Introduction to urban climate

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https://www.architecturaldigest.com/story/architect-new-yorks-central-park-incredibly-unexpected-legacy

Today's session

Outline

- **Concepts of urban climate**
- Urban atmosphere
- Airflow
- Energy balance

Concepts

The study of the physical, chemical and biological processes operating to produce or change the state of the urban atmosphere is **urban meteorology** and the study of the statistically preferred states of urban weather is **urban climatology**.

The description of urban climate processes is a complex task due to the **heterogeneity of urban landscapes** – see the figure on the left for an example of the numerous types of fabric, patterns of surface cover, complex 3-D urban structure and urban metabolism associated with emissions of heat, water and air pollutants into the atmosphere.

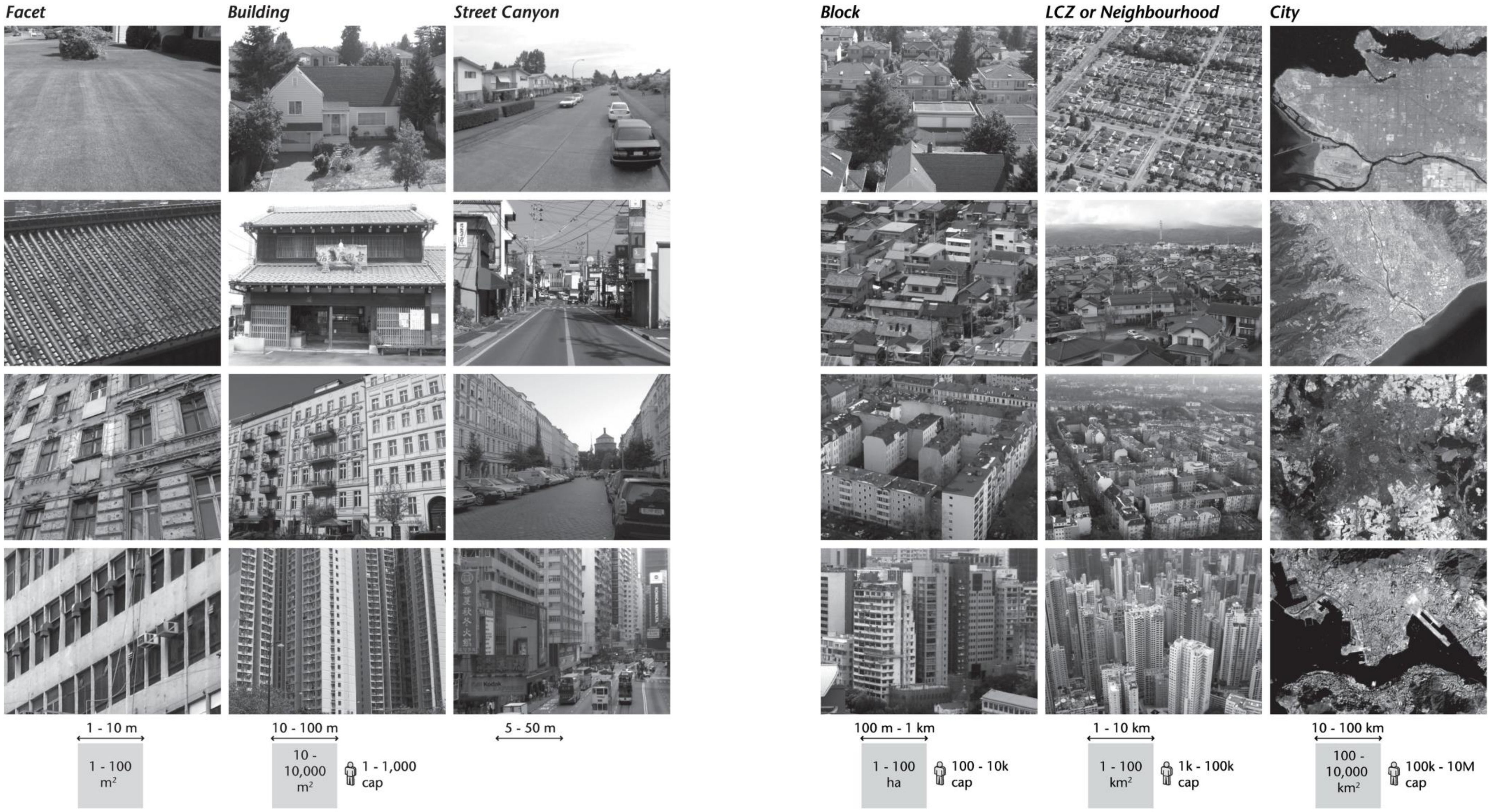
Oke et al. (2017)

Concepts

The study of urban climates relies on some essential concepts and definitions. In this context, the role of **scale** is probably the single most important key to understanding the impact of cities on the atmosphere.

Tokyo, Japan (Source: Stewart & Oke et al., 2012)

Concepts



Oke et al. (2017)

Concepts

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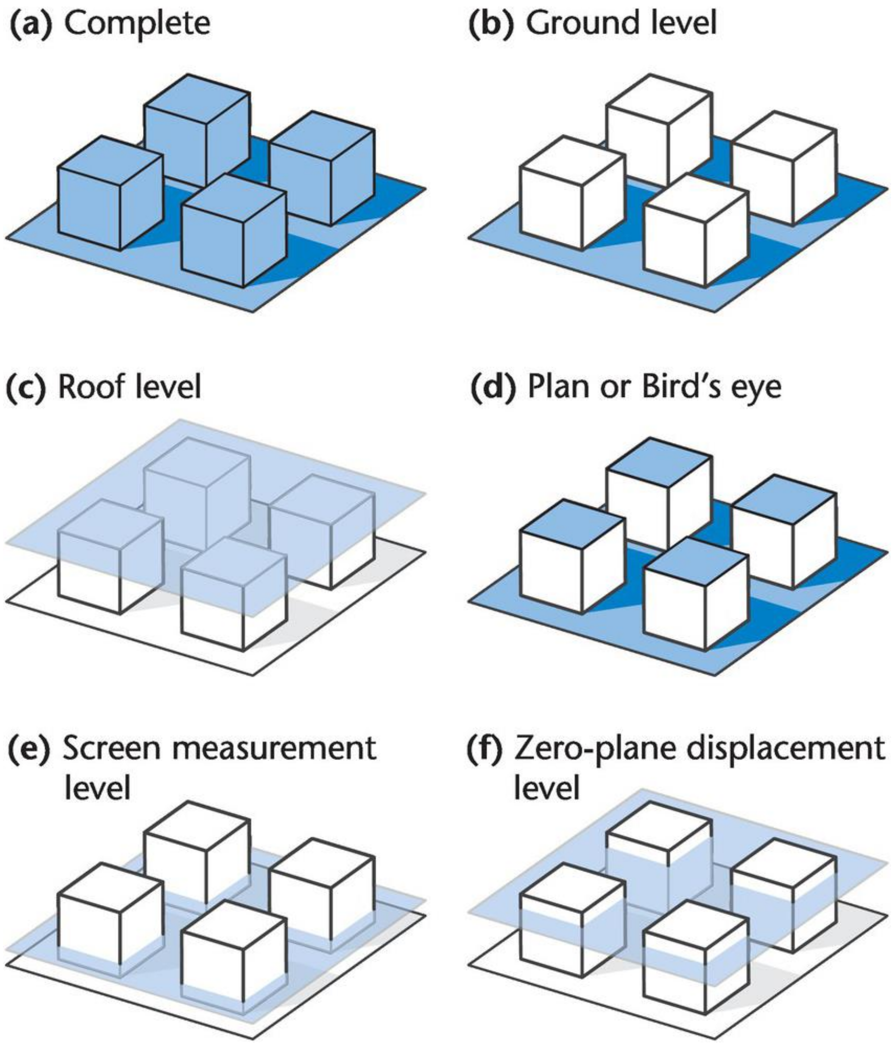
Definitions of the Urban Land Surface

The land surface controls the *exchanges of energy, mass and momentum* and it usually experiences the most extreme climate (i.e. where it is hottest or coldest, driest or most moist, where flow is brought to rest).

Near the surface is also where the greatest variability in microclimates exists (i.e. the greatest range of values from place to place and day to night). Yet, defining the relevant "surface" is not always simple and this is especially the case in an urban environment.

Potential definitions, or perspectives, of the 'surface' (in blue) of a highly simplified representation of an urban system.



Oke et al. (2017)

Concepts

Properties of the Urban Surface

An urban system is composed of an almost limitless number of climatically-active surfaces. They consist of a range of fabrics each of which has different climatic properties including the following:

- **Radiative:** geometry, absorptivity, reflectivity, transmissivity, emissivity.
- **Thermal:** specific heat, heat capacity, thermal conductivity, thermal diffusivity, thermal admittance.
- **Moisture:** interception and storage capacity, permeability, stomatal characteristics, chemical nature.
- **Aerodynamic:** roughness, zero-plane displacement, porosity.

These *mosaics* of active surfaces generate a *"collection of microclimates"*. For example, there is a remarkably wide variety of atmospheric conditions co-existing in a single house lot during a fine summer day. It is not unusual to find sunny portions of a roof with surface temperatures of more than 50°C whilst a nearby shaded wall or plants in the garden are 30 degrees cooler; over an open lawn it may be breezy yet just around the corner of the house the air is almost still.

Image by coolingsingapore.sg

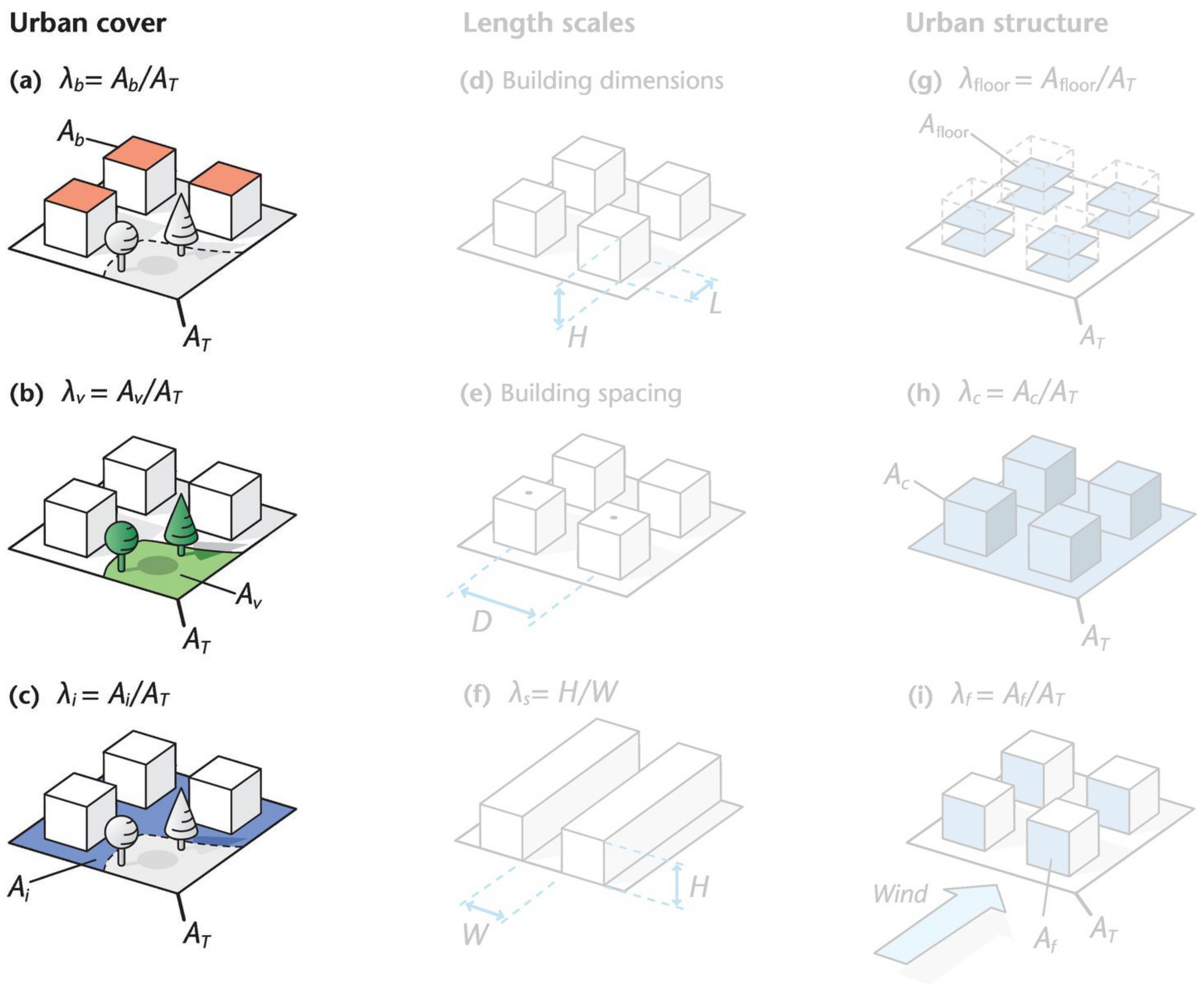
Concepts

Surface cover

A simple way to describe the main components of an urban system at coarser scales than facets is to express the **plan area fraction** occupied by a cover or element type (A_x) within a total ground surface area (A_T) that is large enough to be representative of the area of interest:

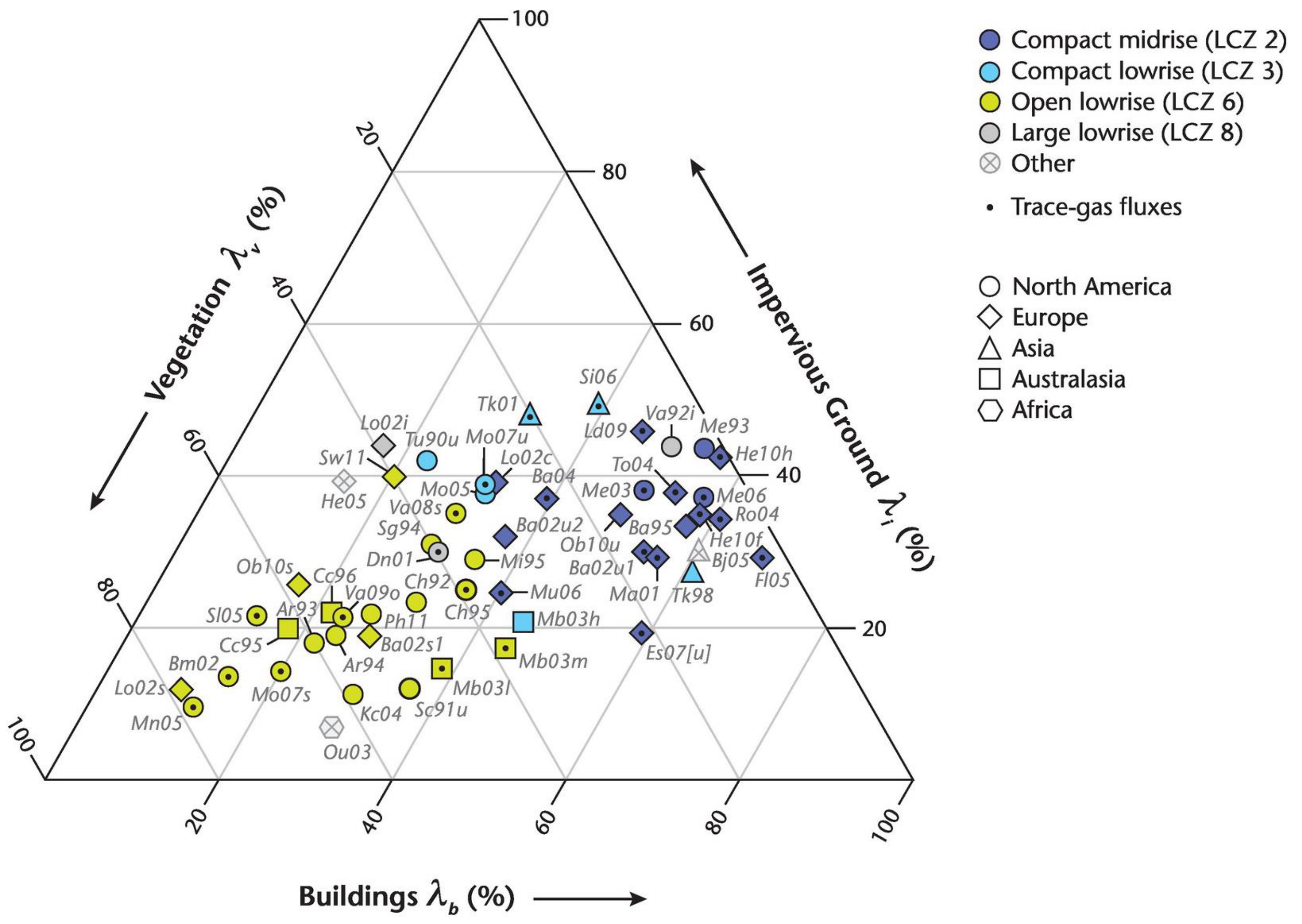
$$\lambda_x = \frac{A_x}{A_T}$$

where the subscript *x* stands for the cover type that can be buildings (b), vegetation (v), impervious ground (i) (roads, parking lots, etc.), frontal building area (f), etc

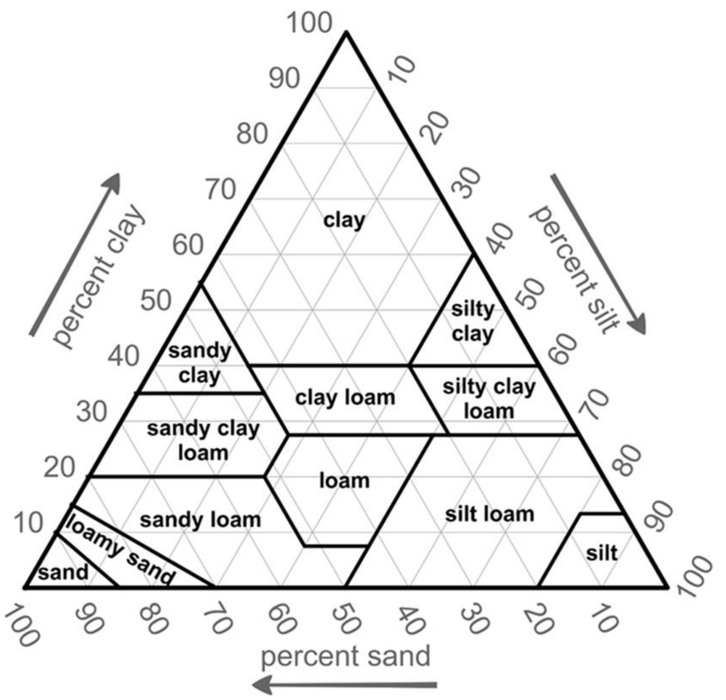


Oke et al. (2017)

Concepts



Oke et al. (2017)



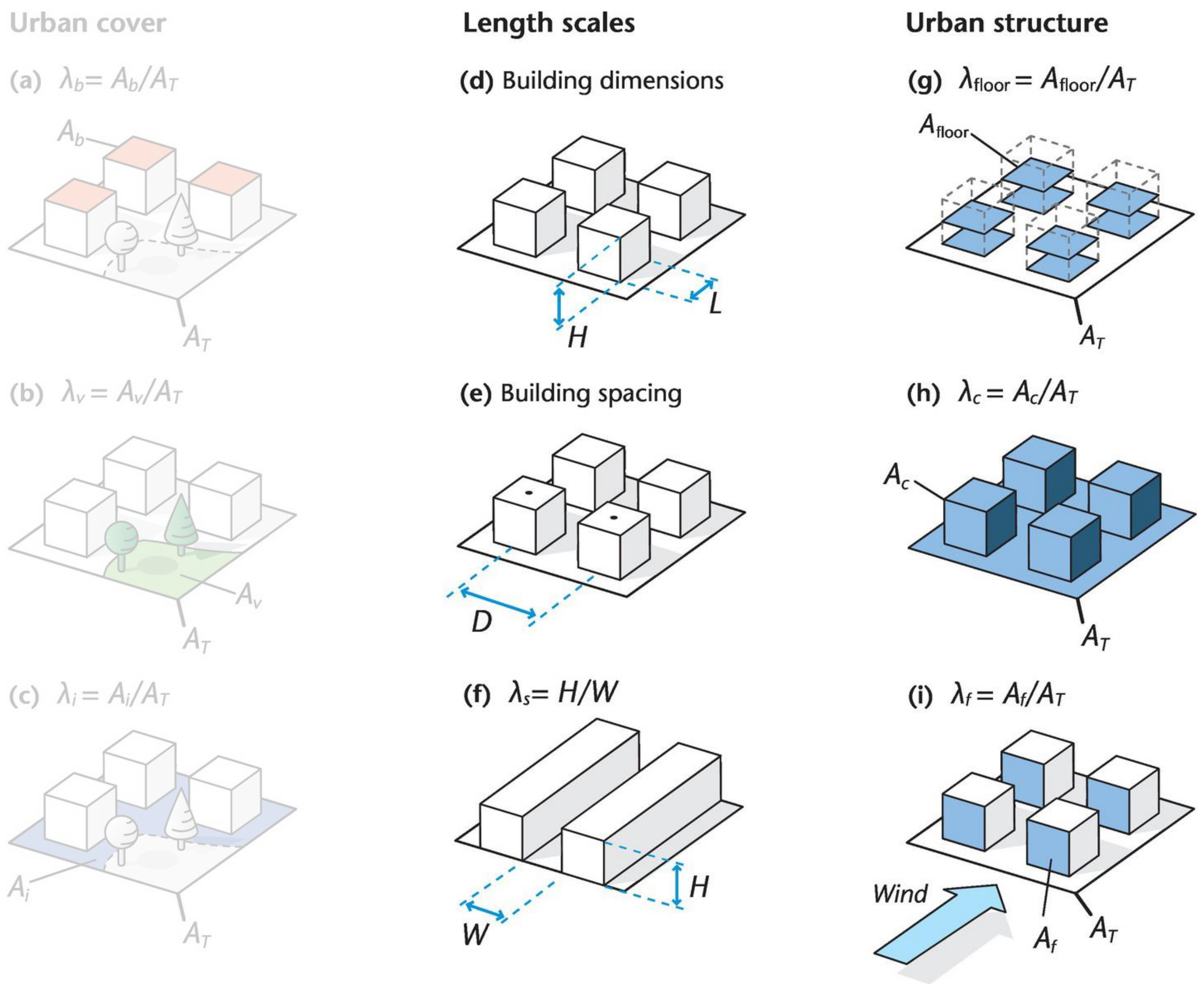
Groenendyk et al. (2015), PloS ONE

Concepts

Dimensions & structure

The simplest are the element (building) dimensions: the height (*H*), width and length (*L*), their spacing, i.e. the distance between centroids (*D*). Other important metrics include:

- the **canyon aspect ratio** (λ_s) which describes built density as the ratio of height and width of the canyon walls
- the **complete aspect ratio** (λ_c) which relates the total external surface area to the total plan area
- the **frontal aspect ratio** (λ_f) which indicates the fractional barrier presented by the buildings as “seen” by the oncoming wind flow



Oke et al. (2017)

Concepts

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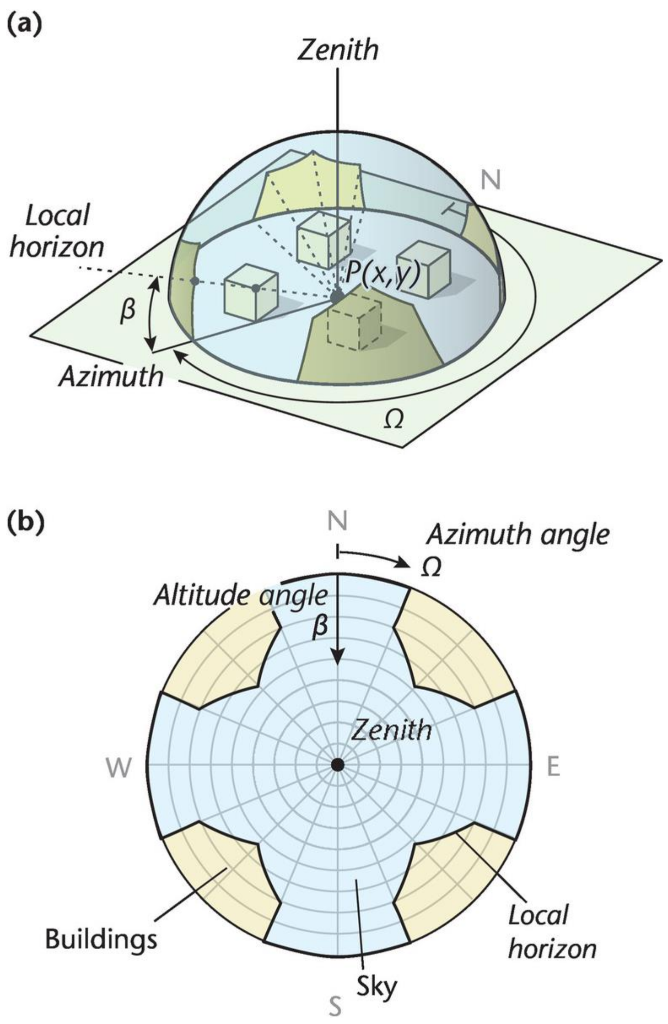
Dimensions & structure

Unlike the measures of structure discussed up to this point that quantify a larger urban area (block, neighbourhood), the **sky view factor** (ψ_{sky}) is a three-dimensional measure for a single point on a surface.

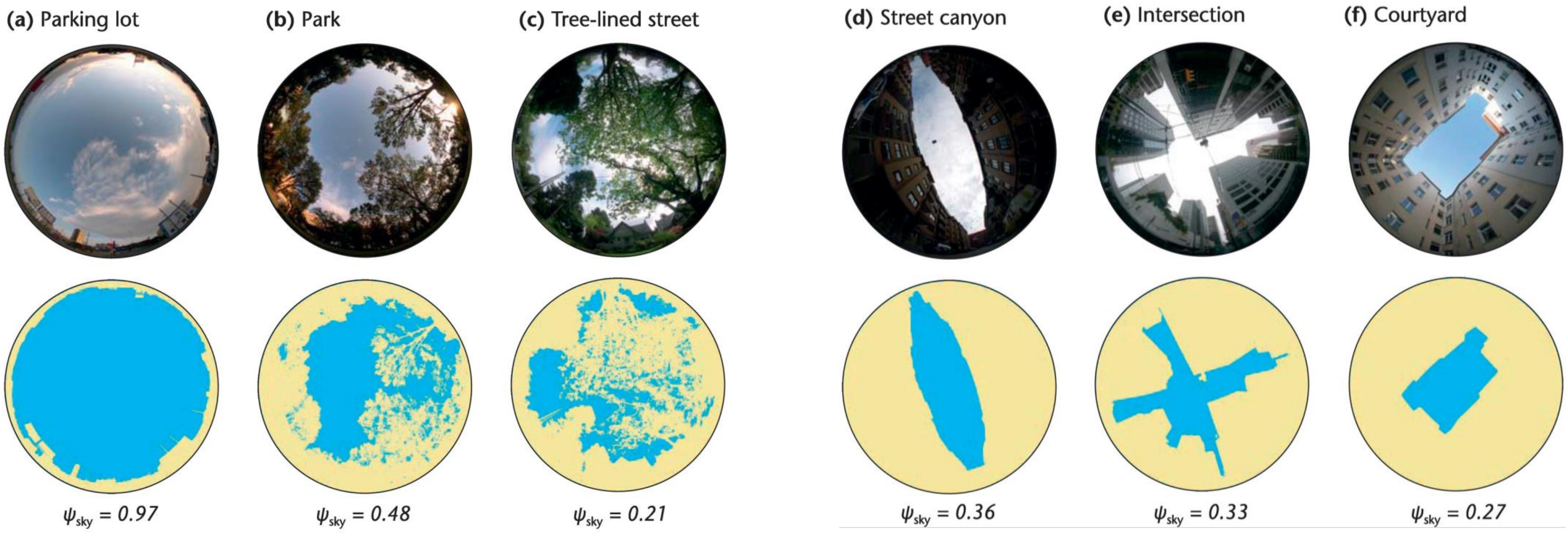
It is defined as the fraction of the radiative flux leaving the surface at this point that reaches the atmosphere above the urban canopy, i.e. the “sky”. The sky view factor is significant for **radiation** calculations such as solar access and the nocturnal cooling of street canyons.

For example, on top of a roof with no horizon screening by other buildings or hills $\psi_{sky} = 1$. But in the middle of a street canyon floor ψ_{sky} depends on the depth and width of the canyon (i.e., it is loosely related to H/W). In the bottom corners of the canyon it is even lower than in the middle.



Oke et al. (2017)

Concepts

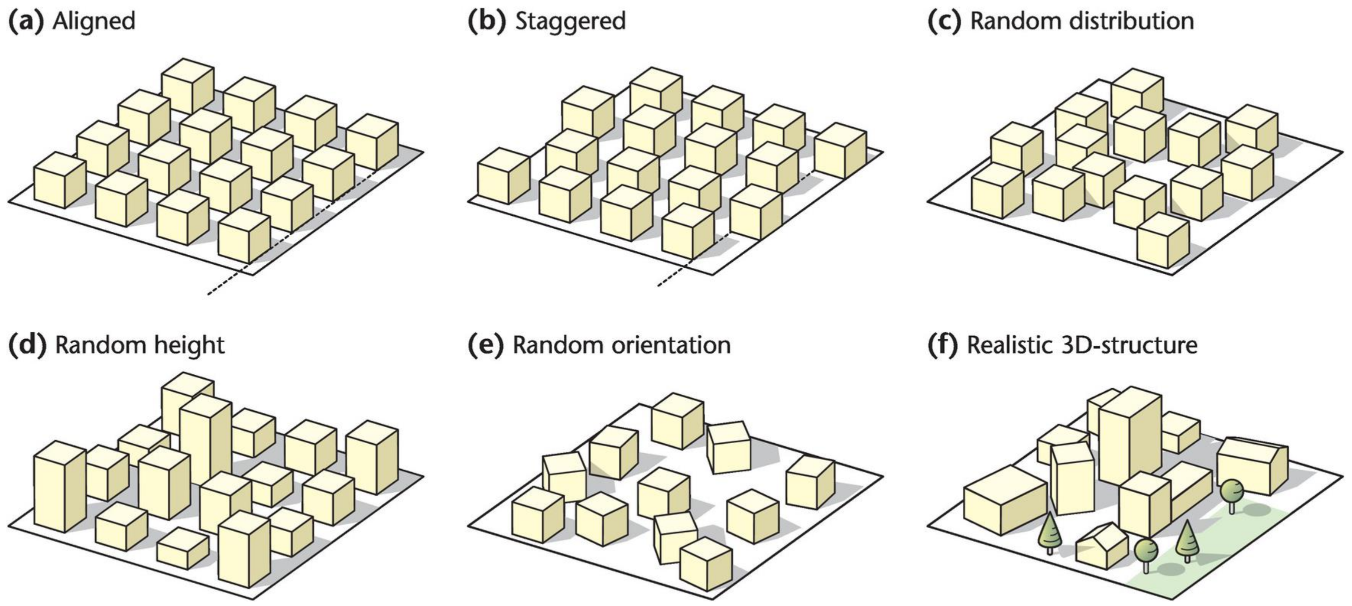


Sky view photographs obtained using a fish-eye lens at a range of urban sites. The sky view factors (ψ_{sky}) are calculated for points at the ground. Note the values of ψ_{sky} must consider the angular distortion of the lens and the cosine response of the surface. They are not simply the area covered by sky (in blue) projected onto a flat circle. Source: Oke et al. (2017).

Concepts

Dimensions & structure

The **spatial organization** of urban elements can also be important. Common simplified patterns of element arrays include: aligned (elements located with approximately equal spacing and aligned both front-to-back and side-to-side with clear channels through), staggered (elements offset front-to-back and/or side-to-side) and random (elements scattered with no organized pattern across the array). Such patterns can exert control upon aspects of urban climates, for example **airflow paths** and the turbulence generated as air passes through and over the different array types.

