EPFL

CIVIL-309: URBAN THERMODYNAMICS

Assist. Prof.
Dolaana Khovalyg

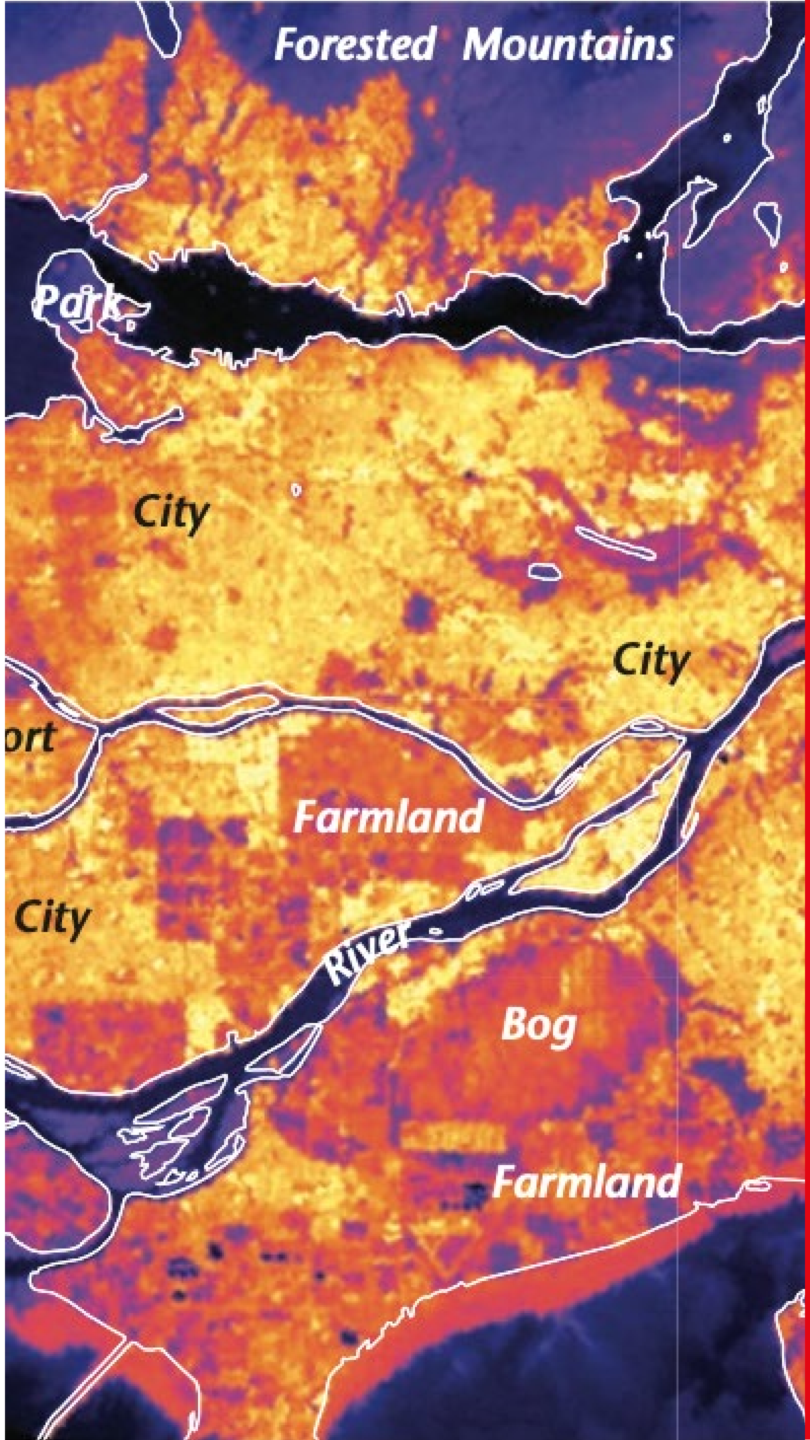
Lecture 07:
Water bodies-environment interaction

11 November 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	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

Dr. Kun Lyu


Forested Mountains
Park
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Farmland
City
River
Bog
Farmland

CONTENT:

Urban water bodies

- What are the differences between the water bodies? (e.g., size)

1.

Water body A

Water body B

2.

Water body A

Water body B

3.

Water body A

Water body B

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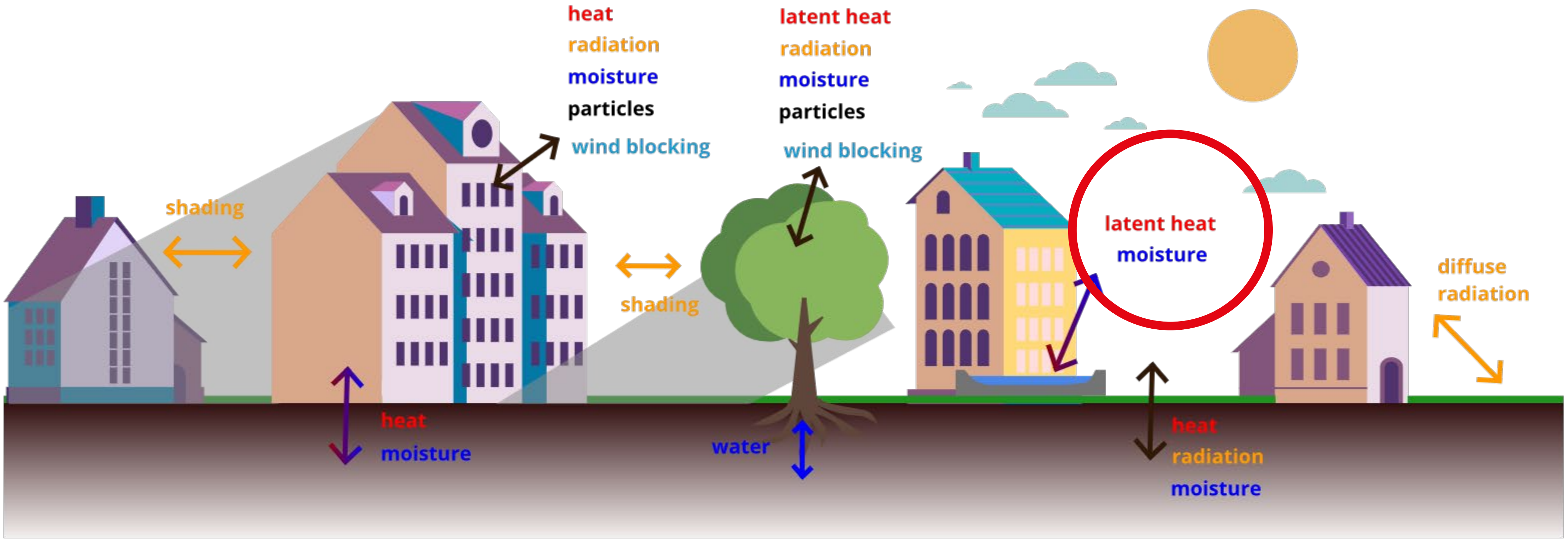
Blue areas-Environment Interaction: Introduction

- Blue areas interact *directly* with the atmosphere above. They also have an *indirect* effect on buildings and vegetation.
- Blue areas receive radiation from the Sun. They mainly contribute to the change in atmospheric conditions by the production of **latent heat** and the release of **moisture**.



Cities and Urbanism: Urban Scales

Reminder from L1

Microscale | Local scale | Mesoscale

Length: 10^0 (1 m) — 10^1 (10 m) — 10^2 (100 m) — 10^3 (1 km) — 10^4 (10 km) — 10^5 m (100 km)

Facet | Building | Block | LCZ/Neighbourhood | City

Street canyon

- **Homogeneity** vs. **heterogeneity** of urban properties (the *smallest* homogeneous urban unit – *an urban block*)
- Spatially, something **homogeneous** at a *one length scale* might be **heterogeneous** *at another* (3D vs 1D treatment of atmospheric properties at the building scale and city scale)

Urban Water Bodies: Introduction

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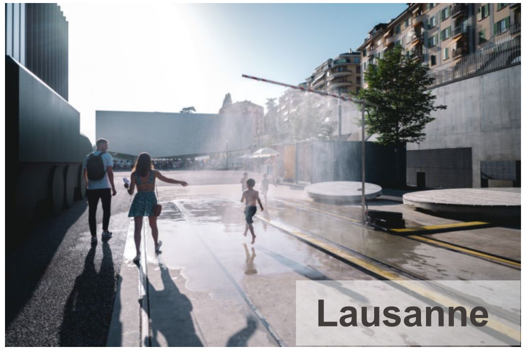
- **Blue areas** or **water bodies** are elements of the urban environment mainly made of water:
  - At the **urban scale**: rivers, sea, and lakes
  - At the **local scale**: ponds, pools, and fountains
- A water body is characterized by its **location**, **geometry**, **volume of water** and **the area of *free water surfaces in contact with the atmosphere***.
- The *appropriate location* and *form* of water elements significantly affect the **attractiveness** and *strengthening* of the **identity** of **places** in **cities**.
- Water bodies *contribute* to the **mitigation of the UHI** by the physical process of **water evaporation**.



Urban Water Bodies: Introduction

- The **atmosphere** over blue bodies is:
  - *Temperate* (usually warmer in winter and cooler in summer) due to the thermal properties of water (its high heat capacity).
  - With *faster wind speeds*, due to the negligible roughness of water surfaces.
- For **cities** exposed to **expanded surfaces of water** bodies, are observed:
  - An *inflow* of *fast*, *clean* and more *humid* air from these blue areas.
  - A *thermal circulation* of *fresh air* from blue areas that is warmed up over the city and recirculate down to the sea when weather is stable.
- To benefit from these effects, streets should be **wide and open** to the blue areas. On the opposite, if the effects of blue areas are undesirable, buildings should *obstruct* the flow coming from them.
- Water bodies have thermal inertia: peak temperature is reached with a *delay* with respect to peak air temperature.

