EPFL

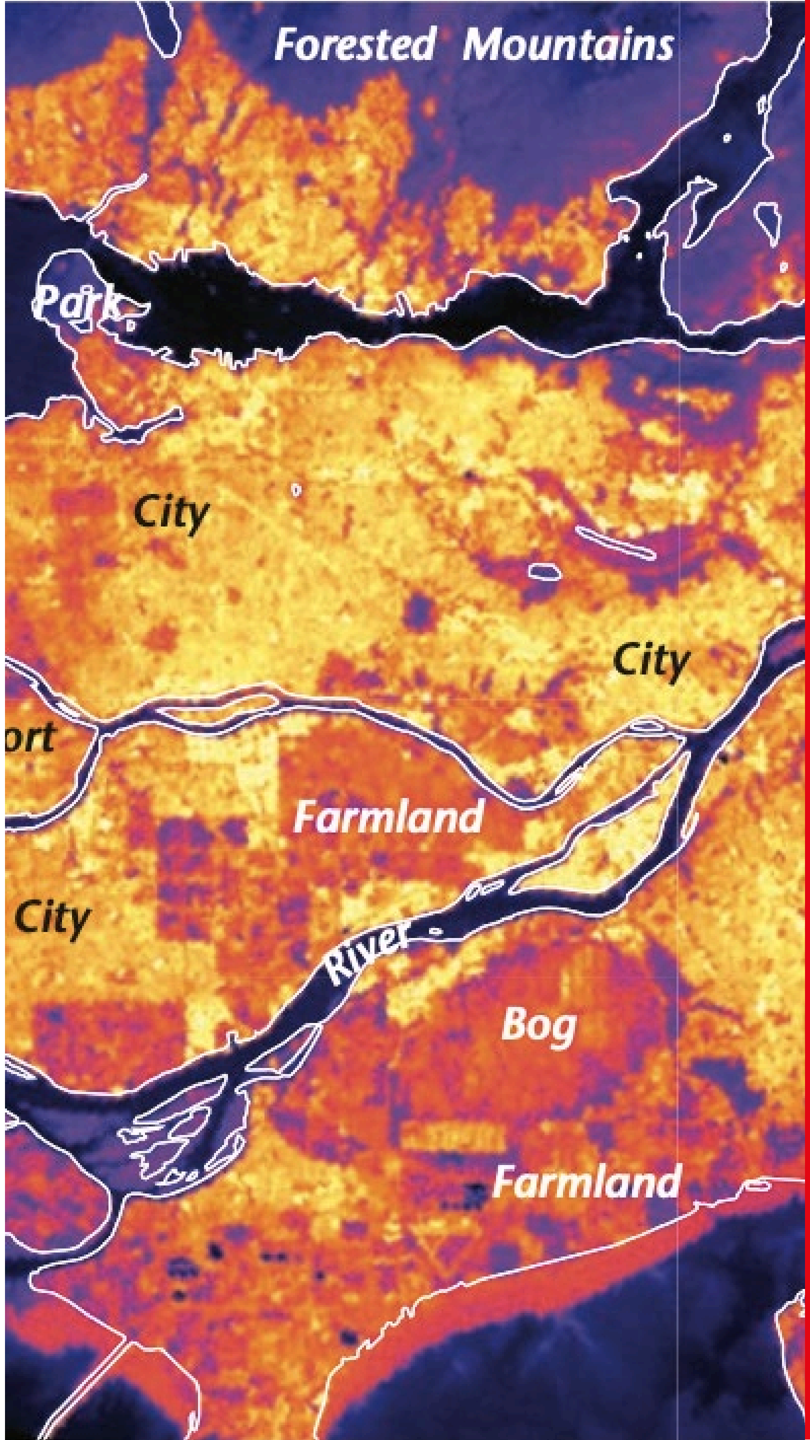
CIVIL-309: URBAN THERMODYNAMICS

Assist. Prof. Dolaana Khovalyg

Lecture 01:

Course overview. Urban characteristics and the UHI effect.

9 September 2024



CONTENT:

I. Introduction to the course
- Content, schedule, grading
- Group project overview

II. Urban characteristics
- 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
- Consequences

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Course Information: People

- **Dolaana KHOVALYG, Assist. Professor**

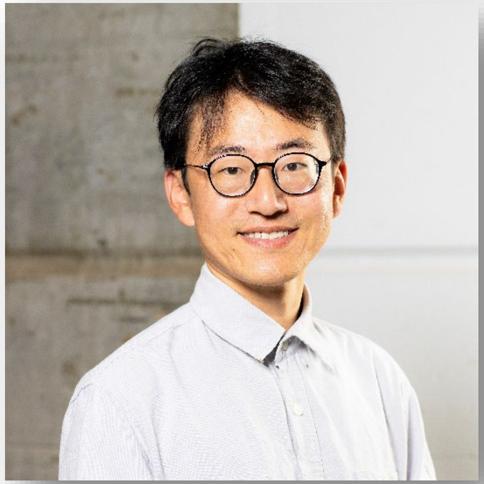
  dolaana.khovalyg@epfl.ch

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

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

  Research focus: energy reduction of the thermal conditioning in buildings, building physics, well-being and comfort of building occupants

  Teaching activities: CIVIL-309 "*Urban Thermodynamics*", ENG-445 "*Building Energetics*", CIVIL-450 "*Thermodynamics of Comfort in Buildings*"



- **Kun LYU, Postdoctoral Researcher**

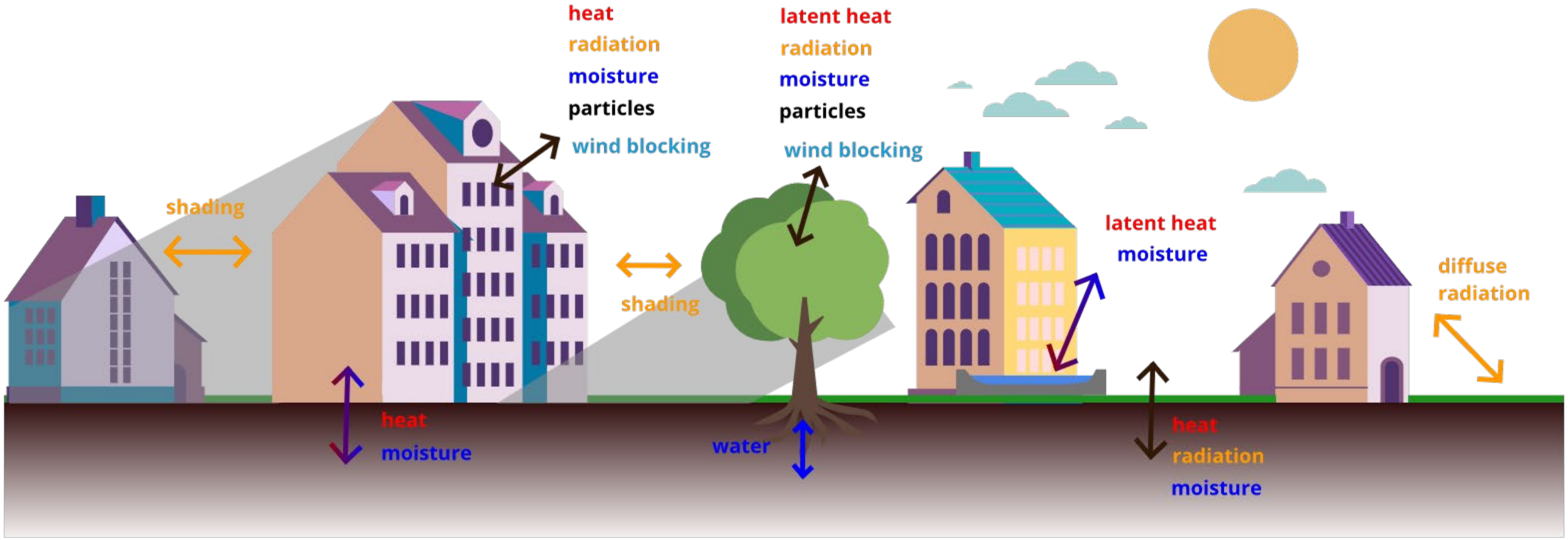
  kun.lyu@epfl.ch

  Research focus: Outdoor thermal comfort, biophilic design, urban heat island effect mitigation

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

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 Objectives: recognize & mitigate poor urban design

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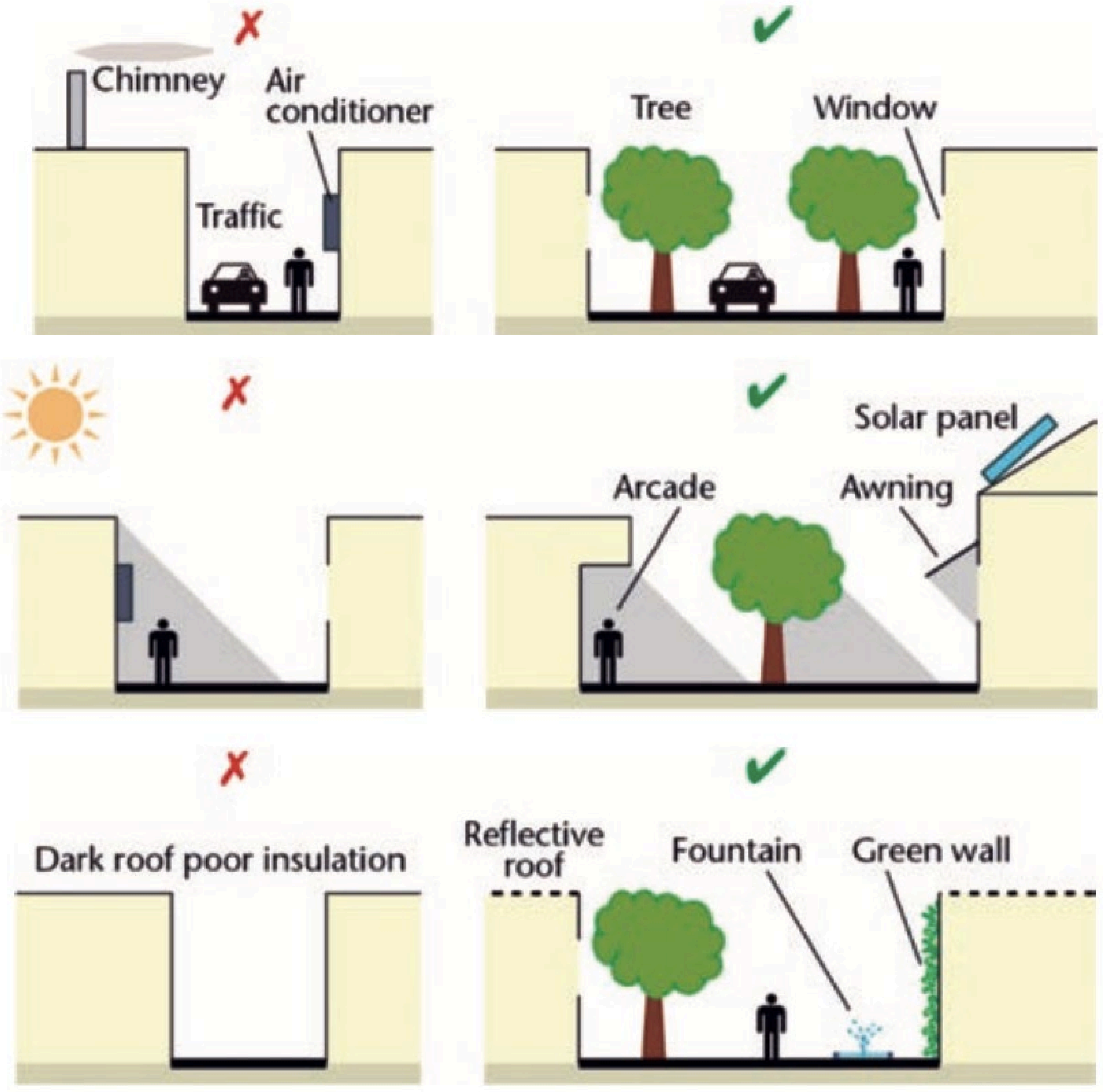
We'll investigate questions such as:

- How do **urban canyons** affect the environment?
- Which **building configurations** are most advantageous?
- Why is **controlling surface reflectivity** important in urban areas?
- How does **evaporative cooling** from trees impact the environment?
- Does **enhancing street ventilation** improve environmental conditions?
- What are **the best strategies** for designing **thermally comfortable streets**?
- How can the **Urban Heat Island (UHI) effect** be minimized?
- *..… and many more!*



Course Information

- **Lectures (L):** Mondays **15:15-17:00**, room INJ 218
- **Practice sessions (P):** Mondays **17:15 – 18:00**, room INJ 218
- **Expected student activities:**

  participate in lectures, practice sessions and group project
- **Grading:**
  - **Quiz** (**30%**), open book exam, individual assessment
  - **Group project** (**70%**), group assessment, peer-evaluation
- **Formation of groups (4-5 ppl per group, 9 x 5 ppl + 2 x 4 ppl) – by Week 3:**
  - **Option 1:** *Self-formation* (you find people that you want to work with)
  - **Option 2:** *Random assignment* (we will assign people to each group randomly)

Course Schedule

Lectures (L) 15:15-17:00, practice sessions (P) 17:15-18:00, room INJ218

Week	Date	Time	ID	Topics	Responsible
1	09.09	2 x 45'	**L1**	**Course overview** (content, evaluation, group project). **Urban characteristics**, **Urban Heat Island (UHI) effect.**	DK
		1 x 45'	**P1**	Exercises based on materials in lecture L1	KL
2	16.09			No class (holiday)	
3	23.09	2 x 45'	**L2**	Overview of **physical parameters**. **Urban environment** and **urban modeling**.	DK, KL
		1 x 45'	**P2**	**Workshop** on how to use the simulation tool **ENVI-met** (basic functions, geometry input, etc.) Exercises based on materials in lecture L2 [HW]	KL
4	30.09	2 x 45'	**L3**	**Heat Transfer**: Conduction and radiation	DK
		1 x 45'	**P3**	Exercises based on materials in lecture L3	KL
5	07.10	2 x 45'	**L4**	**Heat Transfer:** Convection and evaporation	DK
		1 x 45'	**P4**	Exercises based on materials in lecture L4	KL
6	14.10	90'	**Q**	Quiz (open book exam, based on lectures L1-L4)	DK, KL
		1 x 45'	**V**	**Case study site (EPFL Innovation park) visit**, overview of important urban features	DK, KL
7	21.10			Fall Break (no classes)	

Course Schedule

Lectures (L) 15:15-17:00, practice sessions (P) 17:15-18:00, room INJ218

Week	Date	Time	ID	Topics	Responsible
8	28.10	2 x 45’	**L5**	**Building-environment interaction:** thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45’	**P5**	**Group work—simulation practice based on L5**: building-environment interactions, workflow to create and modify building geometry, and materials for building walls and roofs. Data visualization for building surface temperature and visualization for scenario comparison	KL
9	04.11	2 x 45’	**L6**	**Ground-environment interaction:** ground properties, thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45’	**P6**	**Group work – simulation practice based on L6:** relevant parameters for ground materials, soil profile, and data analysis regarding ground-environment interactions	KL
10	11.11	2 x 45’	**L7**	**Water body - environment interaction**: thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45’	**P7**	**Group work – simulation practice based on L7:** workflow to create different water bodies and fountains in ENVI-met and data analysis for water-environment interactions	KL
11	18.11	2 x 45’	**L8**	**Vegetation – environment interaction:** characteristics of vegetation, evapotranspiration, aero- and thermal interaction	KL
		1 x 45’	**P8**	**Group work – simulation practice based on L8:** two modes of vegetation models in ENVI-met and methods to create new vegetation profiles, green walls and roofs, data analysis for vegetation-environment interactions	KL

