Chapter 16
Eddy Covariance Measurements Over Urban Areas

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16.1 Introduction

Throughout the last two decades, numerous research projects applied the eddy covariance (EC) approach to urban ecosystems to directly measure turbulent fluxes between the urban surface and the atmosphere to quantify the exchange of energy, water vapor, greenhouse gases, air pollutants, and aerosols in connection with the assessment of (air pollutant) dispersion and of the urban energy, water, and carbon balances. Numerical models for dispersion, air pollution, and weather forecasting in cities rely on parameterization schemes for turbulence and surface exchange, which should take into account the implications that arise from the extremely rough surface of cities. Although, to date, the physics of dispersion and energy exchange taking place in the urban roughness sublayer (see Sect. 16.1.2) are mostly understood, it is challenging to parameterize and/or simplify them. Similarity theory is likely to fail in the lower part of the roughness sublayer, which is unfortunate because this is where urban residents live and hence it is the most important layer for forecasting products. Further, partitioning of the urban energy balance is strongly modified compared to rural ecosystems, due to the specific properties of the urban surface (3D geometry, roughness, impervious surfaces, anthropogenic heat injections) and due to complex source/sink distributions. The turbulent fluxes

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Table 16.1 Urban scales

Urban scale	Horizontal length scale	Built features	Meteorological scale
Building	10 × 10 m	Single-family house, high-rise	Micro
Canyon	30 × 40 m	Street, canyon	
Block	500 × 500 m	Block, factory	
Neighborhood (local climate zone)	5 × 5 km	City center, residential, industrial zone, etc.	Local
City	25 × 25 km	Urban area	Meso
Urban region	100 × 100 km	City plus its environs	

Adapted from Oke (2006a)

of energy and matter are also modified by human injections of heat, water, and carbon into the urban atmosphere by traffic, space heating, waste management, etc. In this sense, urban ecosystems have additional premises compared to nonurbanized ecosystems.

Many of the restrictions on EC measurements over very rough surfaces, like forests, also apply to urban surfaces. However, there are some differences mainly originating from the presence of a deep urban roughness sublayer, where the flow is significantly influenced by the presence of individual buildings/objects. In analogy to vegetation canopies, the assemblage of buildings, trees, and other objects in a city can be regarded as the "urban canopy" (Oke 1976).

16.1.1 Scales in Urban Climatology

Modifications of the land-atmosphere exchange by urban areas span over space and timescales of several orders of magnitude. Oke (2006a) presented concepts of urban scales that should be appreciated when applying the EC technique in urban environments (see Table 16.1 and Fig. 16.1):

(a) *Building, canyon, and block;* also *"microscale"*: dominated by irregular 3D structures (buildings, trees, roads, gardens, courtyards, plazas). Scale of choice for computational fluid dynamics (CFD) simulations. Restricted use of EC measurements, as it is challenging to attribute source areas.
(b) *Neighborhood scale;* also *"local scale"*: represented by a *Local Climate Zone* (see Sect. 16.1.4) made up of repetitive patches of surface cover, size and spacing of buildings, and human activity (residential, commercial, industry). Scale of choice for EC, as fluxes represent an integral response from a specific urban ecosystem.
(c) *City and urban region;* also "*mesoscale"*: represents typical city-wide pattern (e.g., the urban heat island UHI) and interactions between city and its rural counterpart. Note that a single station cannot represent this scale and representative pairs or networks of rural and urban EC measurements are required.

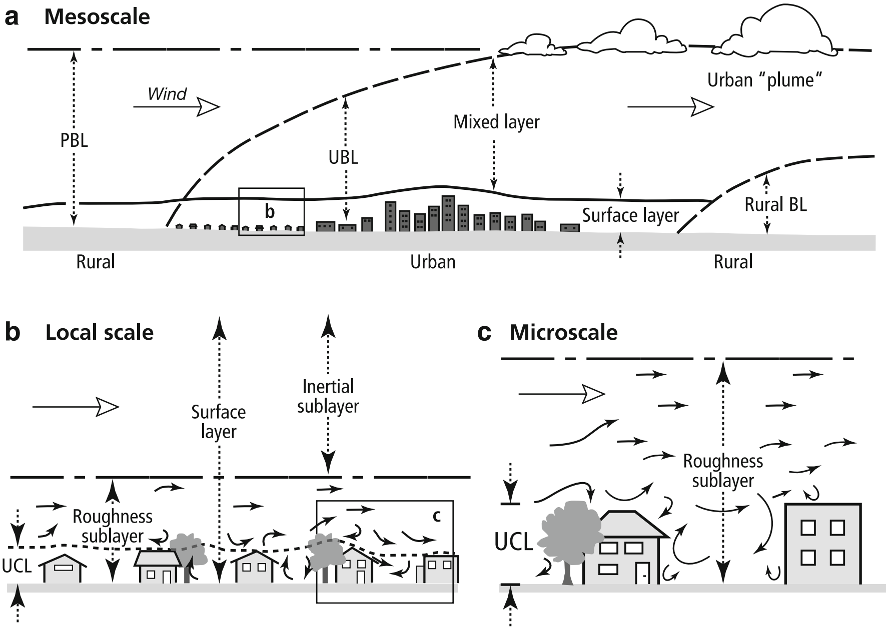

Fig. 16.1 Vertical (planetary boundary layer *PBL*, urban boundary layer *UBL*, urban canopy layer *UCL*) and horizontal scales (**a** mesoscale, **b** local scale, **c** microscale) in urban boundary layers (Adapted from Oke (2006b))