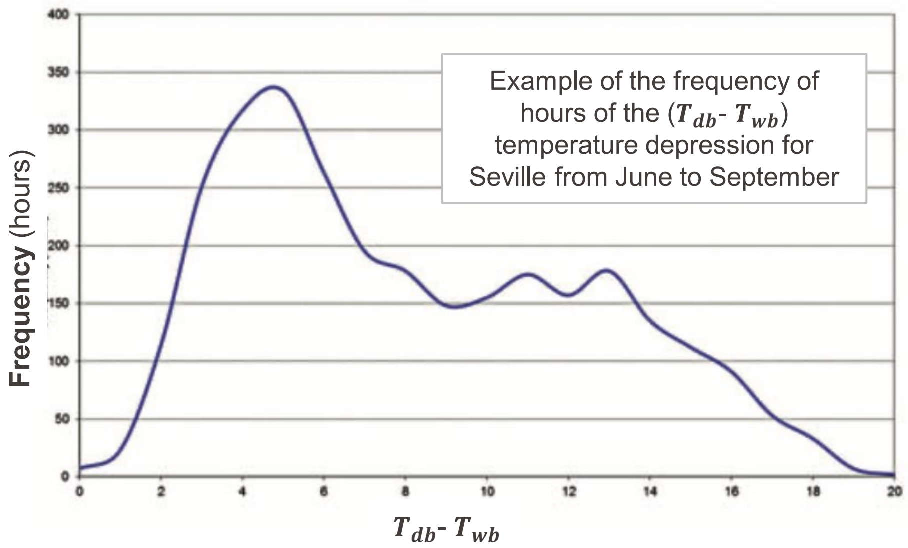
Source: Oke, Urban Climates, p. 440

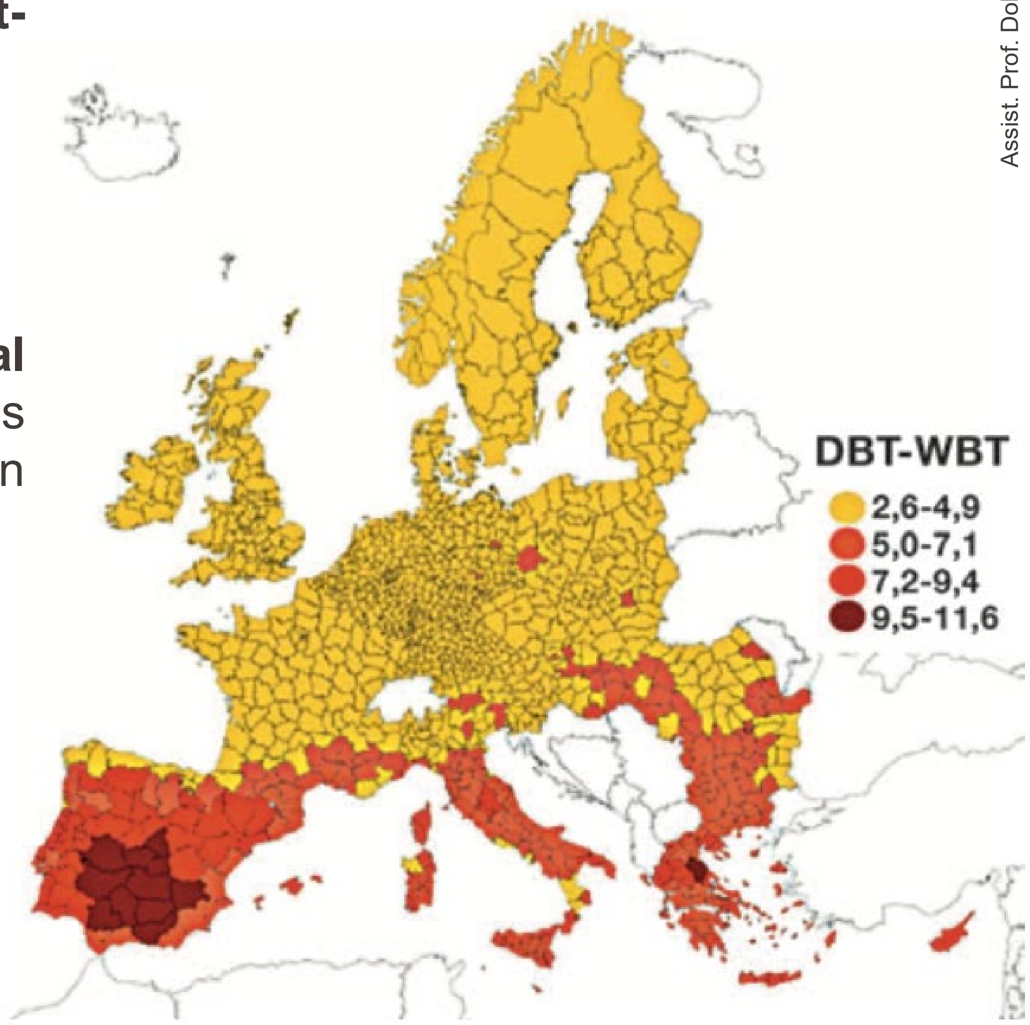
Evaporative cooling: Cooling Degree Days

- The **cooling degree days (CCD)** is the **difference** between **the dry-bulb temperature** (T_{db}) and **the wet-bulb temperature** (T_{wb}) over a day:

$$CDD = \frac{1}{24}\sum_{j=1}^{N\ hours}\left(T_{db}(i) - T_{wb}(i)\right) \quad (7\text{-}1)$$

- The **CCD** provides an estimation of the **potential evaporative cooling**. If water is supplied (e.g., surfaces are wetted), the CCD indicates the *average* change in temperature due to evaporation.





Source: Santamouris and Kolokosta, Urban Climate Mitigation Techniques, p. 128

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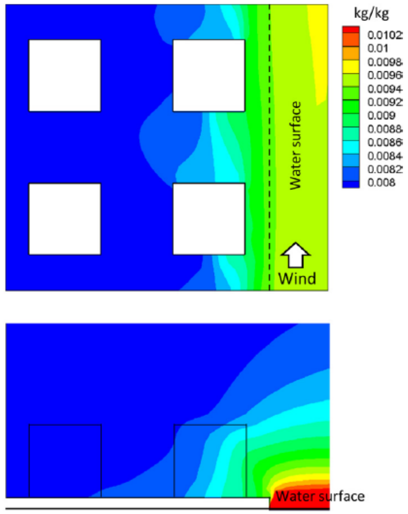
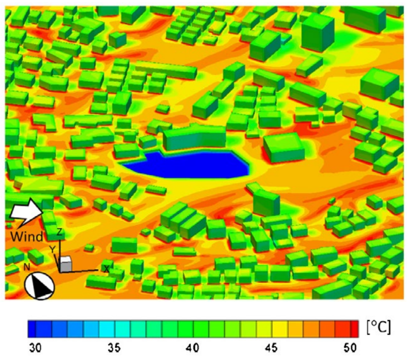
Urban Cooling Islands (UCI)

- Zones inside urban areas with *lower temperatures* due to **the presence** of **vegetation** or/and **water bodies** are referred to as **Urban Cooling Islands (UCI).**

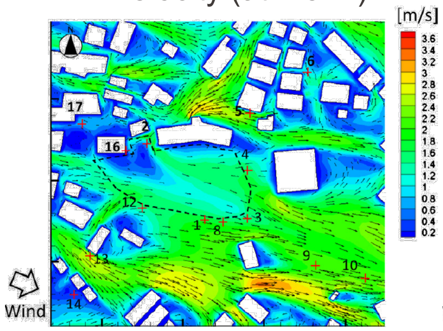
Cooling effect of the pond



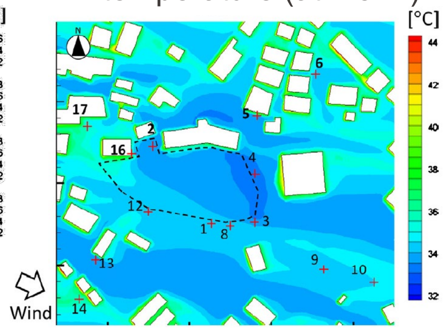
Surface Temperature



Air velocity (at 1.5 m)

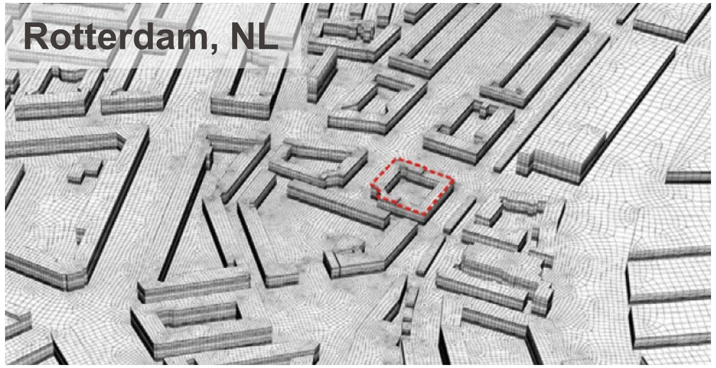


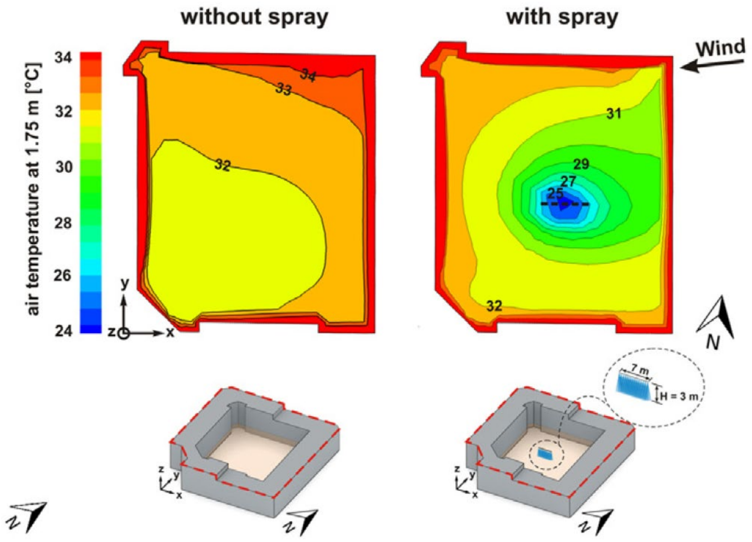
Air temperature (at 1.5 m)



Tominaga et al. (2015) doi.org/10.1016/j.scs.2015.03.011

Water spray system





Montazeri et al. (2017) doi.org/10.1016/j.landurbplan.2016.10.001

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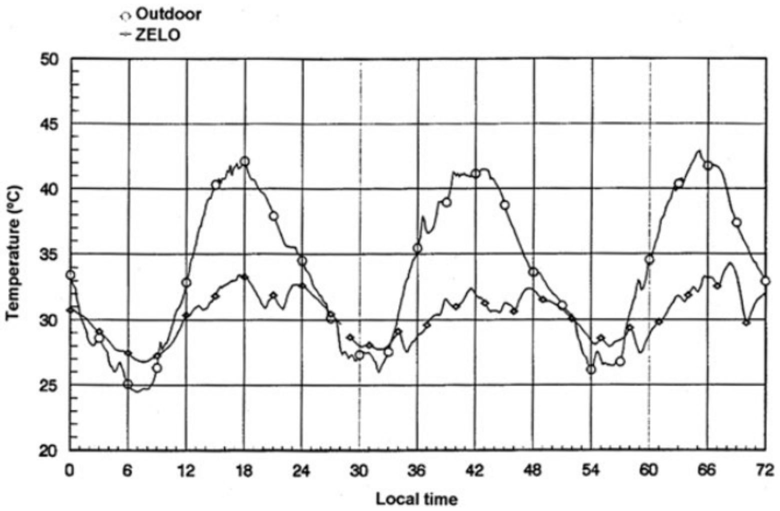
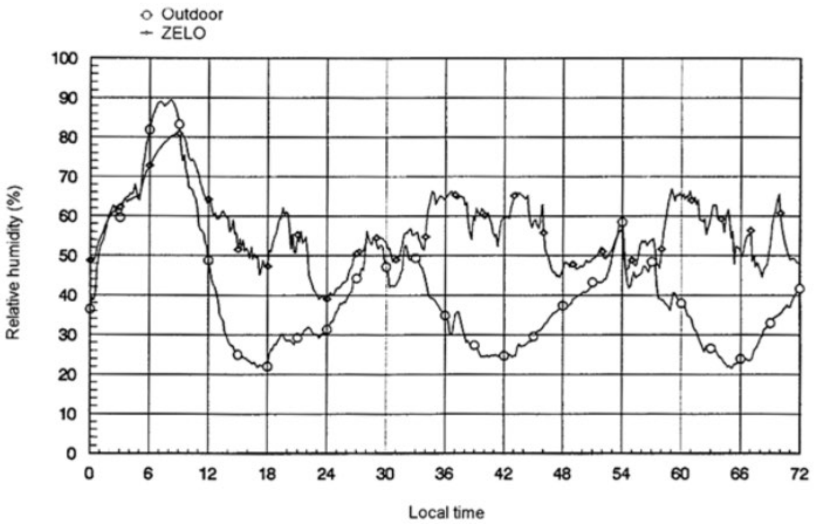
Evaporative cooling: Water sprays

- Droplets of the water sprays evaporate in contact with the surrounding hot air. As cool air is heavier than hot air, a continuous descending flow of cool air is obtained.