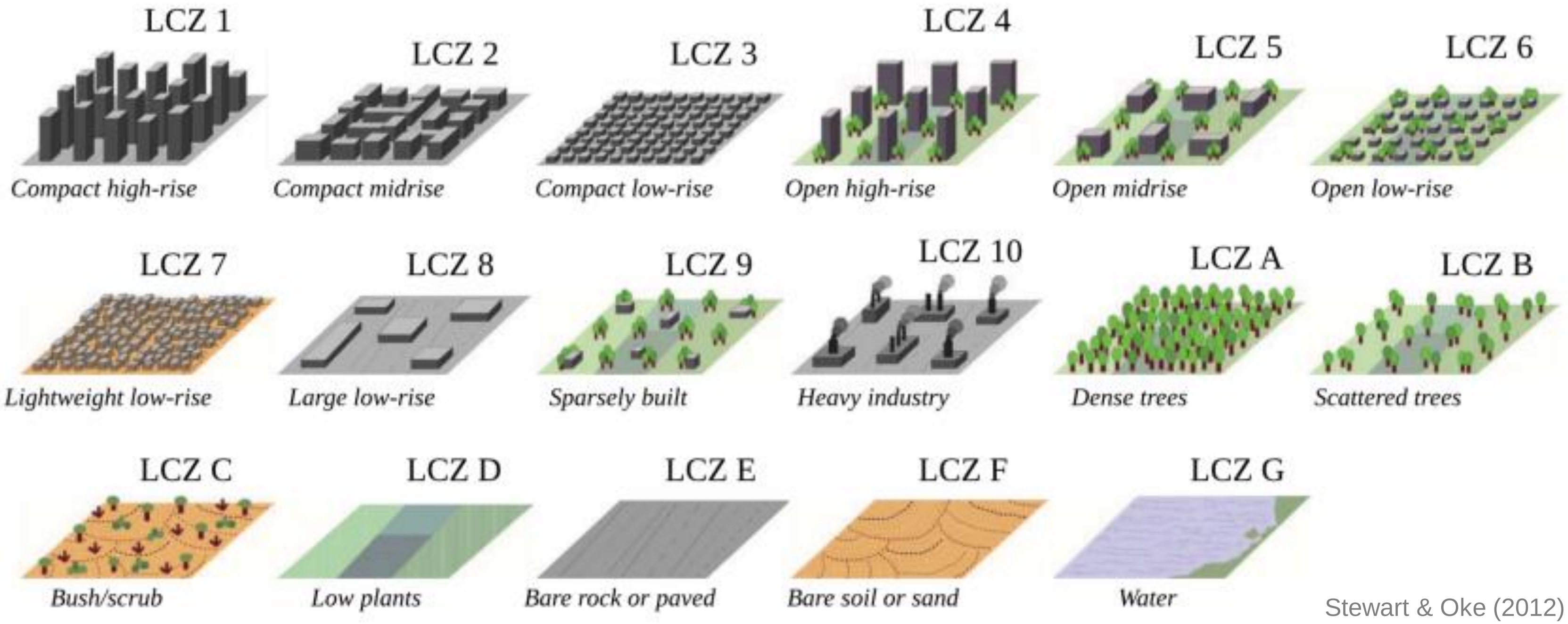


Oke et al. (2017)

Concepts

Land Climate Zones (LCZ)

The four climatically relevant controls on urban climates (fabric, land cover, structure and metabolism) tend to cluster together in a city. For example, the core of many cities has relatively tall buildings packed together densely and the concentration of human activity gives large emissions of heat and air pollution. Toward the other end of the spectrum are districts with low-density housing surrounded by agricultural and open green spaces. Such clustering underlies the notion of **Local Climate Zones (LCZ).**



Stewart & Oke (2012)

Urban climate

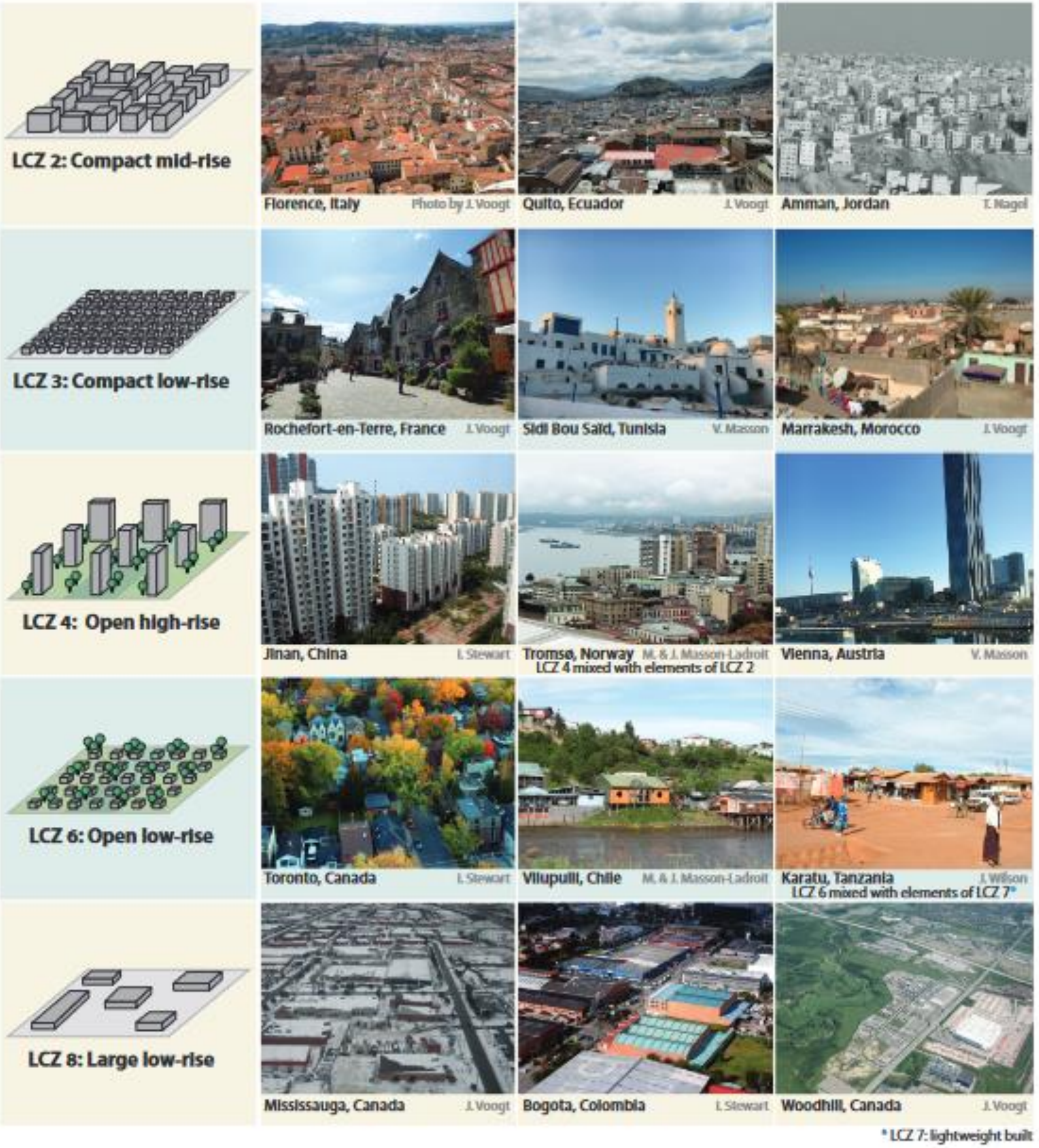


Figure 4

Worldwide local climate zone (LCZ) urban description typology: examples of various neighborhoods classified as LCZ 2, 3, 4, 6, and 8 in cities around the world. Illustrations on the left adapted with permission from Stewart & Oke (53); copyright American Meteorological Society.

[Urban Climates and Climate Change | Annual Review of Environment and Resources]

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Concepts

Land Climate Zones (LCZ)

TABLE 3. Values of geometric and surface cover properties for local climate zones. All properties are unitless except height of roughness elements (m).

Local climate zone (LCZ)	Sky view factor[a]	Aspect ratio[b]	Building surface fraction[c]	Impervious surface fraction[d]	Pervious surface fraction[e]	Height of roughness elements[f]	Terrain roughness class[g]
LCZ 1 *Compact high-rise*	0.2–0.4	> 2	40–60	40–60	< 10	> 25	8
LCZ 2 *Compact midrise*	0.3–0.6	0.75–2	40–70	30–50	< 20	10–25	6–7
LCZ 3 *Compact low-rise*	0.2–0.6	0.75–1.5	40–70	20–50	< 30	3–10	6
LCZ 4 *Open high-rise*	0.5–0.7	0.75–1.25	20–40	30–40	30–40	>25	7–8
LCZ 5 *Open midrise*	0.5–0.8	0.3–0.75	20–40	30–50	20–40	10–25	5–6
LCZ 6 *Open low-rise*	0.6–0.9	0.3–0.75	20–40	20–50	30–60	3–10	5–6
LCZ 7 *Lightweight low-rise*	0.2–0.5	1–2	60–90	< 20	<30	2–4	4–5
LCZ 8 *Large low-rise*	>0.7	0.1–0.3	30–50	40–50	<20	3–10	5
LCZ 9 *Sparsely built*	> 0.8	0.1–0.25	10–20	< 20	60–80	3–10	5–6
LCZ 10 *Heavy industry*	0.6–0.9	0.2–0.5	20–30	20–40	40–50	5–15	5–6

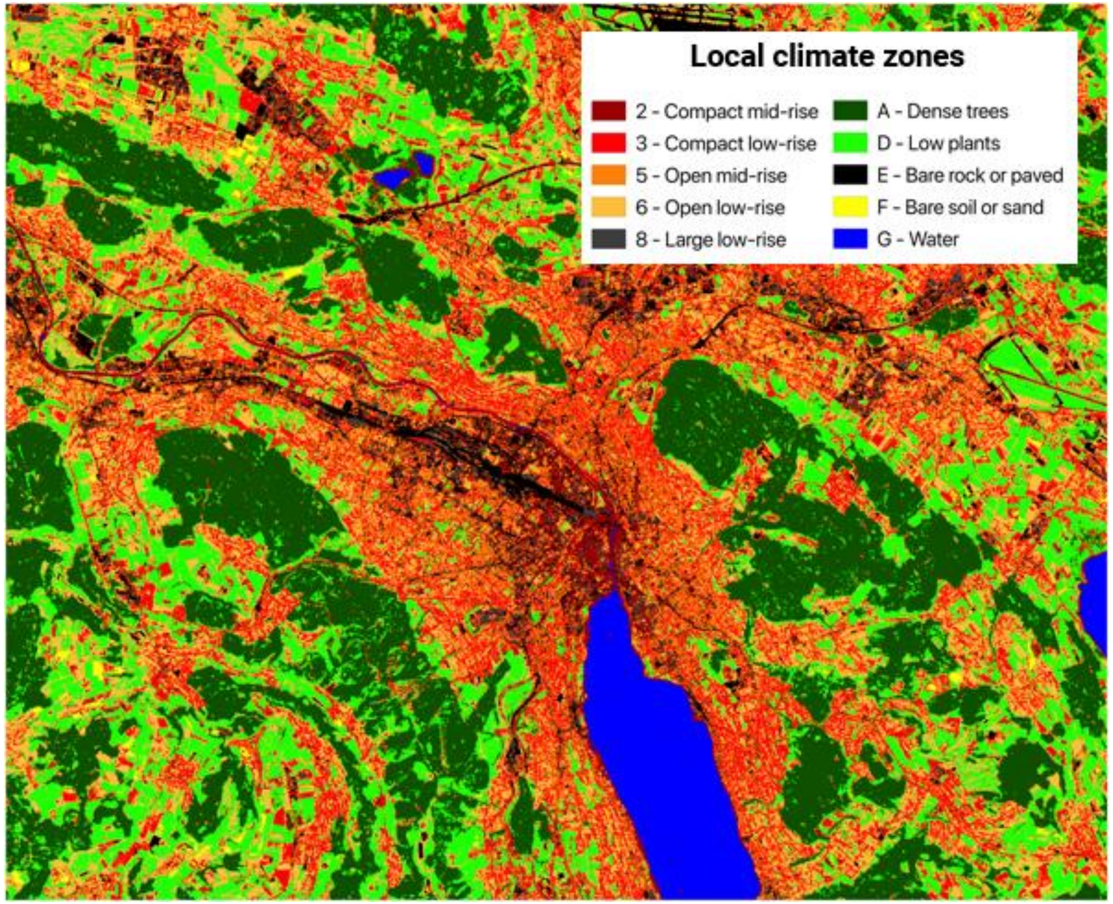
TABLE 4. Values of thermal, radiative, and metabolic properties for local climate zones. All values are representative of the local scale.

Local climate zone (LCZ)	Surface admittance[a]	Surface albedo[b]	Anthropogenic heat output[c]
LCZ 1 *Compact high-rise*	1,500–1,800	0.10–0.20	50–300
LCZ 2 *Compact midrise*	1,500–2,200	0.10–0.20	<75
LCZ 3 *Compact low-rise*	1,200–1,800	0.10–0.20	<75
LCZ 4 *Open high-rise*	1,400–1,800	0.12–0.25	<50
LCZ 5 *Open midrise*	1,400–2,000	0.12–0.25	<25
LCZ 6 *Open low-rise*	1,200–1,800	0.12–0.25	<25
LCZ 7 *Lightweight low-rise*	800–1,500	0.15–0.35	<35
LCZ 8 *Large low-rise*	1,200–1,800	0.15–0.25	<50
LCZ 9 *Sparsely built*	1,000–1,800	0.12–0.25	<10
LCZ 10 *Heavy industry*	1,000–2,500	0.12–0.20	>300

Stewart & Oke (2012)

Concepts

Land Climate Zones (LCZ)



Meteoblue.com

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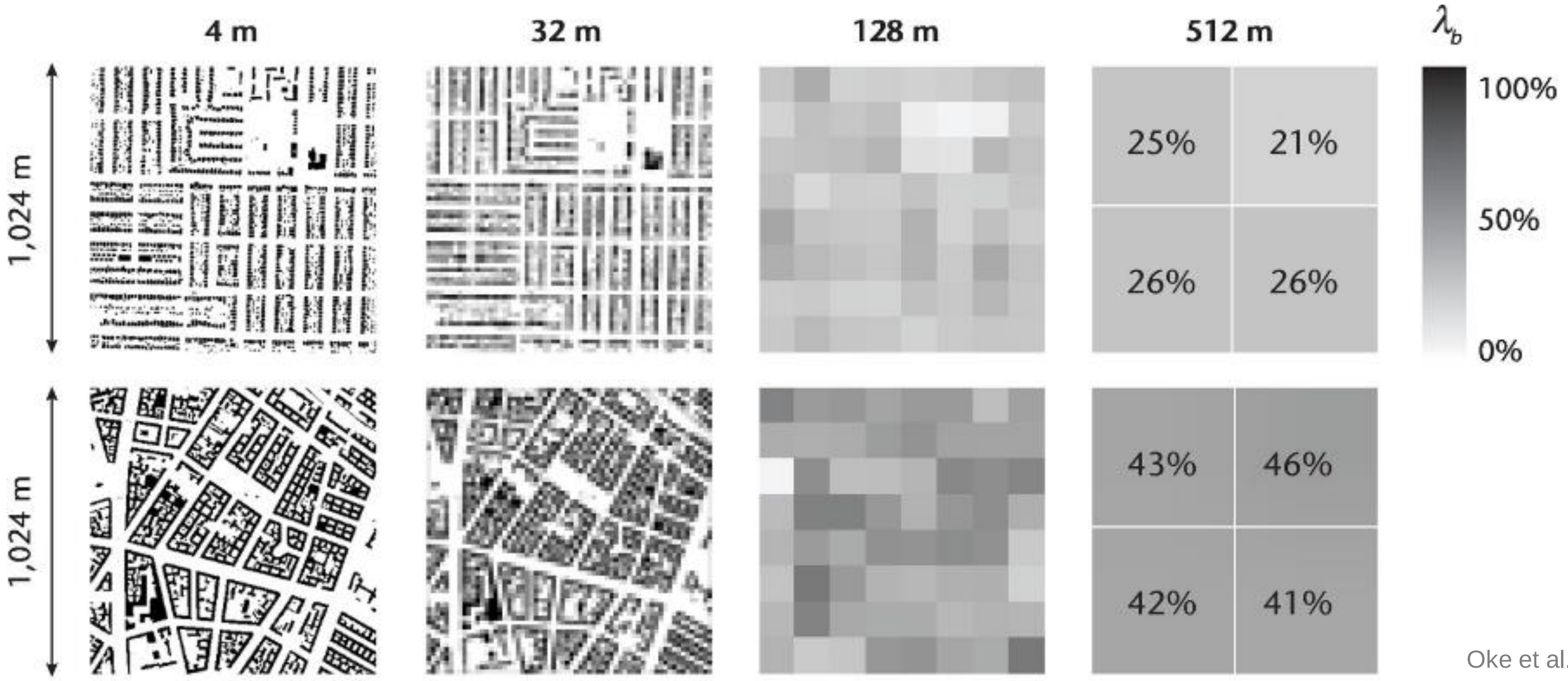
Stewart & Oke (2012)

Concepts

Scale and Surface Homogeneity

Surface properties are generally considered “homogeneous” within a certain control volume. Yet, homogeneity depends on the scale at which the property is determined and on the size of the domain over which it is being examined and applied. Something assumed to be homogeneous at a one length scale might be heterogeneous at another.



Oke et al. (2017)

Today's session

Outline

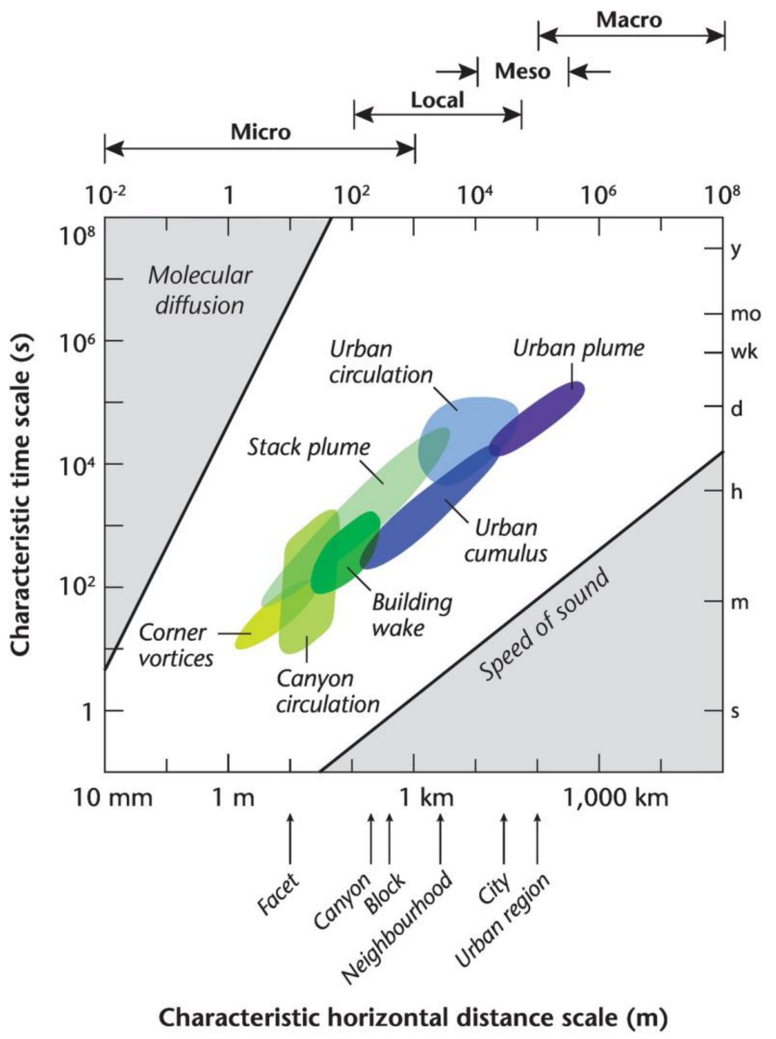
- Concepts of urban climate
- **Urban atmosphere**
- Airflow
- Energy balance

Urban atmosphere

Scales of urban climate phenomena

The majority of urban climate phenomena lie in the microscale, local scale and mesoscale domains. Climatic features cannot remain discrete in a diffusive medium like the atmosphere; they are part of a continuum. Each climate feature combines to form larger ones up to the scale of the whole urban boundary layer. The primary process that merges scales is mixing due to atmospheric turbulence.

Time and horizontal space scales of selected urban climate dynamics and wind phenomena.

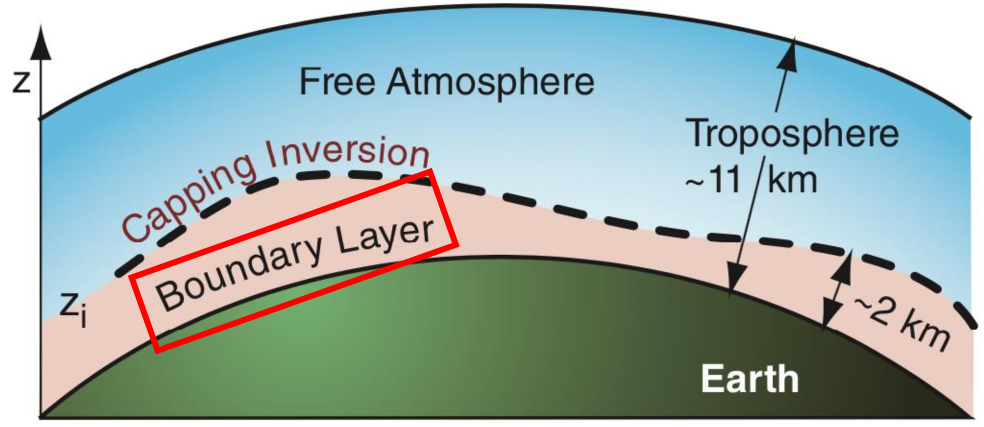


Oke et al. (2017)

Urban atmosphere

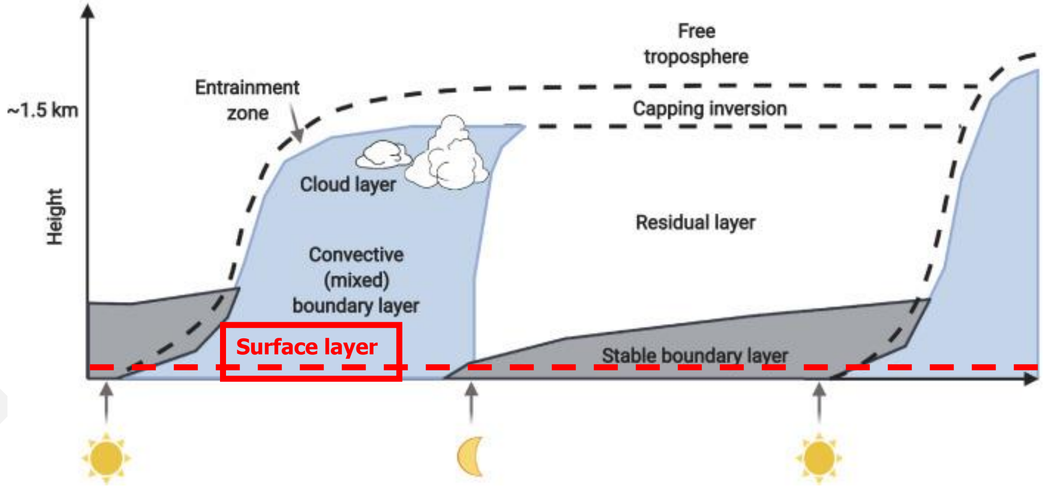
Vertical Structure of the Urban Atmosphere

The lowest part of Earth's atmosphere that is in direct contact with Earth's surface is called the **atmospheric boundary layer (ABL)**. The ABL is between 100 and 3,000 m deep and controlled by the roughness, thermal mixing and the injections of moisture and air pollutants from Earth's surface. The ABL can be subdivided into an outer and inner region. In the outer region thermal effects of Earth's surface dominate. In the inner portion, roughly the lowest 10% of the ABL and more commonly called the **surface layer** (SL), flow is dominated by friction with Earth's surface.



Source: Stull, Practical Meteorology

Schematic of typical layering of the atmosphere over a city (a) by day, and (b) at night. Note the height scale is logarithmic

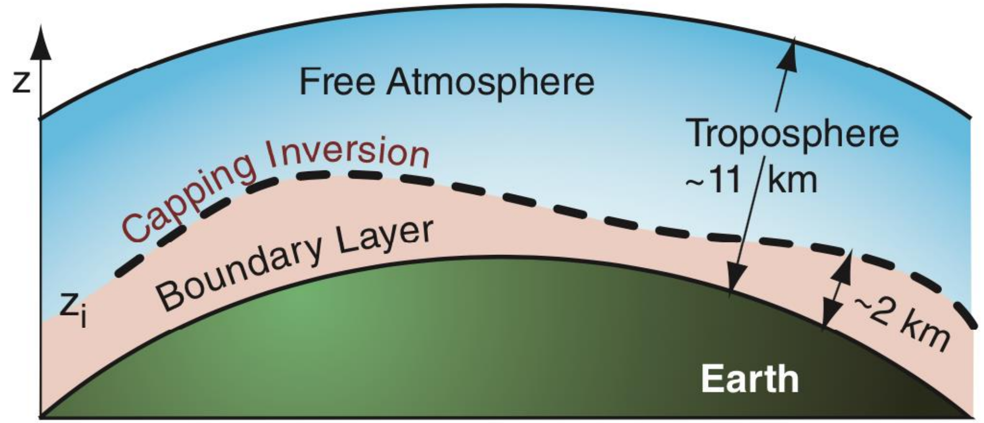


Source: Helbig et al (2021)

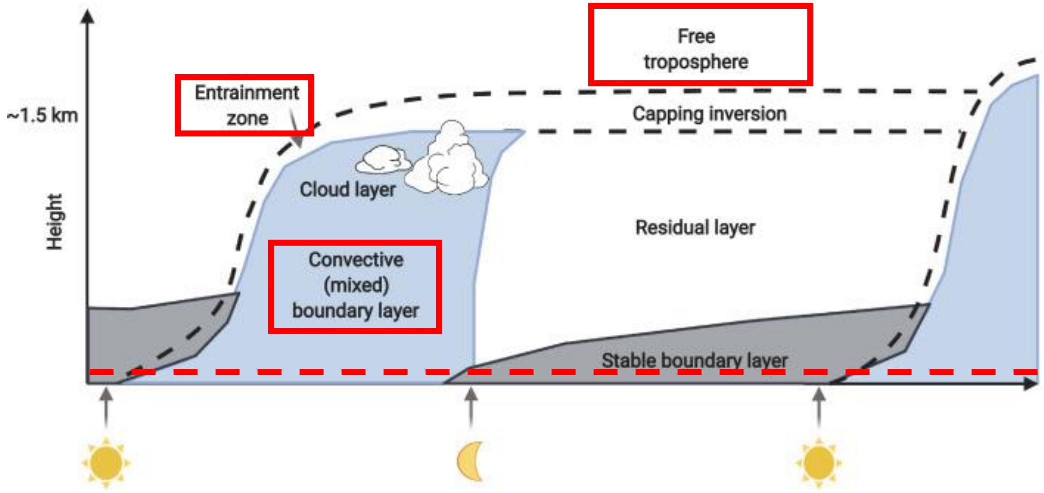
Urban atmosphere

Vertical Structure of the Urban Atmosphere

During daytime, surface heating usually creates large, buoyant thermals which effectively carry surface influences upward until they reach the top of the ABL where further lifting is halted by a capping inversion. This inversion at height zi is the base of the overlying **free atmosphere (FA)**, where influences of Earth's surface are negligible. Just below the FA is the **entrainment zone (EZ)** where buoyant thermals "bombard" the underside of the inversion; some overshoot into the FA through their own inertia and when settling back carry cleaner, warmer and drier air down into the ABL. This daytime situation in the outer layer is often termed **mixed layer (ML)**. The ML refers to the top 90% of the ABL excluding the SL. As its name implies, the ML homogenizes atmospheric properties so that vertical profiles of potential temperature, water vapour, wind speed and direction are almost uniform with height.



Source: Stull, Practical Meteorology

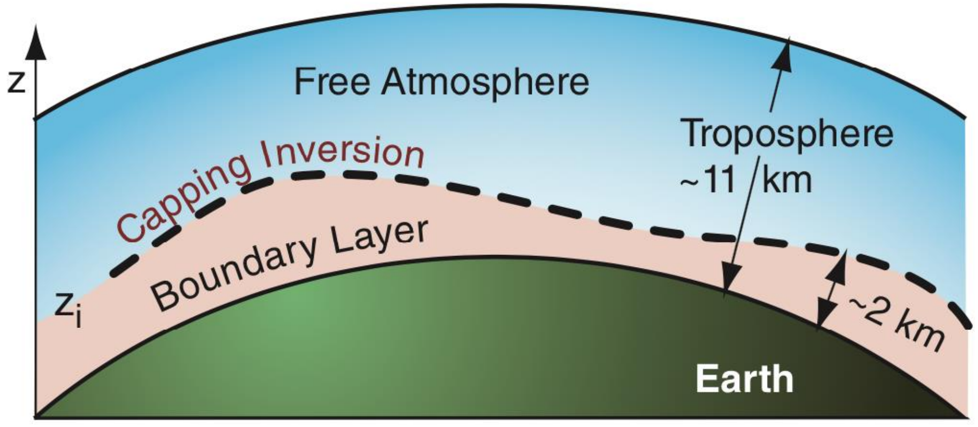


Source: Helbig et al (2021)

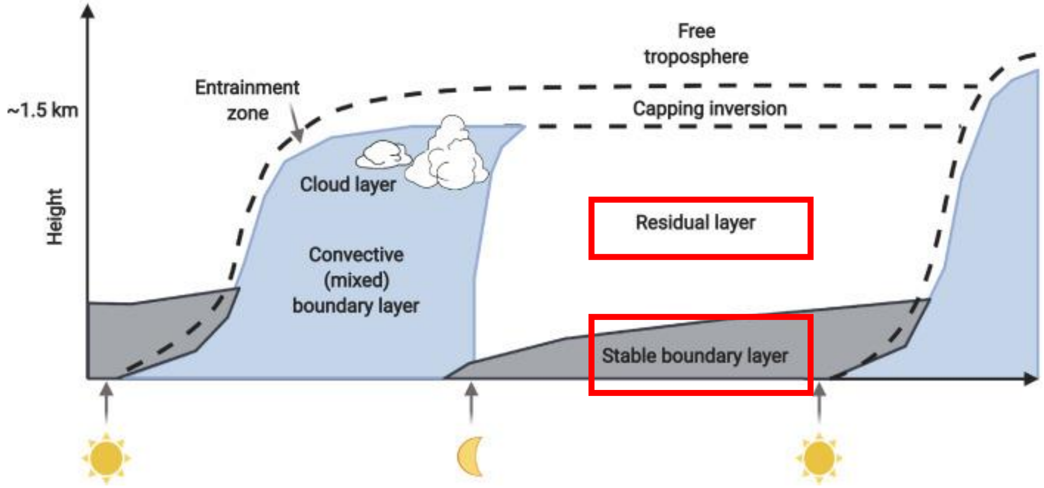
Urban atmosphere

Vertical Structure of the Urban Atmosphere

At night the ABL shrinks as cooling at Earth's surface usually creates a stagnant layer near the ground about 200 to 400 m deep which inhibits vertical mixing – this is the **nocturnal boundary layer (NBL)**. Above the NBL, extending roughly up to the height of the daytime ABL, is a layer with properties preserved from the previous afternoon. This **residual layer (RL)** is capped by the inversion carried over from the daytime entrainment zone. This layer is mixed but little active mixing is going on.



