internal boundary layer height is taken above the displacement height z_d, which is the reference level for flow above the blending height. (For explanation of z_d see Figure 4, Section 3.5.1 and footnote 2 of Table 2)

For example, take a hypothetical densely-built district with z_H of 10 m. This means that z_r is at least 15 m. If this height is chosen to be the measurement level, then the fetch requirement over similar urban terrain is likely to be at least 0.8 km, since fetch = 100 ($z_r - z_d$), and z_d is going to be about 7 m. This can be a significant site restriction because the implication is that if the urban terrain is not similar out to at least this distance around the station site, then observations will not be representative of the local surface type. At less densely developed sites, where heat island and roughness effects are less, the fetch requirements are likely to be greater.

At heights above the blending height, but within the local internal boundary layer, measurements are within an inertial sublayer (Figure 1) where standard boundary layer theory applies. Such theory governs the form of the mean vertical profiles of meteorological variables (including air temperature, humidity, and wind speed) and the behaviour of turbulent fluxes, spectra and statistics. This provides a basis for:

(a) calculation of the source area (or ‘footprint’, see below) from which the turbulent flux or the concentration of a meteorological variable originates; hence this defines the distance upstream for the minimum acceptable fetch; and

(b) extrapolation of a given flux or property through the inertial layer and also downwards into the RSL (and, although it is less reliable, into the UCL). In the inertial layer fluxes are constant with height and the mean value of meteorological properties are invariant horizontally. Hence observations of fluxes and standard variables possess significant utility and are able to characterize the underlying local scale environment. Extrapolation into the RSL is less prescribed.

1.1.4 SOURCE AREAS (‘FOOTPRINTS’)

A sensor placed above a surface ‘sees’ only a portion of its surroundings. This is called the ‘source area’ of the instrument which depends on its height and the characteristics of the process transporting the surface property to the sensor. For upwelling radiation signals (short- and longwave radiation and surface temperature viewed by an infrared thermometer) the field-of-view of the instrument and the geometry of the underlying surface set what is seen. By analogy sensors such as thermometers, hygrometers, gas analyzers, anemometers ‘see’ properties such as temperature, humidity, atmospheric gases, wind speed and direction that are carried from the surface to the sensor by turbulent transport. A conceptual illustration of these source areas is given in Figure 2.

The source area of a downfacing radiometer with its sensing element parallel to the ground is a circular patch with the instrument at its centre (Figure 2). The radius (*r*) of the circular source area contributing to the radiometer signal at height (z_1) is given by Schmid *et al.* (1991):

$$r = z_1 \left(\frac{1}{F} - 1 \right)^{-0.5} \quad (1)$$

where *F* is the view factor, i.e. the proportion of the measured flux at the sensor for which that area is responsible. Depending on its field-of-view, a radiometer may see only a limited circle, or it may extend to the horizon. In the latter case the instrument usually has a cosine response, so that towards the horizon it becomes increasingly difficult to define the actual source area seen. Hence the use of the view factor which

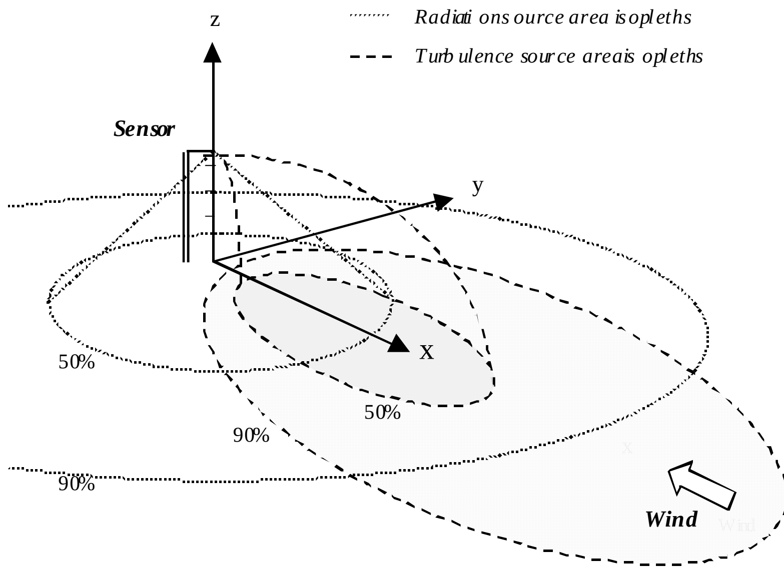


Figure 2 — Conceptual representation of source areas contributing to sensors for radiation and turbulent fluxes or concentrations. If the sensor is a radiometer, 50 or 90% of the flux originates from the area inside the respective circle. If the sensor is responding to a property of turbulent transport, 50 or 90% of the signal comes from the area inside the respective ellipses. These are dynamic in the sense that they are oriented into the wind and hence move with wind direction and stability.

defines the area contributing a set proportion (often selected as 50, 90, 95, 99, or 99.5%) of the instrument's signal.

The source area of a sensor that derives its signal via turbulent transport is not symmetrically distributed around the sensor location. It is elliptical in shape and is aligned in the upwind direction from the tower (Figure 2). If there is a wind the effect of the surface area at the base of the mast is effectively zero, because turbulence cannot transport the influence up to the sensor level. At some distance in the upwind direction the source starts to affect the sensor, these rise to a peak, thereafter decaying at greater distances (for the shape in both the *x* and *y* directions see Kljun *et al.,* 2002; Schmid, 2002). The distance upwind to the first surface area contributing to the signal, to the point of peak influence, to the furthest upwind surface influencing the measurement, and the area of the so-called 'footprint' vary considerably over time. They depend on the height of measurement (larger at greater heights), surface roughness, atmospheric stability (increasing from unstable to stable) and whether a turbulent flux or a meteorological concentration is being measured (larger for the concentration) (Kljun *et al*., 2002). Methods to calculate the dimensions of flux and concentration 'footprints' are available (Schmid, 2002; Kljun *et al.*, 2004).

The situation illustrated in Figure 2 is general but it applies best to instruments placed in the inertial sublayer, well above the complications of the RSL and the complex geometry of the three-dimensional urban surface. Within the UCL the way that effects of radiation and turbulent source areas decay with distance has not yet been reliably evaluated. It can be surmised that they depend on the same properties and resemble the overall forms of those in Figure 2. However, obvious complications arise due to the complex radiation geometry, and the blockage and channelling of flow, that are characteristic of the UCL. Undoubtedly the immediate environment of the station is by far the most critical and the extent of the source area on convective effects grows with stability and the height of the sensor. The distance influencing screen-level (~1.5 m) sensors may be a few tens of metres in neutral conditions, less when it is unstable and perhaps more than a hundred metres when it is stable. At a height of three metres the equivalent distances probably extend up to about three hundred metres in the stable case. The circle of influence on a screen-level temperature or humidity sensor is thought to have a radius of about 0.5 km typically, but this is likely to depend upon the building density.

1.1.5 MEASUREMENT APPROACHES

It follows from the preceding discussion that if the objective of an instrumented urban site is to monitor the local scale climate near the surface, there are two viable approaches:

(a) locate the site in the UCL at a location surrounded by average or 'typical' conditions for the urban terrain, and place the sensors at heights similar to those used at non-urban sites. This assumes that the mixing induced by flow around obstacles is sufficient to blend properties to form a UCL average at the local scale; or

(b) mount the sensors on a tall tower above the RSL and obtain blended values that can be extrapolated down into the UCL.

In general approach (a) works best for air temperature and humidity, and approach (b) for wind speed and direction and precipitation. For radiation the only significant requirement is for an unobstructed horizon. Urban stations, therefore, often consist of instruments deployed both below and above roof-level and this requires that site assessment and description include the scales relevant to both contexts.

1.1.6 URBAN SITE DESCRIPTION

The magnitude of each urban scale does not agree exactly with those commonly given in textbooks. The scales are conferred by the dimensions of the morphometric features that make up an urban landscape. This places emphasis on the need to adequately describe properties of urban areas that affect the atmosphere. The most important basic features are the *urban structure* (dimensions of the buildings and the spaces between them, the street widths and street spacing), the *urban cover* (built-up, paved, vegetated, bare soil, water), the *urban fabric* (construction and natural materials) and the *urban metabolism* (heat, water and pollutants due to human activity). Hence characterization of the sites of urban climate stations needs to take account of these descriptors, to use them in selecting potential sites, and to incorporate them in metadata that accurately describes the setting of the station.

These four basic features of cities tend to cluster together to form characteristic urban classes. For example, most central areas of cities have relatively tall buildings that are densely packed together so the ground is largely covered with buildings or paved surfaces made of durable materials such as stone, concrete, brick and asphalt and where heat releases from furnaces, air conditioners, chimneys and vehicles are large. Near the other end of the spectrum there are districts with low density housing of one- or two-storey buildings of relatively light construction and considerable garden or vegetated areas with low heat releases but perhaps large irrigation inputs.

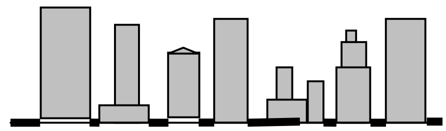
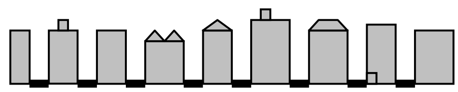
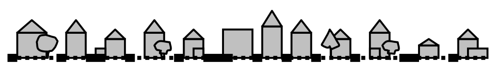
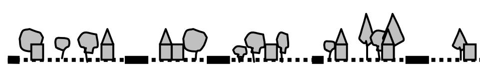
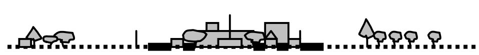
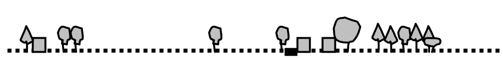
No universally accepted scheme of urban classification for climatic purposes exists. A good approach to the built components is that of Ellefsen (1990/91) who developed a set of Urban Terrain Zone types. He initially differentiates according to 3 types of building contiguity (attached (row), detached but close-set, detached and open-set). These are further divided into a total of 17 sub-types by function, location in the city, and building height, construction and age. Application of the scheme needs only aerial photography, which is generally available, and it has been applied in several cities around the world and seems to possess generality.

