CIVIL-309: URBAN THERMODYNAMICS

**Assist. Prof.
Dolaana Khovalyg**

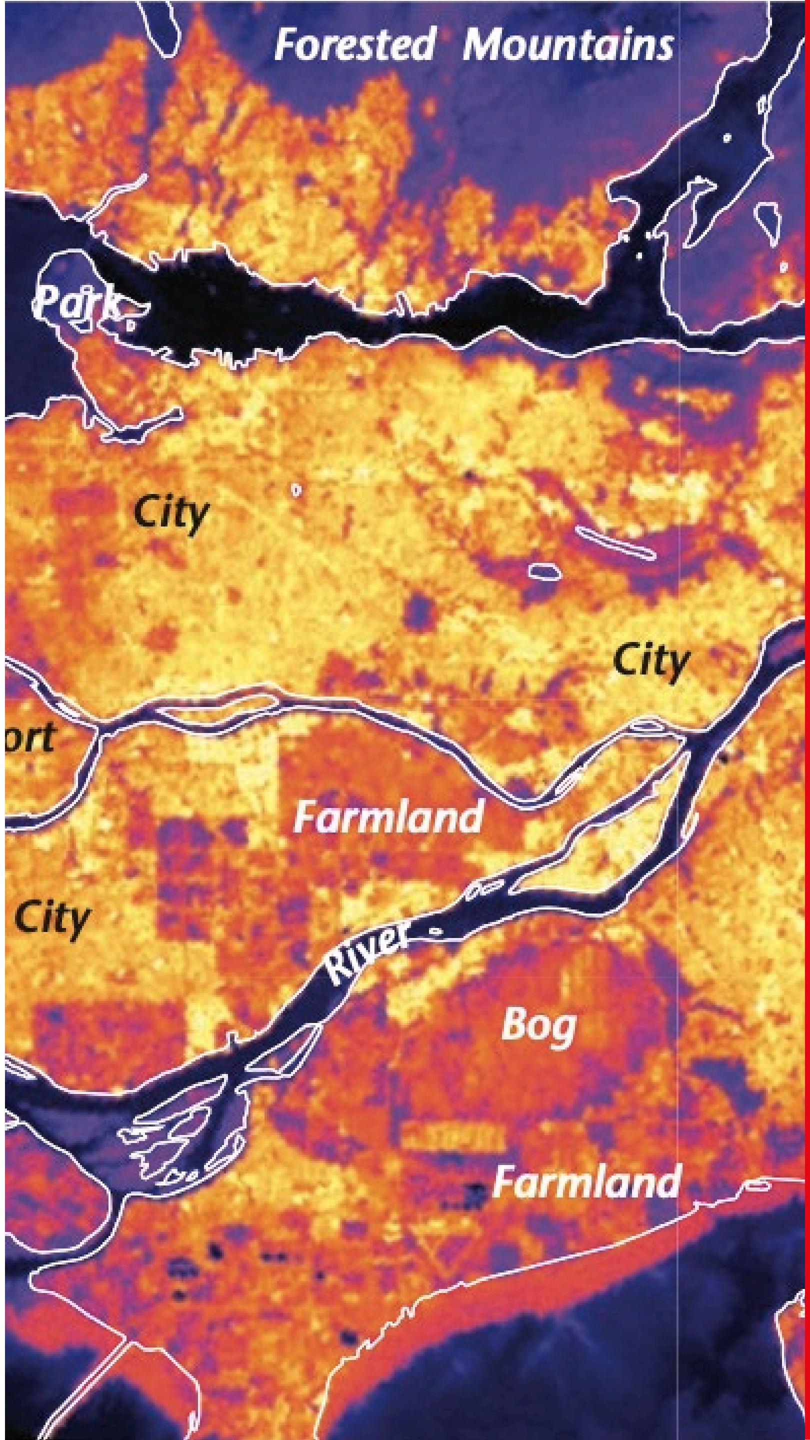
Lecture 05:

Buildings-Environment Interaction

28 October 2024

Course Schedule

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	KL
		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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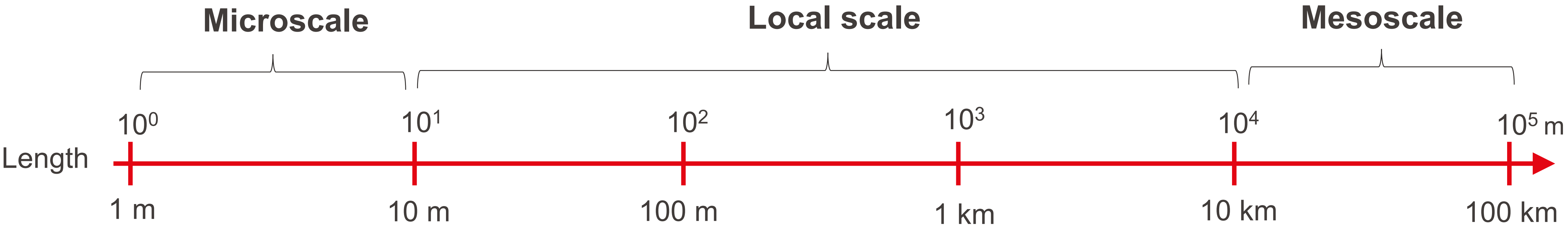
CONTENT:

Urban Scales

Reminder from L1



Microscale

Local scale

Mesoscale

Length

10^0 10^1 10^2 10^3 10^4 10^5 m

1 m 10 m 100 m 1 km 10 km 100 km

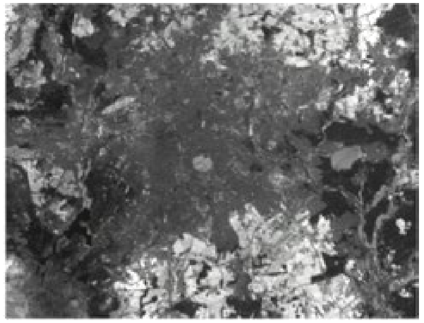
Facet/Surface

Building

Block

LCZ/Neighbourhood

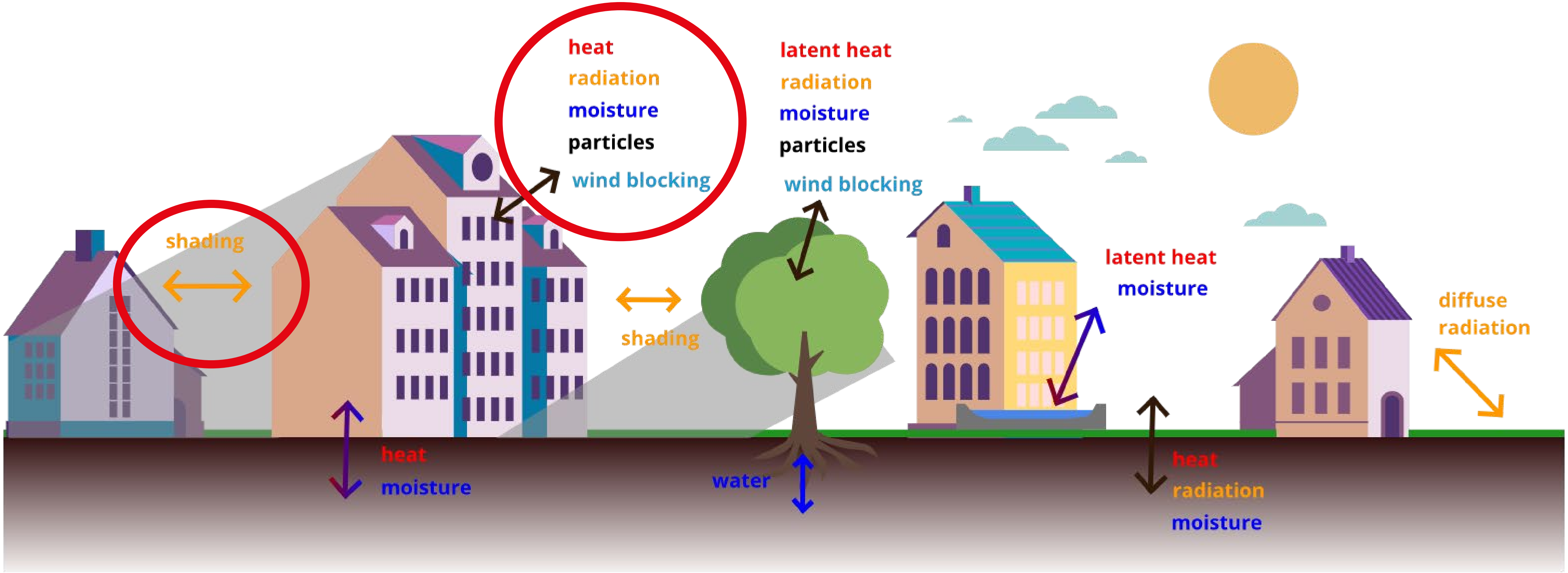
City

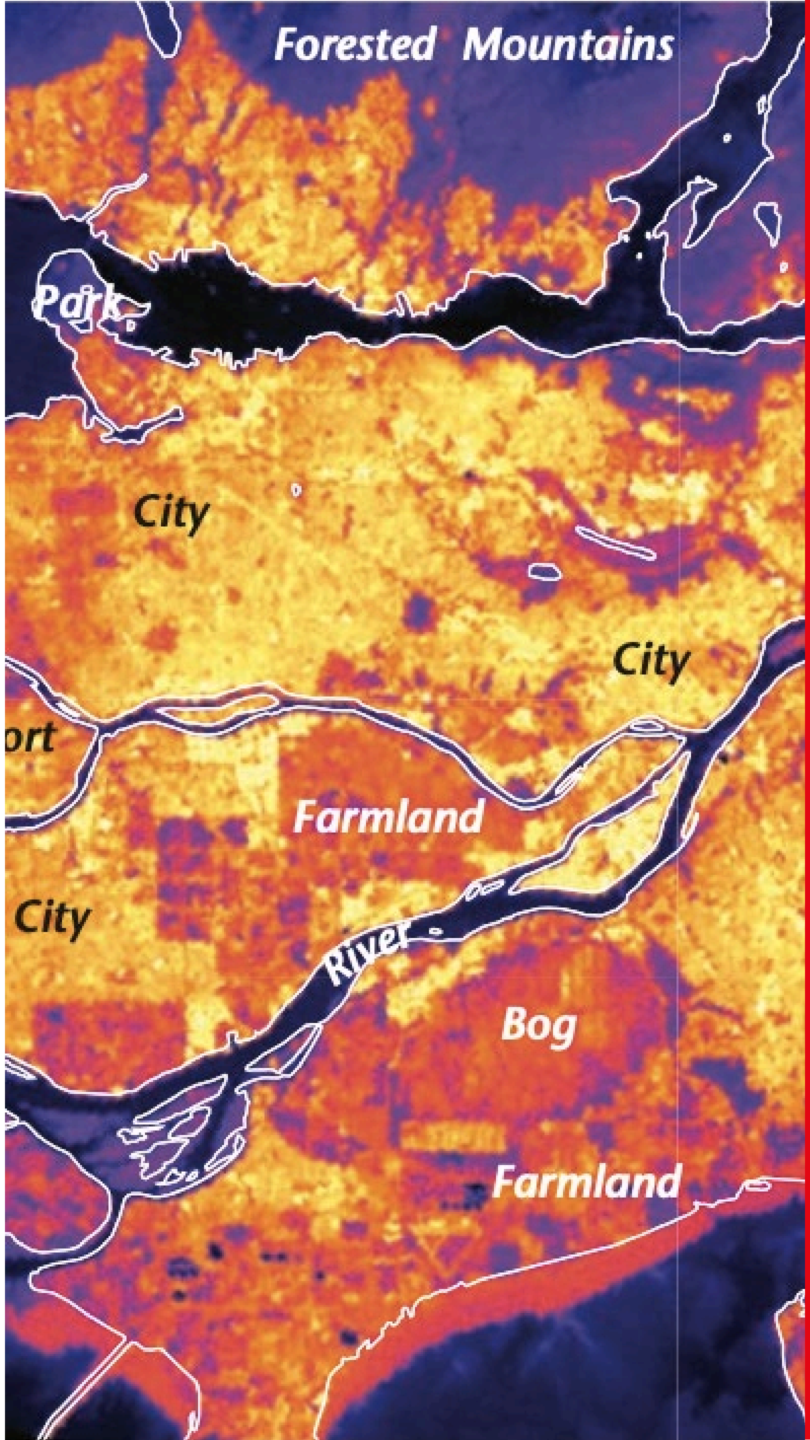


Street canyon

Building-Environment Interaction: Introduction

- **Buildings** *interact directly* with their **surrounding atmosphere** by exchanging **heat**, **moisture**, and **particles**.
- **Radiation exchange** happens with **the surrounding urban elements** in addition to the **Sun.**
- **Positioning** and **shapes of buildings** affect **the wind flow** at the **neighborhood scale.**
- **Buildings** also *interact* with the **ground** directly in contact *by exchanging* **heat** and **moisture**.