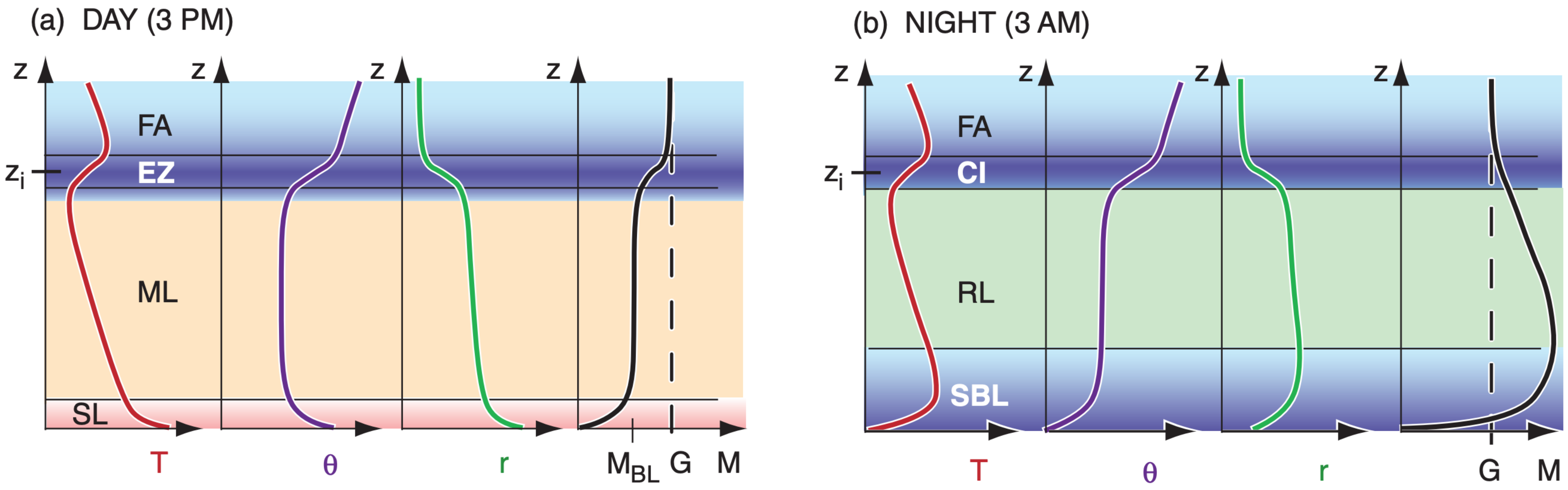
Source: Stull, Practical Meteorology



Source: Helbig et al (2021)

Urban atmosphere

Vertical Structure of the Urban Atmosphere



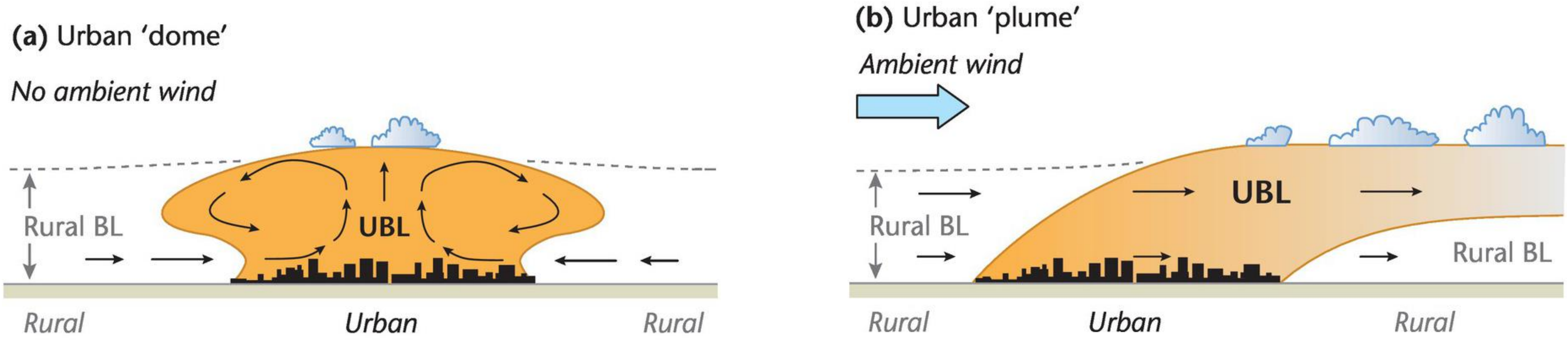
Typical vertical profiles of temperature (T), potential temperature (θ), mixing ratio (r), and wind speed (M) in the ABL. The dashed line labeled G is the geostrophic wind speed (a theoretical wind in the absence of surface drag, see the Atmos. Forces & Winds chapter). M_{BL} is average wind speed in the ABL.

Source: Stull, Practical Meteorology – available [here]

Urban atmosphere

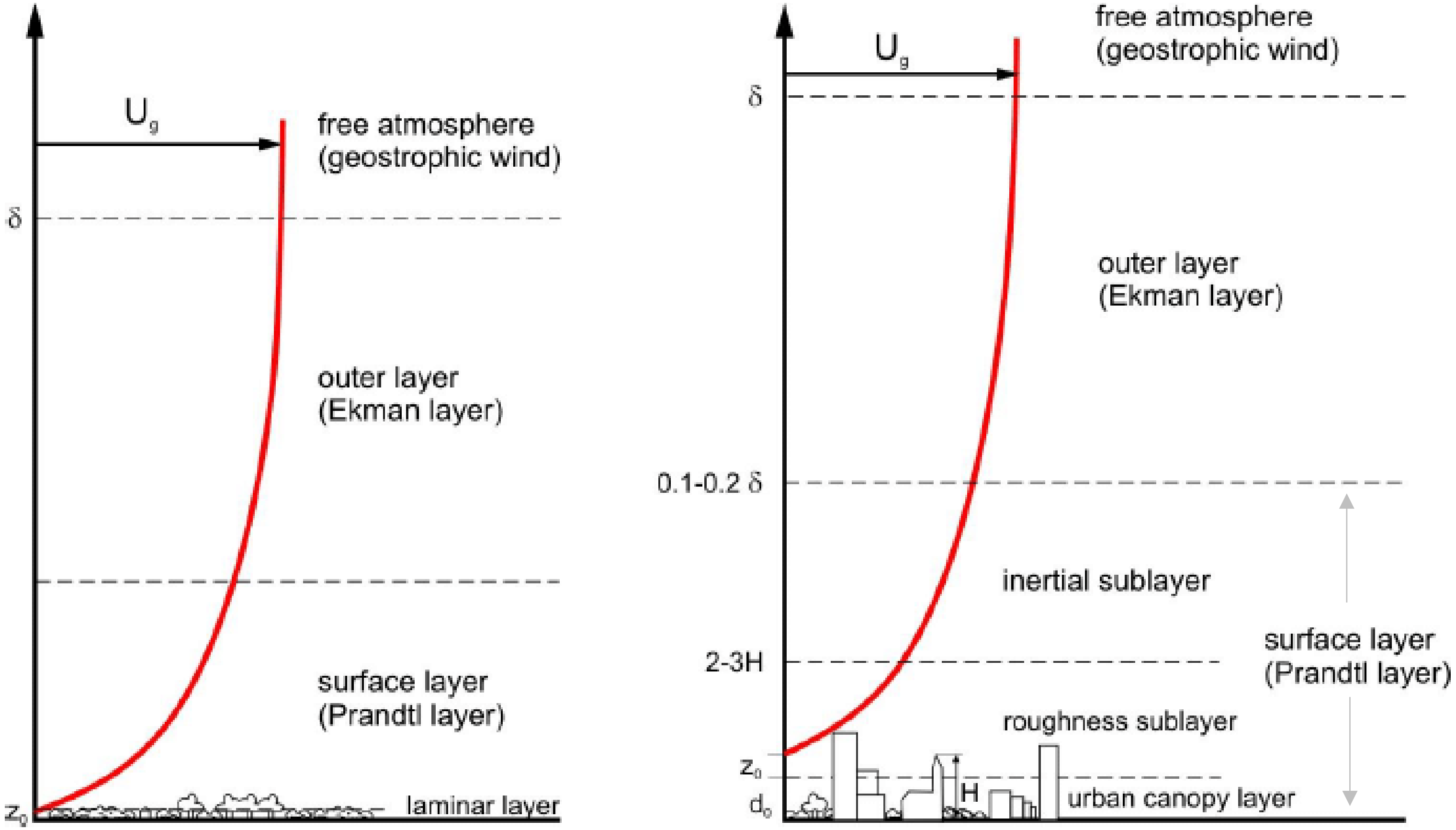
The Urban Boundary Layer

The ABL over a large city has its own structure. Theoretically when a regional wind is absent the climatic influence of a city is restricted to a self-contained **urban dome**. More commonly, there is a regional wind and an internal boundary layer grows upward with distance, starting at the upwind rural-urban border, until it fills the whole ABL – this is the **urban boundary layer**, i.e., the part of the ABL influenced by the presence of a city. At the downwind urban–rural border a new rural boundary layer forms – the layer of urban-modified air becomes isolated aloft, forming the so-called **“urban plume”**. The plume contains the thermal, moisture and kinematic effects of the city for tens of kilometres, and it carries air pollutants for hundreds of kilometres downwind.



Oke et al. (2017)

Urban atmosphere



Satyam & Bin Khalid (2019)

atmospheric properties are **uniformly mixed** by thermal turbulence and usually capped by an inversion

shear-dominated turbulence creates a logarithmic velocity profile (1D approximation)

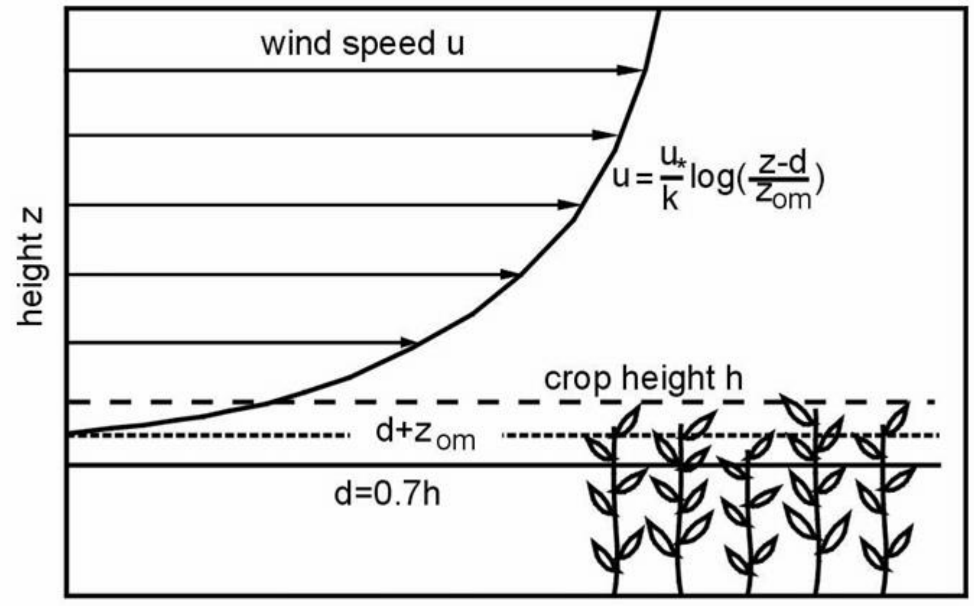
flow is 3D and affected by individual elements.

from ground to the mean height of buildings/trees

H = mean building / tree height
z_0 = roughness length
d_0 = height of zero-plane displacement
δ = depth of ABL

Urban atmosphere

Immerzeel et al. (2006)



Roughness length (z_0) is defined as the height at which the mean velocity is zero due to substrate roughness. Real walls/ground are not smooth and often have varying degrees of roughness, this parameter (which is determined empirically) accounts for that effect.

Zero Plane displacement (d) is defined as the height at which the mean velocity is zero due to large obstacles such as buildings/canopy.

Friction velocity

$$\frac{\partial U}{\partial z} = \overline{u'w'} = \frac{u_*}{kz} \Rightarrow U(z) = \frac{u_*}{k}\log(z) + C \overset{U(z_0)=0}{\Rightarrow} U(z) = \frac{u_*}{k}\log\left(\frac{z}{z_0}\right)$$

Momentum flux   Von Karman constant

$$\textit{if obstacles} \Rightarrow U(z) = \frac{u_*}{k}\log\left(\frac{z-d}{z_0}\right)$$

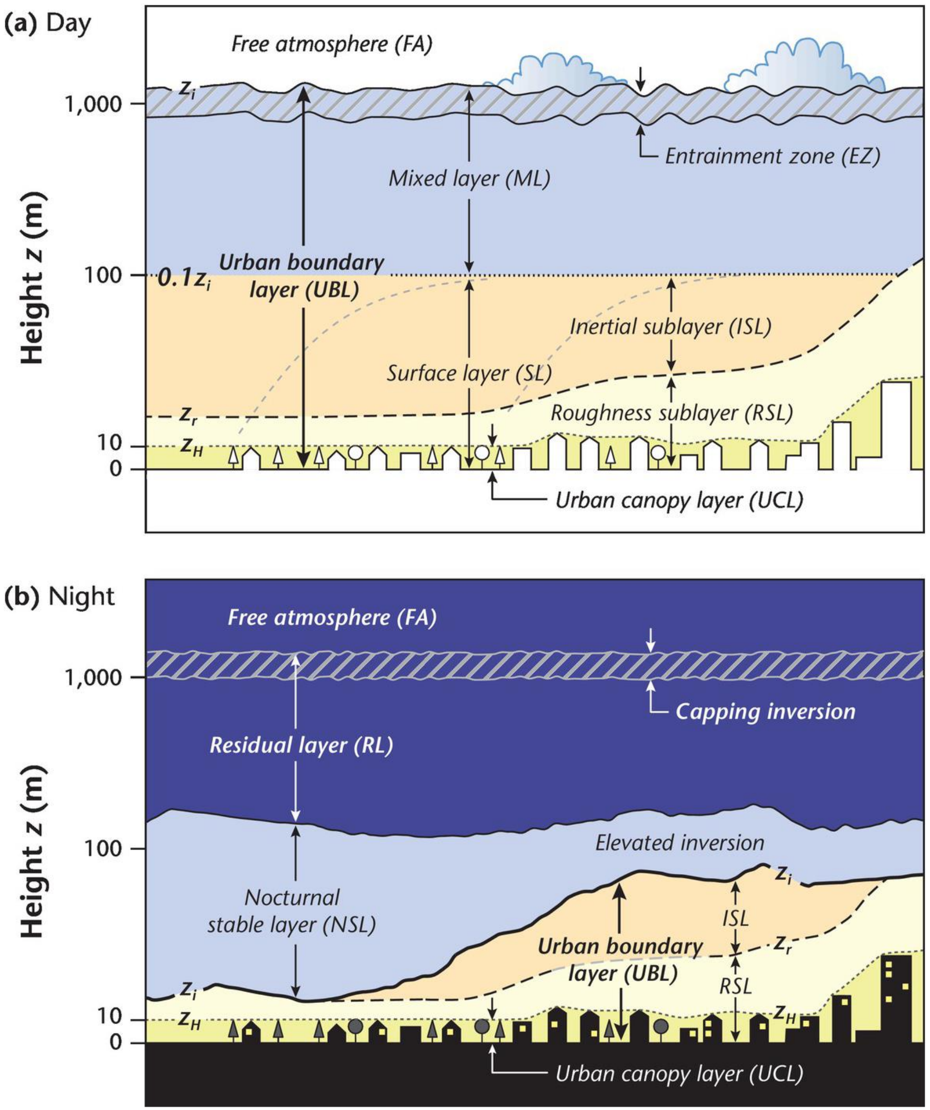
Urban atmosphere

The Urban Boundary Layer

In **daytime**, heating at the urban surface is stronger in most cities compared to the rural surrounding. This creates more vigorous mixing in the ML and entrainment at the top of the UBL which makes it deeper than the equivalent rural ABL; hence, the height of the capping inversion zi is elevated over cities. The strong mixing in the urban ML is responsible for the commonly uniform murkiness of the polluted atmosphere over cities during daytime.

At **night** the NBL found in rural areas is greatly modified in cities. Mixing, caused by heating of the surface due to the nocturnal urban heat island and the greater urban roughness, cause the atmosphere over the city to be better mixed at night.

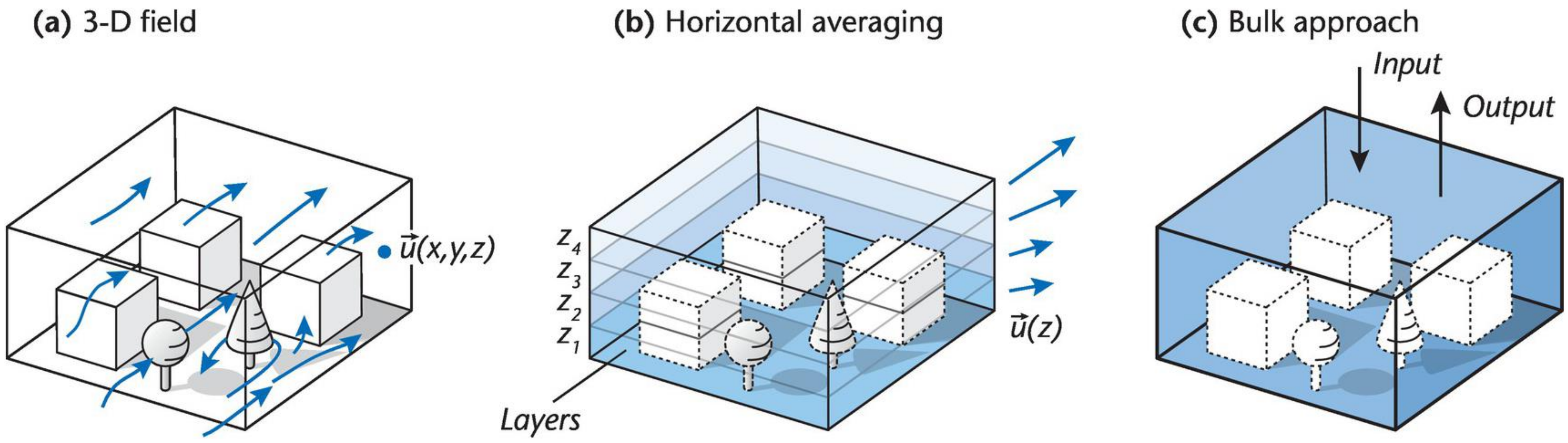
Classification of atmospheric layers comprising the urban climate system. Symbols are as follows: z height above ground; z_H mean building/tree height; W width of street canyons; z_0 roughness length, z_d height of zero-plane displacement; z_i depth of mixed layer (see Oke et al., 2017)



Oke et al. (2017)

Urban atmosphere

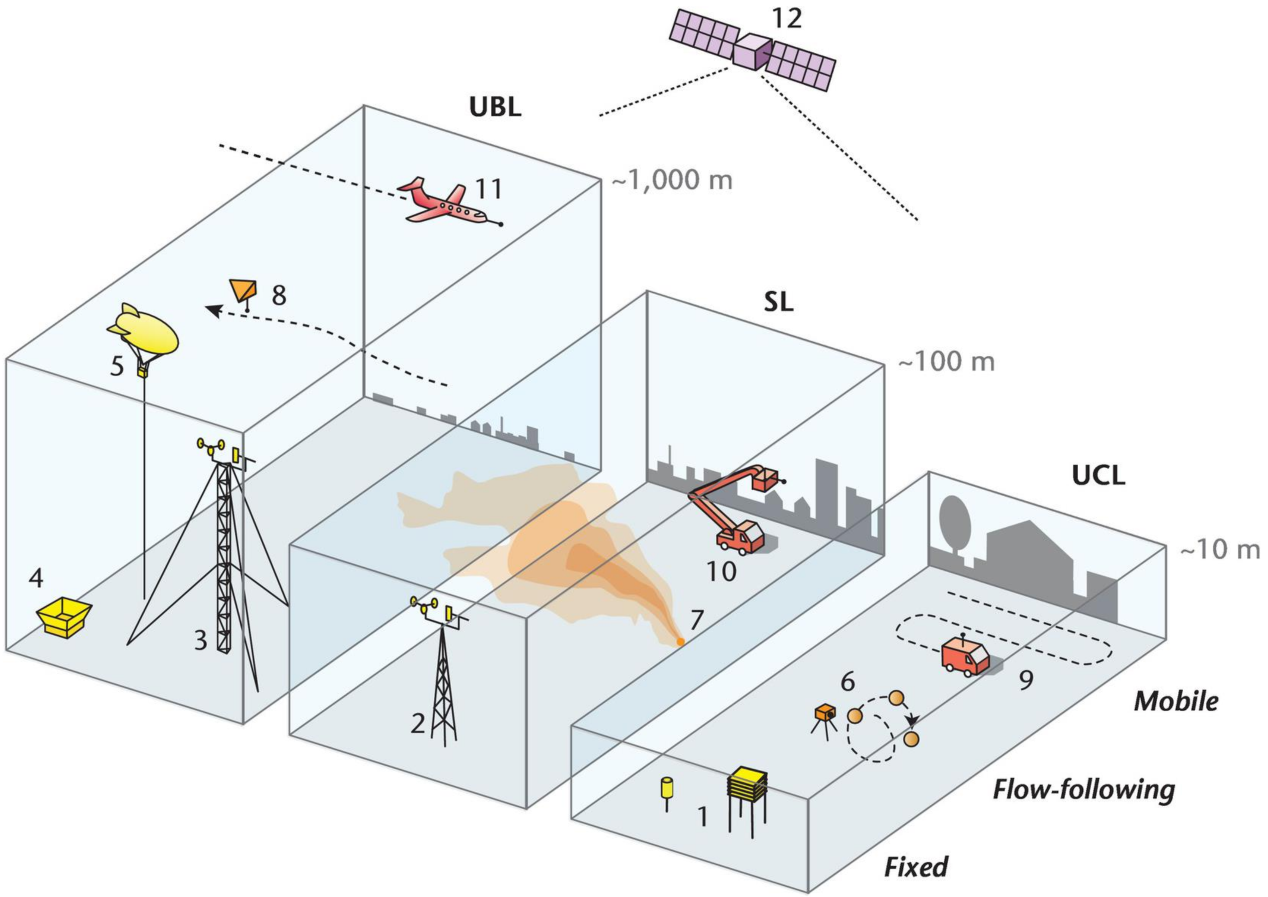
EPFL

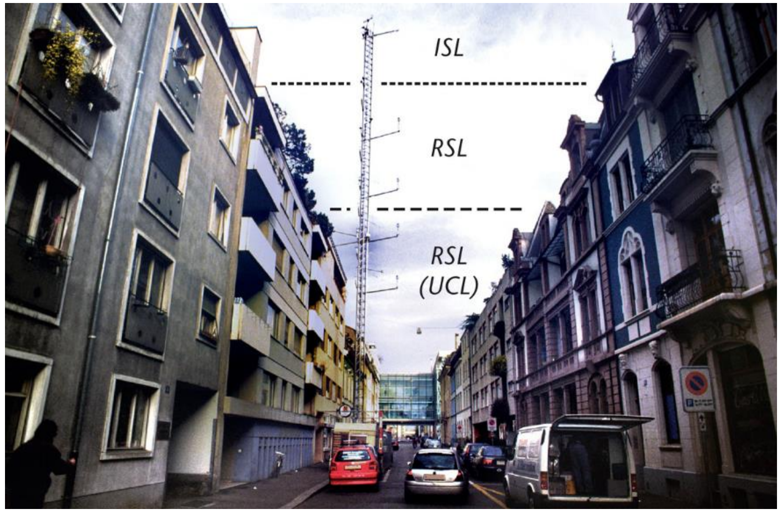


Oke et al. (2017)

Three approaches to **reducing complexity** in urban climate analysis of the UCL. In (a) the atmospheric state at a point is the result of forces and fluxes in three spatial dimensions and time. Any variable is described in a fully 3-D field. In (b) the atmospheric state is averaged horizontally to give a set of vertical layers that is described with an average value. In (c) a bulk approach assigns a bulk average to the transfer of the component through the top of a ‘black box’; internal details of the system are not considered.

Urban atmosphere: monitoring





Conceptual diagram of ground-based, aerial and remote-sensing observational platforms, sorted by their suitability to sample the entire urban boundary layer (UBL, left), the surface layer (SL, centre) or the urban canopy layer (UCL, right), and their sampling approach (up right side).

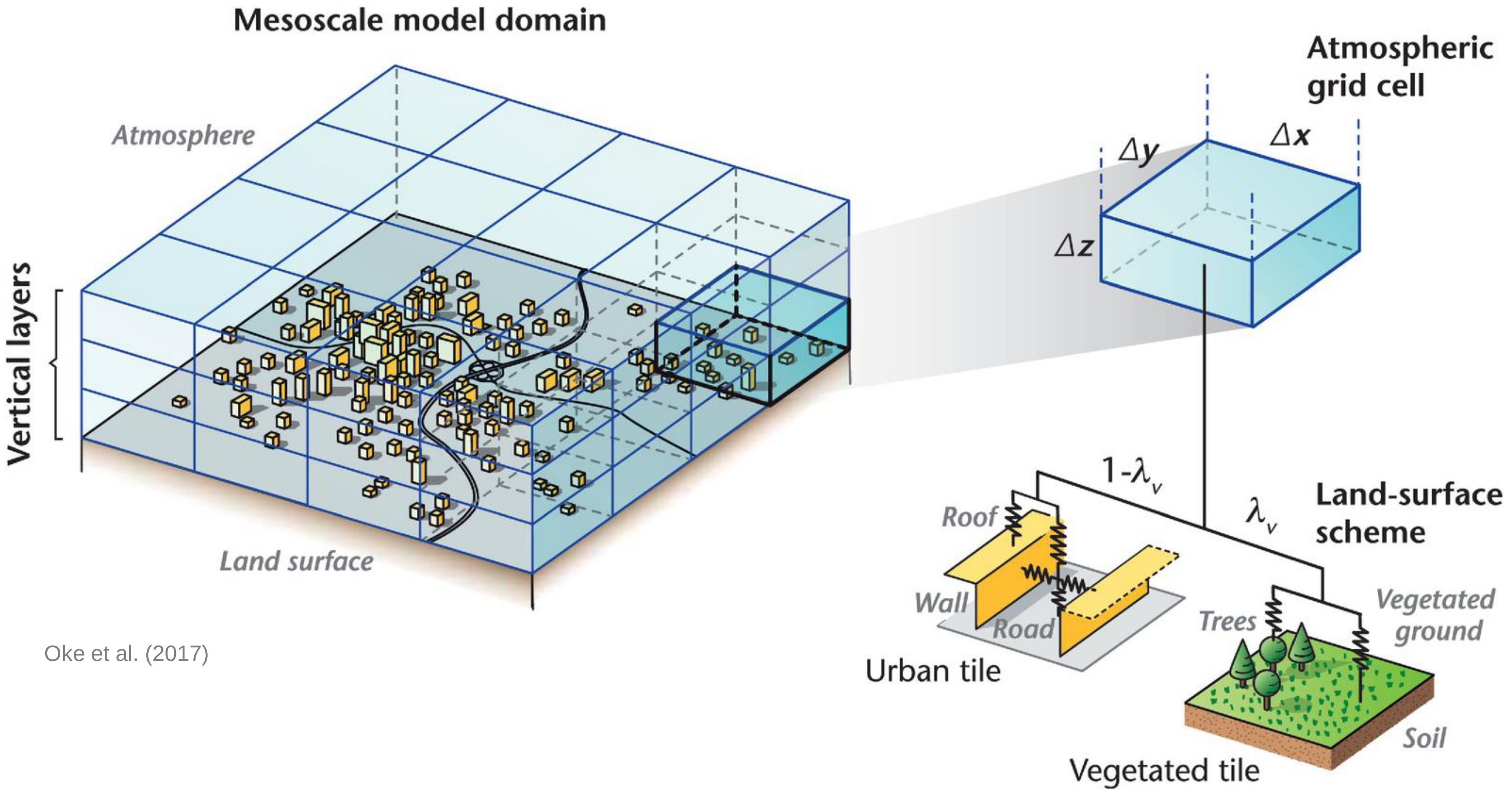
Oke et al. (2017)

Urban atmosphere: physical modeling

Physical scale model of central area of Oklahoma City, United States, in a wind tunnel illustrating that the geometric similarity of building shapes is preserved

Oke et al. (2017)

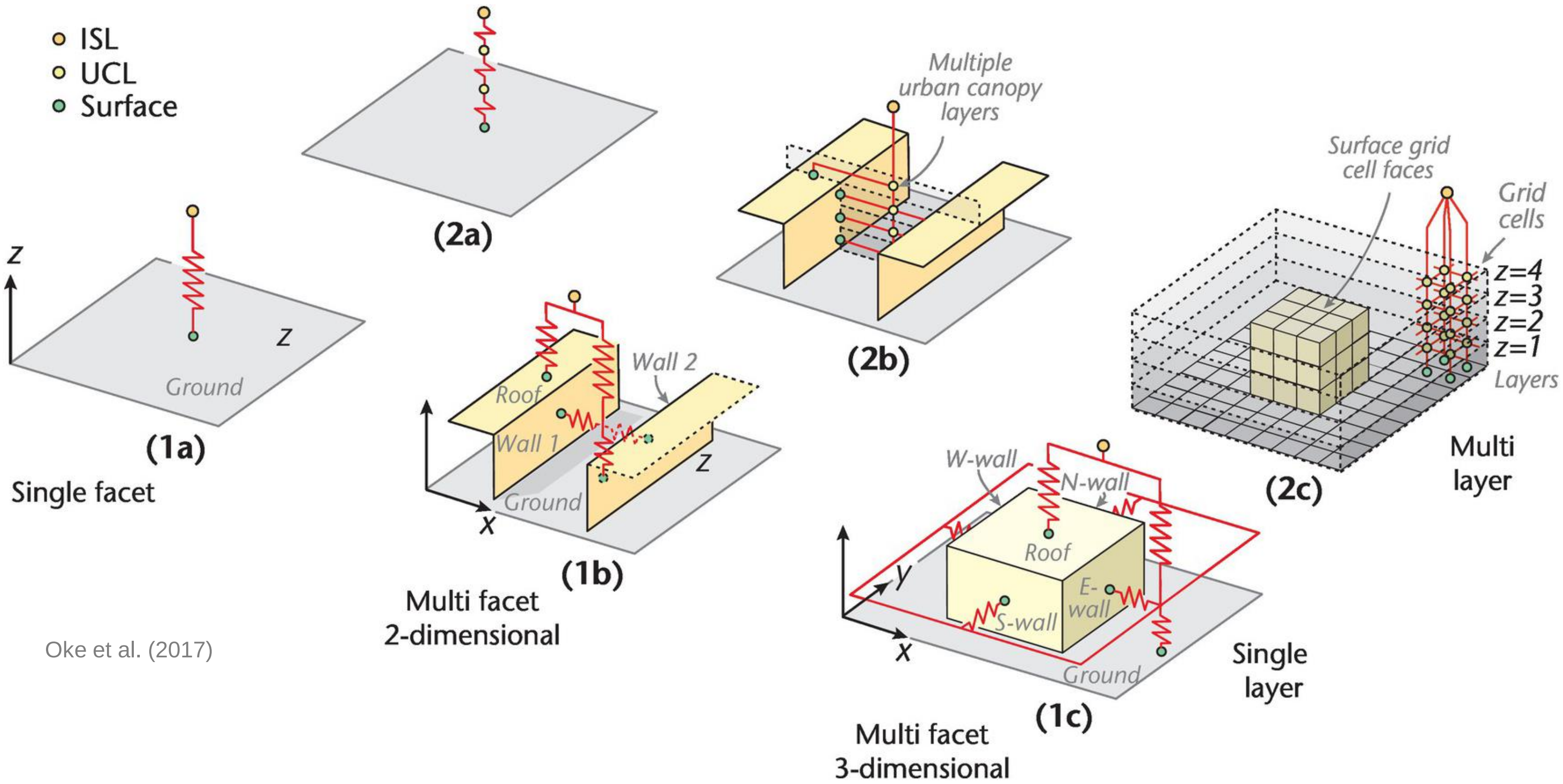
Urban atmosphere: mathematical modeling



Oke et al. (2017)

The computational domain of a 3D mesoscale numerical model with grid cells superimposed on an urban landscape. The right-hand side shows an enlargement of a single grid cell, with the associated tiles for urban and vegetated areas of the land-surface scheme

Urban atmosphere: mathematical modeling



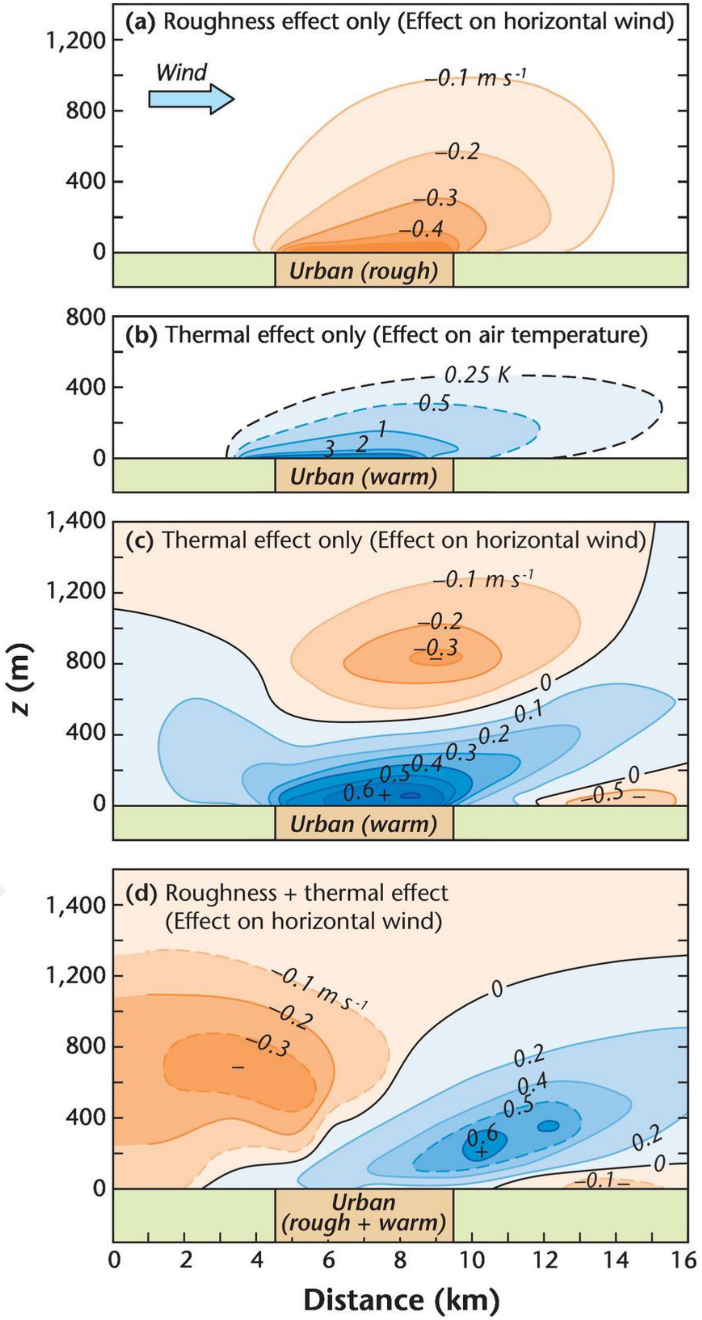
Oke et al. (2017)

Selected modelling strategies for urban canopy models with increasing complexity. From left to right (a to c) complexity of the surface increases from (a) a point, to (b) a 2D canyon cross-section, to (c) representing ground, wall and roof of a simplified cubic building with four facets; the increase from front to back (1 to 2) shows the addition of additional vertical layers in the urban canopy layer (UCL).

