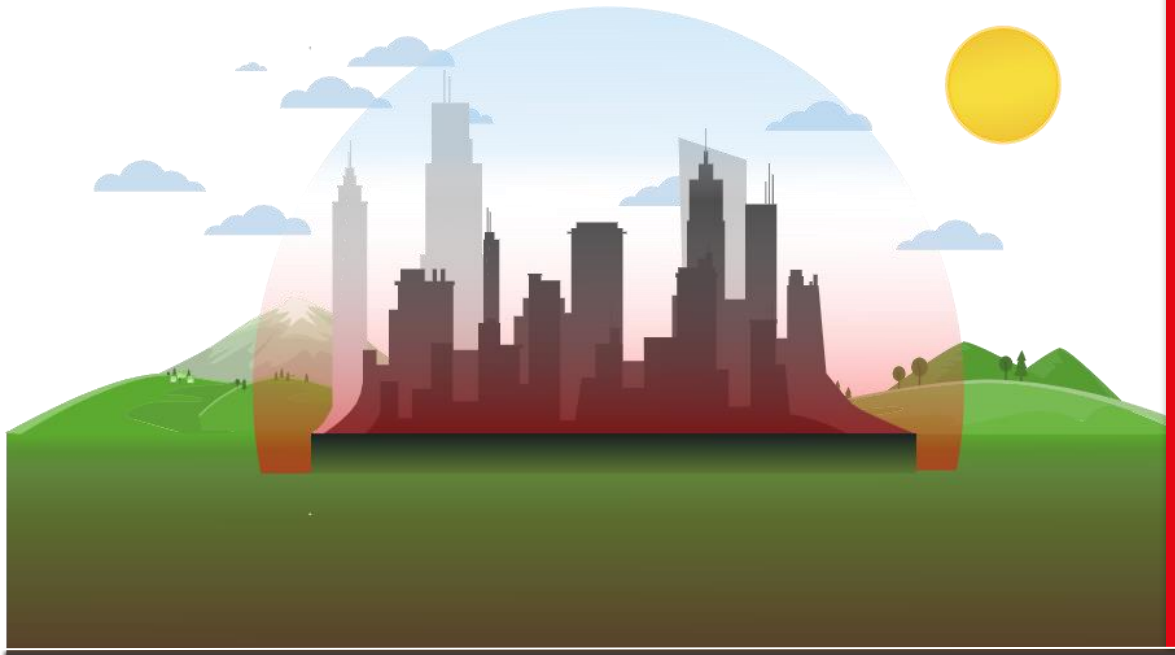
CIVIL-309: URBAN THERMODYNAMICS

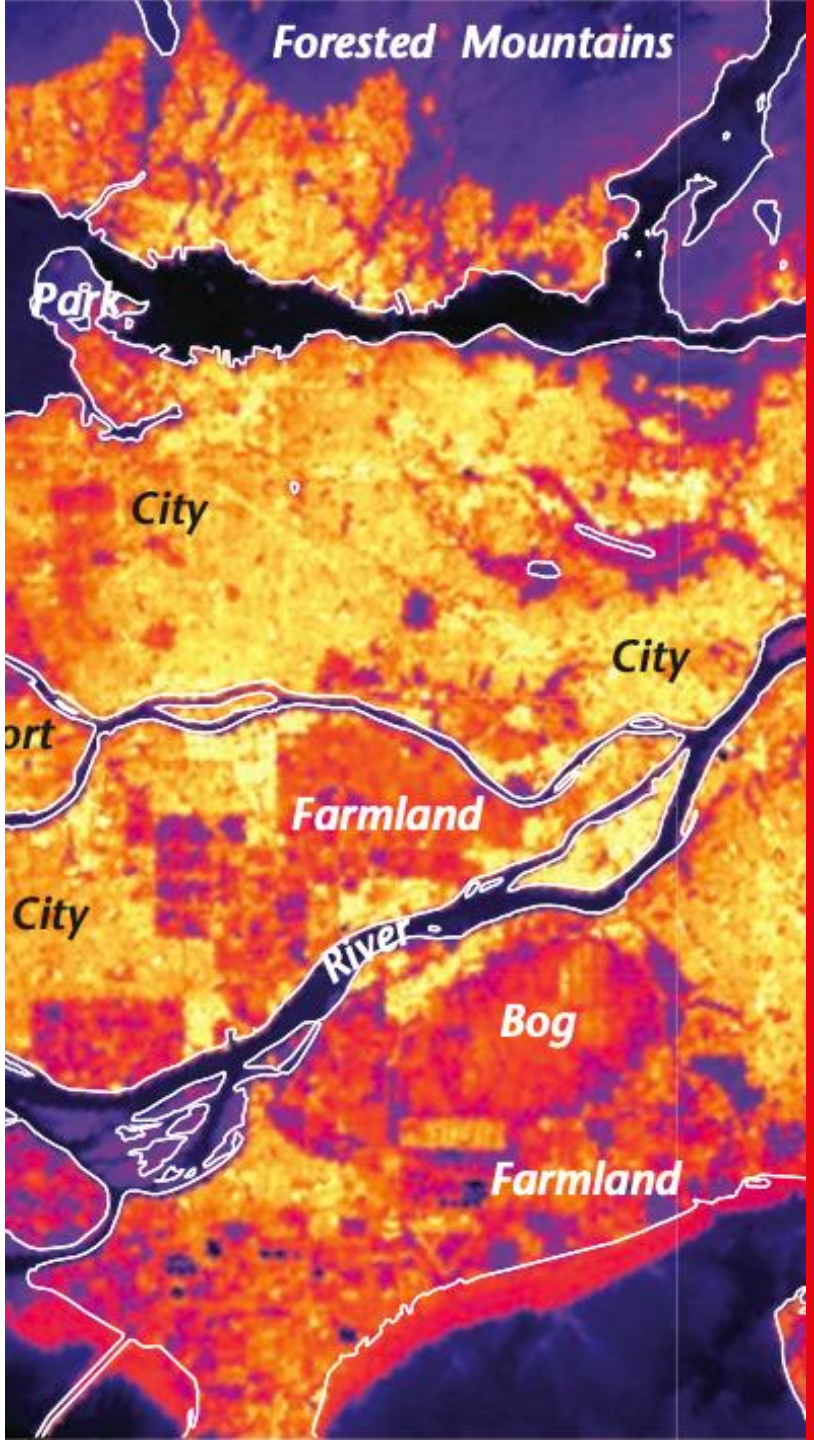
Assist. Prof.
Dolaana Khovalyg



Lecture 01:

Course overview.
Urban characteristics and the UHI effect.

12 September 2025



CONTENT:

I. Introduction to the course

- Content, schedule, grading

II. Urban characteristics

- Intro to the built environment in cities
- Overview of properties
- Local climate zones (LCZ)
- Street canyon aspect ratio (λ_s)
- Sky view factor (ψ_{sky})

III. Urban Heat Island (UHI) effect

- Energy balance for cities, anthropogenic heat
- UHI definition, types, magnitude, dynamics

Course Information: People

- **Dolaana KHOVALYG, Assist. Professor**

  dolaana.khovalyg@epfl.ch

  Head of the **Laboratory of Integrated Comfort Engineering (ICE)**

  Lab website: https://www.epfl.ch/labs/ice/

  Research focus: energy in buildings, building physics, indoor and outdoor human comfort, urban and human heat transfer

  Teaching activities: CIVIL-309 "*Urban Thermodynamics*", CIVIL-407 "*Energy and Comfort in Buildings*", CIVIL-450 "*Thermodynamics of Comfort in Buildings*"

- **Jaafar YOUNES, Postdoctoral Researcher**

  jaafar.younes@epfl.ch

  Research focus: Indoor and outdoor thermal comfort, thermophysiology modeling, heat and mass transfer at human and urban scale, data-driven modeling

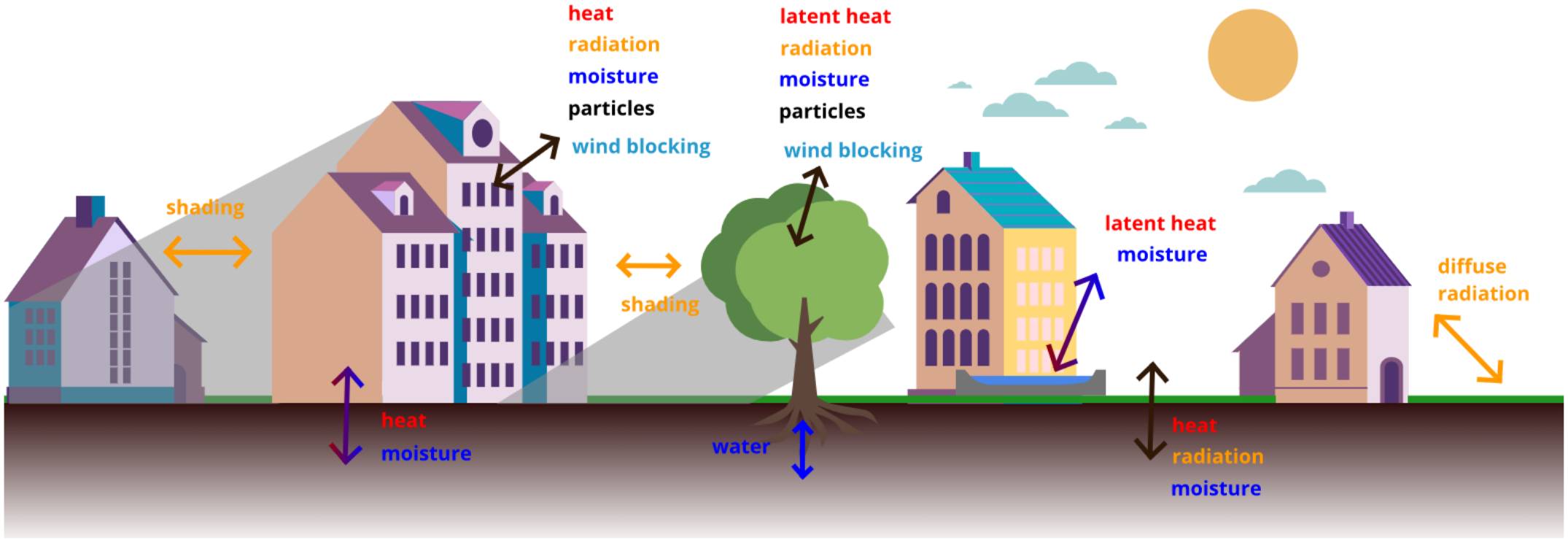
  Teaching activities: CIVIL-309 "*Urban Thermodynamics*"

Course Information

- **Contact hours:**
  - Fridays **13:15-16:00**, room **CH B3 30**
- **Expected student activities:**
  - Attend lectures, participate in discussions, engage with the webtool, data analysis, group work, and writing project reports
- **Course materials:**
  - Lecture slides – posted on Moodle weekly
  - Course projects – assigned on **Week 2** and **Week 8**
  - Webtool: https://citytherm.epfl.ch/ (part II will be developed by Week 8)
- **Grading:**
  - **Course project I (50%)**, individual assignment
  - **Course project II (50%)**, group assignment
    - Formation of groups: **4 persons per group by Week 8** (self-formation by finding people that you want to work with), **only 1 group with 3 people is allowed**
- **Questions:** post on the Moodle Forum for shared answers, or contact us via email or during class breaks

Course Objectives

- Learn **the effect of urban elements** on **urban climate** and **outdoor comfort,** analysis of **urban neighborhoods** from a **thermodynamics perspective**
- Identify **the magnitude of heat exchange** and **type of the exchange** between **different urban elements** such as **buildings**, **vegetation**, **water bodies**, **ground**, and the **surrounding environment**
- Intro to the **Urban Heat Island (UHI) effect** in **cities** and **mitigation strategies,** raise **awareness** of **climate-sensitive urban design**



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Course Schedule

Week	Date	Time	Topics	Instructor
1	12.09	2 x 45’	**Course overview:** content, evaluation, topics **Urban characteristics, Urban Heat Island (UHI) effect**	DK
		1 x 45’	Introduction to the web tool **CityTherm** (part I)	DK
2	19.09	1 x 45’	**Overview of physical parameters**	DK
		1 x 45’	**Introduction to the course project I**	DK, JY
		1 x 45’	Supervised work on the course project I	JY
3	26.09	2 x 45’	**Heat Transfer: Conduction and radiation**	DK
		1 x 45’	Supervised work on the course project I	JY
4	03.10	2 x 45’	**Heat Transfer: Convection and evaporation**	DK
		1 x 45’	Supervised work on the course project I	JY
5	10.10	1 x 45’	**Campus walk:** exploring urban thermodynamics	DK, JY
		2 x 45’	Supervised work on the course project I	JY
6	17.10	3 x 45’	Supervised work on the course project I **Course project I submission deadline: 16:00 on October 17**	JY
7	24.10		**BREAK**	

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Course Schedule

Week	Date	Time	Topics	Instructor
8	31.10	1 x 45'	**Urban modeling and computational tools**	JY
		1 x 45'	Introduction to the web tool **CityTherm** (part II)	JY
		1 x 45'	**Introduction to the course project II**	JY
9	07.11	2 x 45'	**Building-environment interaction:** thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
10	14.11	2 x 45'	**Ground-environment interaction:** ground properties, thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
11	21.11	2 x 45'	**Water body - environment interaction**: thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
12	28.11	2 x 45'	**Vegetation – environment interaction:** characteristics of vegetation, evapotranspiration, aero- and thermal interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
13	05.12	2 x 45'	**Human Outdoor Comfort:** Parameters affecting human comfort and comfort indices (UTCI, PET)	JY
		1 x 45'	**Supervised group work - course project II**	JY
14	12.12	1 x 45'	**Climate-Sensitive Urban Design**: complex interaction of all urban elements and their effect on UHI and outdoor comfort	DK
		2 x 45'	**Supervised group work - course project II**	JY
15	19.12	3 x 45'	Supervised group work on the course project II **Course project II submission deadline: 16:00 on December 19**	DK, JY

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Course Information: Main References

- T.R. Oke, G.Mills, A. Christensen, J.A. Vooght, **Urban Climates**, Cambridge University Press
  - *ebook (PDF file) is available here, 3 printed copies are available in the library*
- S. Medved, **Building Physics: Heat, Ventilation, Moisture, Light, Sound, Fire, and Urban Microclimate**, Springer
  - *ebook (PDF file) is available here, 1 printed copy is available in the library*
- A. Rodrigues, R.A. Sardinha, G. Pita, **Fundamental Principles of Environmental Physics**, Springer
  - *ebook (PDF file) is available here, no printed copy is available in the library*
- N. Mason, P. Hughes, **Introduction to Environmental Physics: Planet Earth, Life and Climate,** Taylor & Francis
  - *ebook (PDF file) is available here, 1 printed copy is available in the library*