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Surface Energy Balance

Reminder from L1

Assist. Prof. Dolaana Khovalyg

- 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:**

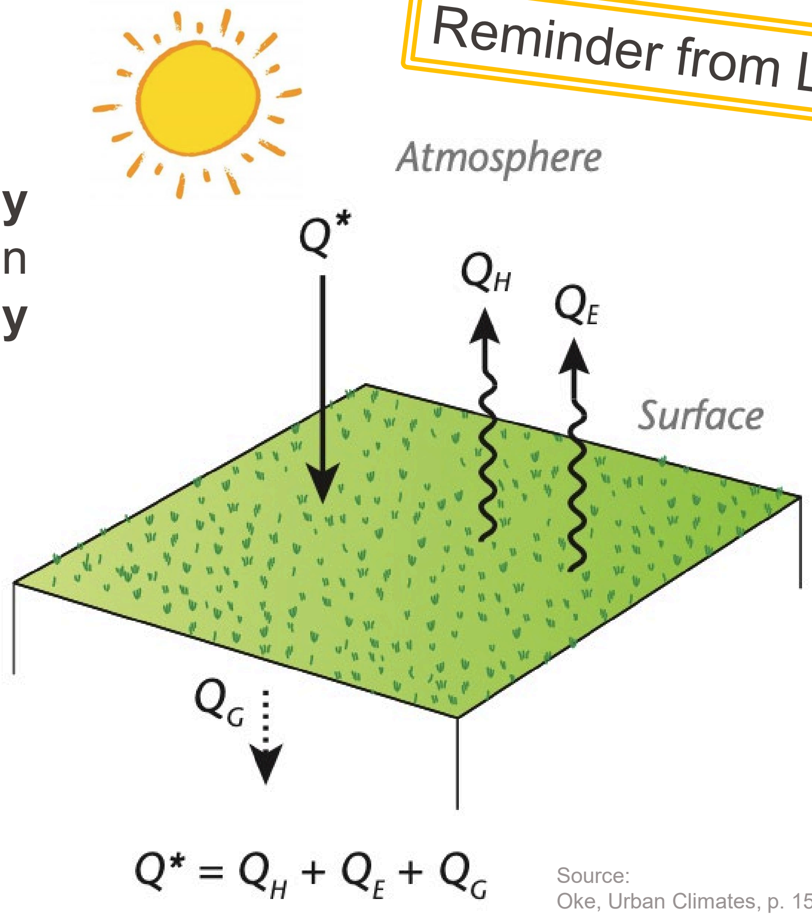
$$Q^* = Q_H + Q_E + Q_G \quad (W/m^2) \qquad \text{(1-2)}$$

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

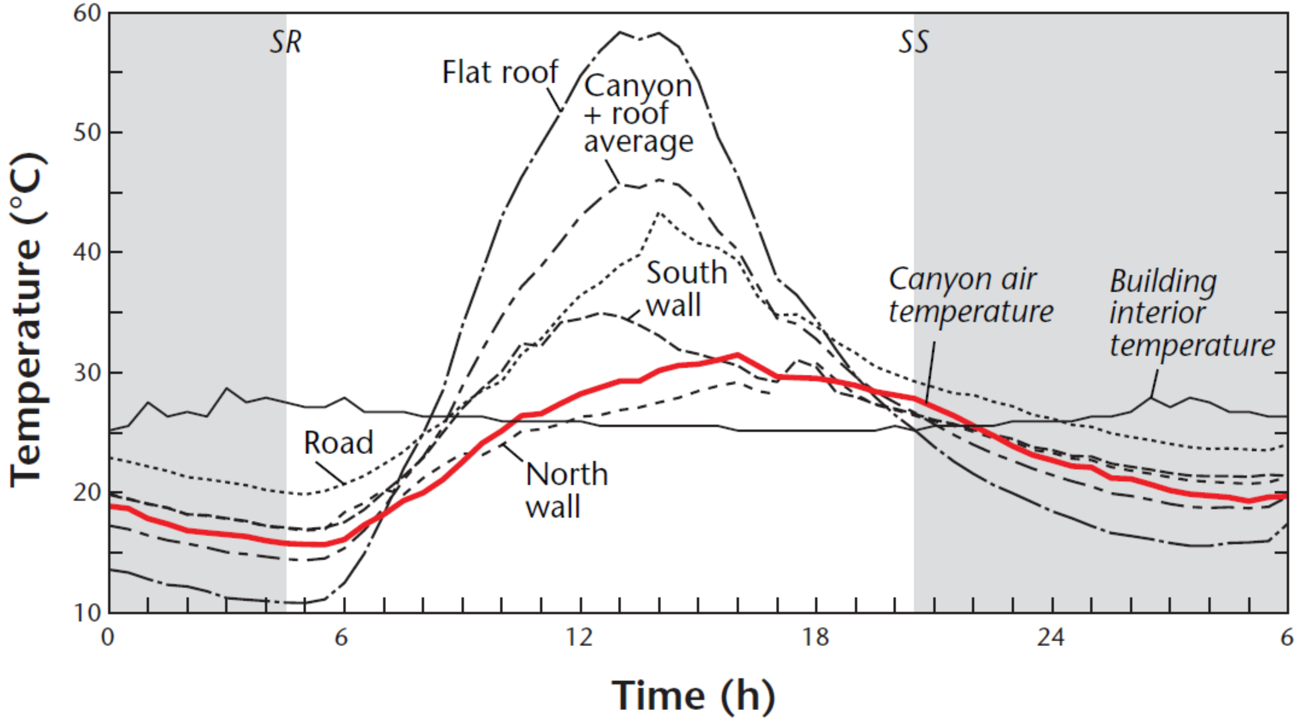
- The **daily** and **seasonal pattern** of **the SEB is set** by **the radiation heat flux** Q^* received from the Sun:
  - ○ During day, **Q* > 0** and energy goes into the soil as sensible heat or into the air through convection.
  - ○ During night, **Q* < 0** and energy is released from surfaces.

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)

Urban Surface Energy Balance (SEB)

- The **SEB of a city** is the summation of the SEBs of its many component units (facets, buildings, canyons) and **their interactions with each other**.

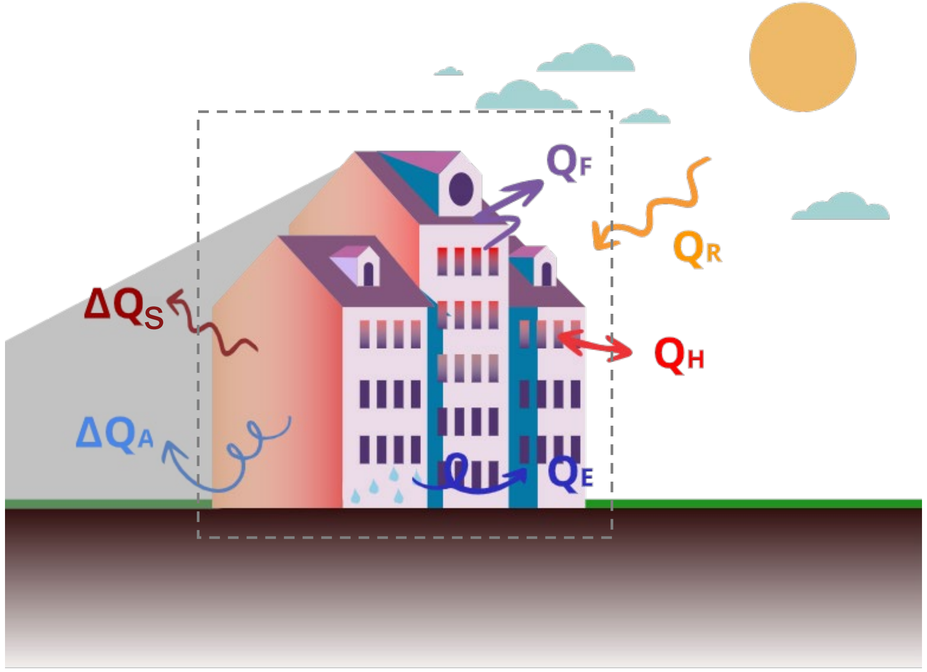
Source: Oke, Urban Climates, p. 203



- **Roofs:** excellent exposure to the Sun and sky, built with surface materials that possess *low albedo* and *uniformly high emissivity* (except those made of certain metals).
- **Roads:** dry most of the time, thus, only Q^*, Q_H and Q_G are involved in the SEB. The major difference between the SEBs of roofs and roads is the *much larger μ* of the paving materials (asphalt, concrete, rock cobble stones).
- **Walls**: almost *the only vertical urban units*, their SEB depends strongly on *orientation*, *exposure* and *access to solar irradiance* and their *sky view.*
- **Lawn** (open stretch of short grass on moist soil): available moisture plays the main role in energy balance, Q_E becomes the largest SEB term for this kind of site and the daytime and daily Bowen Ratio ***B*** can be ~0.31 ~ 0.33, respectively.

Urban Energy Balance: Control Volume approach

- A **building** *interacts* with **the atmosphere**, **the Sun**, **the ground**, **other buildings** and **other urban elements** (e.g., vegetation and water bodies).
- The **building interaction** with its **environment** is **always *at balance***. It is comprised of the radiation budget (Q^*), anthropogenic heat (Q_F), sensible heat (Q_H), latent heat (Q_E), stored heat (ΔQ_S), and advection (ΔQ_A).
- The **energy balance** is a **transient phenomena** (time-dependent). **Each term** experiences **diurnal** and **seasonal** variation.
- 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 SEB, **control volume energy balance** considers **the masses of the volume elements**.



$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (1\text{-}3)$$

Radiation budget

Anthropogenic heat

Sensible heat

Latent heat

Stored heat

Advected heat

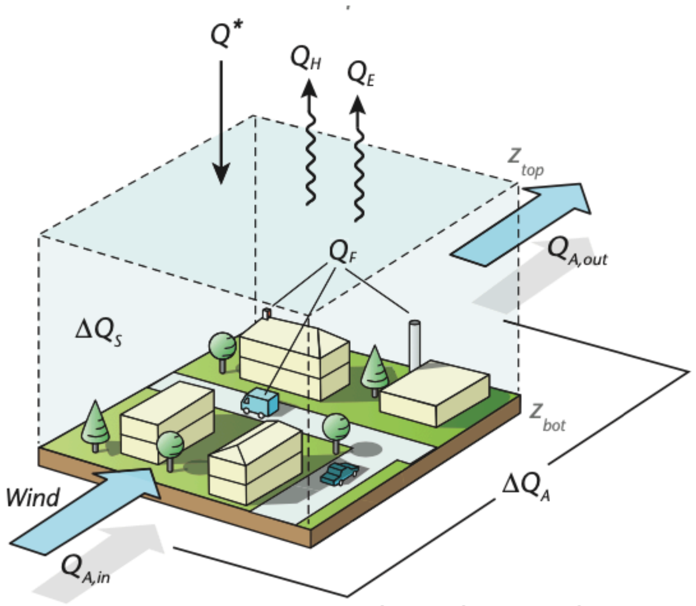
Reminder from L1

Urban Heat Storage

- **Heat is stored** in the urban structure when air temperatures are high (at day time, when $T_{ext} > T_i$)
- **Heat is released** from the urban structure when air temperatures are low (at night time when $T_{ext} < T_i$)

Estimation of Urban Heat Storage ΔQ_S (W/m^2):

1. **Energy Balance Residual Approach (RES):** requires solving Eqn. (1-3) for ΔQ_S (see Eqn.5-1). Requires the measurements of all other parameters, assume that $\Delta \boldsymbol{Q_A}$ is small, has all the uncertainties and errors inherent in obtaining the other terms.
2. **Thermal Mass Scheme (TMS):** heat storage in a volume of the i-th urban component can be calculated form the basic concepts of heat conduction and heat storage (see Eqn. 5-2a,b).
3. **Numerical Simulation** (**TEB**): numerical solution of 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
4. **Parameterization**: {*details in Oke, Urban Climates, p. 174*}

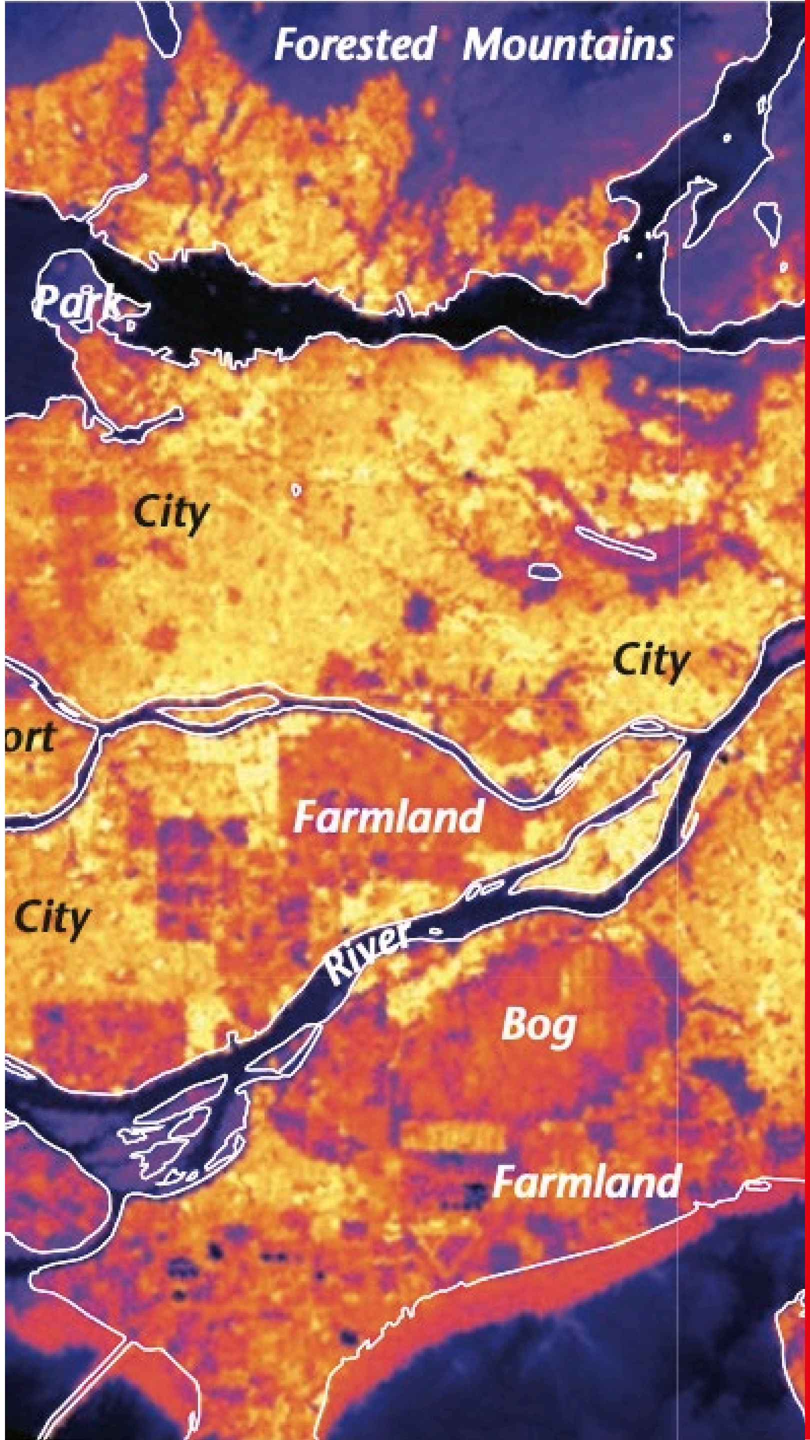


Source: Oke, Urban Climates, p. 157

$$\Delta \boldsymbol{Q_S} = \boldsymbol{Q}^* + \boldsymbol{Q_F} - \boldsymbol{Q_H} - \boldsymbol{Q_E} \qquad (5\text{-}1)$$

$$\Delta \boldsymbol{Q_{S,i}} = \frac{1}{A_i} \cdot \int_0^V \underbrace{C_{p,i} \overbrace{\frac{dT}{dt}}^{\textit{Change in temperature over a given time period}}}_{\textit{Heat storage change}} dV \qquad (5\text{-}2)$$

$$\Delta \boldsymbol{Q_S} = \sum_{\boldsymbol{i}}^{\boldsymbol{N}} \Delta \boldsymbol{Q_{S,i}} \qquad (5\text{-}3)$$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Urban Canyons: Sensible Heat Exchange (Q_H)