Urban atmosphere

Three experiments using the URBMET model are shown. The first (a) incorporates the urban surface as a rough boundary and examines the influence on horizontal wind. The second (b) treats the urban surface as warm and shows its effect on air temperature in the UBL and (c) horizontal wind. The third (d) treats the urban surface as both warm and rough and shows its impact on horizontal wind

Oke et al. (2017)



Today's session

Outline

- Concepts of urban climate
- Urban atmosphere
- **Airflow**
- Energy balance

Air flow

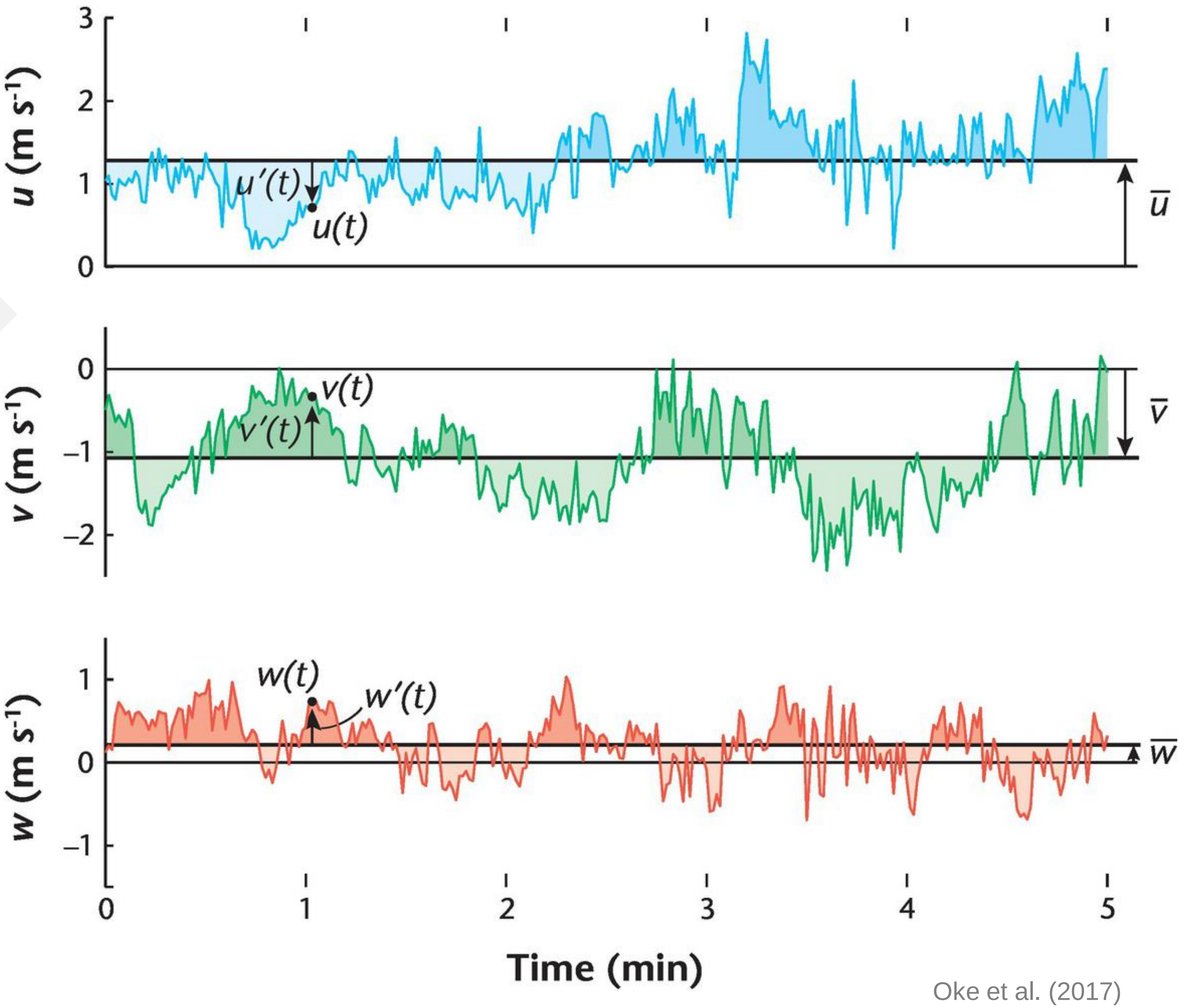
The large-scale driving force of air flows (wind) is usually the **pressure gradient** force responding to the pressure patterns seen on a weather map, but the resulting wind is modified by the atmospheric boundary layer (ABL) of the region. That in turn is modified by the **roughness** and **thermal effects** of the city itself, including responses to the structural form of neighbourhood, the street network and the microscale effects of buildings, trees and even the effect of moving vehicles.

Flow displacement over high-rise buildings in Panama City Beach, United States. Wind is from the ocean

Oke et al. (2017)

Air flow

Traces of the three components of the wind vector recorded inside an urban canyon over a period of 5 minutes.
Reynolds decomposition separates the components (u, v, w) at any time t into a mean wind (denoted by the bar) and a turbulent deviation from it (u′ , v′ , w′).



Oke et al. (2017)

Mean kinetic energy (MKE) per unit mass:

$$\frac{\mathrm{MKE}}{m} = \frac{\overline{u}^2 + \overline{v}^2 + \overline{w}^2}{2} \qquad (\mathrm{m^2\ s^{-2}})$$

Turbulent kinetic energy (TKE) per unit mass:

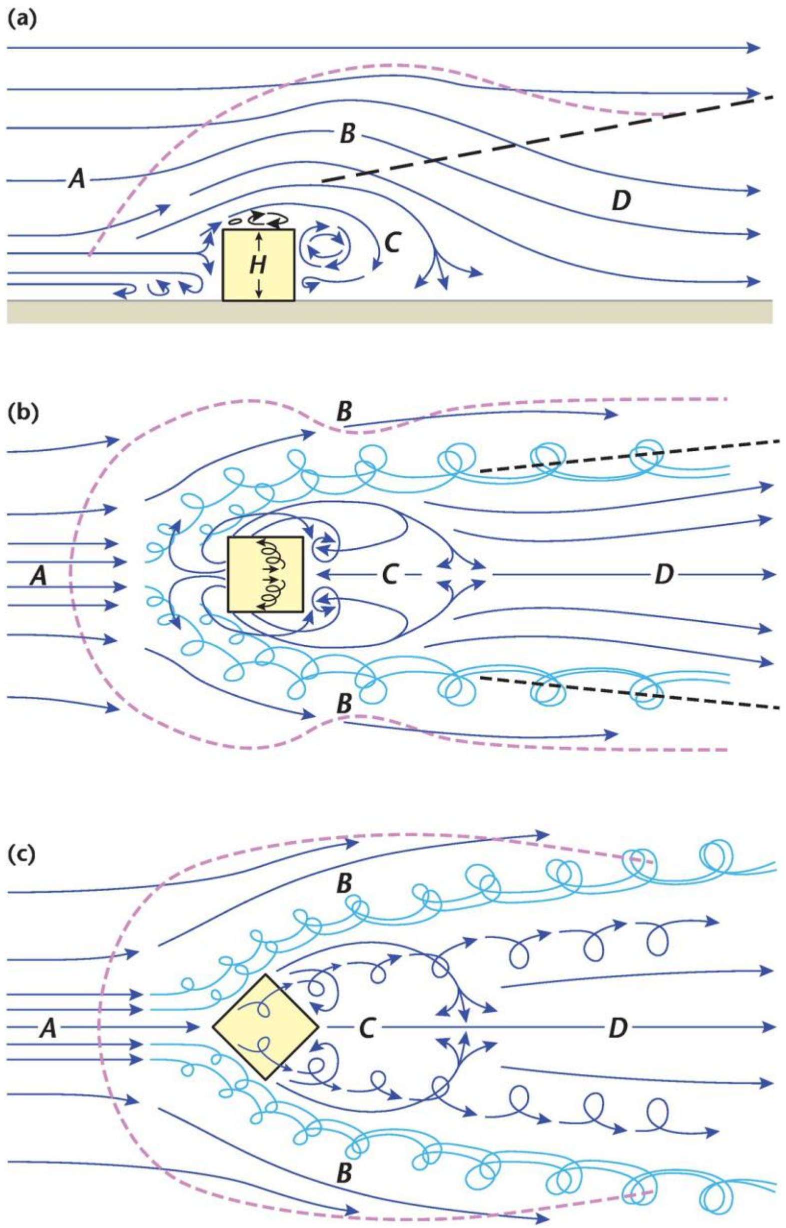
$$\frac{\mathrm{TKE}}{m} = \frac{\overline{u'^2} + \overline{v'^2} + \overline{w'^2}}{2} \qquad (\mathrm{m^2\ s^{-2}})$$

Air flow

Flow in the Roughness Sublayer: buildings

The primary determinants of urban surface roughness are the buildings. Unlike vegetative elements buildings are **impermeable**, inflexible and usually sharp-edged. Their intrusion into the mean wind causes form drag, and forces strong perturbations in their vicinity and downstream, spawning wakes characterized by decreased MKE and increased TKE. Buildings also often possess distinct radiative, thermal and moisture properties so they become the source of dry thermal plumes causing thermal turbulence. Together these <u>mechanical</u> and <u>thermal</u> attributes dictate the length scales of flow

Typical patterns of airflow around an isolated cubic ‘building’. Side and plan views with unobstructed flow **A** from the left at normal incidence (0°), showing the displacement zone **B**, the cavity **C** and the wake **D**.



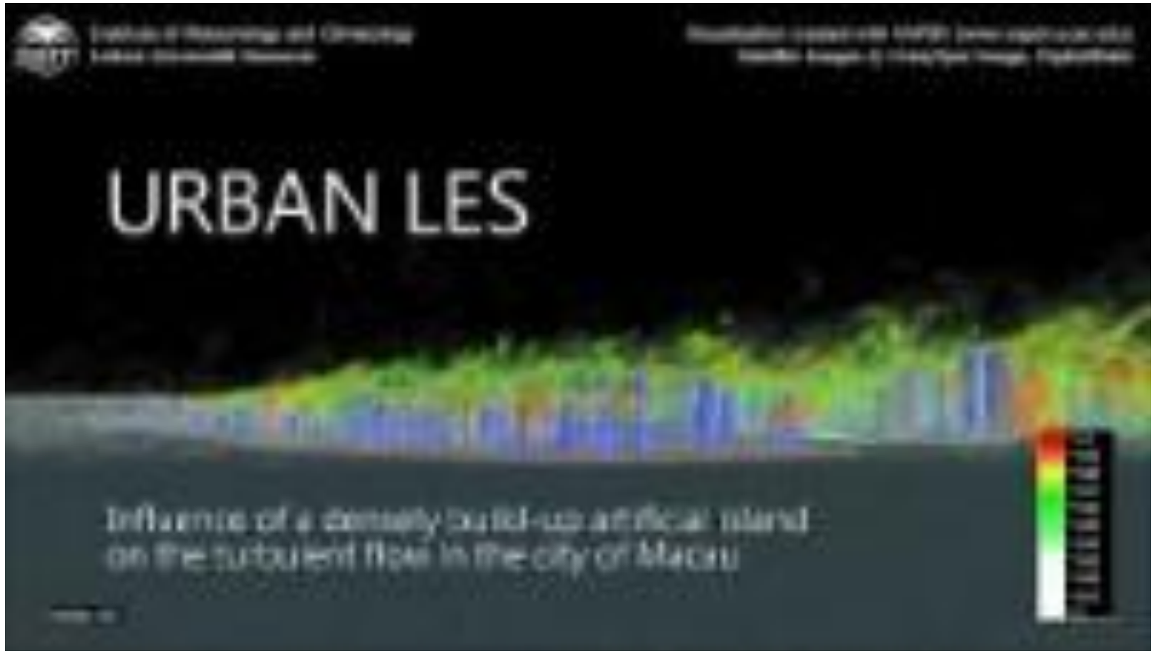
Oke et al. (2017)

Air flow

EPFL

Flow in the Roughness Sublayer: buildings

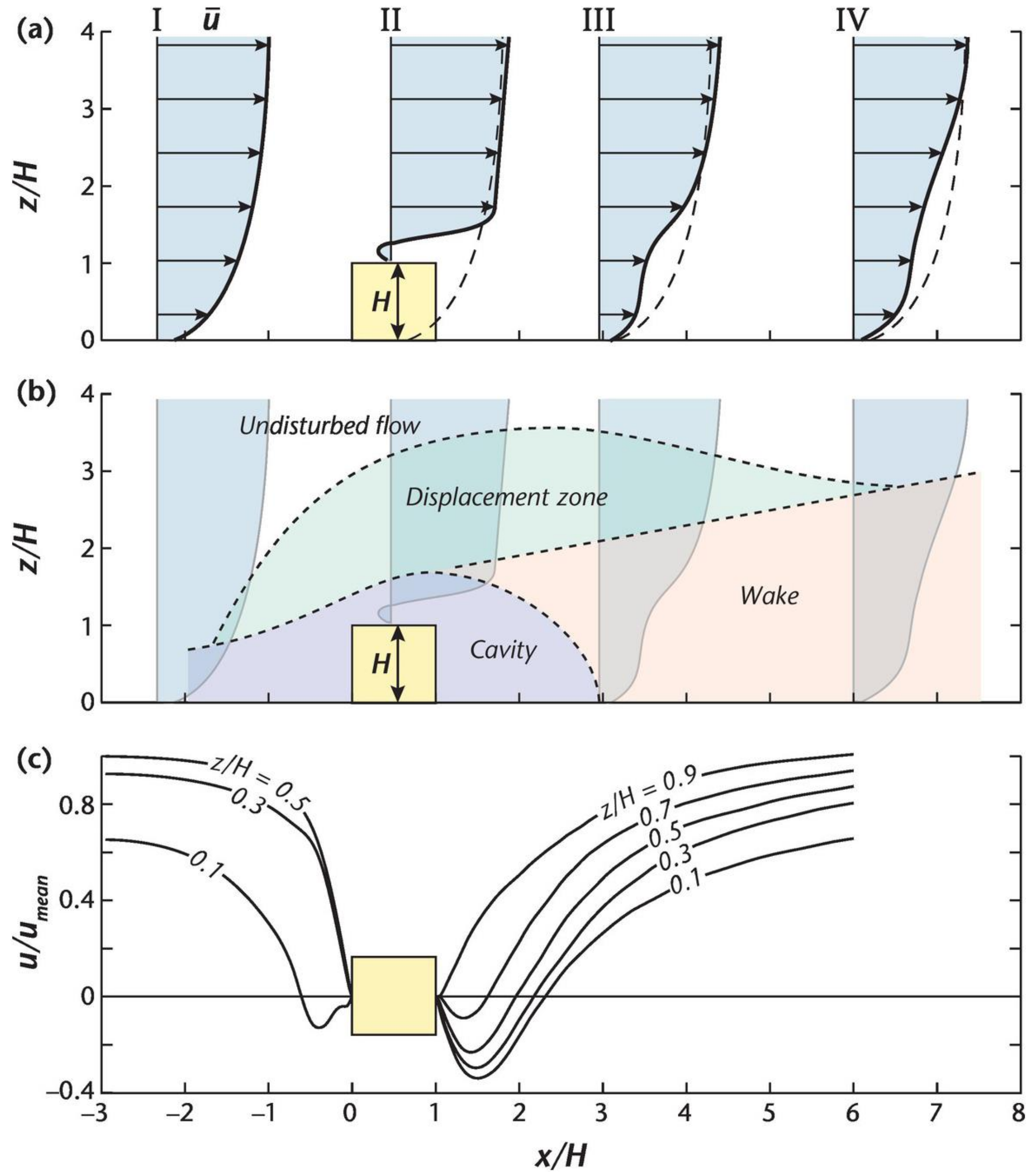
low in the vicinity of a building is highly dynamic for two further reasons: (i) the air must **deflect** around and over the building, (ii) flow over an extensive surface can stay attached to it (the no-slip condition), but when it encounters sharp edges it must **detach**, and flow separation takes place. Immediately behind the corner of a building the lower surface pressure causes flow to recirculate against the approach flow creating a **vortex**.



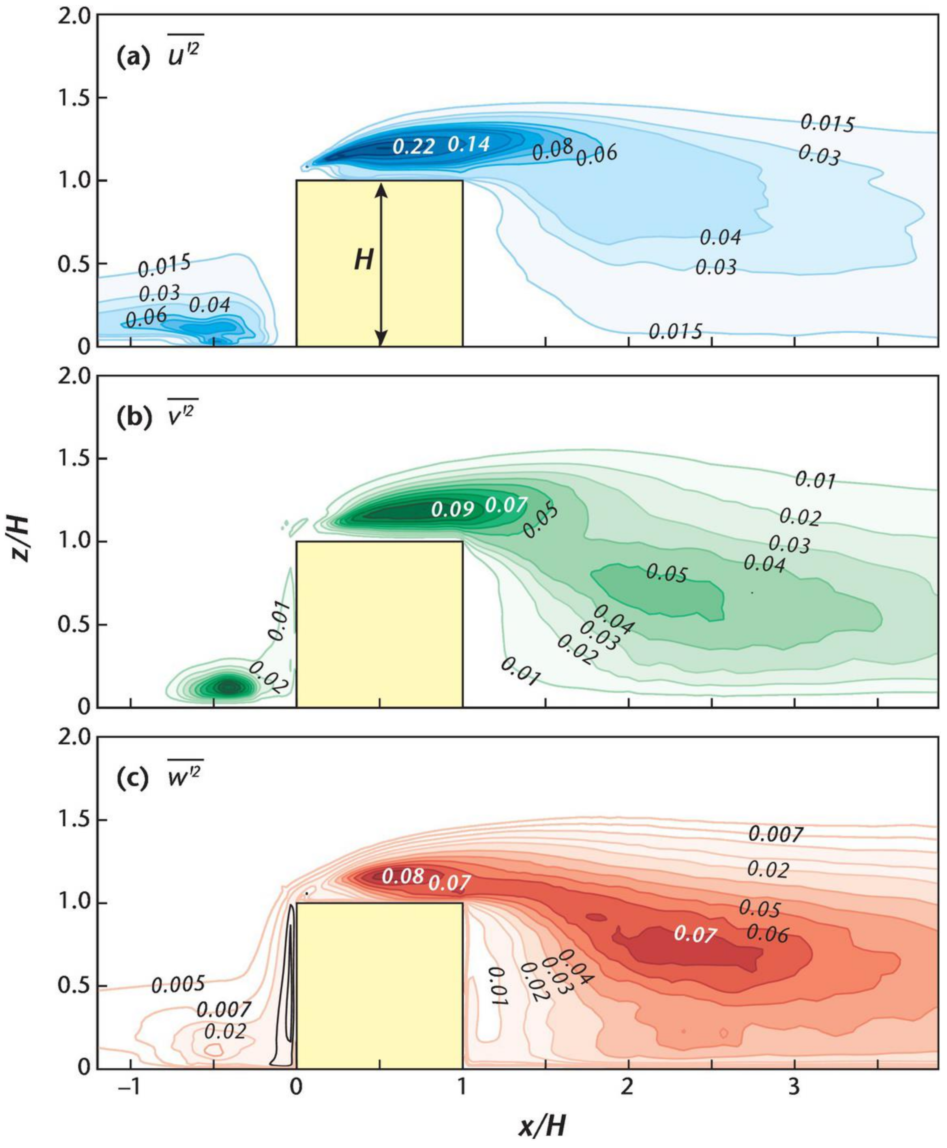
Air flow

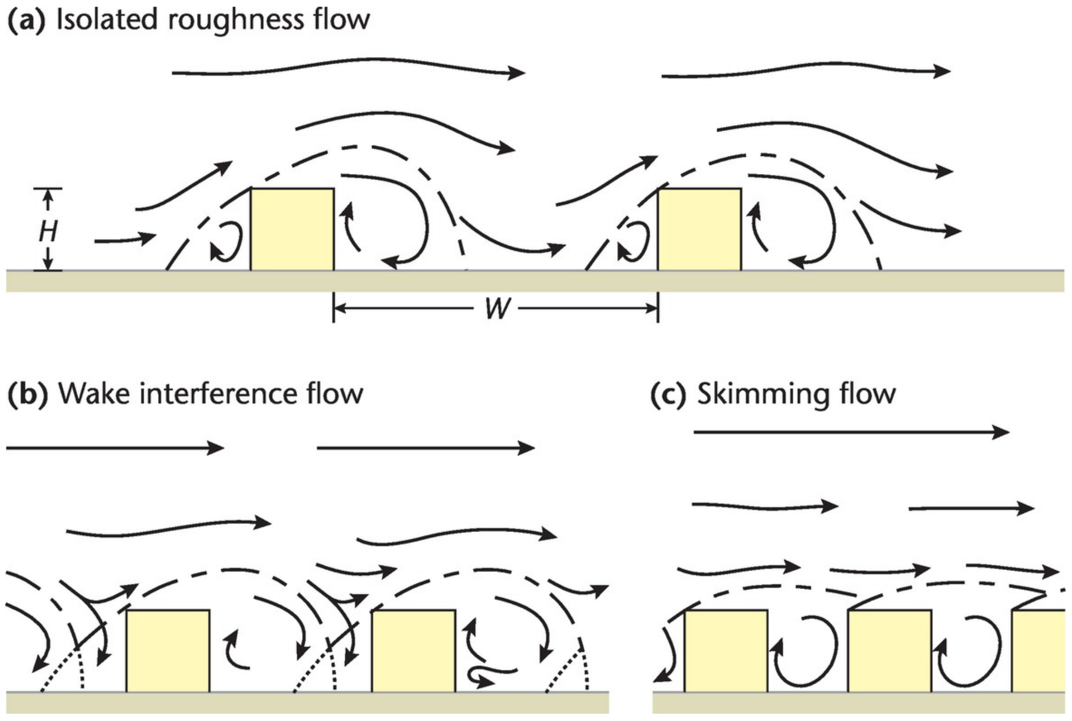
Side view of profiles of **(a)** velocity upwind (I), over (II) and downwind (III and IV) of an isolated cubical building with approach flow from left and normal to front face. **(b)** Zones of the flow. **(c)** Time-averaged *u*-velocity at different heights along the centre-line of the building, with u_{mean} the mean undisturbed wind speed at given height

Oke et al. (2017)



Air flow





Effect of packing density (H/W) on flow régimes over urban-like 'building' arrays in a wind tunnel

Isolines of components of the turbulent kinetic energy (velocity variances) on a plane through the centre of an isolated cubical building. Intensity of turbulent motions (variance) in the (a) along-wind, (b) across-wind, and (c) vertical directions

Oke et al. (2017)

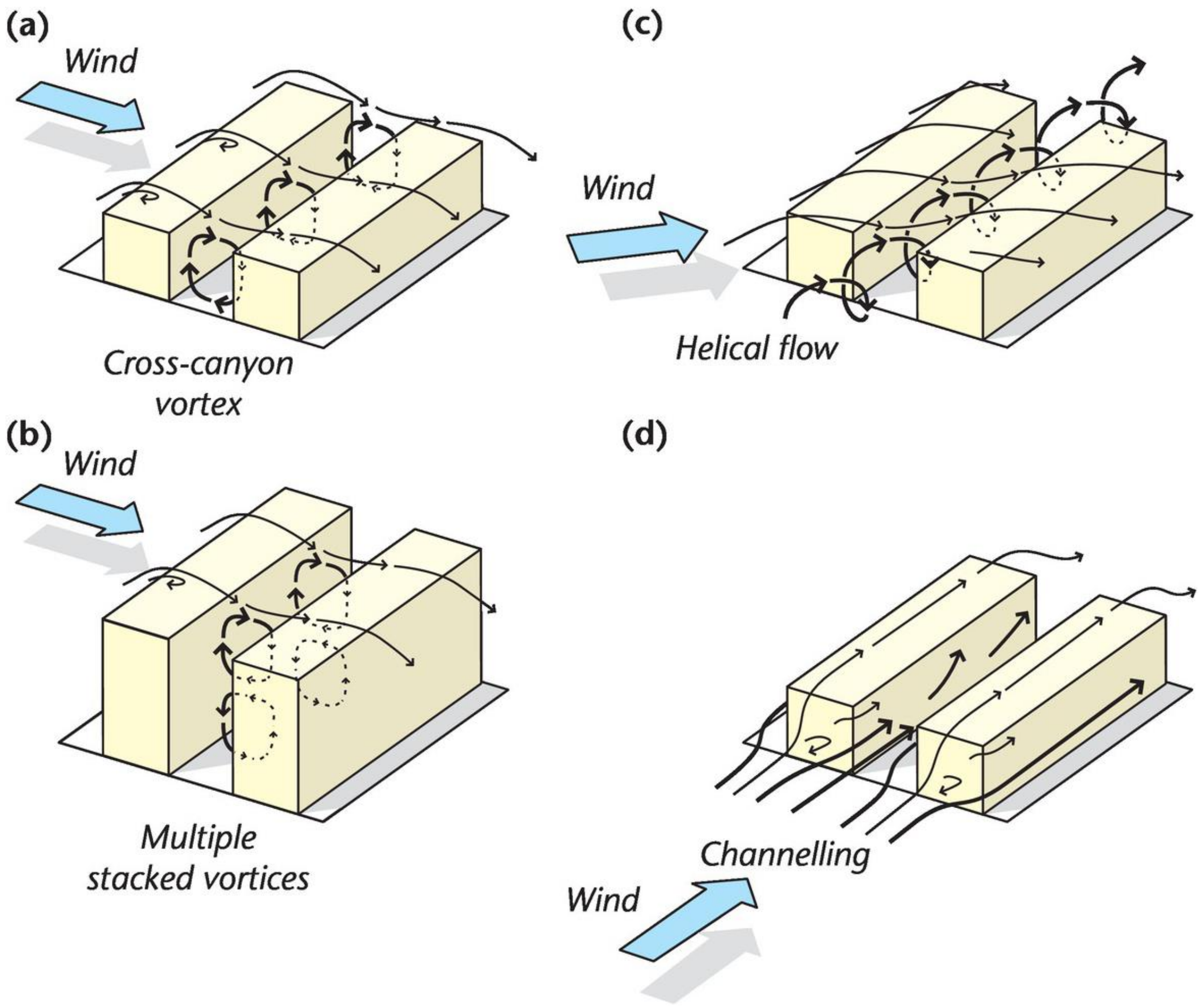
Air flow

EPFL

Flow Patterns in Urban Canyons

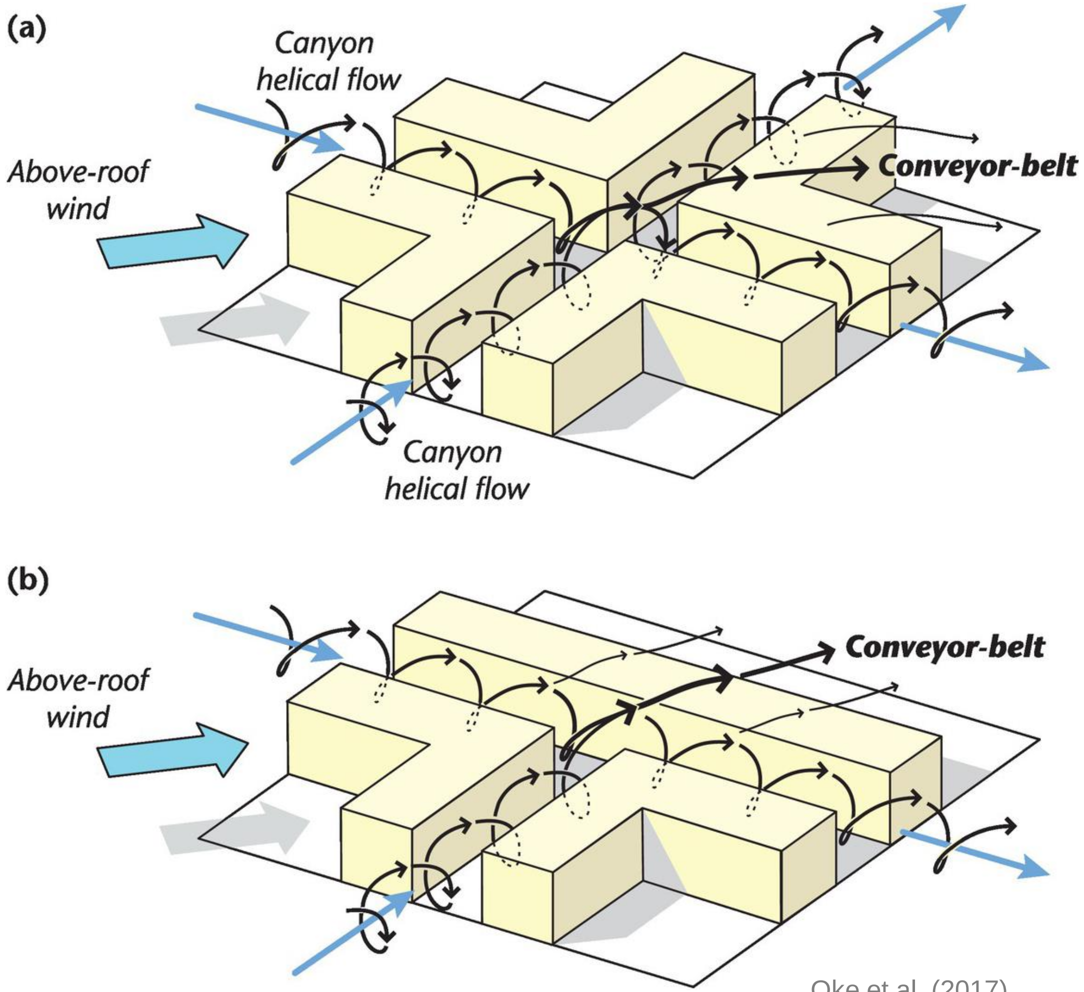
Flow in urban canyons is reasonably well understood, at least for the relatively simple case of intermediate aspect ratios, neutral flow (strong winds and/or weak heating/cooling) and long streets with flanking buildings of similar height and flat roofs. Again, flow is driven by the above-roof wind, especially its horizontal direction relative to the axis of the canyon (angle-of-attack, φ_c), and four main conditions exist:

- Cross-canyon vortex
- Stacked vortices
- Helical vortex
- Channeling



Oke et al. (2017)