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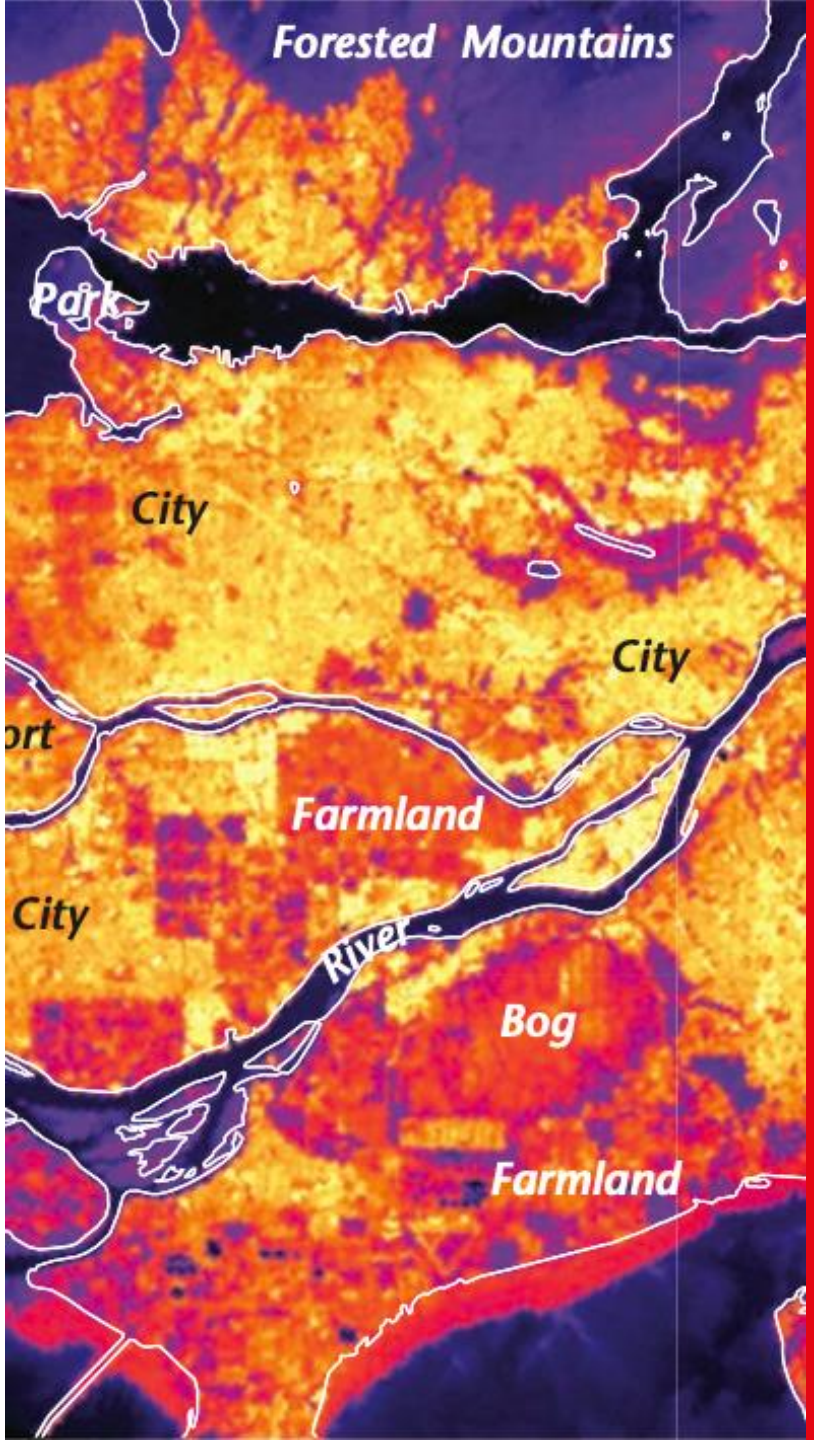

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Introduction: Cities

- **0.5%** of the *world surface* is covered by **urban areas**. In *Europe*, it is **4.4%** of the land that is covered **by built-up areas** (around twice the surface of Portugal).
- More than half of the **world's population** lives in urban areas (**56%**). In *Europe*, it is **75%** of the population.
- *Rapid* **urbanization**: by 2050, urban population is expected to double and 7 of 10 people in the world will live in cities. Urban land growth is expected to *at least double*.
- Major **challenges** emerges from the *speed* and *scale* of *urbanization*:
  - Ecological (climate, resources, biodiversity, etc.)
  - Social (housing, transport, basic services, jobs, etc.)
- Cities use $2/3$ of **global energy use** and account for more than **70%** of **greenhouse gas emissions**.

Cities inhabitants, January 2017:

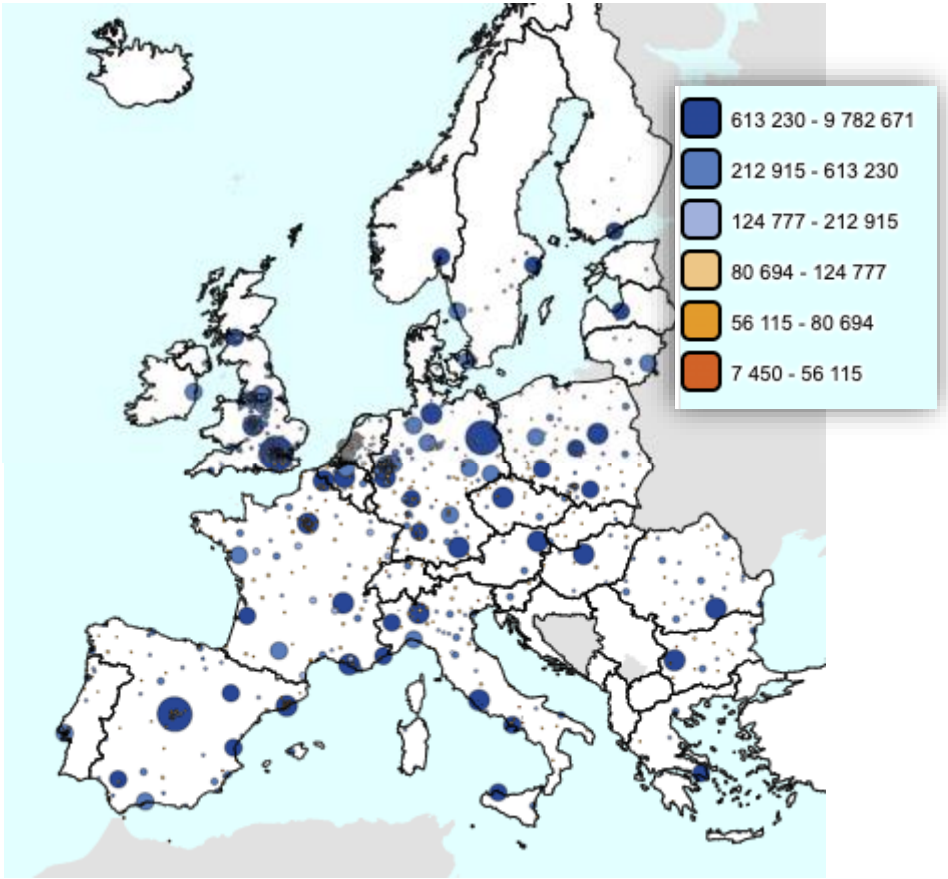

Image from websource

Introduction: Cities

Question: What are the **distinct features** of **the built environment** in **cities**?

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What are the distinct features of the built environment in cities?

Connect to
responseware.eu
Session ID: **civil309**

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URBAN DESIGN MANAGEMENT
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HIGH POPULATION DENSITY
NEIGHBORHOODS
SKYSCRAPERS VS SMALLER BUILDINGS
ARCHITECTURE
TIGHT
BUILDINGS
URBANISATION
BUILDINGS HEIGHT
DENSITY
POLLUTION
TREES
BULDINGS HEIGHT
HIGH-RISES
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MATERIAL, FUNCTIONALITY, AREA, SIZE, H...
THE HEIGHT OF BUILDINGS, THE DENSITY
HEIGHT OF BUILDINGS
LAUSANNE LOOKS MORE DENSE WHILE IN CHI...

Introduction: Built and Natural environment interaction

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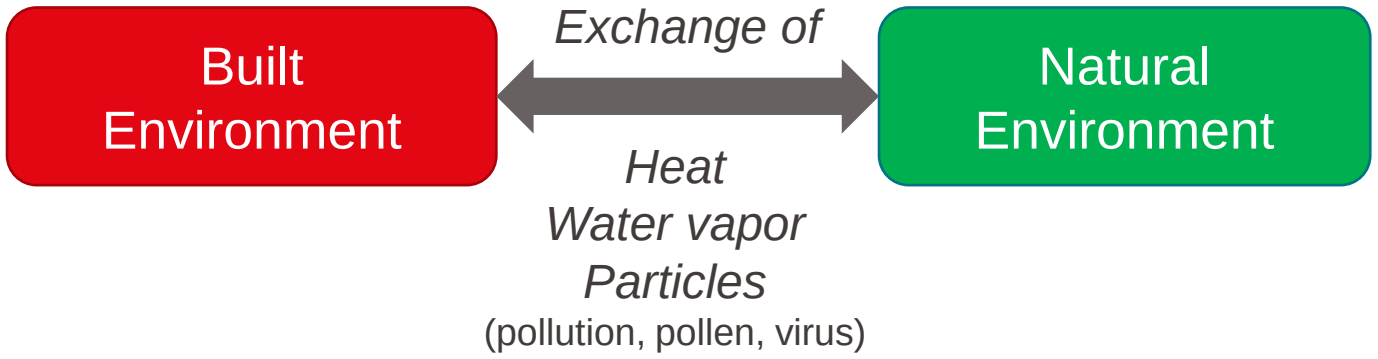
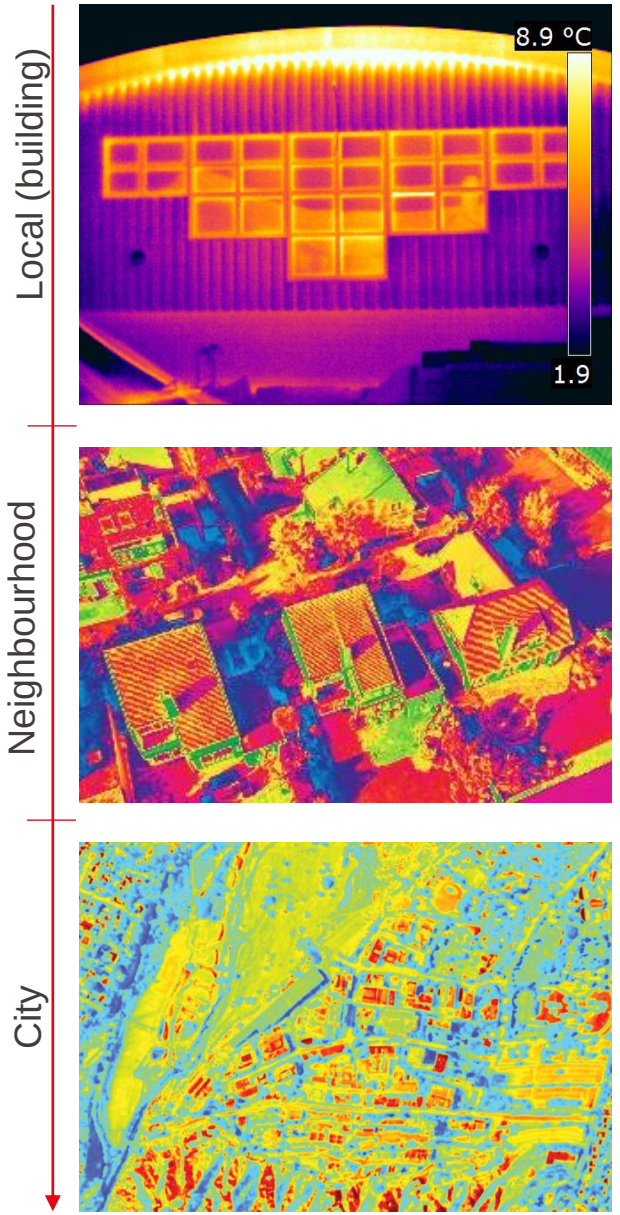
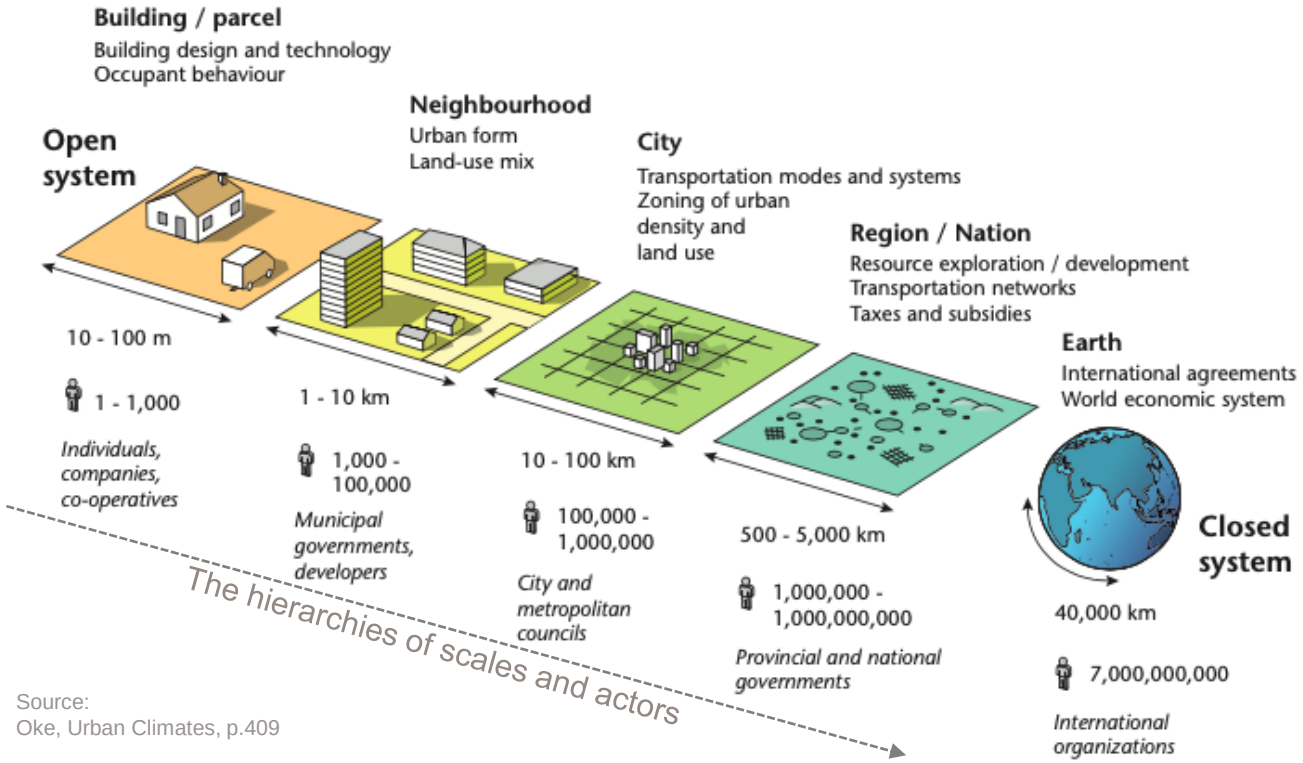
- The **city environment** and **its microclimate** difers from the rural environment (area surrounding cities):
  - *Accumulation* of solar energy that *form heat islands*
  - *Decrease* of the local wind speed
  - *Decrease* solar irradiation and hours of sunshine due to *pollution*
  - Faster water run-off due to more impermeable surfaces
- The **wind spreads** *these urban effects* to the *countryside*
- **Importance of the scales** (local, regional, global): these urban effects *do not occur the same way* at *different scales*.





