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SITING AND EXPOSURE OF METEOROLOGICAL INSTRUMENTS AT URBAN SITES

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1. INTRODUCTION

There is a growing need for meteorological data in urban areas in support of air pollution research and management, but measurement poses substantial challenges. Most densely-developed sites make it impossible to conform to the standard WMO Guidelines for site selection and instrument exposure (WMO, 1996) due to obstruction of airflow and radiation exchange by buildings and trees, unnatural surface cover and waste heat and water vapour from human activities. New guidelines (Oke, 2004) to assist in this task form the basis of the first part of this paper. Here emphasis is on those variables of greatest use in air pollution applications. Valid and repeatable results can be obtained despite the heterogeneity of cities, but it requires careful attention to principles and concepts specific to urban areas. Guidelines must be applied intelligently and flexibly, rigid 'rules' have little utility. It is necessary to consider exposures over non-standard surfaces at non-standard heights, splitting observations between more than one location, or being closer to buildings or anthropogenic heat and vapour sources than is normal WMO recommended practice.

1.1. Definitions and concepts

1.1.1. Scales

The success of an urban station depends on an appreciation of the concept of scale. There are three scales of interest in urban areas (Oke, 1984):
(a) *Microscale* – typical scales of urban microclimates are set by the dimensions of individual elements: buildings, trees, roads, streets, courtyards, gardens, etc., extending from less than one to hundreds of metres. WMO guidelines for an open-country climate station are designed avoid microclimate effects and to standardize, as far as is practical – a set height of measurement, single surface cover, minimum distances to obstacles and

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little horizon obstruction. The aim is to achieve climate observations free of extraneous microclimate signals to characterize local climates. Avoiding anomalous microclimate influences is hard to achieve.

(b) *Local scale* – this scale includes climatic effects of landscape features, such as topography, but excludes microscale effects. In cities this means the climate of neighbourhoods with similar types of urban development (surface cover, size and spacing of buildings, activity). 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.

An essential difference between the climate of urban areas and that of open-country sites is that the vertical exchanges of momentum, heat and moisture occur in a layer of significant thickness - called the urban canopy layer (UCL). The height of the UCL is approximately equivalent to the mean height of the main roughness elements (buildings and trees), z_H . Whilst the microclimatic effects of individual surfaces and obstacles persist for a short distance away from their source they blend, in the horizontal and vertical, by turbulence. The distance depends on the magnitude of the effect, the wind speed and the stability. Effects may persist up to a few hundred metres horizontally. In the vertical, individual element effects are discernable in the roughness sublayer (RSL) up to the blending height, z_r. Field measurements indicate z_r can be as low as $1.5z_H$ at densely built (closely spaced) sites, but greater than $4z_H$ in low density areas (Grimmond and Oke, 1999; Rotach, 1999; Christen, 2003). Instruments placed above z_r 'see' a blended, spatially-averaged signal representative of the local scale.

Each local scale surface type (e.g. distinct neighbourhood) generates an internal boundary layer that grows with fetch at a rate depending on the roughness and stability. In rural conditions height:fetch ratios vary from as small as 1:10 in unstable conditions to as large as 1:500 in stable cases (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 ratio of about 1:100 is more typical. Given the nature of the UCL the height of the internal boundary layer is taken above the displacement height z_d (typically $z_d \sim 0.5 – 0.7z_H$; Grimmond and Oke 1999). So in a densely-built district (z_H = 10 m), it means $z_r \geq 15$ m and the fetch requirement over similar urban terrain is likely to be at least 0.8 km. This is a real site restriction because if the urban terrain is not similar out to at least this distance around the 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. Above the blending height, but within the local internal boundary layer, measurements are within an inertial sublayer where boundary layer theory applies.

1.1.2. Source Areas ('Footprints')

A sensor placed above a surface 'sees' only a portion of its surroundings. This is its 'source area' which depends on the height and the process transporting the surface property to the sensor. For upwelling radiation and surface temperature viewed by an infrared thermometer the field-of-view of the instrument and the surface geometry 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.

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 (e.g. Schmid *et al.* (1991). Depending on its field-of-view, a radiometer may see only a limited circle, or it may extend to the horizon. The instrument usually has a cosine response, so that towards the horizon it becomes increasingly difficult to define the actual source area seen, so the view factor is defined as the area contributing a set proportion of the instrument's signal (typically 50, 90, 95, 99, or 99.5%).