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Lectures (L) 15:15-17:00, practice sessions (P) 17:15-18:00, room INJ218

Week	Date	Time	ID	Topics	Responsible
12	25.11	2 x 45’	**L9**	**Human Outdoor Comfort:** Parameters affecting human comfort and comfort indices (UTCI, PET)	DK
		1 x 45’	**P9**	**Group work – simulation practice based on L9:** methods to calculate thermal comfort indices from ENVI-met simulation, dynamic thermal comfort simulation	KL
13	02.12	3 x 45’	--	**Intermediate presentations of group projects**	DK, KL
14	09.12	2 x 45’	**L10**	**Climate-Sensitive Urban Design**: complex interaction of all urban elements and their effect on UHI and outdoor environmental quality	KL
		1 x 45’	**P10**	**Group work – simulation practice based on L10:** developing an integrated solution in ENVI-met for the climate-sensitive urban design	KL
15	16.12	2 x 45’	**L11**	**Urban Energy** (renewable energy sources in cities). **Summary of the course.**	DK
		1 x 45’	**P11**	**Group work** - finalizing the analysis and the report	KL
Submission of group projects and peer-evaluation by 23.12 (12:00)					

- **Lecture slides** will typically be available 1-2 days before the class meeting
- A file with **exercises** will be uploaded ***prior*** to **the corresponding lecture**
- A file with **solutions** will be uploaded ***after*** **the exercise session**

Course Information: Main References

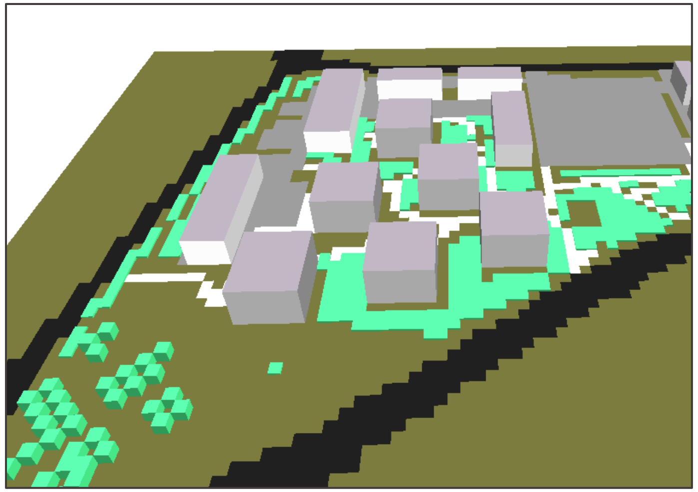
- T.R. Oke, G.Mills, A. Christensen, J.A. Vooght, **Urban Climates**, Cambridge University Press
  - *ebook (PDF file) is available here, 3 printed copies are available in the library*
- S. Medved, **Building Physics: Heat, Ventilation, Moisture, Light, Sound, Fire, and Urban Microclimate,** Springer
  - *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*

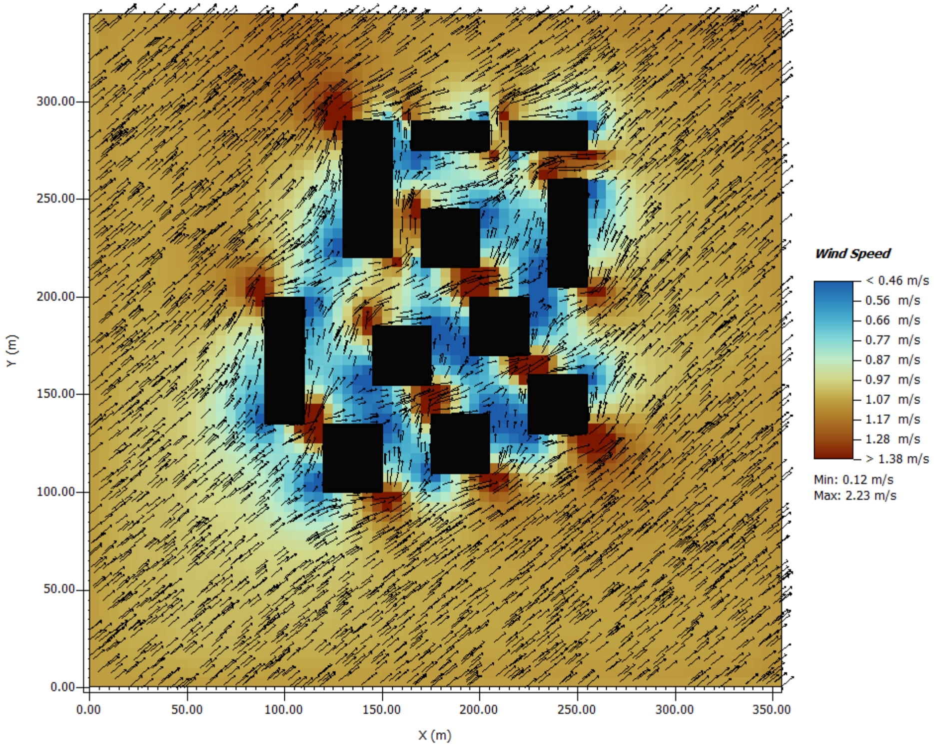
Group Project: Aims and Objectives

- **Aim:** To understand **the influence** of **urban elements** on the **urban microclimate**, investigate their **interactions**, and explore *possible* **urban overheating mitigation strategies** for the given site.

- **Objectives:**

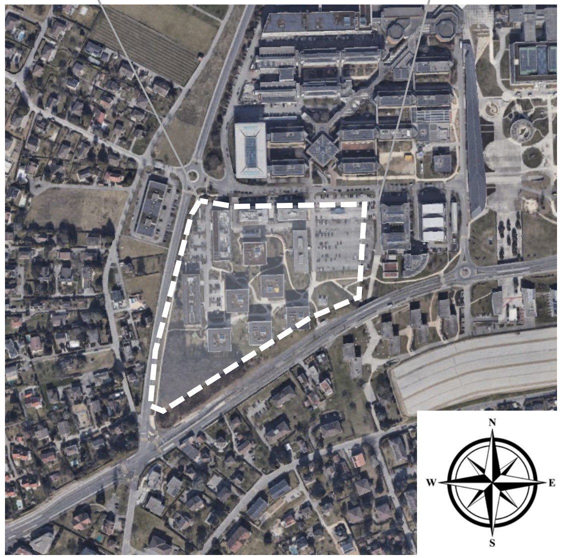
  1. **Critically** examine **current site conditions** (e.g., LCZ, material properties, urban morphological parameters, green elements, climate characteristics) **in relation to the microclimate**;
  2. Identify, *illustrate* and *compare* **individual effects** of **buildings**, **ground cover**, **vegetation**, **water** on the urban microclimate;
  3. Examine **the *combined* effects** of **multiple urban elements** on **microclimate** and **propose *optimised* intervention solutions.**





Group Project: Case study –Innovation Park

- **Site of interest: Innovation Park of EPFL**
- It includes:
  - 6 square buildings of the Innovation park
  - 5 other surrounding buildings
  - 1 large parking area
  - Roads and pedestrian pathways
  - Trees, grass and forest
- The surface of the area of interest covers about 11 hectares. The **highest building** is **22 m tall.**
- The **prevailing wind direction** comes from the **northeast** and **southwest** with an average wind speed of $\mathbf{1.6\ m/s}$.
- The **pavement materials** are **asphalt**, **grass**, **cement** and **stabilized sand**.
- **Vegetation** is present with **a forest** at the **South-West corner** of the area and **trees scattered** between the buildings.



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Group Project: Case study –Innovation Park

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3D model from: https://sketchfab.com/models/db0ca2f22d97466c931bfcc2cd764283/embed?utm_source=website&utm_campaign=blocked_scripts_error

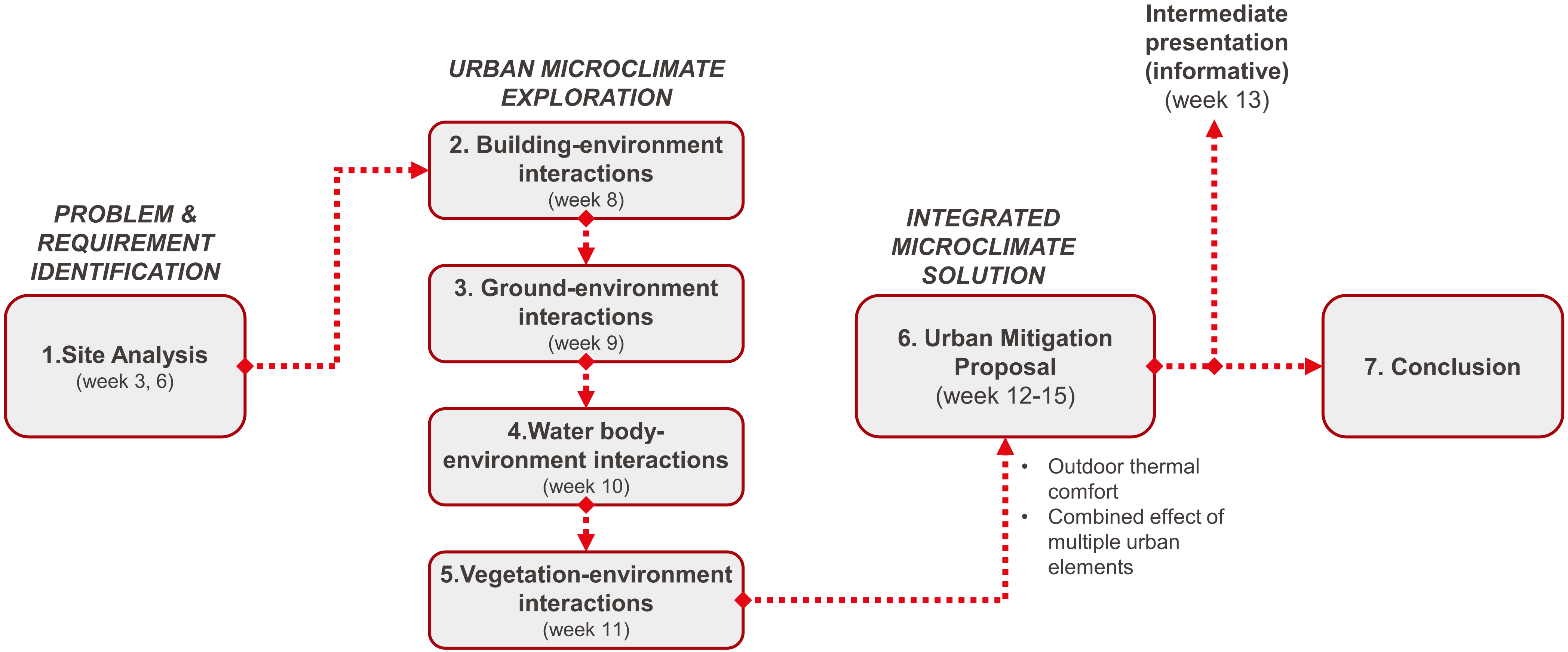
EPFL Group Project: Overview

- **Each simulation introduces** a **new element** or **changes** to **the existing configuration** (base case). The urban elements *should be introduced gradually* in order to see *their individual effect*.
- **Critically analyze** the **improvement of previous simulation** (cases 1 – 5) and **propose integrated solution** (case 6, you may introduce new elements different from cases 2-5).
- **Holistic assessment** of **energy balance** and **microclimate condition** (including **outdoor thermal comfort**).

Case Number	Base Case	Building Modification	Ground Modification	Water body Modification	Vegetation Modification	Integrated Solution
Potential modifications	---	*Building geometry, wall and roof material, green wall and roof*	*Ground cover, permeable surface, cool pavement*	*Fountain, pool, pond (depth, size, shape of water body)*	*Vegetation type, configuration, green space size and shape*	*Combined effects, impact on thermal comfort*
1	✓					
2	✓	✓				
3	✓		✓			
4	✓			✓		
5	✓				✓	
6	✓	✓	✓	✓	✓	✓

Group Project: Project structure

- For more details, see ***project description*** *and* ***report structure template****.*



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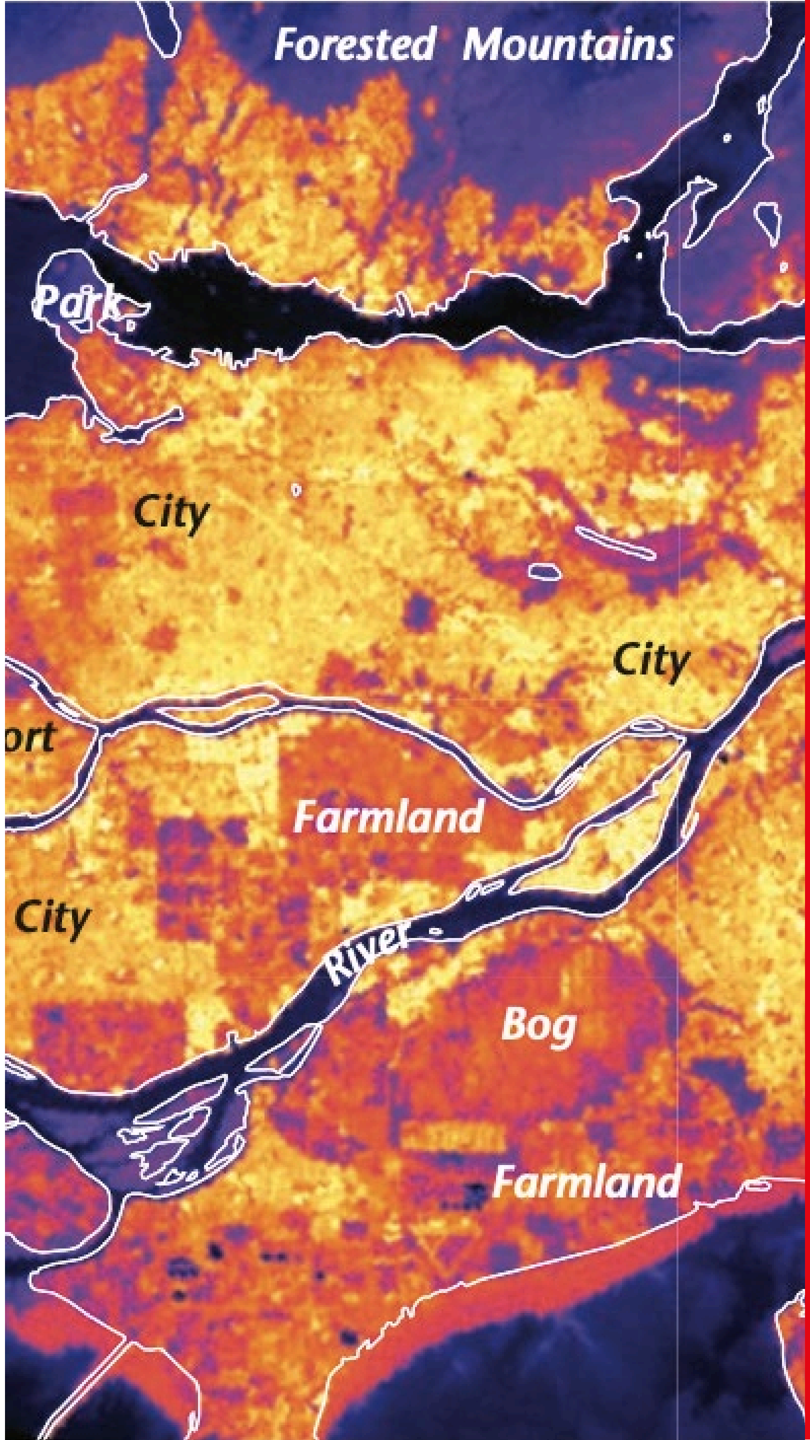