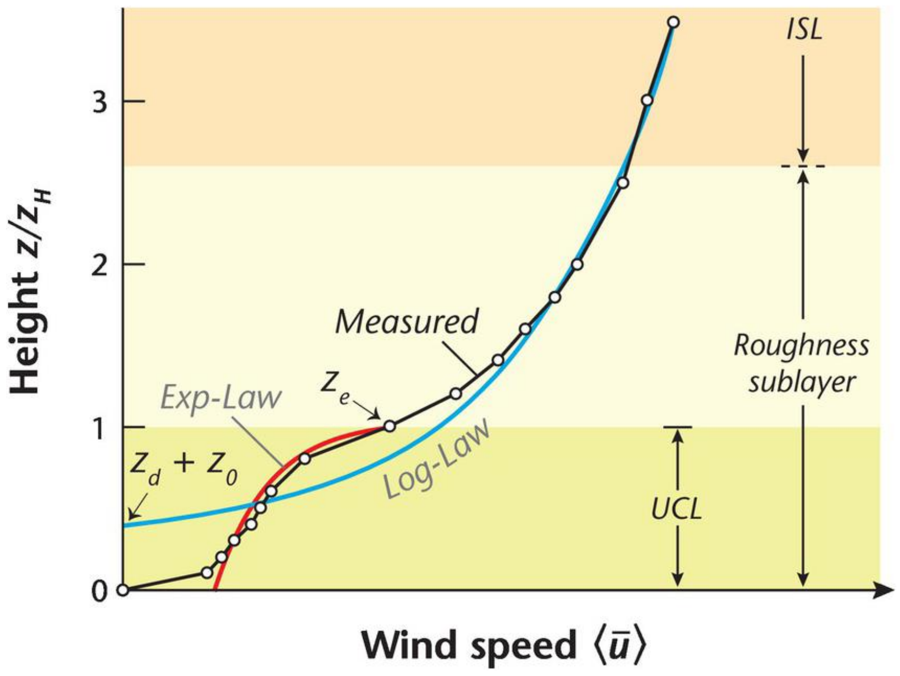
Air flow

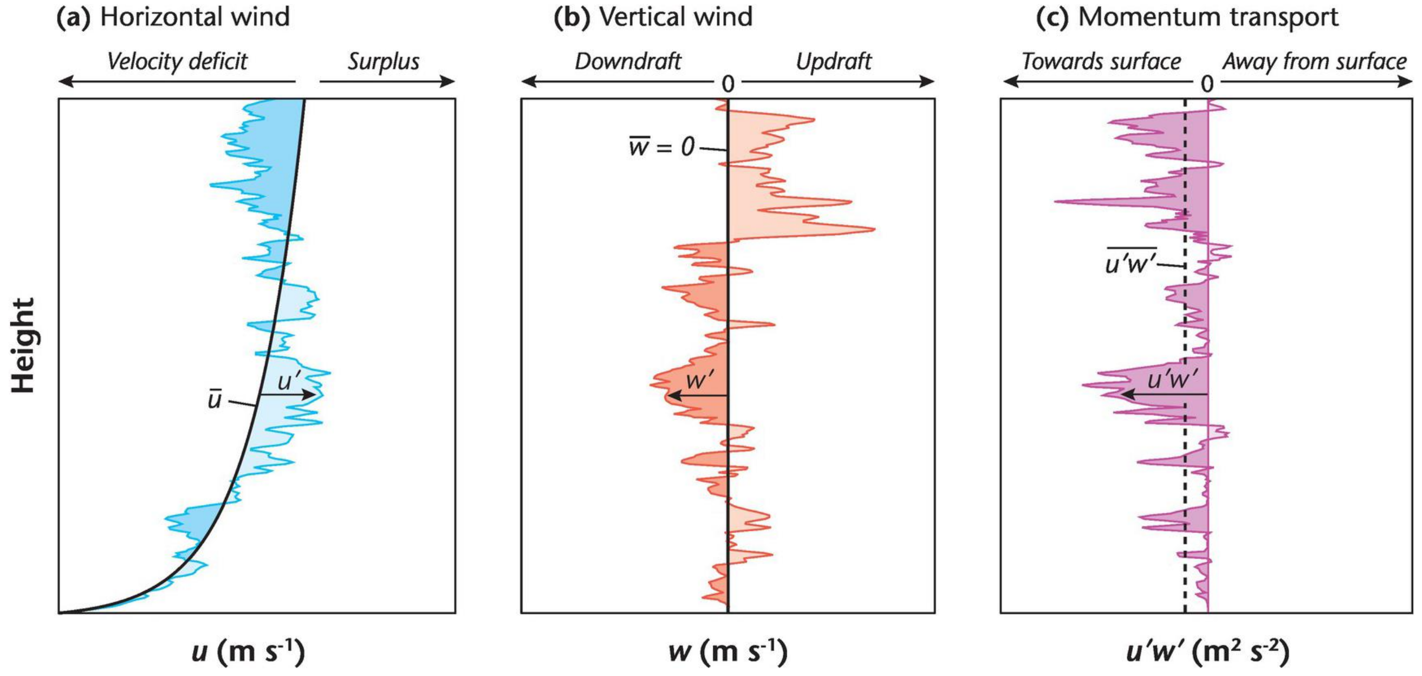


Oke et al. (2017)

Schematic depiction of 3D flow at **(a)** an intersection on an orthogonal street grid with above-roof flow diagonal to the grid, and **(b)** similar, but at a T-junction. Light blue arrows show the mean flow direction whilst the black arrows depict the actual helical motion

Air flow



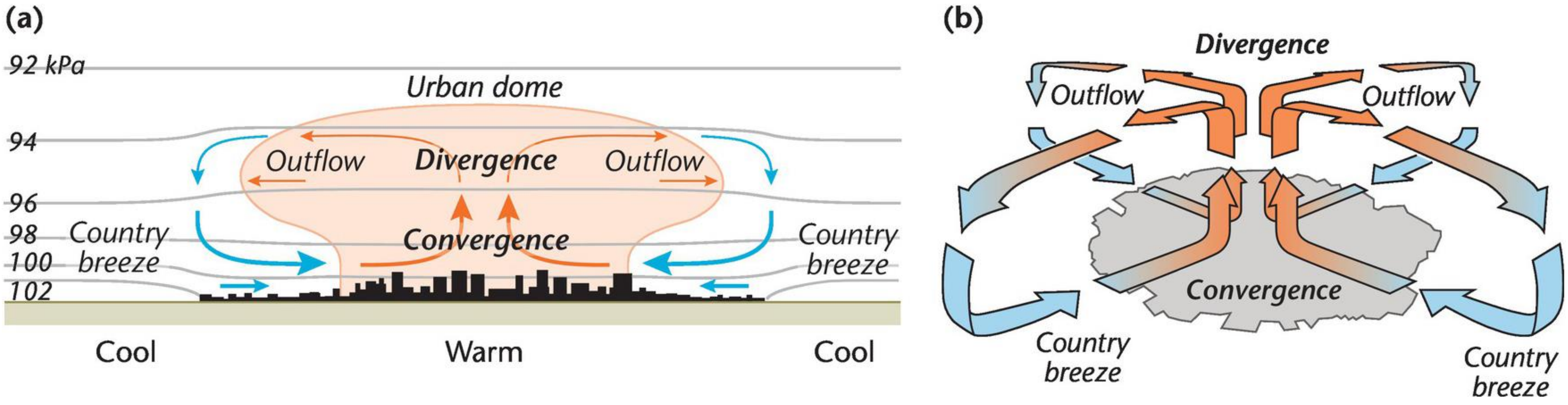


Oke et al. (2017)

Wind profile in the RSL and ISL measured in a wind tunnel over an array of cubes

Schematic profiles of instantaneous (very variable, thin curves in color) and time mean (black line) wind velocities (a,b) and the related kinematic downward flux of horizontal momentum (c)

Air flow



Oke et al. (2017)

Schematic of the urban heat island circulation (UHIC). (a) Idealized 2D air pressure distribution (thin horizontal arrows represent horizontal pressure gradient forces), and dotted lines are isobars (lines of equal atmospheric pressure in kPa). The thick lines are the resulting circulation. (b) Highly simplified view of the 3D circulation pattern

Today's session

Outline

- Concepts of urban climate
- Urban atmosphere
- Airflow
- **Energy balance**

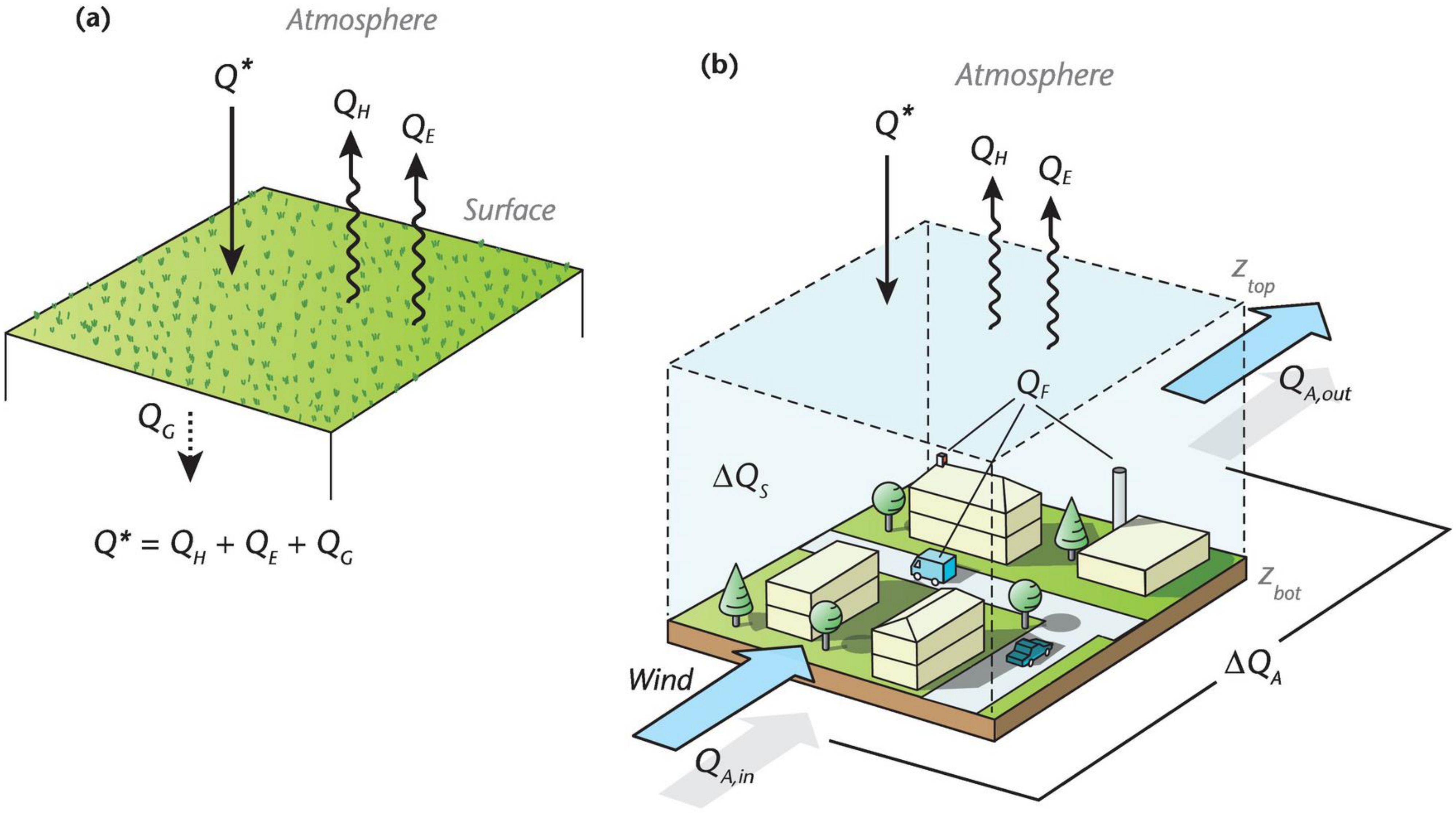
Energy balance

The **surface energy balance (SEB)** is the fundamental starting point if we are to understand and predict surface microclimates and climates of the atmospheric boundary layer (ABL). It is a statement of the **conservation of energy** which is applicable to surfaces and volumes at all spatial and temporal scales. It is used here to assess the transfer and storage of energy within an urban system and between that system and the atmosphere.
For urban systems, energy balances can be written for individual facets (roofs, walls, roads etc.), for urban elements immersed in the urban atmosphere (human body, buildings), for the entire surface-atmosphere interface, or for selected layers of the atmosphere.

An extreme case of the replacement of natural properties (surface geometry, materials) by built ones (including anthropogenic heat for space cooling) that radically alter the surface water and energy balances

Oke et al. (2017)

Energy balance

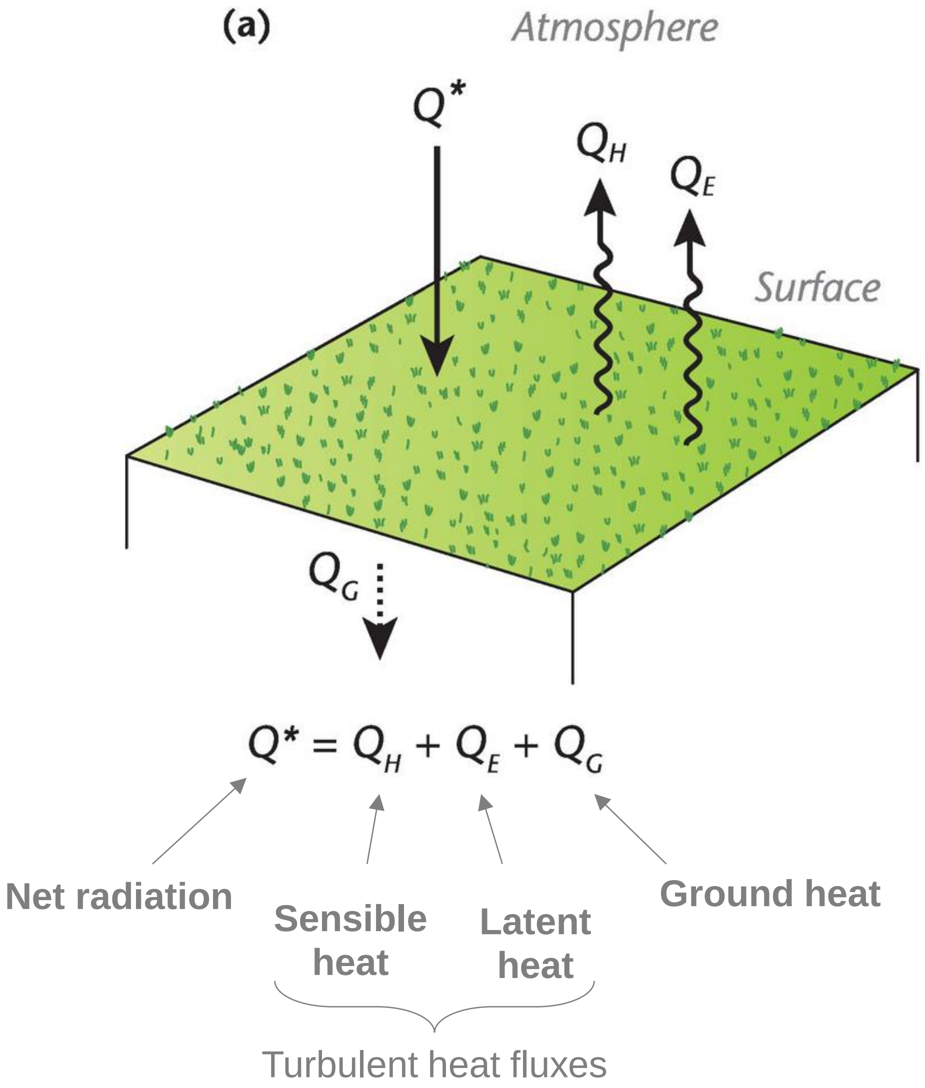


$$Q^* = Q_H + Q_E + Q_G$$

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

Oke et al. (2017)

Energy balance

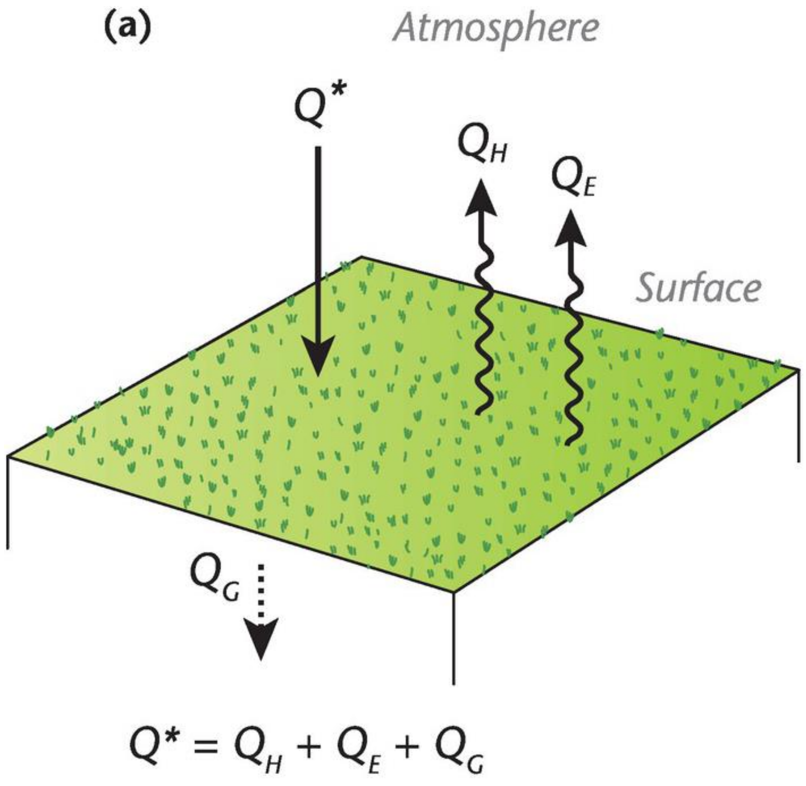


In a nutshell, variations in the climate of a surface and of the ABL are driven by the SEB, which describes the net result of energy exchanges (flux densities in W m^{-2}) by radiation, convection and conduction between a facet, an element or a land surface and the atmosphere.

The relevant flux densities at a non-urban land surface are:

- the **net all-wave radiation** Q^* (we'll see this in detail in a moment)
- the **ground heat flux** Q_G, that transfers sensible heat by conduction to the ground;
- the two turbulent heat fluxes that exchange energy between the surface and atmosphere:
  - the **sensible heat flux density** Q_H
  - the **latent heat flux density** Q_E

Energy balance



Energy conservation means those fluxes must balance at a surface

$$\frac{dU}{dt} = Q^* - Q_H - Q_E - Q_G = 0$$

infinitely thin surface layer (U = total heat energy stored)

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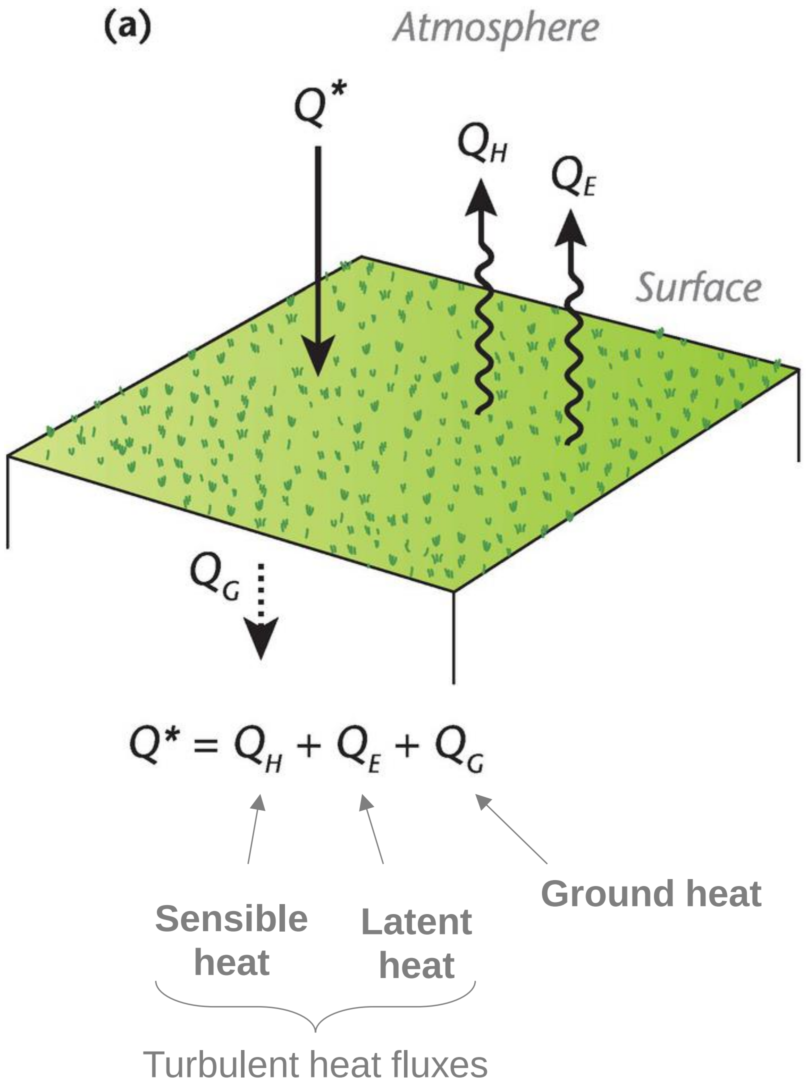
Energy balance



Ground heat flux (Q_G) is driven by the difference of temperatures across a ground layer, multiplied by the heat capacity and the inverse of resistance:

$$Q_G = C\frac{\Delta T}{r}$$

Sensible heat (Q_H) is driven by temperature differences between the surface and atmosphere, and minimizes temperature differences within the atmosphere by mixing warmer and cooler eddies:

$$Q_H = C_a\frac{(T_s - T_a)}{r_a}$$

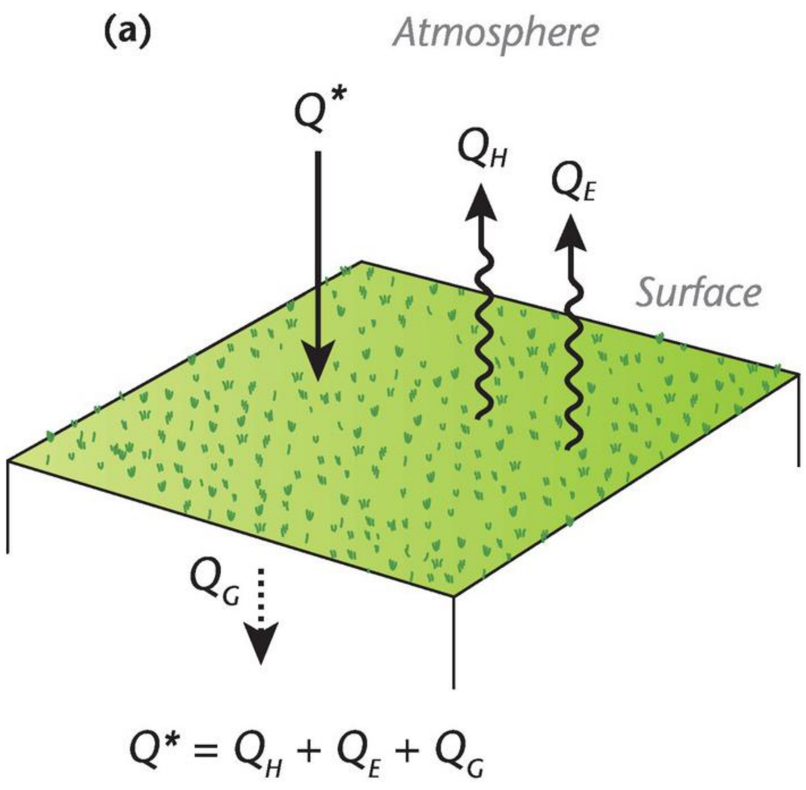
Where $C_a = \rho c_p$, ρ [kg m^{-3}] is the mean air density, c_p [J kg^{-1} K^{-1}] is the specific heat of dry air at constant pressure, and r_a is the aerodynamic resistance [s m^{-1}].

Latent heat (Q_E) is the consequence of transporting water vapour (a mass flux density E of water or evaporation in kg m^{-2} s^{-1}) and the associated latent heat towards or away from the surface. By latent heat we refer to the energy that was used to vapourize the water mass, i.e.;

$$Q_E = L_v \cdot E$$

where L_v is the latent heat of vapourization (2.464 MJ kg^{-1} at 15ºC)

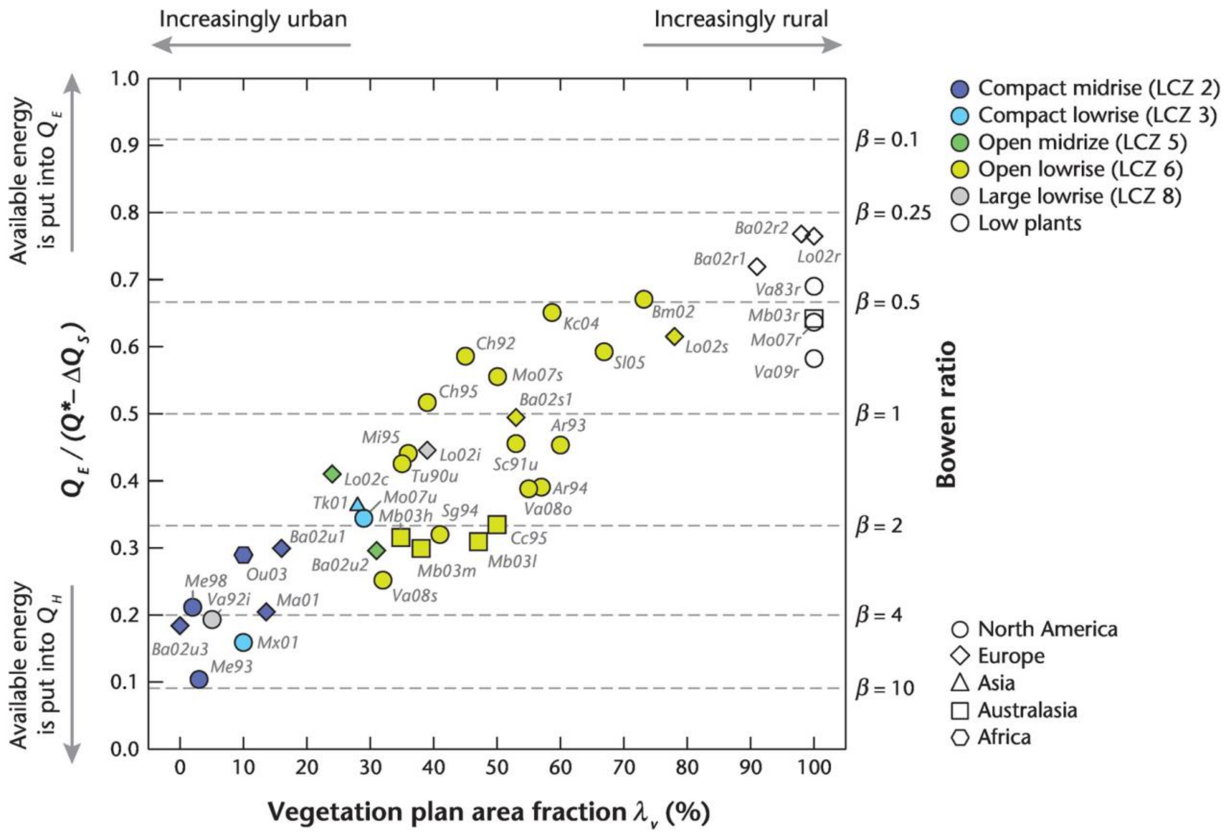
Energy balance



Sensible heat

Latent heat

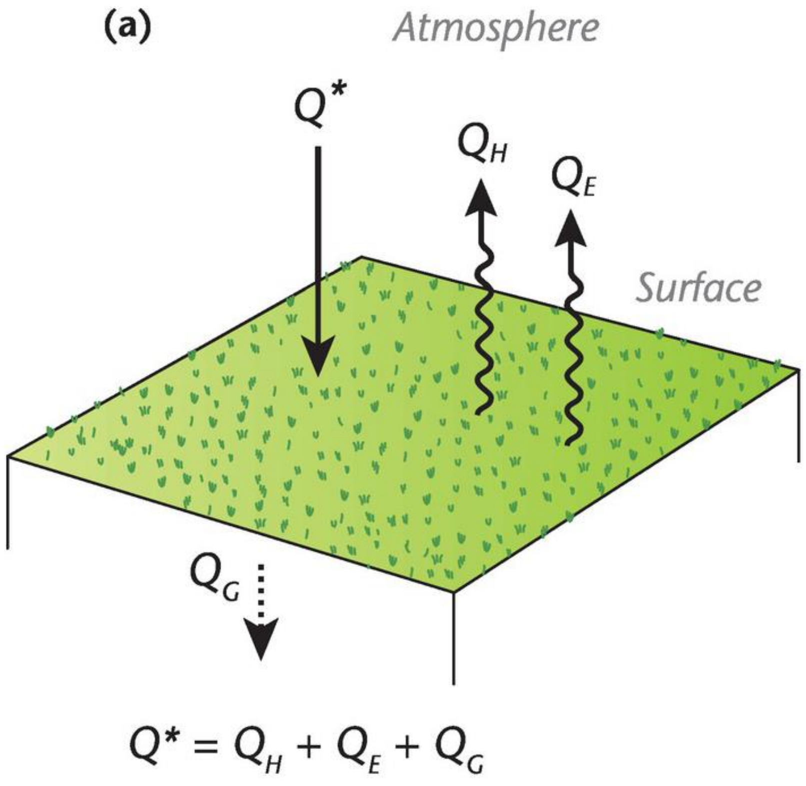
Bowen ratio: $\beta = \dfrac{Q_H}{Q_E}$



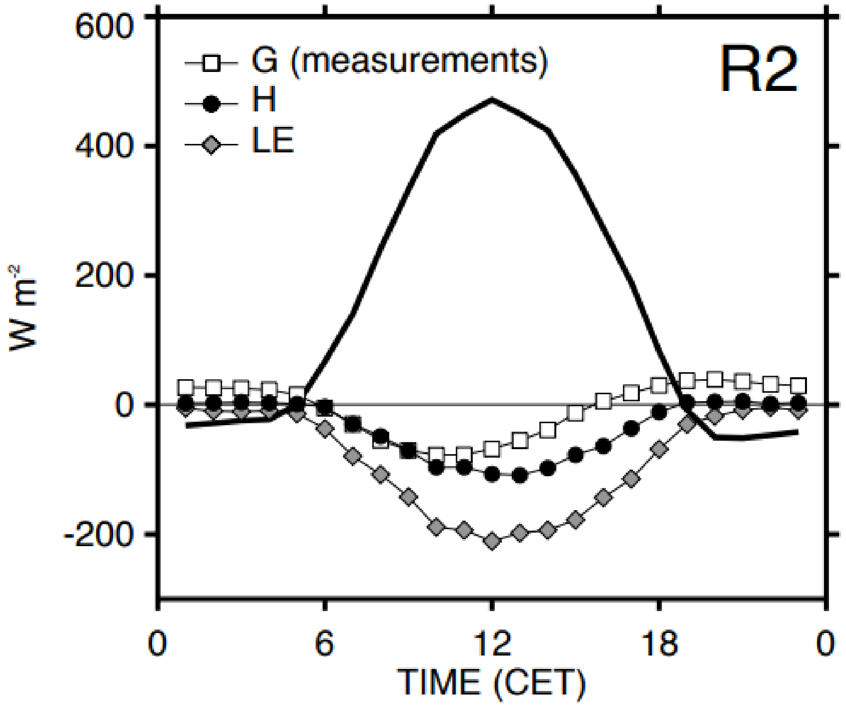
Relation between vegetation plan area fraction and partitioning of daily total turbulent fluxes.

