Physical fluxes in urban environment

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PHYSICAL FLUXES IN URBAN ENVIRONMENT

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URBAN METABOLISM: THE METEOROLOGICAL VIEW

Meteorologists are most interested in understanding how energy in the form of radiation and heat influences the urban climate and how this energy is transported, transformed and stored (e.g. in urban building structures). They also are interested in the effects of precipitation on cities, how storm water runoff is changed and how much water is emitted into the atmosphere through evapotranspiration. In addition, they want to know how much cities worldwide contribute to climate change through their emissions to the global carbon cycle. For meteorologists to address the challenges of sustainable cities and urban planning, information on the distribution and flows of energy, water and carbon in typical urban systems have to be known.

From a meteorological perspective, the urban metabolism of a city is strongly dependent on the prevailing regional and local climate and its built-up structure. Together these define the microclimate within the street canyons, on the roads, in the buildings, and at any other place in an urban area. In this context, the urban energy, water and carbon balances are presented in this Chapter.

URBAN ATMOSPHERE

Layers and Scales

A key issue of importance for urban investigations is the definition of the appropriate scale of a study area. A classification of urban canopy layer (UCL) elements according to scale considerations is given in Table 4.1. Vertically, the urban atmosphere can be divided into layers as illustrated in Figure 4.1. The lower atmosphere that is influenced by the urban structure is called the urban boundary layer (UBL). From the ground up to roughly the average height of roughness elements like buildings or trees (z_h) is the UCL. It is produced by micro-scale processes in their immediate surroundings. The UCL is part of the roughness sublayer (RSL) which is dependent on the height and density of roughness elements and extends to the height $z_* = a \cdot z_h$ where a ranges between 2 and 5 (Raupach *et al.* 1991). Above this is the inertial sublayer (ISL) where under ideal conditions vertical fluxes of energy or matter can be expected to be constant with height. The upper part of the UBL, which is to a large extent determined by meso-scale advective processes, is referred to as the outer urban boundary layer (Rotach *et al.* 2005).

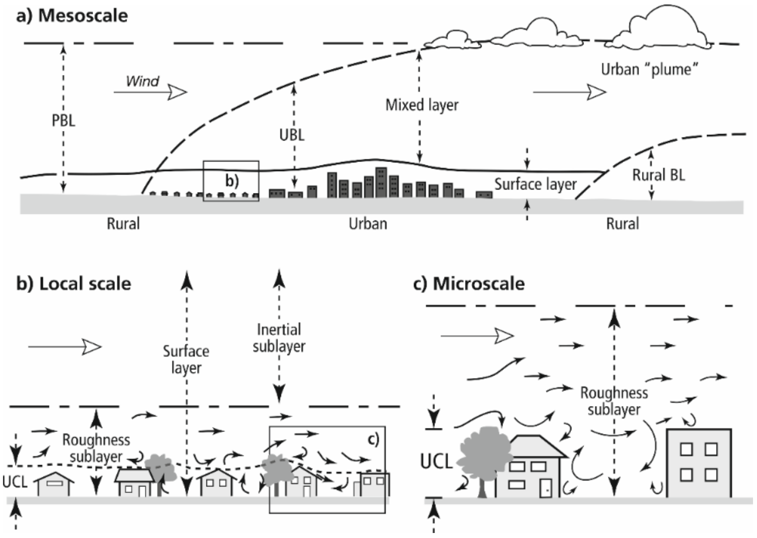
***Table 4.1**: Classification of elements of the urban canopy layer (UCL) and their scales (adapted from (Oke 2006).*

UCL units	Built features	Meteorological scale	Typical horizontal length scales
1. Element	Individual surface element (pavement, trees etc.)	Micro	< 10 m × 10 m
2. Building	Building	Micro	10 m × 10 m
3. Canyon	Street, canyon, property	Micro	30 m × 40 m
4. Block	Block, neighbourhood, factory	Micro/Local	0.5 km × 0.5 km
5. Land-use class (UTZ, UCZ, LCZ, UZE)*	City center, residential, or industrial zone	Local	5 km × 5 km
6. City	Urban area	Local/Meso	25 km × 25 km
7. Urban region	City plus its environs	Meso	100 km × 100 km

* *A number of different classifications at this scale exist including: Urban Terrain Zones (Ellefsen 1990/91), Urban Climate Zones (Oke 2006), Local Climate Zone (Stewart & Oke 2012), Urban Zones for Energy partitioning (Loridan & Grimmond 2012).*

Processes and Variability

The exchange of mass and scalars in the urban atmosphere is governed by several processes linked to the heterogeneity of the 3D urban structure. These have a direct influence on the emission and distribution of energy, water and carbon and their transport to the atmosphere. Enhanced mechanical and thermal turbulence in cities change the wind field and induce perturbed streamlines which have an influence on micro to local-scale transport processes.