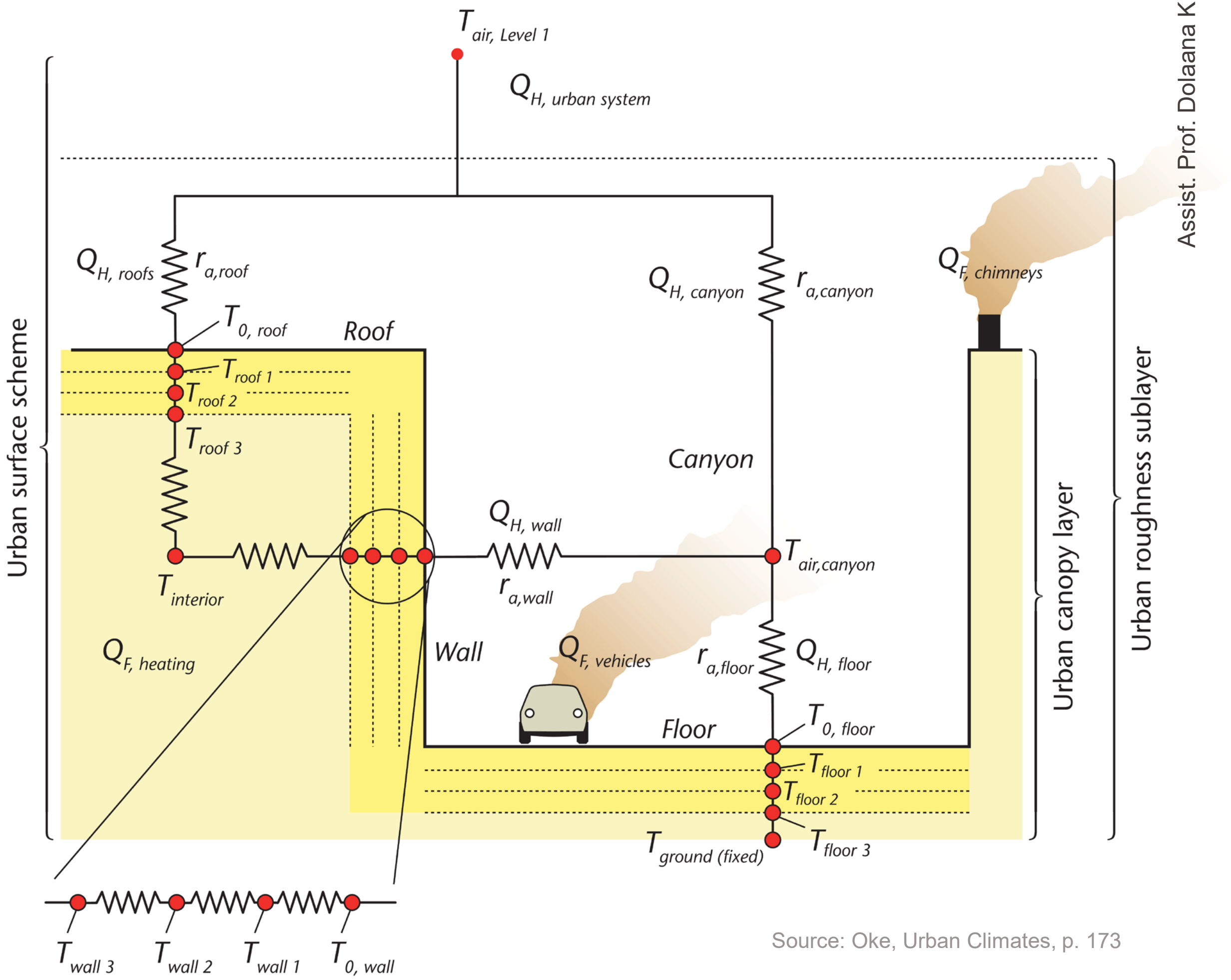
- Analysis of the **sensible heat Q_H** *(conduction + convection)* in the **urban canopy** can be focused on **canyon-plus-roof system** considering **a network of thermal resistances** involving *walls*, *roof surfaces*, and *a street in-between*.

- **Thermal resistance** of the $i-th$ **element** (e.g., a wall, a roof) having **conductive heat transfer** *through* n *number of layers* in a *series*:

$$R_i = R_{i,1} + R_{i,2} + \cdots + R_{i,n} \quad (3\text{-}6b)$$

- The **total thermal resistance** of the system when **multiple pathways exist** (e.g., simultaneous heat conduction through the walls, windows, and a roof):

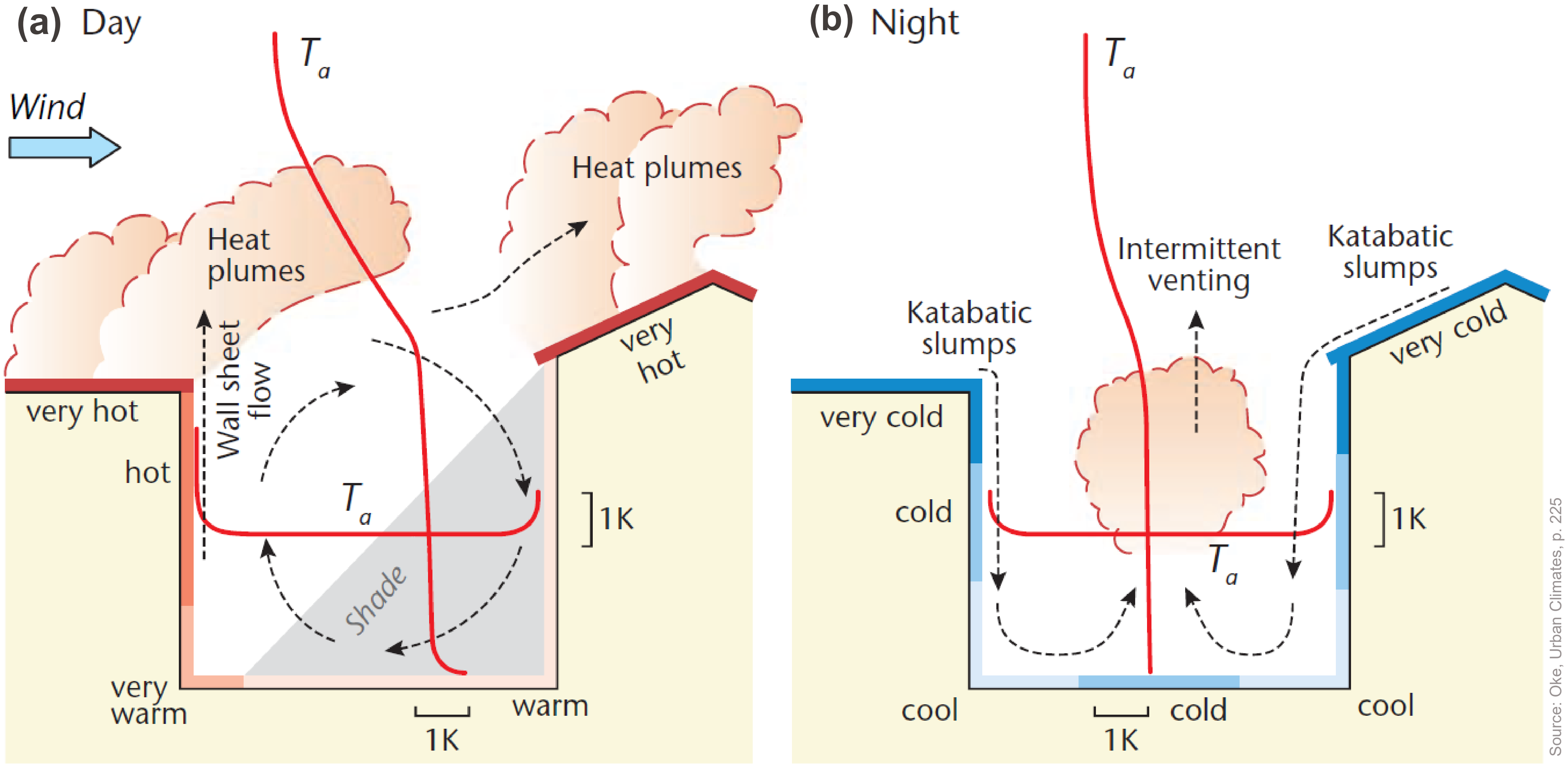
$$\frac{1}{R^*_{tot}} = \frac{1}{R^*_1} + \frac{1}{R^*_2} + \cdots + \frac{1}{R^*_N} \quad (3\text{-}7b)$$



Source: Oke, Urban Climates, p. 173

* The resistances need to be *weighted* **by the areal fraction** of *different surfaces*.

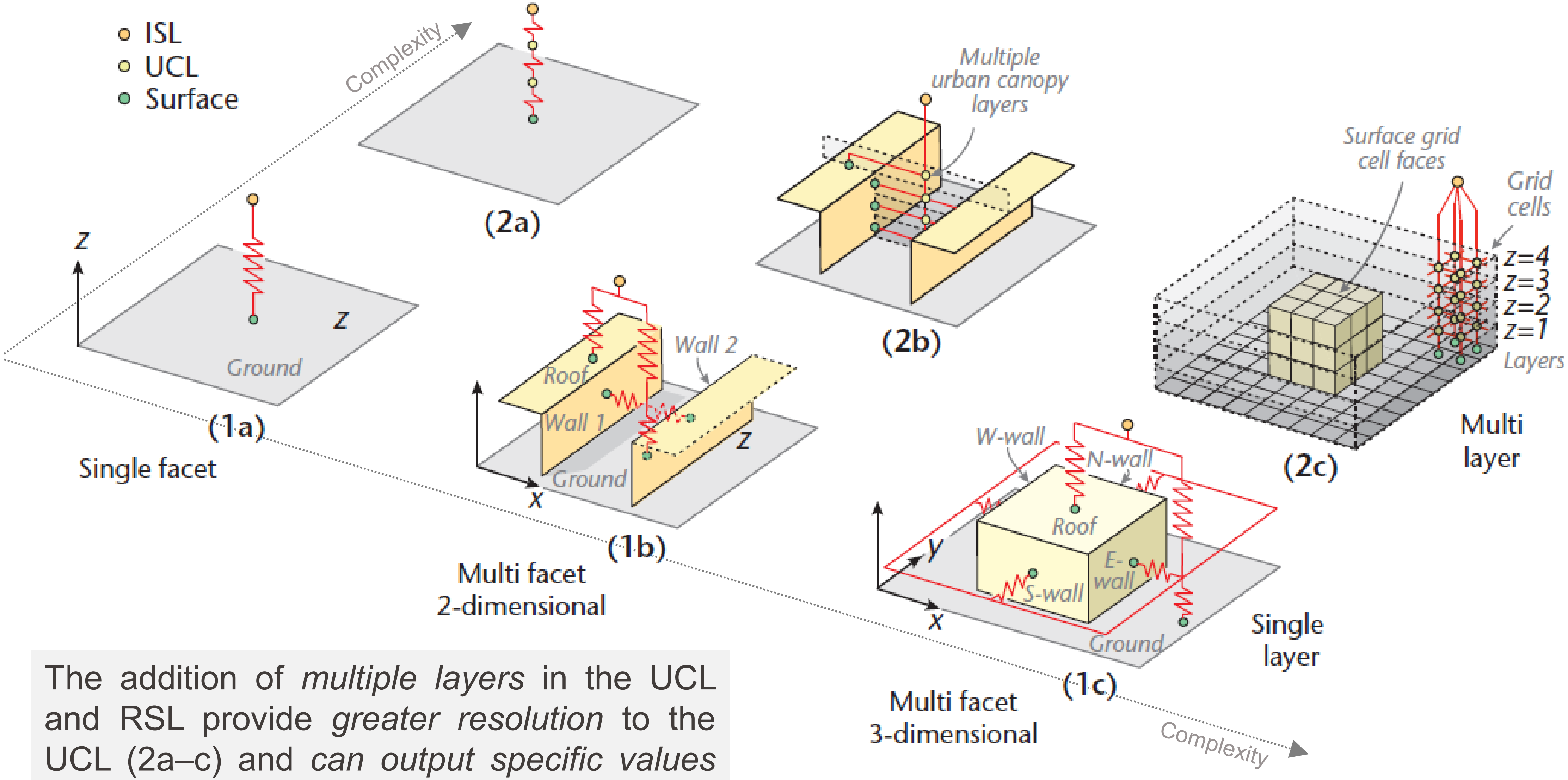
Urban Canyons: Sensible Heat Exchange (Q_H)



Source: Oke, Urban Climates, p. 225

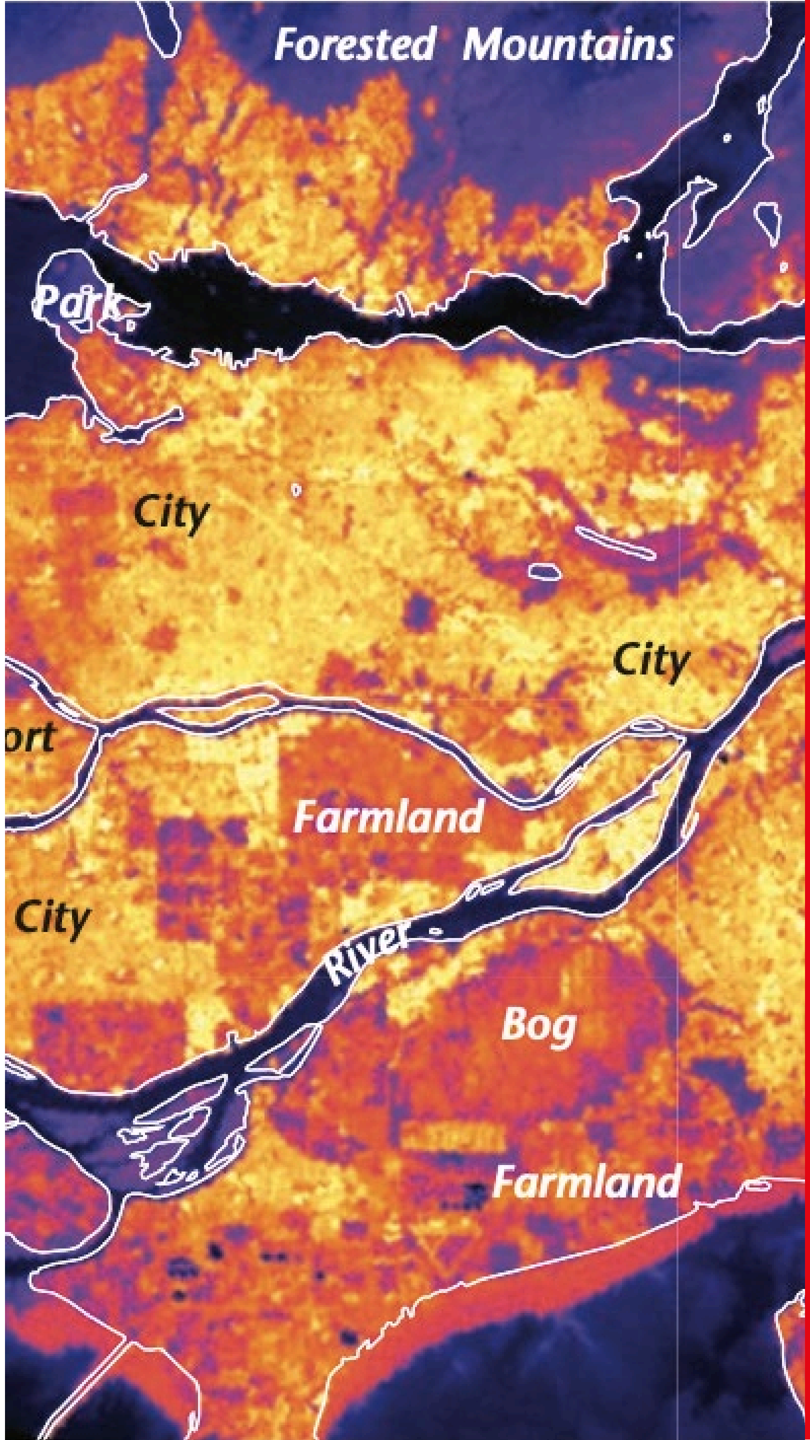
Schematic representation of *typical diurnal sequence* of **vertical profiles of air temperature** in the UCL and RSL of an urban area in (a) **daytime**, (b) **at night** (on a day with light winds and little or no cloud).