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Introduction: Cities

- **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:

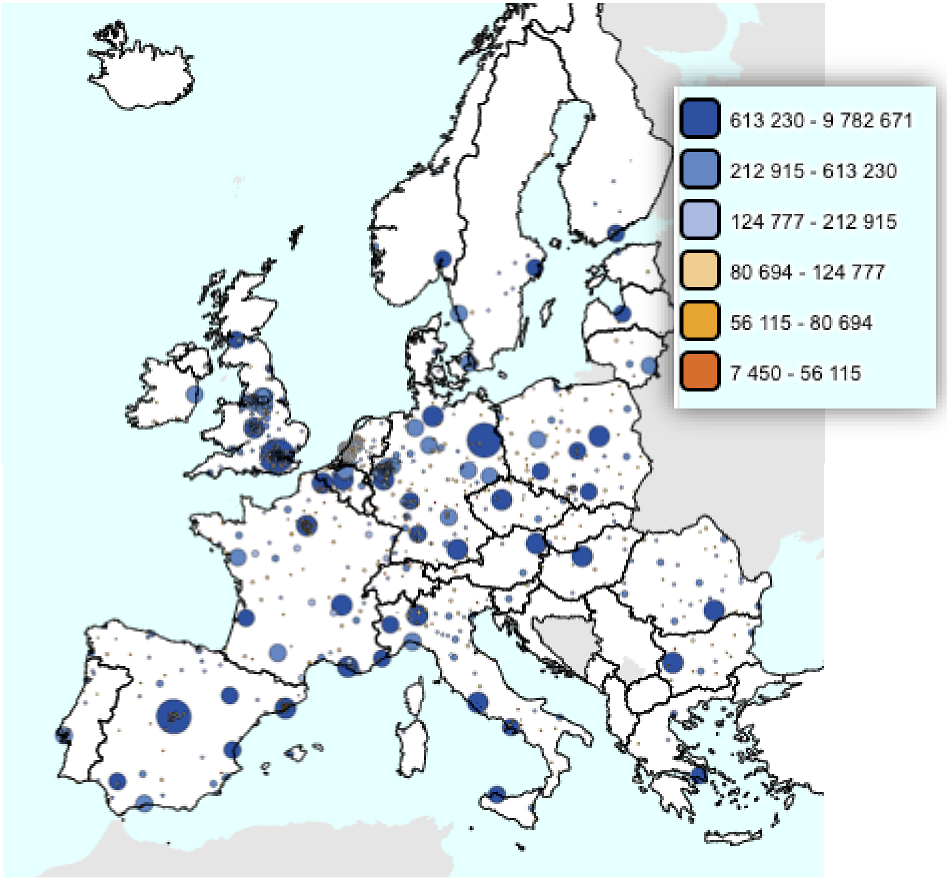

Image from websource

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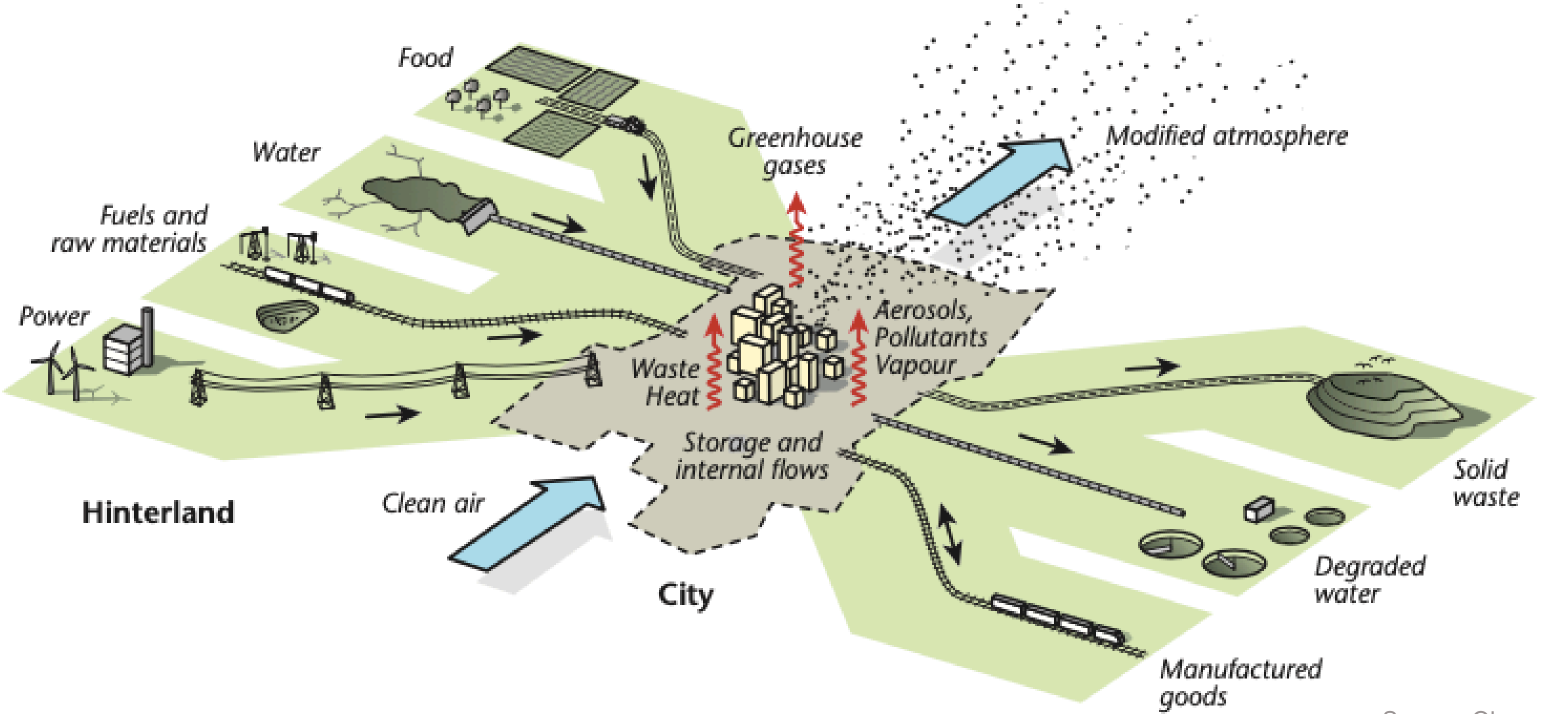
Introduction: Urban Ecosystem

- **City**: ***integrated* open system** of **living things interacting** with **their physical environment** (Douglas, 1983).
- **Urban metabolism**: analogy of the city to a single living organism which imports and exports energy and mass and transforms materials. It cannot exist without support from the outside.



Source: Oke, Urban Climates, p. 4

Interaction between the Built and Natural environments

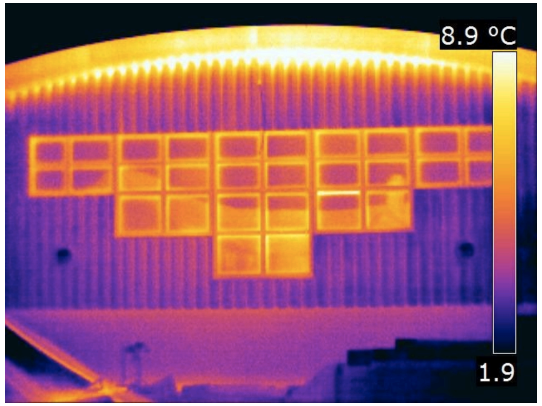
- The **city environment** and **its microclimate** *defers* from the one of its surroundings:
  - *Accumulation* of solar energy that *form heat islands*
  - *Decrease* of the local wind speed
  - *Decrease* solar irradiation and hours of sunshine due to *pollution*
  - More *intense* flooding with faster run-off
- 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*.

Built Environment ⟷ Natural Environment

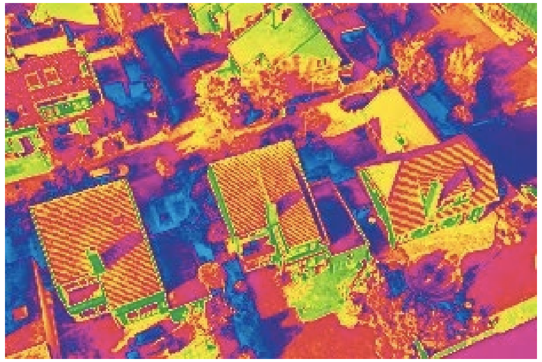
Exchange of

Heat
Water vapor
Particles
(pollution, pollen, virus)

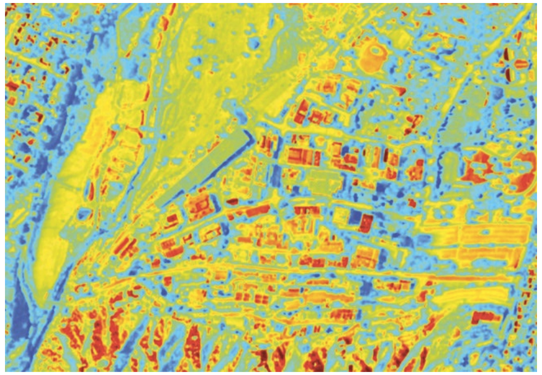
Local (building)



Neighbourhood



City



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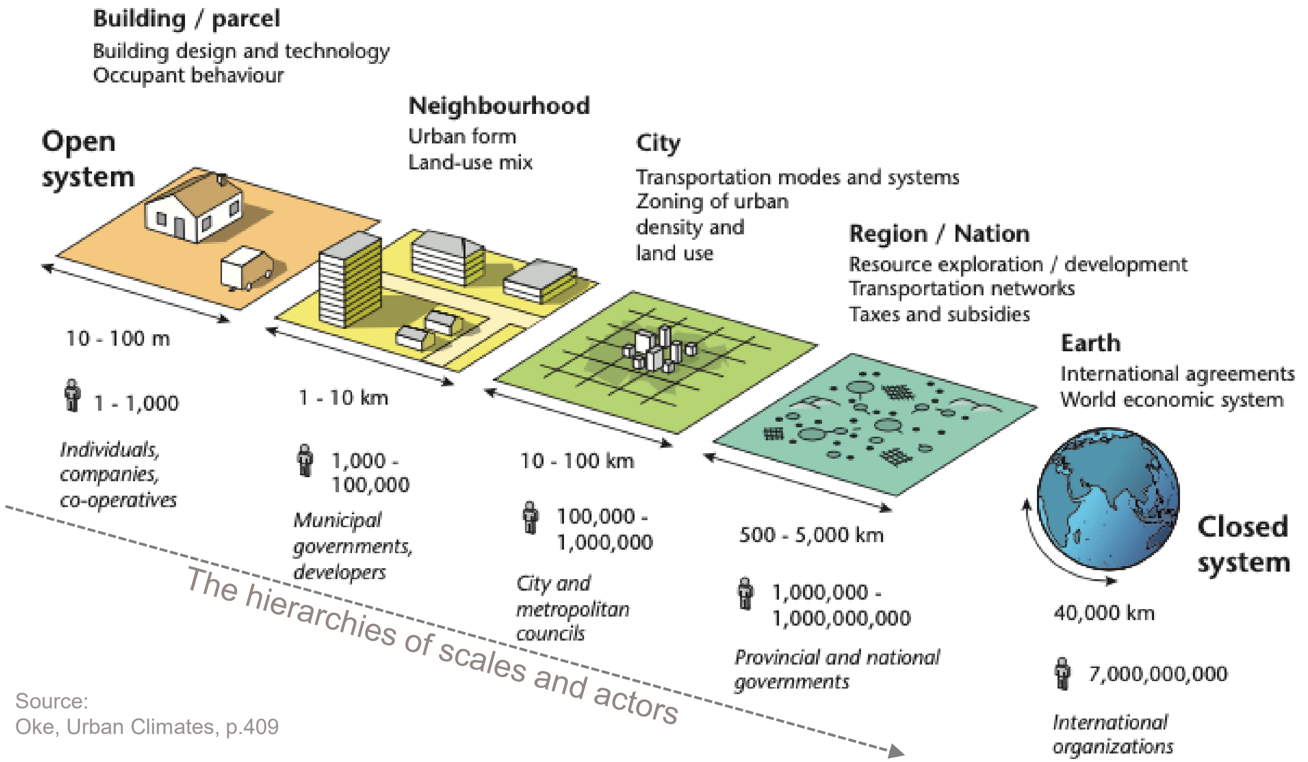
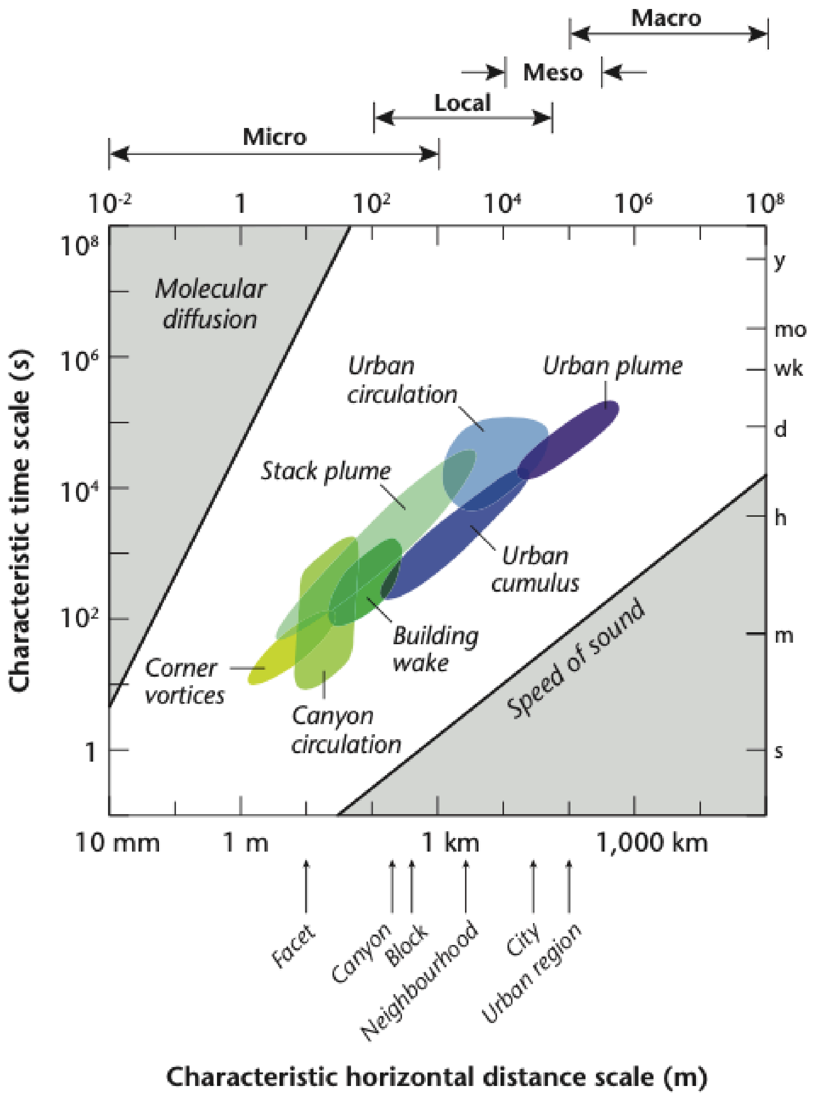
Urban characteristics: Urban scales