Oke et al. (2017)

Energy balance

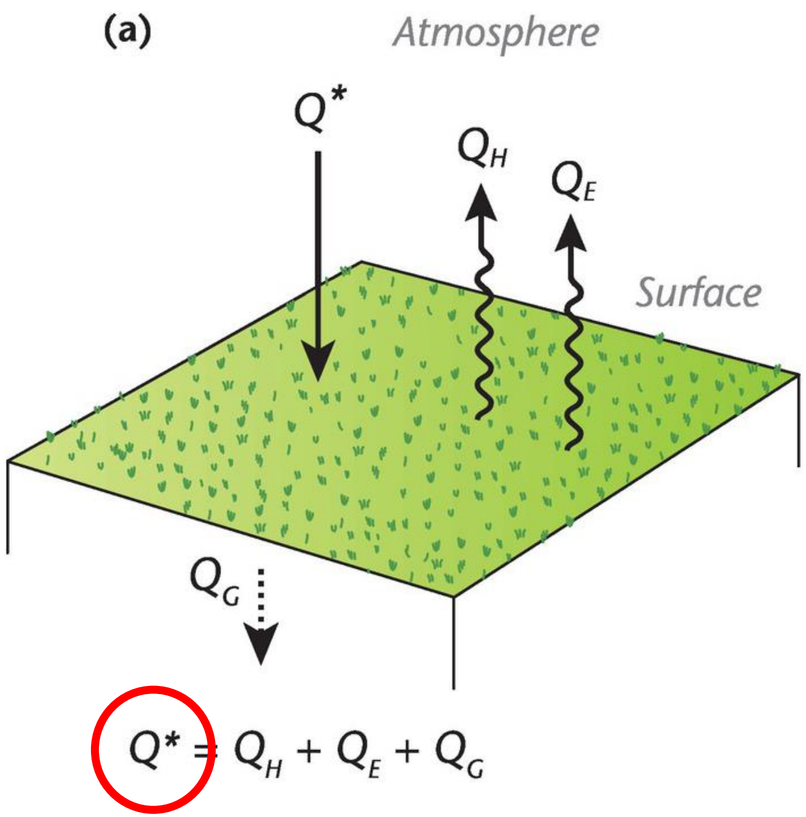


Christen et al. (2003)

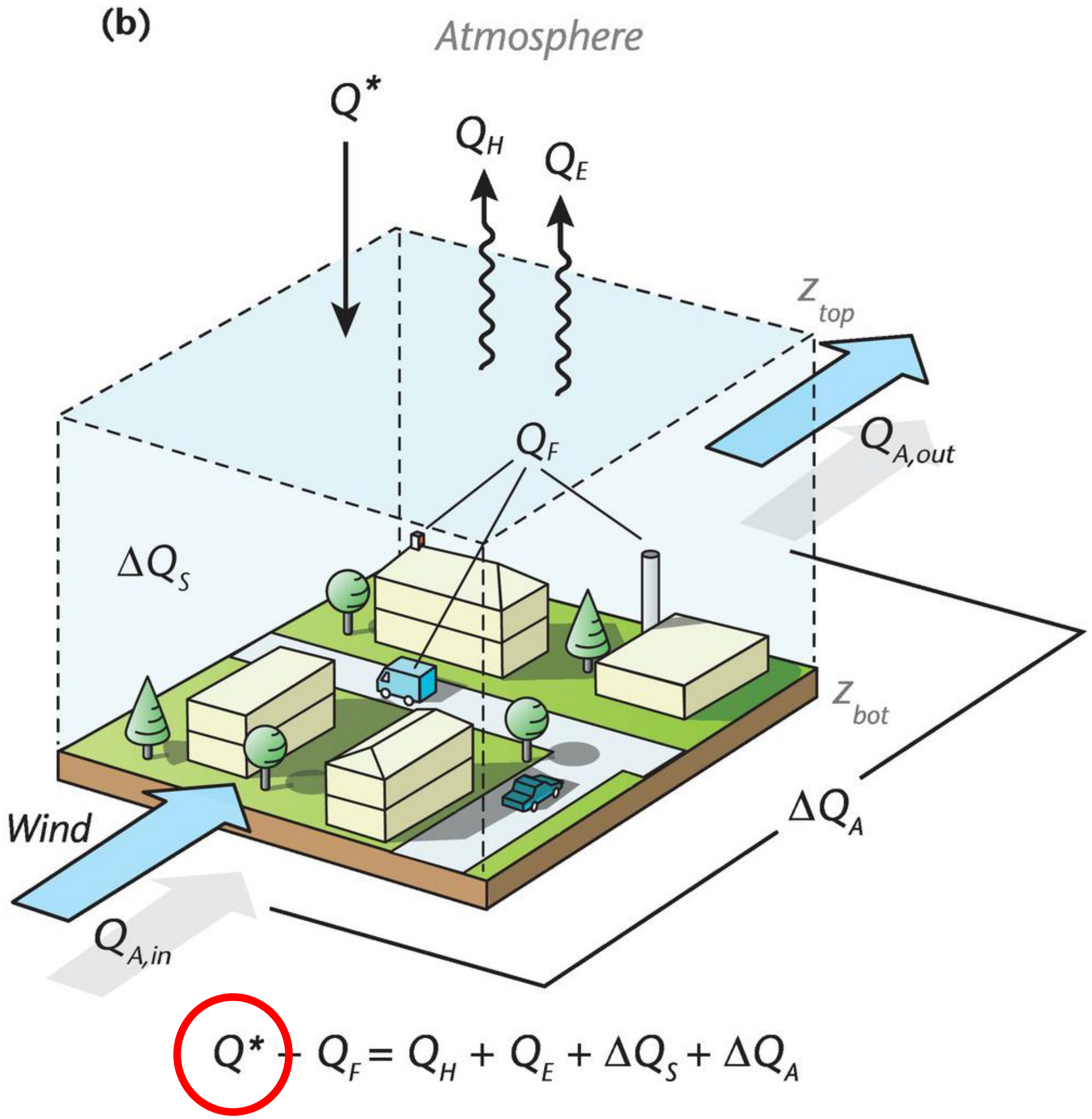


The pattern of radiation receipts from the Sun sets the fundamental daily and seasonal rhythms of external energy supply. The SEB requires that the daytime radiation surplus at the surface ($Q_* > 0$) is conducted in the form of sensible heat into the soil (QG) or convected by turbulent transport into the lower atmosphere (QH and QE). At night all flux densities usually reverse sign. The surface becomes a net emitter of radiation ($Q_* < 0$) and the surface cools, forming a temperature inversion in the lowest layer.

Energy balance



Net Radiation



Oke et al. (2017)

Energy balance

Radiation

Radiation from the Sun is the most important driver of climates near the ground. In cities, the dynamic pattern of **sunlight** and **shadow** in streets, as the solar beam is blocked by obstructions like buildings and trees, is a distinctive feature. Pedestrians often choose to walk on the shaded, rather than the sunny side of the street if the climate is hot or vice versa

Note how the urban structure of **Marrakech**, Morocco (which is situated in a hot and arid climate) limits solar access below roof-level and creates shaded spaces for pedestrians and outdoor markets. This design minimizes the exposure of building walls and streets to direct sunshine and potentially excessive heat gain

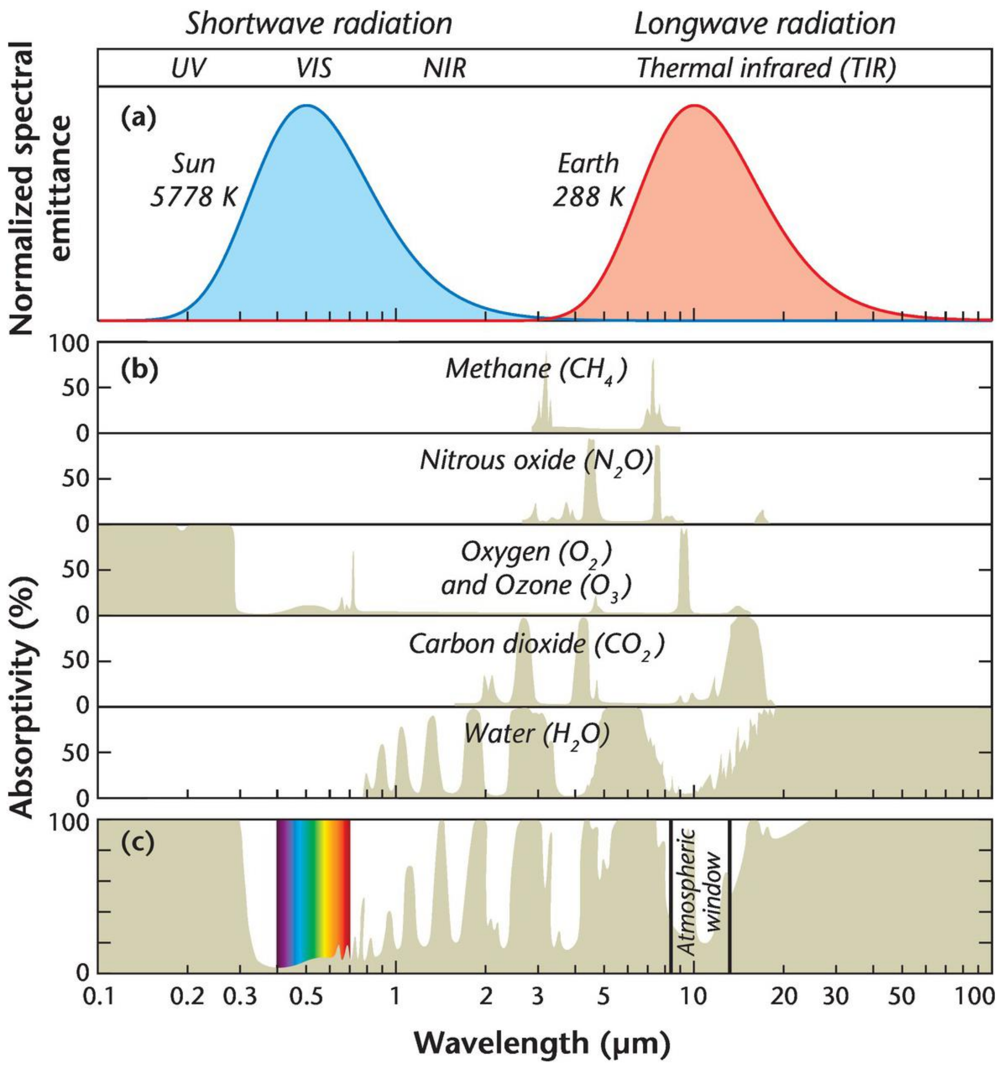
Oke et al. (2017)

Energy balance

Radiation

Radiation is emitted by all objects with a temperature (T) greater than absolute zero (0 K). It may be described as a series of electromagnetic waves of differing wavelengths (λ) that emanate from the radiating object.
The energy emitted by a body at a given wavelength and temperature is described by Planck's Law. When plotted for all wavelengths a characteristic Planck curve emerges, which describes the emission of radiation by a body that is a perfect emitter (blackbody):

- the Sun has a temperature of ~5,780 K and emits most of its radiation in the range 0.1 to 3 μm → **shortwave or "solar" radiation (K)**
- he Earth-Atmosphere system has a mean temperature of 288 K and emits in the range 3 to 100 μm → **longwave or "thermal infrared" radiation (L)**



Oke et al. (2017)

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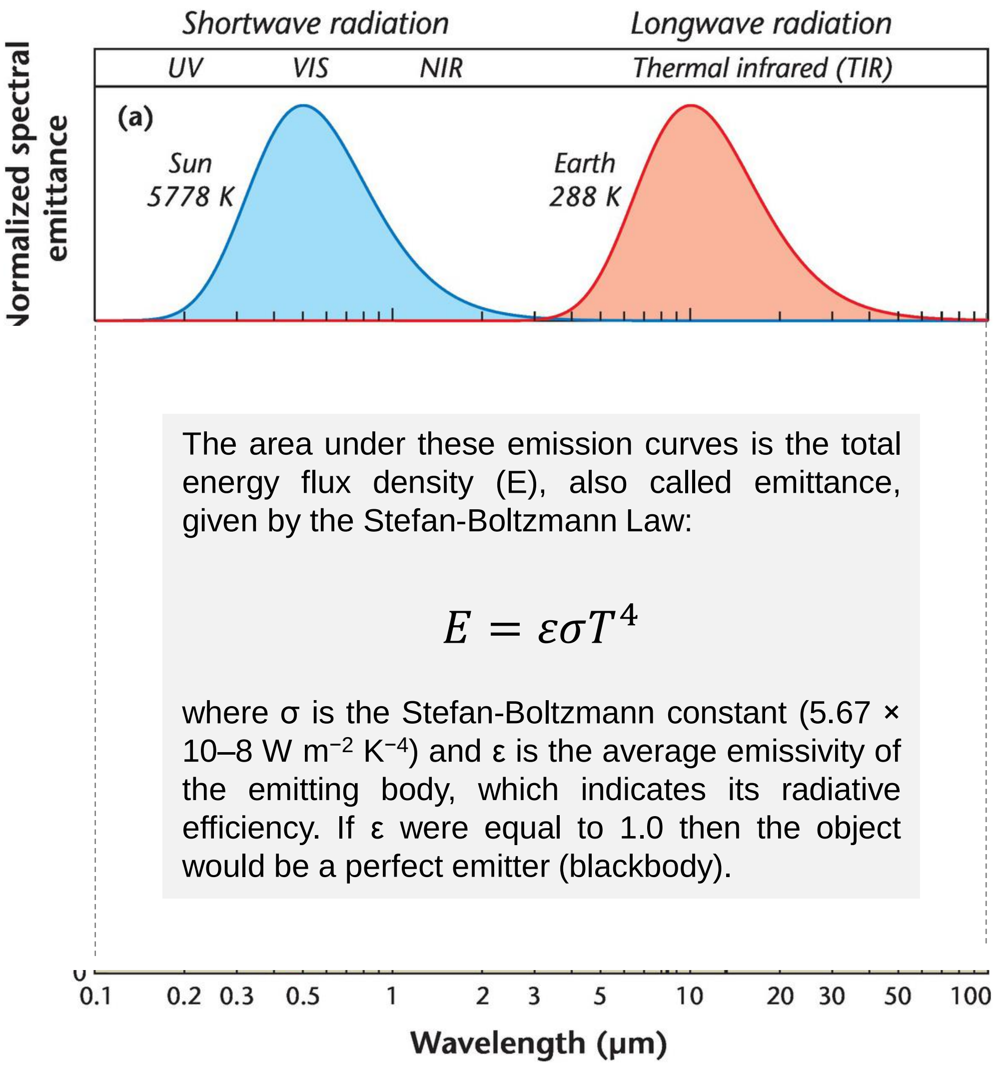


The area under these emission curves is the total energy flux density (E), also called emittance, given by the Stefan-Boltzmann Law:

$$E = \varepsilon \sigma T^4$$

where σ is the Stefan-Boltzmann constant (5.67 × 10–8 W m^{-2} K^{-4}) and ε is the average emissivity of the emitting body, which indicates its radiative efficiency. If ε were equal to 1.0 then the object would be a perfect emitter (blackbody).

Oke et al. (2017)

Energy balance

Radiation

When radiation of a given wavelength encounters a medium it experiences one of three fates:

- **absorption** which in most cases results in heating of the medium or sometimes enables a chemical reaction;
- **reflection** which redirects the path of the radiation backwards and;
- **transmission** which allows the radiation to pass through the medium.

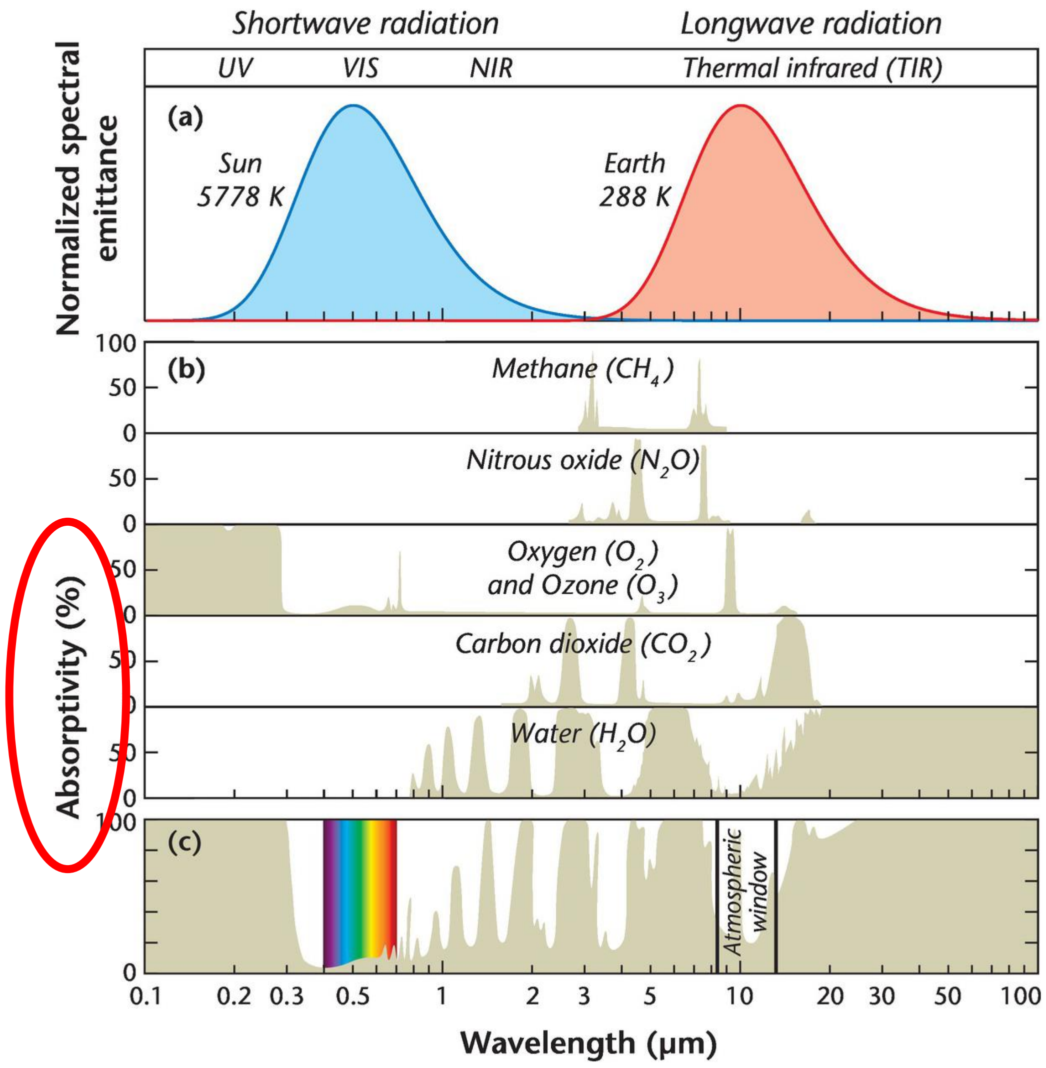
We can therefore write a statement of **radiant energy conservation**:

$$\varphi_\lambda + \omega_\lambda + \tau_\lambda = 1$$

Absorptivity $\in [0,1]$

Transmissivity $\in [0,1]$

Reflectivity $\in [0,1]$



Oke et al. (2017)

Energy balance

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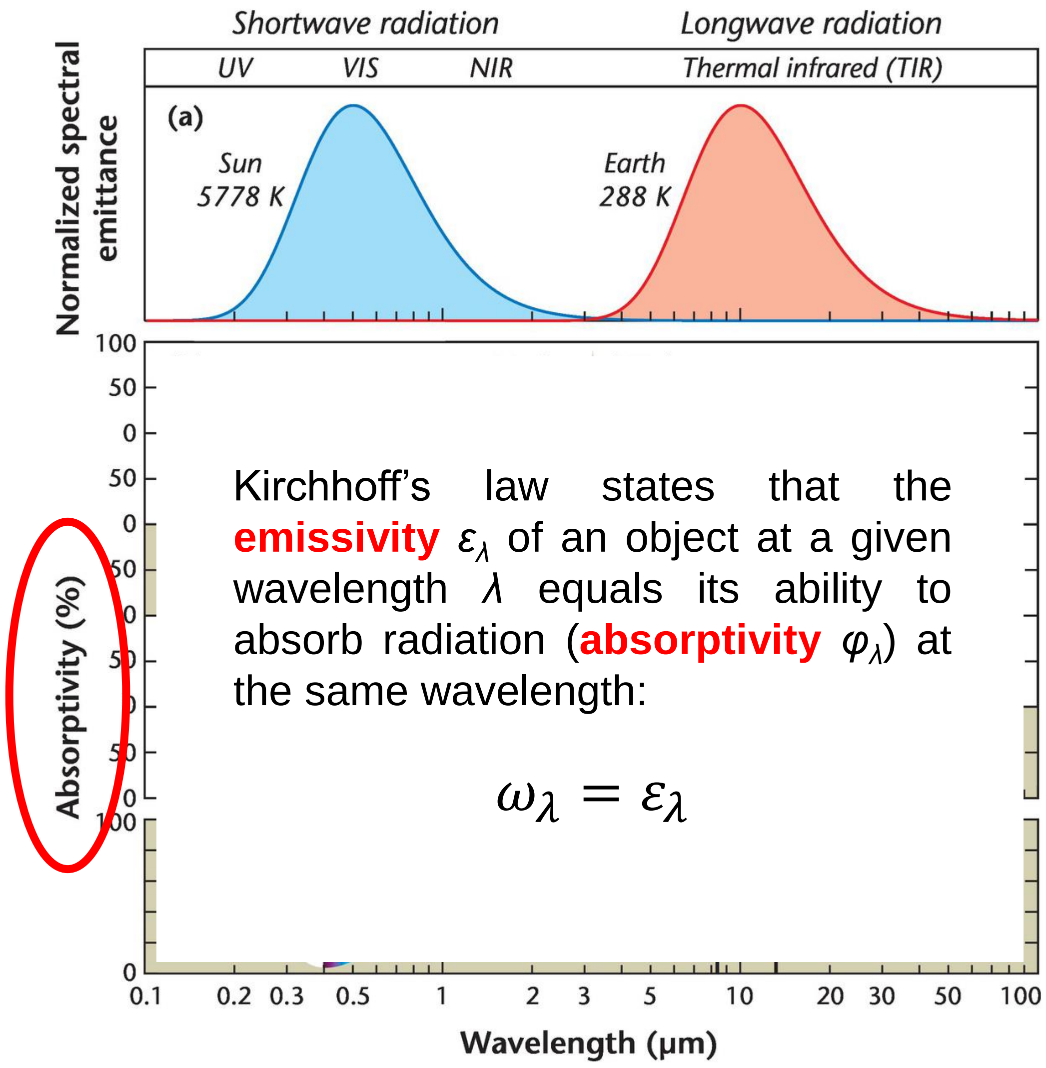
- **transmission** which allows the radiation to pass through the medium.

We can therefore write a statement of **radiant energy conservation**:

$$\omega_\lambda = 1 - \varphi_\lambda$$

if radiation strikes a surface that is solid and opaque, then $\tau_\lambda = 0$ and absorptivity = 1 - reflectivity



Kirchhoff's law states that the **emissivity** ε_λ of an object at a given wavelength λ equals its ability to absorb radiation (**absorptivity** φ_λ) at the same wavelength:

$$\omega_\lambda = \varepsilon_\lambda$$

Oke et al. (2017)

Energy balance

Radiation and aerosols

Aerosols are small solid or liquid particles suspended in the atmosphere. Aerosol **size**, which varies over several orders of magnitude, is an important attribute that influences residence time, settling velocity, interactions with radiation and impacts precipitation formation.

Aerosols have direct and indirect effects on the transfer of radiation. Direct effects include **scattering**, i.e. redirection of the beam from its original path, and absorption. Backscattering refers to a redirection in the hemisphere towards the source and is equivalent to reflection. Indirect effects include the growth of haze and cloud droplets which, in turn, affect the radiative properties of the atmosphere.

Sunshine boosts aerosol controls – Physics World

Energy balance

The surface radiation budget

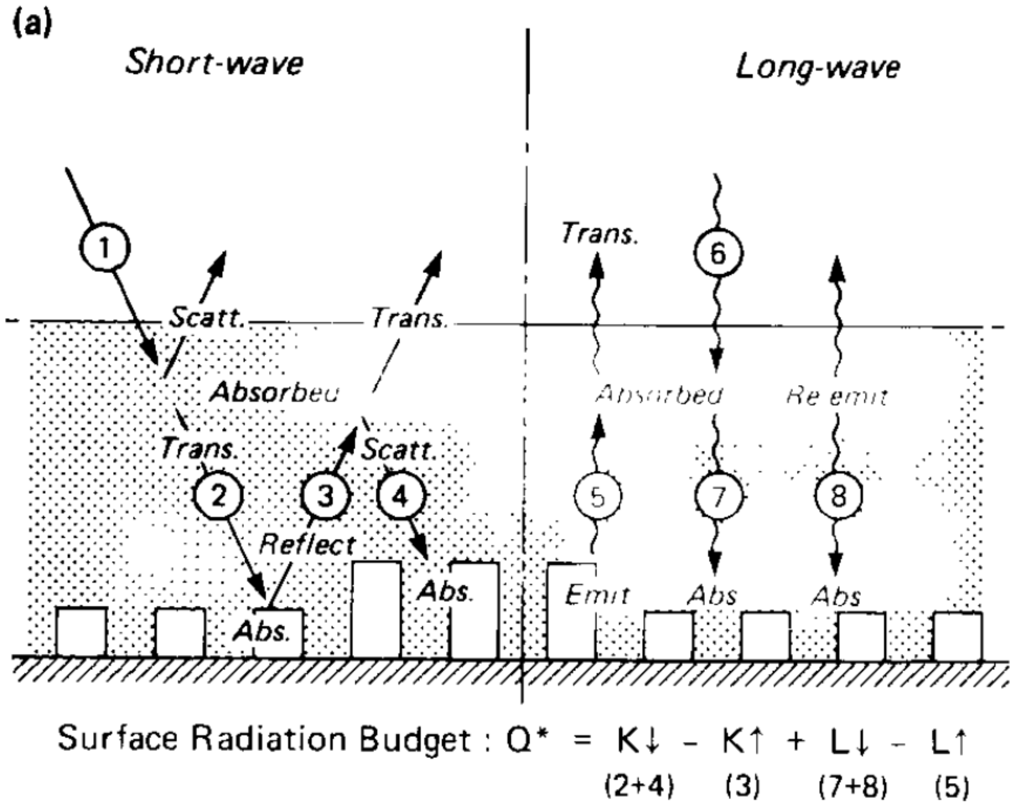
The radiation budget at any surface may be stated:

$$Q^* = K^* + L^* = (K_\downarrow - K_\uparrow) + (L_\downarrow - L_\uparrow)$$

incoming outgoing

Shortwave Longwave

where Q^*, K^* and L^* are the budgets of net allwave, net shortwave and net longwave radiation flux density, respectively. Arrows indicate **incoming** and **outgoing** fluxes at the surface. For urban areas, “surface” can refer to a leaf, a wall, roof, or even a building or urban canyon.



Oke (1988)

Energy balance

EPFL

The surface radiation budget

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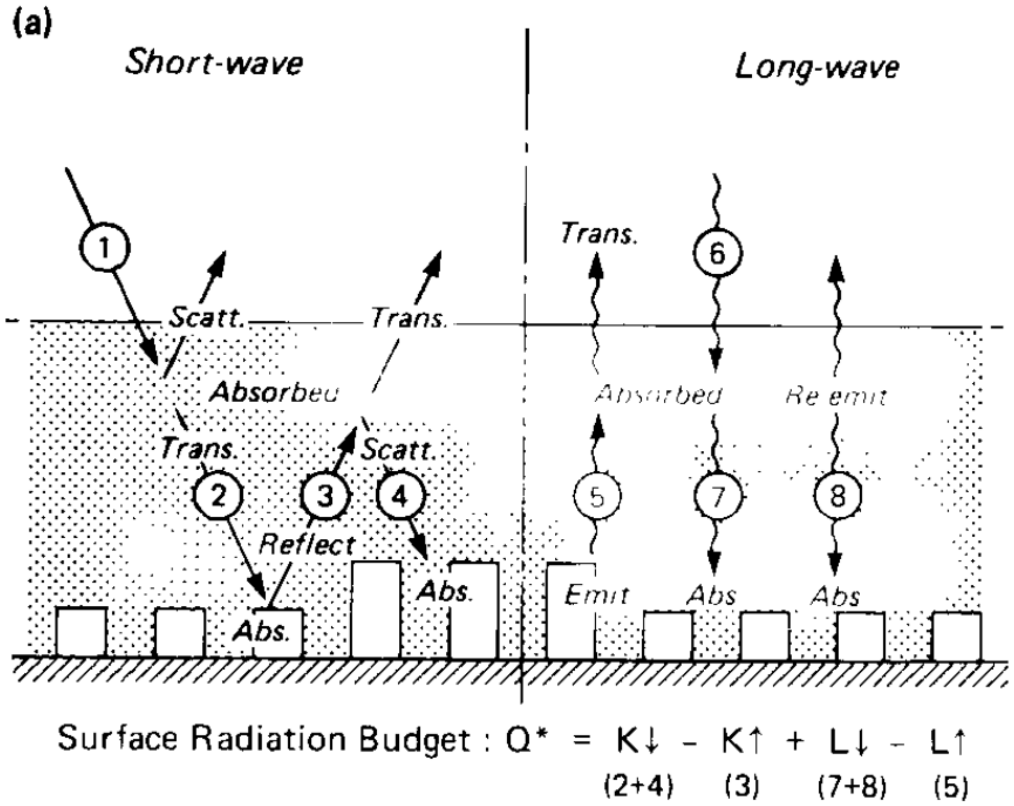
$$Q^* = K^* + L^* = (K_\downarrow - K_\uparrow) + (L_\downarrow - L_\uparrow)$$

$$= K_\downarrow - \alpha K_\downarrow + \varepsilon_a \sigma T_a^4 - (1-\varepsilon_s)\varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4$$

- Incoming from Sun (1)
- reflected (3)
- Emitted from atmosphere and clouds (6)
- Reflected from surface (8)
- Emitted from surface (5)



Oke (1988)

Energy balance

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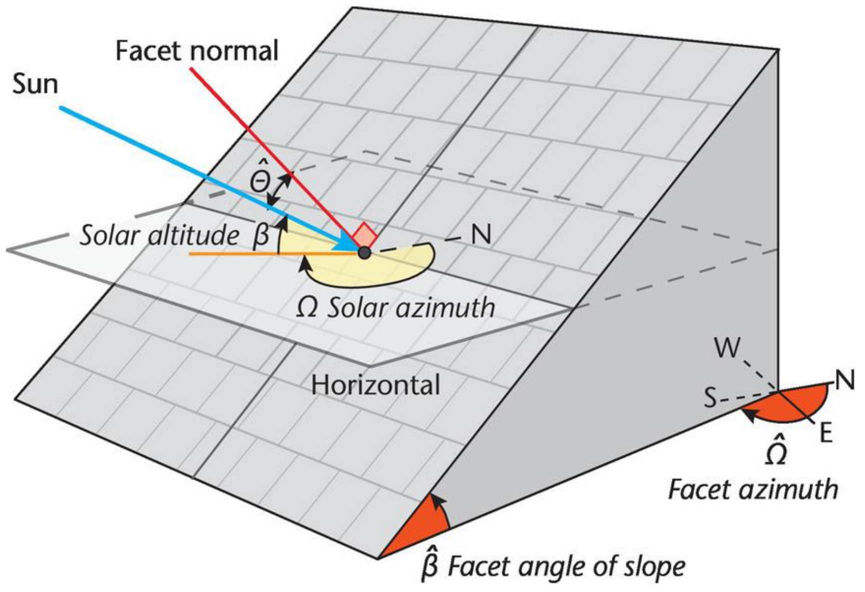
$$= K_\downarrow - \alpha K_\downarrow + \varepsilon_a \sigma T_a^4 - (1-\varepsilon_s)\varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4$$

Incoming from Sun = direct (S) + diffuse (D) irradiance

1 2 + 4



Radiation geometry for direct-beam irradiance (***S***) on an inclined urban facet, such as the roughly south-facing sloping roof illustrated. Whilst for any particular surface, the facet angle of slope ($\hat{\beta}$), facet azimuth ($\hat{\Omega}$), and the location of the normal to the facet are fixed (red angles), solar altitude (β), and solar azimuth (Ω), change constantly over the course of a day and with seasons

Oke et a. (2017)

Energy balance

EPFL

The surface radiation budget

The radiation budget at any surface may be stated:

$$Q^* = K^* + L^* = (K_\downarrow - K_\uparrow) + (L_\downarrow - L_\uparrow)$$

$$= K_\downarrow - \alpha K_\downarrow + \varepsilon_a \sigma T_a^4 - (1 - \varepsilon_s)\varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4$$

reflected

3

Reflectivity = Albedo (α)

Los Angeles Is Painting the Streets White (Again), and Your City Might Be Next | ArchDaily

Energy balance

EPFL

The surface radiation budget

The radiation budget at any surface may be stated:

$$Q^* = K^* + L^* = (K_\downarrow - K_\uparrow) + (L_\downarrow - L_\uparrow)$$

$$= K_\downarrow - \alpha K_\downarrow + \varepsilon_a \sigma T_a^4 - (1-\varepsilon_s)\varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4$$

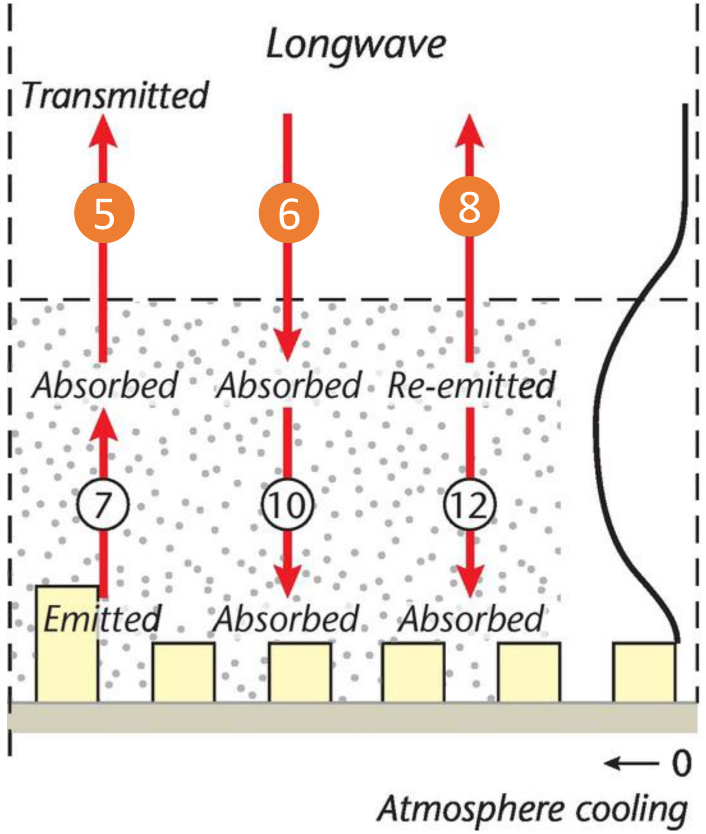
Emitted from atmosphere and clouds 6

Reflected from surface 8

Emitted from surface 5

Reflectivity:

$$\varphi_\lambda = 1 - \omega_\lambda = 1 - \varepsilon_\lambda$$



Oke et a. (2017)

Energy balance

EPFL

Radiation in the urban canopy layer

There are three attributes of the urban surface at greater than the neighbourhood scale that distinguish it from a simple flat and homogenous surface. Firstly, is the great diversity of its constituent materials with their distinctive reflectivities and emissivities; secondly, its 3D structure has innumerable facets, each of which has a unique slope and aspect, and thirdly, the possibility that facets can emit or reflect to each other or block such exchanges

Table 5.3 Materials, dimensions and radiative and thermal properties of the building and canyons simulated by TUF-3D.