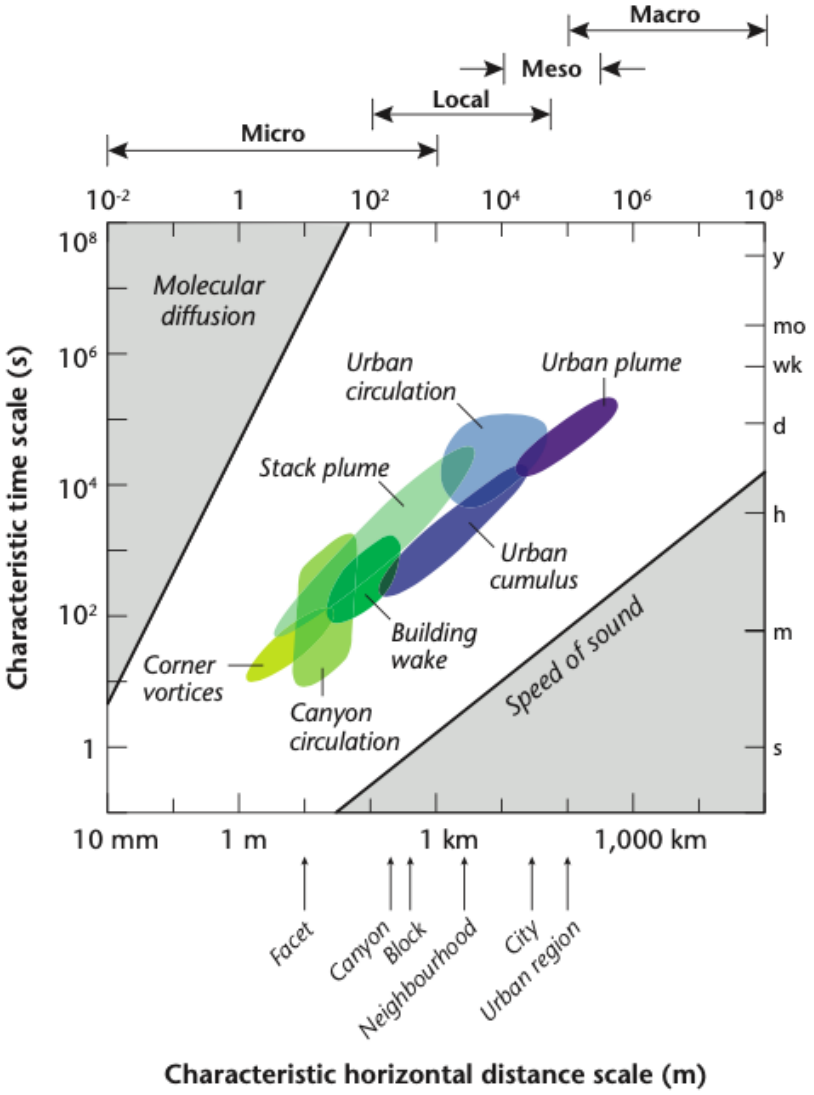
Urban characteristics: Urban scales

- Each **space scale** faces *different physical phenomena* of *different times scales*. Space and time scale are correlated.
- Each **climate feature** *combines to form larger ones* **up to the scale** *of the whole urban boundary layer*.
- Each space scale is linked to **different urban objects** and **different actors**.



Source:
Oke, Urban Climates, p.409

Time and horizontal space scales of selected urban dynamics and wind phenomena:



Source: Oke, Urban Climates, p. 29

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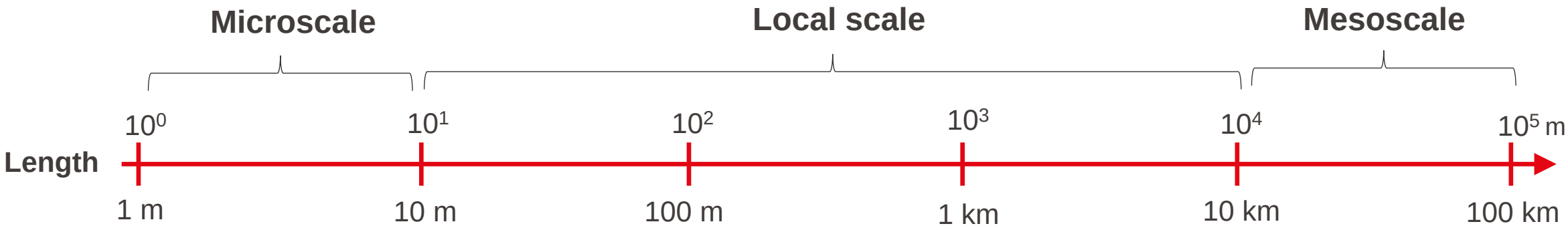
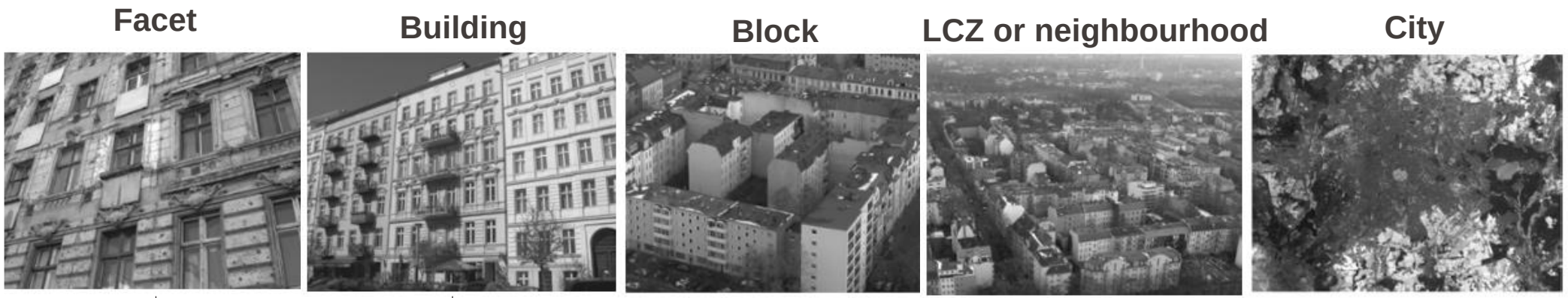
Urban characteristics: Urban scales





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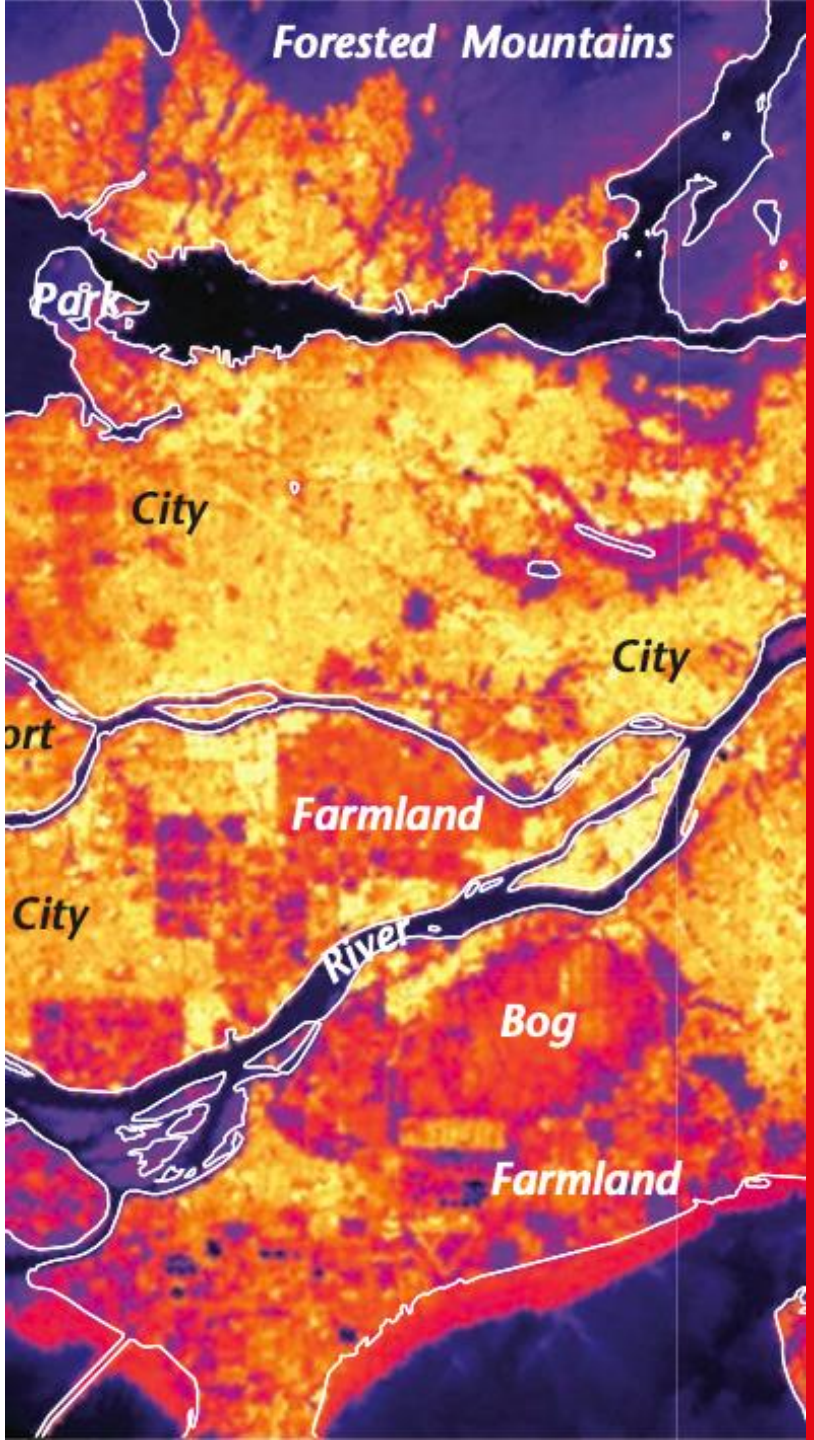

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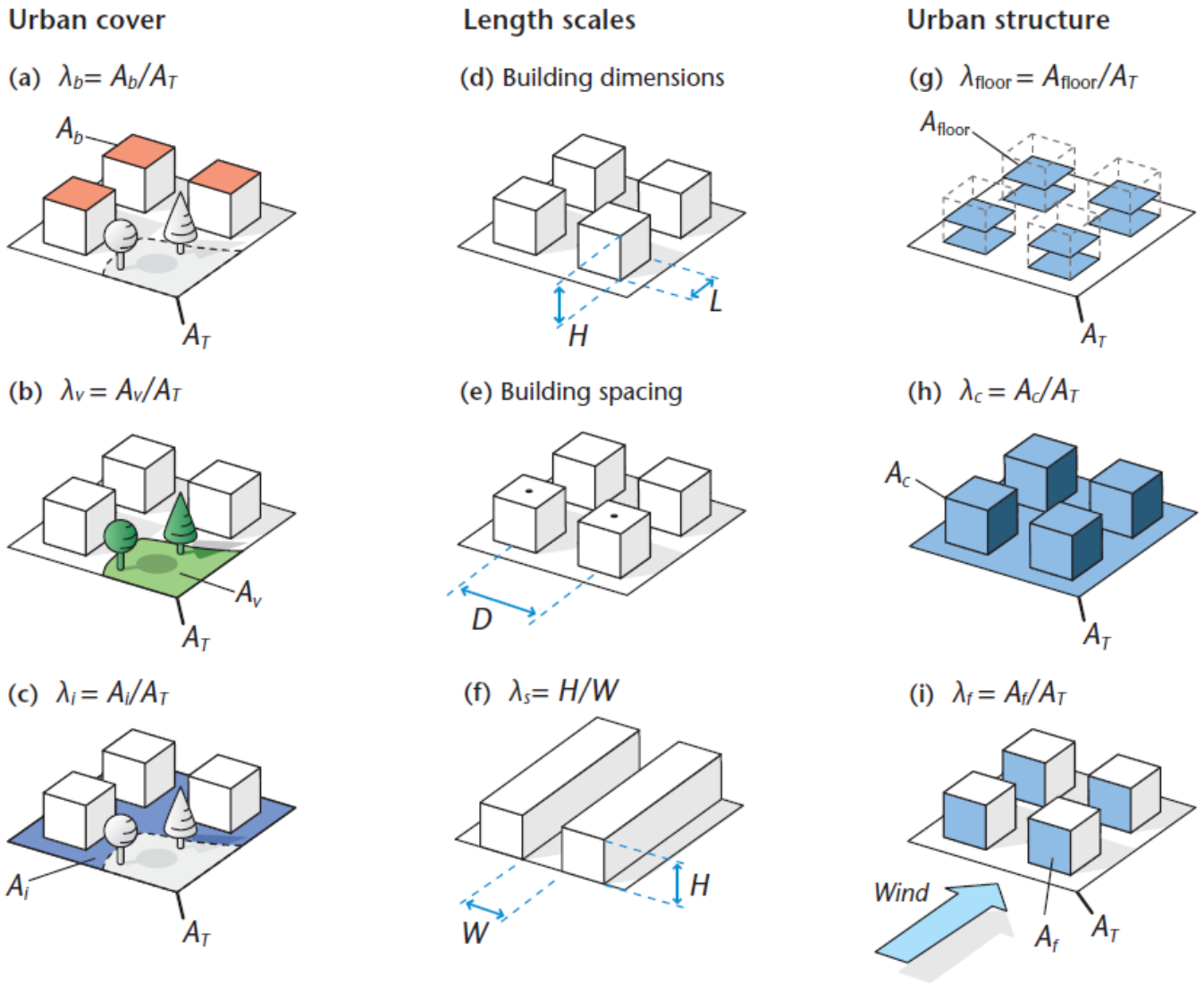
Urban characteristics: Overview of urban properties