Ellefsen's scheme can be used to describe urban structure for roughness, airflow, radiation access and screening. It can be argued that it indirectly includes aspects of urban cover, fabric and metabolism because a given structure carries with it the type of cover, materials, and degree of human activity. Ellefsen's scheme is less useful, however, when built features are scarce and there are large areas of vegetation (urban forest, low plant covers grassland, scrub, crops), bare ground (soil or rock), and water (lakes, swamps, rivers). A simpler scheme of Urban Climate Zones (UCZ) is illustrated in Table 1. It incorporates groups of Ellefsen's zones, plus a measure of the structure, z_H/W, (see Table 1, Note 2) shown to be closely related to both flow, solar shading and the heat island, and also a measure of the surface cover (%Built) that is related to the degree of surface permeability.

The importance of UCZ, is not their absolute accuracy to describe the site but their ability to classify areas of a settlement into districts, that are similar in their capacity to modify the local climate, and to identify potential transitions to different urban climate zones. Such a classification is crucial when beginning to set up an urban station so that the spatial homogeneity criteria are met approximately for a station in the UCL or above the RSL. In what follows it is assumed that the morphometry of the urban area, or a portion of it, has been assessed using detailed maps, and/or aerial photographs, satellite imagery (visible and /or thermal), planning documents or at least a visual survey conducted from a vehicle and/or on foot. Land use maps can be helpful but it should be appreciated that they depict the *function* and not necessarily the *physical form* of the settlement. The task of urban description should result in a map with areas of UCZ delineated.

Herein the UCZ as illustrated in Table 1 are used. The categories may have to be adapted to accommodate special urban forms characteristic of some ancient cities or of unplanned urban development found in some less-developed countries. For example, many towns and cities in Africa and Asia do not have as large a fraction of the surface covered by impervious materials, roads may not be paved.

***Table 1**: Simplified classification of distinct urban forms arranged in approximate decreasing order of their ability to impact local climate [Oke, 2004 unpublished]*

Urban Climate Zone, UCZ[1]	*Image*	*Rough-ness class*[2]	*Aspect ratio*[3]	*% Built (imperm-eable)*[4]
1. *Intensely developed urban with detached close-set high-rise buildings with cladding, e.g. downtown towers*		8	> 2	> 90
2. *Intensely developed high density urban with 2 – 5 storey, attached or very close-set buildings often of brick or stone, e.g. old city core*		7	1.0 – 2.5	> 85
3. *Highly developed, medium density urban with row or detached but close-set houses, stores & apartments e.g. urban housing*		7	0.5 – 1.5	70 - 85
4. *Highly developed, low or medium density urban with large low buildings & paved parking, e.g. shopping mall, warehouses*		5	0.05 – 0.2	70 - 95
5. *Medium development, low density suburban with 1 or 2 storey houses, e.g. suburban housing*		6	0.2 – 0.6, up to >1 with trees	35 - 65
6. *Mixed use with large buildings in open landscape, e.g. institutions such as hospital, university, airport*		5	0.1 – 0.5, depends on trees	< 40
7. *Semi-rural development, scattered houses in natural or agricultural area, e.g. farms, estates*		4	> 0.05, depends on trees	< 10

Key to image symbols: buildings; vegetation; impervious ground; pervious ground

[1] A simplified set of classes that includes aspects of the schemes of Auer (1978) and Ellefsen (1990/91) plus physical measures relating to wind, thermal and moisture controls (columns at right). Approximate correspondence between UCZ and Ellefsen's urban terrain zones is: 1(Dc1, Dc8), 2 (A1-A4, Dc2), 3 (A5, Dc3-5, Do2), 4 (Do1, Do4, Do5), 5 (Do3), 6 (Do6), 7 (none).

[2] Effective terrain roughness according to the Davenport classification (Davenport *et al.*, 2000); see Table 2.

[3] Aspect ratio = z_H/W is average height of the main roughness elements (buildings, trees) divided by their average spacing, in the city centre this is the street canyon height/width. This measure is known to be related to flow regime types (Oke 1987) and thermal controls (solar shading and longwave screening) (Oke, 1981). Tall trees increase this measure significantly.

[4] Average proportion of ground plan covered by built features (buildings, roads, paved and other impervious areas) the rest of the area is occupied by pervious cover (green space, water and other natural surfaces). Permeability affects the moisture status of the ground and hence humidification and evaporative cooling potential.

2 Choosing a location and site for an urban station

2.1 Location

First, it is necessary to clearly establish the purpose of the station. If there is to be only one station inside the urban area it must be decided if the aim is to monitor the greatest impact of the city, or of a more representative or typical district, or if it is to characterize a particular site (where there may be perceived to be climate problems or where future development is planned). Areas where there is the highest probability of finding maximum effects can be judged initially by reference to the ranked list of UCZ types in Table 1. Similarly the likelihood that a station will be typical can be assessed using the ideas behind Table 1 and choosing extensive areas of similar urban development for closer investigation.

The search can be usefully refined in the case of air temperature and humidity by conducting spatial surveys, wherein the sensor is carried on foot, or mounted on a bicycle or a car and traversed through areas of interest. After several repetitions, cross-sections or isoline maps may be drawn (see Figure 3), revealing where areas of thermal or moisture anomaly or interest lie. Usually the best time to do this is a few hours after sunset or before sunrise on nights with relatively calm airflow and cloudless skies. This maximises the potential for the differentiation of micro- and local climate differences. It is not advisable to conduct such surveys close to sunrise or sunset because weather variables are changing so rapidly then that meaningful spatial comparisons are difficult.

If the station is to be part of a network to characterize spatial features of the urban climate then a broader view is needed. This consideration should be informed by thinking about the typical spatial form of urban climate distributions. For example, the isolines of urban heat and moisture 'islands' indeed look like the contours of their topographic namesakes (Figure 3). They have relatively sharp 'cliffs', often a 'plateau' over much of the urban area interspersed with localised 'mounds' and 'basins' of warmth/coolness and moistness/dryness. These features are co-located with patches of greater or lesser development such as clusters of apartments, shops, factories or parks, open areas or water. So a decision must be made: is the aim to make a representative sample of the UCZ diversity, or is it to faithfully reflect the spatial structure?

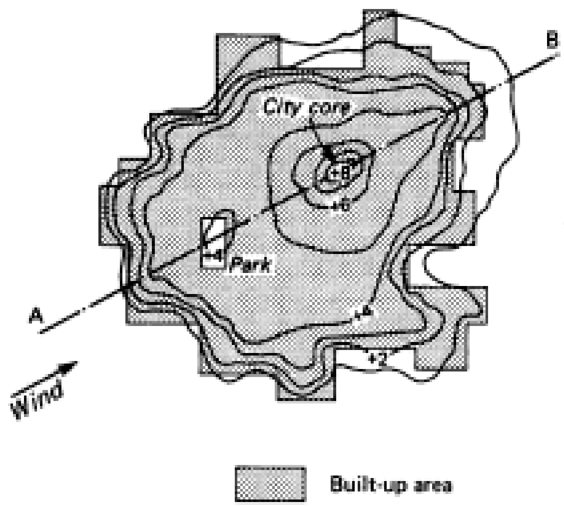


Figure 3 — Typical spatial pattern of isotherms in a large city at night with calm, clear weather illustrating the heat island effect [after Oke, 1982].

In most cases the latter is too ambitious with a fixed-station network in the UCL. This is because it will require many stations to depict the gradients near the periphery, the plateau region, and the highs and lows of the nodes of weaker and stronger than average urban development. If measurements are to be made from a tower, with sensors above the RSL, the blending action produces more muted spatial patterns and the question of distance of fetch to the nearest border between UCZs, and the urban-rural fringe, become relevant. Whereas a distance to a change in UCZ of 0.5 to 1 km may be acceptable inside the UCL, for a tower-mounted sensor the requirement is likely to be more like a few kilometres fetch.

Since the aim is to monitor local climate attributable to an urban area it is necessary to avoid extraneous microclimatic influences or other local or mesoscale climatic phenomena that will complicate the urban record. So unless there is specific interest in topographically-generated climate patterns, such as the effects of cold air drainage down valleys and slopes into the urban area, or the speed-up or sheltering of winds by hills and escarpments, or fog in river valleys or adjacent to water bodies, or geographically-locked cloud patterns, etc., it is sensible to avoid locations subject to such local and mesoscale effects. On the other hand if a benefit or hazard is derived from such events, it may be relevant to design the network specifically to sample its effects on the urban climate, such as the amelioration of an overly hot city by sea or lake breezes.

2.2 Siting

Once a choice of UCZ type and its general location inside the urban area is made the next step is to inspect the map, imagery and photographic evidence to narrow down candidate locations within a UCZ. What are sought are areas of reasonably homogeneous urban development without large patches of anomalous structure, cover or materials. The precise definition of 'reasonably' however is not possible; almost every real urban district has its own idiosyncrasies that reduce its homogeneity at some scale. A complete list is therefore not possible but examples of what to avoid are: unusually wet patches in an otherwise dry area, individual buildings that jut up by more than half the average building height, a large paved parking lot in an area of irrigated gardens, a large, concentrated heat source like a heating plant or a tunnel exhaust vent. Proximity to transition zones between different UCZ types should be avoided, as should sites where there are plans or the likelihood of major urban redevelopment. The level of concern with anomalous features decreases with distance away from the site itself, as discussed in relation to source areas.