- 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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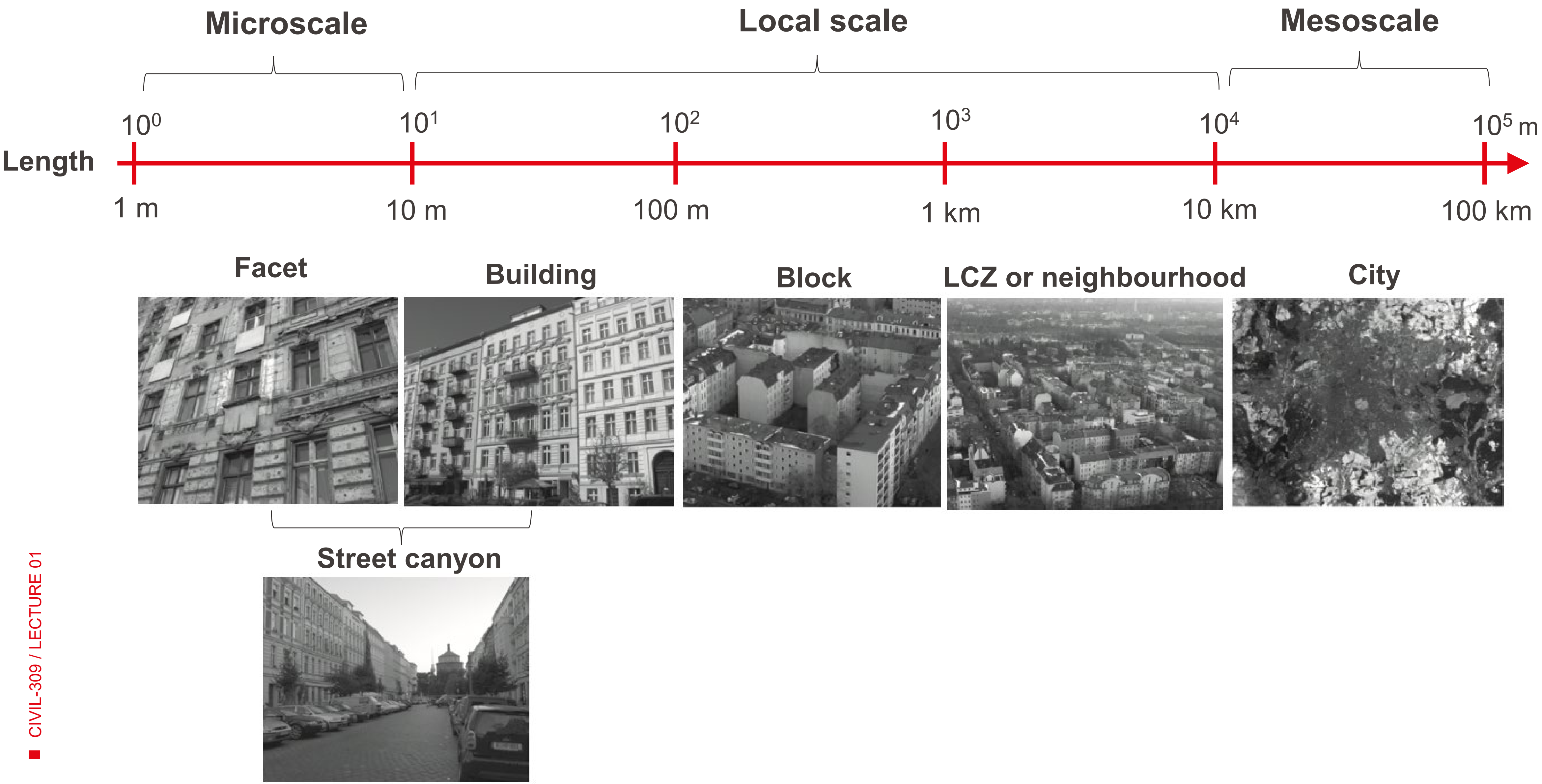
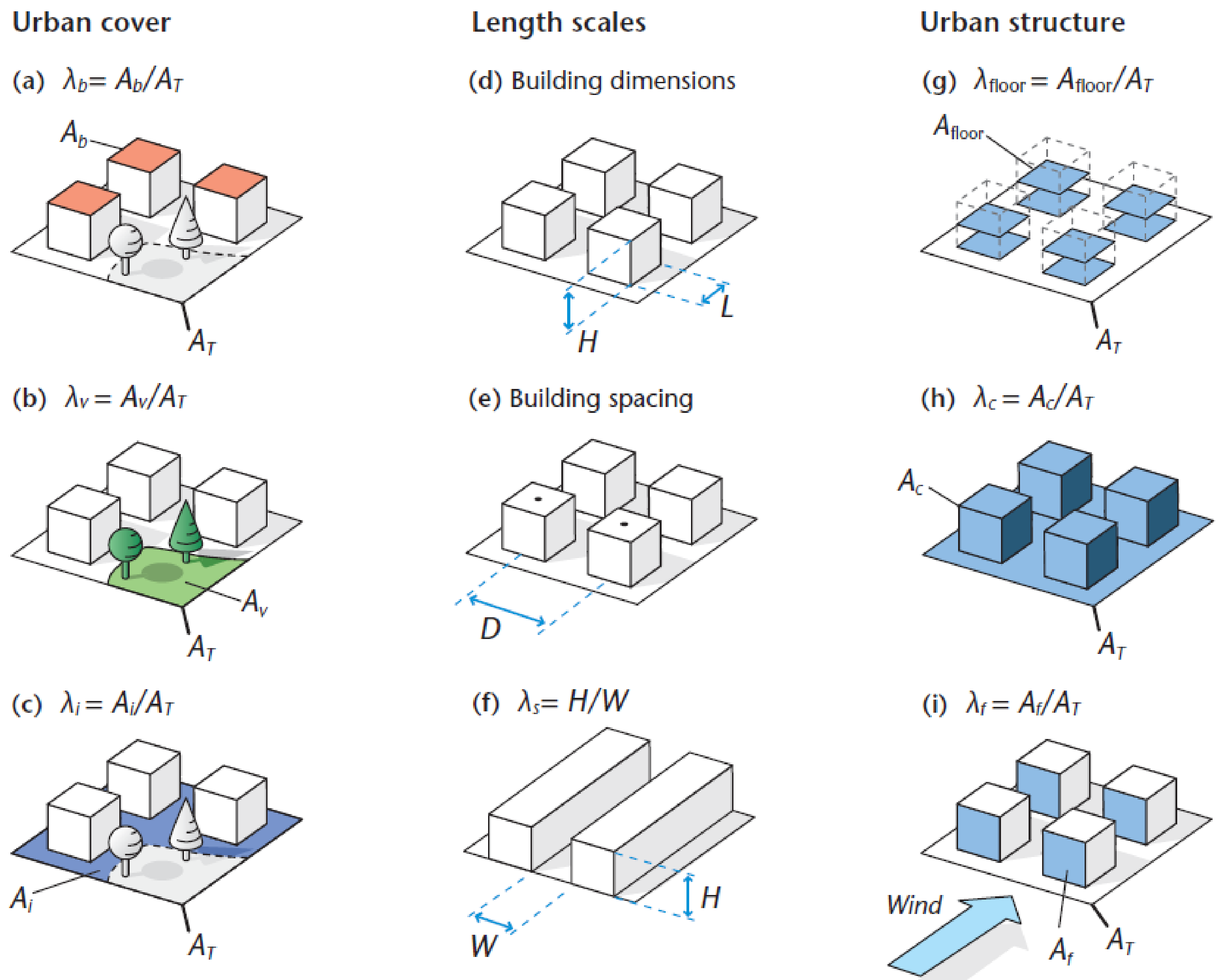
Urban characteristics: Urban scales



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)

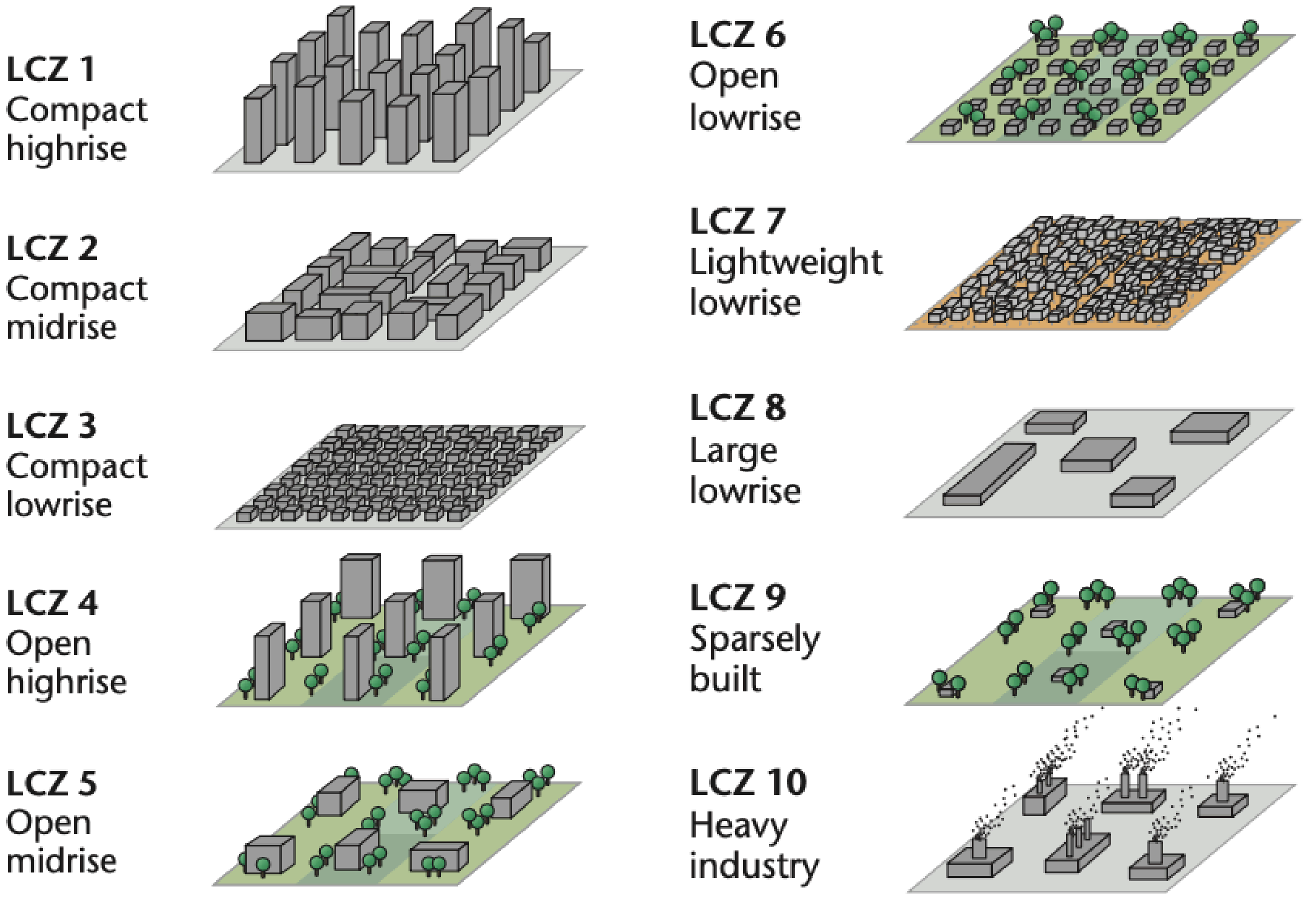
Parameters describing urban cover, length scales and urban structure:

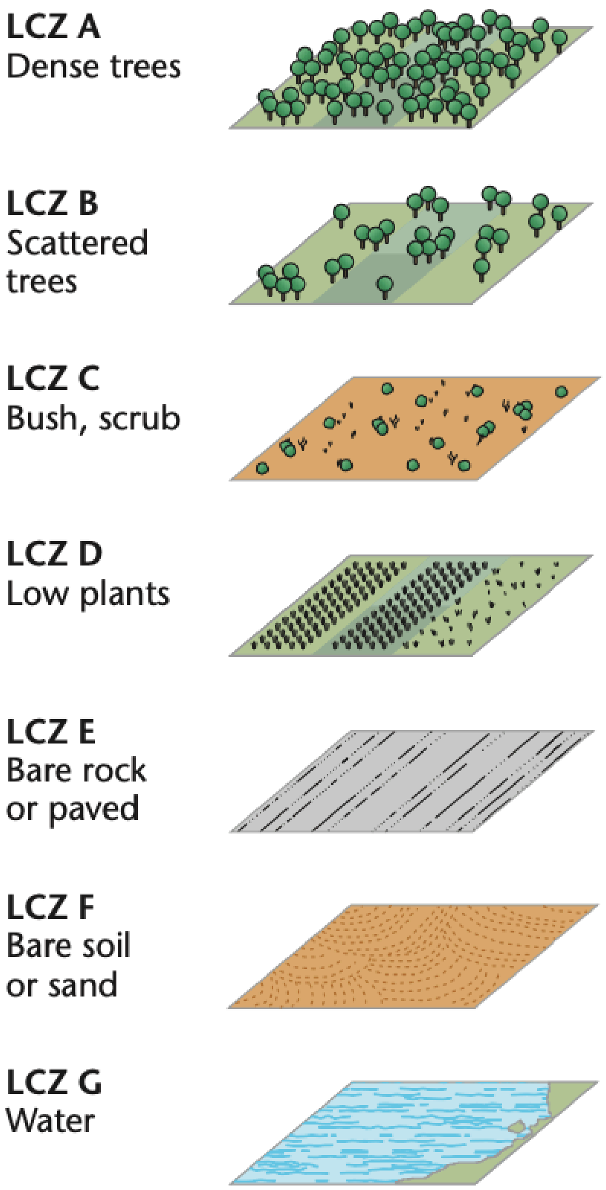


Source: Oke, Urban Climates, p. 21-22

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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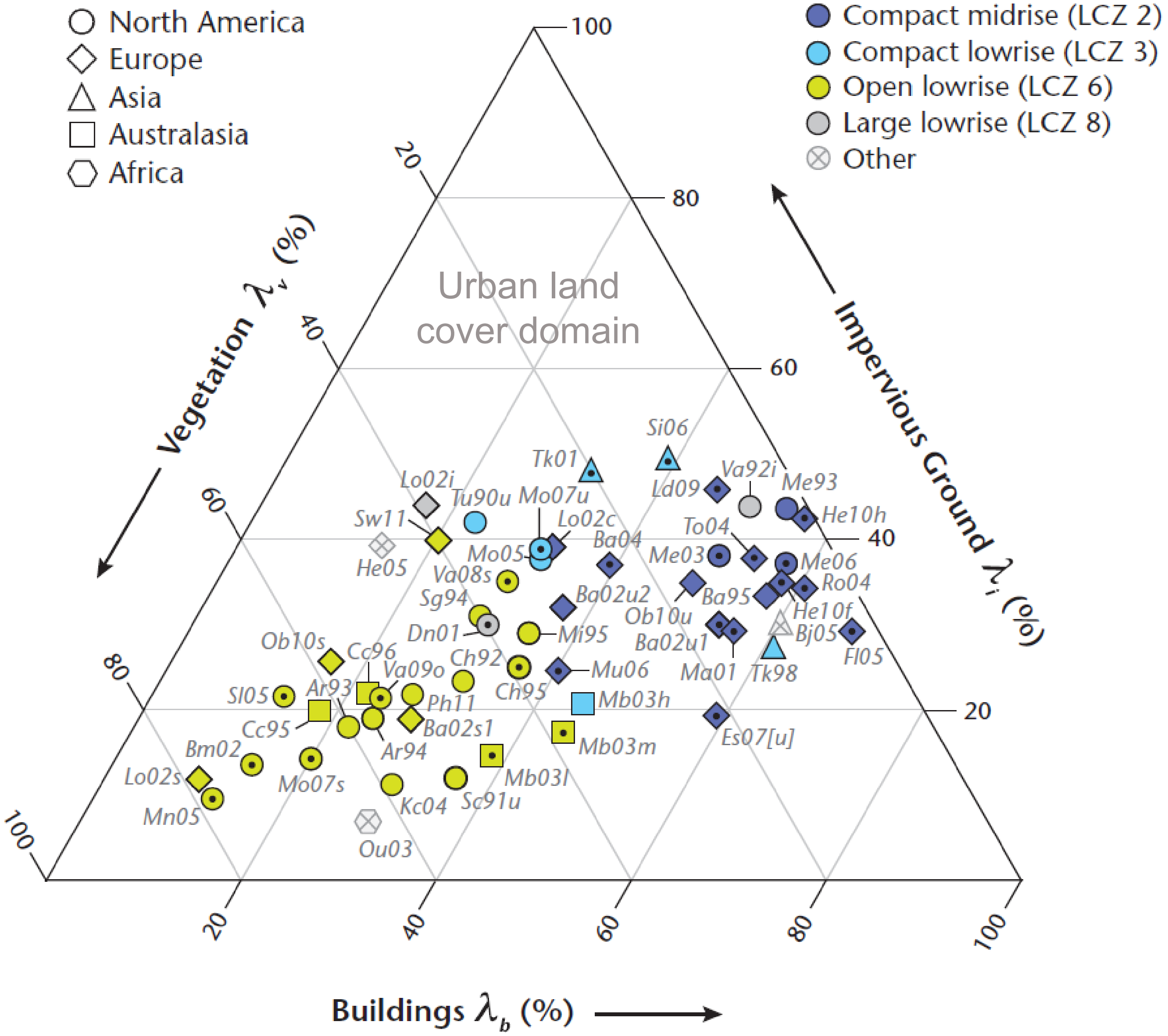
Urban characteristics: Local Climate Zones (LCZ)

- **Local climate zone LCZ**: **categorization** of the **urban landscape types** per their ability to *modify* **local surface 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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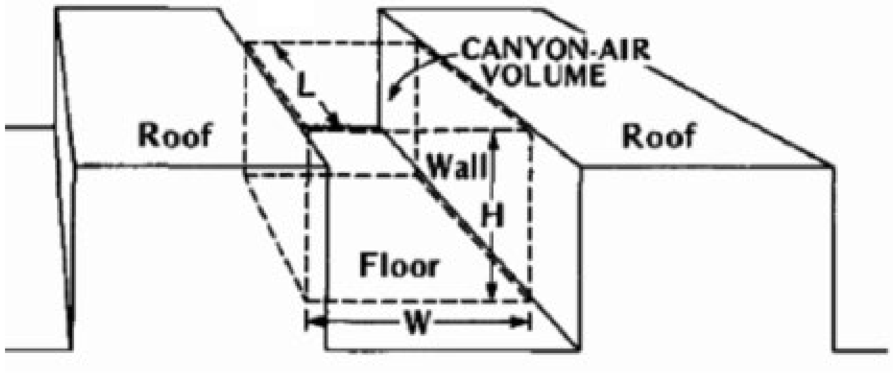
Urban characteristics: Street canyon

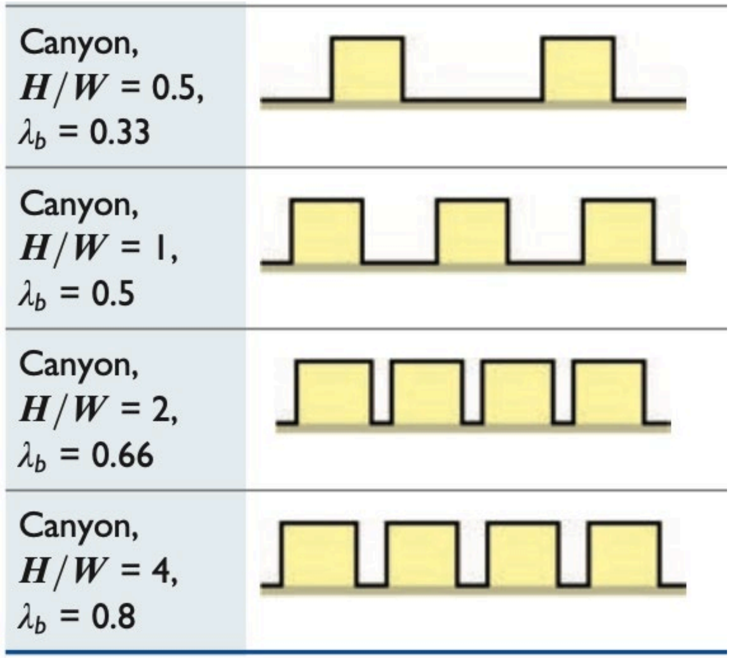
- **Urban canyon** or **street canyon**: structure *formed* by *a street with its three facets*: **canyon floor** (usually a road), and **two sides** (the walls of flanking buildings)



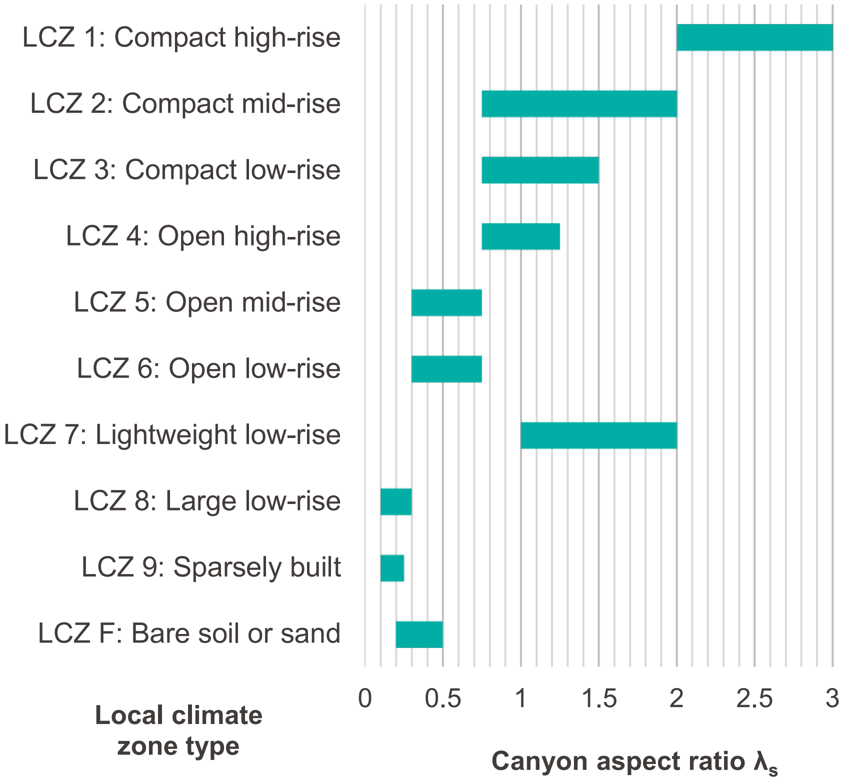
- **Canyon aspect ratio λ_s**: the ratio between the **height (H)** and **width (W)** of an urban canyon

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

- 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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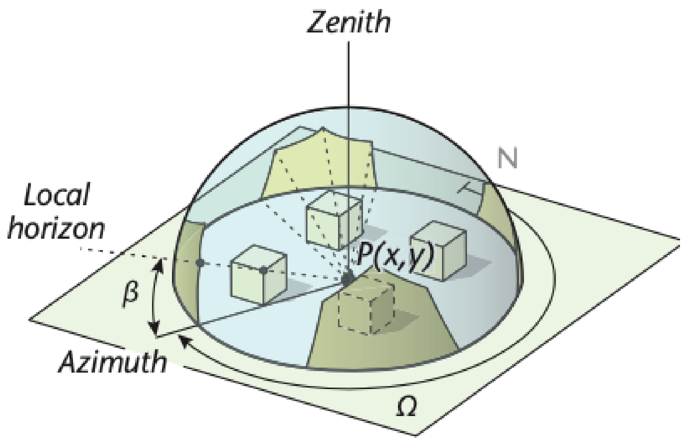
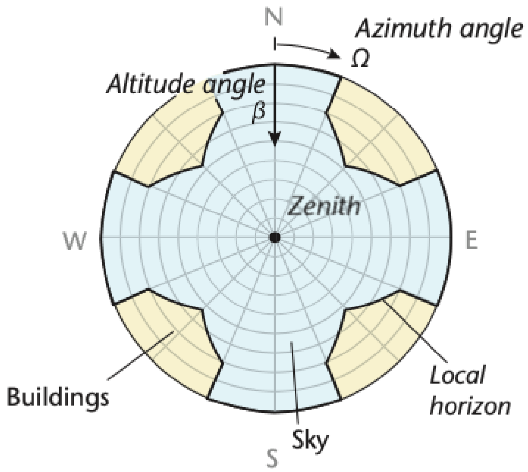
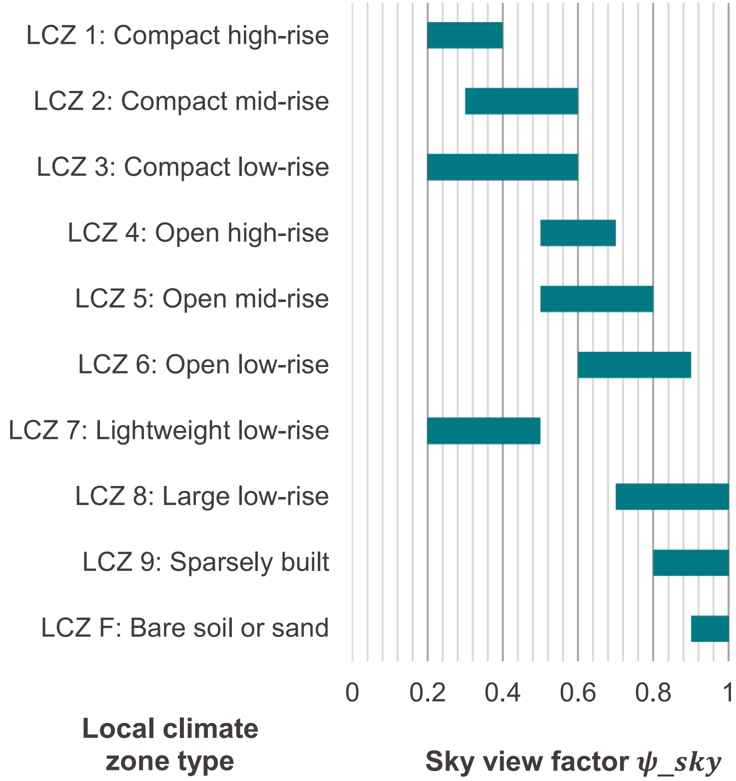
Urban characteristics: Sky view factor

- **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.





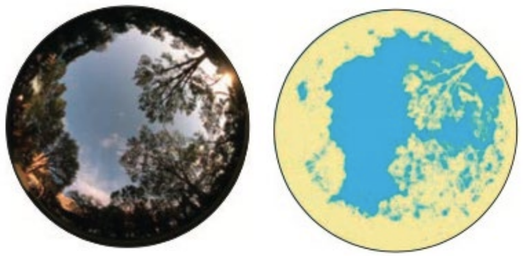
Source: Oke, Urban Climates, p. 23



Parking lot:

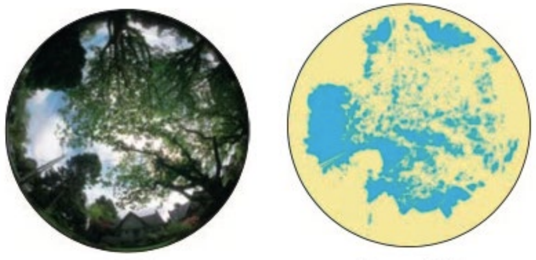
$\psi_{sky} = 0.97$

Park:



$\psi_{sky} = 0.48$

Tree-lined street:

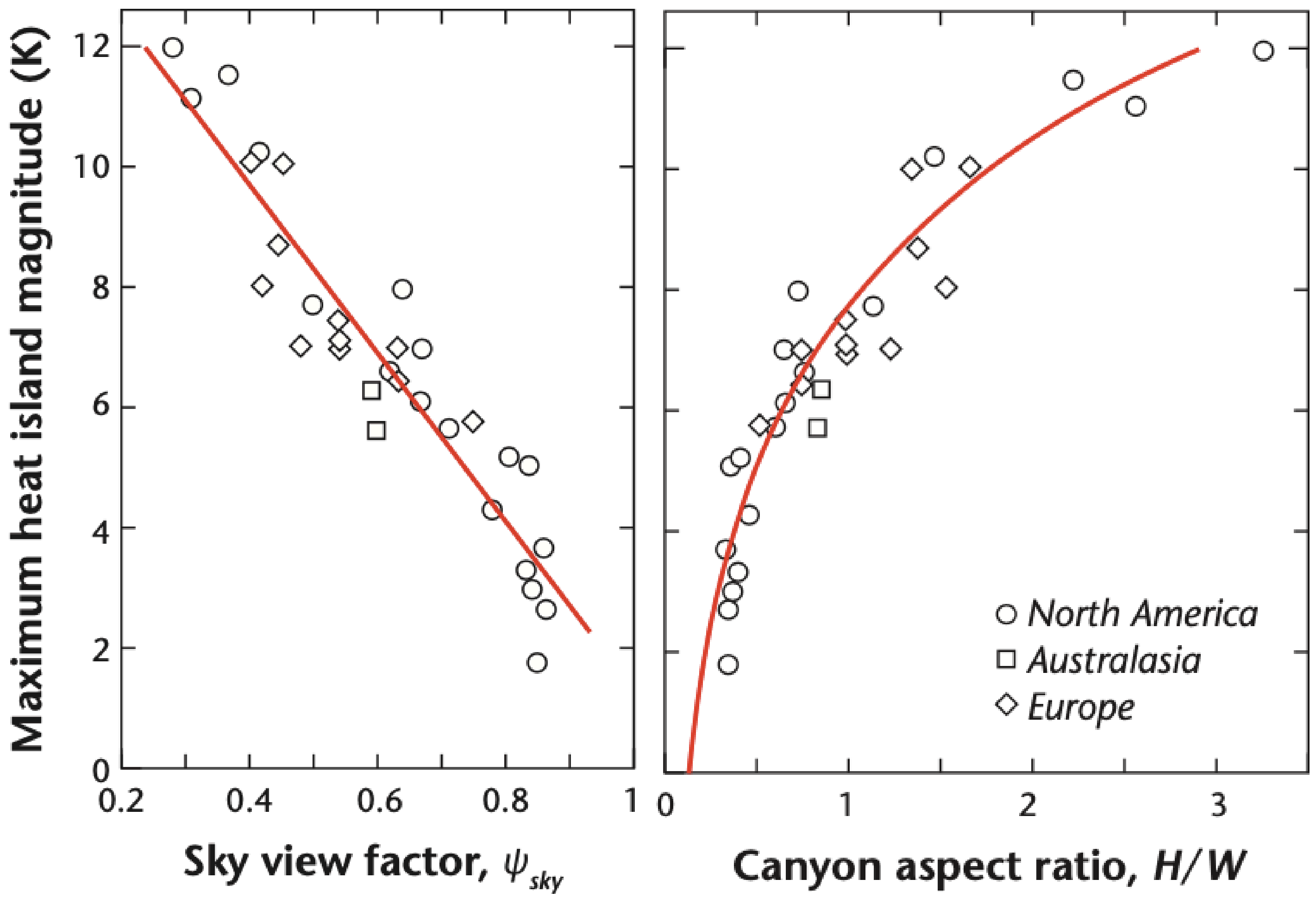


$\psi_{sky} = 0.21$

Source: Oke, Urban Climates, p. 24

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

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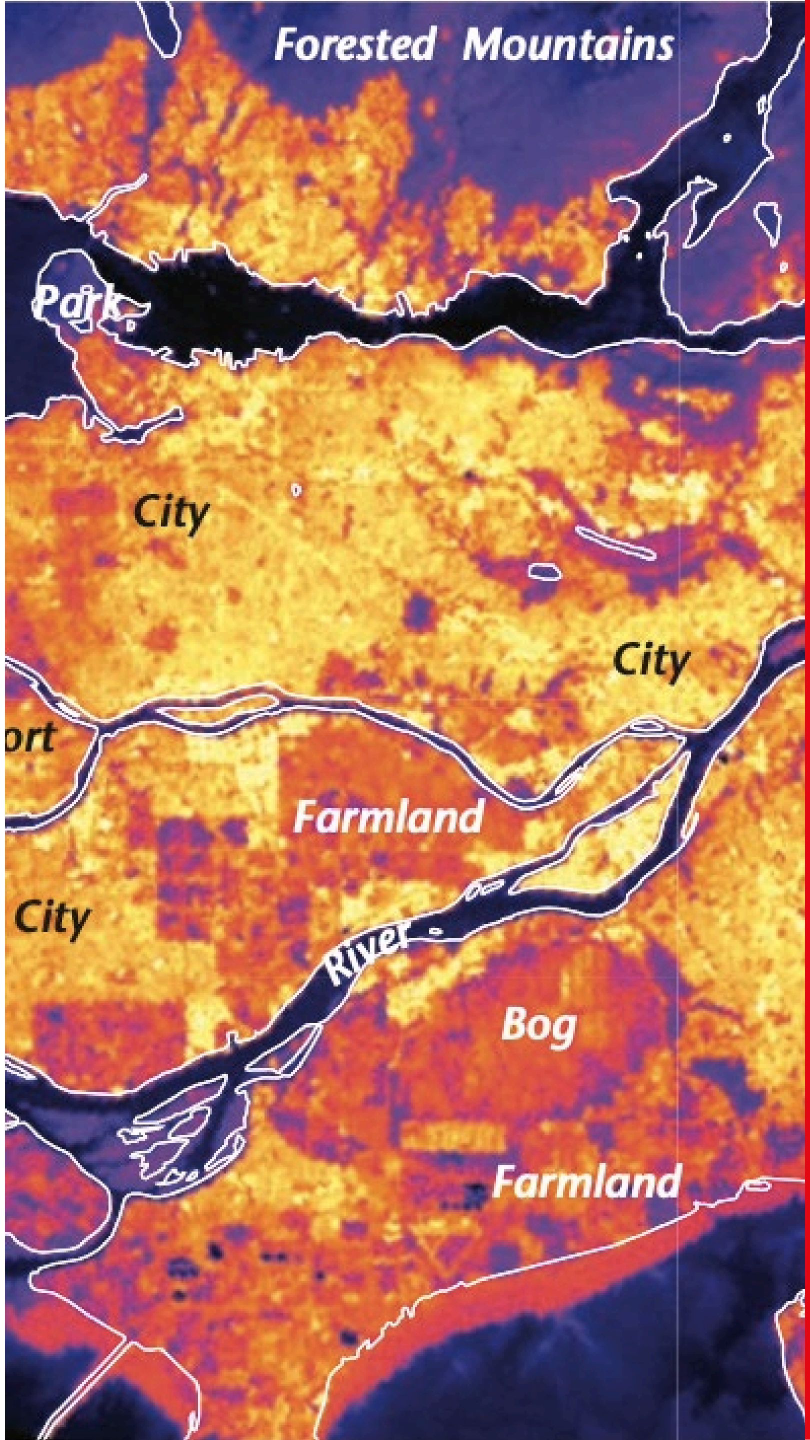


CONTENT:

I. Introduction to the course
- Content, schedule, grading
- Group project overview

II. Urban characteristics
- Overview of properties
- Local climate zones (LCZ)
- Street canyon aspect ratio (λ_s)
- Sky view factor (ψ_{sky})

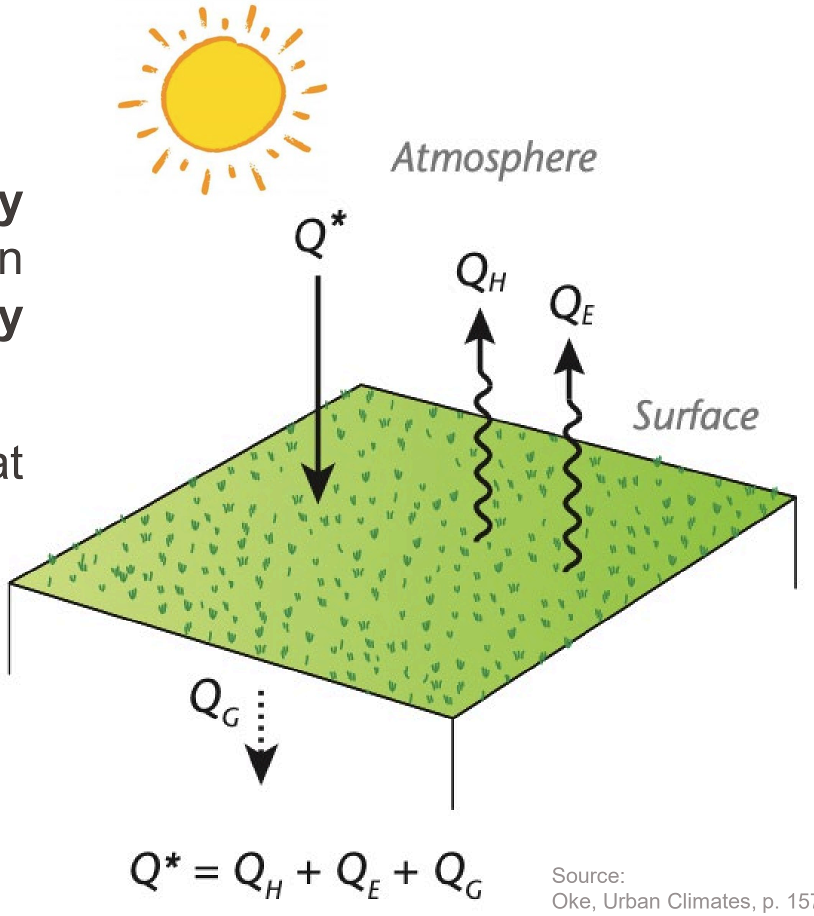
III. **Urban Heat Island (UHI) effect**
- **Energy balance for cities, anthropogenic heat**
- **UHI definition, types, magnitude, dynamics**
- **Consequences**

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):

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

Net allwave radiation heat flux — Sensible heat flux — Latent heat flux — 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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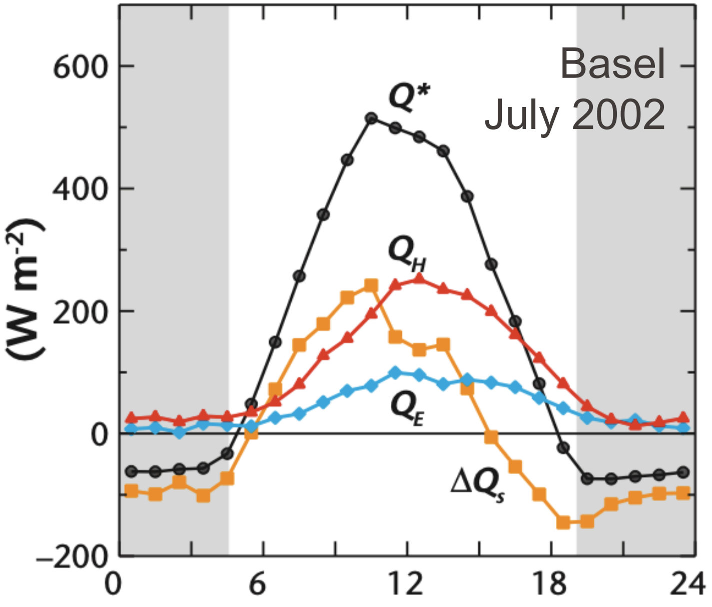
Energy Balance in Urban areas

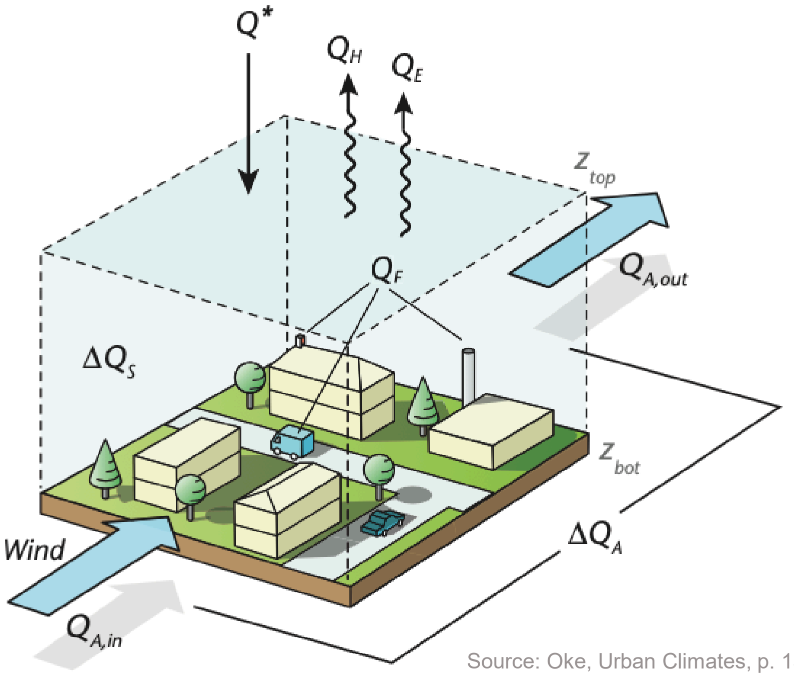
- **Urban areas** *differ significantly* from **rural areas** by their *surface geometry* and *properties*. It leads to *a very different dynamic* of *physical processes*.
- The **energy balance** of an **urban element** is made of **a control volume** that contains **sources** and **sinks** of **energy**.
  - 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, Anthropogenic 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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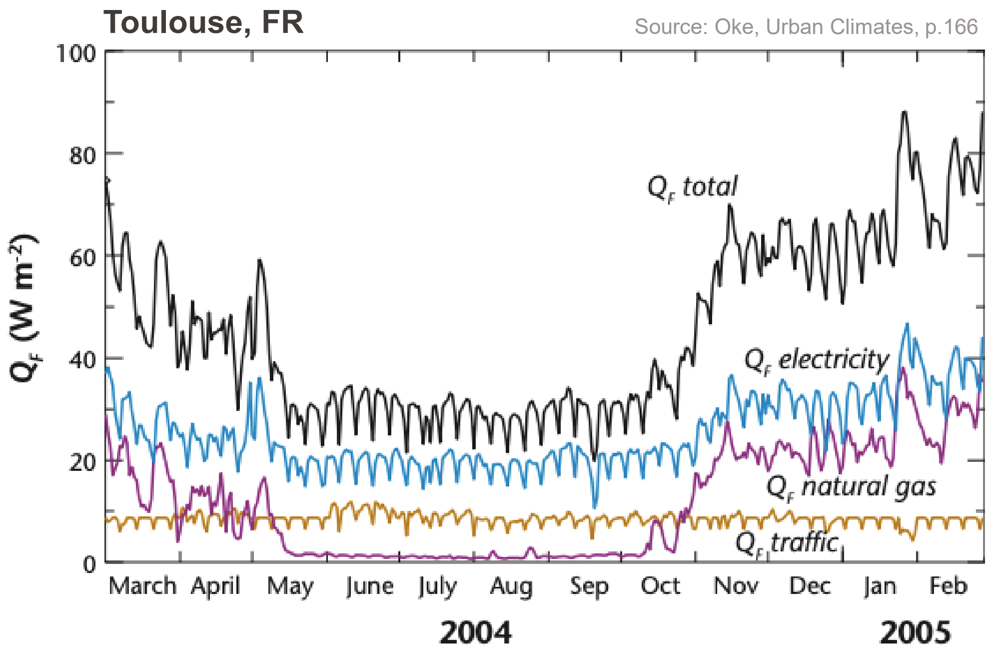
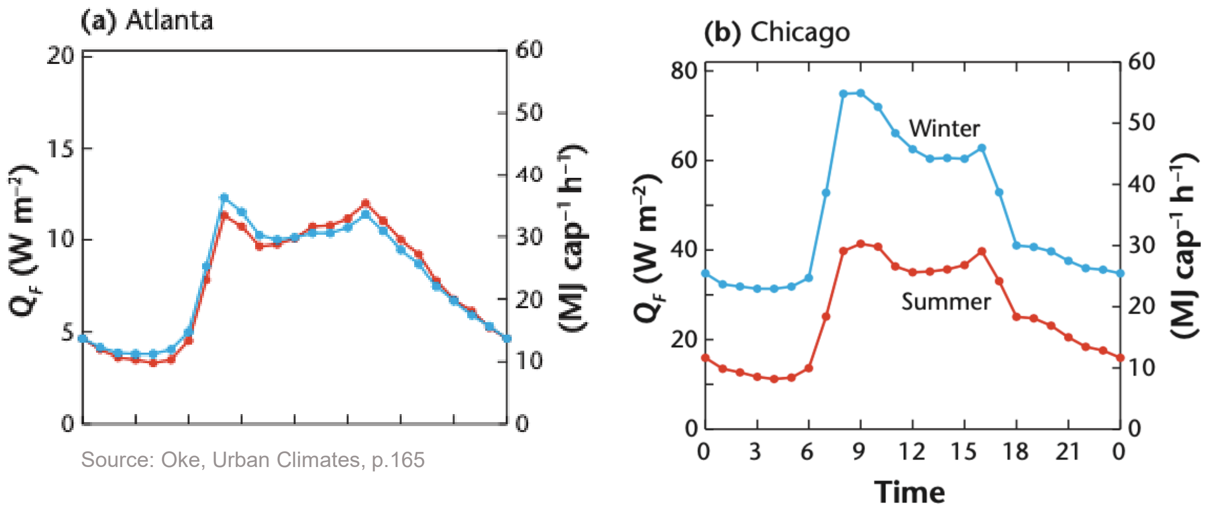
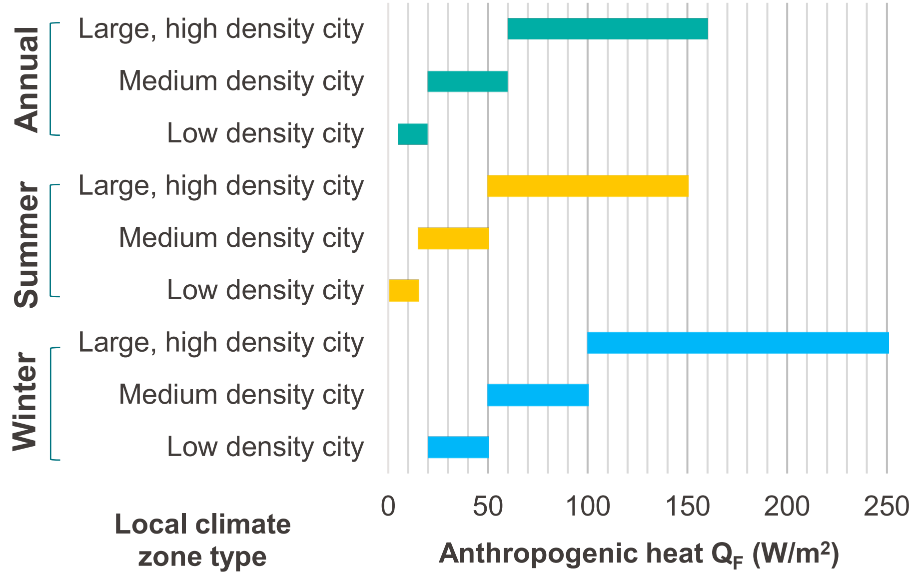
Anthropogenic Heat