Given urban areas are not spatially homogeneous, atmospheric measurements in the UBL are strongly dependent on the spatial and temporal source/sink distribution. This leads to strict requirements for the siting of measurement instruments (Feigenwinter *et al.* 2012, Oke 2006) as vertical turbulent fluxes, for example, are extremely sensitive to strong local sources in combination with prevailing wind directions (Lietzke & Vogt 2013). Ideal sites are hard to find and it is thus of great importance to know the source area of atmospheric measurements, i.e. the urban area for which observations are representative of.

***Figure 4.1**: Scales and Layers (planetary boundary layer PBL, urban boundary layer UBL, urban canopy layer UCL) in the urban atmosphere (Feigenwinter et al. 2012, adapted from Oke 2006).*

METHODS

The energy, water and carbon balances of an urban system can be determined by considering their physical flows in and out of a control volume, which, considering mass conservation, leads to a volume balance approach as depicted in Figure 4.2.

The measurement of the fluxes is achieved with different, often very specific methods. These methods are discussed in the subsequent sections together with the respective processes they measure. One elementary and widely used method to derive the vertical exchange of energy and mass as part of an air volume, the Eddy Covariance (EC) method, is presented here, since this method was mainly used in the BRIDGE project (Chrysoulakis et al. 2013), as described in Chapter 5.

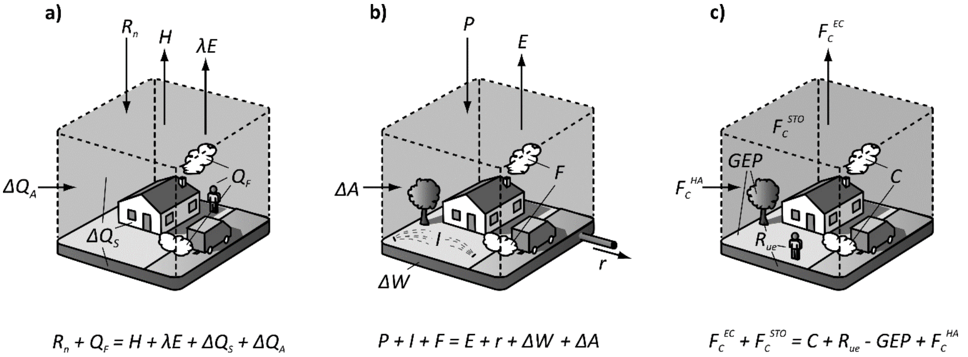


Figure 4.2*: Schematic depiction of the (a) Urban Energy Balance; (b) Urban Water Balance; and (c) Urban Carbon Balance from a micrometeorological perspective. The directions of the arrows represent positive fluxes. Adapted from (Feigenwinter et al. 2012).*

The EC method relies on the fact that atmospheric turbulence is usually the main vertical transport mechanism in the ISL of the UBL. High frequency variations (typically 10-20 Hz) of the vertical wind component *w* and the scalar *s* of interest (e.g. H_2O or CO_2) are measured and, after decomposing into mean and turbulent parts by applying Reynolds averaging, their covariance $\overline{w's'}$ gives the vertical turbulent exchange rate of the respective scalar. The primes denote the deviations from the mean and the overbar the average.

Measurements have to be situated at the top of the control volume (Figure 4.2), which is ideally inside the ISL, to capture the vertical transport in and out of the volume. The instrument of choice is usually an ultrasonic-anemometer-thermometer in combination with a gas-analyzer that measures the scalars of interest (see Chapter 5 for details). An extensive overview on the EC method is given in Aubinet *et al.* (2012).