The source area of a sensor that derives its signal via turbulent transport is not symmetrically distributed about the sensor location. It is elliptical in shape and is aligned in the upwind direction from the tower. The influence of the ground area at the base of the mast is zero, because turbulence cannot transport the influence up to the sensor level. Further upwind the source starts to affect the sensor, this effect rises 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 position and shape of the ellipse source area ('footprint') vary considerably over time depending 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) and best apply to instruments placed in the inertial sublayer, above the complications of the RSL and the complex geometry of the three-dimensional urban surface. Within the UCL the source areas of instruments cannot be evaluated reliably due to the obvious complications of the complex flow and radiation environments in the UCL. The immediate surroundings of the station will have the greatest effect and the extent of the turbulent source areas will grow 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. A rule-of-thumb is that the circle of influence on a screen-level temperature or humidity sensor has a radius of about 0.5 km, but this is likely to depend upon the building density.

1.1.3. Measurement Approaches

It follows from the preceding discussion that if the goal of an urban site is to monitor the local scale climate, 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 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 measure blended values that can be extrapolated down into the UCL.
In general approach (a) works best for air temperature and humidity, and (b) for wind speed and direction and precipitation. For radiation the main requirement is 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.

1.1.4. Urban Site Description

The dimensions of the morphometric features comprising the urban landscape confer the dimensions of urban climate scales. This emphasizes the need to adequately describe the properties of urban districts that affect the atmosphere. The most important 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). Proper description of a site should include measures of these descriptors. Then they can be used to select potential sites, and be incorporated in the site metadata to accurately describe the setting of the station.

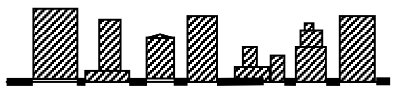
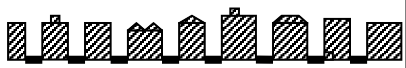
These four features tend to cluster together to form characteristic urban classes. For example, in the central areas of cities many have tall buildings relative to street width that are densely packed (*structure*) so the ground is largely covered with buildings or paved surfaces made of durable materials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

There is no universally accepted scheme of urban classification for climatic purposes. The Urban Terrain Zone scheme of Ellefsen (1990/91) are a good start. They emphasize structure and indirectly reflect aspects of cover, fabric and metabolism because a given structure carries with it the type of cover, materials, and degree of human activity. Application of the scheme needs only aerial photography. A new simple scheme of Urban Climate Zones (UCZ) is forwarded (Fig. 1). It incorporates groups of Ellefsen's zones, plus a measure of the structure, z_H/W (W – element spacing or street width) known to be related to flow, solar access and the heat island, plus a measure of the surface cover (%Built) 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 with similar capacity to modify the local climate, and to identify potential transitions to different urban climate zones. Such classification is crucial when setting up an urban station to ensure that spatial homogeneity criteria are met for a station in the UCL or above the RSL. The number and description of classes may need adaptation to accommodate the special nature of some cities.

2. CHOOSING A LOCATION AND SITE FOR AN URBAN STATION

First, it is necessary to 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. Areas having the highest probability of maximum effects can be judged from the ranked list of UCZ types in Figure 1. Similarly whether a station will be 'typical' can be assessed using the ideas behind Figure 1 to select 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

Urban Climate Zone, UCZ [1]	*Image*	*Rough-ness class*[2]	*Aspect ratio*[3]	*% Built (imper-meable)*[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	1.2 – 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
4. Highly developed, low density urban with large low buildings & paved parking, e.g. shopping mall, warehouses		5	0.05 – 0.2	75 - 95
5. Medium development, low density suburban with 1 or 2 storey houses, e.g. suburban housing		6	0.2 – 0.5, up to >1 with tall 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 with scattered houses in natural or agri-cultural 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 scheme of Ellefsen (1990/91) plus physical measures relating to wind, thermal and moisture controls (columns at right).
[2] Effective terrain roughness according to the Davenport classification (Davenport *et al.*, 2000).
[3] Aspect ratio = z_H/W - related to flow regime types and thermal controls (solar shading and longwave screening).. Tall trees increase this measure significantly.
[4] Av. fraction of ground covered by built features (buildings, roads, paved and other impervious areas) the rest of the area is occupied by pervious cover. Permeability affects the ability to store moisture and hence the moisture status of the ground.

Figure 1. Classification of distinct urban forms arranged in approximate decreasing order of their ability to impact local wind, temperature and humidity climate (Oke, 2004).

or a car and traversed through areas of interest to see if there are areas of thermal or moisture anomaly or interest. 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 maximizes the potential for the differentiation of micro- and local climate differences.