- **Cities** are **characterized** by the **fraction of their surface** allocated to *buildings*, *vegetation* or *pavement* and by the **geometry of their elements**.
- Main urban properties: **fabric** (materials), **surface cover,** and **urban structure**
- **Parameters describing urban cover and structure:**
  - Building plan area fraction (λ_b)
  - Vegetated plan area fraction (λ_v)
  - Impervious plan area fraction (λ_i)
  - Canyon aspect ratio (λ_s)
  - Floor space ratio (λ_{floor})
  - Complete surface ratio (λ_c)
  - Frontal aspect ratio (λ_f)

Parameters describing urban cover, length scales and urban structure:



Source: Oke, Urban Climates, p. 21-22

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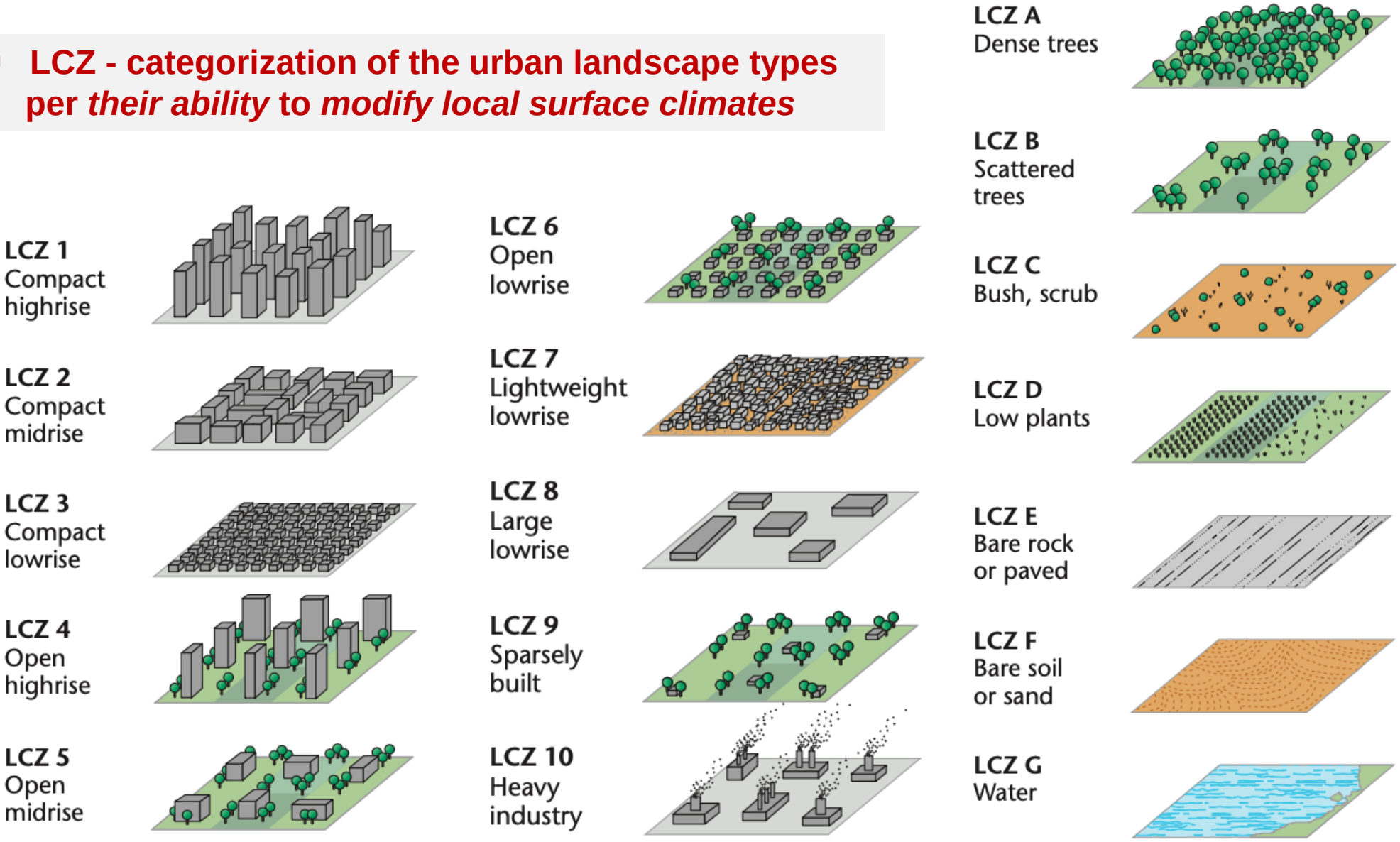
Urban characteristics: Local Climate Zones (LCZ)

- **LCZ - categorization of the urban landscape types per *their ability* to *modify local surface climates***



Source: Oke, Urban Climates, p. 26

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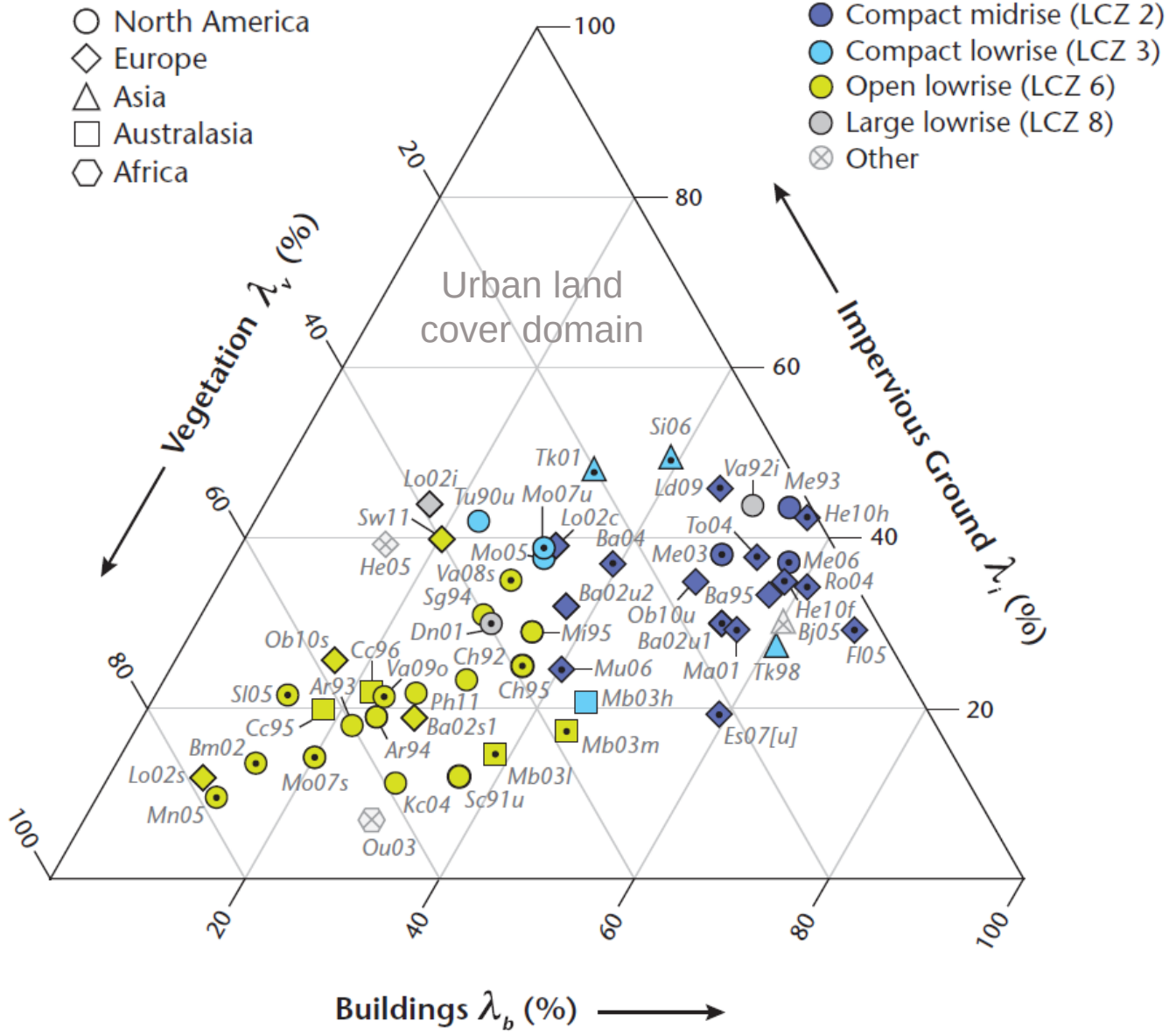
Urban characteristics: Local Climate Zones (LCZ)

- **Local climate zone LCZ**: **categorization** of the **urban landscape types** per their ability to *modify* **local climates**
- LCZ type indicates impermeability, roughness, thermal behavior, *use of energy* and *water*
- Other types of categorizations:
  - **land use classes** (expresses urban function, irrelevant for physics)
  - **climatopes** (no explicit description of the surface, define areas with similar microclimatic characteristics, relevant for urban planning)



Source: Oke, Urban Climates, p. 21-22

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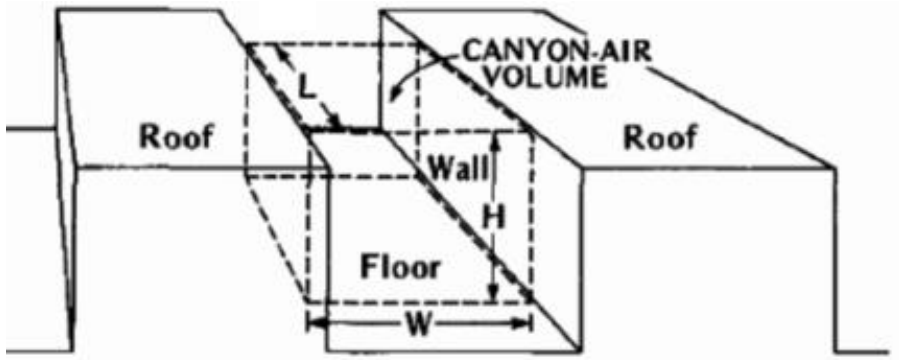
Urban characteristics: Street canyon

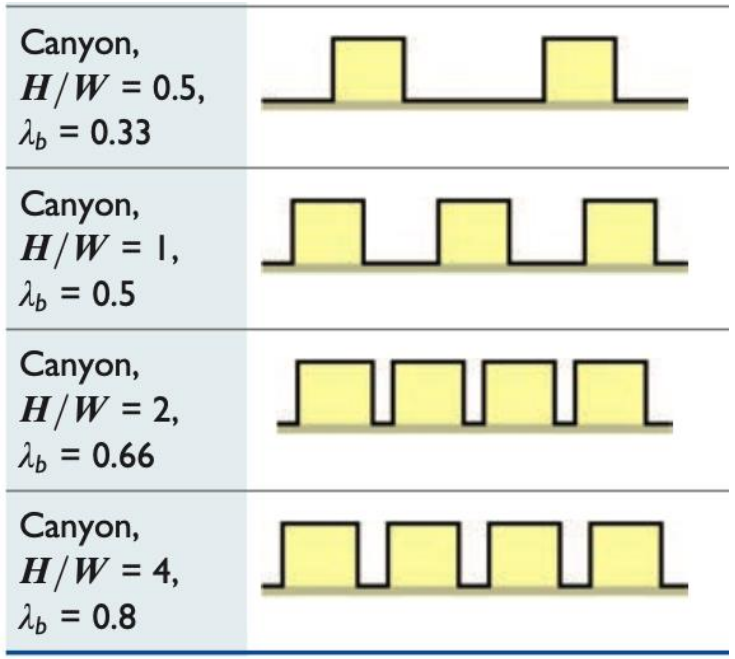
- **Urban canyon** or **street canyon**: structure *formed* by *a street with its three facets*: **canyon floor** (usually a road), and **two sides** (the walls of flanking buildings)

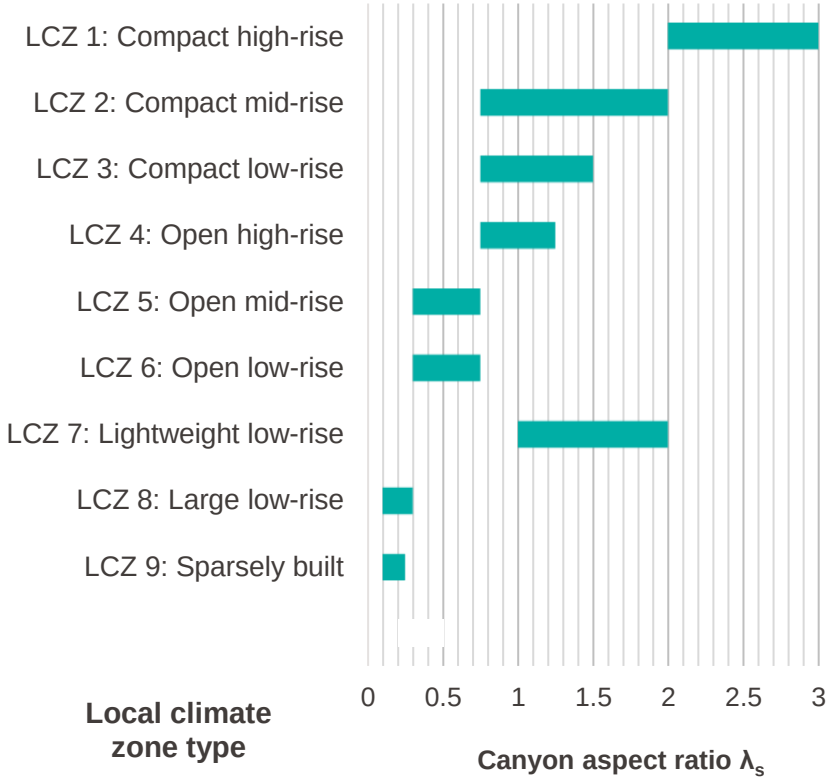


- **Canyon aspect ratio λ_s**: the ratio between the **height (H)** and **width (W)** of an urban canyon

$$\lambda_s = \frac{H}{W} \quad (1\text{-}1)$$

- Assessment of the canyon aspect ratio is important for understanding **radiation access**, **shade** and **trapping**, **wind effects**, **thermal comfort** and **dispersion** of **pollutants**.