- **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.



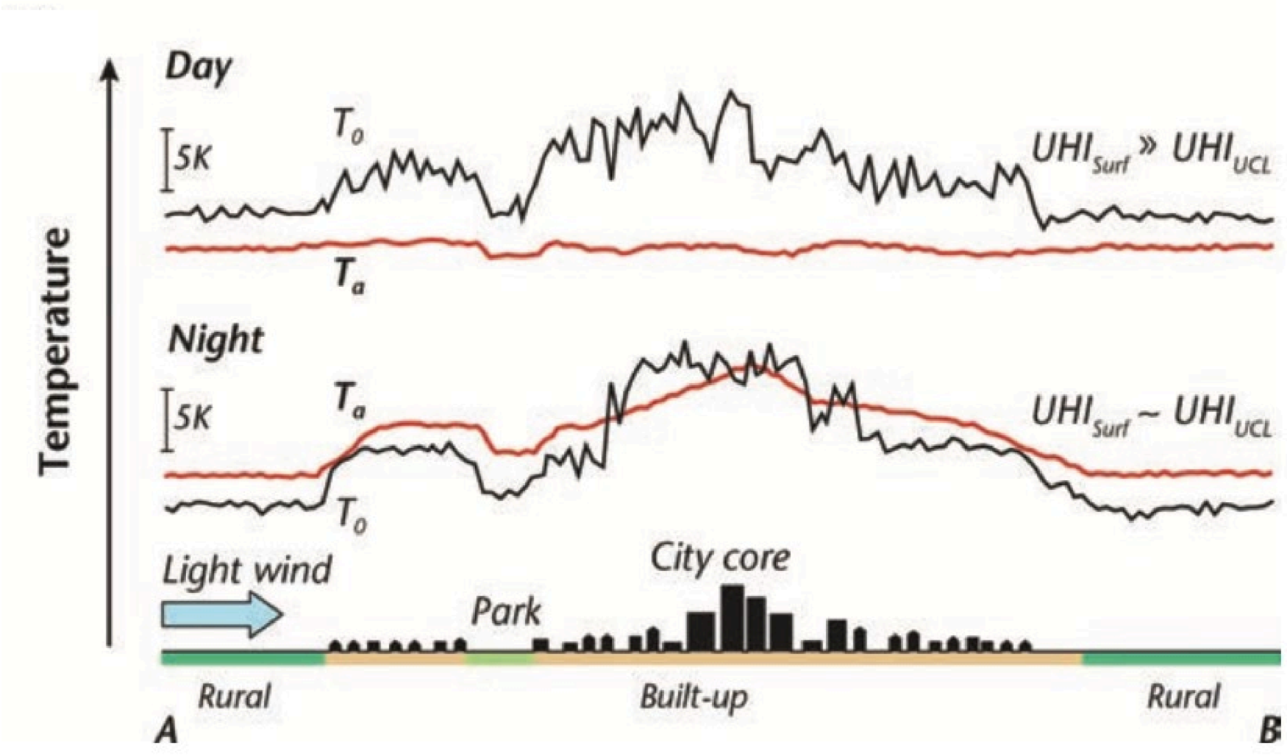


Source: Oke, Urban Climates, p.165



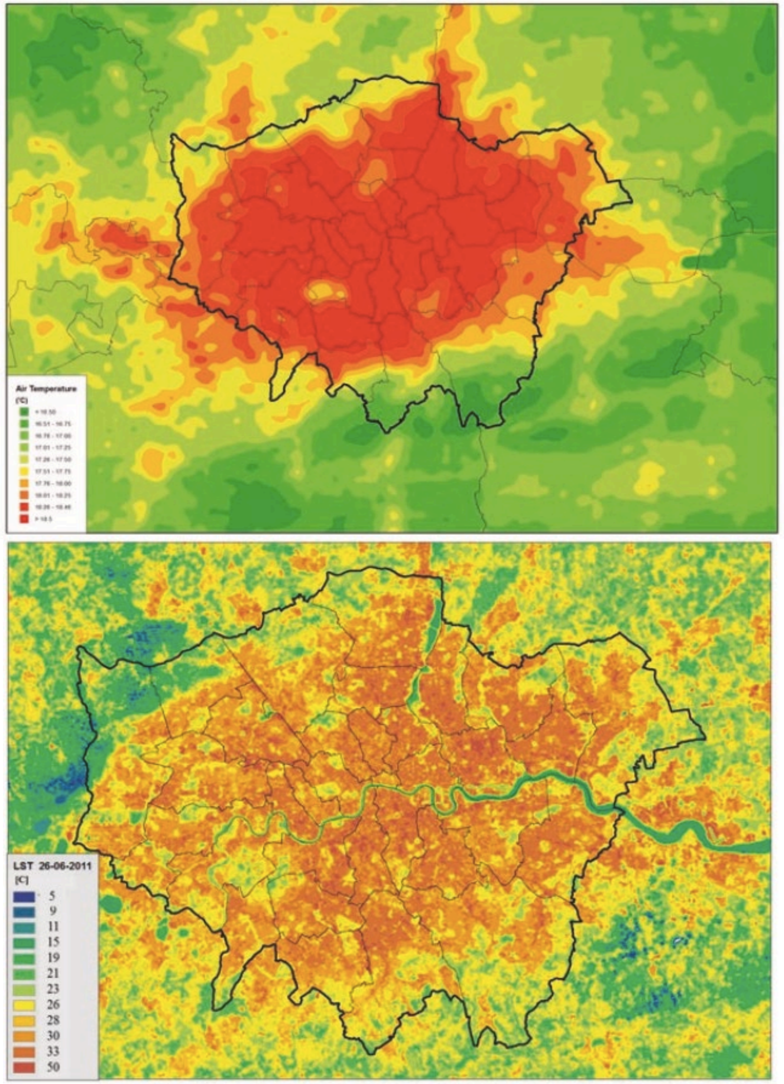
Urban Heat Island (UHI) effect

- **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**

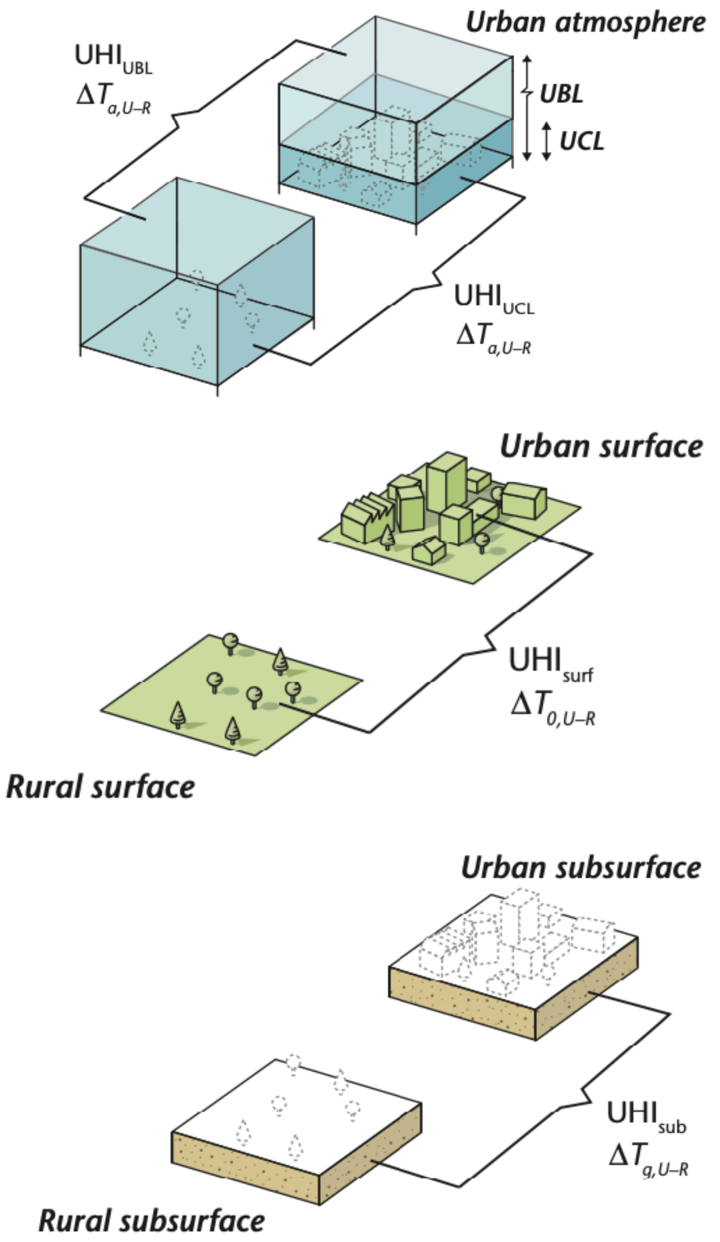


Source: Palme & Salvati, Urban microclimate modelling for comfort and energy studies, p. 33

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 effect*
- **UHI types**:
  - Air temperature → Urban canopy layer UHI
  - Surface temperature → Surface UHI
  - Ground temperature → Subsurface UHI

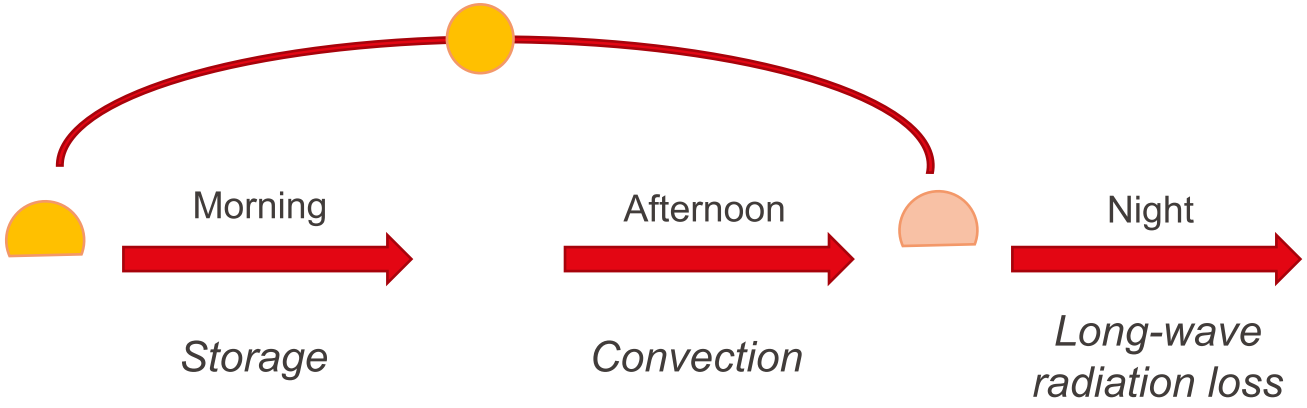
Global change ↑ Urban canopy layer UHI ↑ Surface UHI ↕ Subsurface UHI



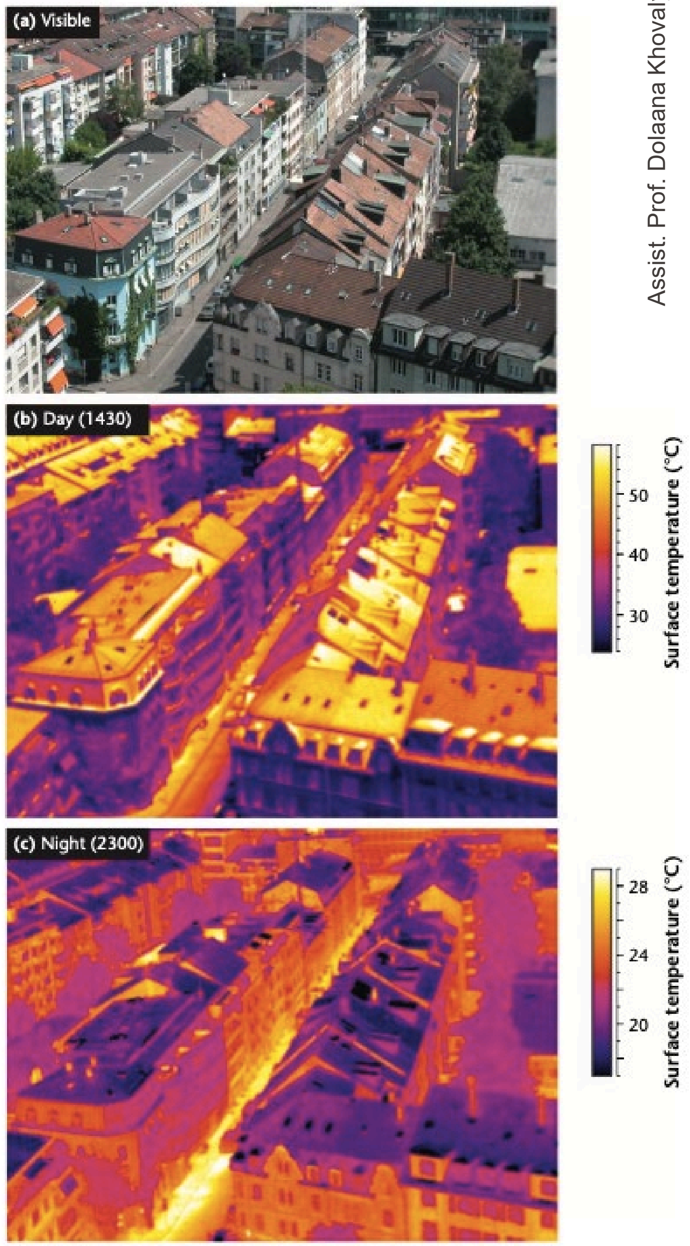
Source: Oke, Urban Climates, p. 199

Urban Heat Island (UHI): Dynamics

- **Temporal** and **spatial variation** of **each type of UHI**: UHI varies ***daily***, with ***season*** and with ***weather***.
- **Diurnal variation of UHI**: 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