In practice, for each candidate site a footprint should be estimated for radiation (e.g. equation 1) and for turbulent properties. Then key surface properties such as the mean height and density of the obstacles and characteristics of the surface cover and materials should be documented within these footprints. Their homogeneity should then be judged, either 'by eye' or using statistical methods. Once target areas of acceptable homogeneity for a screen-level or high-level (above-RSL) station are selected, it is helpful to identify potential 'friendly' site owners to host it. If a government agency is seeking a site it may already own land in the area for other purposes or have good relations with other agencies or businesses (offices, works yard, spare land, rights of way) including schools, universities, utility facilities (electricity, telephone, pipeline) and transport arteries (roads, railways). These are good sites, both because access may be permitted but also because they also often possess security from vandalism and may allow connection to electrical power. The roofs of buildings have been used often as the site for meteorological observations. This may often have been based on the mistaken belief that at this elevation the instrument shelter is freed from the complications of the UCL. In fact roof tops have their own very distinctly anomalous microclimates that lead to erroneous results. Airflow over a building creates strong perturbations in speed, direction and gustiness that are quite unlike the flow at the same elevation away from the building or near the ground (Figure 5). Flat-topped buildings may actually create flows on their roofs that are counter to the main external flow and speeds vary from extreme jetting to a near calm. Roofs are also constructed of materials that are thermally rather extreme. In light winds and cloudless skies they can become very hot by day and cold by night. Hence there is often a sharp gradient of air temperature near the roof. Further, roofs are designed to be waterproof and to shed water rapidly. This together with their openness to solar radiation and the wind makes them anomalously dry. In general, therefore, roofs are very poor locations for air temperature, humidity, wind and precipitation observations unless the instruments are placed on very tall masts. They can however be good for observing incoming radiation components.

After the site is chosen it is essential that the details of the site characteristics (metadata) are fully documented (see Section 4).

3 Exposure of instruments

3.1 Modifications to standard practice

In many respects the generally accepted standards for the exposure of meteorological instruments set out in Part I of the *Guide* apply to urban sites. However, there will be many occasions when it is impossible or makes no sense to conform. This section recommends some principles that will assist in such circumstances, but all eventualities cannot be anticipated. The recommendations here remain in agreement with general objectives in Chapter 1 of Part I of the *Guide* (see *Representativeness*, *Site selection*, including surface cover *representative of the locality*).

Many urban stations have been placed over short grass in open locations (parks, playing fields) and as a result they are actually monitoring modified rural-type conditions, not *representative* urban ones. This leads to the curious finding that some rural-urban pairs of stations show no urban effect on temperature (Peterson, 2003).

The guiding principle for the exposure of sensors in the UCL should be to locate them in such a manner that they monitor conditions that are *representative* of the environment of the selected UCZ. In cities and towns it is inappropriate to use sites similar to those which are standard in open rural areas. Instead it is recommended to site urban stations over surfaces that, within a microscale radius, are representative of the local scale urban environment. The *%Built* category (Table 1) is a crude guide to the recommended underlying surface. The most obvious requirement that cannot be met at many urban sites is the *distance from obstacles*— 'the site should be well away from trees, buildings, walls or other obstructions' (Chapter 1, Part I of the *Guide* on *siting and exposure)* Rather, it is recommended that the urban station be centred in an open space where the surrounding aspect ratio (z_H/W) is approximately representative of the locality. When installing instruments at urban sites it is especially important to use shielded cables because of the ubiquity of power lines and other sources of electrical noise at such locations.

3.2 Temperature

3.2.1 *Air temperature*

The sensors in general use to measure air temperature, including their accuracy and response characteristics, are appropriate in urban areas. Careful attention to radiation shielding and ventilation is especially recommended. In the UCL a sensor assembly may be relatively close to warm surfaces such as a sunlit wall, road, or a vehicle with a hot engine, or it may receive reflected heat from glassed surfaces. Therefore shields should be of a type to block radiation effectively. Similarly, an assembly placed in the lower UCL may be too well sheltered, so forced ventilation of the sensor is recommended. If a network includes a mixture of sensor assemblies with/without shields and ventilation this may contribute to inter-site differences, so practices should be uniform.

The surface over which air temperature is measured and the exposure of the sensor assembly should follow the recommendations given above in the previous section, i.e.

the surface should be typical of the UCZ and the thermometer screen or shield should be centred in a space with approximately average z_H/W. In very densely built-up UCZ this might mean it is located only 5 to 10 m from buildings that are 20 to 30 m high. If the site is a street canyon, z_H/W only applies to the cross-section normal to the axis of the street. The orientation of the street axis may also be relevant because of systematic sun-shade patterns. If continuous monitoring is planned, north-south oriented streets are favoured over east-west ones because there is less phase distortion, although daytime course of temperature may be rather peaked. At non-urban stations the screen height is recommended to be between 1.25 and 2 m above ground level. Whilst this is also acceptable for urban sites it may be better to relax this requirement to allow greater heights. This should not lead to significant error in most cases, especially in densely built-up areas, because observations in canyons show very slight air temperature gradients through most of the UCL, as long as location is more than 1 m from a surface (Nakamura and Oke, 1988). Measurements at heights of 3 or 5 m are little different from those at the standard height, have slightly greater source areas and place the sensor beyond the easy reach of damage or the path of vehicles. It also ensures greater dilution of vehicle exhaust heat and reduces contamination from dust. Air temperatures measured above the UCL, using sensors mounted on a tower, are influenced by air exchanged with the UCL plus the effects of the roofs. Roofs are much more variable thermally than most surfaces within the UCL. Most roofs are designed to insulate and hence to minimize heat exchange with the interior of the building. As a result roof surface temperatures often become very hot by day whereas the partially shaded and better conducting canyon walls and floor are cooler. At night circumstances are reversed with the roofs being relatively cold and canyon surfaces warmer as they release their daytime heat uptake. There may also be complications due to release of heat from roof exhaust vents. Therefore, whereas there is little variation of temperature with height in the UCL, there is a discontinuity near roof-level both horizontally and vertically. Hence if a meaningful spatial average is sought then sensors should be well above mean roof-level, $> 1.5z_H$ if possible, so that mixing of roof and canyon air is accomplished. Given air temperature data from an elevated sensor it is difficult to extrapolate it down towards screen-level because currently no standard methods are available. Similarly there is no simple, general scheme for extrapolating air temperatures horizontally inside the UCL. Statistical models work but they require a large archive of existing observations over a dense network, that is not usually available.

3.2.2 *Surface temperature*

Surface temperature is not commonly measured at urban stations but it can be a very useful variable to use as input in models to calculate fluxes. A representative surface temperature requires averaging an adequate sample of the many surfaces, vertical as well as horizontal, comprising an urban area. This is only possible using infrared remote sensing either from a scanner mounted on an aircraft or satellite, or a downward-facing pyrgeometer, or one or more radiation thermometers of which the combined field-of-view covers a representative sample of the urban district. Hence accurate results require that the target is sampled appropriately and its average emissivity is known.

3.2.3 *Soil and road temperature*

It is desirable to measure soil temperature in urban areas. The heat island effect extends down beneath the city and this may be of significance to engineering design for water pipes or road construction. In practice measurement of this variable may be difficult at more heavily developed urban sites. Bare ground may not be available, the soil profile is often highly disturbed and at depth there may be obstructions or anomalously warm or cool artefacts (e.g. empty, full, leaky water pipes, sewers, heat conduits). In urban areas the measurement of grass minimum temperature has almost no practical utility. Temperature sensors are often embedded in road pavement, especially in areas subject to freezing. They are usually part of a monitoring station for highway weather. It is often helpful to have sensors beneath both the tire track and the centre of the lane.

3.3 Atmospheric pressure

At the scale of urban areas it will probably not be necessary to monitor atmospheric pressure if there is already a synoptic station in the region. If pressure sensors are included the recommendations of Chapter 3, Part I of the *Guide*, apply. In rooms and elsewhere in the vicinity of buildings there is the probability of pressure ‘pumping’ due to gusts, also interior-exterior pressure differences may exist if the sensor is located in an air conditioned room. Both difficulties can be alleviated if a static pressure head is installed (see Part I, Section 3.8 of the *Guide*).

3.4 Humidity

The instruments normally used for humidity (Part I, Chapter 4 of the *Guide*) are applicable to the case of urban areas. The guidelines given in Section 3.2.1 for the siting and exposure of temperature sensors in the UCL, and above the RSL, apply equally to humidity sensors.

Urban environments are notoriously dirty (dust, oils, pollutants). Several hygrometers are subject to degradation or require increased maintenance in urban environments. Hence if psychrometric methods are used the wet-bulb sleeve has to be replaced more frequently than normal and close attention is necessary to ensure the distilled water remains uncontaminated. The hair strands of a hair hygrometer can be destroyed by polluted urban air, hence their use is not recommended for extended periods. The mirror of dew-point hygrometers and the windows of ultraviolet and infrared absorption hygrometers need to be cleaned frequently. Some instruments degrade sufficiently that the sensors have to be completely replaced fairly regularly. Because of shelter from wind in the UCL forced ventilation at the rate recommended in Part I Section 4.2 of the *Guide* is essential, as is the provision of shielding from extraneous sources of solar and longwave radiation.

3.5 Wind speed and direction

The measurement of wind speed and direction is highly sensitive to flow distortion by obstacles. Obstacles create alterations to the average wind flow and turbulence. Such effects apply at all scales of concern, including the effects of local relief due to hills, valleys and cliffs, sharp changes in roughness or in the effective surface elevation (z_d, see below), perturbation of flow around clumps of trees and buildings, individual trees and buildings and even disturbance induced by the physical bulk of the tower or mounting arm to which the instruments are attached.

3.5.1 *Mean wind profile*

However, if a site is on reasonably level ground, has sufficient fetch downstream of major changes of roughness and is in a single UCZ without anomalously tall buildings, then a mean wind profile such as that in Figure 4 should exist. The mean is both spatial and temporal. Within the UCL no one site can be expected to possess such a profile. Individual locations experience highly variable speed and direction shifts as the airstream interacts with individual building arrangements, streets, courtyards and trees. In street canyons the shape of the profile is different for along-canyon, versus across-canyon flow (Christen *et al.* 2002) and depends on position across and along the street (DePaul and Shieh, 1986). Wind speed gradients in the UCL are small until quite close to the surface. As a first approximation the profile in the UCL can be described by an exponential form (Britter and Hanna, 2003) merging with the log profile near roof-level (Figure 4).