Source: Oke, Urban Climates, p. 140

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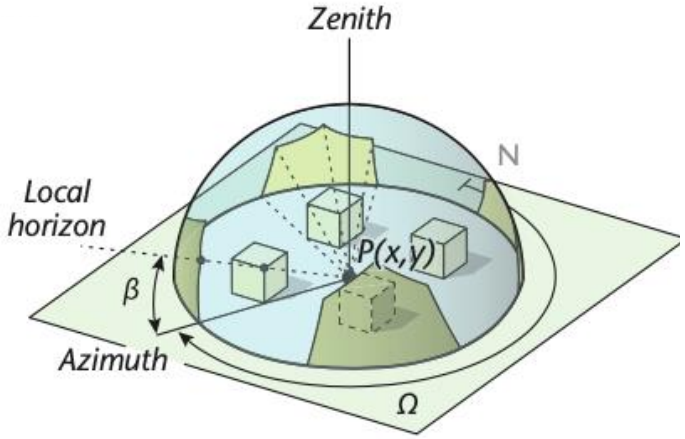
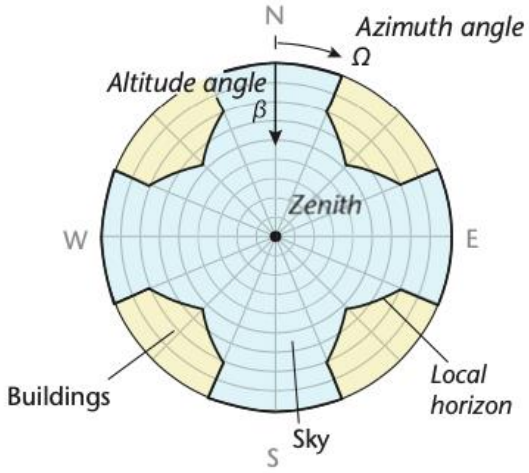
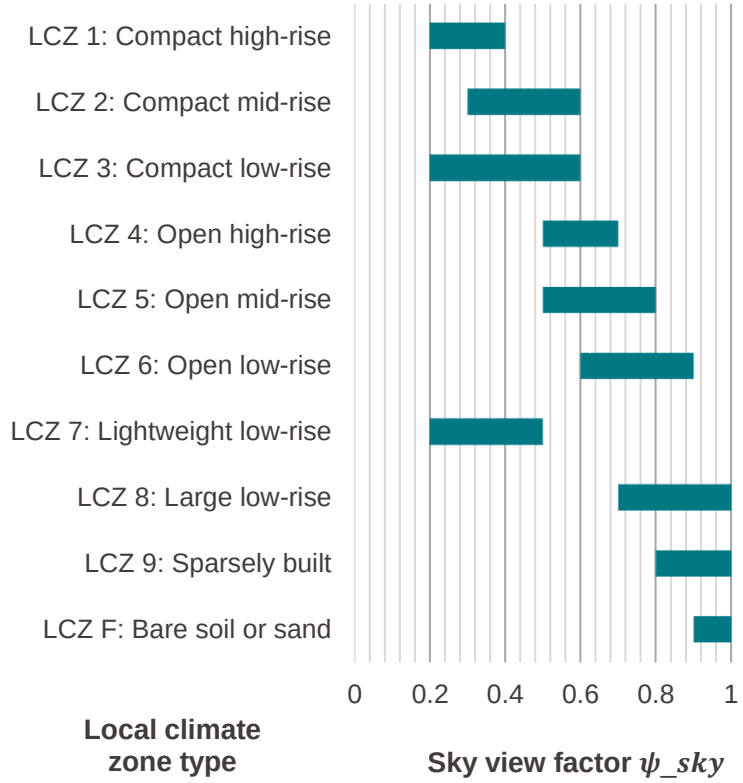
Urban characteristics: Sky view factor

- **Sky view factor ψ_{sky}: fraction of the radiative flux leaving the surface** *at a given point* **that reaches the atmosphere above the urban canopy**.
- $\psi_{sky} = 1$ for a point at the top of a roof with *no horizon screening* by other buildings or hills. *Open areas* have *high* sky view factor whereas *obstructed* configurations have *a low* sky view factor.

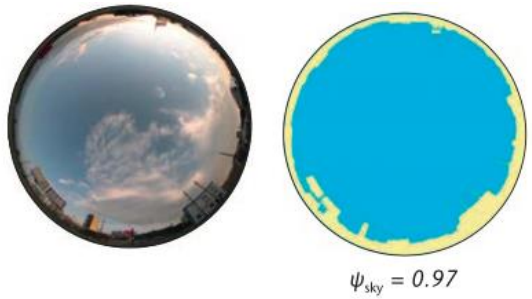




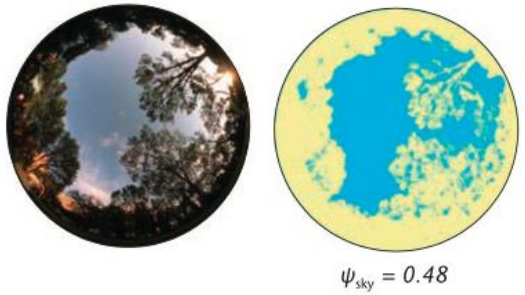
Source: Oke, Urban Climates, p. 23



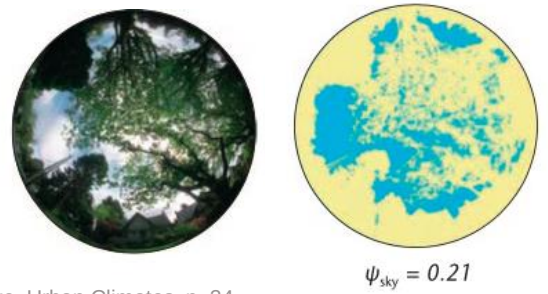
Parking lot:



Park:



Tree-lined street:



Source: Oke, Urban Climates, p. 24

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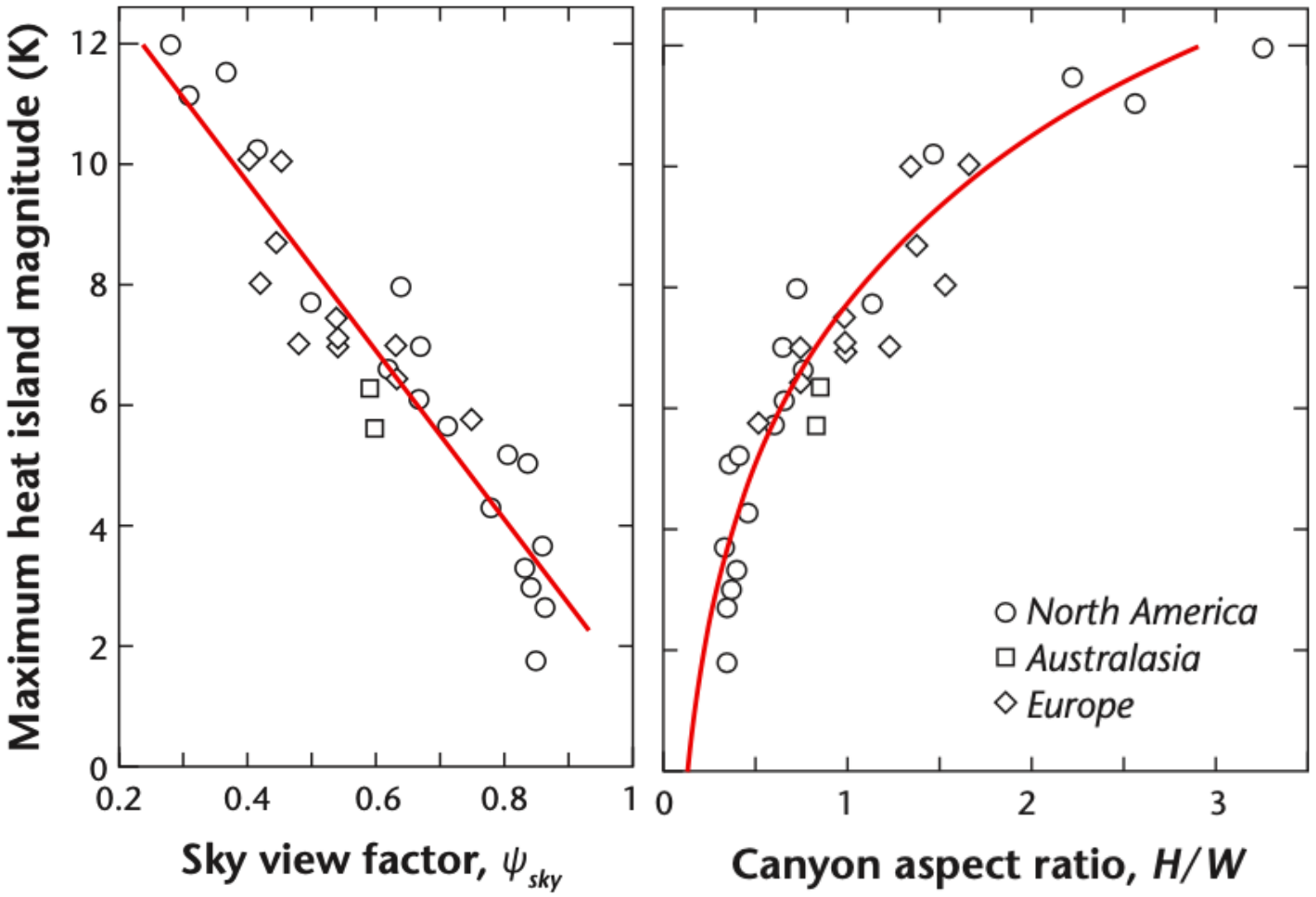
Urban characteristics: Canyon Aspect Ratio vs. Sky view

- The **sky view factor** ψ_{sky} and the **canyon aspect ratio** λ_s are *correlated* to the **urban heat island effect** (valid for all types and sizes of cities)
- **Sky view factor** ψ_{sky} and the **canyon aspect ratio** λ_s are **universal indicators** of the **thermal behavior** of **urban areas** (even though these characteristics are less precise than actual *physical properties* describing the physical behavior of urban areas)



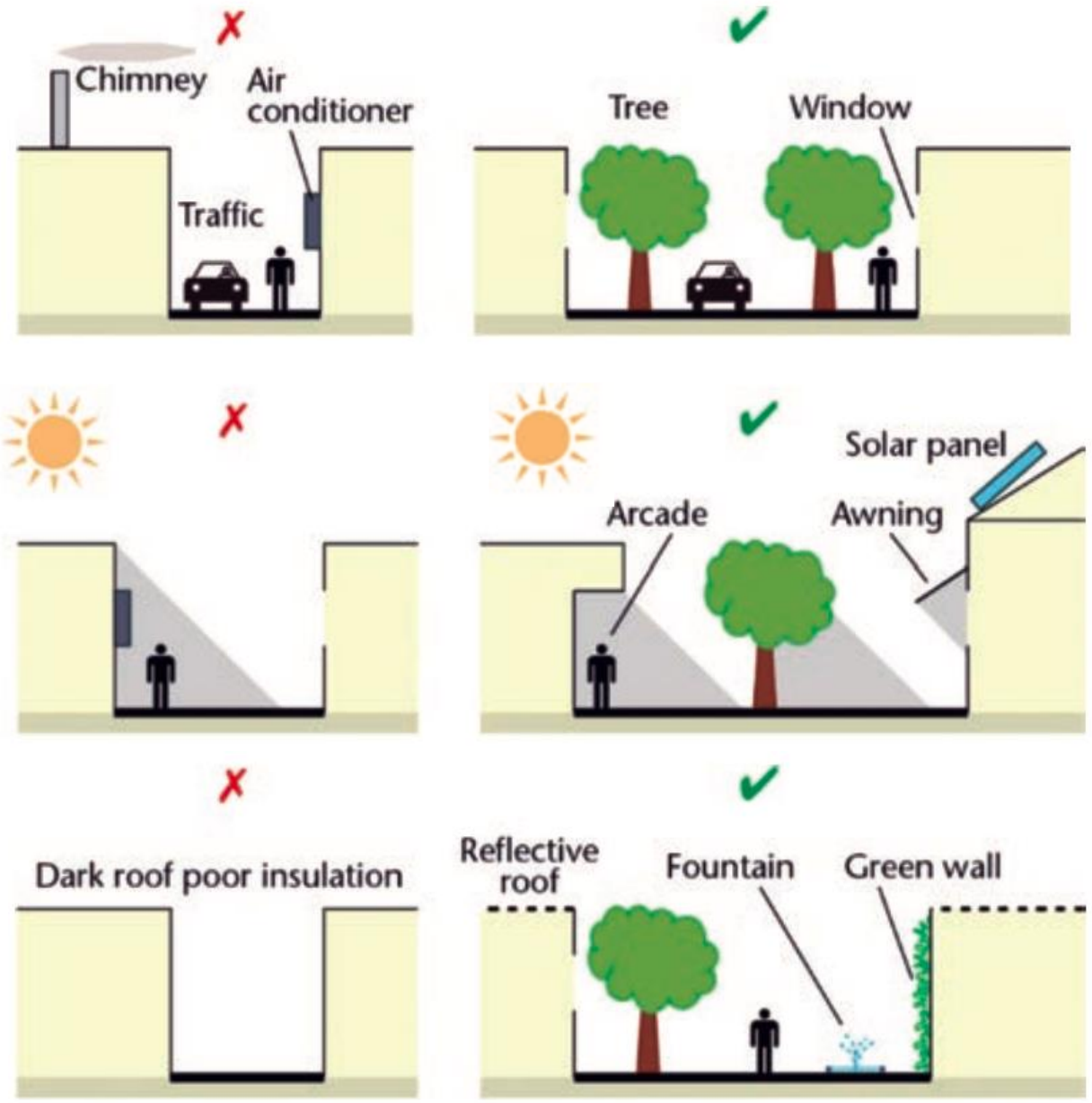
Source: Oke, Urban Climates, p. 216

Recognize & mitigate poor urban design

Discussion topics:

- What **design measures** make certain **urban canyon** configurations *more favorable*?
- How **these measures** *modify* the urban environment?