Urban Canopy: Heat Exchange Analysis



The addition of *multiple layers* in the UCL and RSL provide *greater resolution* to the UCL (2a–c) and *can output specific values* for screen-level, mid-canyon, roof-level, etc.

Source: Oke, Urban Climates, p. 72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Urban Canyons: Shortwave Radiation Exchange (K^*)

- Urban surface exposed to **shortwave** (**direct** and **diffuse**) radiation flux [*see L3, slides 29-30 for a surface*]:

$$K_{\downarrow,i} = S_i + D_{sky,i} + D_{env,i} \quad \text{(3-32b)}$$

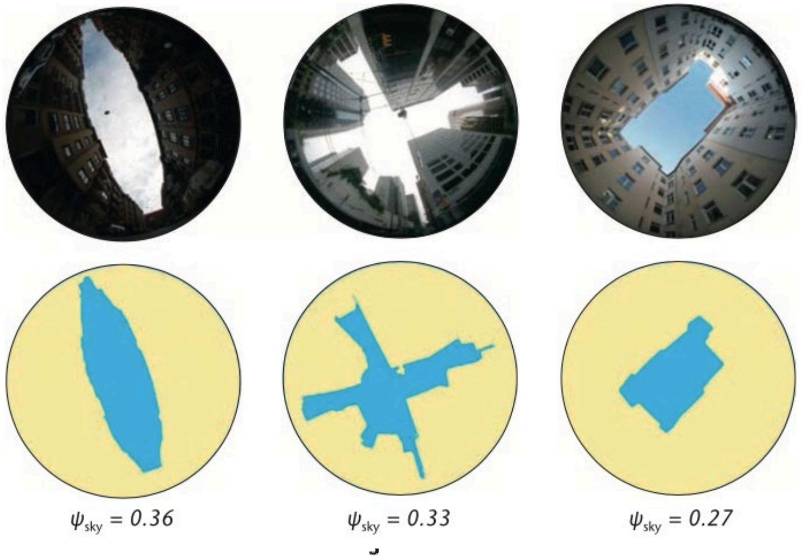
- **Diffuse irradiance from the sky ($D_{sky,i}$)** *entering* the *urban environment* and *reaching* the *urban surface* $(i-th)$ mainly depends on **the sky view factor $\psi_{i \to sky}$**:

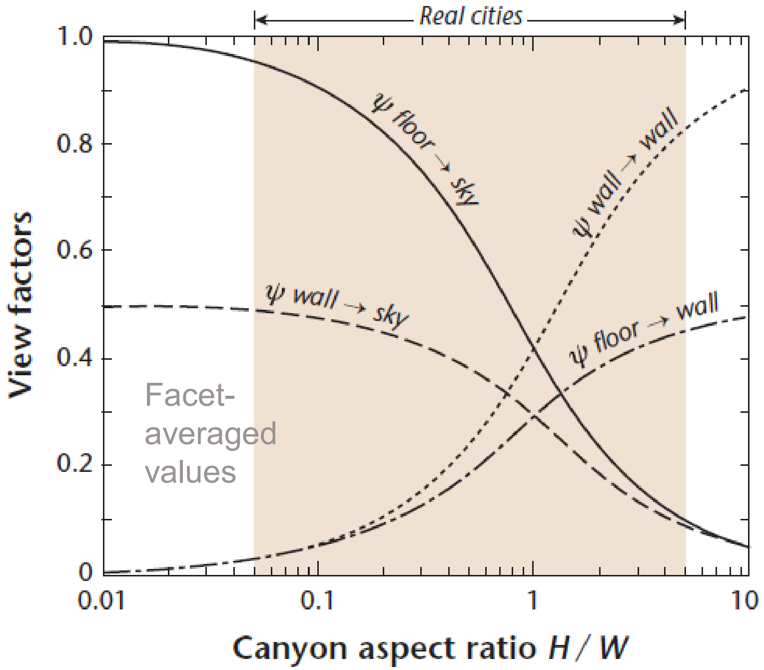
$$D_{sky,i} = D_{sky,0} \cdot \psi_{i \to sky} \quad \text{(5-4)}$$

$D_{sky,0}$ - diffuse radiation on a horizontal surface with an unobstructed sky view

- **Urban contribution** to **diffuse shortwave irradiance ($D_{env,i}$)** is *the integral* of **all reflection events** that **impinge on the surface**. The complex urban geometry leads to *heterogeneous distribution* of *diffuse radiation*, hence urban surfaces are commonly divided *into smaller units* (***j***) to determine their individual contribution:

$$D_{env,i} = \sum_{j=1}^{N-1} K_{\uparrow,j} \cdot \psi_{i \to j} \quad \text{(5-5)}$$

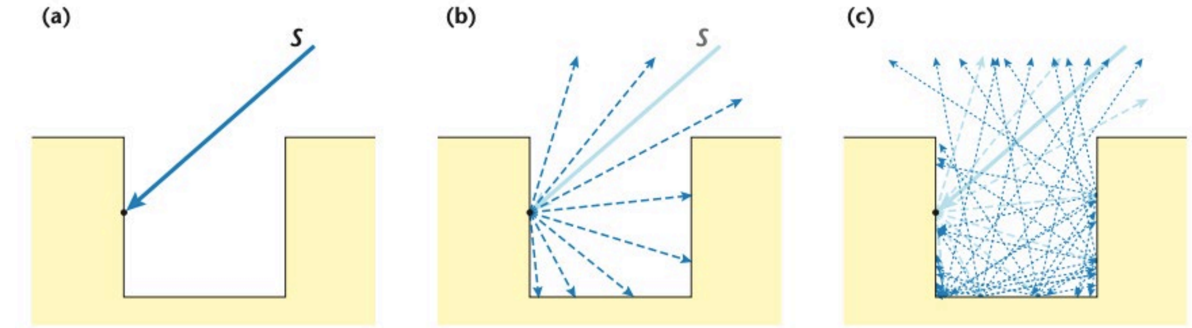




Source: Oke, Urban Climates, p. 137

Urban Canyons: Shortwave Radiation Exchange (K^*)

- **Urban diffuse irradiance** in urban canyons is **shortwave radiation *reflected* from its surfaces**:
  - Once *direct-beam* enters the canyon, it is reflected *ad infinitum* with progressively less energy being exchanged, because each surface absorbs a portion of the radiation they receive.



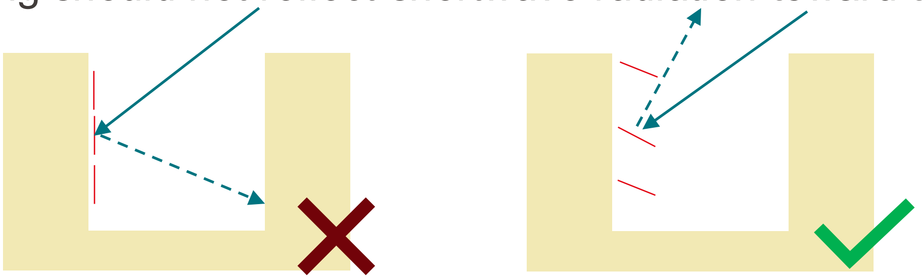
The receipt of direct-beam irradiance through the canyon top

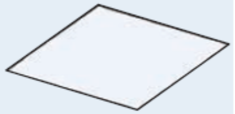
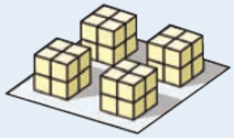
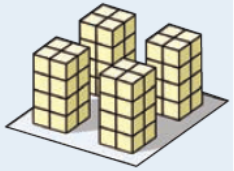
1st reflection from the canyon facets

2nd reflection from the canyon facets

Oke, Urban Climates, p. 135

- The narrower **a street canyon** is…
  - View factor $\psi_{i\rightarrow env}$ increases while the factor $\psi_{i\rightarrow sky}$ decreases
  - The *more shortwave radiation* will be *reflected* and *absorbed*
  - *The lower albedo of a canyon than that of its constituent facets*
  - The *greater global radiation budget (Q*) increase*
- **Direct solar radiation** is prevented from reaching urban surfaces by *shading urban elements.*
  - Shading *should not reflect shortwave radiation* toward the *canyon*



Urban form	H/W	λ_c	Albedo α	Change in absorption
	0	1	0.40	
	0.5	1.5	0.32	+17%
	1	2	0.27	+21%
	2	3	0.23	+27%

Source: Oke, Urban Climates, p. 140

Urban Canyons: Longwave Radiation Exchange (L^*)

- **Incoming longwave radiation** *reaching* the $\boldsymbol{i-th}$ *urban surface:*

$$L_{\downarrow,i} = \underbrace{L_{\downarrow,sky,0} \cdot \psi_{i\to sky}}_{\text{Input from the portion of the sky hemisphere “seen”}} + \underbrace{\sum_{j=1}^{N}\left(L_{\uparrow,j} \cdot \psi_{i\to j}\right)}_{\text{Input from the surrounding environment}} \quad (5\text{-}6)$$

where $L_{\downarrow,sky,0}$ - incoming longwave radiation on a horizontal surface with an unobstructed sky view

- **Outgoing longwave radiation** *from the* $\boldsymbol{j-th}$ *urban surface:*

$$L_{\uparrow,j} = \underbrace{\varepsilon_j \cdot \sigma \cdot T_j^4}_{\text{emission}} + \underbrace{(1-\varepsilon_j) \cdot L_{\downarrow,j}}_{\text{reflection}} \quad (3\text{-}39b)$$

- In urban canyons, the behavior of all surfaces is mutually dependent (e.g., $L_{\downarrow,j}$ depends on $L_{\downarrow,i}$)

- **Effect of the $\psi_{i\to sky}$ view factor:**
  - Canyons with high λ_s(small $\psi_{i\to sky}$): the portion of $L_{\uparrow,i}$ escaping the canyon is small (mainly intercepted and absorbed by other surfaces)
  - Portion of the $L_{\downarrow}$ from the “cold” sky is small, most input from relatively warm surfaces
  - Cooling is small at the bottom of canyons with high λ_s (deep and narrow).

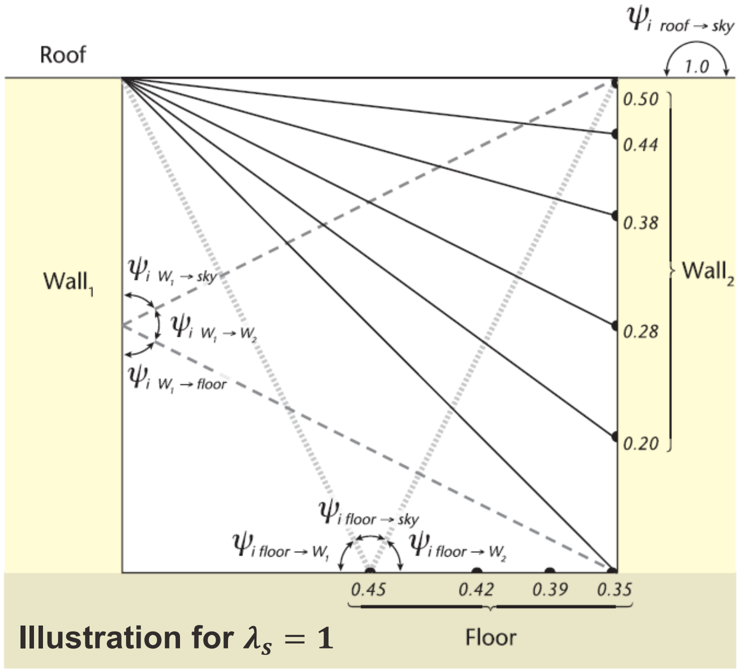
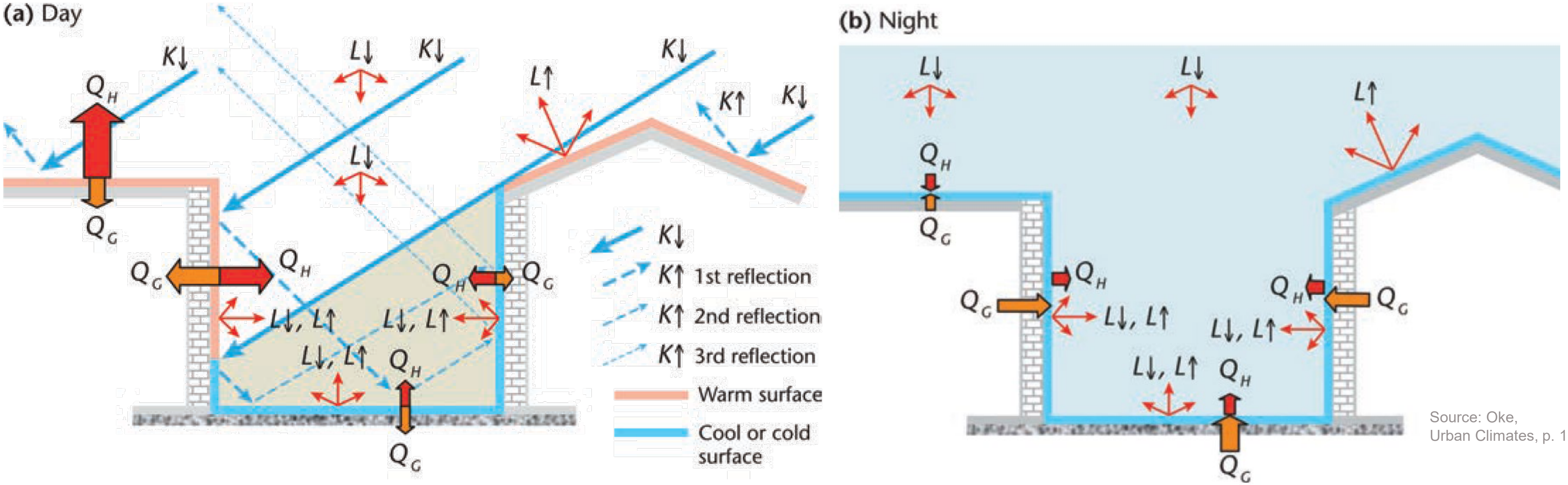