16.1.2 The Urban Atmosphere

The surface layer of an urban ecosystem can be conceptually divided into two sublayers: the urban roughness sublayer (RSL) closer to the urban canopy responding to individual microscale elements, and the overlying inertial sublayer (ISL) due to the mixing of all sub-neighborhood scales in the RSL. The lowest part of the urban RSL from the ground up to the height of buildings z_h is called "urban canopy layer" (UCL). The restricted convective and radiative coupling between the airspace located in the canopy (e.g., street canyons) and the roughness sublayer above roofs allows the UCL to maintain its own climate. Microclimatic effects only persist for a short distance away from their source until they are blended, horizontally and vertically, by turbulence. In the horizontal, these effects may persist for a few hundred meters, while in the vertical, they are evident in the urban RSL, which extends from ground level to the blending height z_r that ranges from about 1.5 z_h over densely built-up areas up to 5 z_h in low density areas (Grimmond and Oke 1999). Exchange in the RSL is not only driven by turbulent exchange, but also by dispersive fluxes ("form-induced" fluxes) that – in contrast to permeable and irregular natural canopies – contribute significantly to the exchange in the UCL through stationary vortices arising from the flow around buildings and other large

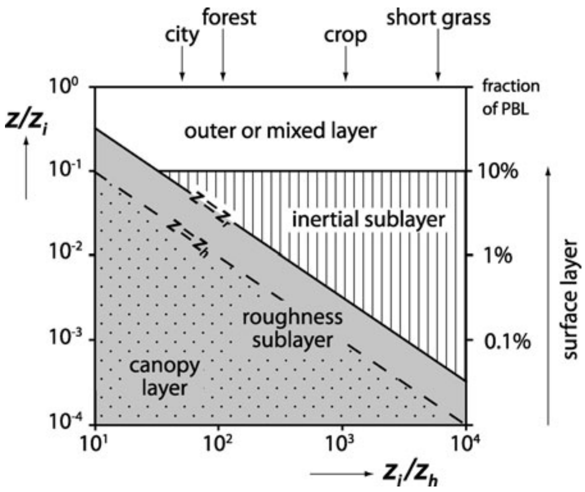

Fig. 16.2 The surface-specific different depths of *PBL* sublayers. z_i refers to the height of the PBL. (Adapted from Rotach (1999))

surface elements. EC measurements above z_r, that is, in the ISL, are supposed to measure a blended, spatially averaged signal that is representative of the local scale. Main differences in the vertical structure of the urban surface layer compared to nonurbanized ecosystem are the substantial depths of the RSL (Fig. 16.2) and the importance of nonturbulent exchanges (small-scale advection, dispersive fluxes). Note also in Fig. 16.2 that the ISL may even disappear at the expense of the RSL at urban sites with tall buildings.

16.1.3 Exchange Processes in the Urban Atmosphere

The main features that govern the vertical turbulent exchange of mass and scalars in the urban atmosphere can be characterized as follows (adapted from Roth 2000):

– *An intense shear layer* forms near the top of the canopy, *whose properties (turbulent kinetic energy, high turbulence intensities) differ systematically from those of the overlying inertial sublayer* due to wakes behind buildings and vortices of canyon flows.
– *Wake diffusion* behind roughness elements and *form drag* due to pressure differences across individual roughness elements (bluff-bodies) lead to high turbulent kinetic energy, efficient vertical and horizontal mixing, and create stationary vortices that can lead to significant dispersive fluxes.
– *3D organization of sources/sinks* (sunlit/shaded roofs, streets and walls, cold/hot spots, wet/dry spots, point and line sources of pollutants) results in a complex system of active surfaces and dissimilarities in the energy and mass transport due to high spatial variability.

– *Extreme surface heterogeneity* at all length-scales makes it nearly impossible to establish uniform, so local advection is very likely.
– *Organized motions,* manifested in ramp structures and sweeps and ejections, originate from a certain regularity of building structures that are very efficient in transporting heat.
– *Larger boundary-layer heights and reduced atmospheric stability* are created by the enhanced mechanical mixing and the UHI effect.

The urban surface layer is strongly influenced by the growth rate of internal boundary layers, whose properties are crucial to the location of the source areas for EC sensors. The flow structures and thermodynamic properties of internal boundary layers, generated by local scale surfaces, are adapted to the properties of their respective surface types. The growth rate of internal boundary layers depends on roughness and stratification. Since cities tend to neutral conditions, due to enhanced mechanical and thermal turbulence associated with large roughness and the heat island effect, we propose a typical height/fetch ratio in the range of 1:25–1:50. If surface properties inside the required fetch are not similar, then the measurements will not be representative of the local urban ecosystem. Fetch requirements can therefore be a significant restriction when choosing a site location.

It follows from the preceding discussion that a good characterization of the source area is of highest importance for the correct interpretation of the measurements. Footprint models (see Chap. 8) can provide reliable estimates of the turbulent transfer processes in the ISL, where Monin-Obukhov similarity theory (MOST) applies. Below this level, that is, in the RSL, complications arise due to the complex 3D geometry of buildings and the blockage and channeling of flow, which characterize the UCL, so the turbulent fluxes of momentum, energy, moisture, and pollutants are height dependent (Rotach 2001).

16.1.4 Characterization of the Urban Surface–Atmosphere Interface

The wide range of urban land covers and urban land uses presents a large variety of boundary conditions to the atmosphere, which manifest themselves in the specific properties of the urban surface relating to its roughness (the size, shape and separation of buildings, trees and other large structures), the radiative, thermal, and moisture characteristics and their spatial arrangement, and the pattern of emissions (e.g., carbon dioxide). These properties are organized uniquely in any given urban area. Recognition of this is of highest importance to understand the spatial and temporal variability of surface-atmosphere exchanges within cities (Grimmond et al. 2004) and has an important impact on the interpretation of the results from urban studies.

A useful tool to characterize urban areas and districts, and a necessity for the interpretation and comparability of meteorological measurements in cities, is the scheme of *Local Climate Zones (LCZ)* (Stewart and Oke 2009; Stewart 2009).