- **Water sprays** are more effective when:
  - A droplet radius < 0.5 mm
  - At certain height above the ground for human comfort
  - Nozzles distributed uniformly with no overlap
  - Functioning until *wet-bulb temperature* is reached

- In Sevilla during the Expo'1992, for 128 **micronizers** sheltered with a continuous flow rate of 7.2 l/h (ZELO system) were used. A maximum drop of 10 K air temperature was reached and temperature was always maintained lower than outdoor air temperature.

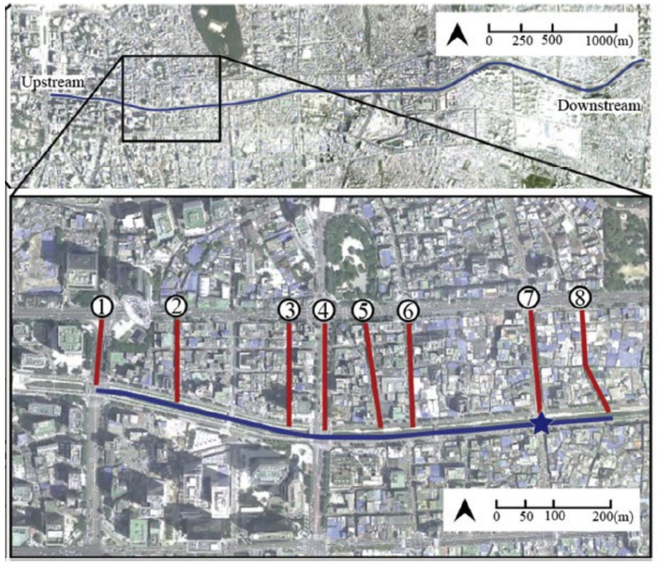




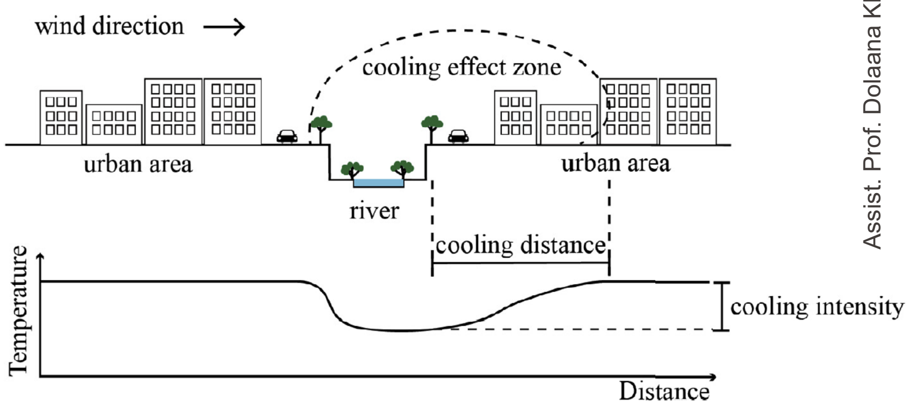
Source: Santamouris and Kolokosta, Urban Climate Mitigation Techniques, p. 124

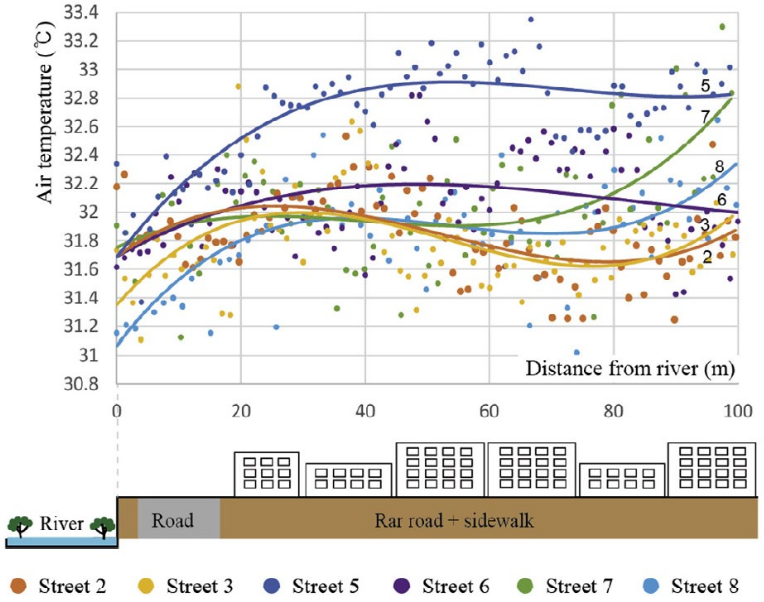
Evaporative cooling: Rivers

- The effect of **rivers** on microclimate (extent and magnitude) depends on:
  - River width
  - Road and building density of surrounding area
  - Wind speed
- Murakawa et al. (1991) measured an air temperature difference of about 3-5 °C between the river and the city for wind speeds of 1-5 m/s.
- Two indicators of water cooling effect: ***Cooling intensity*** and ***cooling distance***