Illustration for $\lambda_s = 1$

Oke, Urban Climates, p. 135

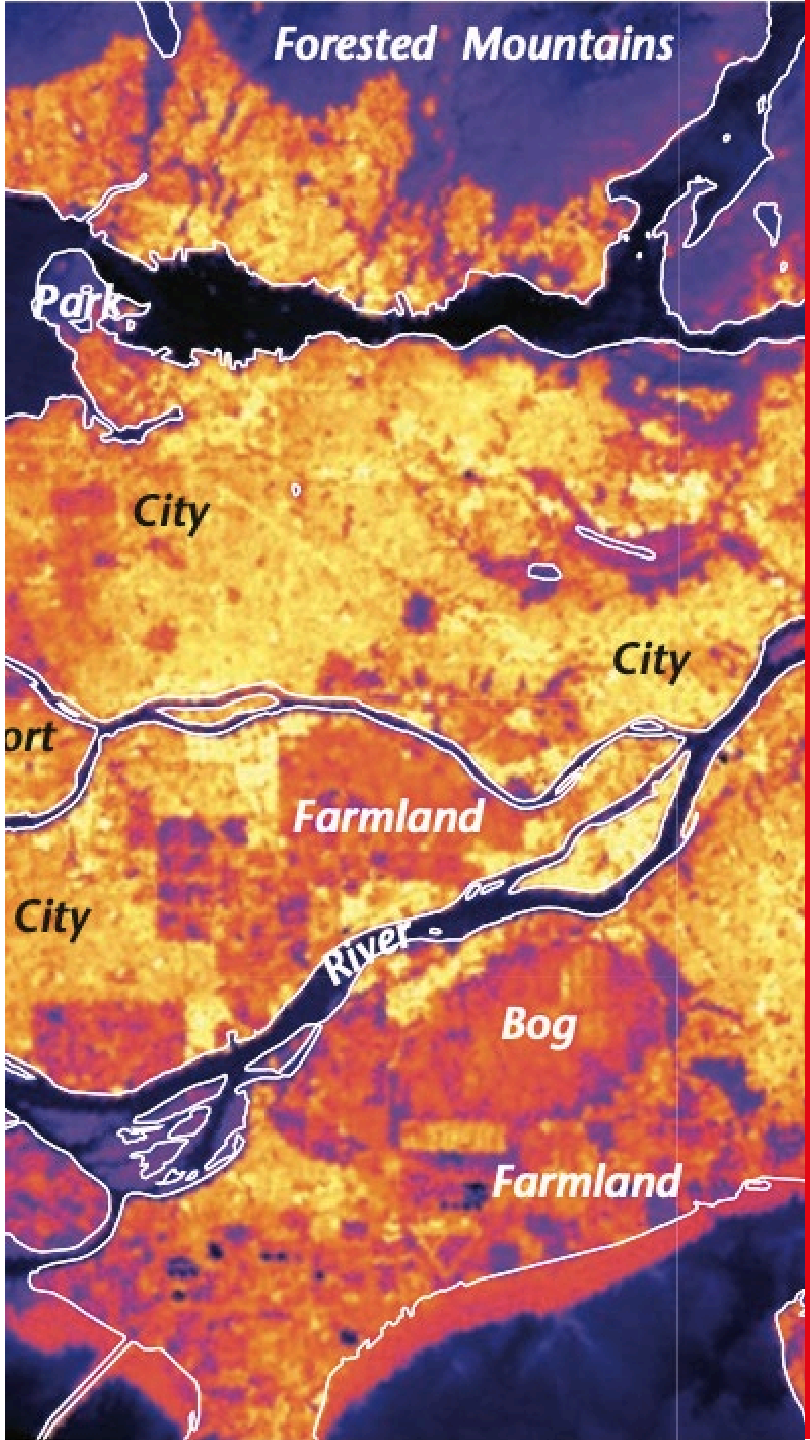
Urban Canyons: Radiative Heat Exchange (Q^*)



Source: Oke,
Urban Climates, p. 188

- **Daytime exchange *within the canyon*:**
  - ○ **Restricted solar irradiance**, *depends on* **shadow patterns** (function of Sun-Earth geometry, canyon orientation, and $\lambda_s = H/W$ ratio). The larger λ_s, the smaller is average solar access.
  - ○ **Multiple reflection** between facets increases **overall absorption** of both **short-** and **longwave radiation.**
  - ○ The **walls** and **floor** (=ground), having *high thermal admittance* μ, **store heat**.

- **Nighttime exchange *within the canyon*:**
  - ○ Longwave radiation budget **L*** is negative $(L_\downarrow < L_\uparrow)$
  - ○ **Cooling** is *weaker* within the canyon than *at the roof-level*, because of **the reduced sky view factor** and **dissipation** of **the heat stored**. The strength of cooling is controlled by:
    - – *Antecedent temperatures* of canyon facets;
    - – λ_s(sets the sky view and the view factor of surfaces);
    - – *Emissivity* values of surfaces
    - – The *effective radiating temperature* of the sky (controlled by cloud cover)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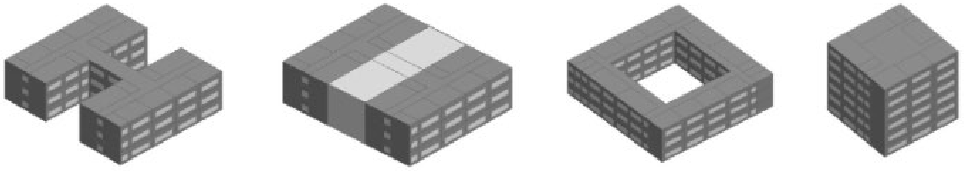
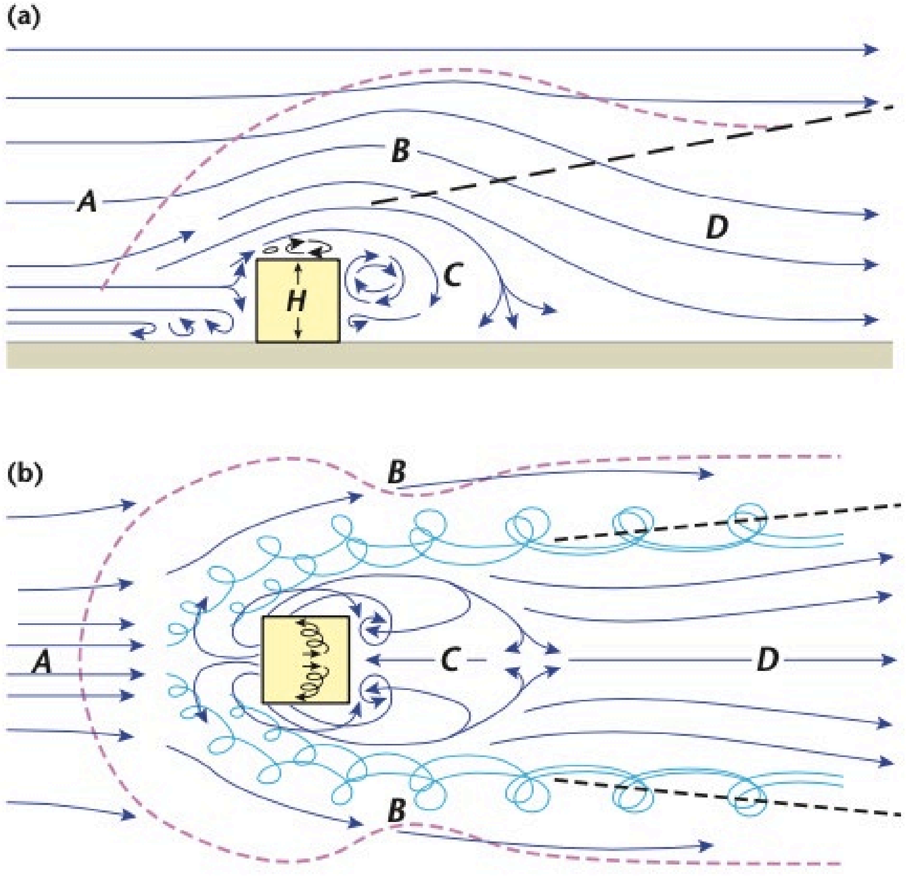
Aerodynamic Interaction: Isolated Buildings

- **Importance of understanding the air flow around buildings:**
  - To control **the heat dissipation** due to the wind flow around building (elevated convection is avoided in cold seasons but preferred in warm seasons).
  - To **control the wind speed** entering *the building ventilation.*
  - To control **particle dispersion** and **pollution stagnation**. Wind and **mixing** is encouraged in the area of high pollution density.

- Buildings induce **roughness** and complex **3D wind patterns** (on a flat terrain, the wind flow is *mostly horizontal),* wind profile is deformed.

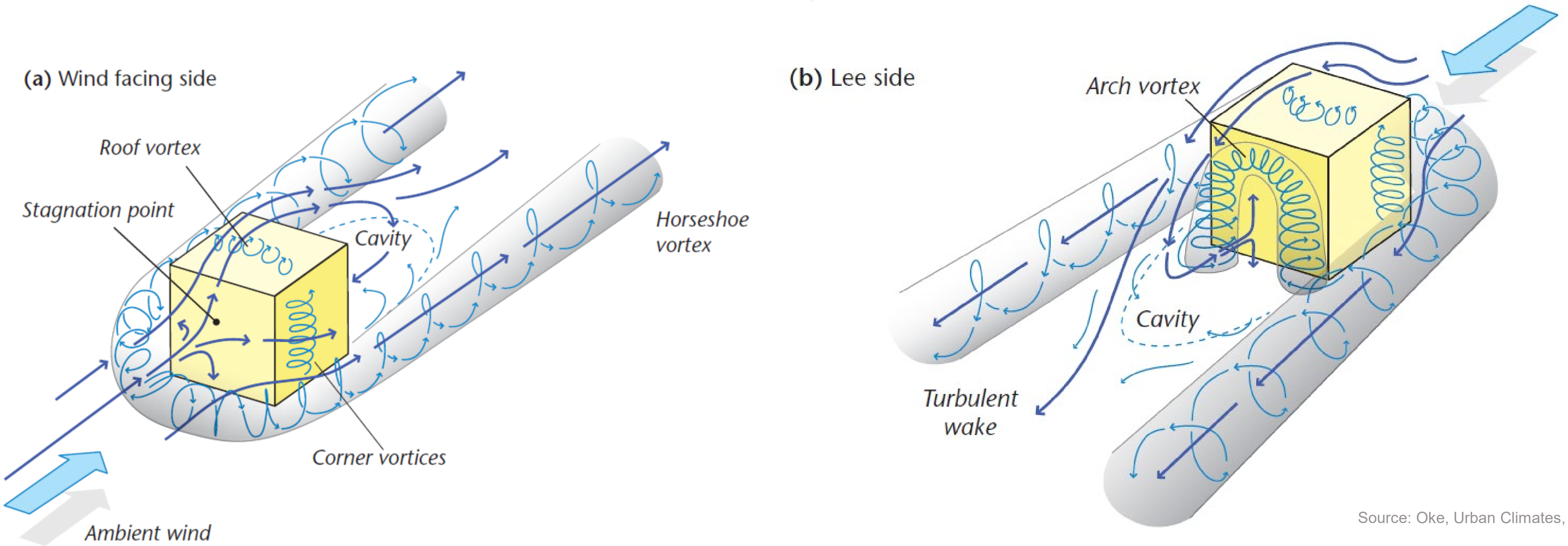
- The **air flow behavior** around **a single building**:
  - **Deflected** *around* and *above* the building
  - **Detaches** on *sharp edges* or when *wind speed* is *high* (**flow separation**)
  - **Recirculates** in *low pressure* regions.



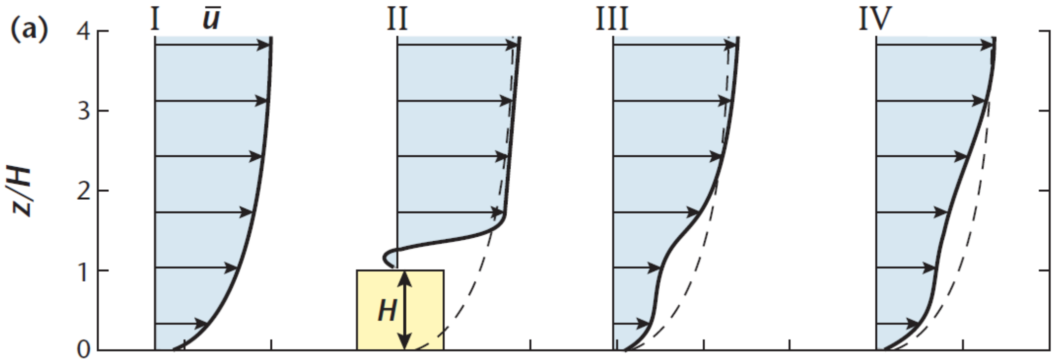


Source: Oke, Urban Climates, p. 83

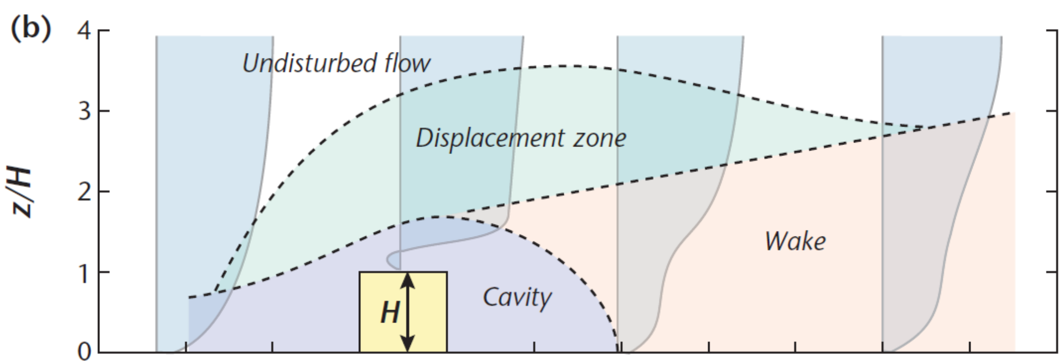
Aerodynamic Interaction: Isolated Buildings



Source: Oke, Urban Climates, p. 84



Wind velocity profile



Zones of the flow

Oke, Urban Climates, p. 85

Buildings-Environment Aerodynamic Interaction

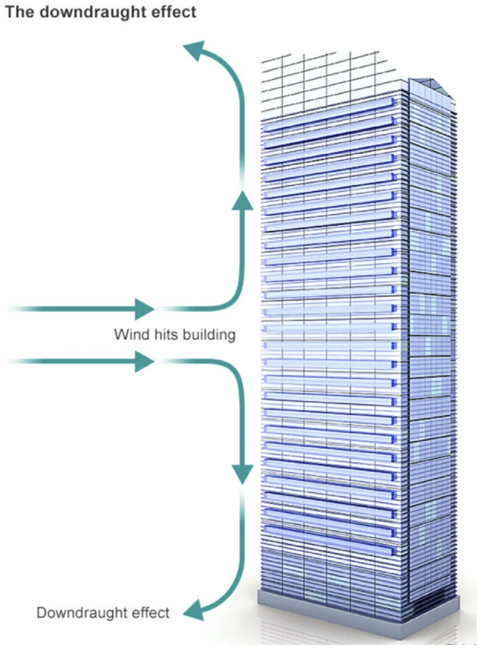
- Video illustration: https://www.youtube.com/watch?v=UEgk2Bgz16s

Aerodynamic Interaction: Tall Buildings

- The effect **of tall buildings** on the wind are *stronger* compared to the moderate-sized buildings:
  - The magnitude of **the perturbation** to the **pressure** and **velocity** fields can be greater and the momentum injected downward is potentially larger, *strong blasts* occur at building sides, the stagnation point is at higher level.
  - Tall buildings *deflect the strong high-altitude wind to pedestrian level* on *punctual zones* (a pedestrian can suddenly encounter a blast of strong wind sufficient to knock him over).