An essential first step is to evaluate the physical nature of the urban terrain in terms of transitions and inhomogeneity. The properties of radiation and airflow heavily depend on the dimensions of the roughness elements and their spatial arrangement, which can be characterized by some typical measures related to geometric features, surface fractions, and length scales. Partly based on such measures, Stewart and Oke (2009) present a field site classification of *Local Climate Zones* (LCZ) that includes a "Built Series." The main features of urban structure parameters and the "Built Series" of LCZ are presented in Fig. 16.3.

Typical relationships for urban roughness length z_0 and zero plane displacement height d derived from mean building height z_h are: $z_0/z_h = 0.1$ and $d/z_h = 0.5$, respectively (Grimmond et al. 1998). Measurements at a chosen location should represent the properties of the respective LCZ, which means that the source areas of the sensors are fully representative for the LCZ under investigation.

16.2 Conceptual Framework for Urban EC Measurements

Starting from the early 1980s, experimental attempts using EC technique in cities have been performed in conjunction with the phenomenon of the urban heat island (UHI) (e.g., Oke 1976) to better quantify the fluxes that contribute to the urban energy balance (UEB), that is, the sensible and latent heat flux and, indirectly, the storage heat flux, that is the most problematic flux to quantify in the UEB. This has led to the need for better parameterizations in numerical forecast models for urban areas and has motivated researchers to investigate the urban-specific structure of turbulence by the means of the EC technique. Most recently, more attention has been paid to the measurement of CO_2 fluxes in cities, and efforts are underway by the International Association for Urban Climate (IAUC) to organize and document urban flux sites into the URBAN FLUX NETWORK (accessible by the IAUC homepage on www.urban-climate.org).

A complete review of existing studies is beyond the scope of this chapter, however, several comprehensive reviews of urban turbulence studies that abstract the most important findings of the last decades are available. Roth (2000) provides an excellent "Review of turbulence over cities" based on stringently selected high-quality experimental results published up to the year 2000, Arnfield (2003) reviewed "Two decades of urban climate research," and Grimmond (2006) summarizes the "Progress in measuring and observing the urban atmosphere." Though the latter two are written from a more general point of view, all three give insight into the state of the art of EC measurements in urban environments. In addition, we refer to the BRIDGE report (Grimmond et al. 2010) for a comprehensive overview of existing studies related to energy, water, and CO_2 fluxes in cities.

BUILT SERIES

LOCAL CLIMATE ZONE (LCZ)		Sky view factor[1]	Aspect ratio[2]	Building surface fraction[3] (%)	Impervious surface fraction[4] (%)	Natural surface fraction[5] (%)	Height of roughness elements[6] z_H (m)	Terrain roughness class[7]	Anthropogenic heat flux density[8] Q_F (Wm^{-2})
B1: Compact highrise		0.2–0.5	>2	40–60	40–60	<10	>35	8	50–300
B2: Compact midrise		0.3–0.6	0.75–1.25	40–70	30–50	<15	8–25	6-7	<75
B3: Compact lowrise		0.3–0.5	1–1.5	50–70	20–30	<15	3–8	6	<75
B4: Open-set highrise		0.4–0.7	0.75–1.25	20–40	30–40	30–40	>30	7–8	<50
B5: Open-set midrise		0.8–0.9	0.3–0.5	20–40	20–40	20–40	8–25	5–6	<25
B6: Open-set lowrise		0.6–0.8	0.5–0.75	20–50	20–30	30–50	3–8	5–6	<25
B7: Extensive lowrise		>0.9	0.1–0.3	30–50	40–50	<20	3–10	5	<50
B8: Lightweight lowrise		0.3–0.5	1–1.5	50–80	<10	10–30	2–4	4–5	<5
B9: Sparsely developed		>0.9	0.1–0.2	10–20	<20	60–80	3–25	5–6	<10
B10: High-energy industrial		0.7–0.9	0.2–0.5	20–30	20–40	40–50	5–10	5–6	>300

1. Proportion of sky hemisphere visible from ground level.
2. Mean height-to-width ratio of street canyons (B1 thru B4, B6, B8) and building spacing (B5, B7, B9, B10).
3. Proportion of zone plan surface covered by buildings.
4. Proportion of zone plan surface covered by impervious materials.
5. Proportion of zone plan surface covered by natural materials.
6. Geometric average of building heights.
7. Based on Davenport *et al.* (2000) classification of effective terrain roughness.
8. Mean annual anthropogenic heat flux density. Varies significantly with latitude and season.

Fig. 16.3 The "Built Series" of local climate zones (Adapted from Stewart (2009))

16.2.1 Turbulence Characteristics

The results from Roth (2000) and the studies investigated therein show strong similarities in the integral statistics and (co)spectra of turbulent flows over both urban environment and plant canopies. Roth concludes that urban turbulence may be interpreted in the framework of plane mixing-layer flows (Raupach et al. 1996) with modifications to take into account wake turbulence. Work by Kastner-Klein and Rotach (2004), Kanda (2006), Moriwaki and Kanda (2006), Moriwaki et al. (2006) and Christen et al. (2009a) confirmed many of the analogies of urban RSL statistics to those found in plant-canopy flows. Similarly, organized structures have been shown to be very efficient in the transport of heat (Feigenwinter and Vogt 2005; Oikawa and Meng 1995; Christen et al. 2007) and, though to a lesser amount, water vapor and CO_2 (Moriwaki and Kanda 2006) in urban environments.

16.2.2 The Volume Balance Approach

In the following, we review specific aspects of the turbulent fluxes of sensible and latent heat and CO_2 in the context of a *volume balance approach* according to Fig. 16.4, which is the preferred concept for urban ecosystems due to their 3D nature.