Seoul, KR, Cheonggye River

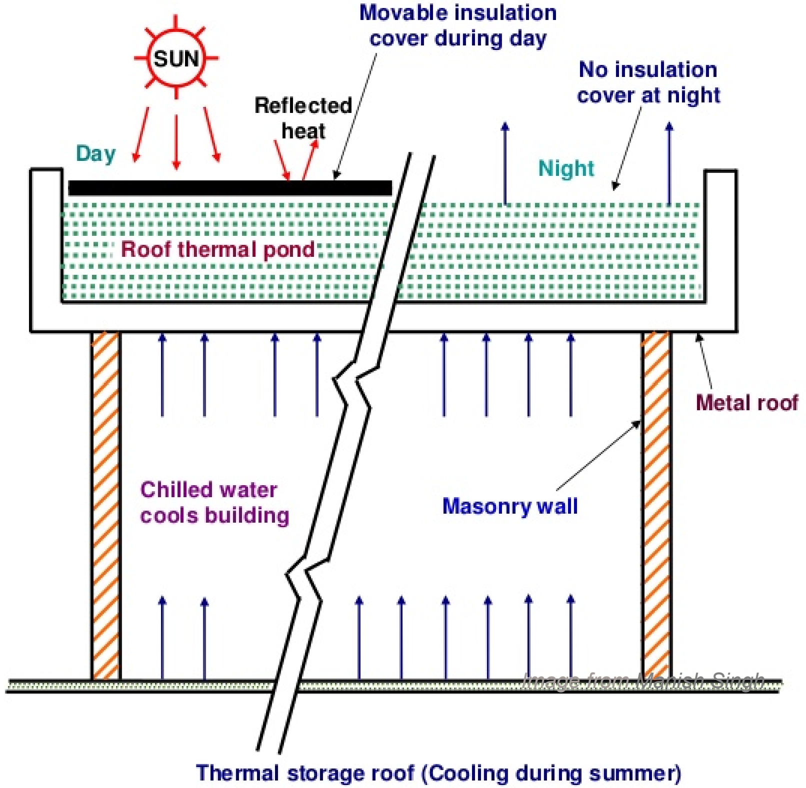


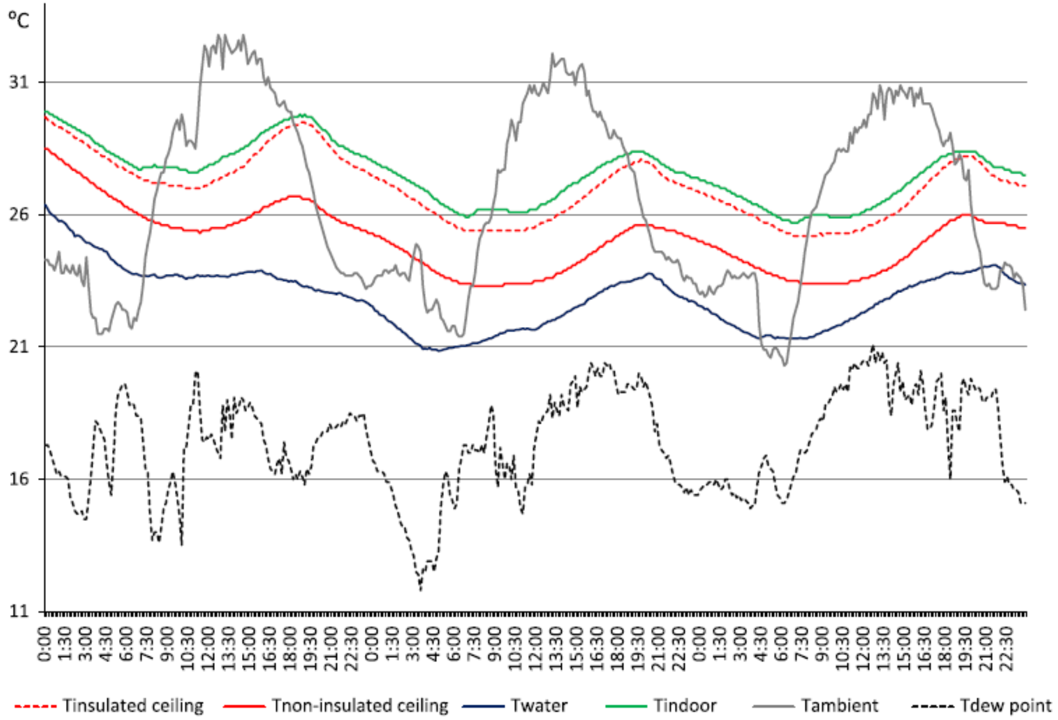


Park et al. (2019) doi.org/10.1016/j.landurbplan.2018.10.022

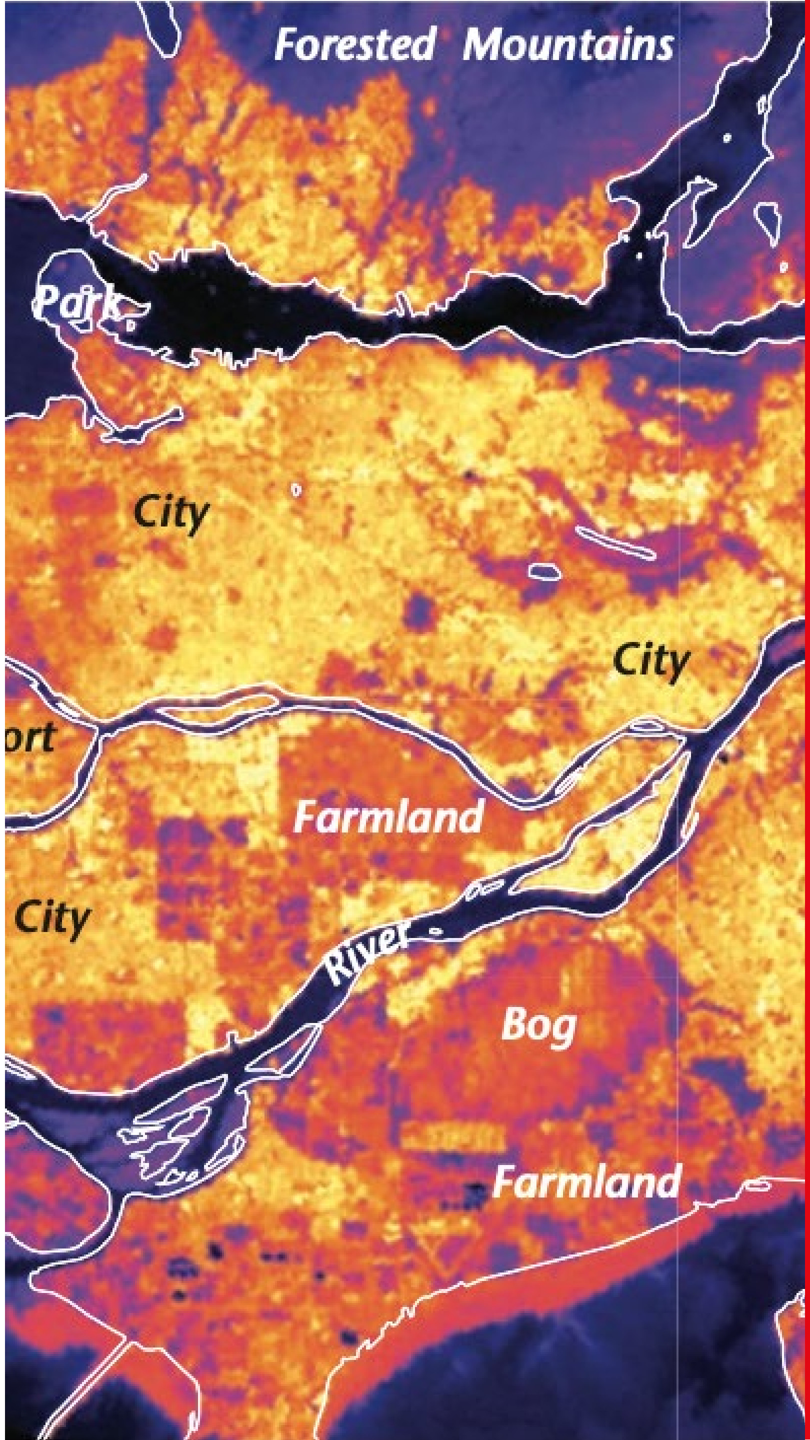
Evaporative cooling: Roof Ponds

- Roof ponds can be used for passive cooling by taking advantage of the **storage capacity of water.**
- The ponds are *typically* **covered during the day** to prevent heating (excessive evaporation), and **open at night** to be cooled.





Apanaki et al. (2014) doi.org/10.1016/j.apenergy.2014.02.040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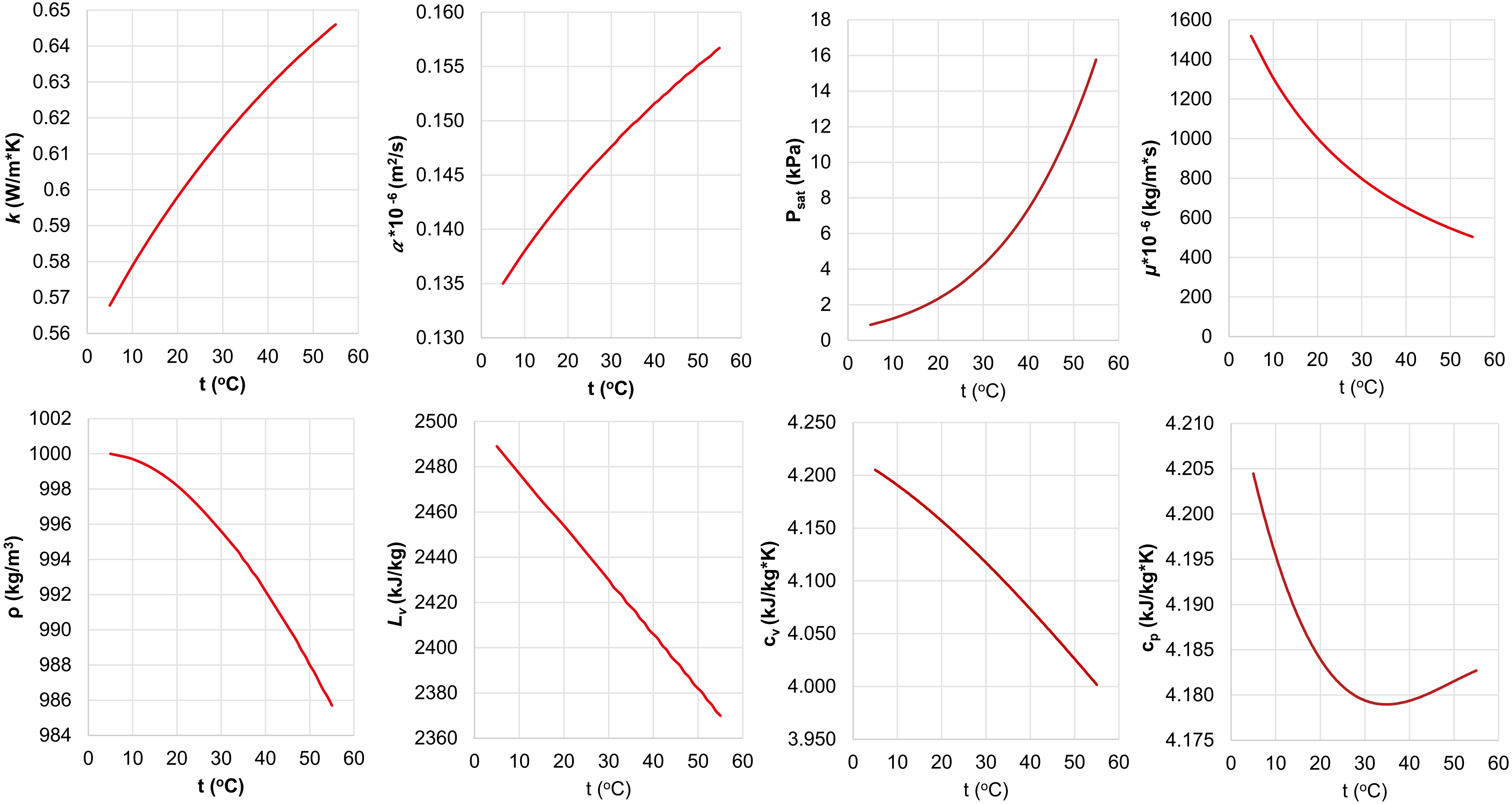
Water: Thermo-Physical Properties

Source: Oke, Urban Climates, p. 169

Material	State	Heat capacity C (MJ m^{-3} K^{-1})	Thermal conductivity k (W m^{-1} K^{-1})	Thermal diffusivity κ (m^2 s^{-1} × 10^{-6})	Thermal admittance μ_s (J m^{-2} s$^{-1/2}$ K^{-1})
Construction and building materials in dry state (built sites)					
Asphalt road	Range	1.92–2.10	0.74–1.40	0.38–1.04	1,205–1,960
	Typical	1.94	0.75	0.38	1,205
Concrete	Aerated	0.28	0.08	0.29	150
	Dense	2.11	1.51	0.72	1,785
Stone	Typical	2.25	2.19	0.97	2,220
Brick	Typical	1.37	0.83	0.61	1,065
Natural materials (rural and undeveloped urban sites)					
Sandy soil (40% porosity)	Dry	1.28	0.3	0.24	620
	Saturated	2.96	2.2	0.74	2,550
Clay soil (40% porosity)	Dry	1.42	0.25	0.18	600
	Saturated	3.10	1.58	0.51	2,210
Peat soil (80% porosity)	Dry	0.58	0.06	0.10	190
	Saturated	4.02	0.5	0.12	1,420
Water[1]	4°C, still	4.18	0.57	0.14	1,545
Air[1]	10°C, still	0.0012	0.025	21.5	5
	Turbulent	0.0012	~125	~10 x 10^6	390

[1] Properties depend on temperature

Water: Thermo-Physical Properties



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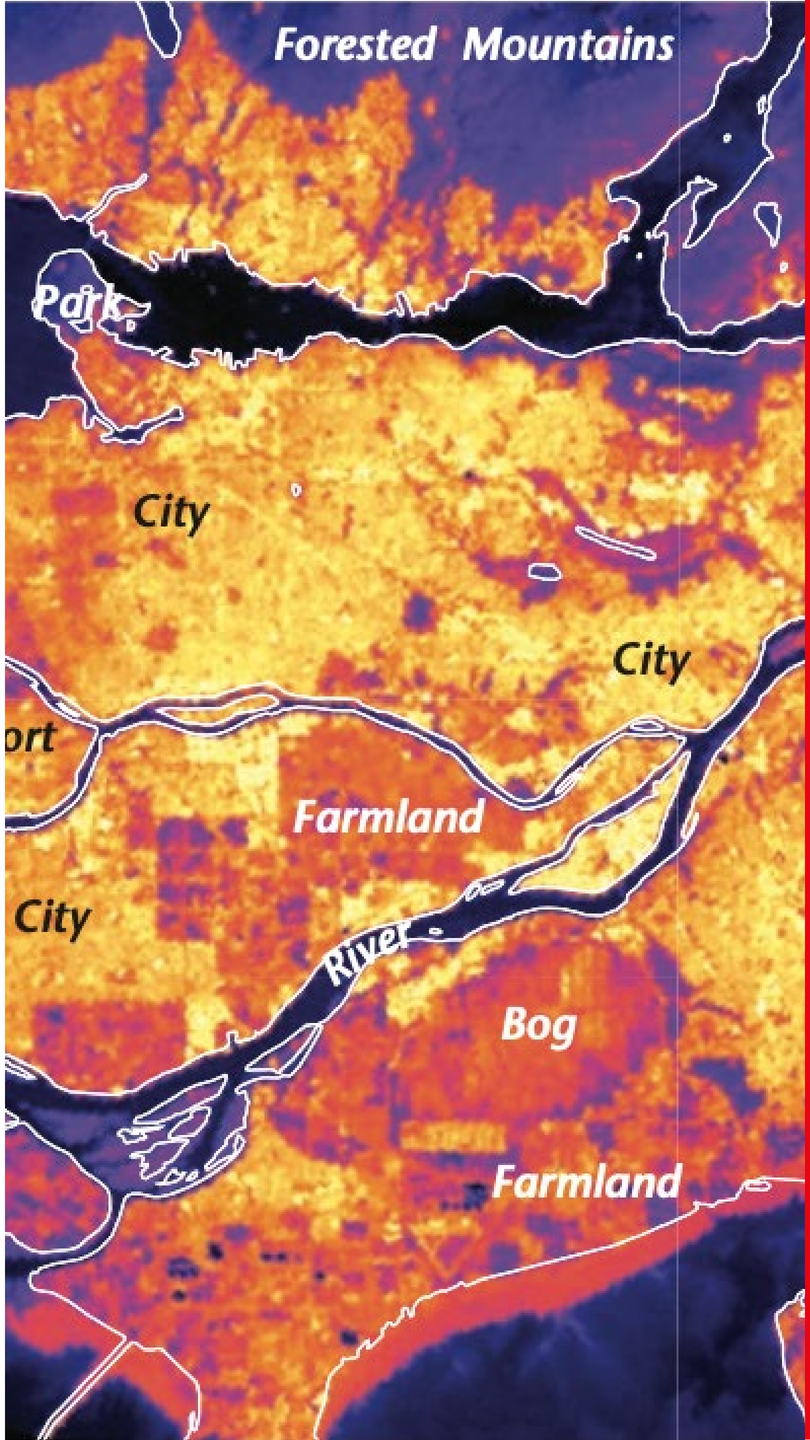
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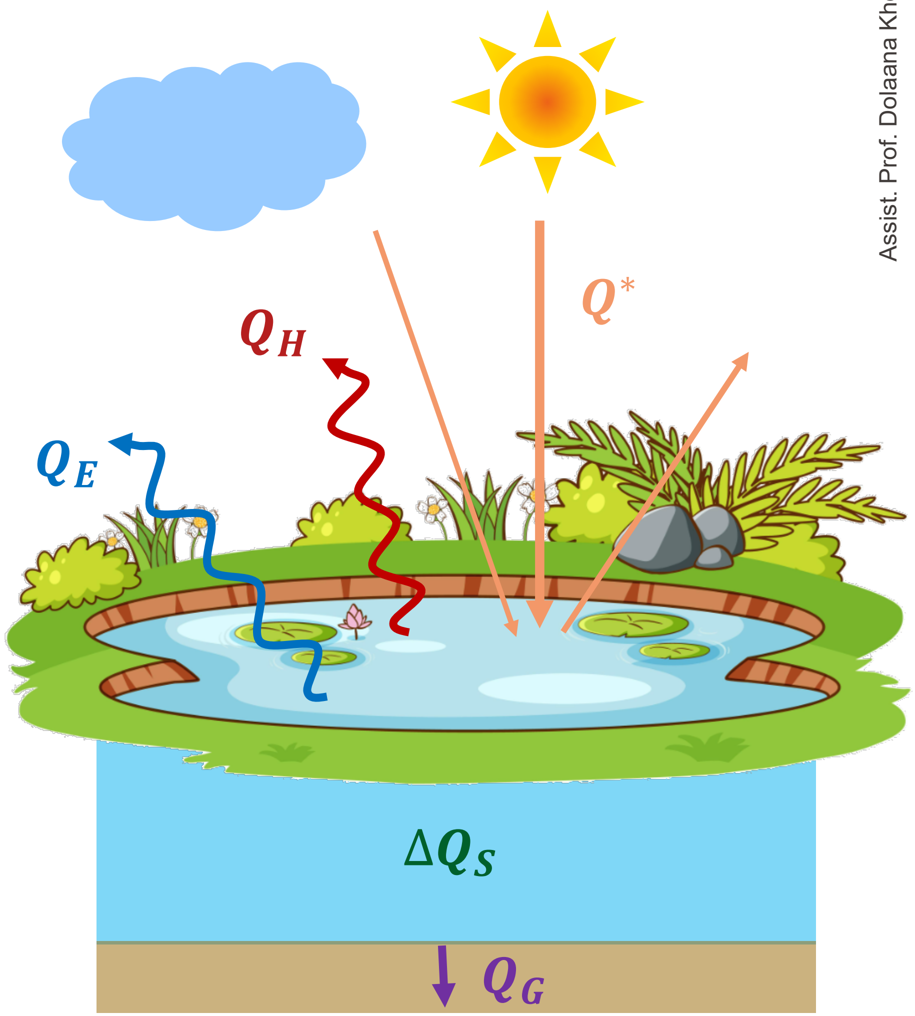
Energy Balance of Water Bodies