For inhomogeneous urban areas, the EC method is more suitable than other approaches, such as the flux-gradient relations, which normally fail in the RSL (Christen 2005, Piringer *et al.* 2002, Roth & Oke 1995). Measurements higher up in the ISL are difficult in urban areas due to a lack of higher towers and because of fetch considerations. Therefore, care needs to be taken when using micrometeorological techniques to consider averaging time, the flux source area and sensor placement to ensure representativeness of the flux in an urban context (Foken 2008, Grimmond 2006, Schmid & Rotach 1997).

PHYSICAL FLUXES

Energy fluxes - Urban Energy Balance

Introduction

Following the volume balance approach, the energy balance of an urban system (Urban Energy Balance - UEB) can be determined by considering the energy flows in and out of the control volume:

$$R_n + Q_F = H + \lambda E + \Delta Q_S + \Delta Q_A$$

where R_n is the net all wave radiation, Q_F is the anthropogenic heat flux, H is the turbulent sensible heat flux, λE is the turbulent latent heat flux, ΔQ_S is the net storage change within the control volume and ΔQ_A is the net advected flux. All terms are usually expressed as energy flux density per horizontal, or vertical area (typically W m^{-2}, also MJ m^{-2} d^{-1} for temporal sums). In the following sections each of the UEB terms are discussed.

Theoretical knowledge of the processes forming the UEB and the resultant effects on the urban boundary layer is well developed based on numerous observational studies. For typical urban areas, the daytime energy balance is characterized by a significant storage heat flux term, a strong sensible heat flux away from the surface and weak evapotranspiration. As a consequence of strong nocturnal release of stored heat, both turbulent heat fluxes remain directed upward on average at night, a notable difference to the rural environment. This has consequences for the stability of the urban ISL and the RSL which are thermally unstable most of the time (Christen 2005).

Net all wave radiation R_n

Net all wave radiation (R_n) is the balance between the incoming (↓) and outgoing (↑) short- (*SW*) and long-wave (LW) radiation fluxes and represents the primary source of energy in the UEB:

$$R_n = SW\downarrow - SW\uparrow + LW\downarrow - LW\uparrow$$

Measurements can be made using pyranometers for the shortwave fluxes and pyrgeometers for the long-wave fluxes, or by using net radiometers. In a typical urban atmosphere radiative fluxes are, if compared to their rural counterparts, altered by pollutants. Whereas SW↓ will be reduced, LW↓ is greater. In typical mid-latitude cities, these changes are normally opposed by a lower shortwave albedo due to darker surface materials (whereas in low-latitude cities, walls and roofs are generally brighter) and a higher surface temperature at night, which augments the long-wave emission (Oke 1987). The net effect on urban/rural radiation differences therefore remains small (Oke 1987, Rotach *et al.* 2005).

Anthropogenic heat flux Q_F

The anthropogenic heat flux (Q_F) derives mainly of combustion exhausts by stationary and mobile sources (Grimmond 1992, Sailor 2010). Thus, its contribution to the UEB tends to be highest in cold climates in the wintertime when the energy input from human sources is comparatively large (primarily due to domestic heating). But even in summertime it may become significant for cities with high air conditioning usage. Q_F is difficult to determine because of its strongly varying patterns in space and time and because it cannot be measured directly. It is therefore not surprising that many different approaches to estimate this term can be found in literature.

A common approach is to estimate Q_F based on inventories of existing socio-economic data, e.g. from energy use data (Sailor 2010). These kinds of data have been analysed as part of the BRIDGE project (Allen *et al.* 2010, Iamarino *et al.* 2012, Lindberg *et al.* 2013, Chapter 5). A second approach, if daily or yearly totals of the energy balance equation are considered, and ΔQ_S can be assumed to be zero, allows calculation of Q_F as the residual term (Christen & Vogt 2004, Pigeon *et al.* 2007a), or with storage heat flux measurements at a monthly diurnal time-scale (Offerle *et al.* 2005). A third approach explored as part of the BRIDGE project, uses micro-scale analysis of the eddy covariance data (Kotthaus & Grimmond 2012) to determine the amount of energy released from buildings. This uses the 'spikes' of heat, water, and CO_2 10 Hz data, which impact the departure of the mean used in the eddy covariance calculation.

The spatial and temporal patterns of Q_F, have large impacts on the urban climate and is impacted by many of the urban planning alternatives (Chapter 3), therefore understanding the role and size of this term is important.