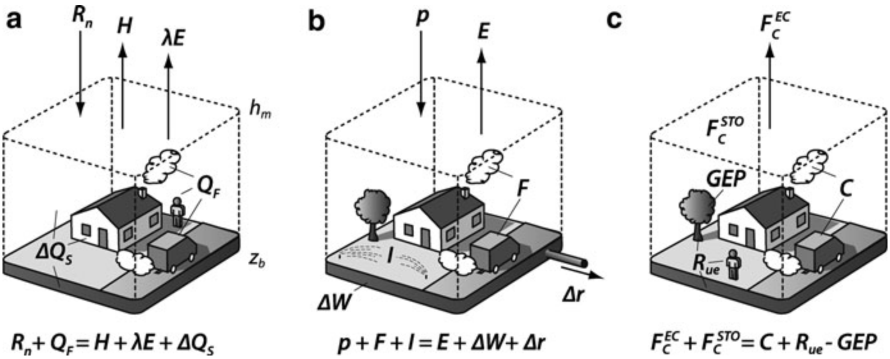

Fig. 16.4 Conceptual diagrams illustrating the volume balance approach for (**a**) the urban energy balance, (**b**) the urban water balance, and (**c**) the urban carbon balance. *All arrows* indicate the definition of positive flux densities. Note that advective fluxes are not considered. For a description of symbols see the text

16.2.2.1 Turbulent Heat Fluxes in the Context of Urban Energy Balance Studies

The urban surface energy balance is typically approached as a *volume budget* (Fig. 16.4). The upper boundary of the budget volume h_m is chosen to be above the roughness sublayer height z_r in the ISL, in order to provide horizontal homogeneity for EC and radiation measurements. The lower boundary z_b is located in the subsurface where annual substrate temperature variations approach zero (Fig. 16.4a):

$$R_n + Q_F = H + \lambda E + \Delta Q_S \tag{16.1}$$

Net all-wave radiation (R_n) and the turbulent flux densities of sensible and latent heat (H and λE) can be directly measured at h_m, the latter two terms by EC. The two additional terms account for the *anthropogenic heat flux density* Q_F and the *net storage heat flux density* ΔQ_S in the budget volume. Since these terms are unique to urban environments, they are briefly discussed.

The *anthropogenic heat flux density* Q_F is an extra input term to account for injections of sensible and latent heat to the atmosphere by human activity (combustion processes, heating/cooling of buildings, heat released by the human metabolism). Clearly those heat injections are not homogeneously distributed in the UCL, but often can be constrained both horizontally and vertically. Care has to be taken that EC systems measuring H and λE are located sufficiently distant from anthropogenic point and line heat sources (engines, ventilation systems, chimneys, etc.) but are still able to capture the integrative, local scale heat release by Q_F. Common methods for the estimation of Q_F are *inventory approaches* (top-down modeling of energy consumption statistics, traffic load data, etc.), *building energy models and traffic models* (bottom-up modeling) or by assuming energy balance closure and using *long-term (*e.g., annual, with ΔQ_S approaching zero) measurements of R_n, H, and λE. The annual residual term is then Q_F (Christen and Vogt 2004; Offerle et al. 2005; Pigeon et al. 2007a). Typical values of Q_F (see also Fig. 16.3) range between 10 and 15 W m^{-2} for suburban areas (LCZ B6 open-set lowrise), 20 and 30 W m^{-2} in more compact built-up areas (LCZ B3 compact lowrise), but can exceed 400 W m^{-2} in extreme cases such as reported for restricted areas, such as the central business district of Tokyo (Ichinose et al. 1999).

The *net storage heat flux density* ΔQ_S can be written as the sum of changes in the heat storage in the subsurface ground materials (ΔQ_{Sg}), in buildings (ΔQ_{Sb}), in vegetation (ΔQ_{Sv}) and in indoor and outdoor air (ΔQ_{Sa}). Both ΔQ_{Sv} and ΔQ_{Sa} are small compared to ΔQ_{Sg} and ΔQ_{Sb}. Since a direct measurement of ΔQ_S is impractical in an urban area, two empirical methods are commonly applied to estimate ΔQ_S (Roberts et al. 2006): First, the *energy-balance residual approach,* where all other terms are measured (Q_F might be estimated) and Eq. 16.1 is solved for ΔQ_S; second, the *thermal mass scheme* (TMS), which uses an array of temperature measurements (surface and intra-material) to estimate the rate of change of sensible heat of many representative materials and facets of the urban interface. Using weighting factors based on survey data, the measured rate of change in temperature of the "urban body" is used to calculate the energy released or removed from the interface. In comparison to non-urbanized ecosystems, ΔQ_S can be a substantial term (up to almost 60% of R_n) in the surface energy balance.

16.2.2.2 Evapotranspiration in the Context of Urban Water Balance Studies

In analogy to the urban energy balance, the urban water balance can be written as a *volume budget* (Fig. 16.4b, Oke 1987):

$$P_r + I + F = E + \Delta W + \Delta r \tag{16.2}$$

Similar to the water balance in non-urbanized ecosystems, all terms are expressed in mm per unit time. In the urban setting, this requires integration over a sufficiently large area or catchment to retrieve a representative water balance at the local scale. Inputs to the balancing volume are precipitation P_r, and anthropogenic water input by irrigation I and combustion processes F. Irrigation water supply I can be substantial, and can exceed monthly water input by precipitation in dry cities (e.g., by lawn sprinkling). F is typically small and can be approximated using direct CO_2 flux measurements (see Sect. 16.2.2.3). Outputs are evapotranspiration E, typically measured by EC at h_m, and runoff Δr. Runoff in urban systems is greatly enhanced relative to non-urbanized ecosystems, because impervious surface materials and infrastructure, such as sewer systems, promote rapid runoff. The only significant storage within the balancing volume occurs in the subsurface materials (ΔW) as other urban surface materials (roofs, walls) are typically relatively impervious and hence water storage is negligible.