10 min for the discussion in groups



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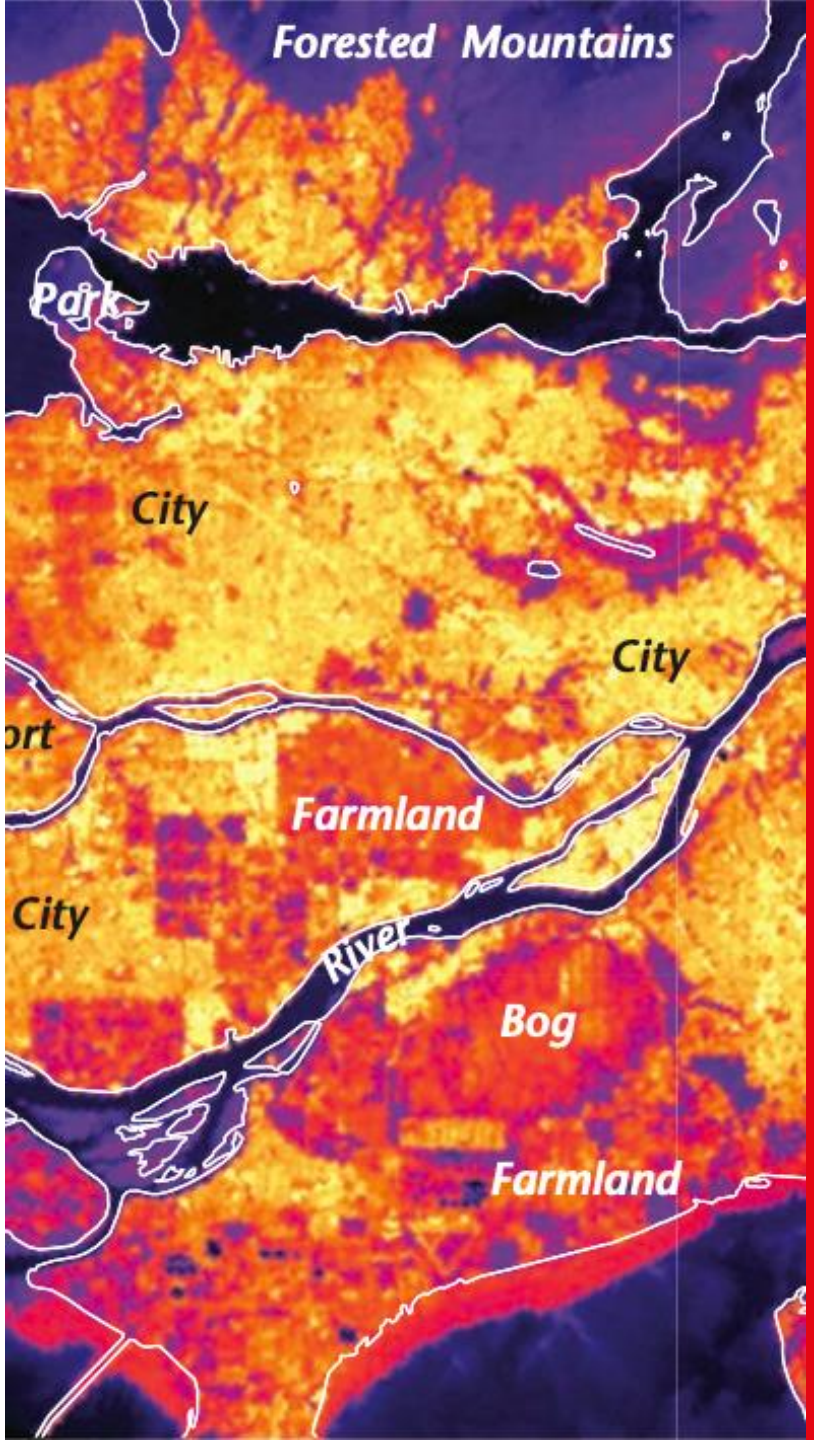

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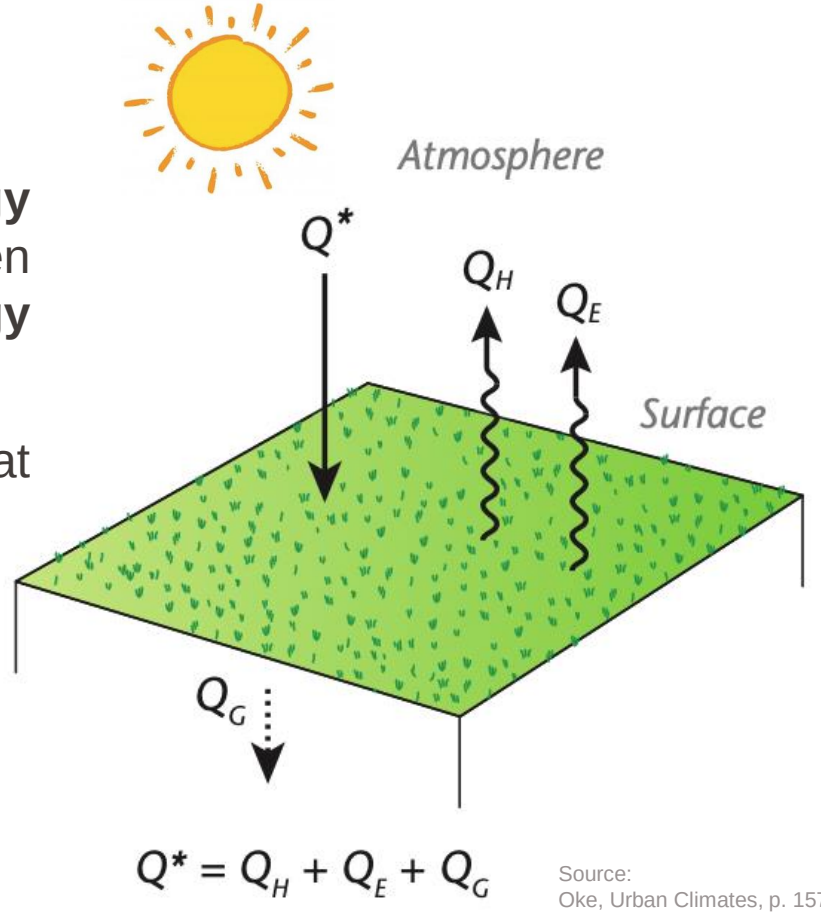
Energy Balance in Rural areas

- The **surface energy balance (SEB)** - **the net result of energy exchanges** by ***radiation***, ***convection*** and ***conduction*** between **a surface element** and **the atmosphere.** Due to **energy conservation**, the surface *should always be* at balance.
- **SEB formulation** for **a rural area** (no built elements, no heat sources):

(1-2) $$Q^* = Q_H + Q_E + Q_G \quad (W/m^2)$$

- Q^*: Net allwave radiation heat flux
- Q_H: Sensible heat flux
- Q_E: Latent heat flux
- Q_G: Ground heat flux (conduction to the soil)



Source: Oke, Urban Climates, p. 157

* the balance in Eqn. (1-2) *simplified* by considering only *vertical fluxes* over the surface

- The **daily** and **seasonal pattern** of **the SEB is set** by **the radiation heat flux** Q^* received from the Sun:
  - During day, **Q* > 0** and energy goes into the soil as sensible heat or into the air through convection.
  - During night, **Q* < 0** and energy is released from surfaces.

Note that in Oke's book "*Urban Climates*" **the net heat flux** in units of W/m^2 is labeled as [Q] (capitalized), while in other sources it could be labeled as [$\dot{q}$] (e.g., in Medved's book)

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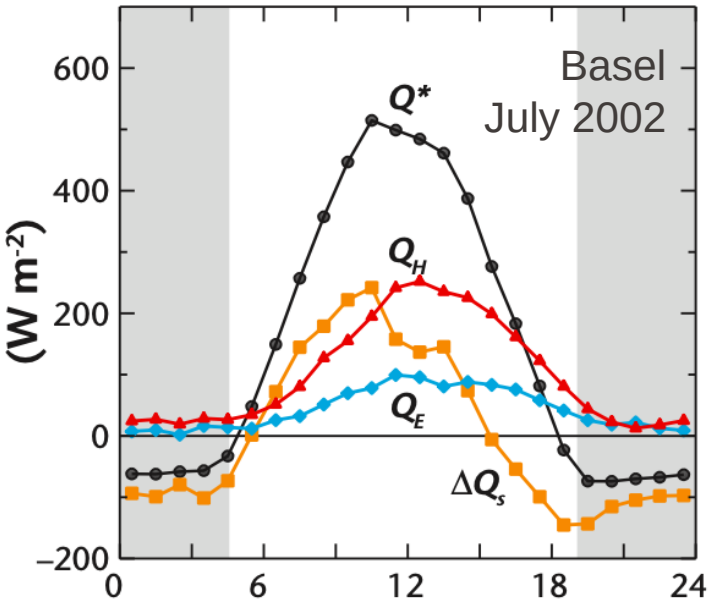
Energy Balance in Urban areas

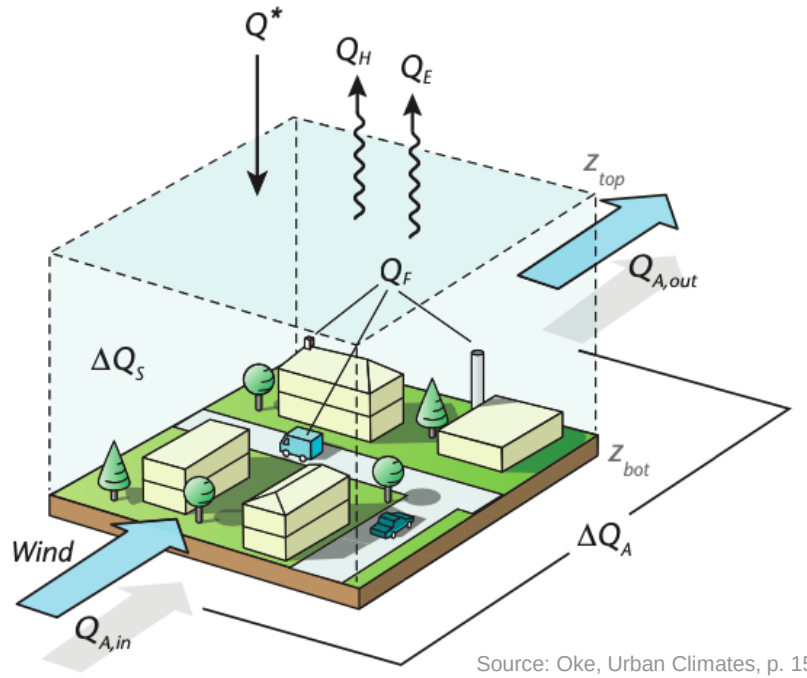
- **Urban areas** *differ significantly* from **rural areas** by their *surface geometry* and *properties*. It leads to *a very different dynamic* of *physical processes*.
- The **energy balance** of an **urban element** is made of **a control volume** that contains **sources** and **sinks** of **energy**.
  - Although the *urban element* is *a combination of surfaces*, the **energy balance** is *not only the sum of these surfaces* as these **surfaces also interact with each other**.
  - Contrary to the surface energy balance (SEB), the **masses of the volume elements** are considered.

(1-3) $$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (W/m^2)$$

Net radiation
Anthopogenic heat
Sensible heat
Latent heat
Stored heat
Advected heat (considered ~0 in practice)



Source: Oke, Urban Climates, p. 161



Source: Oke, Urban Climates, p. 157

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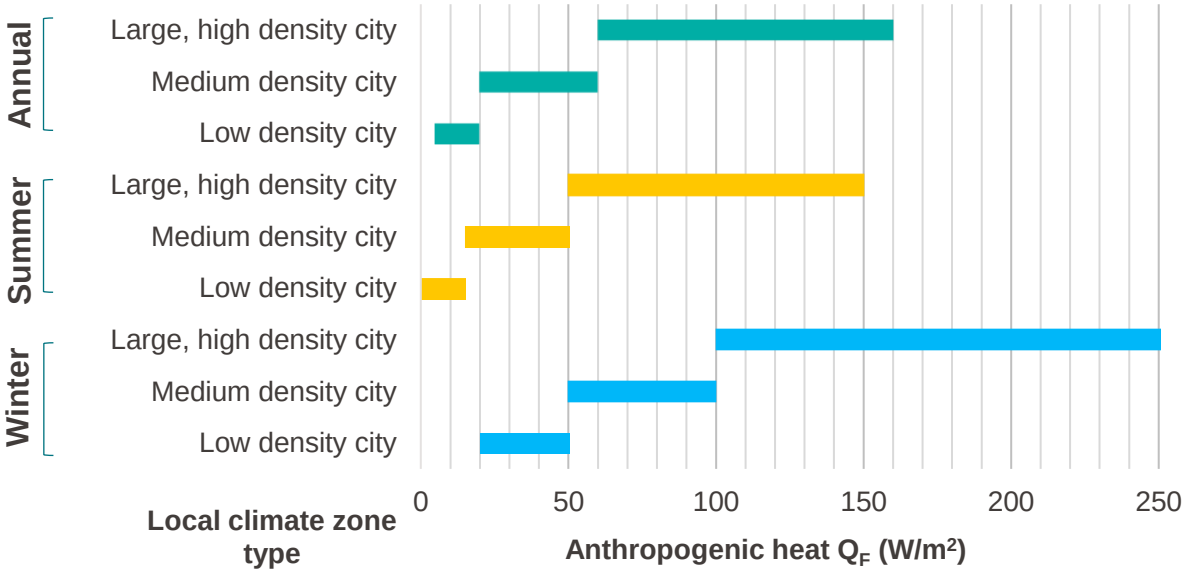
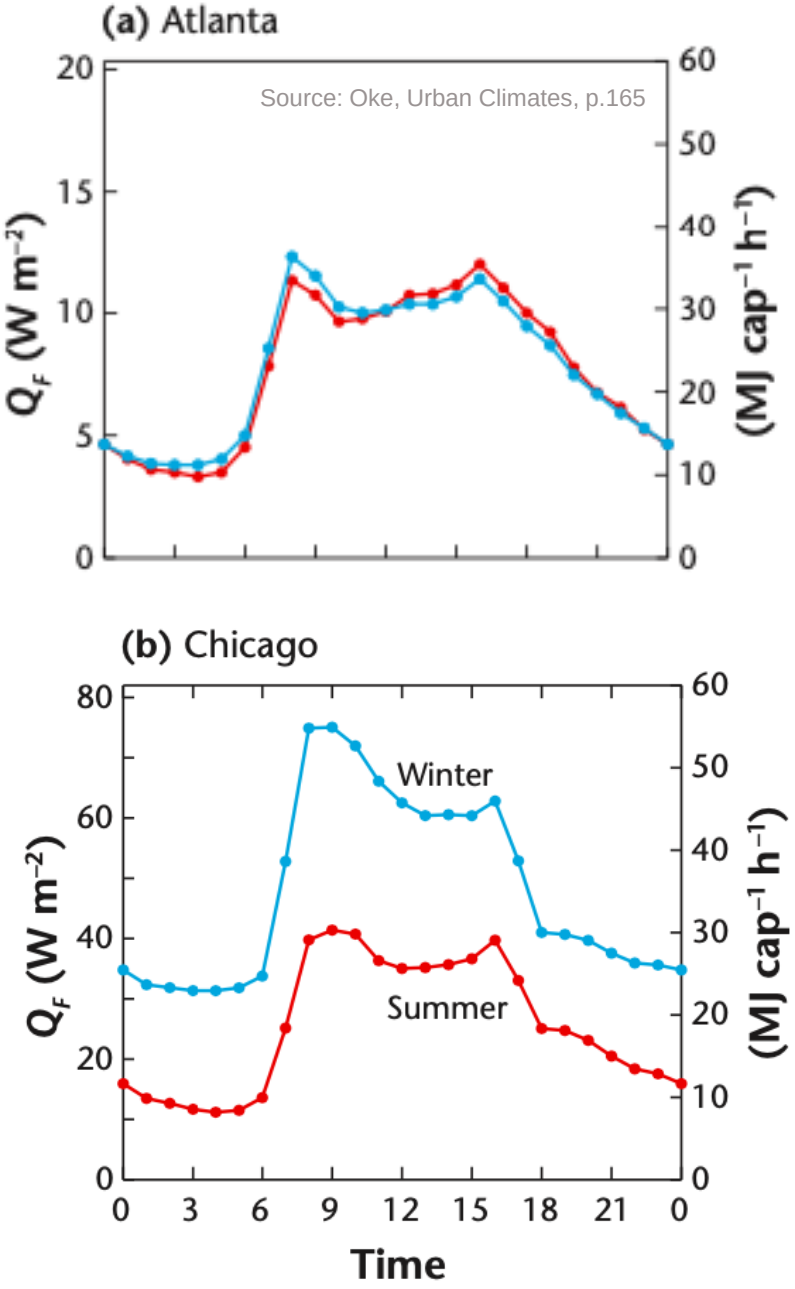
Anthropogenic Heat