Turbulent sensible heat flux H

The vertical transport of energy by the sensible heat flux (H) as measured by the EC method is expressed:

$$H = \rho c_p \overline{w'T'}$$

where ρ is the air density (kg m^{-3}) c_p is the specific heat capacity of air (J kg^{-1} K^{-1}) and $\overline{w'T'}$ is the average of the product of the turbulent fluctuations of air temperature T and the vertical wind speed w (K m s^{-1}). During daytime this term is primarily driven through energy input by R_n, while at night storage release from the urban structure keeps H at a higher level compared to rural areas.

Turbulent latent heat flux λE

The turbulent latent heat flux λE transports moisture away from the surface because of a change of state (e.g. condensation, evaporation). This depends primarily on the availability of water, particularly the presence of vegetated areas (transpiration) or wet surfaces (evaporation). Similar to the sensible heat flux it can be written as:

$$\lambda E = L_v \overline{w'\rho'_v}$$

with Lv the latent heat of vaporization (J kg^{-1}) and ρ'_v the fluctuating water vapor density (kg m^{-3}). λE can be measured directly using the EC method (e.g. a sonic anemometer coupled with an open-path infrared gas analyzer). The quantification of λE is complicated by the extremely heterogeneous sources of moisture. This term is discussed further in the next Section, when evapotranspiration (its water equivalent) is considered.

Net storage change ΔQ_S

The rate of change of heat storage (ΔQ_S) consists of the uptake or release of energy by the ground, buildings and vegetation and in the volume. It includes the changes of latent and sensible heat content in the air of the considered control volume. The latter changes are often neglected as they are small compared to the heat storage changes in urban materials.

ΔQ_S within an urban control volume can be theoretically expressed as the sum of storage fluxes for single surface elements (Offerle *et al.* 2005):

$$\Delta Q_S = \sum_i \frac{\Delta T_i}{\Delta t} (\rho C)_i \Delta x_i \lambda_{pi}$$

where $\Delta T/\Delta t$ is the rate of temperature change, ρC (J m^{-3} K^{-1}) is the volumetric heat capacity, Δx (m) is the element thickness and λ_p (m^2) is the plan area index for each element i (Offerle *et al.* 2005).

As cities are not expected to cool down, or heat up during a year, the annual total of ΔQ_S has to be zero by definition (Christen 2005, Offerle *et al.* 2005). This is helpful in calculating annual surface energy balances and in assigning annual residuals to other terms as, for example, the anthropogenic heat flux. ΔQ_S is a spatially and temporally variable term of the energy balance, depending on differences in surface type and radiant loading. It is of particular relevance in the urban energy balance as it can account for more than half of the daytime net radiation at highly urbanized sites (Roberts *et al.* 2006).

Direct measurements in urban areas are practically unattainable due to the complexity of urban structures and materials. ΔQ_S therefore has to be determined by indirect methods or models. As for most fluxes that are not directly measureable, there is a lack of standard for the determination of urban heat storage and quite a range of methods exist. A commonly used method is to consider the storage flux term as the residual of the energy balance (e.g. Christen & Vogt 2004, Grimmond & Oke 1995, Grimmond & Oke 1999, Roth & Oke 1994, Spronken-Smith *et al.* 2006):

$$\Delta Q_S = R_n - H - \lambda E$$

ΔQ_A and Q_F are here considered as negligible. Another widely used parameterization approach is based on relations between the net-all wave radiation $R_n$and the storage heat flux ΔQ_S for typical surface materials (Camuffo & Bernardi 1982, Grimmond & Oke 1991, Oke *et al.* 1981).

Net advected flux ΔQ_A

Storage change in a control volume due to advection can be expressed as a result of the flow in and out of the volume as:

$$\Delta Q_A = Q_A^{in} - Q_A^{out}$$

The scale of the advection is critical relative to the scale of interest. Local-scale advection has largely been neglected for a long time in urban measurement studies based on assuming that the fetch conditions were similar so the term could be considered to be small and the theoretical assumption of horizontal homogeneity was adopted. However, the fetch is rarely sufficiently extensive and consistent, so the latter is often questionable.