- Blue areas interact with the atmosphere, buildings and other urban elements *somewhat similarly* to ground and vegetation.
- The water bodies interaction with their environment is always *at balance*. It is the sum of radiation, sensible heat, **latent heat**, ground heat and stored heat.

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

Radiation budget | Sensible heat | Latent heat | Ground heat | Stored heat



Q^* - **<u>net</u> allwave radiation heat flux** (W/m^2)
Q_H - **sensible heat flux** (W/m^2)
Q_E - **latent heat flux** (W/m^2)
Q_G - **ground heat flux** (sensible heat by conduction to the substrate) (W/m^2)
ΔQ_S - **stored heat in the water body** (W/m^2)

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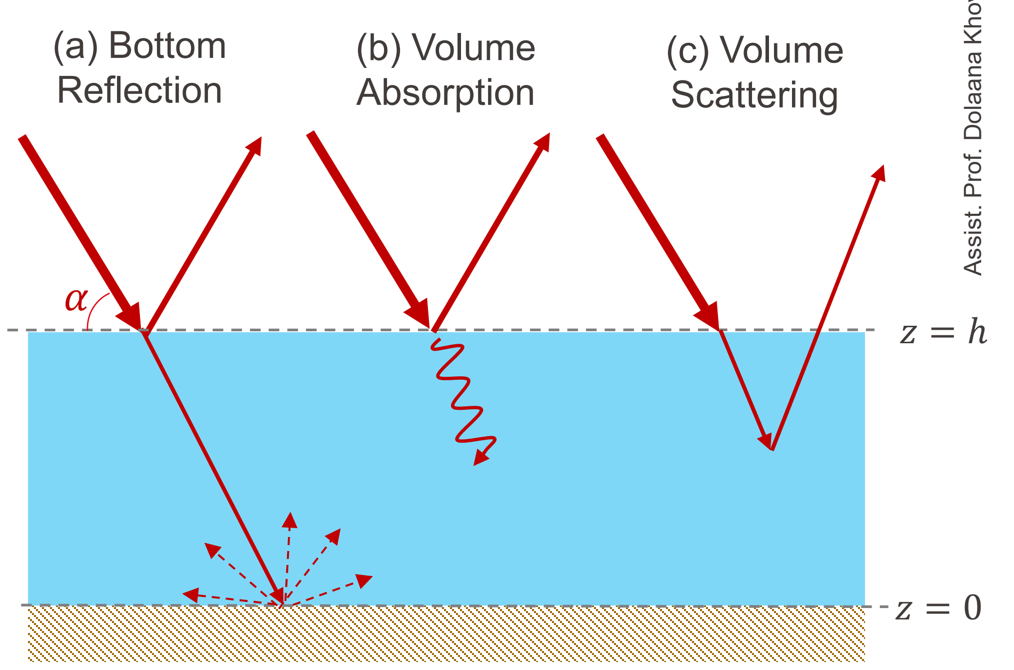
Water body: Radiation Budget

- The **radiation balance** of a water body is not straightforward as radiation can penetrate to *considerable depth* in water. Thus, radiation exchange not only happens on the *water surface* but also within *the volume of water*.
- **Radiation** *entering* a water body can *interact* with it in *several different ways* depending on the **absorption** and **backscattering processes** within a water body mainly caused by the water molecules themselves and by dissolved or suspended substances.



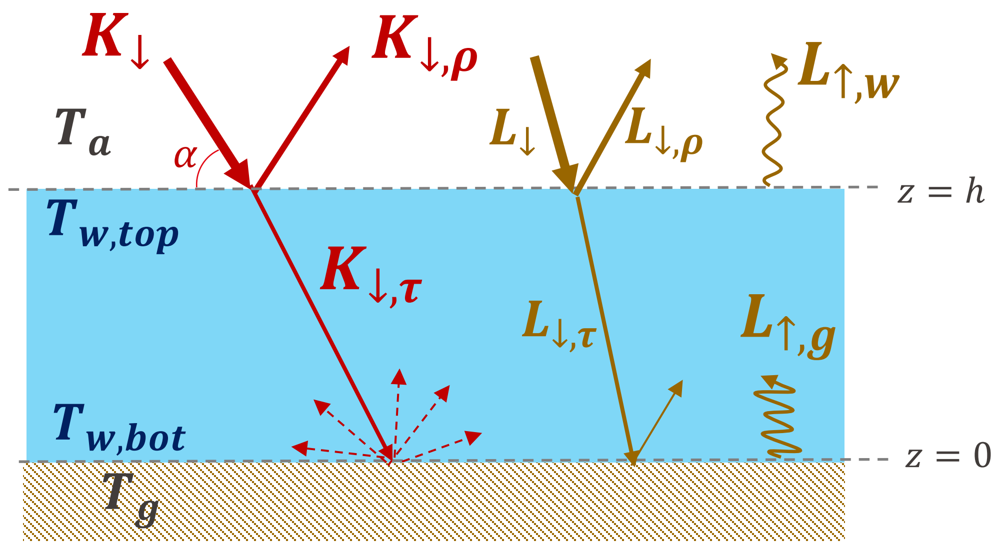
- **Case (a), clear water with bottom reflection**
  - **Radiation budget on the top surface** $(z = h)$ **:**

$$Q^* = (K_\downarrow - K_{\downarrow,\rho}) + (L_\downarrow - L_\uparrow) \quad (3\text{-}37)$$

$$Q^*_{top} = (K_\downarrow - \rho \cdot K_\downarrow) + (L_\downarrow - \rho \cdot L_\downarrow - \varepsilon \cdot \sigma \cdot T^4_{w,top})$$

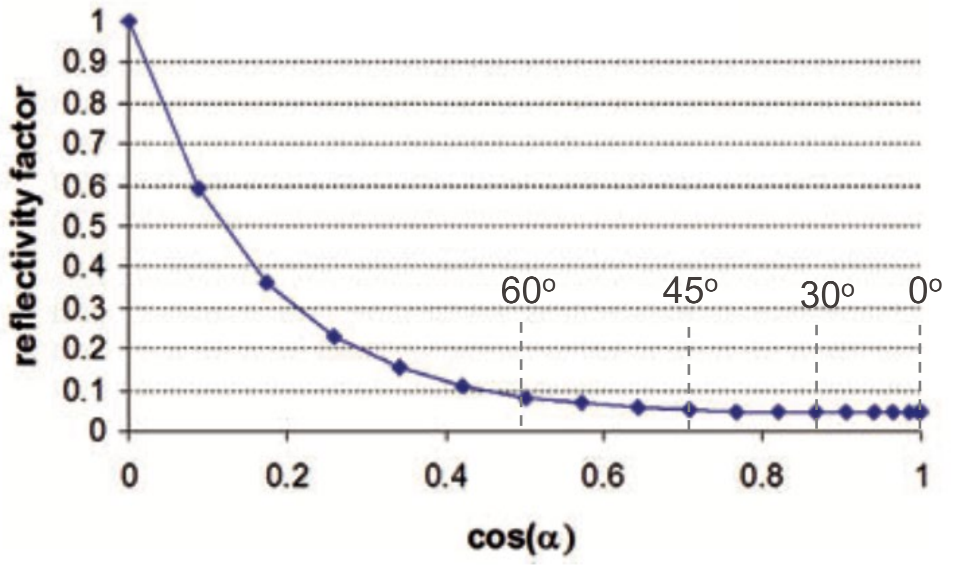
  - **Radiation budget on the bottom surface** $(z = 0)$**:**