If the station is to be part of a network to characterize spatial features of the urban climate then a broader view is needed informed by knowledge of the typical spatial form of urban climate distributions (e.g. isolines of urban heat and moisture ‘islands’). It must be decided if the aim is to observe a representative sample of the UCZ diversity, or is it to faithfully reflect the spatial structure? The latter is usually too ambitious with a fixed-station network in the UCL because it requires many stations to depict the gradients near the periphery, the plateau region, and the nodes of weaker and stronger than average urban development. With sensors above the RSL, the blending action produces muted spatial patterns and fetch distance to the nearest UCZ transition, or the urban-rural fringe, is critical. In the UCL a distance to a change of UCZ of 0.5 to 1 km may be acceptable, but for a tower-mounted sensor the requirement is likely to be more like a few kilometres. Since the aim is to monitor local climate attributable to an urban area it is sensible to avoid locations extraneous microclimatic influences or non-urban local or mesoscale climatic phenomena that will complicate the urban record.

Once a UCZ type and its general location inside the urban area are chosen potential candidate sites are selected from map, imagery and photographic evidence and a foot survey. Areas of reasonably homogeneous urban development without large patches of anomalous structure, cover or materials, or a transition zone to a different UCZ are ideal. The precise definition of ‘reasonably’ however is not possible. For each candidate site the expected range of footprint areas should be estimated for radiation and turbulent properties. Key surface properties (e.g. mean height and density of obstacles, surface cover, materials) within the footprint areas should be documented. Their homogeneity should then be judged, 'by eye' or by statistical methods.

3. EXPOSURE OF INSTRUMENTS

A curious legacy of open country standardization is that many urban stations are placed over short grass in open locations (parks, playing fields). As a result they monitor modified rural-type conditions, not representative urban ones (Peterson, 2003). The guiding principle for the exposure of sensors in the UCL should be to locate them so they monitor conditions that are representative of the environment of the selected UCZ. The %Built category (Figure 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. Instead it is recommended that the urban station be centred in an open space where the surrounding aspect ratio (z_H/W) is representative of the locality.

3.1. Temperature

Standard thermometry is appropriate for urban observations but radiation shielding and ventilation is even more necessary. In the UCL a sensor may be close to warm or highly reflective surfaces (sunlit wall, road, glass or hot vehicle). Hence shields must block radiation effectively. Similarly, the lower UCL may be so sheltered that forced ventilation of the sensor is essential.

In accord with the above the surface should be typical of the UCZ and the thermometer screen/shield 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. If the site is a street canyon, z_H/W only applies to the cross-section normal to the axis of the street. The recommended open-country screen height of 1.25 to 2 m above ground level acceptable for urban sites but on occasion it may be better to relax this requirement to allow greater heights. Observations in canyons show slight air temperature gradients in the UCL (Nakamura and Oke, 1988), so as long as the sensor is >1 m from a wall error should be small, especially in densely built-up areas. Measurements at heights of 3 or 5 m are little different from those at the standard height. They even benefit by having larger source areas, the sensor is beyond the easy reach of vandals or the path of vehicles, and exhaust heat from vehicles is diluted.

Too often roofs are sites for meteorological observations. This may arise in the mistaken belief that at this elevation sensors are free from microclimates, such as those in the UCL. In fact roof tops have strongly anomalous microclimates. To be good insulators roofs are constructed of materials that are thermally extreme. In light winds and cloudless skies they become very hot by day, and cold by night, with sharp temperature gradients near the roof. Roofs design also ensures they are waterproof and shed water rapidly. This together with their openness to solar radiation and wind makes them anomalously dry. Roofs are also commonly affected by release of heat from roof exhaust vents.

Air temperatures above roof-level using towers, are influenced UCL and roof effects. Whilst there is little variation of temperature with height in the UCL, there is a discontinuity near roof-level both horizontally and vertically. Hence if meaningful spatial averages are sought sensors should be well above mean roof-level so that adequate blending is accomplished (>1.5z_H if possible). Currently there are no methods to extrapolate air temperature data from above the RSL down into the UCL. Similarly, apart from statistical methods that require a large set of training data from a dense station network there is no scheme to extrapolate air temperatures horizontally inside the UCL.

3.2. Humidity

The guidelines 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) which means hygrometers are subject to degradation and require increased maintenance in urban environments. For example wet-bulb wicks become contaminated, hair strands disintegrate and the mirror of dew-point hygrometers and the windows of ultraviolet and infrared absorption hygrometers need to be cleaned frequently. Increased shelter in the UCL means forced ventilation is essential.