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**:

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

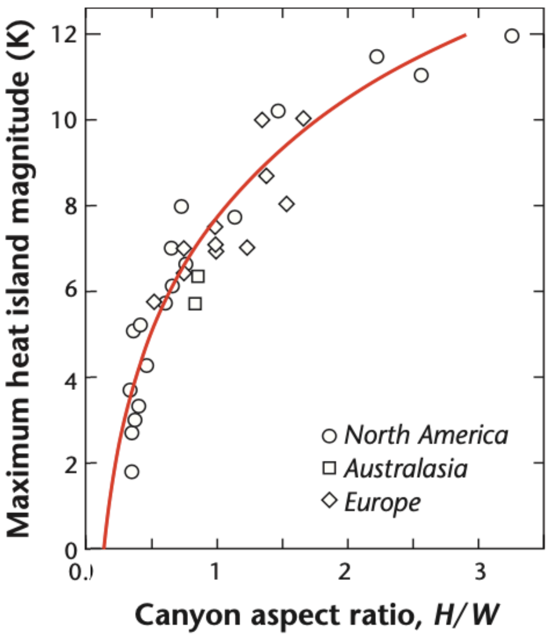
$\boldsymbol{H}\ (m)$ – average height of the streets, $\boldsymbol{W}\ (m)$ – average width of the streets

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

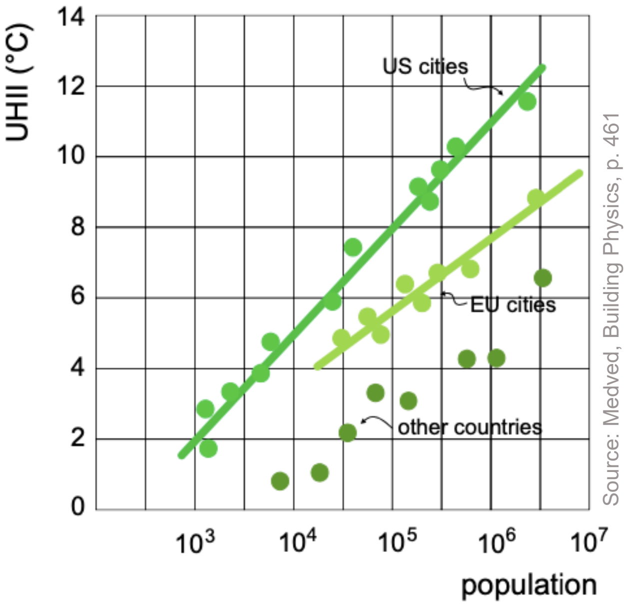
North America: $$UHI_{mag} = 2.96 \cdot \log(P) - 6.41 \quad (1\text{-}6)$$

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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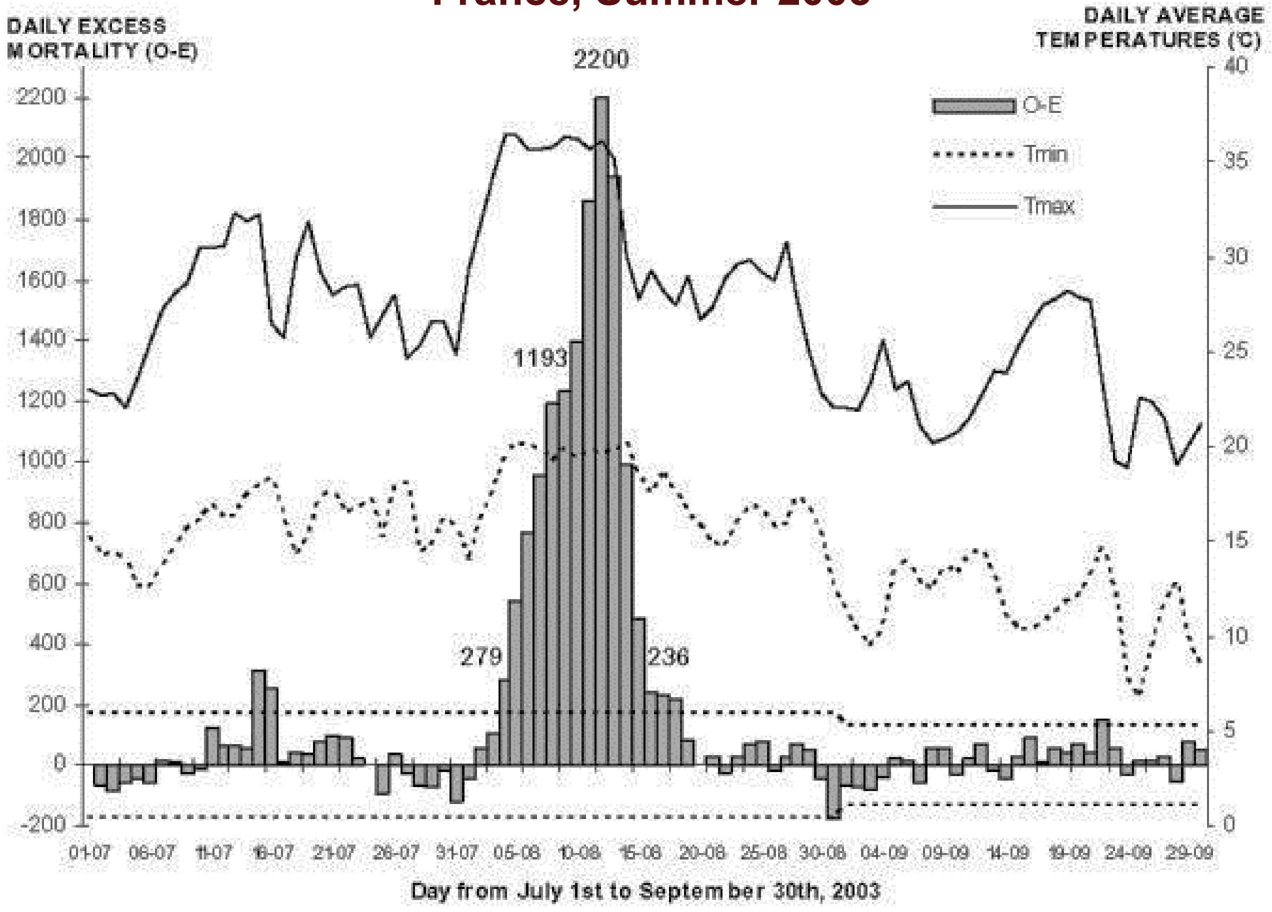
Urban Heat Island (UHI): Consequences

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**

France, Summer 2003



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

Urban Heat Island (UHI) effect

Name **urban elements** that can lead to **exacerbated UHI effect** of the district shown in the picture.

Source: Air pollution hotspots in Europe (phys.org)

Urban Heat Island (UHI) effect

- **Main causes of the UHI**:
  1. **Decreased long-wave radiation loss** to the sky due to the *increase in blockage*
  2. **Increased absorption of short-wave radiation** due to *increased reflection* and use of *low-albedo materials*
  3. **Increased absorption of long-wave radiation** due to *air pollution*
  4. **Increased sensible heat storage** due to the use of materials with *high thermal transmittance* (e.g., concrete, asphalt, brick)
  5. **Decreased evapotranspiration** due to the reduced presence of soil, water bodies, and vegetation
  6. **Increased anthropogenic heat production** due to *buildings and heavy traffic*
  7. **Decreased convective heat transport** due to a *reduction in wind speed*

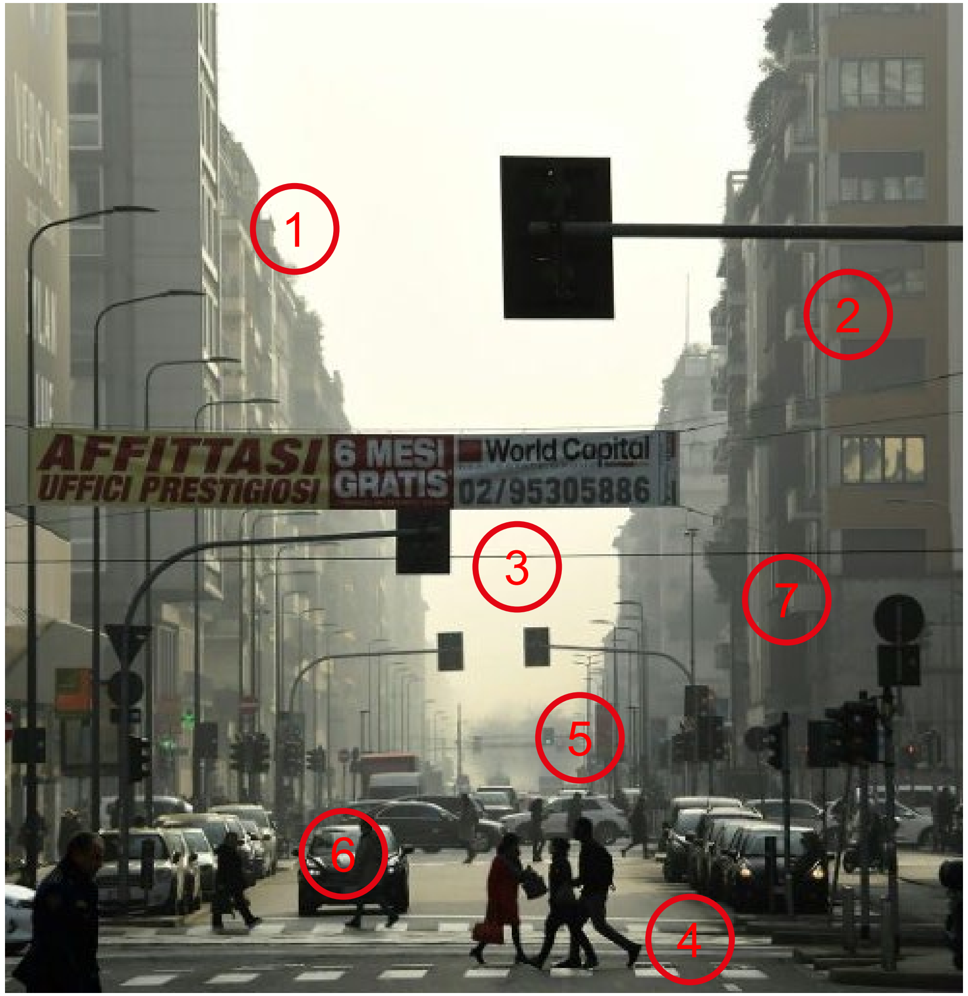
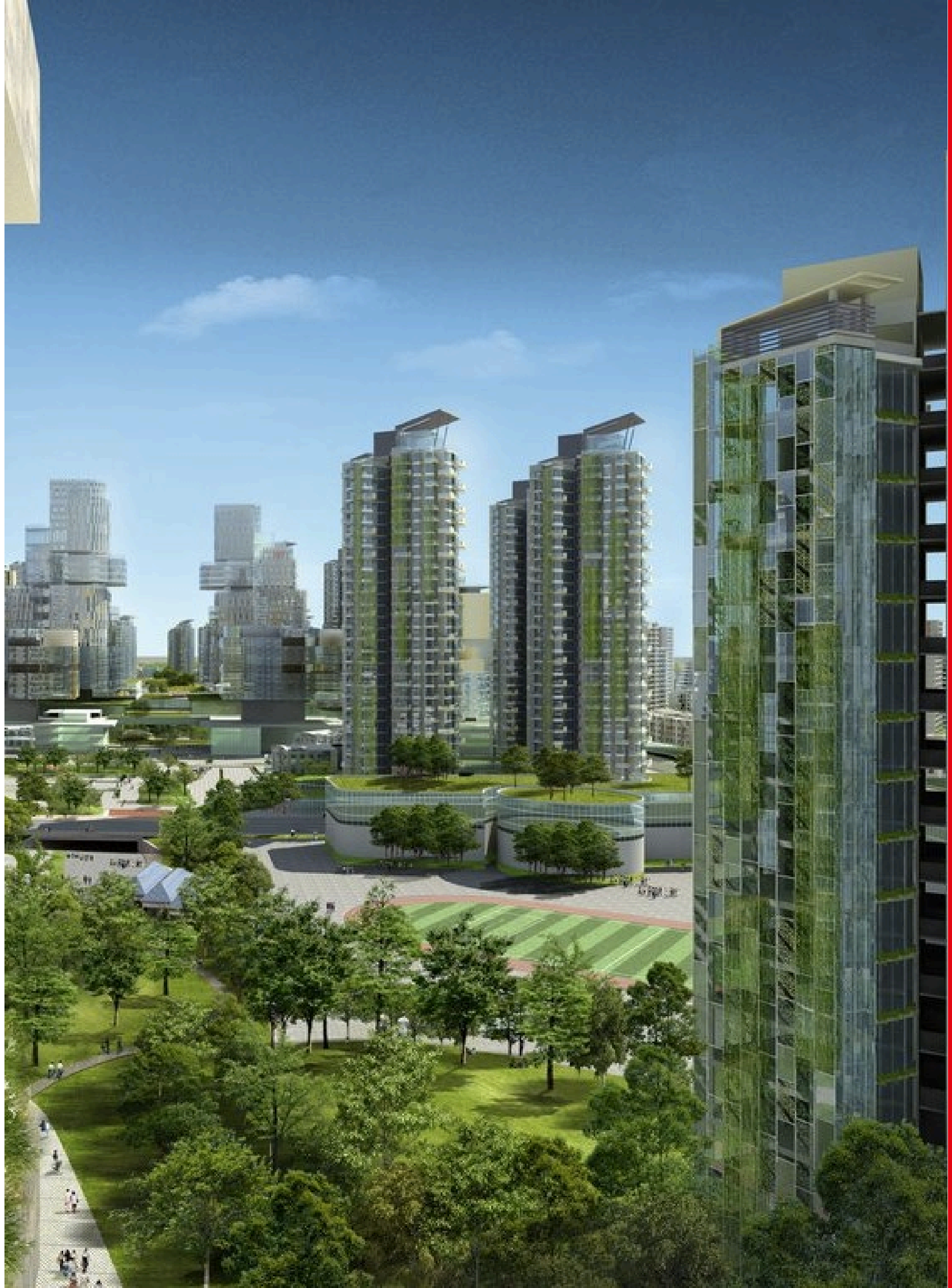


Image from: Air pollution hotspots in Europe (phys.org)

Source: Kubilay, A., Derome, D. & Carmeliet, J. (2017), 'Coupling of physical phenomena in urban microclimate: A model integrating air flow, wind-driven rain, radiation and transport in building materials', Urban Climate 24



Thank you for your attention

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