In the inertial sublayer Monin-Obukhov similarity theory applies, including the logarithmic law:

$$\overline{u}_z = (u_* / k)\{ln[(z - z_d)/z_0] + \Psi_M\left(\frac{z}{L}\right)\} \quad (11.2)$$

where u_* is the friction velocity, k is von Karman's constant (0.40), z_0 is the surface roughness length, z_d is the zero-plane displacement height (Figure 4), L is the Obukhov stability length (= $-u_*^3/[k(g/\theta_v)Q_H]$), where g is the gravitational acceleration, θ_v the virtual potential temperature and Q_H the turbulent sensible heat flux), and ψ_M is a dimensionless function that accounts for the change in curvature of the wind profile away from the neutral profile with greater stability or instability[1]. In the neutral case (typically with strong winds and cloud) when ψ_M is unity, equation (2) reduces to:

$$\overline{u}_z = (u_* / k) ln[(z - z_d)/z_0] \quad (11.3)$$

[1] For more on L and the form of the ψ_M function, see a standard micrometeorology text, e.g. Stull, 1988; Garratt, 1992 or Arya, 2001. Note that u_* and Q_H should be evaluated in the inertial layer above the RSL.

The wind profile parameters can be measured using a vertical array of anemometers, or measurements of momentum flux or gustiness from fast-response anemometry in the inertial layer, but estimates vary with wind direction and are sensitive to errors (Wieringa, 1996; Verkaik, 2000). Methods to parameterize the wind profile parameters z_0 and z_d for urban terrain are also available (for reviews see Grimmond and Oke, 1999; Britter and Hanna, 2003). The simplest involve general descriptions of the land use and obstacles (Davenport *et al.*, 2000, see Tables 1 and 2; Grimmond and Oke, 1999), or a detailed description of the roughness element heights and their spacing from either a Geographic Information System of the building and street dimensions, or maps and aerial oblique photographs, or airborne/satellite imagery and the application of one of several empirical formulae (for recommendations see Grimmond and Oke, 1999).

It is important to incorporate the displacement height z_d into urban wind profile assessments. Effectively this is equivalent to setting a base for the logarithmic wind profile that recognizes the physical bulk of the urban canopy. It is like setting a new 'ground surface' aloft, where the mean momentum sink for the flow is located (Figure 4). Depending on the building and tree density this could set the base of the profile at a

Table 2 : *Davenport classification of effective terrain roughness (revised 2000)*[1].

Class	z_0 *(m)*	*Landscape description*
4 *" Roughly open"*	**0.10**	Moderately open country with occasional obstacles (e.g. isolated low buildings or trees) at relative horizontal separations of at least 20 obstacle heights.
5 *"Rough"*	**0.25**	Scattered obstacles (buildings) at relative distances of 8 to 12 obstacle heights for low solid objects (e.g. buildings). *(Analysis may need z_d)*[2]
6 *"Very rough"*	**0.5**	Area moderately covered by low buildings at relative separations of 3 to 7 obstacle heights and no high trees. *(Analysis requires z_d)*[2]
7 *"Skimming"*	**1.0**	Densely built-up area without much building height variation. *(Analysis requires z_d)*[2]
8 "Chaotic"	**2.0**	City centres with mix of low and high-rise buildings. *(Analysis by wind tunnel advised)*

[1] Abridged version (urban roughness only) of Davenport *et al.*, (2000); for classes 1 to 3 and for rural classes 4 to 8 see Part I, Chapter 5, Annex and Aguilar *et al.* (2003).

[2] First order values of z_d are given as fractions of average obstacle height, viz: 0.5 z_H, 0.6 z_H and 0.7 z_H for Davenport Categories 5, 6 and 7, respectively.

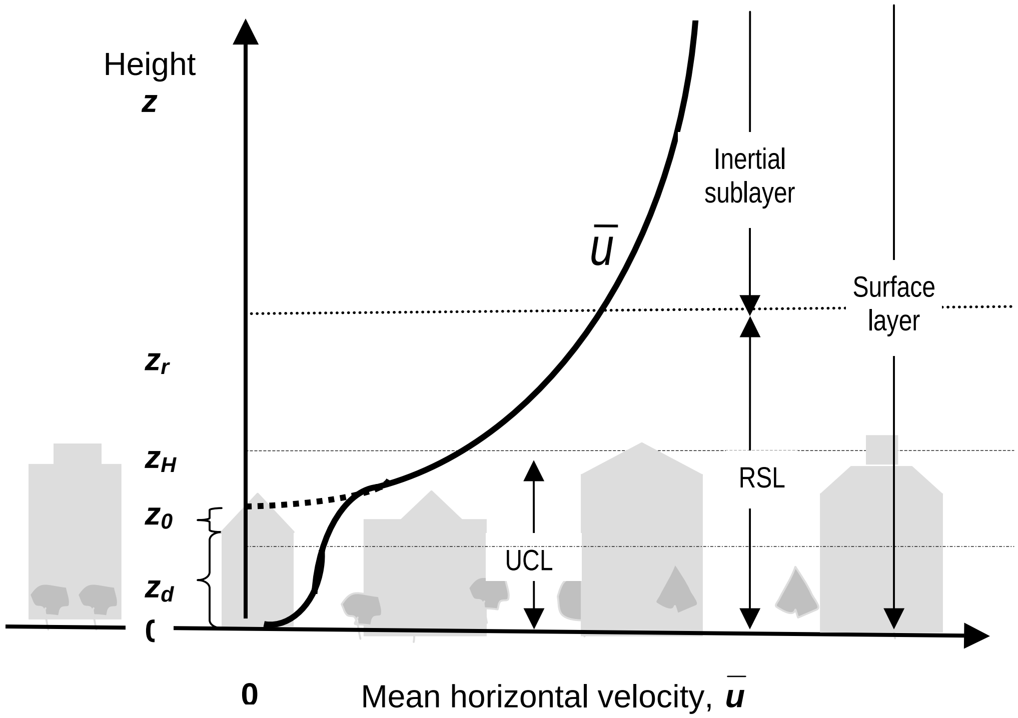


Figure 4 Generalized mean (spatial and temporal) wind velocity ($\overline{U}$) profile in a densely developed urban area including the location of sublayers of the surface layer. The measures on the height scale are the mean height of the roughness elements (z_H), the roughness sublayer (z_r, or the blending height), the roughness length (z_0) and zero-plane displacement length (z_d). Dashed line – profile extrapolated from the inertial sublayer; solid line - actual profile.

height between 0.5 and 0.8z_H (Grimmond and Oke, 1999), hence failure to incorporate it in calculations causes large errors. First estimates can be made using the fractions of z_H given in the footnote of Table 2.

3.5.2 *Height of measurement and exposure*

The choice of height at which wind measurements should be made in urban areas is a challenge, but if some basic principles are applied meaningful results can be attained. Poor placement of wind sensors in cities is the source of considerable wasted resources and effort and leads to potentially erroneous calculations of pollutant dispersion. Of course this is even a source of difficulty in open terrain due to obstacles and topographic effects. This is the reason why the standard height for rural wind observations is set at 10 m above ground, not at screen-level, and why there the anemometer should not be at closer horizontal distance from obstructions than ten obstacle heights (Part I, Chapter 5.9.2 of the *Guide*). In typical urban districts it is not possible to find such locations, e.g. in a UCZ with 10 m high buildings and trees it would need a patch that is at least 100 m in radius. If such a site exists it is almost certainly not representative of the zone. It has already been noted that the roughness sublayer, in which the effects of individual roughness elements persist, extends to a height of about $1.5z_H$ in a densely built-up area and perhaps higher in less densely developed sites. Hence in the example district the minimum acceptable anemometer height is at least 15 m, not the standard 10 m. When building heights are much taller, an anemometer at the standard 10 m height would be well down in the UCL, and given the heterogeneity of urban form and therefore of wind structure, there is little merit in placing a wind sensor beneath, or even at about, roof-level.

It is well known from wind tunnel and field observations that flow over an isolated solid obstacle, like a tall building, is greatly perturbed both immediately over and around it. These include modifications to the streamlines, the presence of recirculation zones on the roof and in the so-called ‘bubble’ or cavity behind it, and wake effects that persist in the downstream flow for tens of building height multiples that affect a large part of the neighbourhood (Figure 5).

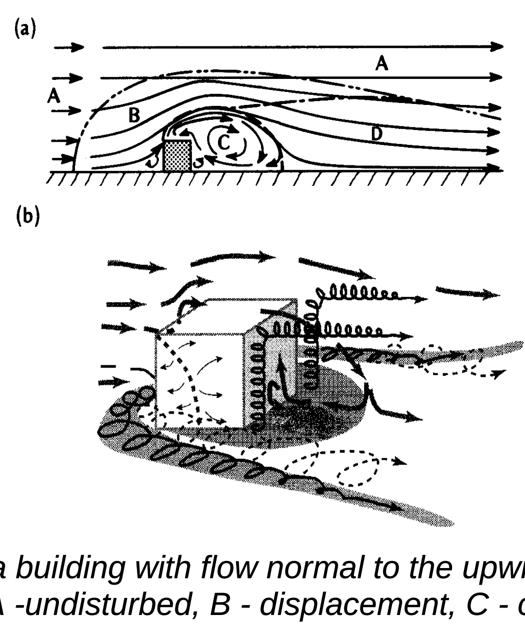


Figure 5. 2-D flow around a building with flow normal to the upwind face (a) stream lines and flow zones; A -undisturbed, B - displacement, C - cavity, D – wake (after Halitsky, 1963), and (b) flow, and vortex structures (simplified after Hunt et al., 1978).

There are many examples of poorly exposed anemometer-vane systems in cities. The data registered by such instruments are erroneous, misleading, potentially harmful if used to obtain wind input for wind load or dispersion applications, and wasteful of resources. The inappropriateness of placing anemometers and vanes on short masts on the top of buildings cannot be over-emphasized. Speeds and directions vary hugely in short distances, both horizontally and vertically. Results from instruments deployed in this manner bear little resemblance to the general flow and are entirely dependent on the specific features of the building itself, the mast location on the structure, and the angle-of-attack of the flow to the building. The circulating and vortex flows seen in Figure 5 mean that if the mast is placed ahead of, on top of, or in the cavity zone behind a building, direction measurements could well be counter to those prevailing in the flow outside the influence of the building's own wind climate (i.e. in zone A of Figure 5a), and speeds are highly variable. To get outside the perturbed zone wind instruments must be mounted at a considerable height. For example, it has been proposed that such sensors should be at a height greater than the maximum horizontal dimension of the major roof (Wieringa, 1996). This implies an expensive mast system, perhaps with guys that subtend a large area and perhaps difficulties in obtaining permission to install. Nevertheless, this is the only acceptable approach if meaningful data are to be measured.