3.3. Wind Speed and Direction

The measurement of wind speed and direction is highly sensitive to distortion of the mean flow and turbulence by obstacles. Concerns arise at all scales, including the effects of local relief (hills, valleys, cliffs), sharp changes in roughness length (z_0)or the zero-plane displacement (z_d), clumps of trees and buildings, individual trees and buildings even the disturbance induced by the anemometer mast or mounting arm.

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 nearby, then a mean log wind profile should exist in the inertial layer above the RSL. Within the RSL and 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 buildings, 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). As an engineering 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.

The wind profile parameters z_0 and z_d 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). Methods to parameterize the wind profile parameters z_0 and z_d for urban terrain are also available (Grimmond and Oke, 1999; Davenport *et al.*, 2000, Britter and Hanna, 2003). It is essential to incorporate z_d into urban wind profile assessments. Depending on the building and tree density this could set the base of the profile at a height between 0.5 and $0.8z_H$ (Grimmond and Oke, 1999).

The choice of height at which to measure wind in urban areas is a challenge, but if some basic principles are applied meaningful results can be attained. For rural observations the measurement height is set at 10 m above ground and the sensor should not be nearer to obstructions than ten obstacle heights. In most urban districts it is not possible to find such locations, e.g. in a UCZ with 10 m high buildings and trees a patch of at least 100 m radius is needed. If such a site exists it is unlikely to be representative of the zone. The RSL extends to a height of about $1.5z_H$ in a densely built-up area, and even 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.

Laboratory and field observations show flow over a building creates strong perturbations in speed, direction and gustiness unlike the flow at an open site (Figure 2). These include modifications to the streamlines, recirculation zones on the roof and in the lee cavity behind the building, and wake effects that persist downstream for tens of building heights. Flat-topped buildings create flows on their roofs that are counter to the external flow and speeds vary from jetting to near calm. In general, roofs are very poor locations for climate observations unless the sensors are on tall masts.

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. To get outside the perturbed zone wind instruments must be mounted at a considerable height, typically at a height greater than the maximum horizontal dimension of the major roof (Wieringa, 1996). This implies an expensive mast system for which it may be difficult to obtain permission. Nevertheless, this is the only acceptable approach if meaningful data are to be measured.

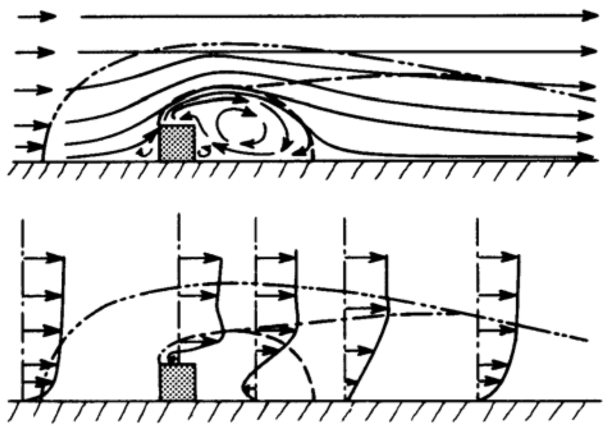


Figure 2. Flow (top) and the wind profile (bottom) around and over a sharp-edged building (Halitsky, 1963)

The following recommendations are made:
(a) in urban areas with low element height and density (UCZ 6 and 7) it may be possible to use the ‘open country’ exposure guidelines. To use the standard (10 m) height, obstacles should be < 6 m tall on average and > 10 times their height from the mast;
(b) in more densely built districts, with relatively uniform height and density of the elements (buildings and trees), the anemometer should be mounted on a mast of open construction at 10 m or 1.5 times the mean height of the elements, whichever is 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.
(e) instruments on open construction masts should be mounted on booms long enough to keep the sensors at least two, better three, tower diameters from the mast.
(f) sensors mounted on tall or isolated buildings must consider effects of the structure on the flow. 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 aim is to ensure all wind measurements are made at heights sufficient to ensure 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. The idea is to gain accurate measurements at whatever height is necessary to reduce error, rather than measuring at a standard height. This may mean the wind site is separate from the location of the other measurement systems. It may also result in wind observations at several different heights in the same settlement, necessitating extrapolation of the measured values to a common height using the log law. A suitable reference height may be 50 m above z_d.