16.2.2.3 CO_2 Fluxes in the Context of Urban Metabolism Studies

In analogy to the energy and water balance, the urban carbon balance is also approached as a *volume budget* with the upper boundary at h_m, although the lower boundary is the 3D surface in order to avoid transformations between CO_2 and organic carbon pools (Fig. 16.4c). In urban ecosystems, there is import of carbon as construction material, food, etc. and export of carbon in form of waste, litter, and lawn clippings (Churkina 2008), so it is more straightforward to focus on transformation processes between the atmosphere and the surface (respiration, combustion, photosynthesis) rather than tracking the complex carbon pools. This approaches the carbon balance simply as a mass balance of CO_2 in the UCL.

Using the eddy covariance approach, the integrative turbulent mass flux density of CO_2 (F_c^{EC}) is measured in μmol m^{-2} s^{-1} at h_m:

$$F_c^{EC} + F_c^{STO} = C + R_{ue} + GEP \tag{16.3}$$

The exchange at the surface between urban carbon pools and the atmosphere can be separated into *combustion processes C*, *urban ecosystem respiration* R_{ue}, and *photosynthesis GEP*. F_c^{STO} is the storage change over time in the indoor and outdoor air between the surface and the measurement level h_m (see also Sect. 16.4.1).

In contrast to non-urbanized ecosystems, CO_2 exchange between urban surfaces and the atmosphere is nearly always positive and often dominated by emissions from fossil-fuel combustion processes, *C*. Mass flux densities of fossil-fuel combustion can be conceptually separated into emissions from vehicles C_V and emissions from buildings C_B due to space heating and industrial processes. Similar to the anthropogenic heat release Q_F, sources of C_V and C_B are not distributed homogeneously in the vertical or horizontal and C_V is released from mobile sources at ground level, while C_B comes from point sources (venting systems, chimneys). C_V and C_B follow diurnal, weekday, and seasonal human activity cycles (traffic load, heating requirements).

Further, urban ecosystem respiration R_{ue} is not only the result of autotrophic and heterotrophic respirations in urban soils and vegetation R_{SV}, but also includes waste decomposition R_W and human respiration R_M. Respiration in soils and vegetation R_{SV} is promoted by intensive irrigation and fertilization, that are common in heavily managed residential ecosystems. Residential lawns can regularly reach respiration flux densities larger than 10 μmol m^{-2} s^{-1} (lawn) for well-watered plots under warm summertime conditions (Christen et al. 2009b). Also human respiration R_M can be a significant term in the carbon balance. Moriwaki and Kanda (2004) estimated for a densely populated urban area in Japan (118 inhabitants ha^{-1}) that human body respiration is 2.2 μmol m^{-2} s^{-1}, which contributes at their site to 38% to the total F_c^{EC} in summer and 17% in winter.

Urban vegetation (trees, lawns, gardens, etc.) also can be expected to show higher productivity and higher annual total carbon sequestration due to: (1) water availability by irrigation, (2) generally warmer and more conservative temperatures in urban ecosystems (urban heat island) that extend the vegetation period and reduce frost damage, and (3) fertilization by elevated atmospheric nitrogen deposition and elevated CO_2 concentration in cities (Trusilova and Churkina 2008). On the other hand, air pollution can also lead to significant physiological stress and damage and reduce *GEP* in areas where in particular O_3 concentrations are high.

16.2.3 Other Trace Gases and Aerosols

Few studies exist concerning eddy covariance measurements of other non-CO_2 trace gases and aerosols in cities. With the development and availability of new fast response instruments based on narrow band spectroscopy and mass spectrometry (see Sects. 2.4.4 and 10.3.2 also Chap. 2), it is very likely that in the context of air pollution and greenhouse gas emission reduction strategies, EC-based studies will become more common in the near future, since the technique provides an excellent tool to improve and evaluate emissions inventories, and to better understand urban atmospheric chemistry. Recent studies reported EC measurement of VOC fluxes (Velasco et al. 2005a, b, 2009; Langford et al. 2009), N_2O fluxes (Famulari et al. 2009) and aerosol fluxes including their composition (Dorsey et al. 2002; Longley et al. 2004; Donateo et al. 2006; Järvi et al. 2009b).

16.3 Challenges in the Siting of Urban EC Stations

Despite the heterogeneity of urban surfaces, valid and representative results can be obtained if attention is paid to some principles and concepts specific to urban areas. However, choosing an "ideal" location for EC measurement in cities is hardly possible; the limitations set by logistical and experimental difficulties encountered in urban environments are much higher even than they are for forests. Observations may therefore be limited to certain aspects of turbulent exchange in urban ecosystems since measurements campaigns with more than one measurement tower/location are the exception. Due to logistical, safety restrictions and the need to have public and regulatory acceptance, measurements often have to be performed from existing towers, which are restricted in height and/or with non-adequate fetch. A good companion is flexibility, because it is necessary to consider "nonstandard" exposures in terms of height, surfaces, buildings, and anthropogenic sources of heat, water vapor, and CO_2 (Oke 2006b).

EC measurements reported from urban ecosystems are collected driven by different motivations, and to address various spatial scales. Most commonly, EC systems are implemented to measure integrative fluxes from a "typical" LCZ. In that case, EC systems should be mounted on sufficiently tall towers near the top or above the RSL, but within the ISL of the internal boundary layer of the underlying LCZ. Given the various properties of urban districts it follows that the placement of towers and instruments must be adapted to the respective LCZ. The patchiness of LCZs in an urban landscape limits the vertical extent of the internal boundary layers z_{ib} that develop over each LCZ and form the upper boundary for LCZ-specific measurements. The lower boundary is the height of the RSL z_r so as to avoid the influence of individual roughness elements. The resulting narrow height-range $z_r < z < z_{ib}$, along with logistical limitations often require trade-offs between an acceptable level of RSL influence (e.g., measure in the upper RSL) and nonideal footprints (e.g., measure above z_{ib} for selected stabilities and wind directions but exclude certain cases from analysis). We therefore strongly recommend checking the estimates given by simple footprint models (refer to Chap. 8) before deciding on placement of a flux tower. Note that source areas for turbulent fluxes and radiation sensors are unlikely to match, so special care must be taken so as to gather energy balance measurements that represent the same LCZ.