Faced with such realities, sensors should be mounted so that their signal is not overly compromised by their support structure. The following recommendations are made:

(a) in urban districts with low element height and density (UCZ 6 and 7) it may be possible to use a site where the 'open country' standard exposure guidelines can be met. To use the 10 m height the closest obstacles should be at least 10 times their height distant from the anemometer and not be more than about 6 m tall on average;

(b) in more densely built-up districts, with relatively uniform element height and density (buildings and trees), wind speed and direction measurements should be made with the anemometer mounted on a mast of open construction at 10 m or 1.5 times the mean height of the elements, whichever is the greater ;

(c) in urban districts with scattered tall buildings the recommendations are as in (b) but with special concern to avoid the wake zone of the tall structures; and

(d) it is not recommended to measure wind speed or direction in densely-built areas with multiple high-rise structures unless a very tall tower is used.

Anemometers on towers with open construction should be mounted on booms (cross-arms) that are long enough to keep the sensors at least two, better three, tower diameters distance from the side of the mast (Gill *et al.*, 1967). Sensors should be mounted so that the least frequent flow direction passes through the tower. If this is not possible or if the tower construction is not very open, two or three booms with duplicate sensors may have to be installed to avoid wake effects and upwind stagnation produced by the tower itself.

If anemometer masts are to be mounted on tall or isolated buildings the effects of the dimensions of that structure on the flow must be considered (see Part II, Chapter 5.3.3 of the *Guide*). This is likely to require analysis using wind tunnel, water flume or computational fluid dynamics models specifically tailored to the building in question, and including its surrounding terrain and structures.

The object is to ensure that all wind measurements are made at heights where they are representative of the upstream surface roughness at the local scale and are as free as possible of confounding influences from micro- or local scale surface anomalies. Hence the emphasis on gaining accurate measurements at *whatever height is necessary to reduce error* rather than measuring at a *standard height*. This may require splitting the wind site from the location of the other measurement systems. It may also result in wind observations at several different heights in the same settlement. That will necessitate extrapolation of the measured values to a common height, if spatial differences are sought or if the data are to form input to a mesoscale model. Such extrapolation is easily achieved by applying the logarithmic profile (equation 2) to two heights:

$$\overline{u}_1 / \overline{u}_{ref} = \ln(z_1 / z_0) / \ln(z_{ref} / z_0) \qquad (11.4)$$

where z_{ref} is the chosen reference height, z_1 is the height of the site anemometer and z_0 is the roughness length of the UCZ. In urban terrain it is correct to define the reference height to include the zero-plane displacement height, i.e. both z_1 and z_{ref} have the form ($z_x - z_d$), where the subscript x stands for ‘1’ or ‘ref’. A suitable reference height may be 50 m above displacement height.

Other exposure corrections for flow distortion, topography, and roughness effects can be made as recommended in Chapter 5, Part I of the *Guide* (see exposure correction). It may well be that suitable wind observations cannot be arranged for a given urban site. In that case it is still possible to calculate the wind at the reference height using wind observations at another urban station or the airport using the ‘logarithmic transformation’ model of Wieringa (1986):

$$\overline{u}_{zA} = \overline{u}_{zB}\left[\frac{ln(z_r / z_{0B}) \cdot ln(z_A / z_{0A})}{ln(z_B / z_{0B}) \cdot ln(z_r / z_{0A})}\right] \qquad (11.5)$$

where the subscripts A and B refer to the site of interest where winds are wanted and the site where standard wind measurements are available, respectively. The blending height z_r should here either be taken as $4z_H$ (Section 1.1) or be given a standard value of 60 m; the method is not very sensitive to this term. Again, if either site has dense, tall roughness elements, the corresponding height scale should incorporate z_d.

3.5.3 *Wind sensor considerations*

Instruments used to measure wind speed, direction, gustiness and other characteristics of the flow in non-urban environments are applicable to urban areas. In cities wind direction should always be measured, as well as speed, in order to allow azimuth-dependent corrections of tower influence to be made. If mechanical cup anemometers are used, the dirtiness of the atmosphere requires an increased frequency of maintenance and close attention to bearings and corrosion . If measurements are made in the UCL gustiness may increase the problem of cup over-speeding and too much shelter may cause anemometers to operate near or below their threshold minimum speed. This must be addressed through heightened maintenance and perhaps the choice of fast-response anemometers, propeller-type anemometers or sonic anemometers. Propeller anemometers are less prone to over-speeding, and sonic anemometers, having no moving parts are practically maintenance free. However, they are expensive, need sophisticated electronic logging and processing and not all models work when it is raining.

3.6 Precipitation

The instruments and methods for the measurement of precipitation given in Chapter 6, Part I of the *Guide* are also relevant to urban areas. The measurement of precipitation as rain or snow is always susceptible to errors associated with the exposure of the gauge, especially the wind field in its vicinity. Given the urban context and the highly variable wind field in the UCL and the RSL, concerns arise from four main sources:

(a) the interception of precipitation during its trajectory to the ground by nearby collecting surfaces such as trees and buildings;

(b) hard surfaces near the gauge may cause splash-in to the gauge, and over-hanging objects may drip into the gauge;

(c) the spatial complexity of the wind field around obstacles in the UCL causes very localised concentration or absence of rain- or snow-bearing airflow; and

(d) the gustiness of the wind in combination with the physical presence of the gauge itself causes anomalous turbulence around it that leads to under- or over-catch.

In open country standard exposure requires that obstacles should be no closer than two times their height. In some ways this is less restrictive than for temperature, humidity or wind. However, in the UCL the turbulent activity created by flow around sharp-edged buildings is more severe than that around natural obstacles and may last for greater distances in their wake. Again, the highly variable wind speeds and directions encountered on the roof of a building make it a site to be avoided.

On the other hand, unlike temperature, humidity and wind, the object of precipitation measurement is often not for the analysis of local effects, except perhaps in the case of rainfall rate. Some urban effects on precipitation may be initiated at the local scale (e.g. by a major industrial facility) but may not show up until well downwind of the city. Distinct patterns within an urban area are more likely to be due to relief or coastal topographic effects.

Selecting an extensive open site in the city, where normal exposure standards can be met, may be acceptable but it almost certainly will mean that the gauge will not be co-located with the air temperature, humidity and wind sensors. While the latter sensors need to be representative of the local scale urban structure, cover, fabric and metabolism of a specific UCZ, precipitation does not have to be.

However, the local environment of the gauge is important if the station is to be used to investigate intra-urban patterns of precipitation *type*. For example, the urban heat island has an influence on the survival of different forms of precipitation, e.g. snow or sleet at cloud-base may melt in the warmer urban atmosphere and end up as rain at the ground. This may mean rural and suburban sites get snow when the city centre registers rain.

It is recommended that precipitation gauges in urban areas:

(a) be located in open sites within the city where the standard exposure criteria can be met (e.g. playing fields, open parkland with a low density of trees, an urban airport); or

(b) be located in conjunction with the wind instruments if a representative exposure for them is found. At other than low density built-up sites this probably means mounting the gauge above roof-level on a mast. This means the gauge will be subject to greater than normal wind speed and hence the error of estimation will be greater than near the surface, and the gauge output will have to be corrected. Such correction is feasible if wind is measured on the same mast. It also means that automatic recording is favoured and the gauge must be checked regularly to make sure it is level and that the orifice is free of debris;

(c) not be located on the roofs of buildings unless they are exposed at sufficient height to avoid the wind envelope of the building; and that

(d) the measurement of depth of snowfall should be made at an open site or, if made at developed sites, a large spatial sample should be obtained to account for the inevitable drifting around obstacles. Such sampling should include streets oriented in different directions.

Urban hydrologists are interested in rainfall rates, especially during major storm events. Hence tipping bucket rain gauges or weighing gauges have utility. Measurement of rain- and snowfall in urban areas stands to benefit from the development of techniques such as optical rain gauges and radar.

Dew, ice and fog precipitation also occurs in cities and can be of significance to the water budget, especially for certain surfaces, and may be relevant to applications such as plant disease, insect activity, road safety and as a supplementary source of water resources. The methods outlined in Chapter 6, Part I of the *Guide* are appropriate for urban sites.

3.7 Radiation

There is a paucity of radiation flux measurements conducted in urban areas, currently. For example, there are almost none in the Global Energy Balance Archive (GEBA) of the World Climate Programme or in the Atmospheric Radiation Measurement (ARM) Programme of the US Department of Energy. Radiation measurement sites are often located in rural or remote locations specifically to avoid the aerosol and gaseous pollutants of cities that 'contaminate' their records. Even when a station has the name of a city, the metadata usually reveal they are actually located well outside the urban limits. If they are in the built-up area only incoming solar (global) radiation is likely to be measured, neither incoming longwave nor any fluxes with outgoing components are monitored. It is mostly short-term experimental projects focussing specifically on urban effects that measure both the receipt and loss of radiation in cities. All short- and longwave fluxes are impacted by the special properties of the atmosphere and surface of cities, and the same is true for the net all-wave radiation balance that effectively drives the urban energy balance (Oke, 1988).

All of the instruments, calibrations, corrections, and most of the field methods outlined in relation to the measurement of radiation at open country sites in Chapter 7, Part I of the *Guide,* apply to the case of urban areas. Only differences, or specifically urban needs or difficulties, are mentioned here.

3.7.1 *Incoming fluxes*

Incoming solar radiation is such a fundamental forcing variable of urban climate that its measurement should be given a high priority when a station is established or upgraded. Knowledge of this term together with standard observations of air temperature, humidity and wind speed, plus simple measures of the site structure and cover, allows a meteorological pre-processor scheme (i.e. methods and algorithms used to convert standard observation fields into the variables required as input by models, but not measured; e.g. fluxes, stability, mixing height, dispersion coefficients, etc.) such as OLM (Berkowicz and Prahm, 1982; Olesen and Brown, 1992), HPDM (Hanna and Chang, 1992) or LUMPS (Grimmond and Oke, 2002) to be used to calculate much more sophisticated measures such as atmospheric stability, turbulent statistics, the fluxes of momentum, heat and water vapour. These in turn make it possible to predict the mixing height and pollutant dispersion (COST 710, 1998; COST 715, 2001). Further, solar radiation can be used as a surrogate for daytime cloud activity and is the basis of applications in solar energy, daylight levels in buildings, pedestrian comfort, legislated rights to solar exposure and many other fields. At automatic stations the addition of solar radiation measurement is simple and relatively inexpensive.