To date ΔQ_A has only been investigated at the local-scale in urban environments in cities with meso-scale circulations, such as diurnal sea-breeze circulations (e.g. Pigeon *et al.* 2007b), or drainage flows (e.g. Spronken-Smith *et al.* 2006) where it has been shown to be important. The circulations between the city and the surroundings (e.g. Lemonsu *et al.* 2001) and because of local-scale features (e.g. urban parks, Spronken-Smith *et al.* 2000) are thought to be important influences in urban areas. However, these processes remain under-studied in urban areas because of the vast array of instrumentation needed and the need to couple the observations with 3D modelling (e.g. Pigeon *et al.* 2007b). In the BRIDGE, the role of advection has been considered at the local-scale in London (Kotthaus & Grimmond 2013a and 2013b, Loridan *et al.* 2013).

Water Fluxes - Urban Water Balance

Introduction

The urban environment is significantly different to natural hydrological watersheds in terms of land use, water flows and surface cover leading to the modification of the hydrological cycle. In addition, the transport and removal of water through the piped water system adds an anthropogenic component. Artificial surfaces found in urban areas enhance the surface runoff leading to an enhanced risk of flooding and the transport of pollutants (Burian *et al.* 2002), along with a reduction in infiltration leading to lower replenishment of groundwater (Stephenson 1994).

The Urban Water Balance (UWB) applies the principle of mass conservation to the transfer of water through a specific domain, or catchment (Grimmond *et al.* 1986), allowing the study of both spatial and temporal patterns of water supply and usage (Mitchell *et al.* 2001). It can be written as (Grimmond & Oke 1991):

$$P + I + F = E + r + \Delta W + \Delta A$$

where P is precipitation, I is the urban piped water supply, F is water release due to human activity, E is evapotranspiration, r is runoff, ΔW is net change in water storage and ΔA is the net advection of moisture in and out of the control volume. Each of the terms is usually expressed as a depth of water, or as a volume per unit time. It is also common to express individual terms as a percentage of the annual precipitation (often assumed to be the main input into the system) especially in the study of individual components such as runoff and evapotranspiration (e.g. Berthier *et al.* 2006, Xiao *et al.* 2007).

Precipitation P

Precipitation is a key input into the UWB as the amount and intensity directly impact the potential magnitude of evapotranspiration, runoff and infiltration and the amount of recharge to surface and groundwater stores. The components of total precipitation (P) are:

$$P = P_r + P_h + P_s + P_m$$

where P_r is rainfall, P_h is hail, P_s is snow and P_m is atmospheric moisture which condenses on contact with the surface in the form of fog, mist or dew. The form of precipitation dictates the timing of the availability of water for runoff, infiltration and evapotranspiration. Snow and hail, which fall in a solid/ semi-solid state, have to undergo a change of state to liquid or gaseous form and thus for a time period may be recorded as an increase in storage in the UWB. Depending on the climate, this can last for many months and affect the UWB at a later date through runoff or evaporation (e.g. Järvi *et al.* 2014, for Helsinki).

Precipitation measurement within urban areas has traditionally used tipping bucket raingauges. Radar can provide spatial information, but cannot be used alone due to uncertainty in its accuracy (Berne *et al.* 2004, Vieux & Bedient 2004).

Piped Water Supply I

The total piped water supply (I) consists of:

$$I = I_U + I_R + I_G + I_S$$

where I_U is the internal residential/commercial/industrial water use, I_R is water used for irrigation, I_G is grey or other reused water and I_S is the leakage to/from the piped network.

The magnitude of the water supplied is driven by a combination of demand from urban inhabitants and supply by the water utility companies or agencies, which is determined by availability of surface and groundwater supplies. Measurement of the supplied water is often from water utility company water meters (e.g. Morris *et al.* 2007).

Irrigation is a major component of piped water use in urban areas, where seasonal precipitation and weather patterns are particularly variable (Mitchell *et al.* 2001), with variability in irrigation related to specific weather events (Grimmond & Oke 1986). However, determining the actual amount of irrigation (as with other water usage) is a much more complex problem as it is related to the human perception and behaviour (e.g. Arnfield 2003, Grimmond & Oke 1986).

Anthropogenic Water Release due to Combustion F

Anthropogenic water release due to combustion of fuels and from industry consists of:

$$F = F_M + F_I + F_V + F_W$$

where F_M is the release of moisture from air conditioning, heating and cooling applications, F_I is the moisture released from industry, F_V is the moisture released due to combustion of from vehicles and F_W is consumption of bottled water. This term has not been neither widely investigated, nor often considered in UWB models (e.g. Grimmond *et al.* 1986, Mitchell *et al.* 2001), but in large cities this term can become more important (Moriwaki & Kanda 2004). In Tokyo, Japan local-scale EC observations over a heavily urbanised area (very little vegetation) displayed significantly large latent heat fluxes (> 100 W m^{-2} and at times greater than observed sensible heat flux) in the summer months, as a result of anthropogenic moisture release from building cooling systems (Moriwaki *et al.*2008).