Facet	Material	Depth *d* (m)	Albedo α	Emissivity ε	Thermal conductivity *k* ($W\ m^{-1}\ K^{-1}$)	Heat capacity *C* ($MJ\ m^{-3}\ K^{-1}$)
Walls	Concrete	0.2	0.25	0.90	0.80	1.33
Roof	Gravel, insulation over concrete	0.1	0.12	0.92	0.06	1.00
Floor	Asphalt over concrete	0.3	0.15	0.94	1.21	1.95

Oke et al. (2017)

Energy balance

EPFL

Radiation in the urban canopy layer

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Oke et al. (2017)

$$C = \rho c_p$$

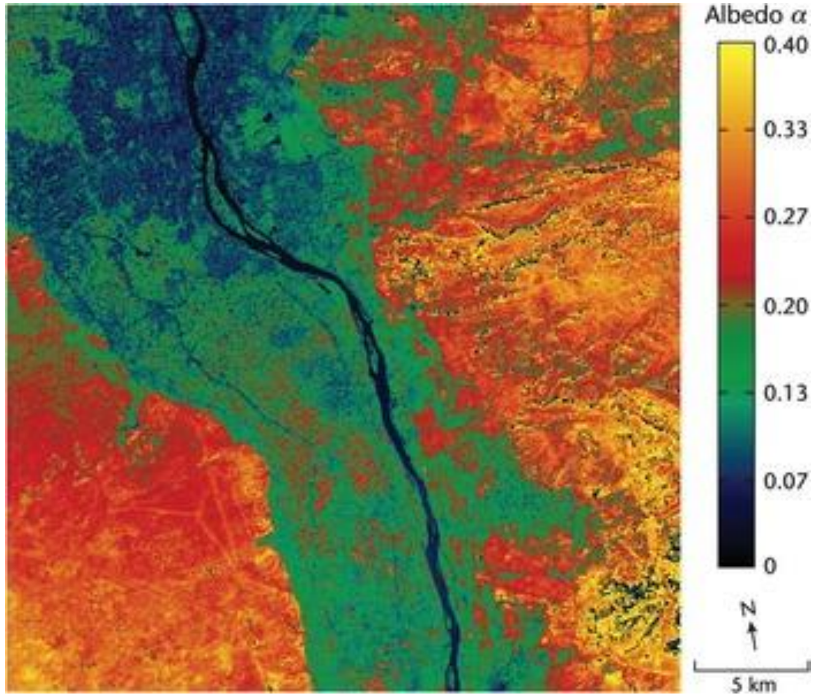
density — Specific heat

Thermal admittance (or inertia): $\mu = \sqrt{k \cdot C}$

Energy balance

Radiation in the urban canopy layer

A satellite image of albedo α in the Greater Cairo area and the surrounding landscape. The dark blue line extending south-north is the River Nile. Variations in albedo are associated with topography, crop type and growth stage. Blue (lowest albedo) is urbanized; green is irrigated farmland and; reds and yellows are desert or bare rock.



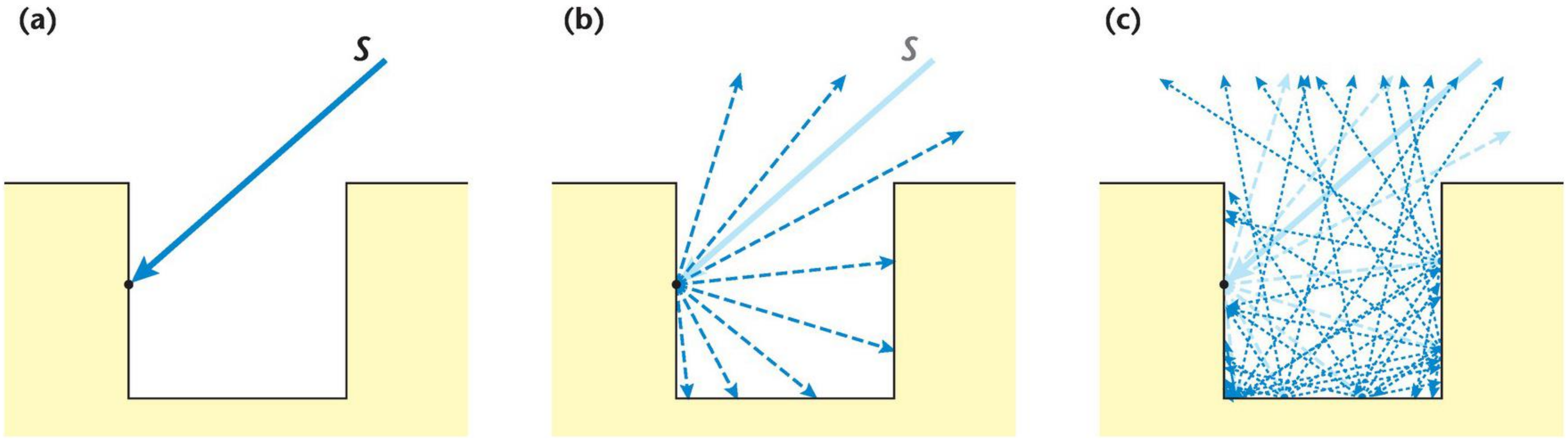
Urban–rural differences	$\Delta\alpha_{U-R}$
Urban – rural	**-0.05**
	-0.09–+0.03
Urban – rural (with snow)[6]	-0.55–-0.11

Oke et al. (2017)

Surface	Albedo α
Natural surfaces	
Bare ground[1]	
Soil (dark colour, wet)	0.05–0.10
Soil (dark colour, dry)	0.10–0.13
Soil (light colour, wet)	0.12–0.18
Soil (light colour, dry)	0.18–0.30
Desert sands	0.20–0.45
Low vegetation	
Grass (long → short)	0.16–0.26
Crops	0.18–0.25
Wetlands	0.07–0.19
Tundra	0.08–0.19
Forests	
Deciduous (bare → leaf)	0.13–0.20
Orchards	0.07–0.15
Coniferous	0.11–0.13
Water[2]	
$\beta > 60°$	0.03–0.10
$10° < \beta < 60°$	0.10–0.50
Overcast	0.05–0.10
Snow and ice[3]	
Fresh, cold, clean snow	0.80–0.90
Wet, clean snow	0.50–0.75
Old, porous, dirty snow	0.40–0.50
Sea ice, multi-year	0.55–0.75
Sea ice, first year	0.30–0.60
Glacier ice	0.20–0.40
Urban surface materials	
Roads	
Asphalt (fresh → weathered)	0.05 0.27
Concrete[4]	0.10–0.35
Walls	
Concrete	0.10–0.35
Brick (colour, red → white)	0.20–0.60
Grey and red stone	0.20–0.45
Limestone	0.40–0.64
Wood	0.22

Energy balance

Radiation in the urban canopy layer



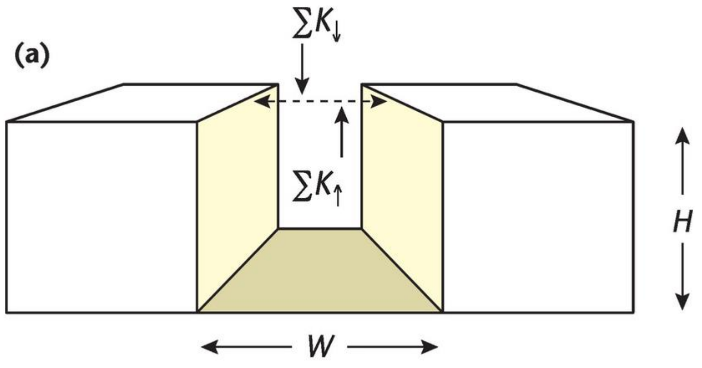
Impact of the geometric configuration of an urban canyon on radiation exchanges. The case is simplified by limiting consideration to a single incoming ray with two reflections and to 2D; in reality the form is 3D (i.e. also into and out of the page). **(a)** The receipt of direct-beam irradiance through the canyon top, **(b)** first reflection from the canyon facets, **(c)** second reflection. Input and reflection of diffuse sky radiation is not depicted.

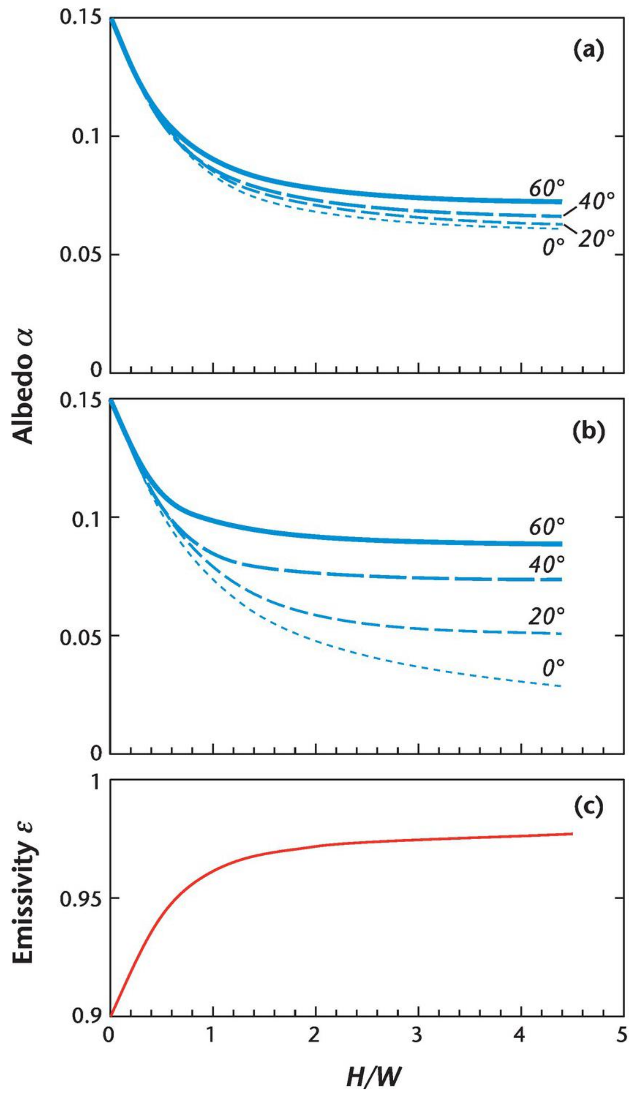
Oke et al. (2017)

Energy balance

Oke et al. (2017)

Radiation in the urban canopy layer





The effective albedo values of a canyon are lower than the average of the three facet values, both due to canyon trapping and the fact that significant fractions of the facets are in shade. The shape of the relation on the right shows the impact of geometry on albedo becomes much smaller beyond an aspect ratio of unity. It also illustrates that the effect of latitude is important as the altitude angle (β) determines the extent to which radiation penetrates into the canyon. Hence, the diurnal variations of canyon effective albedo are influenced by both the albedo of individual components of the canyon and by H/W

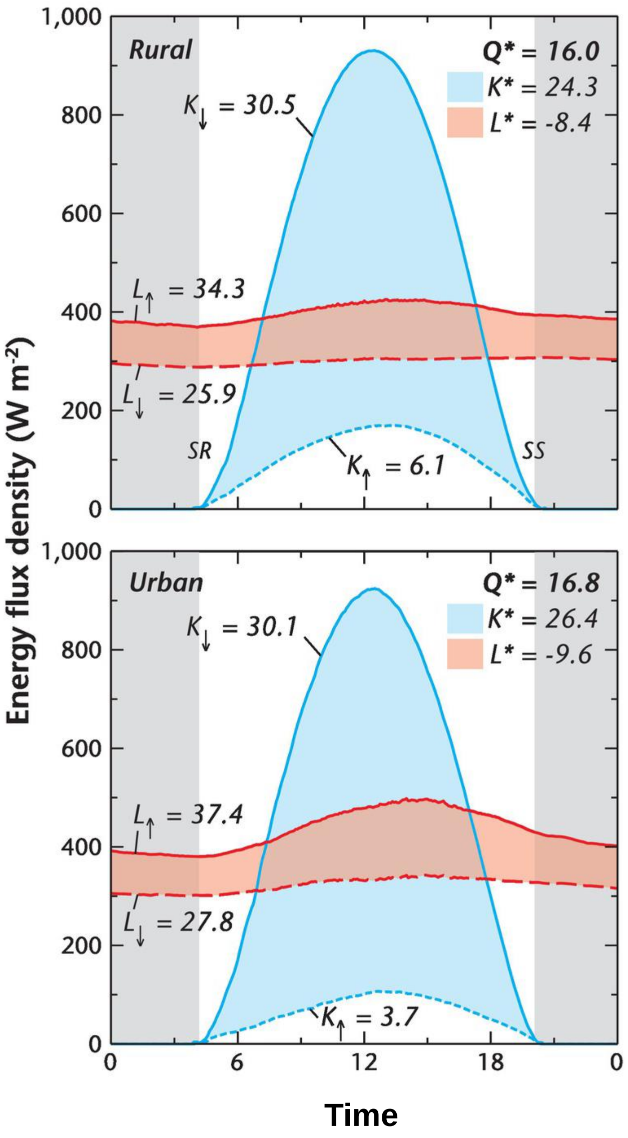
Energy balance

Urban–Rural Differences of Net Radiation

All terms comprising the surface radiation budget are altered by the surface and atmospheric changes introduced by urban development.

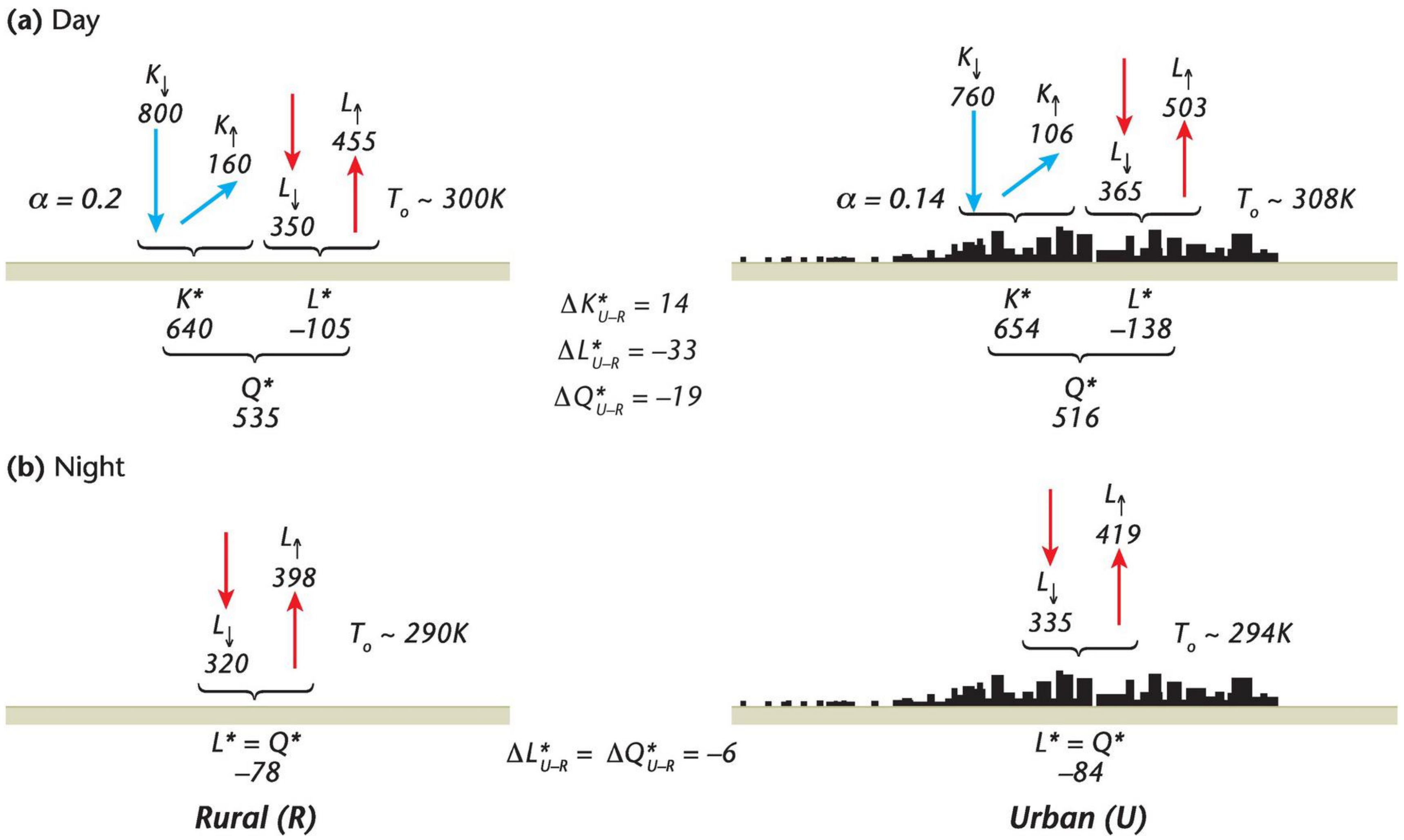
Modification of individual components of the radiation budget for a suburb of Vancouver, Canada, relative to a nearby rural area.

In clear conditions **K↓ in the urban area is depleted and L↓ is enhanced by the polluted and warmer UBL** in comparison to the rural area. The upwelling fluxes K↑ and L↑, which include the effects of the urban surface, are also altered: **K↑ is reduced due to the lower urban albedo** 0.12 compared to 0.2 in the rural area and **L↑ is usually enhanced in comparison with rural values because of the persistent warmth of the urban surface**



Oke et al. (2017)

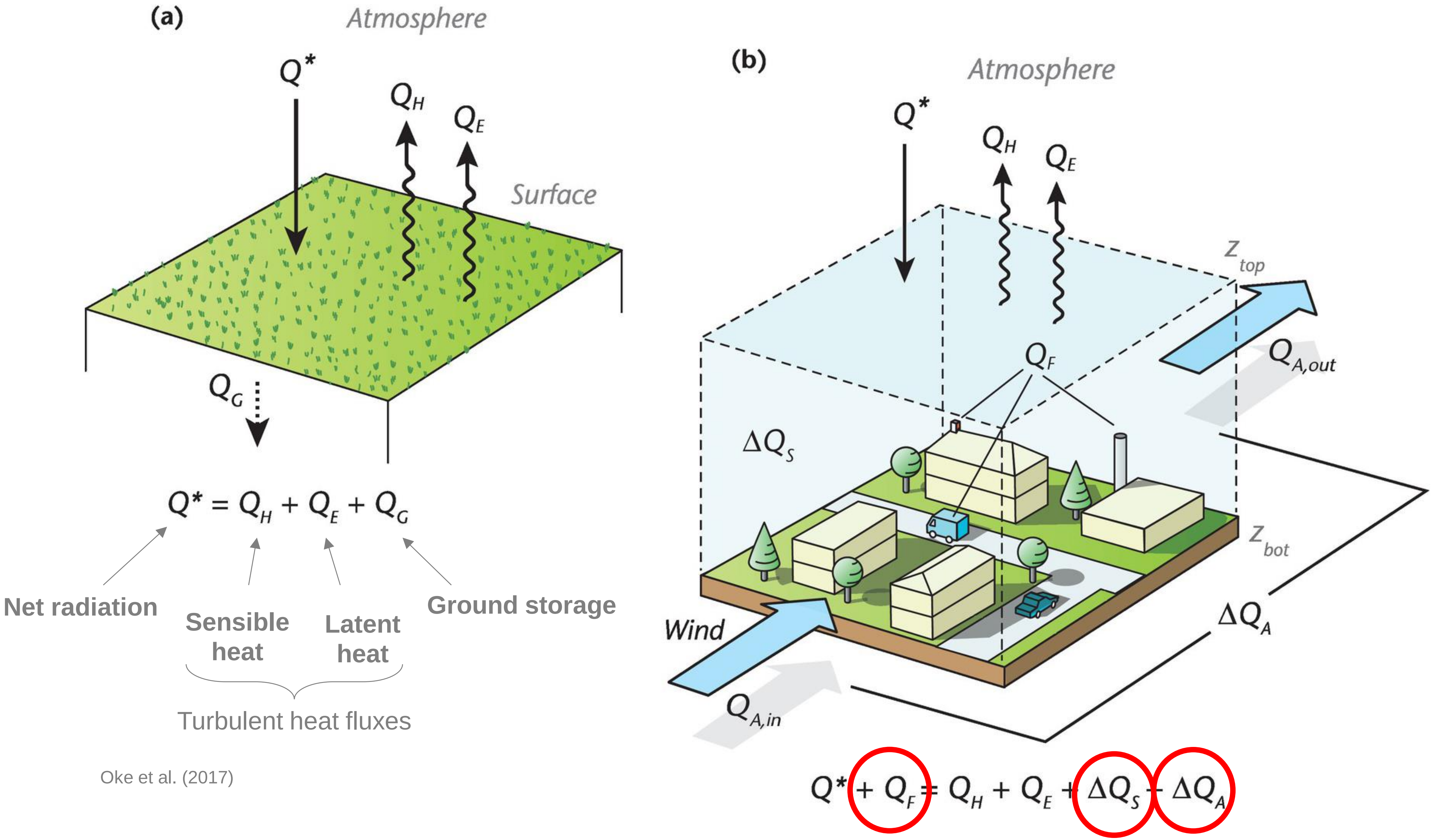
Energy balance



Schematic representation of surface radiation balances at typical urban and rural sites in the mid-latitude at (a) midday and (b) night on a cloudless day in summer

Oke et al. (2017)

Energy balance



Oke et al. (2017)

Energy balance

EPFL

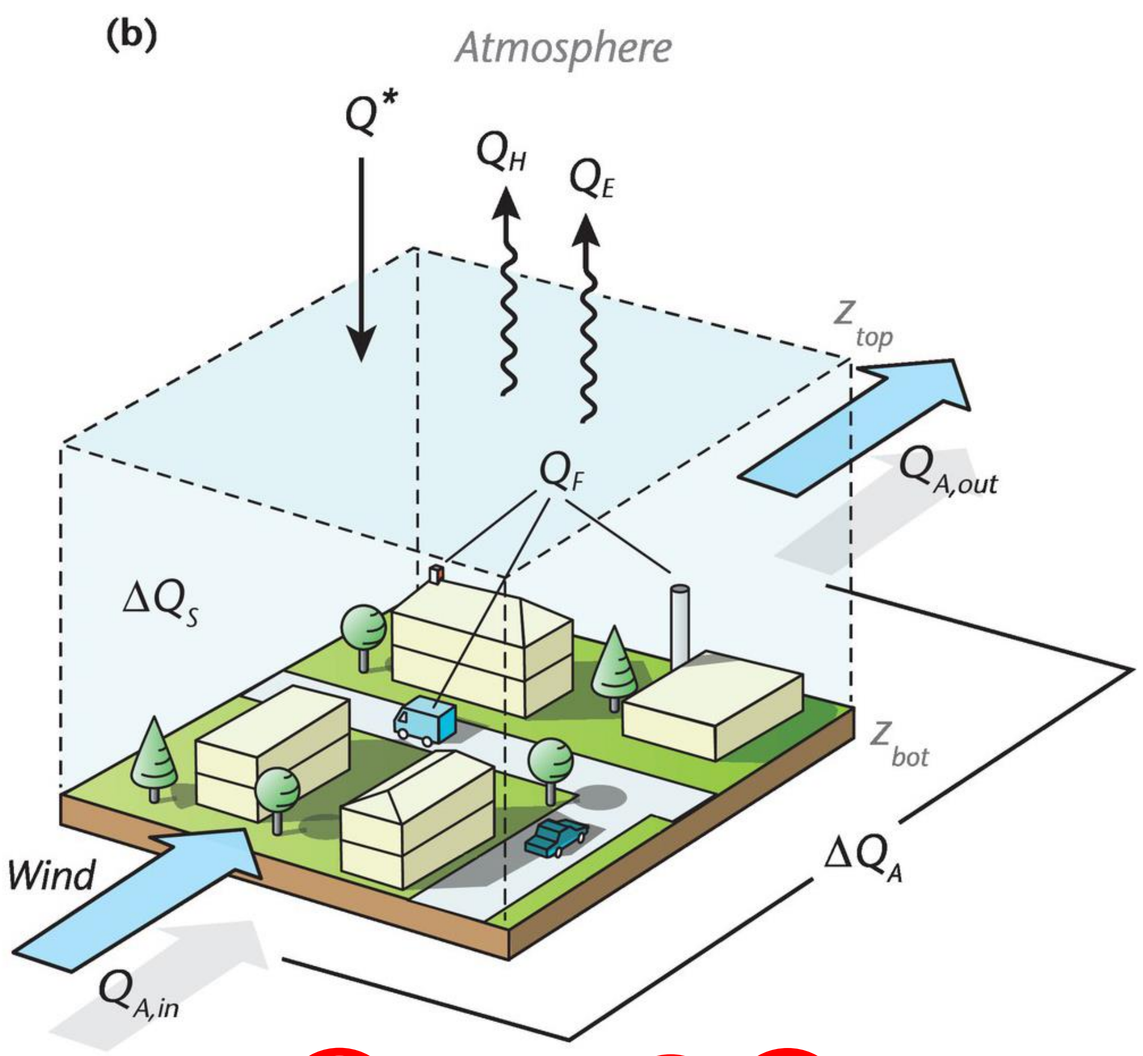
Energy Balance of Urban Systems

A 3-D treatment greatly complicates the formulation of energy conservation, but it can be made more tractable in practice by defining a conceptual volume, which integrates the entire urban ecosystem. Here the new terms are:

Anthropogenic heat flux (*Q_F*) is the heat released inside the volume due to human activities associated with living, work and travel

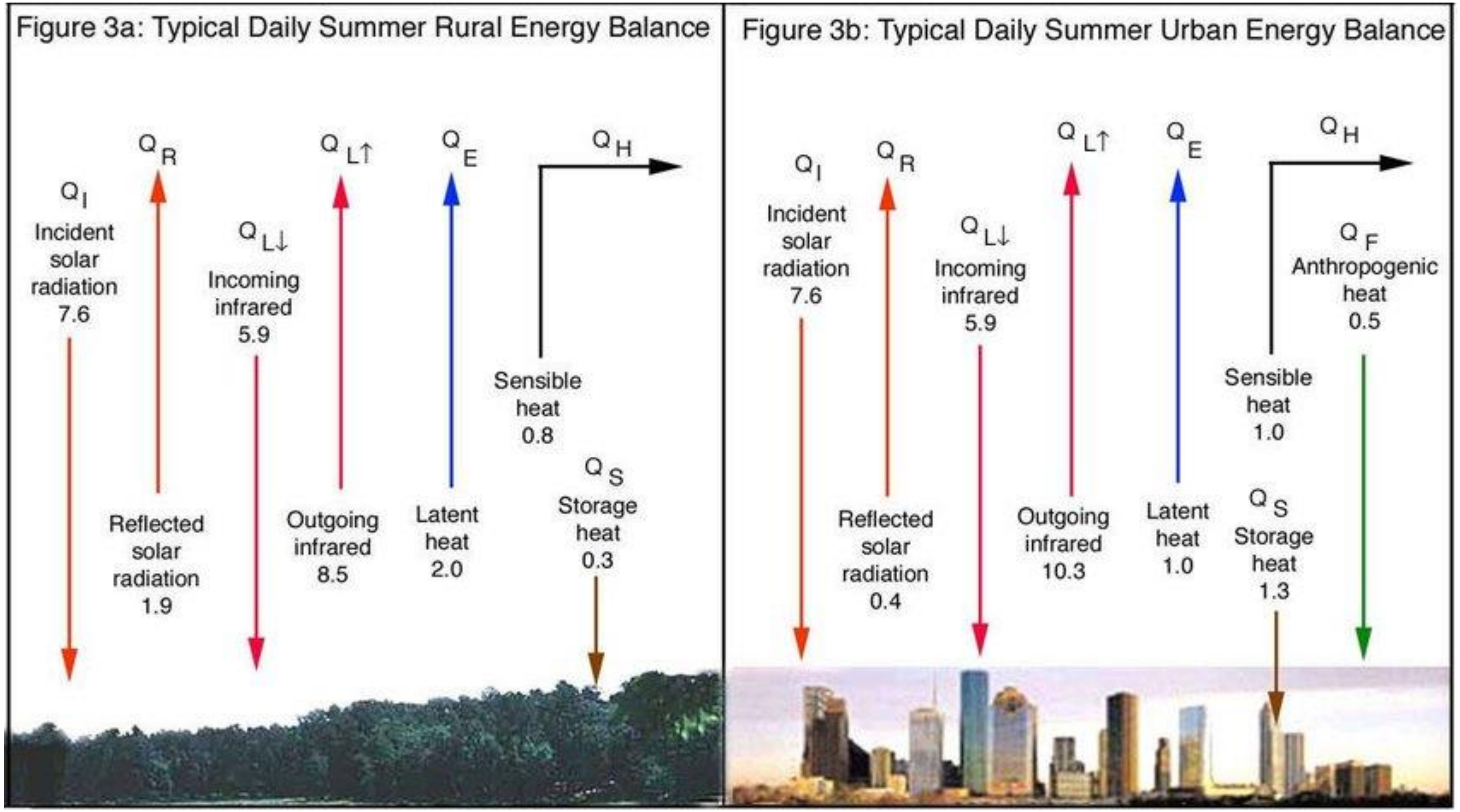
Heat storage (*ΔQ_S*) is the net heat storage change by all the fabric of the city including its construction materials, trees, ground and air contained in the volume

Advection flux (*ΔQ_A*) is the net energy added to, or subtracted from, the volume by windborne transport through any of the volume's sides (often neglected)



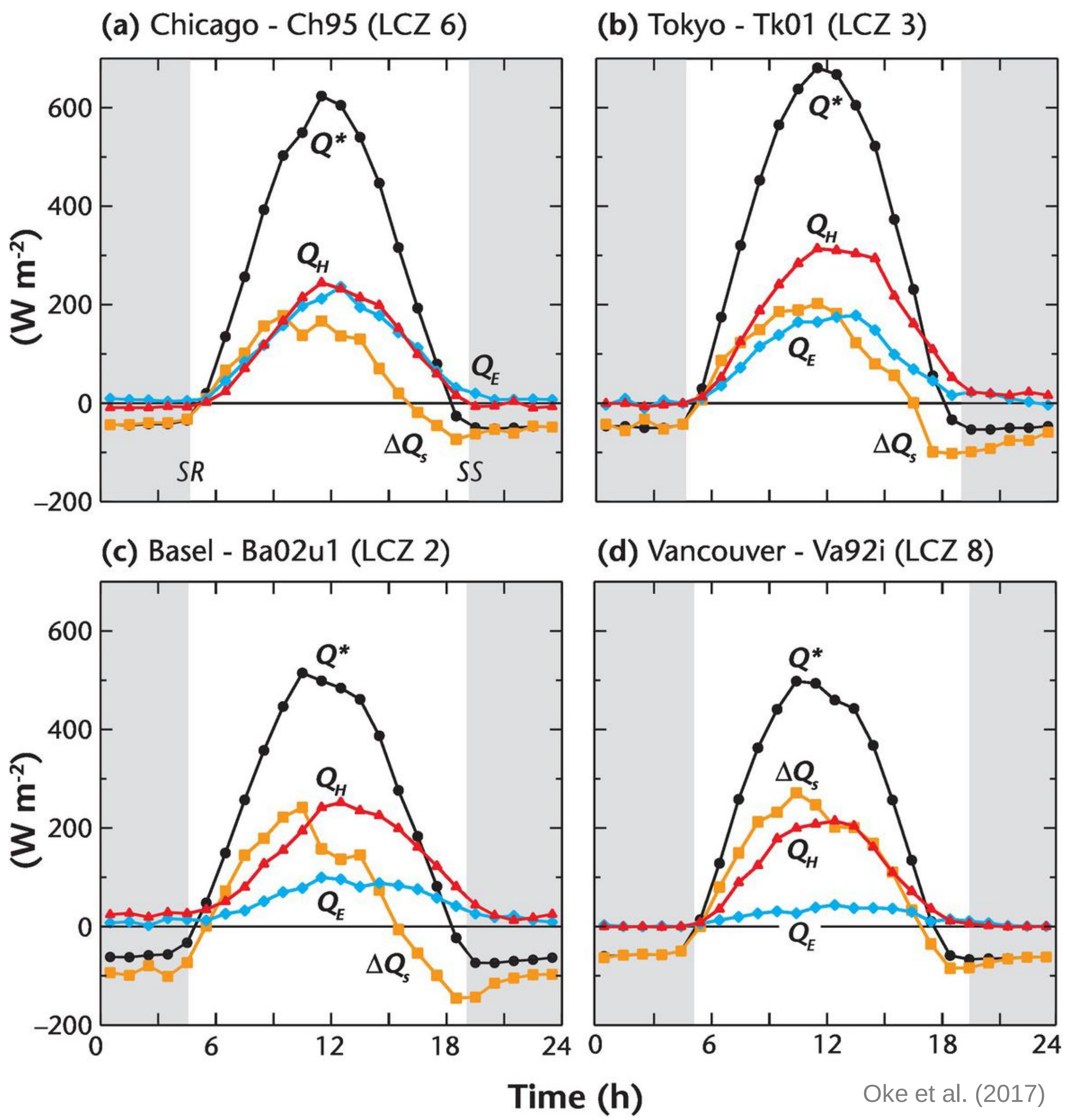
$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S - \Delta Q_A$$

Energy balance



A qualitative description of typical rural and urban surface energy balance processes. The values are in units of kWh m^2 day^{-1}. Figure courtesy of R. Sass, Rice University. Source: Shepherd 2005, https://doi.org/10.17226/13328.