The exposure requirements for pyranometers and other incoming flux sensors are relatively easily met in cities. The fundamental needs are for the sensor to be level, free of vibration, free of any obstruction above the plane of the sensing element including both fixed features (buildings, masts, trees, and hills) and ephemeral ones (clouds generated from exhaust vents or pollutant plumes). So a high, stable and accessible platform like the roof of a tall building is often ideal. It may be impossible to avoid short-term obstruction of direct-beam solar radiation impinging on an up-facing radiometer by masts, antennae, flag poles and similar structures. If this occurs the location of the obstruction and the typical duration of its impact on the sensing element should be fully documented (see Section 4). Methods to correct for such interference are mentioned in Chapter 7, Part I of the *Guide*. It is also important to ensure there is not excessive reflection from very light-coloured walls that may extend above the local horizon. It is essential to clean the upper domes at regular intervals. In heavily polluted environments this may mean daily.

Other incoming radiation fluxes are also desirable but their inclusion depends on the nature of the city, the potential applications and the cost of the sensors. The fluxes (and their instruments) are: incoming direct beam solar (pyrheliometer), diffuse sky solar (pyranometer fitted with a shade ring or a shade disk on an equatorial mount), solar ultraviolet (broadband and narrowband sensors, and spectrometers) and longwave radiation (pyrgeometer). All have useful applied value: beam (pollution extinction coefficients), diffuse (interior daylighting, solar panels), ultraviolet (depletion by ozone and damage to humans, plants and materials), longwave (monitoring nocturnal cloud and enhancement of the flux by pollutants and the heat island).

3.7.2 *Outgoing and net fluxes*

The reflection of solar radiation and the emission and reflection of longwave radiation from the underlying surface, and the net result of short-, long- and all-wave radiant fluxes are currently seldom monitored at urban stations. This means that significant properties of the urban climate system remain unexplored. The albedo, that decides if solar radiation is absorbed by the fabric or is lost back to the atmosphere and Space, will remain unknown. The opportunity to invert the Stefan-Boltzmann relation and solve for the surface radiant temperature is lost. The critical net radiation that supports warming/cooling of the fabric, and the exchanges of water and heat between the surface and the urban boundary layer is missing. Of these, net all-wave radiation data is the greatest lack. Results from a well-maintained net radiometer are invaluable to drive a pre-processor scheme and as a surrogate measure of cloud.

The main difficulty in measuring outgoing radiation terms accurately is the exposure of the down-facing radiometer to view a representative area of the underlying urban surface. The radiative source area (Equation 1, Figure 2), should ideally 'see' a representative sample of the main surfaces contributing to the flux. In the standard exposure cases, defined in the relevant sections of Chapter 7, Part I of the *Guide*, a sensor height of 2 m is deemed appropriate over a short grass surface. At that height 90% of the flux originates from a circle of diameter 12 m on the surface. Clearly a much greater height is necessary over an urban area in order to sample an area that contains a sufficient population of surface facets to be representative of that UCZ. Considering the case of a radiometer at 20 m (at the top of a 10 m high mast mounted on a 10 m high building) in a densely developed district, the 90% source area has a diameter of 120 m at ground level. This might seem sufficient to 'see' several buildings and roads, but it must also be considered that the system is three-dimensional, not quasi-flat like the grass. At the level of the roofs in the example the source area is now only 60 m in diameter, and relatively few buildings may be viewed.

The question becomes whether the sensor can 'see' an appropriate mix of climatically active surfaces? This means not only does it see an adequate set of plan-view surface types, but also is it sampling appropriate fractions of roof, wall, and ground surfaces, including the correct fractions of each that are in sun or shade? This is a non-trivial task that depends on the surface structure and the positions of both the sensor and the Sun in space above the array. Soux *et al.*, 2004 developed a model to calculate these fractions for relatively simple urban-like geometric arrays, but more work is needed before guidelines specific to individual UCZ types are available. It seems likely that the sensor height has to be *greater* than that for turbulence measurements. The non-linear nature of radiative source area effects is clear from Equation (1) (refer Figure 2). The greater weighting of surfaces closer to the mast location means the immediate surroundings are most significant. In the previous example of the radiometer at 20 m on a 10 m building, 50% of the signal at the roof-level comes from a circle of only 20 m diameter (perhaps only a single building). If the roof of that building, or other surface on which the mast is mounted, has anomalous radiative properties (albedo, emissivity or temperature) it disproportionately affects the flux, which is supposed to be representative of a larger area. Hence roofs with large areas of glass or metal, or with an unusually dark or light colour, or those designed to hold standing water, should be avoided.

Problems associated with down-facing radiometers at large heights include (a) the difficulty of ensuring the plane of the sensing element is level, (b) ensuring that at large zenith angles the sensing element does not 'see' direct beam solar radiation or incoming longwave from the sky, (c) considering whether there is need to correct results to account for radiative flux divergence in the air layer between the instrument height and the surface of interest. To eliminate extraneous solar or longwave radiation near the horizon it may be necessary to install a narrow collar that restricts the field-of-view to a few degrees less than 2π. This will necessitate a small correction to readings to account for the missing diffuse solar input (see Chapter 7, Part I, Annex 7E of the *Guide* for the case of a shade band) or the extra longwave input from the collar.

Inverted sensors may be subject to error because their back is exposed to solar heating. This should be avoided by use of some form of shielding and insulation. Maintaining the cleanliness of the instrument domes and wiping away deposits of water or ice may also be more difficult. Inability to observe the rate and effectiveness of ventilation of instruments at height means that the choice of instruments that do not need aspiration is preferred. The ability to lower the mast to attend to cleaning, replacement of desiccant or polyethylene domes and levelling is an advantage.

It is recommended that:

(a) down-facing radiometers be placed at a height *at least* as large as a turbulence sensor (i.e. a minimum of 2 z_H is advisable) and preferably higher;

(b) the radiative properties of the *immediate surroundings* of the radiation mast are representative of the urban district of interest.

3.8 Sunshine duration

The polluted atmospheres of urban areas cause a reduction of sunshine hours compared with their surroundings or pre-urban values (Landsberg, 1981). The instruments, methods and exposure recommendations given in Chapter 8, Part I of the *Guide* are applicable to the case of an urban station.

3.9 Visibility and meteorological optical range

The effects of urban areas upon visibility and meteorological optical range (MOR) are complex because while pollutants tend to reduce visibility and MOR through their impact on the attenuation of light and the enhancement of certain types of fog, urban heat and humidity island effects often act to diminish the frequency and severity of fog and low cloud. There is considerable practical value in having urban visibility and MOR information to fields such as aviation, road and river transport and optical communications, and thus to include these observations at urban stations.

Visual perception of visibility is hampered in cities. While there are many objects and lights that can serve as range targets, it may be difficult to obtain a sufficiently uninterrupted line-of-sight at the recommended height of 1.5 m. Use of a raised platform or the upper level of buildings is considered non-standard and not recommended.

Observations near roof-level may also be affected by scintillation from heated roofs, or the ‘steaming’ of water from wet roofs during drying, or pollutants and water clouds released from chimneys and other vents.

Instruments to measure MOR, such as transmissometers and scatter meters generally work well in urban areas. They require relatively short paths and if the optics are maintained in a clean state will give good results. Naturally the instrument must be exposed at a location that is representative of the atmosphere in the vicinity but the requirements are no more stringent than for others placed in the UCL. It may be that for certain applications knowledge of the height variation of MOR is valuable, e.g. the position of the fog top or the cloud base.

3.10 Evaporation and other fluxes

Urban development usually leads to a reduction of evaporation primarily due to sealing the surface by built features and the removal of vegetation, although in some naturally dry regions it is possible that an increase may occur if water is imported from elsewhere and used to irrigate urban vegetation.

Very few evaporation measurement stations exist in urban areas. This is understandable because it is almost impossible to interpret evaporation measurements conducted in the UCL using atmometers, evaporation pans or lysimeters. As detailed in Chapter 10, Part I of the *Guide*, such measurements must be at a site that is representative of the area; not closer to obstacles than 5 times their height, or 10 times if they are clustered; not placed on concrete or asphalt; not unduly shaded; and free of hard surfaces that may cause splash-in. In addition to these concerns the surfaces of these instruments are assumed to act as surrogates for vegetation or open water systems. Such surfaces are probably not representative of the surroundings at an urban site. Hence, they are in receipt of micro-advection that is likely to force evaporation at unrealistically high rates.

Consider the case of an evaporation pan installed over a long period, that starts out at a semi-arid site that converts to irrigated agricultural uses, then is encroached upon by suburban development and later is in the core of a heavily developed urban area. Its record of evaporation starts out as very high, because it is an open water surface in hot, dry surroundings, so although actual evaporation in the area is very low, the loss from the pan is forced by advection to be large. The introduction of irrigation makes conditions cooler and more humid so the pan readings drop, but actual evaporation is large. Urban development largely reverses the environmental changes, and it reduces the wind speed near the ground, so pan losses increase but the actual evaporation probably drops. Hence throughout this sequence pan evaporation and actual evaporation are probably in anti-phase. During the agricultural period a pan coefficient might have been applied to convert the pan readings to those typical of short grass or crops. No such coefficients are available to convert pan to urban evaporation, even if the readings are not corrupted by the complexity of the UCL environment. In summary, the use of standard evaporation instruments in the UCL is not recommended.

The dimensions and heterogeneity of urban areas renders the use of full-scale lysimeters impractical (e.g. the requirement to be not less than 100 to 150 m from a change in surroundings). Micro-lysimeters can give the evaporation from individual surfaces, but they are still specific to their surroundings. Such lysimeters need careful attention, including renewing the soil monolith to prevent drying out, and are not suitable for routine long-term observations.