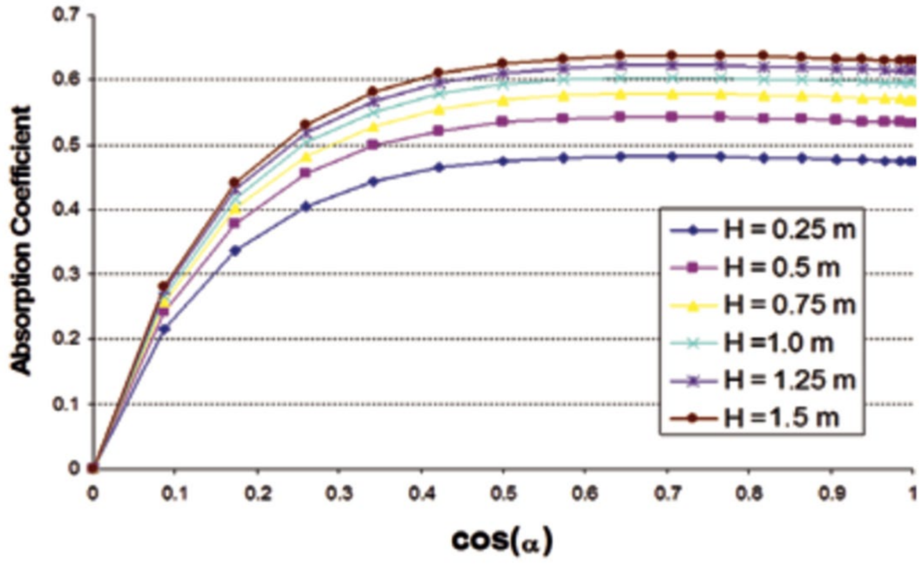
$$Q^*_{bot} = (K_{\downarrow,\tau} - \rho_g \cdot K_{\downarrow,\tau}) + (L_{\downarrow,\tau} - \rho_g \cdot L_{\downarrow,\tau} - \varepsilon_g \cdot \sigma \cdot T^4_g)$$



Water: Radiative Properties

- Radiative properties of water (absorptivity α, reflectivity ρ, and transmittance τ) depend on ***the angle of incidence of the light*** and ***the water depth*** *(path length for solar radiation)*:
  - Reflectivity *only* depends on the solar incident angle. The water has reflectivity < 0.1 when incoming radiation angle α < 65°; the *minimum* reflectivity of **0.05** at zenith (α =0°, $\cos(\alpha)$=1).
  - Absorptivity depends on the solar incident angle α and the pond depth H ; the percentage of radiation absorbed increases with the water depth.
  - Generally, water is transparent to short-wave radiation, however, absorption depends not only on the path length but also strongly on the **turbidity** of the water
- The **low reflectivity of water** is an *advantage* ***to lower the diffuse radiation*** perceived by *urban objects*.





Source: Santamouris and Kolokosta, Urban Climate Mitigation Techniques, p. 124

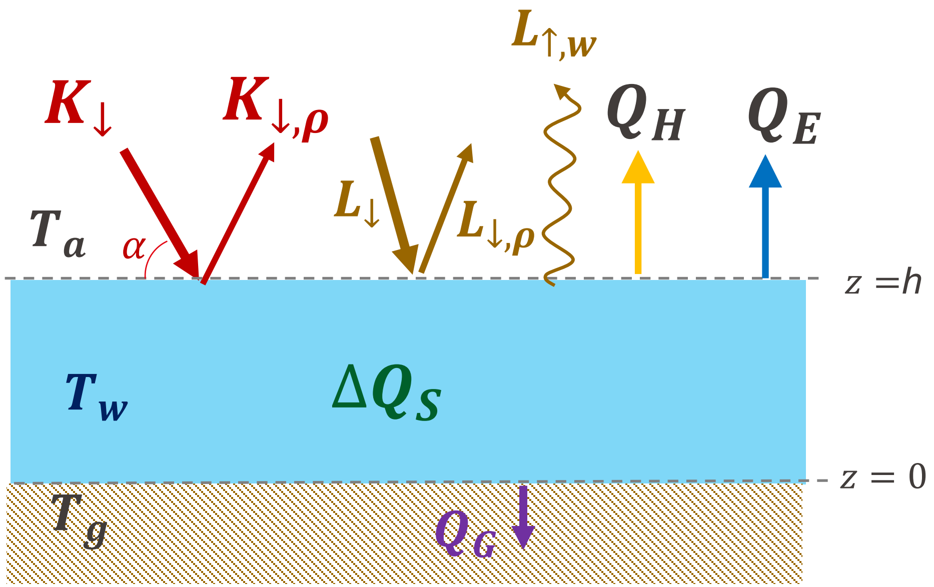
Water body: Thermal Storage

- **The energy balance** of the water body can be expressed for **top** and **bottom surfaces**, as well as for **the water mass**. For shallow bodies, such as artificial water fountains, water temperature could be considered as *uniform*, only depend on time.
- *Radiation* absorbed by water *raises* its temperature. **Thermal inertia** due to **the storage capacity of water** has the advantage to **delay** and **buffer** the temperature increase.
- For a water pond, **the stored heat flux** ΔQ_S is equal to the difference between the radiation absorbed by the pond volume with the heat fluxes lost at the bottom and the top of the pond:

$$\Delta Q_S = (K_{\downarrow,\tau} + L_{\downarrow,\tau}) - (Q_H + Q_E + L_{\uparrow,w} + Q_G) \quad (7\text{-}2)$$

- **Stored heat** ΔQ_S is expressed as a function of the specific heat capacity of water and temperature gradient:

$$\Delta Q_S = \rho \cdot c_p \cdot h \cdot \frac{dT_w}{dt} \quad (7\text{-}3)$$



$K_{\uparrow,\tau} = (K_\downarrow - K_{\downarrow,\rho})$- absorbed shortwave radiation (direct and diffuse)
$L_{\downarrow,\tau} = (L_\downarrow - L_{\downarrow,\rho})$- absorbed longwave radiation from the environment

- Sensible heat flux Q_G by conduction to the substrate:

$$Q_G = h_{conv,w} \cdot (T_w - T_g) \quad (7\text{-}4)$$

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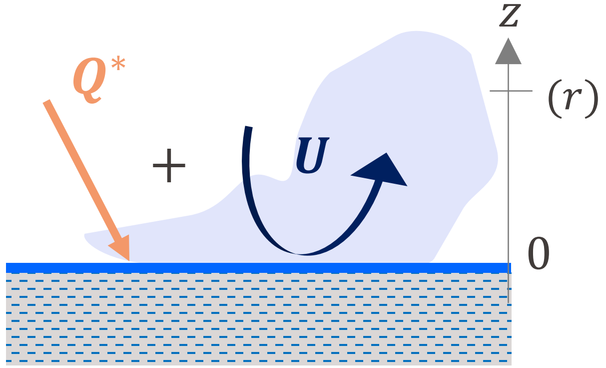
Evaporation rate: Penman method

Reminder from L4

- Assuming *water availability*, the **driving forces** of evaporation are **the supply of energy** (mainly from a radiative heat flux) and **the transport of mass away from the interface** *where evaporation happens* (i.e., the convection/advection of water vapor).

$$\boldsymbol{E_{pot}} = \frac{m}{m+\gamma}\cdot\left(\frac{Q^* - Q_G}{L_v}\right) + \frac{\gamma}{m+\gamma}\cdot E_a \quad \text{(4-27)}$$

Radiation term $\boldsymbol{E_S}$ — Aerodynamic term $\boldsymbol{E_T}$



- $\boldsymbol{E_a}$ $(kg/m^2\cdot s)$ - drying power of air:

(4-20b) $E_a = \rho\cdot C_W\cdot U\cdot(q_s - q_r)$

q_s (kg/kg) - specific humidity at the reference height (r) assuming saturated air at T_r,
q_r (kg/kg) – actual specific humidity at the reference height (r),
C_W $(-)$ - bulk transfer coefficient for water vapor, U $(\frac{m}{s})$ – air speed at reference height

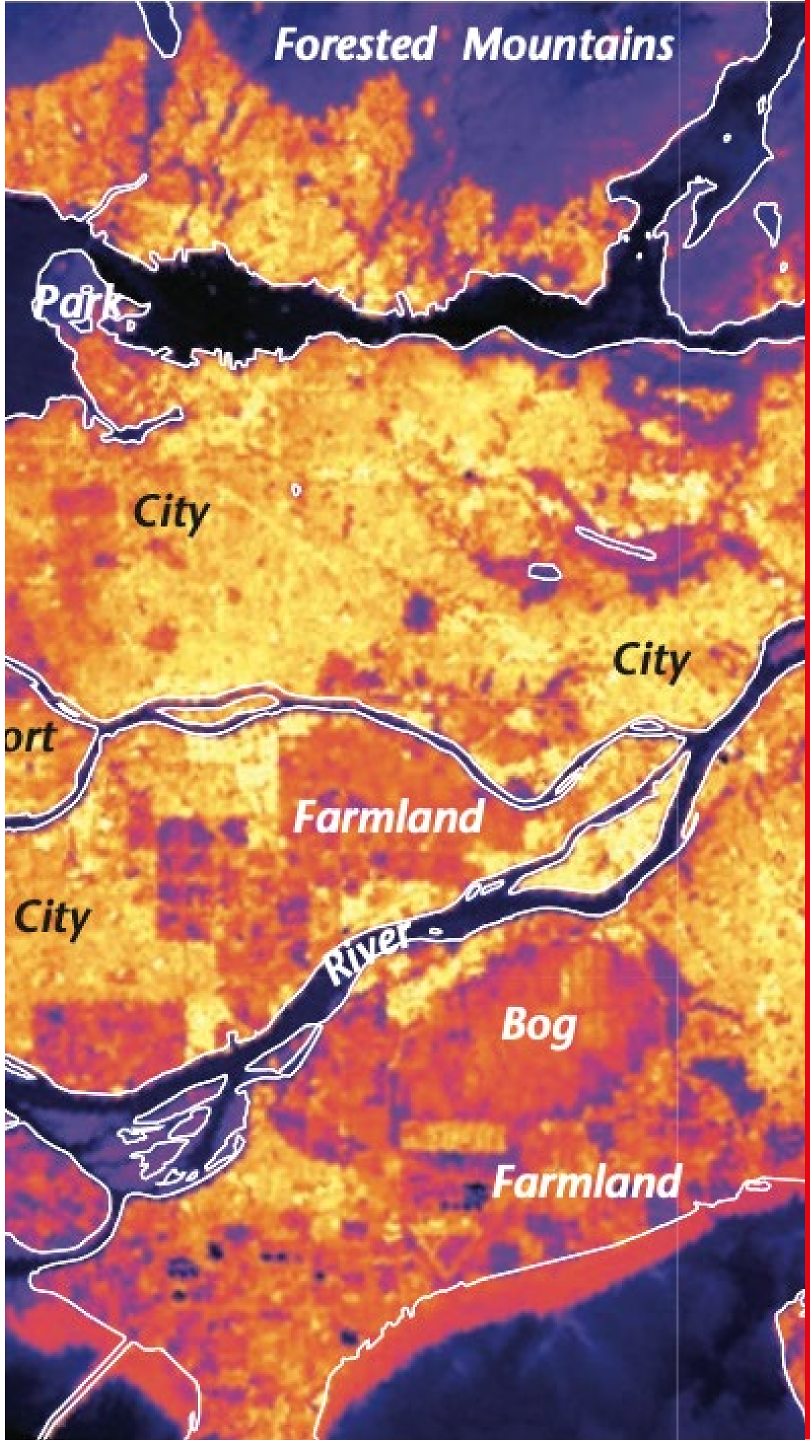
- $\boldsymbol{m}$ (kPa/K) - slope of the saturated vapor pressure versus temperature curve at $(T_r + T_0)/2$:

$$m = \frac{p_{v,0} - p_{v,sat\_r}}{T_0 - T_r} \cong \frac{dp_{v,sat}}{dT} \quad \text{(4-28a)}$$

$$m = 4098\cdot\frac{0.6108\cdot e^{\frac{17.27\cdot t_r}{t_r+237.3}}}{(t_r+237.3)^2} \quad \text{(4-28b)}$$

- $\boldsymbol{\gamma}$ (kPa/K) - psychrometric constant:

$$\gamma = \frac{c_p\cdot p_a}{0.622\cdot L_v} \quad \text{(4-24)}$$



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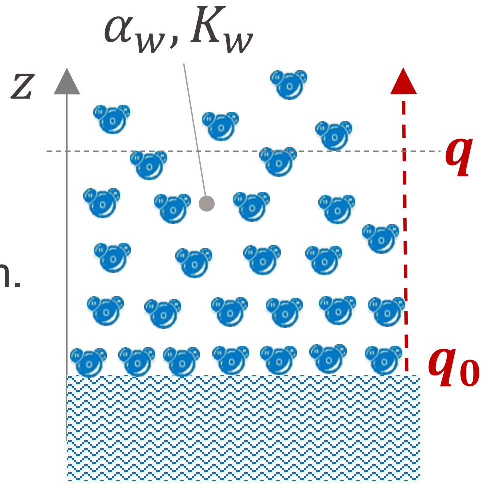
Evaporation rate: Transport of Water Vapor

Reminder from L4

- The expression of the **evaporation rate** $\boldsymbol{E}$ $(\frac{kg}{m^2 s})$ due to **the transport of water vapor** over a **surface** depends whether the **flow** is **laminar** or **turbulent**.