- **Anthropogenic heat Q_F** (W/m^2): **heat** *released* **from human activities** to **the atmosphere**
- **Main sources of anthropogenic heat:**
  - Human and animal metabolisms
  - Use of electric devices
  - Combustion of fuels
- Anthropogenic heat is *higher* during the day. It *varies* with the *season* with peaks of heat flux during winter and summer if heating and cooling are used.





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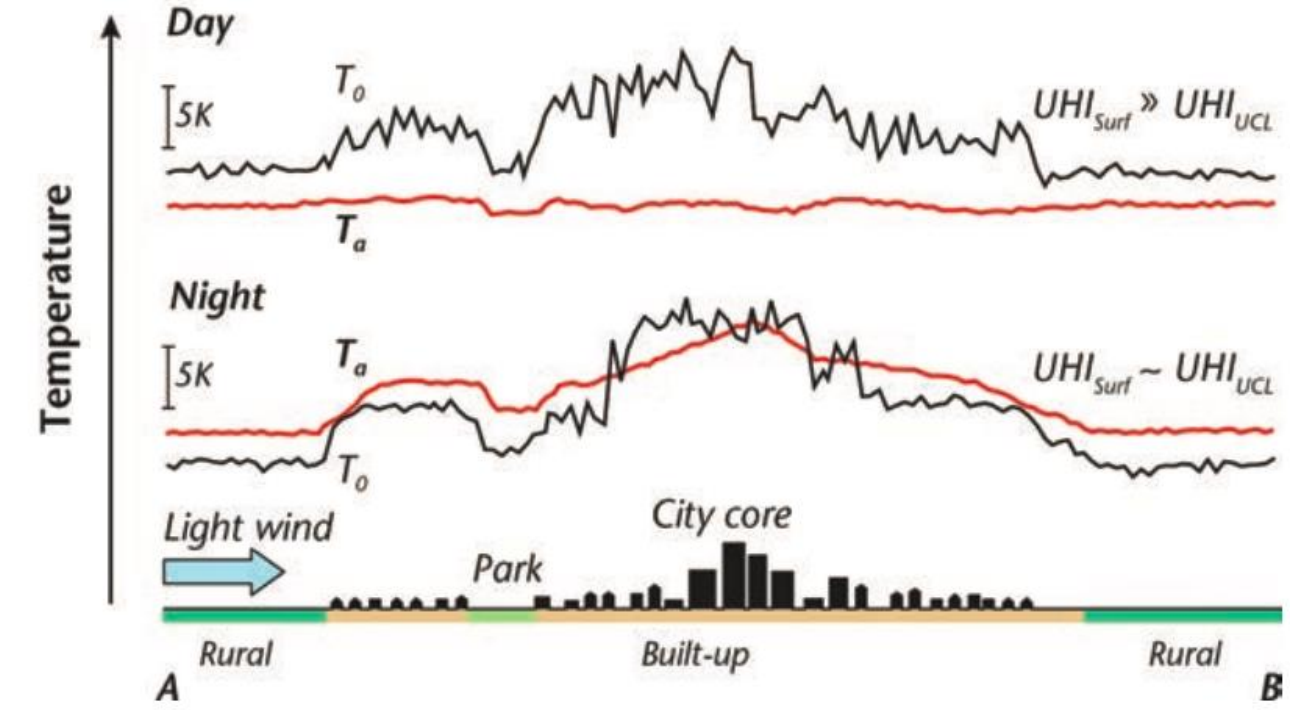
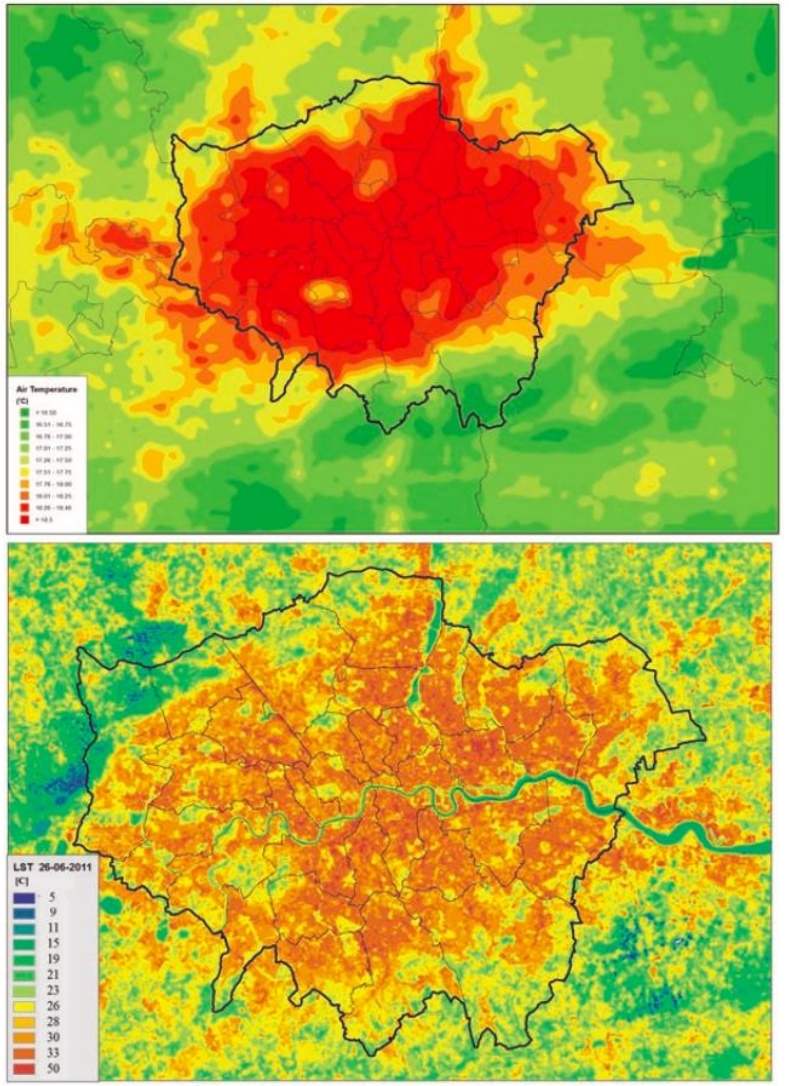
Urban Heat Island (UHI) effect

- **Urban heat island UHI phenomenon**: *urban areas* experience **significantly *higher* temperatures** than their *surrounding rural areas* due to **unintentional climate alterations** caused **by human activities**.



Source: Oke, Urban Climates, p. 200

Surface and _air_ UHI for the city of London



Source: Palme & Salvati, Urban microclimate modelling for comfort and energy studies, p. 33

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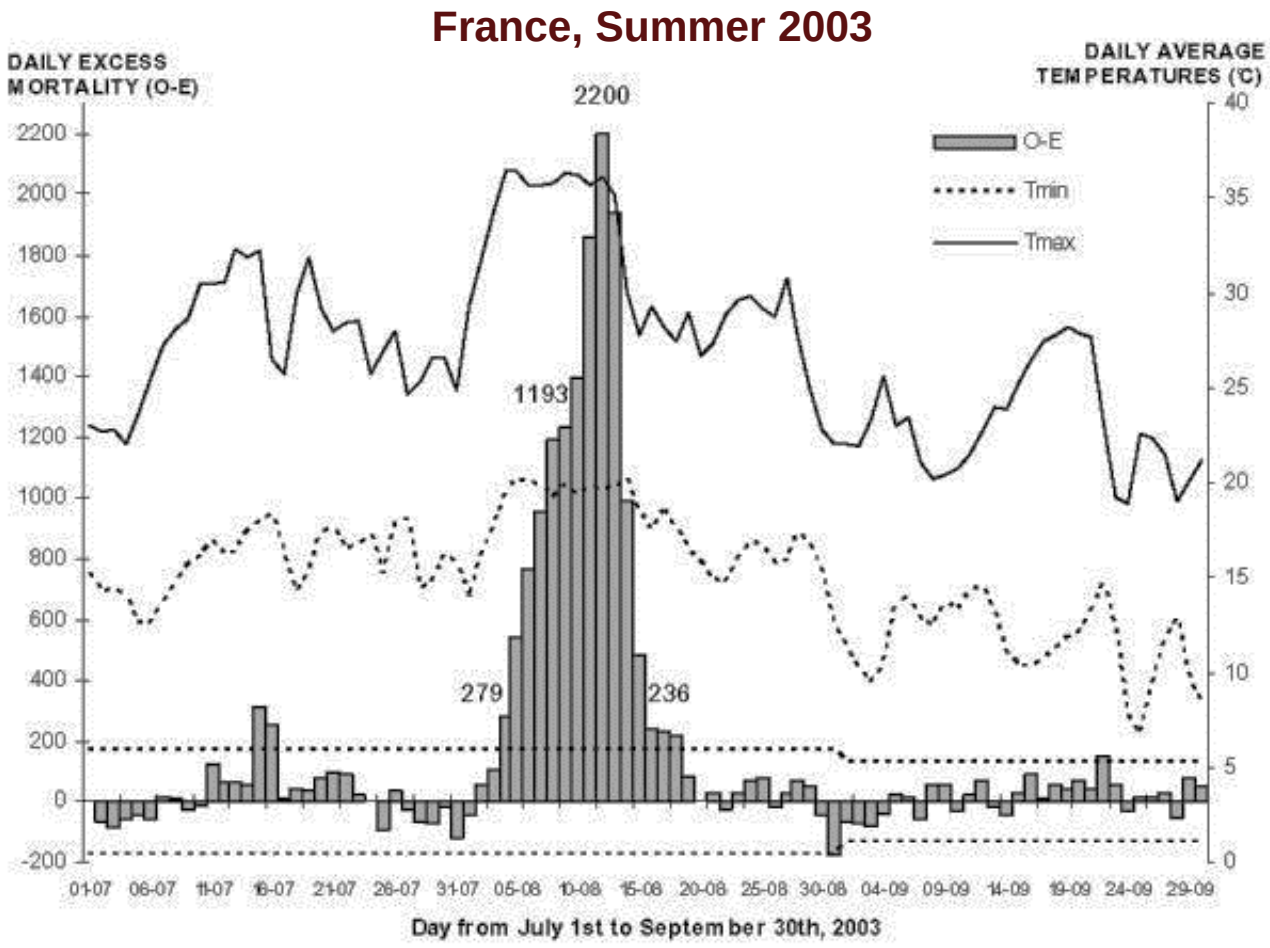
Urban Overheating Effect

1. **Increasing urban temperature records** and **temperature difference** between **urban** and **rural areas**
2. **Lower space heating cost** but **higher space cooling requirements**
3. Increased **heat stress on city residents** in summer
4. **Disruption in biological rhythm** and **threat** to the existence of **plants** and **animals**
5. **Increased rate** of **chemical reactions** leading to **smog** and **pollution**
6. **Contribution to** and **enhanced** by **global climate change**



Source: http://europepmc.org/article/PMC/1950160

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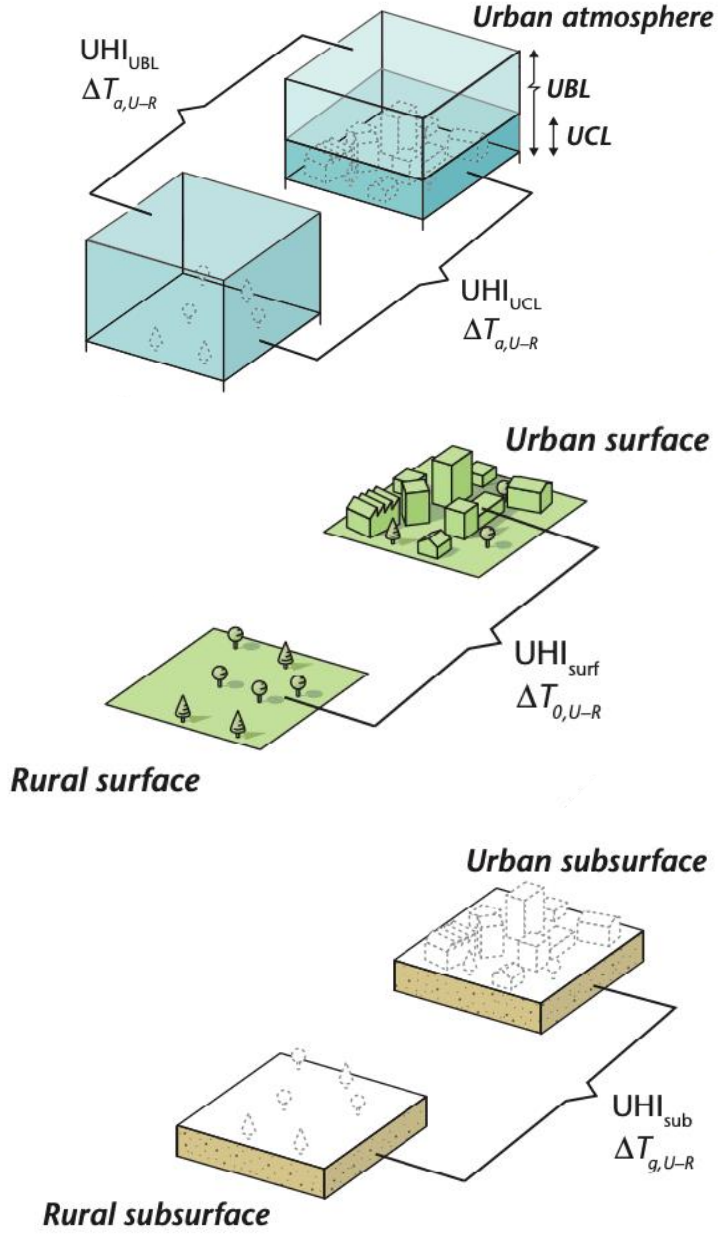
Urban Heat Island (UHI): Types