Spatially-averaged evaporation and other turbulent fluxes (momentum, sensible heat, carbon dioxide) information can be obtained from observations above the RSL. Several of these fluxes are of greater practical interest in urban areas than in many open country areas. For example, the vertical flux of horizontal momentum, and the integral wind statistics and spectra are needed in questions of wind loading on structures and the dispersion of air pollutants. The sensible heat flux is an essential input to calculation of atmospheric stability (e.g. the flux Richardson Number and the Obukhov length) and the depth of the urban mixing layer. Fast response eddy covariance or standard deviation methods are recommended, rather than profile gradient methods. Appropriate instruments include sonic anemometers, infrared hygrometers and gas analyzers and scintillometers. The sensors should be exposed like wind sensors: above the RSL but below the internal boundary layer of the UCZ of interest. Again, such measurements rely on the flux ‘footprint’ being large enough to be representative of the local area of interest.

If such flux measurements are beyond the financial and technical resources available, a meteorological pre-processor scheme such as OLM, HPDM or LUMPS (see Section 3.7) can be an acceptable method to obtain aerially representative values of urban evaporation and heat flux. Such schemes only require spatially representative observations of incoming solar radiation, air temperature, humidity and wind speed, and general estimates of average surface properties such as albedo, emissivity, roughness length and the fractions of the urban district that are vegetated or built-up or irrigated. Clearly the wind speed observations must conform to the recommendations in Section 3.5. Ideally the air temperature and humidity should also be observed above the RSL, but if only UCL values are available this is usually acceptable because such schemes are not very sensitive to these variables.

3.11 Soil moisture

Knowledge of urban soil moisture can be useful, e.g. to gardeners and in the calculation of evaporation. Its thermal significance in urban landscapes is evidenced by the remarkably distinct patterns in remotely-sensed thermal imagery. By day any patch with active vegetation or irrigated land is noticeably cooler than built, paved or bare land. However, the task of sampling to obtain representative values of soil moisture is daunting.

Some of the challenges presented include the fact that large fractions of the urban surface are completely sealed over by paved and built features; much of the exposed soil has been highly disturbed in the past during construction activity or abandonment of old urban uses; the 'soil' may actually be largely formed from the rubble of old buildings and paving materials or have been imported as soil or fill material from distant sites; or the soil moisture may be affected by seepage from localised sources such as broken water pipes or sewers or be the result of irrigation. All of this leads to a very patchy urban soil moisture field that may have totally dry plots situated immediately adjacent to over-watered lawns. Hence whilst some idea of local scale soil moisture may be possible in areas with very low urban development, or where the semi-natural landscape has been preserved, it is almost impossible to characterise in most urban districts. Here again it may be better to use rural values that give a regional background value rather than have no estimate of soil moisture availability.

3.12 Present weather

If human observers, or the usual instrumentation is available, observation of present weather events and phenomena such as rime, surface ice, fog, dust and sand storms, funnel clouds and thunder and lightning can be valuable, especially those with practical implications for the efficiency or safety of urban activities, e.g. transport. If archiving facilities are available, the images provided by web cameras can provide very helpful evidence of clouds, short-term changes in cloud associated with fronts, fog banks that ebb and flow, low cloud that rises and falls, and the arrival of dust and sand storm fronts.

3.13 Cloud

Cloud cover observation is rare in large urban areas but such information is very useful. All of the methods and instruments outlined in Chapter 15, Part I of the *Guide* are applicable to urban areas. The large number and intensity of light sources in cities combined with a hazy, sometimes polluted, atmosphere makes visual observation more difficult. Where possible the observational site should avoid areas with particularly bright lighting..

3.14 Atmospheric composition

Monitoring of atmospheric pollution in the urban environment is increasingly important, but is a specialist discipline not dealt with in this chapter. Chapter 17, Part I of the *Guide* treats the subject in the broader context of the Global Atmospheric Watch (GAW).

3.15 Profiling techniques for the urban boundary layer

Urban influences extend throughout the planetary boundary layer (Figure 1), so as well as the need to use towers and masts to obtain observations above the RSL there is a need to probe higher. Of special interest are effects on the wind field and the vertical temperature structure including the depth of the mixing layer and their combined role in affecting pollutant dispersion.

All of the special profiling techniques outlined in Chapter 5, Part II of the *Guide* are relevant to the case of urban areas. Acoustic sounders (sodars) are potentially very useful but it must be recognized that they suffer from two disadvantages in settled areas: firstly, their signals are often interfered with by various urban sources of noise (traffic, aircraft, construction activity, even lawnmowers), and secondly, they may not be permitted to operate because of annoyance to residents. Wind profiler radars, radio-acoustic sounding systems (RASS), microwave radiometers, microwave temperature profilers, laser radars (lidars) and modified ceilometers are all suitable systems to monitor the urban atmosphere if interference from ground clutter can be avoided. Similarly balloons for wind tracking, boundary layer radiosondes (minisondes) and instrumented tethered balloons can all be used with good success as long as air traffic authorities allow. Instrumented towers and masts can provide excellent means of placing sensors above roof-level and into the inertial sublayer, and very tall structures may permit measurements into the mixing layer above. However, it is necessary to emphasize the cautions given in Chapter 5, Part II of the *Guide*, (see *Instrumented towers and masts)* regarding potential interference with atmospheric properties by the support structure. Tall buildings may appear to provide a way to reach higher into the urban boundary layer but unless obstacle interference effects are fully assessed and measures instituted to avoid them the deployment of sensors may be unfruitful and probably misleading.

3.16 Satellite observations

Remote sensing by satellite with adequate resolution in the infrared may be relevant to extended urban areas, but an exposition is outside the scope of this chapter. Some information is available in Chapter 8, Part II of the *Guide* and a review is given by Voogt and Oke, 2003.

4 Metadata

The full and accurate documentation of station metadata (refer to Chapter 1, Part I of the *Guide*) is absolutely essential for any station "to ensure the final data user has no doubt about the conditions in which data have been recorded, gathered and transmitted, in order to extract accurate conclusions from their analysis" (Aguilar *et al.*, 2003). It can be argued that this is even more critical for an urban station, because urban sites possess both an unusually high degree of complexity and a greater propensity to change. The complexity makes every site truly unique, whereas good open country sites conform to a relatively standard template. Change means that site controls are dynamic so documentation must be updated frequently. In the following it is assumed that the minimum requirements for station metadata set by Aguilar *et al.* (2003) are all met and also hopefully some or all of the best practices they recommend. Here emphasis is placed on special urban characteristics that need to be included in the metadata, in particular under the Categories 'Local environment' and 'Historical events'.

4.1 Local environment

As explained in Section 1.1, urban stations involve the exposure of instruments both within and above the urban canopy, hence the description of the surroundings must include both the micro- and local scales. Following Aguilar *et al.* (2003), with adaptations to characterize the urban environment, it is recommended that the following descriptive information be recorded for the station:

(a) a map at the local to mesoscale (~1 : 50,000) as in Fig. 6a, updated as necessary to describe large scale urban development changes (e.g. conversion of open land to housing, construction of a shopping centre or airport, new tall buildings, cutting a forest patch, draining a lake, creation of a detention pond). Ideally an aerial photograph of the area should also be provided and a simple sketch map (at 1 : 500,000 or 1 : 1,000,000) to indicate the location of the station relative to the rest of the urbanized region (Fig. 6b and c) and any major geographic features such as large water bodies, mountains and valleys or change in ecosystem type (desert, swamp, forest). An aerial oblique

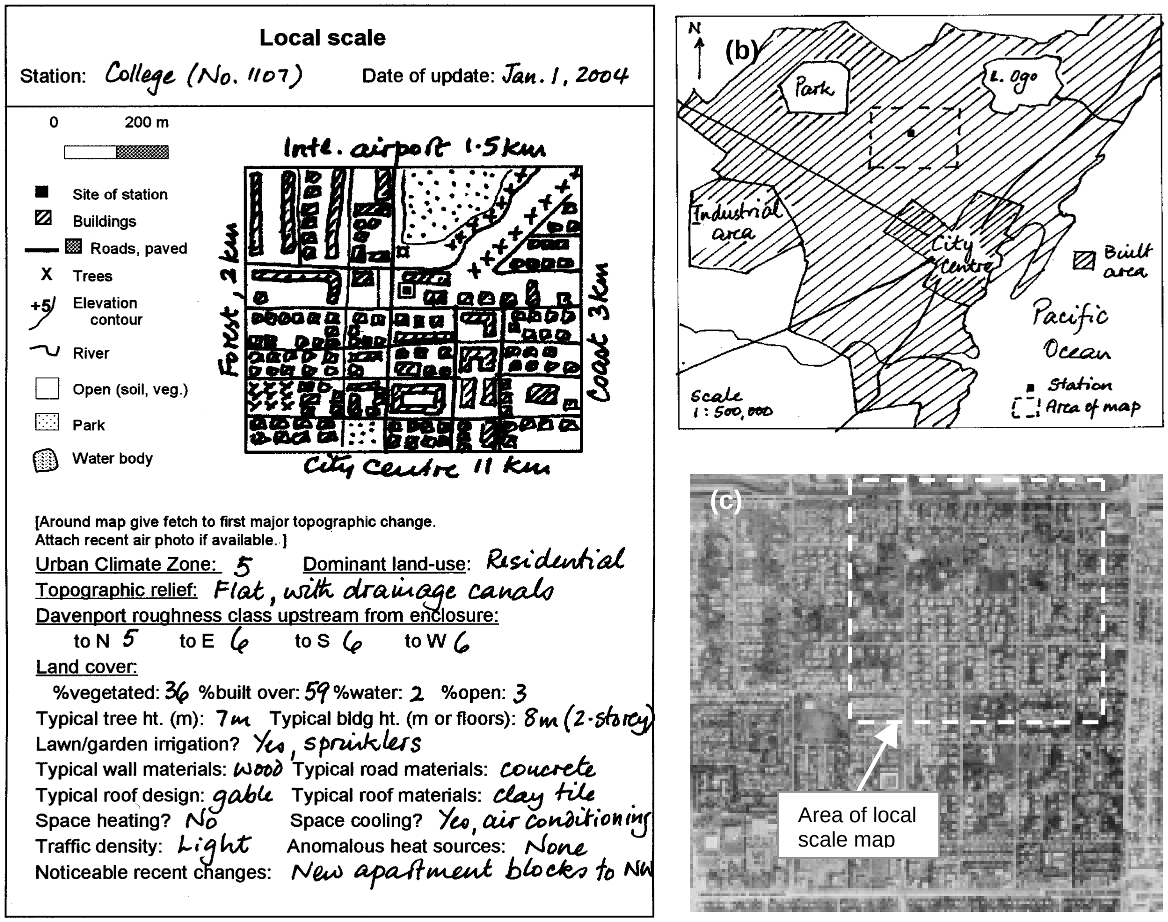


Figure 6 — Minimum information necessary to describe the local scale environment of an urban station, consisting of (a) template to document local setting, (b) sketch map to situate the station in the larger urban region, and (c) an aerial photograph.