Source: Oke, Urban Climates, p. 86

- Tall buildings are required to first be *simulated* and *experimented* with wind tunnels.
- **A few advantages of tall buildings:**
  - They *cool down* the neighboring area due to convection
  - They have a potential to *clean* the air by substantial mixing



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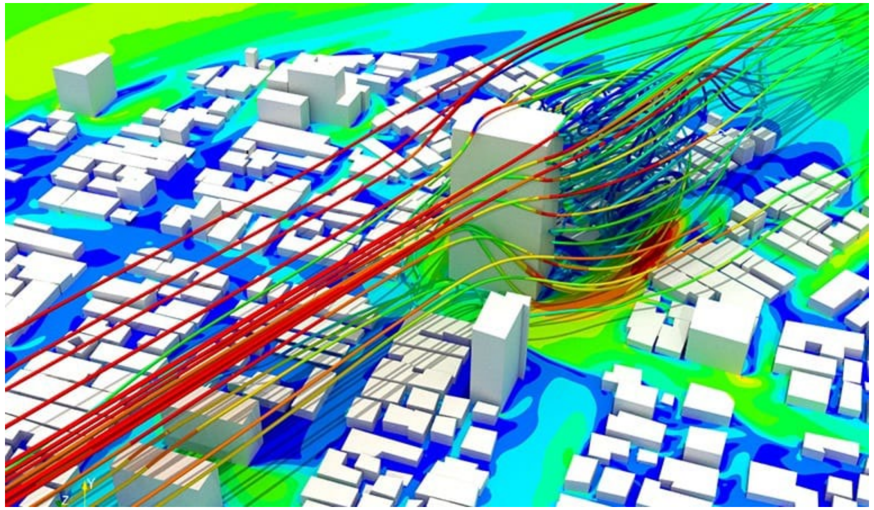
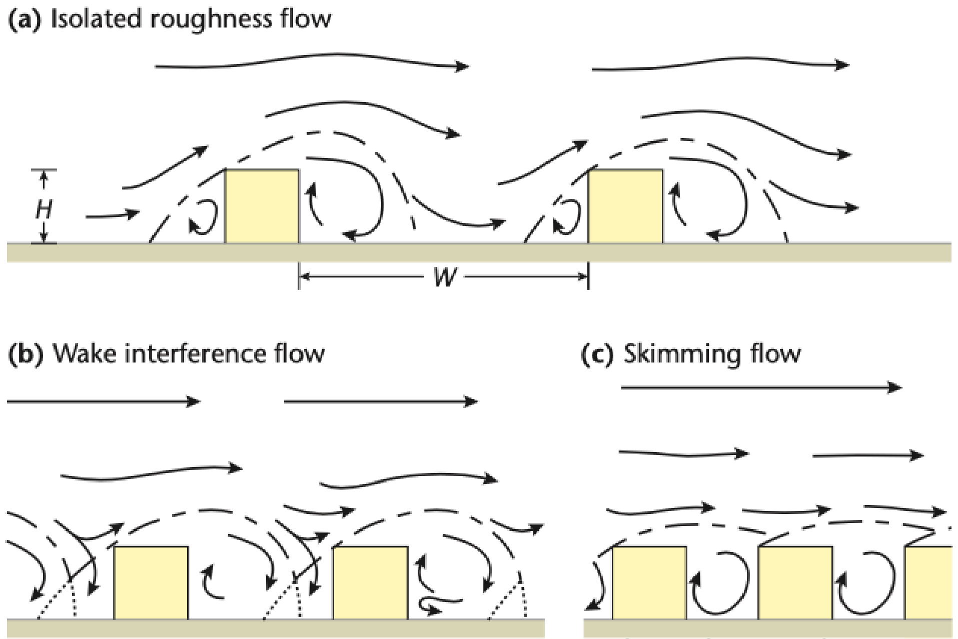


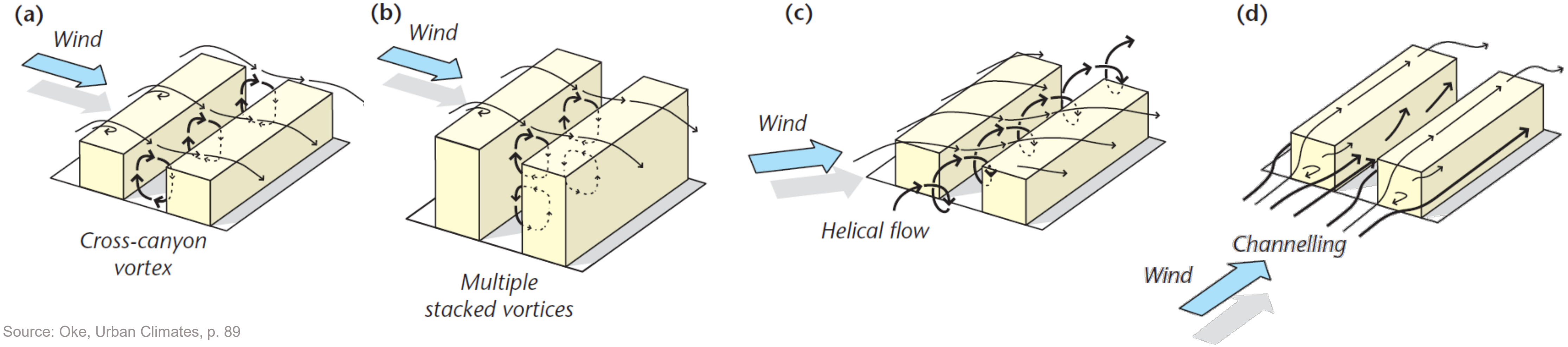
https://www.simscale.com/blog/pedestrian-wind-comfort-validation/

Aerodynamic Interaction: Urban Canyons

- The ***distance between buildings***, their ***height*** and the ***wind velocity*** determines the **interaction between the respective wakes** of the buildings:
  a) **Widely spaced buildings (H/W<0.35)**: individual wakes *don't interact* with each other.
  b) **Closely spaced buildings (0.35<H/W<0.65)**: vortex in the cavity behind the upwind building is reinforced by the flow down the windward face of the next building.
  c) **Densely spaced buildings (H/W>0.65)**: the above-roof flow "skips" across the tops of the buildings with *less tendency* to enter into the street canyons (the flow above the roofs is decoupled from that in the canyons).

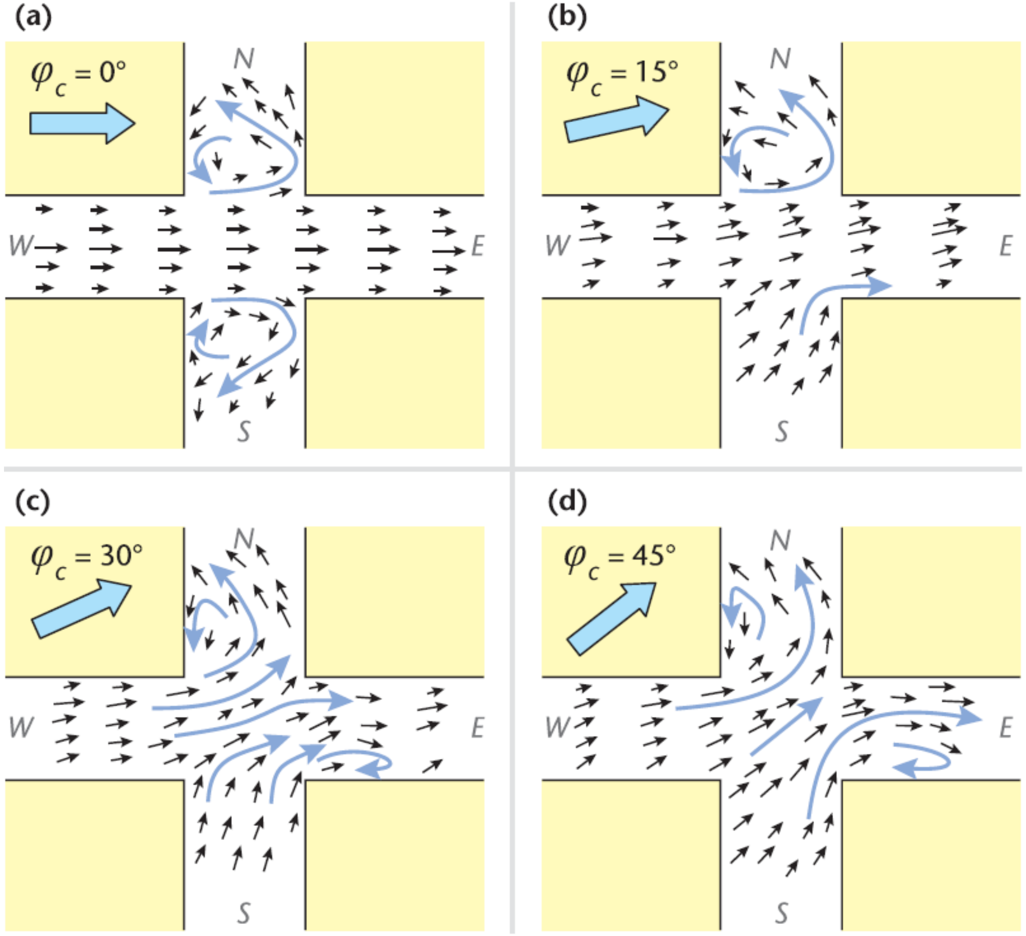


Source: Oke, Urban Climates, p. 88



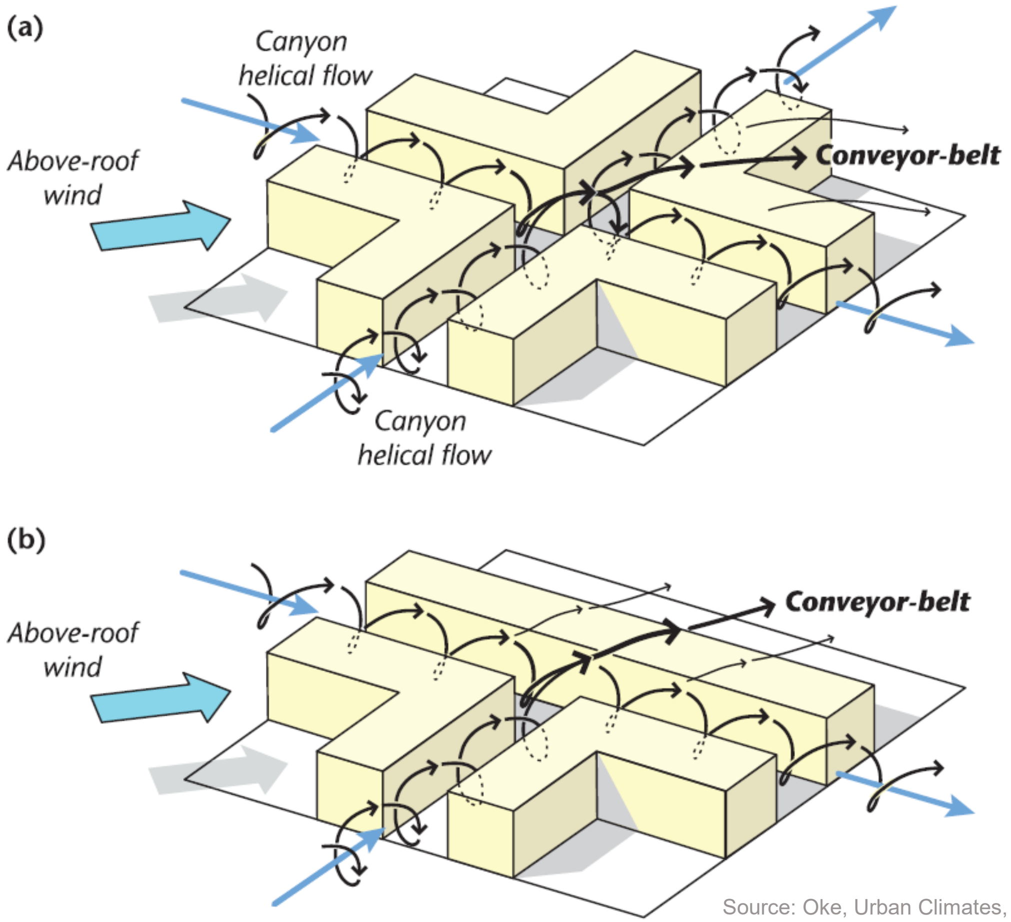
Source: Oke, Urban Climates, p. 89

Aerodynamic Interaction: Urban Canyons



Source: Oke, Urban Climates, p. 91

Typical flow patterns in a 4-way street intersection (numerical simulations of mean horizontal velocity at half canyon height): (a) 0^o, i.e. parallel to the east-west street, (b) 15^o, (c) 30^o, (d) 45^o