Evapotranspiration E

Evapotranspiration includes evaporation of surface water and transpiration through vegetation of water from the sub-surface vadose zone (Xiao *et al.* 2007). The term is used interchangeably with evaporation in many studies where it is impractical to separate the two components (Brutsaert 1982):

$$E = E_V + E_T$$

where E_V is evaporation and E_T is transpiration. Its energy equivalent is the latent heat flux Q_E.

Given that water is typically limited at the surface within cities due to high areal fractions of un-vegetated and impervious surfaces, actual evaporation rates are limited by surface controls and energy availability. When water availability is unlimited the theoretical maximum evaporation is typically referred to as potential evaporation which is usually greater than the actual evaporation (Aston 1977). Despite these limiting factors, E can be one of the most important terms in the UWB as a result of complex microclimates, surface storage and irrigation (Berthier *et al.* 2006, Grimmond & Oke 1986, Grimmond & Oke 1991, Grimmond & Oke 1999, Mitchell *et al.* 2001).

Urban parks and open water bodies are of particular interest due to the relatively high vegetation cover and greater amount of available moisture resulting in distinct microclimates (the former akin to that of a desert oasis) in comparison to surrounding more built up areas (Hathway & Sharples 2012, Spronken-Smith *et al.* 2000, Steeneveld *et al.* 2014). Spronken-Smith *et al.* 2000 observed that daily total evapotranspiration in a park in Sacramento, USA was greater than 300% of the total from the surrounding irrigated suburban area.

Observation of evapotranspiration has been undertaken using mini-lysimeters at the micro-scale (Oke 1979), while at the local-scale, micrometeorological techniques are often applied (e.g. EC). Alternatively when direct measurement is unavailable it can be determined as a residual term of the UWB equation or using the Bowen ratio energy balance (Nouri *et al.* 2012). Goldbach & Kuttler 2013 found in Oberhausen, Germany, using EC, that absolute daily maximum evapotranspiration varied by up to 90% between urban and suburban areas where vegetated surface fractions were 0.18 and 0.58, respectively. Datasets from 19 EC sites located in urban and suburban areas of 15 cities worldwide indicated a positive relation between the active vegetated index (indices based on vegetated fraction and seasonal leaf-area index (Loridan *et al.* 2011)) and mean midday evapotranspiration, with a stronger linear dependence on observed E rates prevalent when active vegetated index was < 0.43 (Loridan & Grimmond 2012).

Runoff r

Runoff is the flow over the surface and through drainage pipes. It represents water that has not been captured by some intermediate store (e.g. tree canopy, roof or surface storage) or has not infiltrated into sub-surface stores within a particular time period. A greater fraction of impervious surfaces in cities in comparison to rural areas leads to more rapid surface flows often enhanced by drainage networks (Semadeni-Davies & Bengtsson 1999). The increase in runoff can lead to a higher probability of flooding and the transport of pollutants (Burian *et al.* 2002, Xiao *et al.* 2007). Urban runoff consists of:

$$r = r_S + r_W + r_O + r_L + r_F$$

where r_S is storm water runoff (through storm drains), r_W is waste water flow (sewer system), r_O is runoff released by snow melt, r_L is surface runoff (e.g. overland flow and roof runoff) and r_F is surface infiltration. The rate and magnitude of runoff are regulated by the rate of precipitation, soil moisture content (influences infiltration), land surface properties (e.g. fraction of vegetation cover and permeability), local topography and the design of the drainage system infrastructure.

Runoff is often either modelled in the UWB due to a lack of measured data or the size of the study catchment (Branger *et al.* 2013, Wang *et al.* 2008), parameterized using infiltration/runoff coefficients (Hollis & Ovenden 1988) or as a residual (Jia *et al.* 2001). However runoff measurement is possible directly using flow meters to determine discharge through a drainage system (Ragab *et al.* 2003b), or controlled study area (Stephenson 1994, Xiao *et al.* 2007), water capture to collect and measure roof runoff (Hollis & Ovenden 1988, Ragab *et al.* 2003a), or indirectly using water balance techniques to determine available water for potential runoff (Inkiläinen *et al.* 2013). In the BRIDGE case studies, the runoff in two small catchments were observed in Helsinki (see Chapter 10 for details).