In addition, some studies use tall towers to investigate regional fluxes from urban-rural landscapes, and special systems have been used to measure the variability of fluxes within the RSL/UCL. EC systems within the RSL can provide localized measurements (e.g., turbulent kinetic energy TKE, statistical moments), but their interpretation is severely limited because many underlying assumptions of the EC theory are not fulfilled (including horizontal homogeneity, vertical direction of relevant flux densities, negligible dispersive fluxes, and negligible advection). It is of great importance to avoid (if not explicitly desired) zones that are characterized by streamlines that have been perturbed by flows around isolated high-rise buildings, roof geometry, street canyons, and flow regimes caused by varying canyon aspect ratios.

16.4 Implications of the Peculiarities of the Urban Boundary Layer on EC Measurements

One of the great advantages of urban sites compared to flux towers in non-urbanized ecosystems is the usually excellent documentation of the urban environment. Aerial photographs, emission inventories, high-resolution maps and 3D surface models, census data, traffic statistics, etc. are typically available from city authorities. It is strongly recommended to make extensive use of those data sets before, during, and after a campaign. With the additional application of footprint models, the source area of an urban flux tower can be described in detail and that allows geostatistical interpretation of the results, the definition of rejection criteria, and passive experimental control.

In the following, the most important derivations related to the EC technique if compared to nonurbanized ecosystems are addressed.

16.4.1 Advection and Storage

While fluxes from grassland, crops, and forests are supposed to be representative of a specific ecosystem, urban fluxes rather represent a specific LCZ, if at all. Since spatial heterogeneity of the roughness elements and of the source/sink distributions is the rule in urban ecosystems; therefore, advective and storage fluxes have to be considered within the concept of the volume balance approach discussed in Sect. 16.2.2.

Advection occurs at three scales in cities. First, at the microscale, advection is expected to be the rule within the UCL, for example, for sensible heat between shadowed and sunlit patches, for latent heat between wet and dry patches, and for air pollutants between high-emission patches (e.g., streets) and passive patches (e.g., courtyards). Microscale advection, however, is not a concern to local scale EC measurements in the ISL, as turbulence blends those effects and the EC system on top of the RSL responds to the integral effects of a microscale patchwork. However, microscale advection also can mean that nonlinear interactions could exist, for example, evapotranspiration is boosted in a small-scale patchwork of dry and wet patches compared to a single large dry patch separated from a large wet patch, even though the relative fractions of wet to dry surfaces might be similar in both cases. Second, at the local scale, advective fluxes are present due to the too close proximity of urban parks, water bodies, and between built-up areas of different density. If the study is not specifically interested in such fluxes, source areas that include several LCZs and steep topography should be avoided. Third, mesoscale advection occurs between the city as a whole and the surrounding rural environment ("urban breeze"), or, for coastal cities, due to the presence of sea breezes (Pigeon et al. 2007b). Further, the surrounding topography may also induce anabatic and katabatic flows similar to those found in connection with other ecosystems (e.g., mountain-valley and/or slope wind systems, drainage flows). In practice, advection is rarely measured in urban field experiments and similar difficulties to those reported from nonurbanized ecosystems (Aubinet et al. 2010) may arise in interpreting the impact of advective fluxes in urban environments.

The considerable height aboveground where EC systems are operated in urban studies can result in non-negligible vertical flux divergences in the air volume below measurement height h_m. A flux divergence of heat and concentrations over time within the balancing volume is explicitly considered in the budget equations and as part of the storage terms (see Sect. 16.2.2 and Fig. 16.4). However, in many applications, instantaneous emissions and uptake at the surface become significant, that is, at the 3D ground–building–air interface, not at h_m. Flux densities measured at h_m by eddy covariance $\overline{w'c_s'}|_{h_m}$ can be "reduced" to a spatial average flux density at the interface, F_0. This is achieved using representative measurements (typically vertical profiles) of the change of concentrations of heat and mass in the air volume over time $\left\langle \partial \overline{c_s} / \partial t \right\rangle$, in analogy to common practice in nonurban ecosystems with tall canopies (see also Eq. 1.24, Sect. 1.4.2):

$$F_s = \overline{w'c_s'}|_{h_m} + \int_0^{h_m} \Lambda_a \left\langle \frac{\partial \overline{c_s}}{\partial t} \right\rangle dz \qquad (16.4)$$

In addition to forest ecosystems, the additional term Λ_a must be introduced; it is the volume fraction of outdoor air in the total balancing volume at a particular height z. In the UCL, buildings occupy a significant fraction of the total volume, so Λ_a can be as small as 30% in dense urban neighborhoods (in forests, the volume occupied by trees is negligible). Strictly speaking, buildings contain airspace as well but "indoor" airspace is mechanically and thermally decoupled from the outdoor atmosphere and the interface of interest is typically the building shell. The vertical profile of Λ_a can be extracted from 3D building data sets, or simply be estimated as a single number in the UCL based on the plan area fraction λ_P of buildings.