- Different UHI exist, they are characterized by their **scales**, their **physical processes**. They have different *temporal* and *spatial* dynamics.
- The **different UHI** require *different* **monitoring** schemes and **models** for simulation
- They ***interact with each other*** resulting in a *global effec*.
- **UHI types**:
  - **Air temperature** → Urban canopy layer UHI
  - **Surface temperature** → Surface UHI
  - **Ground temperature** → Subsurface UHI



Source: Oke, Urban Climates, p. 199

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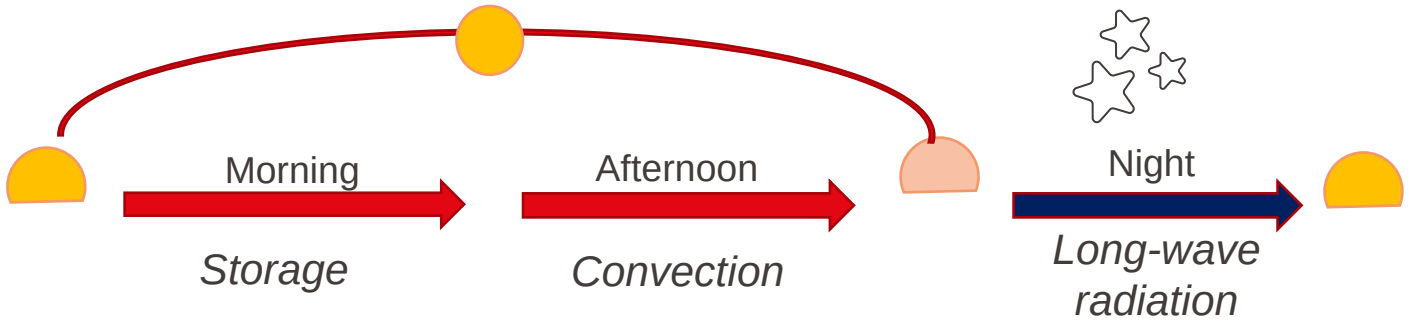
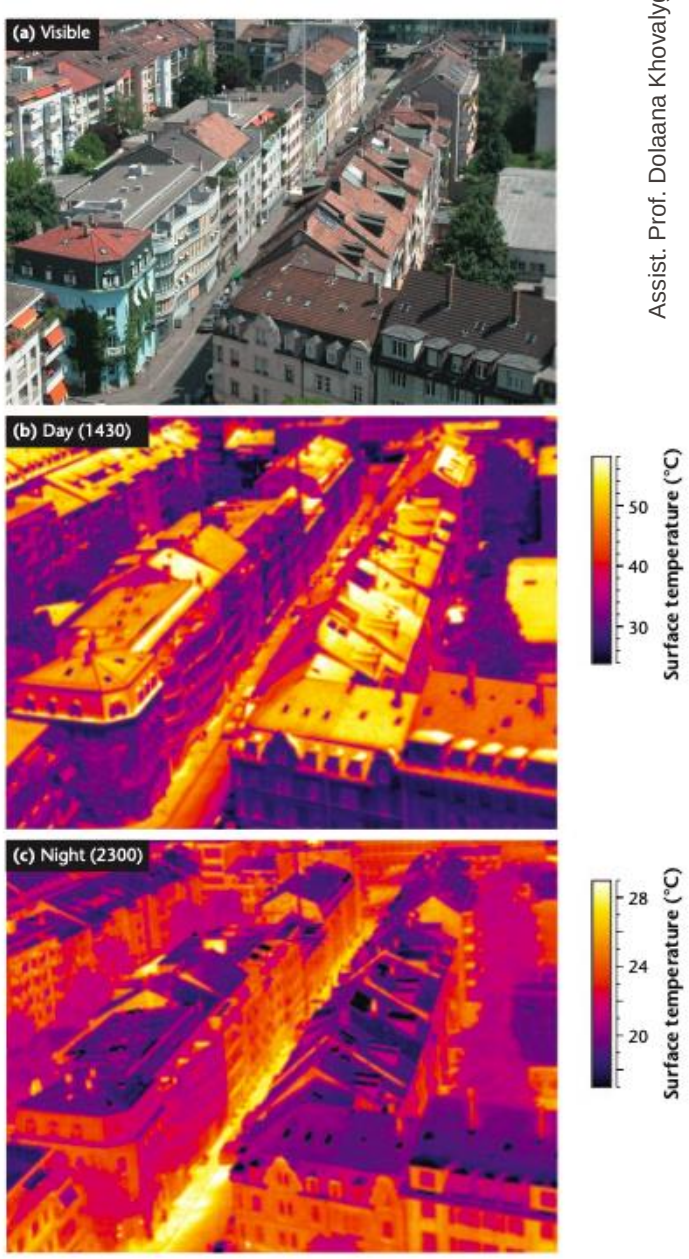
Urban Heat Island (UHI): Dynamics

- **Temporal variation** of **each type of UHI**:
  - UHI varies ***daily***, with ***season*** and with ***weather***
- **Diurnal variation of UHI** is primarily driven by **solar radiation**:
  - During day, heat is *absorbed* by urban surfaces
  - During night, urban surfaces are cooled down via *convection* and *radiation loss*



- **Weather-driven variation of UHI**:
  - It *decreases* with **wind speed** and **cloud cover** as *less sun radiation reaches the urban surface*
- **Seasonality of UHI**:
  - It is *higher* during **summer** and *lower* during **winter**



Source: Oke, Urban Climates, p. 201

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Urban Heat Island (UHI): Magnitude

- **UHI magnitude** or **intensity** UHI_{mag} (K or °C) - difference between urban and rural temperatures:

$$UHI_{mag} = \Delta T_{U-R} = T_U - T_R \quad (1\text{-}4)$$

- The **maximum night UHI intensity** (with respect to air temperature T_{air}) is *correlated* with the ***average*** **canyon aspect ratio**:

$$UHI_{mag} = 7.54 + 3.97\, ln\frac{H}{W} \quad (1\text{-}5)$$

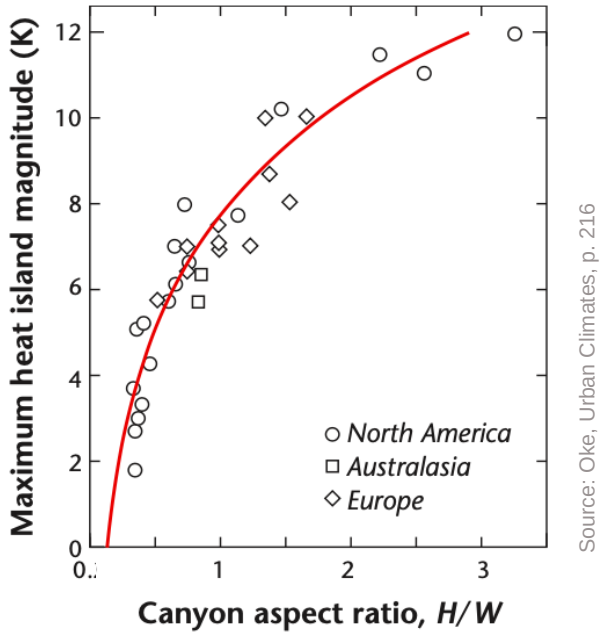
$\boldsymbol{H}$ (m) – average height of the streets, $\boldsymbol{W}$ (m) – average width of the streets

- Empirical expression of **the maximum night UHI intensity** (with respect to T_{air}) as a function of **population**:

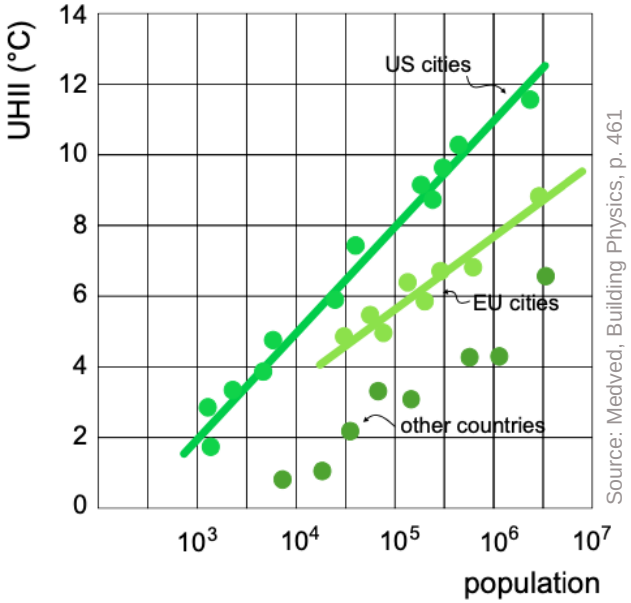
North America: $$UHI_{mag} = 2.96 \cdot \log(P) - 6.41 \quad (1\text{-}6)$$

Europe: $$UHI_{mag} = 2.01 \cdot \log(P) - 4.06 \quad (1\text{-}7)$$

$\boldsymbol{P}$ $(nb\ inhabitants)$ - city population



Source: Oke, Urban Climates, p. 216



Source: Medved, Building Physics, p. 461

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Urban Heat Island (UHI): influencing factors

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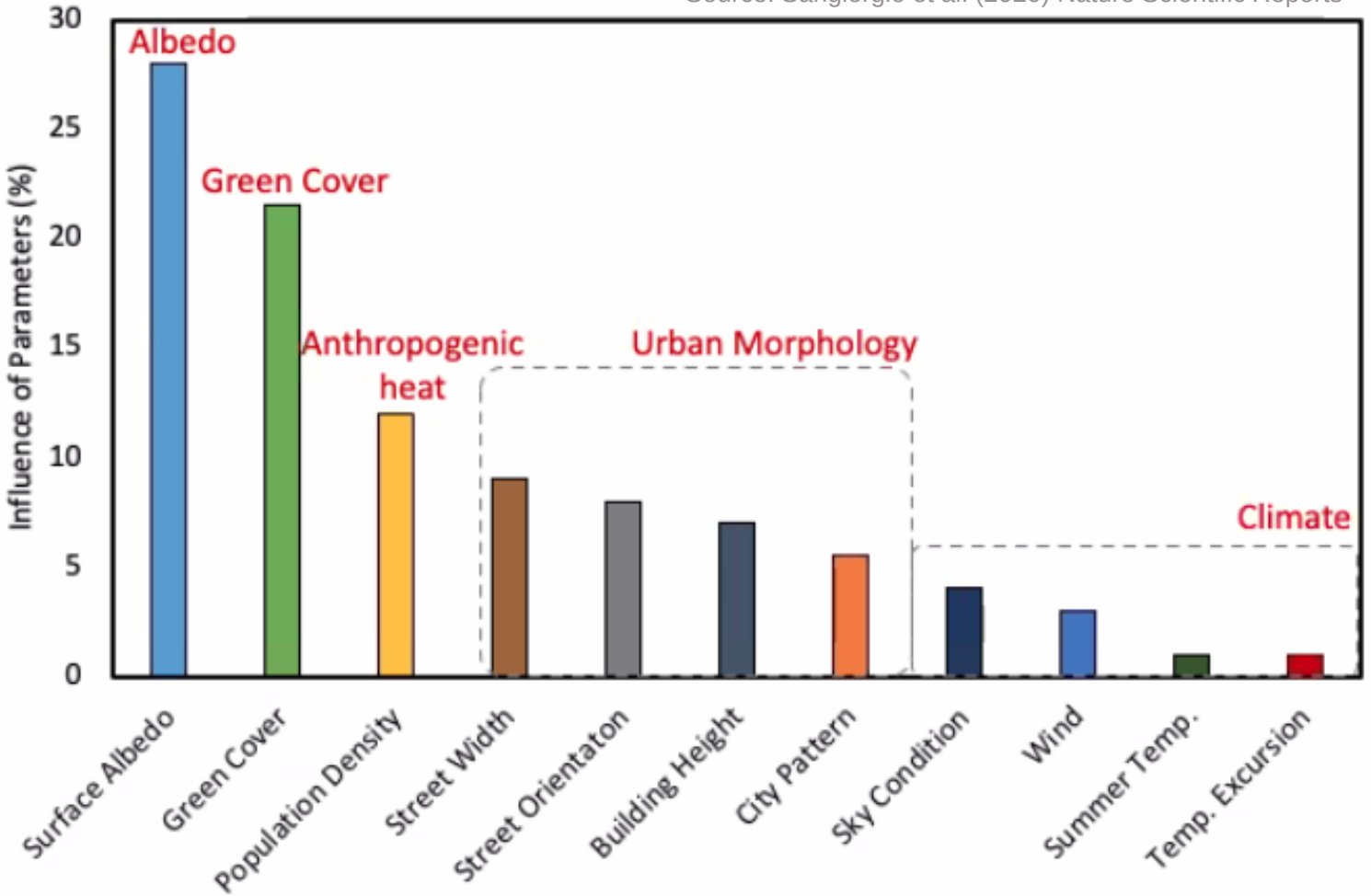
- **Relative importance of parameters influencing the UHI magnitude:**
  - Urban albedo (reflectance)
  - Vegetation
  - Anthropogenic heat
  - Urban morphology
  - Climate

Source: Sangiorgio et al. (2020) Nature Scientific Reports



Thank you for your attention!

Assist. Prof. Dolaana Khovalyg
dolaana.khovalyg@epfl.ch