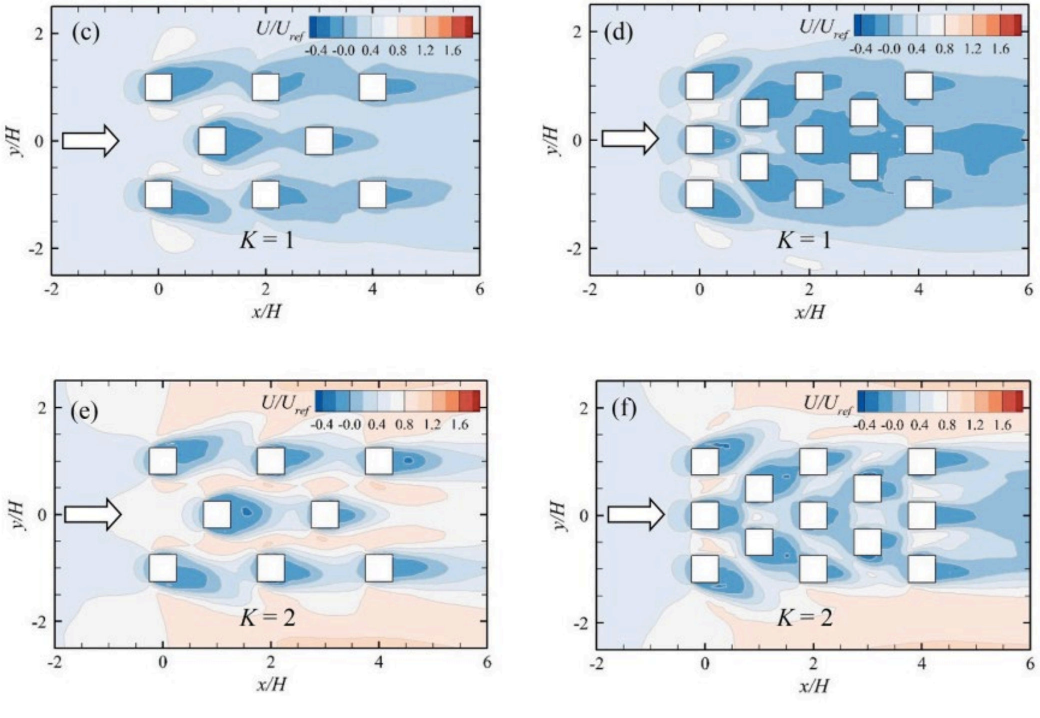


Source: Oke, Urban Climates, p. 92

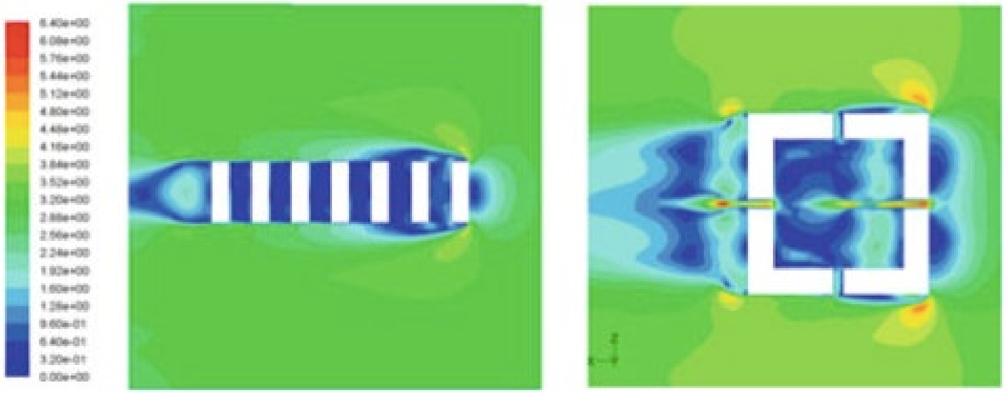
Schematic depiction of 3D flow at
(a) an intersection on an orthogonal street grid with above-roof flow diagonal to the grid, (b) similar, but at a T-junction. Light blue arrows show the mean flow direction whilst the black arrows depict the actual helical motion.

Aerodynamic Interaction: Urban Districts

- The geometric design of urban districts has an influence on the flow pattern **downwind.**
- The *relative placement* of buildings change the wind flow patterns. Factors are: **their spacing**, **alignment**, **rotation**, and **height**.
- Narrow street canyons *trap* the wind coming *transversally* or *prevent it from entering* the canyon. They create a wind tunnel for wind coming *longitudinally* (**channeling**).
- The wind flow interference with buildings *modify the wind profile.*
    - Wind profile is deformed by the front buildings (**windward buildings)**, and the **downwind** buildings are *streamlined* by deformed wind profile.
- As *bursts of wind* are avoided but *mixing* is favored, *a scattered formation* of buildings is preferred.



Source: LiU ET AL. (2021) https://doi.org/10.1016/j.buildenv.2021.107625



Source: Medved, Building Physics, p. 463

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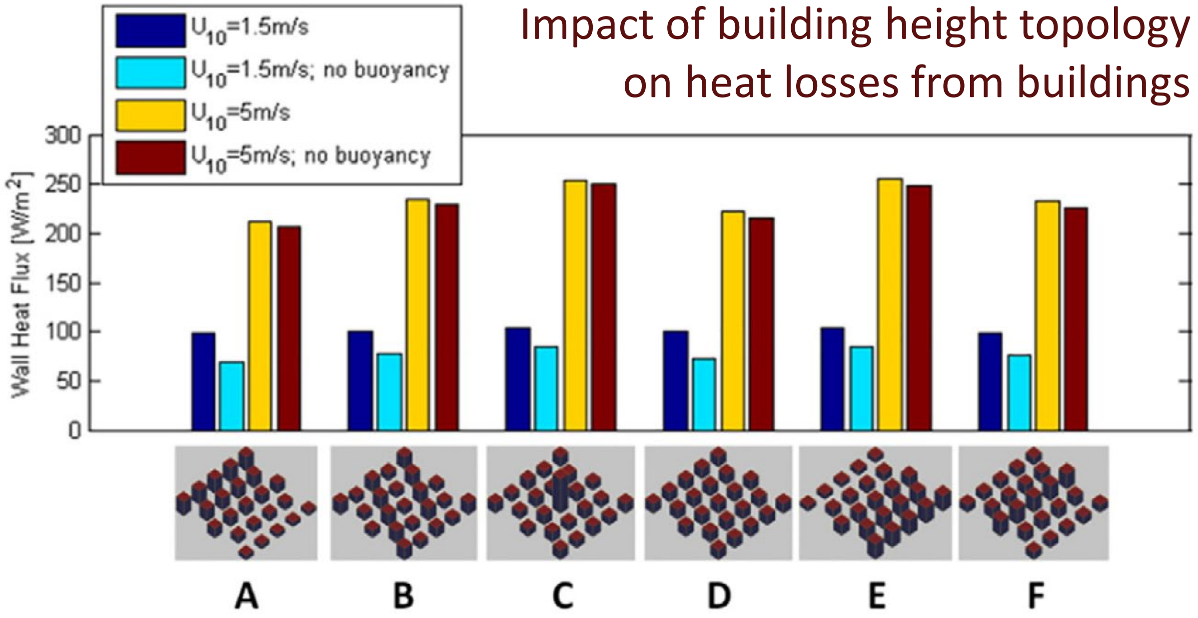
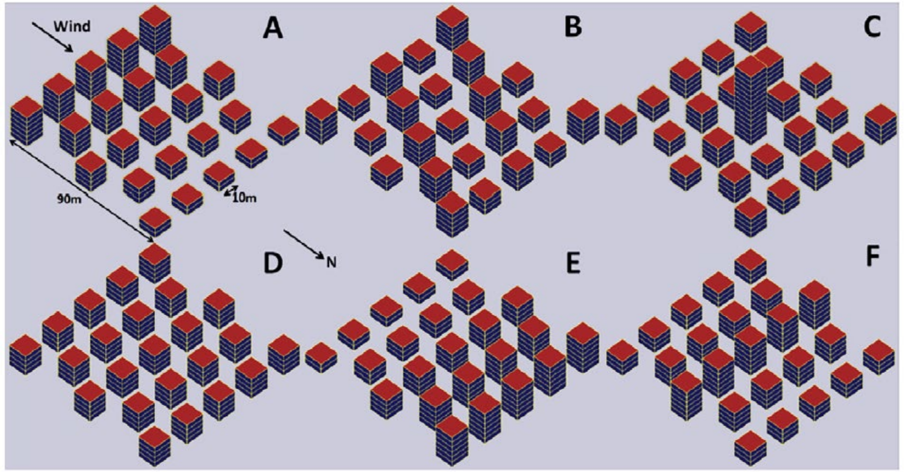
Aerodynamic Interaction: Convective Heat Exchange

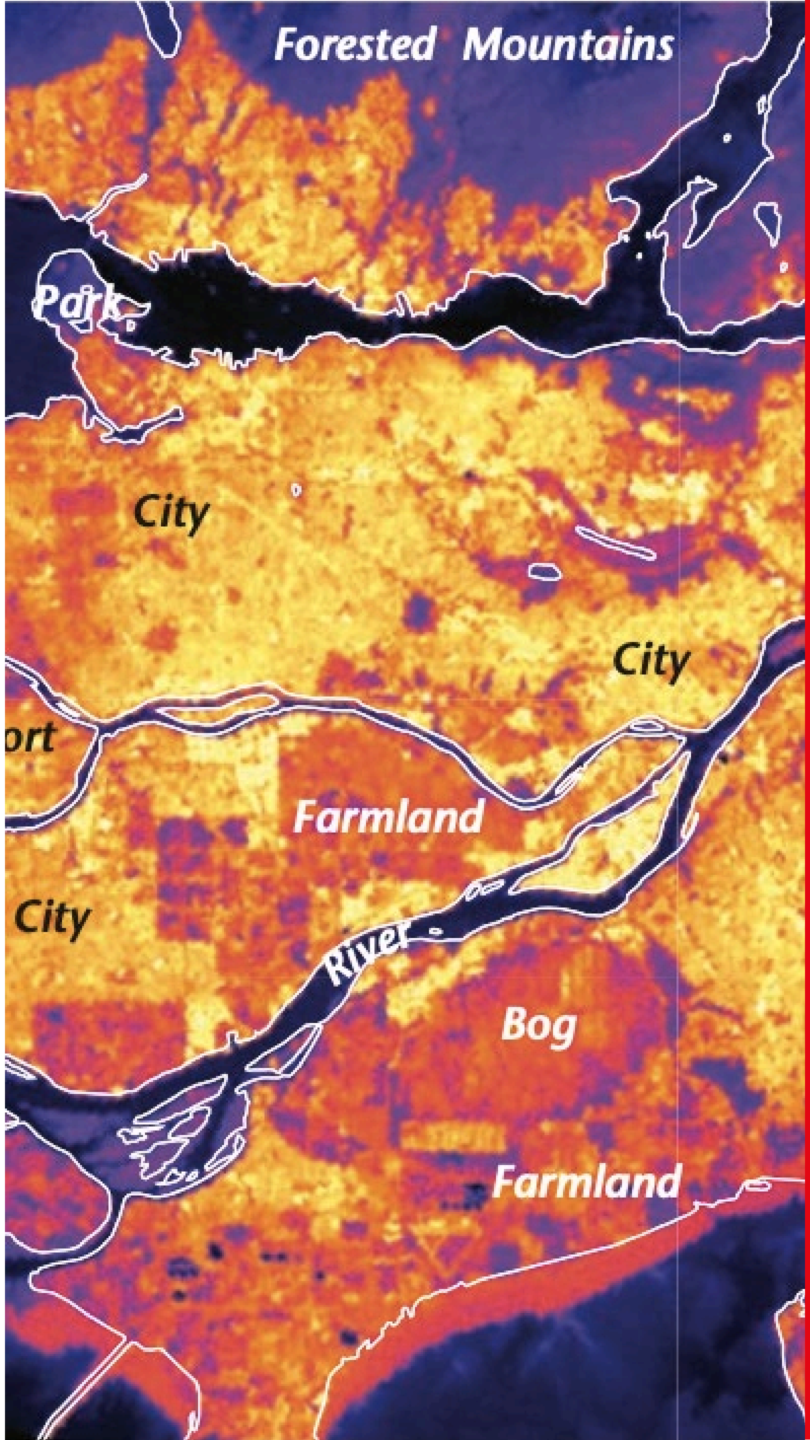
- **Convective heat dissipation from surfaces:**
    - **Summer:** convection can be *advantageous* to *naturally cool* the buildings (air temperature should be lower than indoor temperature)
    - **Winter:** to reduce heat losses from building toward outdoors, *increased convection at the outer interface* is *avoided*
- **Heat removal by convection**:
    - Increases with wind speed due to *forced convection* at high wind speed (e.g., V > 0.5 m/s)
    - *Buoyancy* is stronger for low wind speeds, negligible at high wind speeds.