Table 16.2 summarizes typical values of measured flux divergences of sensible heat ΔQ_{Sa} and carbon dioxide ΔS_a in the air volume below h_m compared to the magnitude of the fluxes measured by an EC system on a 30 m tower in a dense European city center (Vogt et al. 2005). Storage changes were calculated using a

Table 16.2 Average values (June 15–July 15, 2002, Basel-Sperrstrasse) of flux densities measured at the top of an urban 30 m tower and the effect of storage change in air volume below the measurement height

	Sensible heat flux			CO_2 flux		
	Tower	Storage	Corrected	Tower	Storage	Corrected
	$H_{(hm)}$	ΔQ_{Sa}	$H_{(0)}$	$F_{C(h_m)}$	ΔS_a	$F_{C(0)}$
Time	(W m^{-2})	(W m^{-2})	(W m^{-2})	(μmol m^{-2} s^{-1})	(μmol m^{-2} s^{-1})	(μmol m^{-2} s^{-1})
03:00	+21	−3	+18	+5.3	+1.2	+6.5
09:00	+114	+7	+121	+14.8	−3.4	+11.4
15:00	+222	+2	+224	+14.4	+0.0	+14.4
21:00	+23	−5	+18	+11.7	+2.5	+14.2

profile of six thermometers, and ten CO_2 gas multiplexer inlets at various heights and taking into account the vertical profile of Λ_a. Table 16.2 underlines that for sensible heat flux, during the day, flux divergence below h_m is small ($\Delta Q_{Sa} < 5\%$ of H), but more relevant during the night (up to 30% of H). Note that during the night, measured H at tower top stays positive, but the air in the UCL below cools down. For the CO_2 flux, storage in the air below measurement level is even more relevant, in particular in the morning when the onset of thermal mixing "flushes" out CO_2 enriched air from the street canyons, creating an overestimated CO_2 flux at the tower top. For longer time periods, such as daily or yearly totals, storage in the air volume can be neglected for all fluxes.

Finally, note that in our underlying conceptual framework (Fig. 16.4 and Eqs. 16.1, 16.2, 16.3 and 16.4) advection is completely neglected, but in a real urban setting, horizontal advection processes are likely to occur on several scales. So ultimately, the concentration change over time in the volume below h_m could also be the result of horizontal exchange processes.

Another urban-specific challenge arises from the fact that Eq. 16.4 includes the horizontally averaged concentration change $\left\langle \overline{\partial c_s} / \partial t \right\rangle$ at various heights. While air within forest canopies can be expected to be reasonably well mixed (horizontally), we often encounter horizontally disconnected airspaces in the lower UCL, for example, inner courtyards can be separated from street canyons, and show different concentrations and changes over time. Under situations with horizontally isolated airspaces, a single profile is inadequate to quantify the storage change, and ideally, several, horizontally separated measurements are required.

16.4.2 Flow Distortion

Average streamlines that are not parallel to the ground are a problem for flux measurements (Finnigan et al. 2003). Normally, this problem can, at least partially, be overcome by appropriate rotation and calibration procedures (see Sects. 3.2.4 and 7.3.3.2). However, flow distortion in urban environments can also arise from

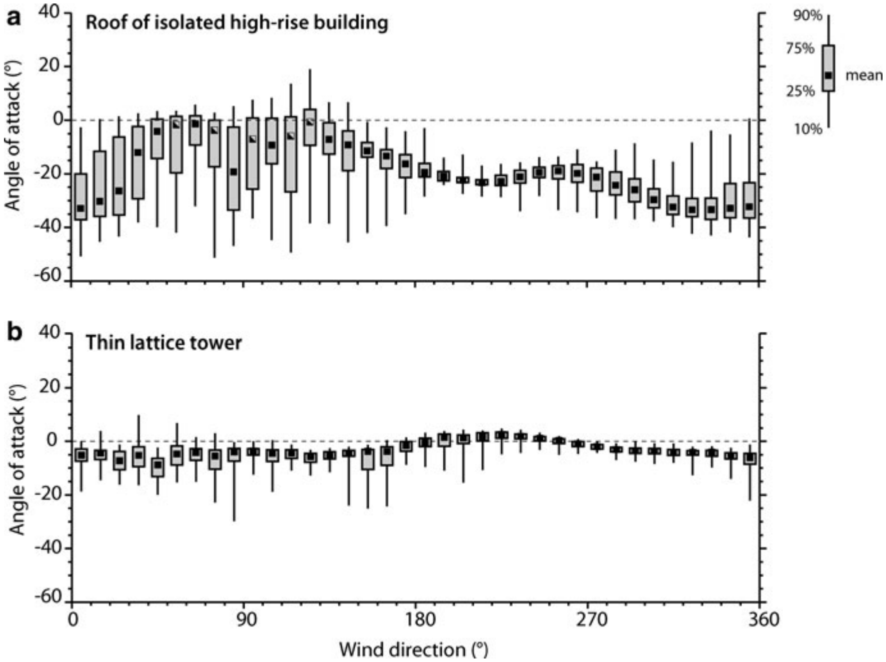

Fig. 16.5 Flow distortion from two selected urban EC measurement sites expressed as average vertical angle of attack: System (**a**) is located 3 m above the roof top of a 120 m high-rise building, (**b**) system is operated on a 20 m lattice tower on the top of a 20 m building

flow separation and deflection around and over local and distant buildings in an urban canopy. In contrast to plant canopies that are mostly permeable and porous, buildings are bluff bodies that are impermeable and inflexible. Therefore, buildings create strong dynamical pressure differences across their facets that in turn leads to significant vertical wind components, decreased mean wind, and enhanced turbulent kinetic energy. For isolated buildings, a displacement of the mean streamlines can be detected several building heights above the roof and significant wake effects can be still found 10–15 times the building's height downwind (e.g., Oke 1987, Fig. 7.6).