photograph can be especially illuminating because the height of buildings and trees can also be appreciated. If available, aerial or satellite infrared imagery may be instructive regarding the presence of important controls on microclimate. For example, relatively cool surfaces by day usually indicate the availability of moisture or materials with anomalous surface emissivity. Hotter than normal areas may be very dry, or have a low albedo or very good insulation. At night relative coolness indicates good insulation and relative warmth the opposite, or it could be a material with high thermal admittance that is releasing stored daytime heat or there is an anomalous source of anthropogenic heat. UCZ and Davenport roughness classes can be judged using Tables 1 or 2.

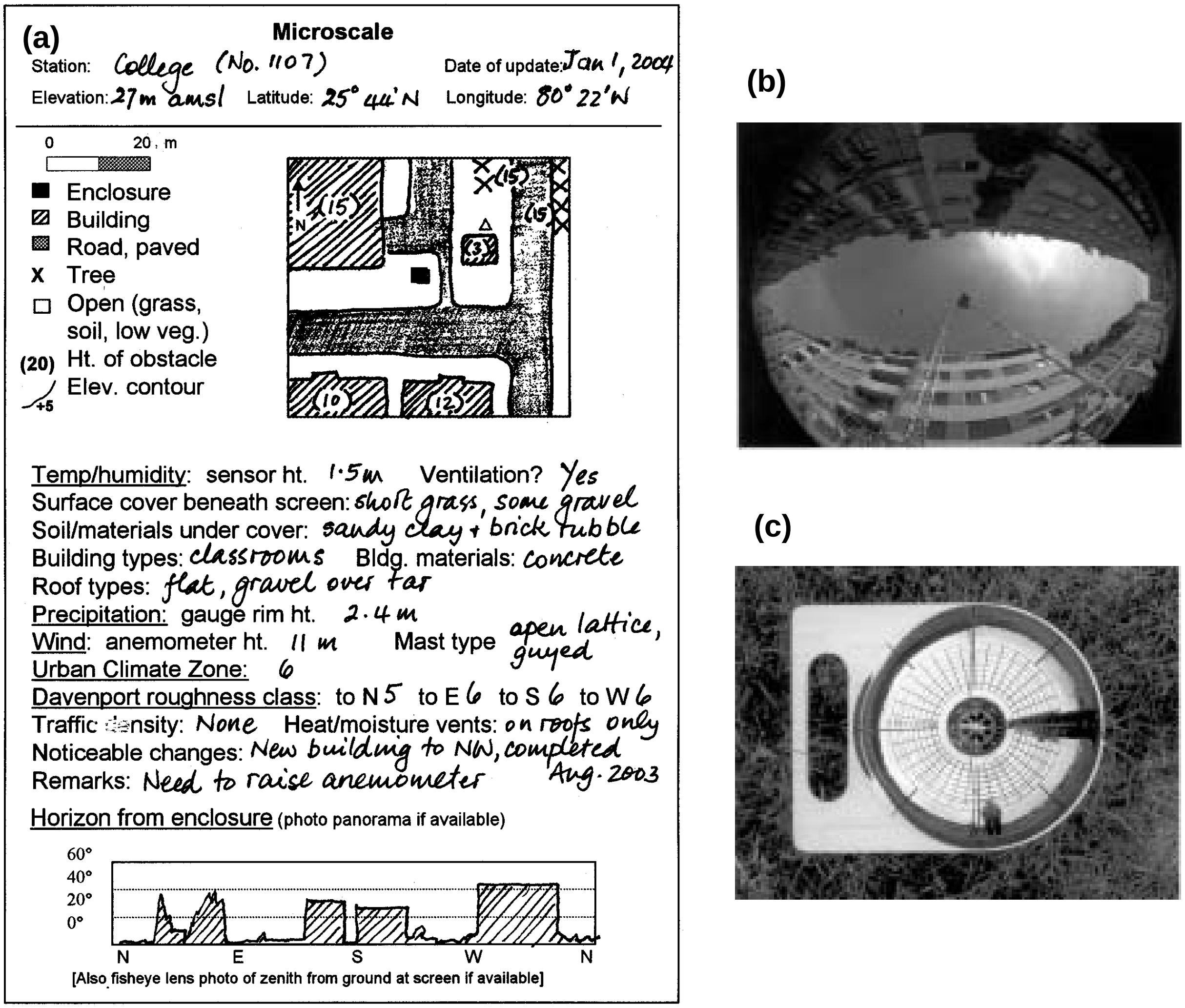


Figure 7 — Information required to describe the microscale surroundings of an urban climate station. (a) Template for metadata file, (b) an example of a fisheye lens photograph of a street canyon illustrating horizon obstruction, and (c) UKMO hemispheric reflector placed on a rain gauge.

(b) microscale sketch map (~1 : 5,000), according to metadata guidelines, updated each year (Figure 7a);

(c) horizon mapping using a clinometer and compass survey in a circle around the screen (as shown in the diagram at the base of the template, Figure 7a), and a fisheye lens photograph taken looking vertically at the zenith with the camera's back placed on the ground near the screen, but not such that any of the sky is blocked by it (Figure 7b). If a fisheye lens is not available a simpler approach is to take a photograph of a hemispheric reflector (Figure 7c). This should be updated every year, or more frequently if there are marked changes in horizon obstruction, such as the construction or demolition of a new building nearby, or the removal of trees;

(d) photographs taken from cardinal directions of the instrument enclosure and of other instrument locations and towers.;

(e) a microscale sketch of the instrument enclosure, updated when instruments are relocated or other significant changes occur;

(f) if some of the station's measurements (wind, radiation) are made away from the enclosure (on masts, roof-tops, more open locations) repeat steps (b) to (d) above for each site.

4.2 Historical events

Urban districts are subject to many forces of change, including new municipal legislation that may change the types of land use allowed in the area, or the height of buildings, or acceptable materials and construction techniques, or environmental, irrigation, or traffic laws and regulations. Quite drastic alterations to an area may result from central planning initiatives for urban renewal. More organic alterations to the nature of a district also arise because of in- or out-migrations of groups of people, or when an area comes into, or goes out of favour or style as a place to live or work. The urban area may be a centre of conflict and destruction. Such events should be documented so that later users of the data understand some of the context for changes that might appear in the urban climate.

4.3 Observance of other WMO recommendations

All other WMO recommendations regarding the documentation of metadata, including station identifiers, geographical data, instrument exposure, type of instruments, instrument mounting and shelters, data recording and transmission, observing practices, metadata storage and access and data processing should be observed at urban stations.

5 Assessment of urban effects

The study of urban weather and climate possesses a perspective that is almost unique. People are curious about the role of humans in modifying the urban atmosphere. So unlike other environments of interest, where it is sufficient to study the atmosphere for its own sake or value, in urban areas there is interest to know about *urban effects*. This means assessing possible changes to meteorological variables as an urban area grows or develops over time, compared to what would have happened had the settlement not been built. This is a question that is essentially unanswerable because the settlement has been built, and even if it hadn't the landscape may well have evolved into a different state than the pre-existing one anyway (e.g. due to other human activity such as agriculture or forestry). The assessment of urban effects is therefore fraught with methodological difficulties and no 'truth' is possible, only surrogate approximations. If an urban station is being established either alone, or as part of a network, to assess urban effects on weather and climate it is recommended that careful consideration be given to the analysis given by Lowry (1977) and Lowry and Lowry (2001).

6 Summary of key points for urban stations

6.1 Working principles

When establishing an urban station, the rigid guidelines for climate stations are often inappropriate. It is necessary to apply guiding principles rather than rules, and to retain a flexible approach. This often means different solutions for individual atmospheric properties and may mean that not all observations at a 'site' are made at the same place.

Because the environment of urban stations changes frequently as development proceeds, frequently updated metadata are as important as the meteorological data gathered. Without good station descriptions it is impossible to link measurements to the surrounding terrain.

6.2 Site selection

An essential first step in selecting urban station sites is to evaluate the physical nature of the urban terrain, using a climate zone classification. This will reveal areas of 'homogeneity'.

Several urban terrain types comprise an urban area. In order to build a picture of the climate of a settlement, multiple stations are required. Sites should be selected that are likely to sample air drawn across relatively homogenous urban terrain and so are representative of a single climate zone. Care is necessary to ensure that microclimatic effects do not interfere with the objective of measuring the local-scale climate.

6.3 Measurements

(a) Air temperature and humidity measurements made within the UCL can be locally representative if the site is carefully selected. If these variables are observed above roof-level, including above the RSL, there is no established link between them and those within the UCL.

(b) Wind and turbulent flux measurements should be made above the RSL but within the internal boundary layer of the selected urban climate zone. Such measurements must establish that the surface 'footprint' contributing to the observations is representative of the climate zone. For wind, it is possible to link the flow at this level and that experienced within the canopy.

(c) Precipitation observations can be conducted either near ground at an unobstructed site, or above the RSL, corrected according to parallel wind measurements.

(d) With the exception of incoming solar radiation, roof top sites are to be avoided, unless instruments are exposed on a tall mast.

(e) Net and upwelling radiation fluxes must be made at heights sufficient to sample adequately the range of surface types and orientations typical of the terrain zone.

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