Impact of building height topology on heat losses from buildings





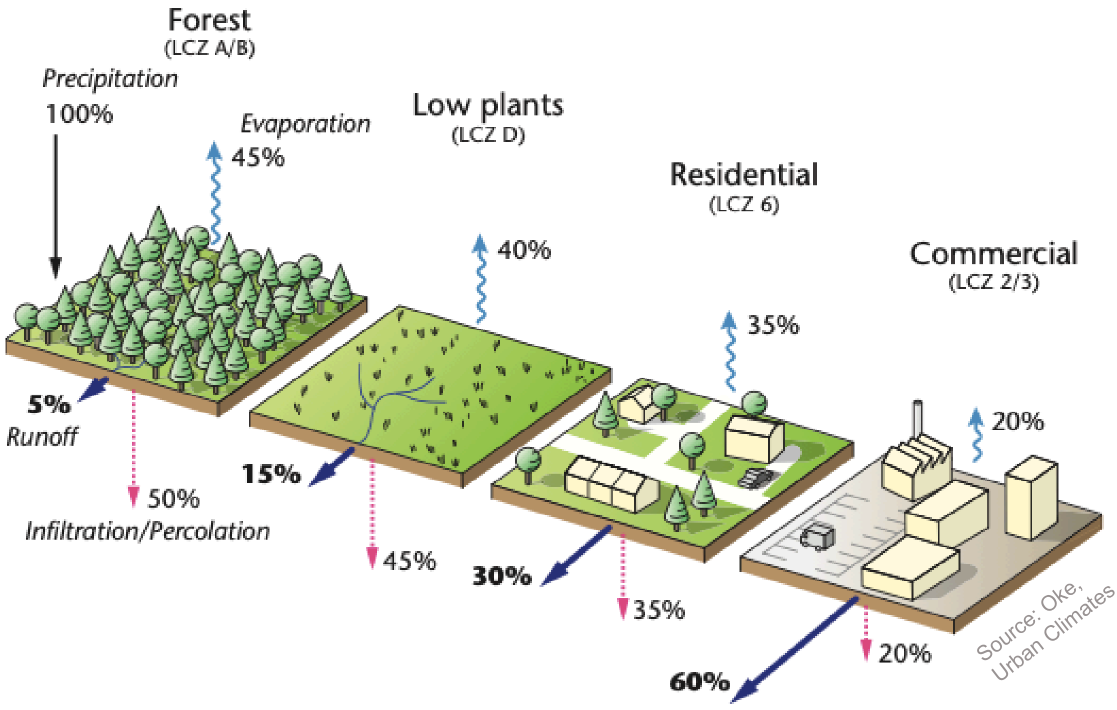
Source: Allegrini & Carmeliet (2017) http://dx.doi.org/10.1016/j.uclim.2017.07.005


Forested Mountains
Park
City
City
ort
Farmland
City
River
Bog
Farmland

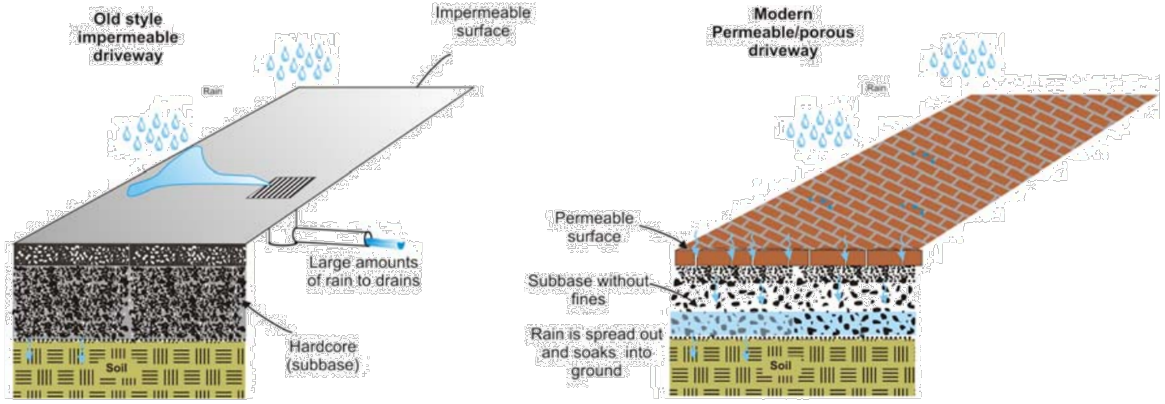
CONTENT:

Urban canopy: Hydrodynamic interaction

- **Evaporation** is *smaller* in cities than in their countryside during the day, hence **humidity being smaller as well**. If less evaporation takes place, more sensible heat is generated.
- Differences of water organization in urban areas compared to rural areas:
  - **Runoff** is greater due to more *impermeable surfaces* (asphalt, concrete, stone, pavers)
  - **Storage of water** is less due to less water from precipitations available.
  - **Evaporation** of water is less due to *less water* available.
- Only water present in the urban atmosphere and at surfaces can be evaporated. Surface water is:
  - *Freely available* at ponds and lakes
  - *Held by a surface* in the pores of *the materials*



Source: Oke, Urban Climates, p. 250

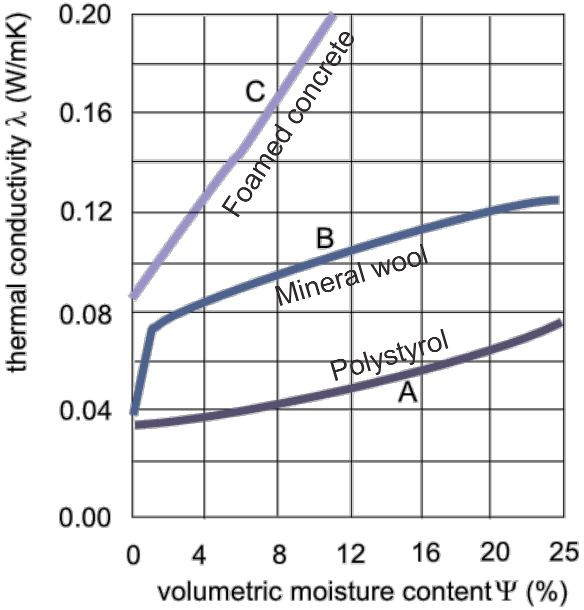


Source: http://data.parliament.uk/DepositedPapers/Files/DEP2010-0563/DEP2010-0563.pdf

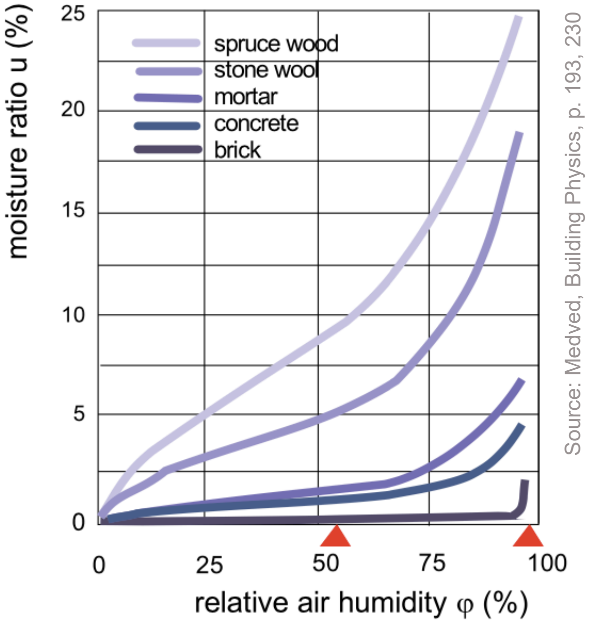
Building Materials: Moisture content

- **Building materials retain water**:
  - They *absorb and release* water
  - They *condensate* water at their surface
- Water infiltrates the building materials by **capillary suction** from ground or **rain run-off** and is **stored** in the **pores** of the material.
- **Sorption of water vapor** happens at building surface (molecules of water vapor adhere to the surface of pores in solid building materials).
- **Hygroscopic urban materials** absorbing moisture from the air: *wood, cellulose fibers, soil, vegetation.*
- **Moisture uptake** in **building materials** is avoided as their thermal conductivity increases and their insulating property decreases.
- Buildings facades are usually strived to be made **impervious to water**.

Increase in thermal conductivity



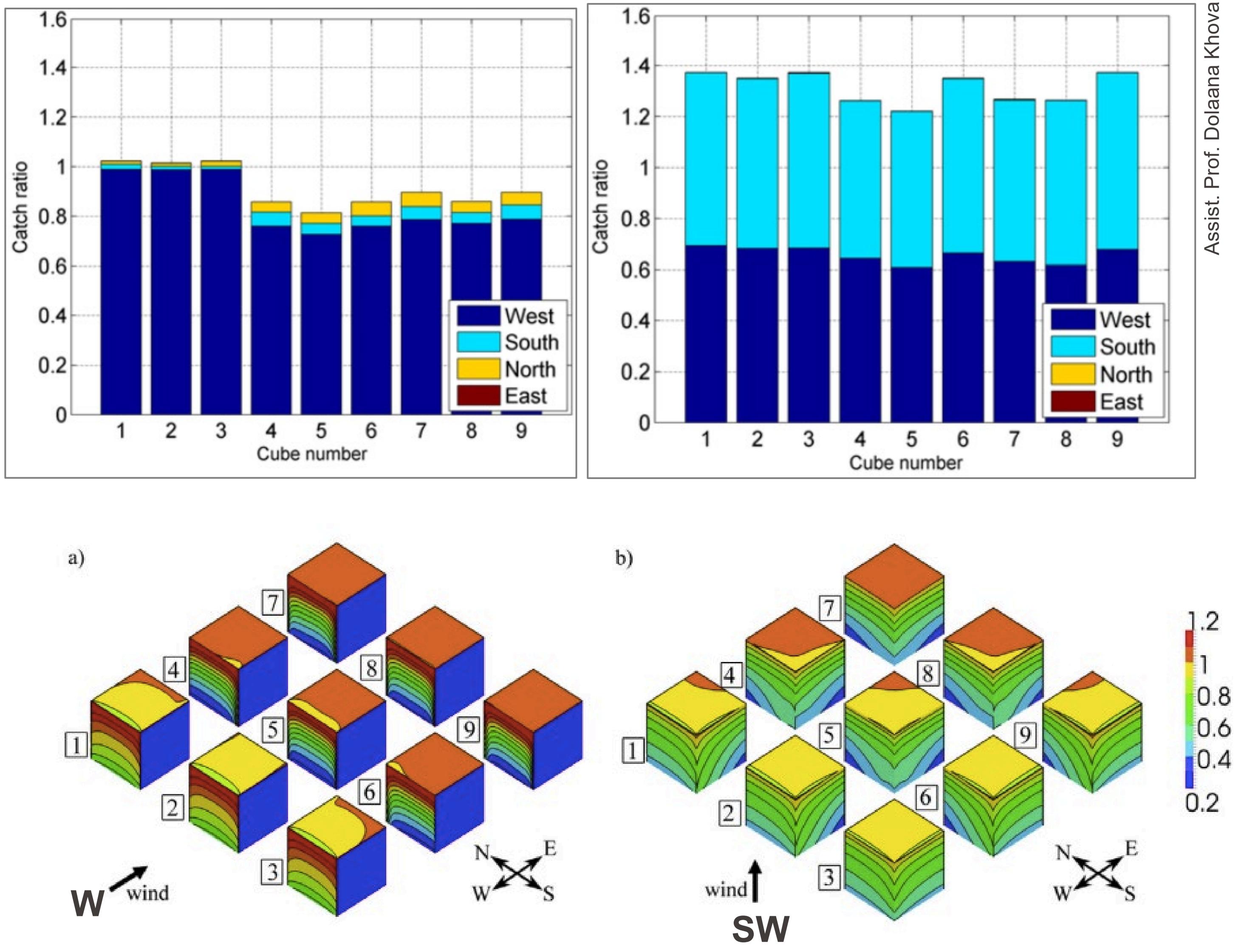
Sorption curves of materials



Source: Medved, Building Physics, p. 193, 230

Urban canopy: Hydrodynamic interaction

- The *vertical urban facets* receive more rain with stronger wind.
- Only *a little fraction of water collected by facets* is available for **evaporation** as the rest goes to the **sewage system**.
- **Water distribution during the rainfall** is highly variable and depends on:
  - Urban geometry
  - Wind direction
  - Wind magnitude
  - Surface materials
- **Catach ratio η -** ratio of wind-driven precipitation R_{wdr} reaching a surface over precipitation R_h with no wind over a horizontal surface

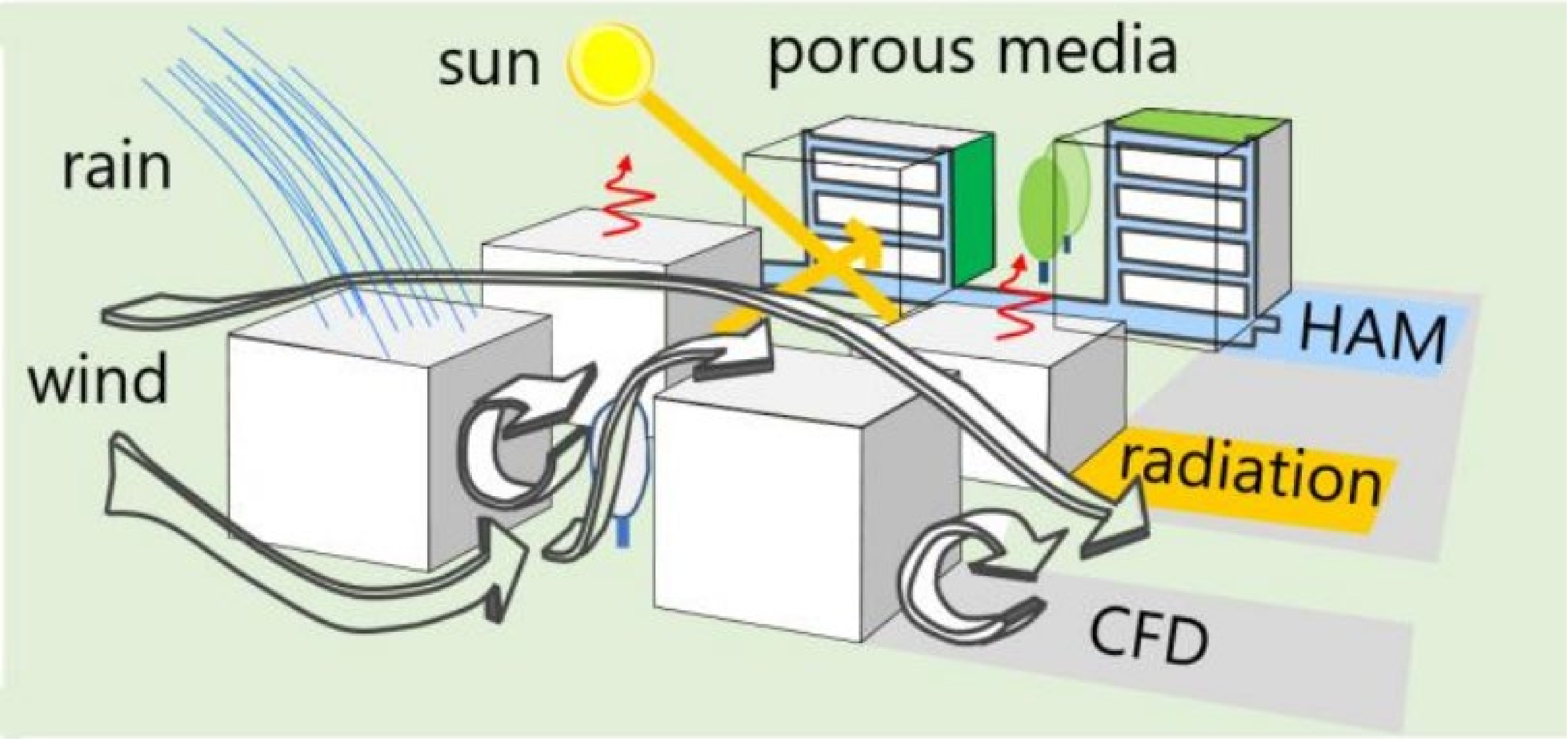


Catch ratio intensity η (-) for wind speed $U = 5\ m/s$ and rainfall intensity $R_h = 1\ mm/h$

Source: Kubilay, 2014, Building and Environment 81:283-295,

Local Urban Microclimate Modeling

Source: Kubilay et a. (2020) doi:10.3390/atmos11121313



- **CFD** – building-resolved computational fluid dynamics
- **HAM** – heat-air-moisture transport in urban materials
- **Radiation** – longwave and solar radiation
- **Wind-driven rain** and **vegetation** model

Thank you for your attention

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