Net Storage Change ΔW

The net change in storage term (ΔW) refers to the change in water storage within the study catchment. Its magnitude is determined by

$$\Delta W = \Delta W_g + \Delta W_m + \Delta W_W + \Delta W_a + \Delta W_n$$

where ΔW_g is the net change in ground water storage, ΔW_m is the net change in soil moisture storage, ΔW_W is surface water storage (e.g. ponds and lakes), ΔW_a is anthropogenic storage (e.g. storm water holding and water butts) and ΔW_n is the net change in snowpack storage.

For large catchments groundwater within the soil and deeper aquifer(s) can be significant. Techniques to measure soil moisture include tensionmeters (Berthier *et al.* 2004), gravimetric sampling (Grimmond & Oke 1986), time domain reflectometry and groundwater levels can be observed through boreholes (Stephenson 1994).

Net Moisture Advection ΔA

The net moisture advection is the horizontal transport of moisture by atmospheric flow. It is driven by flows at a number of atmospheric scales ranging from micro and local-scale turbulence to meso-scale circulations (e.g. sea breezes and valley flow). In many UWB studies the net moisture advection is not considered (e.g. Grimmond *et al.* 1986, Lemonsu *et al.* 2007).

Carbon fluxes - Urban Carbon Balance

Introduction

Compared to energy and water, the urban balance of carbon - in the form of CO_2 - shows greater deviations from its rural counterpart. Anthropogenic CO_2 emissions, derived from the burning of fossil fuels are the major net source for global atmospheric carbon (Denman *et al.* 2007) and cities contribute a great share. Thus, knowledge of the spatiotemporal distribution of sources and sinks in urban environments and the processes that determine atmospheric transport in the UBL is of great importance.

Using a volume budget approach that focuses on surface-atmosphere processes, the Urban Carbon Balance (UCB) can be written as:

$$F_C^{EC} + F_C^{STO} = C + R_{ue} - GEP + F_C^{HA}$$

where F_C^{EC} is the integrative turbulent mass flux density of CO_2, F_C^{STO} is the storage change between the surface and the measurement level, C represents emissions through anthropogenic combustion processes, R_{ue} is the respiration of the urban ecosystem (including from humans), GEP stands for the sink effects due to photosynthesis and F_C^{HA} is the horizontal advection contribution. Terms are usually expressed as CO_2 flux density per horizontal or vertical area (typically μmol m^{-2} s^{-1} or kg m^{-2} a^{-1}.)

Turbulent carbon dioxide flux F_C^{EC}

A common way to determine the turbulent vertical mass flux density of CO_2 (F_C^{EC}) is by the use of the EC method, combining sonic with infrared gas analyzer measurements (a list of urban studies can be found in (Lietzke *et al.* 2014, in review). Two types of gas analyzers are widely used: open path analyzers where CO_2 concentrations are measured instantaneously in the probed air volume (e.g. Moriwaki & Kanda 2004, Vogt *et al.* 2006) and closed path analyzers where air is sucked through a tube into an enclosed measurement system (e.g. Grimmond *et al.* 2002, Järvi *et al.* 2012). The first has the advantage of measuring *in situ* but is sensitive to disturbances of the measurement path, e.g. through rain, dew or dust. The latter measurements are subject to a time lag and an attenuation of the signal, dependent on the length of the tube, but are not influenced by meteorological disturbances (Grimmond *et al.* 2002, Järvi *et al.* 2009).

Summing F_C^{EC} over a defined timescale yields the net urban ecosystem exchange (*NuEE*) rate analogous to the net ecosystem exchange (*NEE*) rates of rural ecosystems. The main contrast to non-urban ecosystems is that the urban surfaces generally act as a CO_2 source; consequently F_C^{EC} is nearly always positive. This results in positive *NuEE* values which are usually higher the more urbanized an area is.