As a consequence, EC measurements near dynamical pressure gradients, that is, near exposed walls and on roofs of buildings, are to be avoided (Oke 2006b). For logistical reasons, it may seem inviting to use isolated high-rise buildings as platforms for EC systems in urban areas, but in nearly all cases they are inappropriate. Figure 16.5a shows the angle of attack versus wind direction from an EC system mounted on a small 3 m mast on the edge of the roof of an isolated high-rise building (building height: 120 m, building width: ~40 m) and gives an idea of the strongly deformed wind in the region directly at the roof's edge. Although the EC system is located six times above the average height of the buildings in this neighborhood ($h_m/z_h \sim 6$) and hence expected to be well within the ISL, flux measurements at this location are impossible. The second example in Fig. 16.5b shows the same graph for an EC system on a 20 m lattice tower on top of a building considered "typical" for the given LCZ (building height: 20 m, building width: ~20 m). Although the vertical location of this EC system is at only $h_m/z_h = 2$, the measurement location shows much less flow distortion. In summary, not only is the height of the EC measurements a determinant of the location of urban flux measurements, but also flow distortion can be a severe limitation in the choice of appropriate platforms and measurement locations.

16.4.3 Night Flux Problem, Gap Filling, and QC/QA

The typical premises that lead to the night flux problem (Chap. 5), – that is, low u_* and a stably stratified and decoupled canopy layer – are rarely found in urban atmospheres. The significant roughness of all urban surface forms produces mechanical turbulence which together with the release of stored and anthropogenic heat promotes thermal turbulence, and this produces a well-mixed ISL day and night. Hence, an underestimation of fluxes during nighttime is considered not as critical in cities as it is in a forest ecosystem. Figure 16.6 shows the nighttime frequency for dynamical stability classes in the ISL at five simultaneously operated sites in and around the city of Basel, Switzerland. The frequency of nighttime stable situations decreases from 60% at the rural sites to only 10% in the city center. Unstable situations dominate the nighttime atmosphere at the urban sites due to significant storage and anthropogenic heat releases (Christen and Vogt 2004).

It follows from this discussion that gap filling of urban EC data is mainly restricted to statistical methods (Chap. 6), since the models for respiration and light response have to be adapted to the specific urban conditions and/or are of lesser importance for certain LCZs. Quality-control tests, as described in Chap. 4, may result in a large number of rejected data, since these tests are heavily based on MOST, which is subject to fail in the urban RSL, and nonstationarity is likely to be increased, in particular during daytime, due to increased thermal convection. However, because there is currently no urban-specific QC/QA framework available, it is recommended that the data be tested using the procedures described in Chap. 4 as a first step. Some restrictions may be eased in a further step.

16.4.4 Service and Maintenance of Instruments

In addition to the particular problems arising from the very nature of a city, as described in previous sections, contamination of instruments (transducers, IRGA windows) due to aerosols is the most crucial issue. This implies increased attention to service and maintain the site and the instruments in particular. Advantages and disadvantages of open- and closed-path systems have been previously discussed in

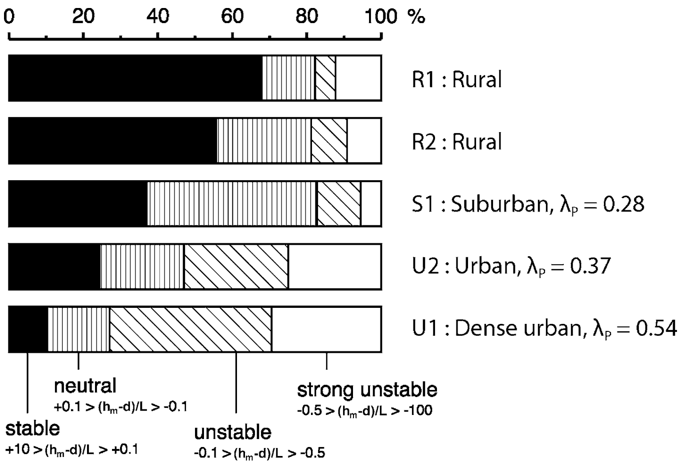

Fig. 16.6 Frequencies of different stability classes for nighttime cases (22–04 h, CET) measured simultaneously at five EC towers in Basel, Switzerland, between 10 June and 10 July 2002 (Modified from Christen and Vogt (2004))

this book (Sect. 2.4.4) and also apply for urban flux towers and instrumentation (Järvi et al. 2009a). However, for both systems, additional care should be taken. For closed-path systems we recommend an interval of a maximum of 1 week for the replacement of the inlet filters, and this may need to be reduced to a few days in heavy polluted environments. The same rule applies to the cleaning interval of open-path sensors. Internal sampling cells of closed-path system IRGAs, though protected by air filters, also need increased attention when exposed to urban polluted air.

16.5 Summary and Conclusions

Using the EC methodology for urban areas is still not a plug-and-play application. With some efforts, however, adequate results from EC measurements in urban areas can be obtained if attention is paid to certain urban-specific peculiarities. Siting of an urban flux tower is much more crucial as it is for sites in non-urbanized ecosystems. It is of highest importance that the researcher is aware of the site-specific influences on the flux measurements, because the "ideal" urban flux site does not exist. Extensive knowledge of the source area characteristics and careful analysis of the flow distortion by the close surroundings of the site are inevitable for a proper interpretation of the measurements. Keeping this in mind and applying the usual data processing chain, flux measurements by the EC technique can be a valuable tool for the characterization of part of the urban metabolism, that is, energy and mass fluxes. Originally restricted to fluxes of energy, water, and carbon, new instruments made the EC technique also attractive to measure fluxes of particle matter, VOC and N_2O, which in turn is helpful for the characterization of the chemistry of the urban atmosphere in the context of air pollution studies.

The instrumentation of an urban and a "nonurban" flux tower is essentially identical and the same advantages and disadvantages for open- and closed-path sensors apply. Some attention should be paid to the increased contamination of instruments and air filters due to the higher air pollution; apart from that, urban flux towers are serviced in the same manner as flux towers in non-urbanized ecosystems.

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