- **Laminar flow: Fick's law** for the evaporation rate at *a horizontal surface*:

$$E = -\rho \cdot \boldsymbol{\alpha_w} \cdot \frac{\partial q}{\partial z} \quad (4\text{-}17)$$

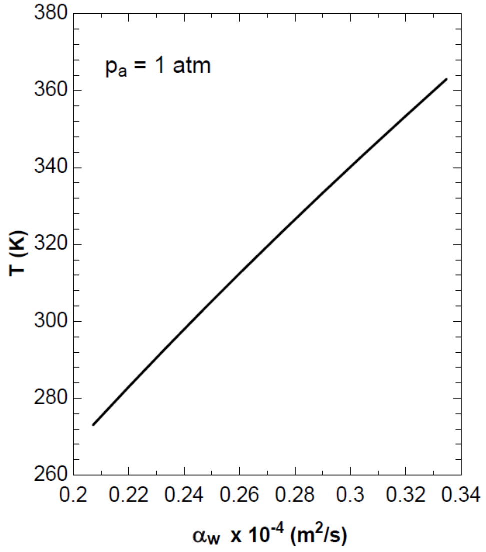
$\boldsymbol{\alpha_w}$ (m^2/s) - molecular diffusivity of water vapor
$\boldsymbol{q}$ (kg/kg) - specific humidity (*see L2, slide 17*)
$\boldsymbol{\rho}$ (kg/m^3) – density of water vapor mixture

- Only valid when molecular exchange is the primary (perhaps the only) transport mechanism.
- Fick's law is not applicable for *urban areas* because the flow in the atmosphere at *the surface layer* at local scale is *always turbulent.*
- It is applicable for mass transfer of *water droplets* as flow around them is mostly laminar

- **Molecular diffusivity of water vapor** $\boldsymbol{\alpha_w}$ (m^2/s)**:**

$$(7\text{-}5) \quad \boldsymbol{\alpha_w} = 1.97 \times 10^{-5} \cdot \left(\frac{p_0}{p_a}\right) \cdot \left(\frac{T}{T_0}\right)^{1.685}$$

- $p_0 = 1\ atm$, $T_0 = 256\ K$
- validity: T range of 273-373 K
- $p_a(atm)$ – atmospheric pressure,
- $T\ (K)$ – film temperature $(T_o + T)/2$



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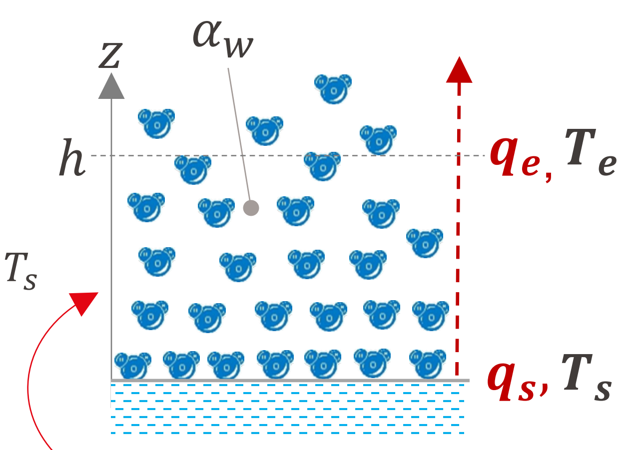
EPFL

Water Sprays: Droplet Lifetime

- Assumptions:
  - A water drop is considered to be a sphere
  - No interaction with among the droplets
  - The whole volume of the water drop is at the temperature T_s
  - Radiation heat transfer is negligible

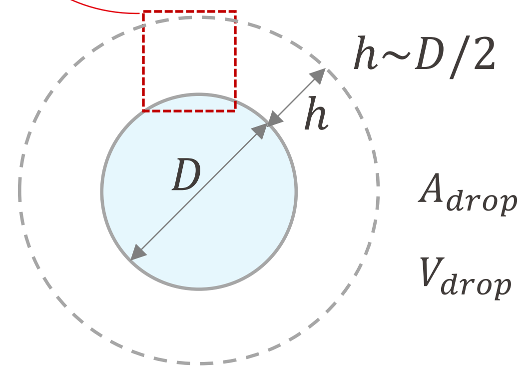


- A **mass balance** on a droplet (mass loss equal to the evaporation rate):

$$\frac{d\,(V_{drop}\cdot\rho_w)}{dt} = -E\cdot A_{drop} \quad (7\text{-}6)$$

- Evaporation rate (in $\frac{kg}{m^2 s}$) of the droplet (per Fick's law):

$$E = \rho\cdot\alpha_w\cdot\frac{(q_s-q_e)}{h} \quad (4\text{-}17a)$$



$$A_{drop} = \pi\cdot D^2$$

$$V_{drop} = \frac{1}{6}\cdot\pi\cdot D^3$$

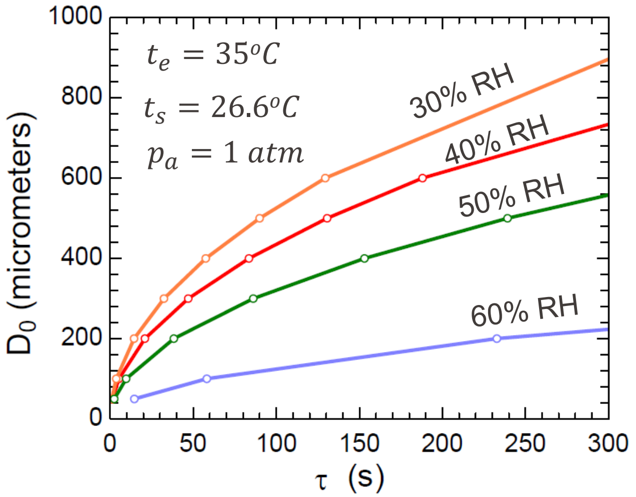
- The **droplet lifetime** τ_l (s) after injection into an air stream:
  - Combining Eqns. (7-6) and (4-17a):

$$\frac{d}{dt}\left(\frac{1}{6}\cdot\pi\cdot D^3\cdot\rho_w\right) = -\left[\rho\cdot\alpha_w\cdot\frac{(q_s-q_e)}{D/2}\right]\cdot(\pi\cdot D^2) \rightarrow \frac{dD}{dt} = -\frac{4\cdot\rho\cdot\alpha_w\cdot(q_s-q_e)}{D\cdot\rho_w}$$

$$\int_{D_o}^{0} D\,dD = -\frac{4\cdot\rho\cdot\alpha_w\cdot(q_s-q_e)}{\rho_w}\cdot\int_0^{\tau_l} dt \rightarrow \frac{D_0^2}{2} = \frac{4\cdot\rho\cdot\alpha_w\cdot(q_s-q_e)}{\rho_w}\cdot\tau_l$$

$$\tau_l = \frac{\rho_w\cdot D_0^2}{8\cdot\rho\cdot\alpha_w\cdot(q_s-q_e)} \quad (7\text{-}7)$$

α_w, ρ_w should be at the film temperature $T_f = (T_e + T_s)/2$
D_0 (m) – initial diameter of the droplet
ρ (kg/m^3) – density of water vapor mixture at T_f
T_s (K) – wet-bulb temperature



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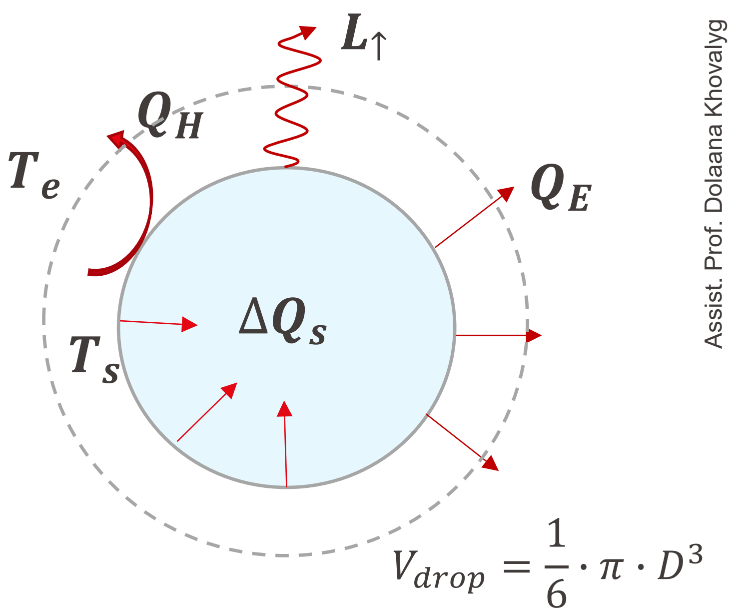
Water Sprays: Energy Balance

- **Energy balance (in W)**: the rate of *decrease* **in droplet internal energy** (energy storage ΔQ_s) is *mainly* balanced by **the rate of latent heat supply** (Q_H) and **sensible heat transfer** (Q_E); radiation heat transfer $L_{\uparrow}$ relatively is *small*.



$$-\Delta Q_s = Q_H + Q_E \quad (7\text{-}8)$$

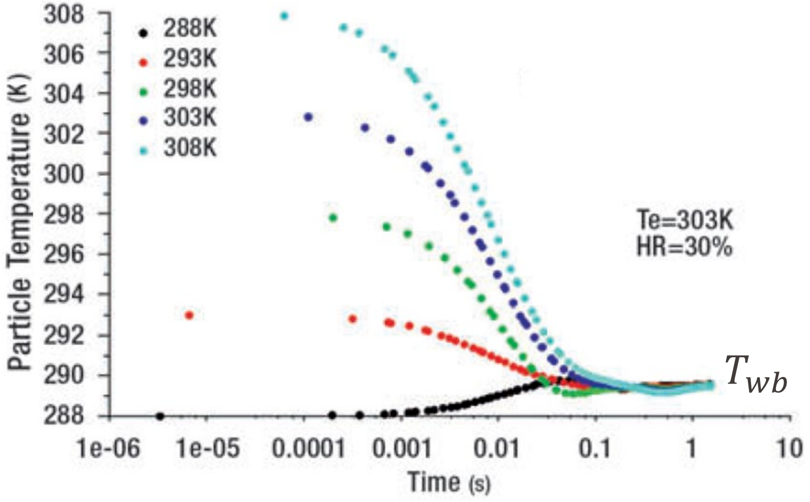
$$-\rho_w \cdot \left(\frac{1}{6} \cdot \pi \cdot D^3\right) \cdot c_v \cdot \frac{dT}{dt} = \pi \cdot D^2 \; [h_{conv} \cdot (T_s - T_e) + L_v \cdot E] \quad (7\text{-}9)$$