Net storage change in the air F_C^{STO}

Fluxes in the RSL are not constant with height (Rotach 2001) and thus a vertical flux divergence over time has to be assumed in the air volume between the urban surface and the measurement level. This is considered in the term F_C^{STO}, which can be determined using representative measurements of the concentration change within the air volume over time (Feigenwinter *et al.* 2012). In an urban environment, this would need several vertical profile measurements to account for the spatial variability within the EC source area - which is rarely feasible. Similar to ΔQ_S, F_C^{STO} can assumed to be zero over a longer time period. On a diurnal scale it becomes relevant as, for example, nocturnally accumulated CO_2 in the shallow UBL and the street canyons is flushed in the morning, when thermal mixing starts, leading to an overestimation of F_C^{EC} compared to the actual emissions (Feigenwinter *et al.* 2012).

Combustion C

Anthropogenic emissions through combustion of fossil fuels are the main contributors to the UCB, consisting of:

$$C = C_B + C_V$$

The combustion from buildings (C_B) and vehicular traffic (C_V) can be distinguished by the type of fuel they burn (natural gas, oil or wood for heating versus gasoline or diesel for driving) and the spatio-temporal emission patterns. Source distribution is, as for Q_F, very heterogeneous. While C_V can be considered as a line source on the bottom of the control volume that is primarily dependent on the diurnal/weekly traffic use behavior, C_B generated by heating depends on climate related human activity (heating in winter, air conditioning in summer), has a distinct seasonal cycle (Lietzke *et al.* 2014, in review) and consists of point sources at certain heights (e.g. chimneys) (Kotthaus & Grimmond 2012). Industry emissions as a part of C_B follow their own patterns that need to be taken into account as appropriate.

Through isotopic analyses of air samples (Clark-Thorne & Yapp 2003, Pataki *et al.* 2003), the fraction of atmospheric CO_2 generated by either C_B or C_V can be derived. Inventory based approaches using fossil fuel consumption data and traffic density analyses (e.g. Helfter *et al.* 2011, Ward *et al.* 2013) can give an estimate on C_B and C_V, or are used as input to model their contributions. Spatiotemporal adequately resolved data is rarely available so that e.g. fuel consumption often has to be scaled down from city to neighbourhood or building-scale (e.g. Christen *et al.* 2011). An indicator of fuel burned for heating purposes can be heating degree days based on outside air temperature and the desired inside air temperature (Lietzke *et al.* 2014, in review).

Urban ecosystem respiration R_{ue}

Urban ecosystem respiration (R_{ue}) can be separated into respiration of soils and vegetation (R_{SV}), waste decomposition (R_W) and human respiration (R_M):

$$R_{ue} = R_{SV} + R_W + R_M$$

Compared to natural ecosystems, urban R_{SV} is influenced by irrigation and fertilization. R_M depends on the density of people that live or work in an area and, on the basis of an individual, the physiological level of activity (active, resting, sleeping etc.). Moriwaki & Kanda 2004 estimated human body respiration emissions at rest to be 8.87 mg CO_2 s^{-1}.

Gross ecosystem productivity GEP

Gross ecosystem productivity (*GEP*) is a measure of the uptake of CO_2 through photosynthesis from the air. In cities, both *GEP* and R_{SV} are primarily dependent on the surface fraction of vegetation (parks, lawns and trees), its density and type and the local climate which determines the seasonal photosynthesis rate. Productivity of urban vegetation is usually high due to irrigation, higher temperatures, less frost damage (urban heat island) and fertilization (e.g. NO_X deposition) (Trusilova & Churkina 2008), but physiological stress due to air pollution may lead to reduced *GEP*. Chamber measurements (Christen *et al.* 2011) help in estimating soil and lawn activity. In urban areas, photosynthesis is typically not able to compensate for the high CO_2 emissions by combustion (Kotthaus & Grimmond 2012, Lietzke & Vogt 2013), but may have a limiting effect on measured fluxes (Coutts *et al.* 2007, Kordowski & Kuttler 2010, Ward *et al.* 2013). Depending on the extent of urbanization, particularly vegetation effects, temporary sink effects can be observed (e.g. Crawford *et al.* 2011, Ramamurthy & Pardyjak 2011).

Net advection F_C^{HA}

Similar to advection in the UEB and UWB, net horizontal advection of CO_2 (F_C^{HA}) in urban areas is rarely addressed in studies. Results from a number of field experiments in forests (Aubinet *et al.* 2010) show, that there is a large uncertainty in quantifying horizontal and vertical advection fluxes. Both terms are large, are coupled and seem not to cancel each other. To date, it is not known how relevant this is for the urban environment.

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