Other exposure corrections for flow distortion, topography, and roughness effects may also have to be applied. If suitable wind observations cannot be made for a given urban site it is still possible to calculate the wind at the reference height using observations at another urban station or the airport using the ‘logarithmic transformation’ model of Wieringa (1986).

3.4. Precipitation

The measurement of precipitation is always susceptible to errors associated with the exposure of the gauge, especially due to the wind field in its vicinity. Given the highly variable wind field in the UCL and the RSL, their are concerns about: (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 causing splash-in to the gauge, and over-hanging objects dripping into the gauge; (c) the variable wind field around obstacles causing localized augmentation or the absence of rain- or snow-bearing airflow; and (d) the gustiness of the wind together with the turbulence around the gauge leading to under- or over-catch. 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.

It is recommended that precipitation gauges in urban areas are:

(a) located at 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) located in conjunction with the wind instruments if a representative wind site is found. This may mean mounting the gauge above roof-level on a mast where it 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 results must be corrected. It also means that automatic recording is favoured.;

(c) not located on the roofs of buildings unless exposed at sufficient height to avoid the wind envelope of the building.

Depth of snowfall should be made at an open site or, if made at developed sites, a large spatial sample must be obtained to account for the inevitable drifting around obstacles.

3.5 Radiation

Very few radiation flux measurements are conducted in urban areas. Most radiation sites are located in rural or remote locations specifically to avoid the aerosol and gaseous pollutants of cities that ‘contaminate’ their records. All short- and longwave fluxes are impacted by the properties of the atmosphere and surface of cities contributing to the net all-wave radiation balance that drives the urban energy balance (Oke, 1988). Incoming solar radiation is a fundamental forcing variable and its measurement should be given high priority when a station is established or upgraded. 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 easily met in cities. What is required is that the sensor be level, free of vibration, free of any obstruction above the plane of the sensing element. So a high, stable and accessible platform like the roof of a tall building is often ideal. It is essential to clean the upper domes at regular intervals. In heavily polluted environments this may mean daily.

Outgoing fluxes of radiation (reflected solar, emitted and reflected longwave and the net short-, long- and all-wave radiant fluxes) are seldom monitored in cities. This means

the albedo and the opportunity to invert the Stefan-Boltzmann relation and solve for the surface radiant temperature and 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 are missing. The main difficulty is to ensure the field-of-view of a down-facing radiometer 'sees' a representative sample of the underlying urban surface including does it see both an adequate set of plan-view surface types, but also appropriate fractions of roof, wall, and ground surfaces, including the correct fractions of each that are in sun or shade? Soux *et al.*, 2004 developed a model to calculate these fractions for relatively simple urban-like geometric arrays. 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 $2z_H$ is advisable) and preferably higher; and
(b) the radiative properties of the immediate surroundings of the radiation mast are representative of the urban district of interest.

3.6. Evaporation and other turbulent fluxes

Like radiation evaporation observations in urban areas are almost non-existent at standard climate stations. The use of atmometers, evaporation pans or lysimeters to measure evaporation in the UCL is not recommended. Their evaporative surfaces are not representative of the surroundings and they are in receipt of micro-advection that is likely to force evaporation at unrealistically high rates. Micro-lysimeters can give the evaporation from individual surfaces, but are unsuitable for long-term observations.

Spatially-averaged evaporation and other turbulent fluxes (momentum, sensible heat, carbon dioxide) at the local scale can be observed using sensors above the RSL. Such fluxes are of practical interest in urban areas. The vertical flux of horizontal momentum, and integral wind statistics and spectra are central to questions of wind loading on structures and the dispersion of air pollutants. The turbulent sensible heat flux is required to calculate atmospheric stability (e.g. flux Richardson Number or 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. Exposure should be as for wind sensors: above the RSL but below the internal boundary layer of the UCZ of interest. Accurate measurements rely on the flux 'footprint' being large enough to be representative of the local area of interest.

4. METADATA

The full and accurate documentation of station metadata is essential "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 is even more critical for an urban station, because their sites possess both complexity and a greater propensity to change over time. Change means that site controls are dynamic so documentation must be updated frequently.