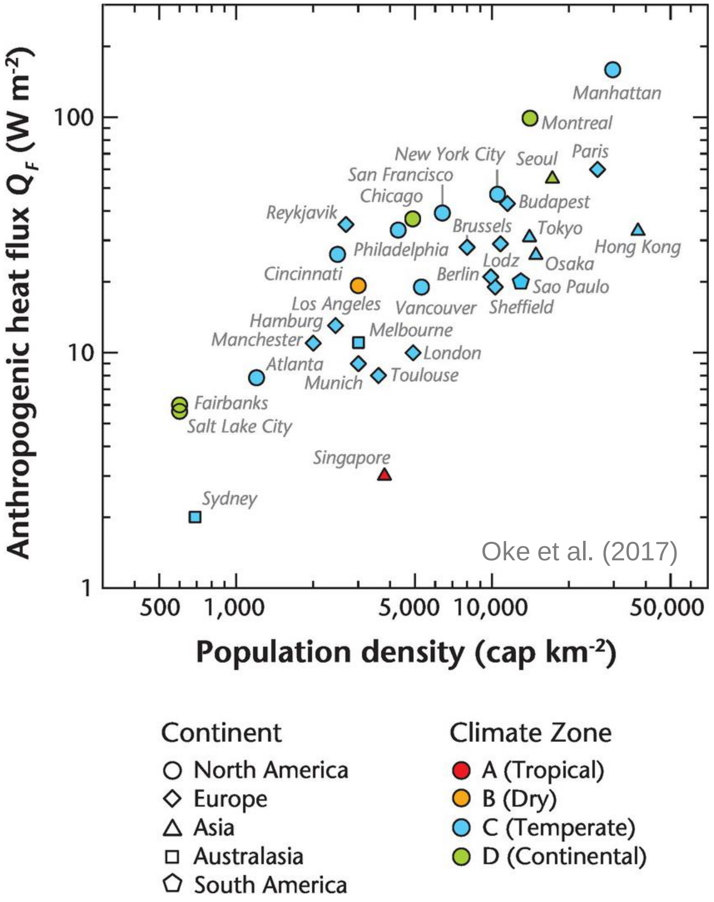
Energy balance



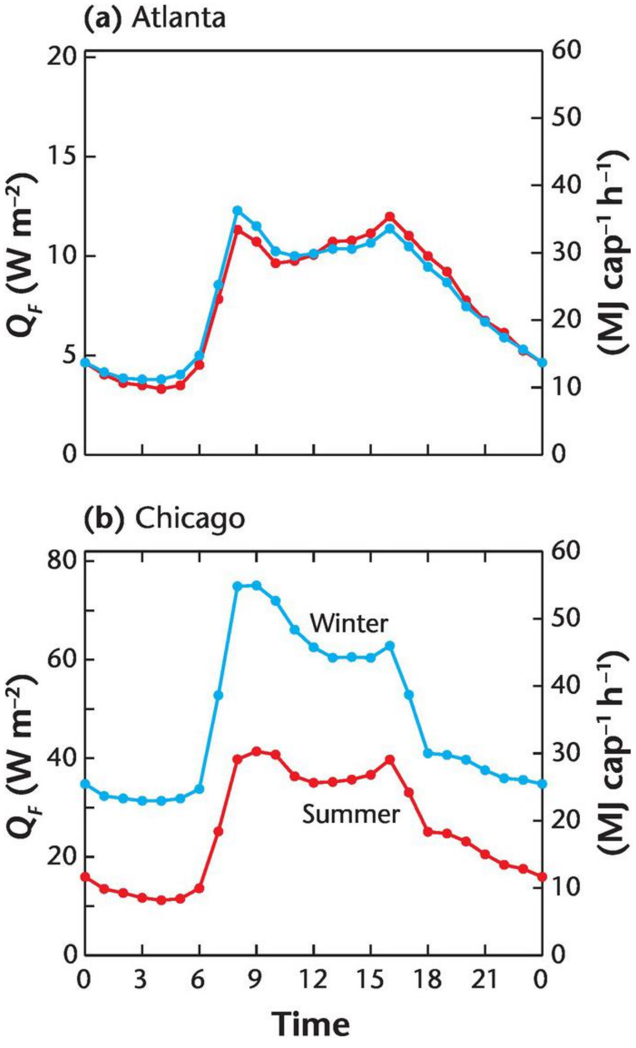
Oke et al. (2017)

Energy balance

Anthropogenic heat flux:



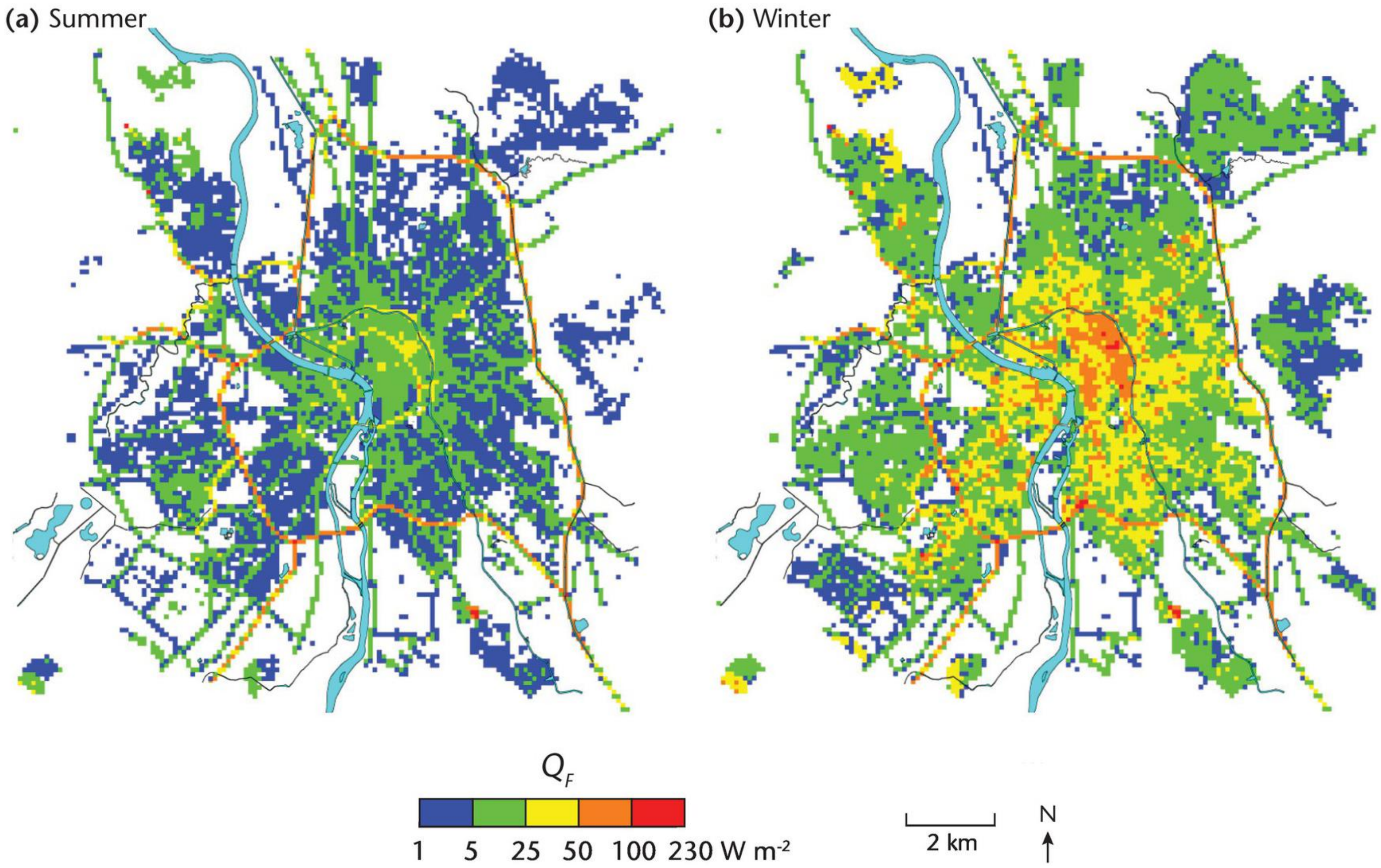
Relation between anthropogenic heat flux density Q_F and population density for cities.



Hourly variation of Q_F in **(a)** Atlanta and **(b)** Chicago, United States in both winter and summer.

Energy balance

Anthropogenic heat flux:



Spatial pattern of modeled anthropogenic heat flux density Q_F for Toulouse. Mean Q_F for **(a)** the summer months (June, July and August), and **(b)** for the winter months (December, January and February) of 2004

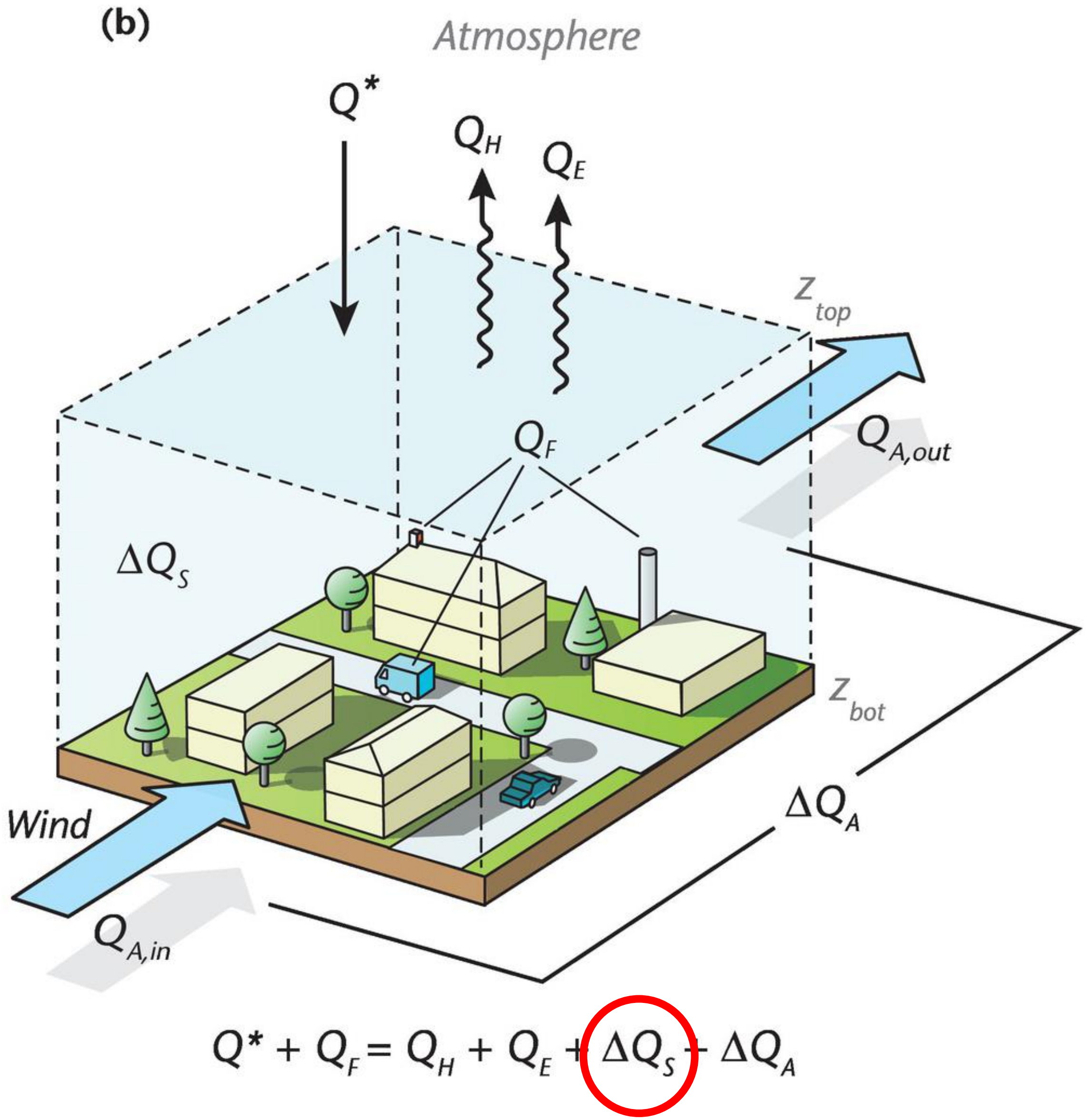
Oke et al. (2017)

Energy balance

Heat storage flux:

$$\Delta Q_S = \sum_{i=1}^{N} \Delta Q_{S,i} = \sum_{i=1}^{N} \frac{1}{A_i} \int_V \quad C_i \frac{dT}{dt} dV$$

where the index i identifies N surface types within the urban volume, A_i is the surface area of component i within the system, and the product $C_i(dT/dt)$ is the heat storage change in the urban fabric, which is integrated with respect to the urban volume – C_i is the heat capacity (J m^{-3} K^{-1}) of the i materials, dT/dt is the change in temperature over a given time period (K s^{-1}) and dV is the volume of the material involved (m^3).

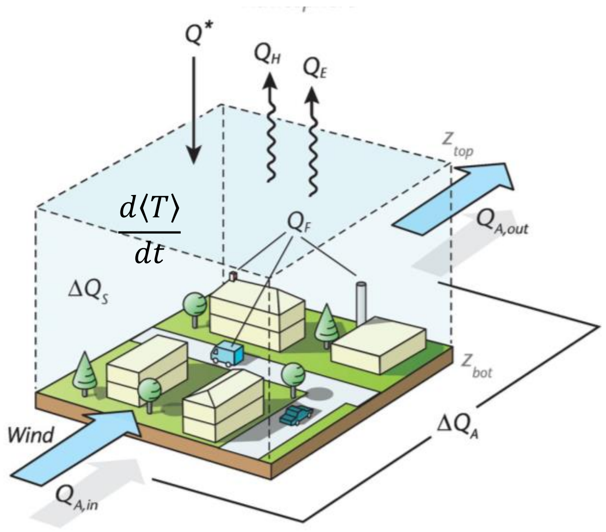


Energy balance

EPFL

Coarse-grained model

Assuming one "effective" temperature only, $\langle T \rangle$, and combining all the aforementioned equations, leads to the following SEB equation:



$$\frac{\textit{Change in internal energy storage}}{\textit{time interval}} = IN - OUT$$

$$C\frac{d\langle T \rangle}{dt} = (K_{\downarrow} - K_{\uparrow}) + (L_{\downarrow} - L_{\uparrow}) + Q_F - \rho C_p \frac{(\langle T \rangle - T_a)}{r_a} - L_v \cdot E - Q_G + \Delta Q_A$$

Radiation budget; Anthropogenic heat flux; Sensible heat flux; Latent heat flux; Ground heat flux; Advection flux

Energy balance

Surface temperatures

Every surface possesses a unique SEB for which there is a single temperature at its interface with the air — the surface temperature T_S that satisfies its combination of radiative, conductive and turbulent fluxes. This temperature is the common boundary in the temperature gradients that generate a sensible heat flux density (Q_H) upwards into the atmosphere, and similarly conducts a sensible heat flux downward into the substrate (Q_G). The SEB for a surface, with thickness z and heat capacity C_s is:

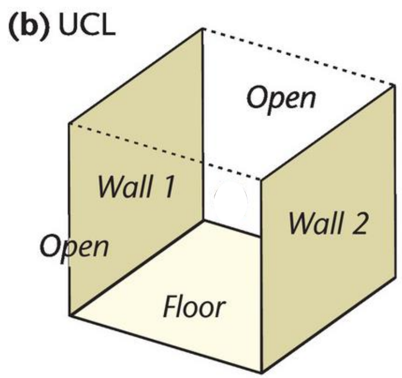
$$C_s \frac{dT_s}{dt} z = Q^* - \rho C_p \frac{(T_s - T_a)}{r_a} - L_v \cdot E - Q_G$$

Net radiation

Sensible Heat flux

Latent Heat flux

“Ground” heat flux
(sensible heat into the substrate)



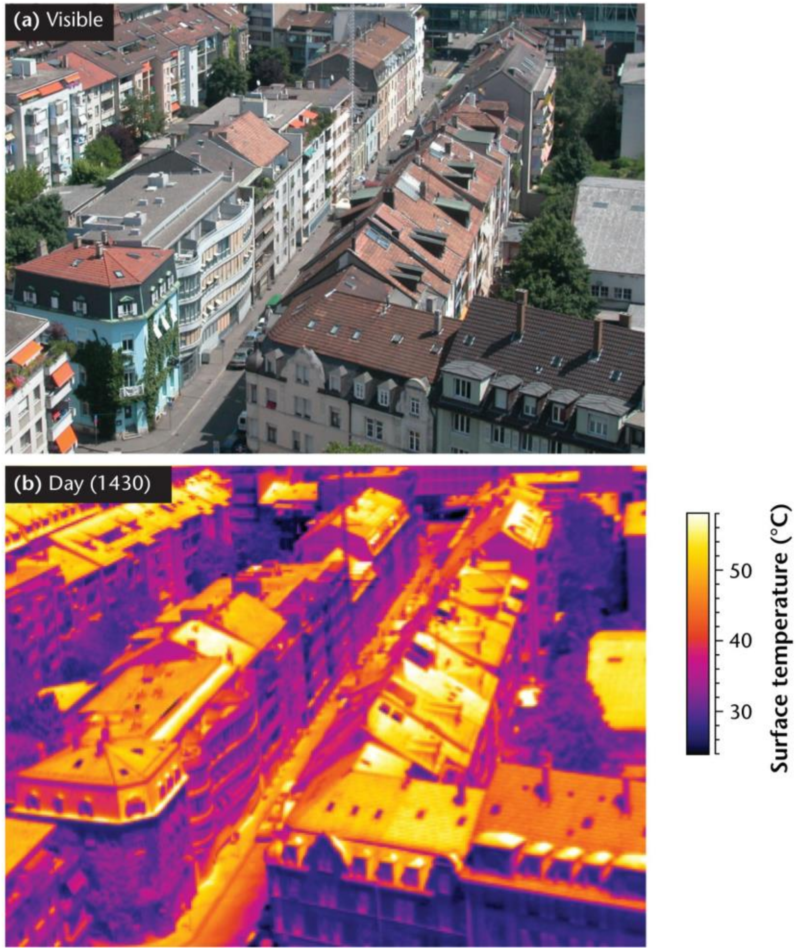
Energy balance

Surface temperatures

Five surface properties exert particularly strong control on T_s:

- **Geometric** (which influence shading and radiation trapping)
- **Radiative** (albedo,emissvity)
- **Thermal** (thermal conductivity and heat capacity (C) (Section 6.3.1) govern the ability to conduct and diffuse heat into/out of the substrate material
- **Moisture** (he availability of water for evaporation and transpiration by plants provides a mechanism for heat loss by latent heat flux)
- **Aerodynamic** (aerodynamic resistance r_a regulates the turbulent fluxes as regulated by surface roughness and wind speed)

Oke et al. (2017)



Photograph of Sperrstrasse canyon in Basel, Switzerland and adjacent courtyards and (b) thermal image of same canyon

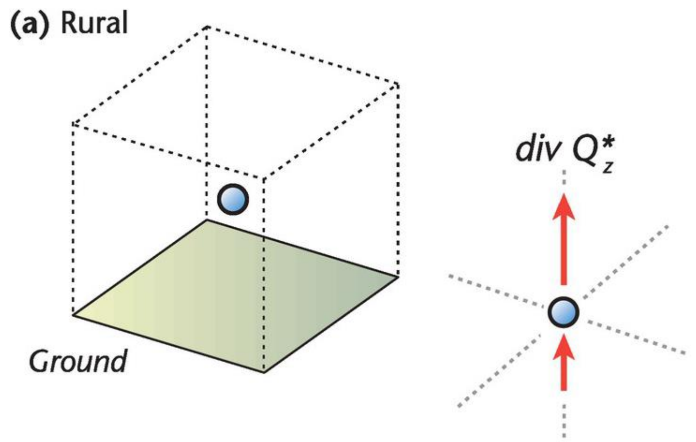
Energy balance

Air temperatures (1D case)

The warming or cooling of an air layer or volume is explained by the EB of a layer or volume of air. Energy exchanges in the volume or layer can occur via radiation, conduction and convection.

For the simple case of a near-surface air layer over a spatially extensive, flat and relatively homogeneous rural surface where there are no net heat transfers in the horizontal plane we only need to consider vertical fluxes for different layers (Figure 7.6a). Convection is the main transport process, but unless fog is actively forming (releasing latent heat) only QH is relevant for changing Ta. It is the change in QH with height not its absolute strength that controls temperature changes in an air layer. An atmospheric layer can also both absorb and emit radiation, leading to:

$$C_a \frac{\partial T_a}{\partial t} = \frac{\partial Q^*}{\partial z} + \frac{\partial Q_H}{\partial z} + Q_F$$

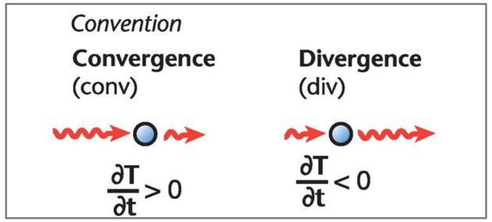


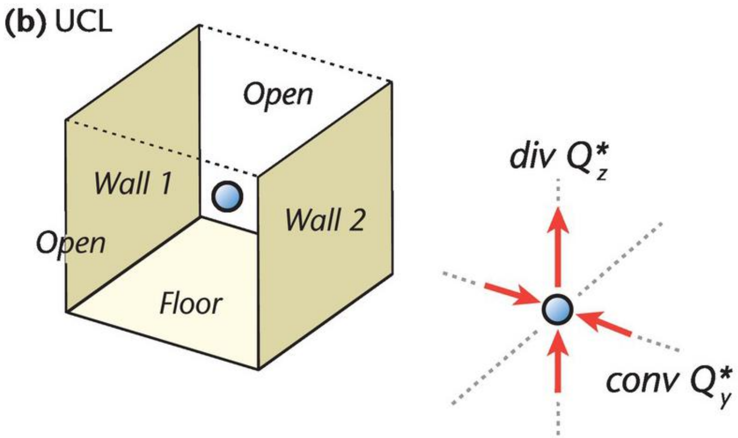
Energy balance

Air temperatures (3D case)

In the surface layer an air volume is often horizontally constrained by surrounding surfaces that participate in surface-air exchange. Thus, we must consider a volume not just a layer. For example, in the UCL, building walls bound the air volume of an urban canyon. Expanding the previous equation to represent a volume, retaining the assumption that no phase changes of water are occurring, and adding the effect of advection by the mean wind in the x-direction, we can write

$$C_a \frac{\partial T_a}{\partial t} = div(Q^*) + div(Q_H) + \bar{u}\frac{\partial \overline{T_a}}{\partial x} + Q_F$$

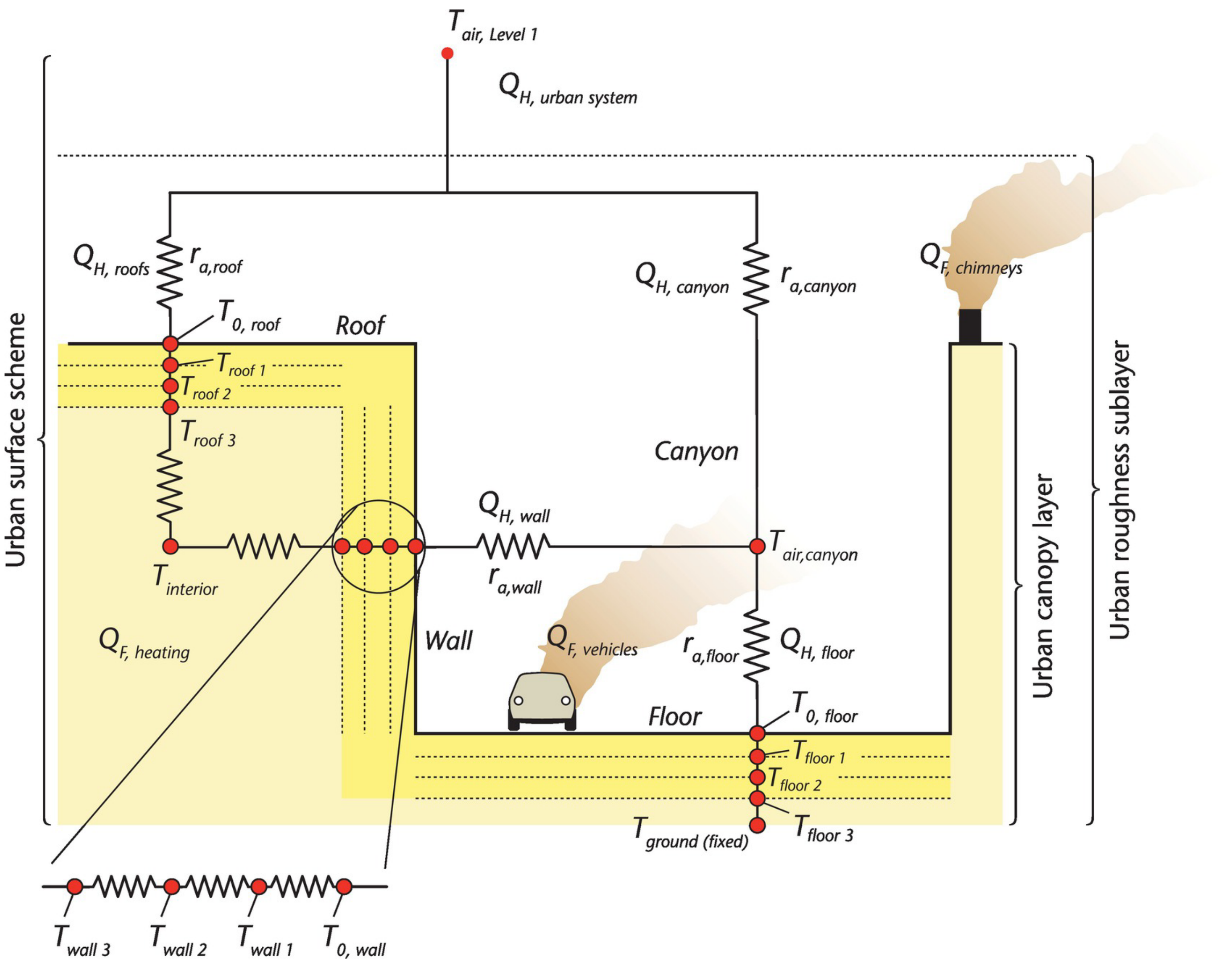




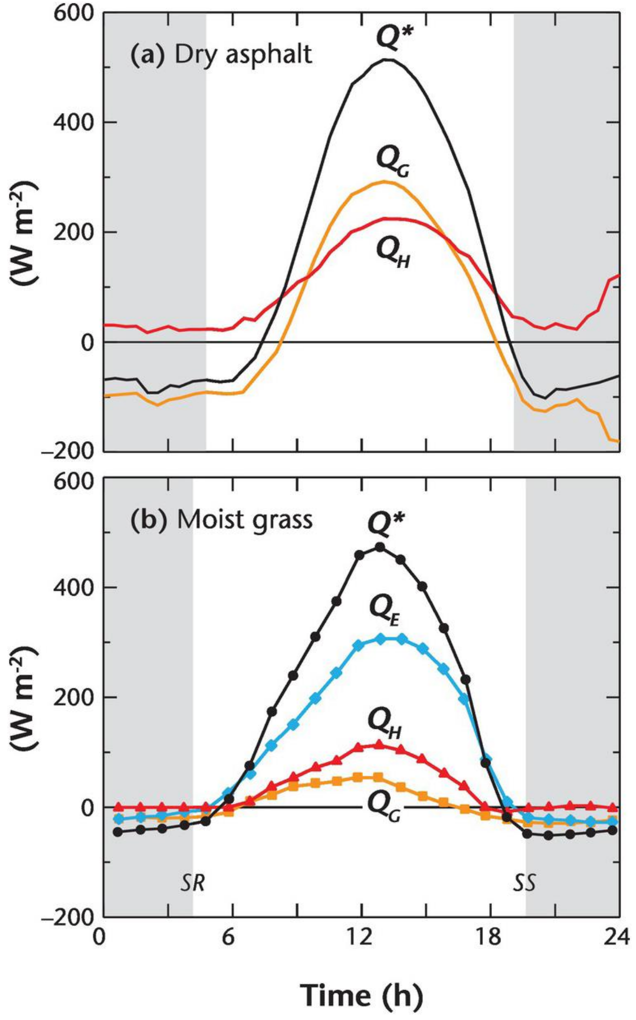
Energy balance

Numerical Simulation

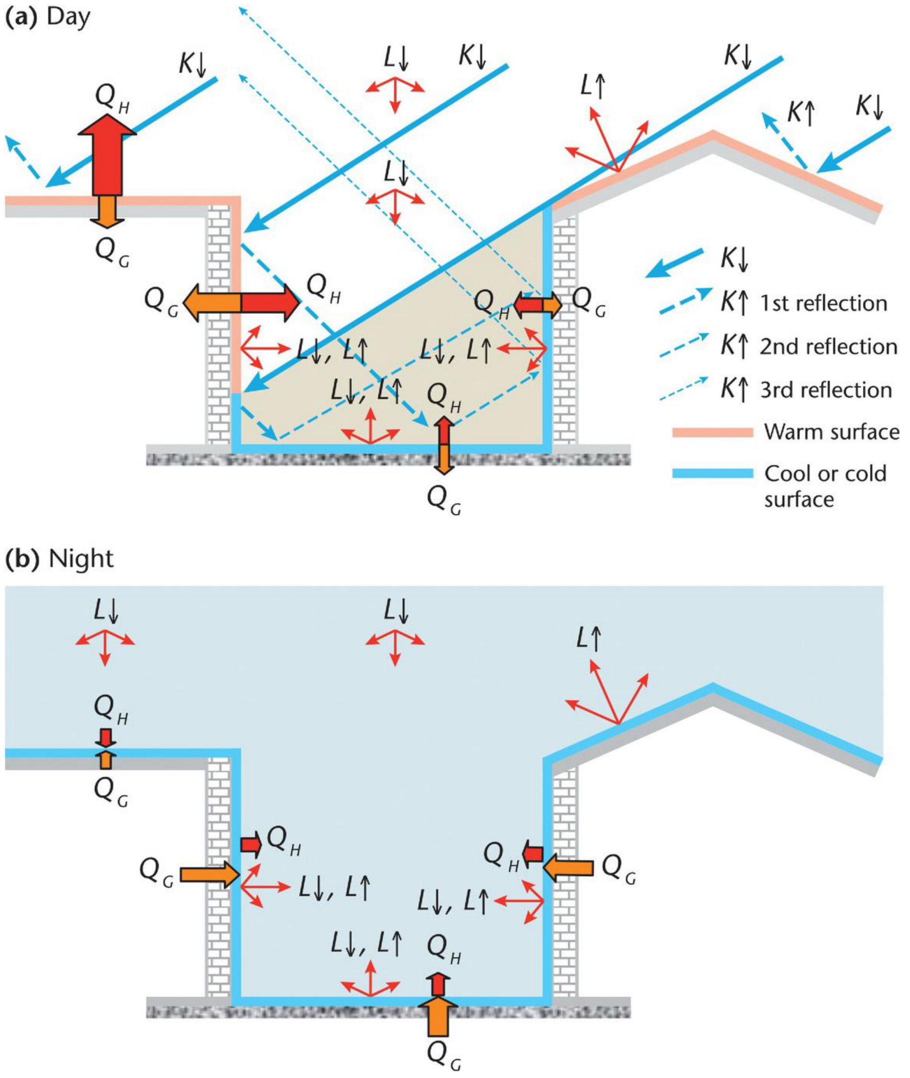
Whilst heat conduction through a single material is relatively simple, that involved in heat loss and gain to and from the interior of heated or cooled buildings, and the ambient environment is relatively complex. Urban climate models (UCM) and Building Energy Models (BEM) are able to numerically solve differential equations for heat conduction in the different facets of an urban canopy and link them to the SEB of the facet and temperature changes.



Energy balance



Example SEBs of unobstructed urban facets: (a) dry asphalt and (b) slightly moist grassed site.



Schematic depiction of the main energy exchange fluxes comprising the SEB of roof and urban canyon facets (a) by day and (b) at night.

Urban climate

EPFL

Optional readings

- Constructed Climates (Online course)
- Vertical structure of conventionally neutral atmospheric boundary layers
- In what conditions an urban heat island can initiate deep convection?
- Magnitude of urban heat islands largely explained by climate and population

Note: for scientific article, access from EPFL or with VPN