Urban stations may expose instruments both within and above the UCL, so site description must include both the micro- and local scales. Metadata should include: (a) a map at the local to mesoscale (~1:50,000) updated regularly to describe urban development changes and ideally an aerial photograph and a simple sketch map (at 1:500,000 or 1:1,000,000) to show the station relative to the rest of the urbanized region and any major geographic features. (b) a microscale sketch map (~1:5,000), according to metadata guidelines, updated each year (see Aguilar *et al*., 2003). (c) horizon mapping using a clinometer and compass survey in a circle around the screen and a fisheye lens photograph looking at the zenith. (d) photographs in the cardinal directions taken from the instrument enclosure. (e) a microscale sketch of the instrument enclosure, updated when instruments are relocated or other significant changes occur. (f) repeat steps (b) to (d) above for any site where measurements of variables are made separate from the enclosure (on masts, roof-tops, more open locations).

5. FLUX MEASUREMENTS AND ESTIMATES RELEVANT TO DISPERSION

Until the 1980s there were very few measurements of local scale fluxes of heat, mass and momentum in urban areas. Those attempted were very short-term studies and the methods employed were experimental. By the 1990s questions regarding the relative merits of eddy covariance and gradient methods, the height of the RSL, the nature of turbulent and radiative source areas, and how to handle the unmeasured anthropogenic and storage heat fluxes were addressed. Today the emergence of robust, affordable, commercial flux instrumentation in combination with agreed field methods has meant that repeatable results, gathered over long periods, for several cities, have become available. This in turn has made it possible to conduct inter-site and inter-city comparisons of roughness, turbulence and both radiative and turbulent fluxes. The results have created data bases suitable for the construction of parameterizations and testing the predictions of models (for reviews see Grimmond and Oke, 1999, 2002; Roth, 2000; Arnfield, 2003). Although further development of methods will occur, workers in urban meteorology now have a more substantial basis for comparison, testing and model development.

Nevertheless, most of this work on turbulence and flux determination remains in the research and experimental domain. To buy, install and maintain many of these sensors is a costly undertaking that is beyond the budget of most monitoring networks. The modest target of the WMO report (Oke, 2004) is progress toward better observation at ordinary climate stations, similar to those operated by national and other meteorological agencies, but located in urban environments. The most critical of those measures for air pollution applications (dispersion calculations or as model inputs) are wind speed, direction and gustiness. Here I stress that the exposure of wind instruments is sensitive to the effects of obstacles. It is hard to comprehend the number of studies in support of network monitoring, dispersion calculations or the ‘validation’ of flow or dispersion models that rely on poorly sited or incorrectly exposed wind sensors. This must arise either because of lack of understanding of scale concepts or because someone has deemed it to be too expensive or difficult to follow the protocols outlined here. However, it is no economy to expose good sensors on short masts near, or especially on, buildings where their readings are dominated by obstacle effects that are often totally at odds with the flow properties sought.

If sited and exposed correctly the relatively simple array of instruments at a standard station in a city are useful to estimate fluxes and more sophisticated turbulence variables of relevance to air pollution analysis. This is possible through use of a meteorological pre-processor scheme: a collection of algorithms to convert standard observations into the input variables required by models but that are not normally measured (e.g. atmospheric stability, fluxes of momentum, heat and water vapour, mixing height, dispersion coefficients, etc.). Examples include OLM (Berkowicz and Prahm, 1982; Olesen and Brown, 1992), HPDM (Hanna and Chang, 1992) or LUMPS (Grimmond and Oke, 2002). Such schemes typically require only spatially representative observations of incoming solar radiation, air temperature, humidity and wind speed, and estimates of average surface properties such as albedo, emissivity, roughness length and the fractions of the area vegetated or built-up or irrigated. Ideally the wind, air temperature and humidity measurements are taken above the RSL, but for temperature and humidity if only UCL values are available, they are usually acceptable because the schemes are not sensitive to these variables.

It is increasingly realistic to foresee the adoption of numerical models to generate fluxes and other meteorological properties which, in turn, will drive mesoscale flow, climate and air quality models of urban atmospheres. Probably the most practical of these, because of the relative simplicity of its input requirements and because it is the most widely adopted scheme so far, is the Town Energy Balance (TEB) model of Masson (2000). TEB is also noteworthy because it has been tested against measured fluxes and climate variables for heavily developed sites in four cities (Masson *et al.*, 2002; Lemonsu *et al.*, 2004). Other models, usually more demanding in their input needs, are available or in development. What sets all these new models apart is their explicit recognition of the UCL, including its three-dimensionality. It is to be expected that in the future there will be an array of 'urban physics packages' that can be coupled to existing mesoscale models. They will vary in the scale they address and the demands they make with respect to input requirements. When validated against well-conducted urban observations such models will be able to complete the circle and provide valuable information to inform the optimal design of observation networks.

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