- **Duration of initial temperature transient [K/s]:** the time required for the droplet to *warm up /cool down* from its injection temperature (T_i) to final temperature (T_{wb}) can be estimated by calculating $\frac{dT}{dt}$:

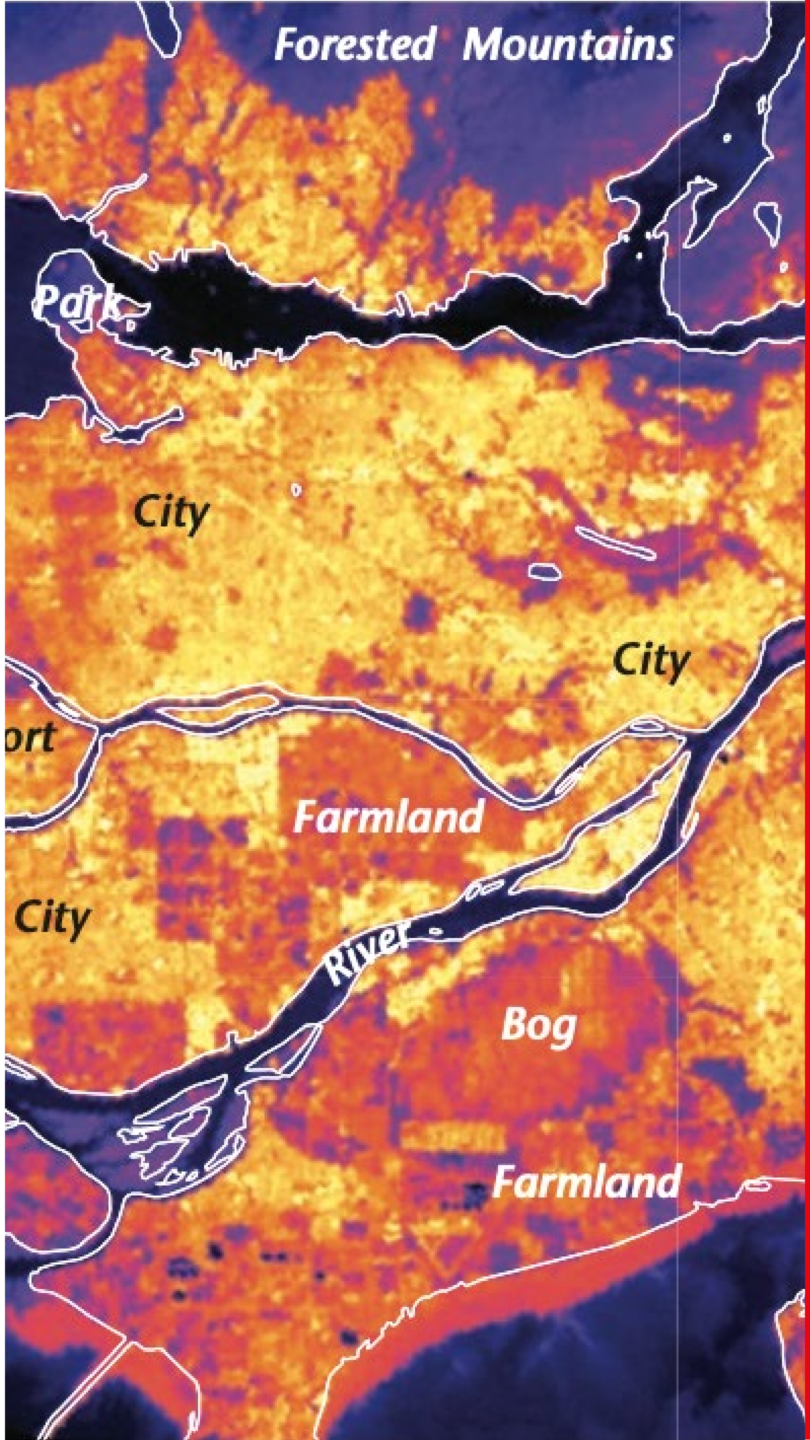
$$\frac{dT}{dt} = -\frac{6}{\rho_w \cdot c_v \cdot D}(Q_H + Q_E)$$

$$\int_{T_s}^{T_{wb}} dT = -\frac{6}{\rho_w \cdot c_v \cdot D}(Q_H + Q_E) \cdot \int_0^{\tau} dt$$

$$\tau = -\frac{\rho_w \cdot c_v \cdot D}{6 \cdot (Q_H + Q_E)} \cdot (T_{wb} - T_s) \quad (7\text{-}10)$$



Source: Santamouris and Kolokosta, Urban Climate Mitigation Techniques, p. 127



CONTENT:

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What are the key factors?

- **Water body:**

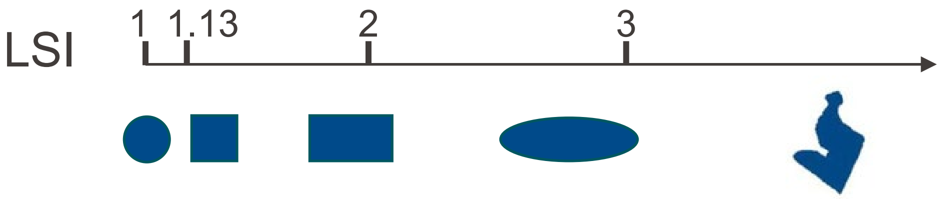
Size and distribution:

Relatively large water body has higher cooling effects than equally distributed small water bodies, however, the latter influence larger urban areas.

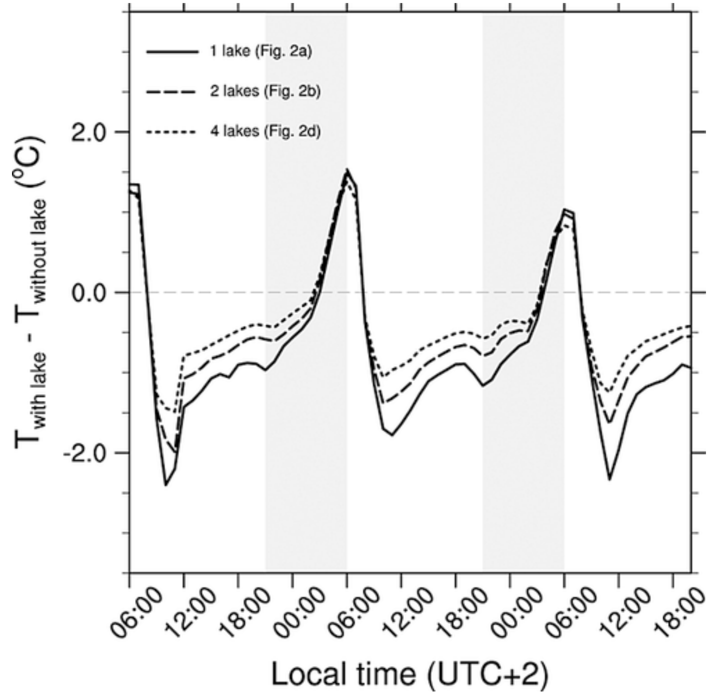
Shape factor:

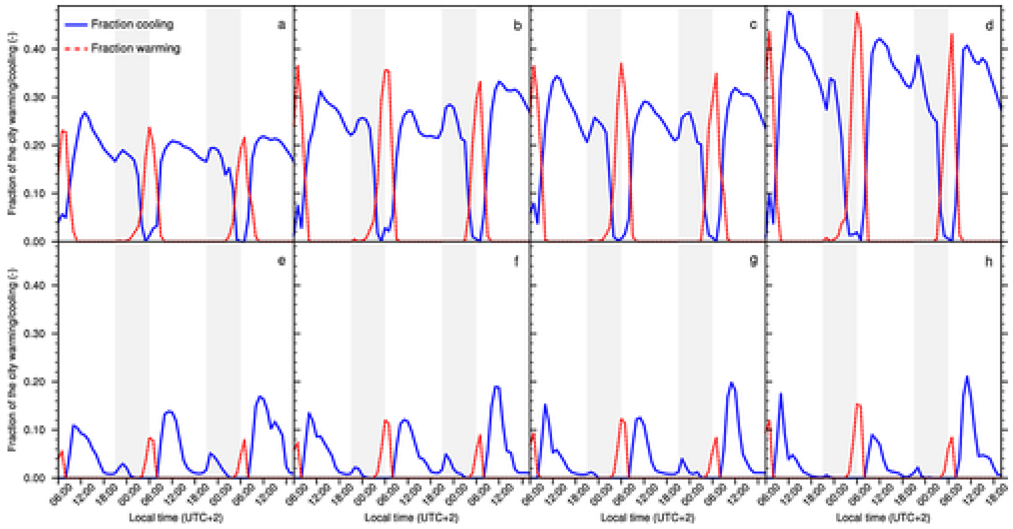
landscape shape index (LSI):

$$LSI = \frac{D}{2\sqrt{\pi \times WA}}$$



Regular shaped water body tend to have higher cooling effect due to efficient cool air dispersion, higher evaporative area, more even water temperature distribution.





Source: Theeuwes & Steeneveld (2013) Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city

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What are the key factors?

- **Littoral zone**

The spatial pattern of different littoral landscapes has great impact on water cooling effect.

Urban form:

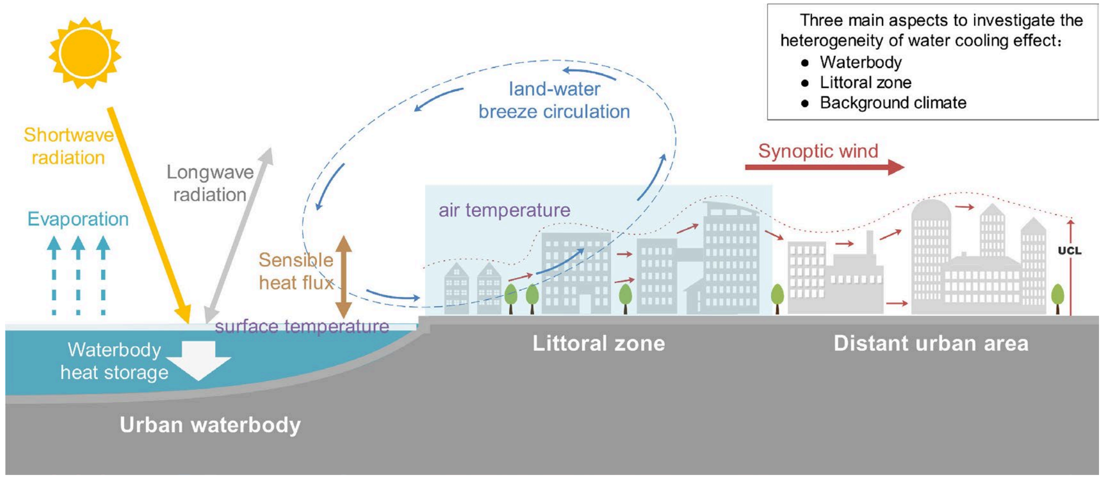
Negative correlation between *street width*, *average building height* and *cooling intensity* and *distance.*

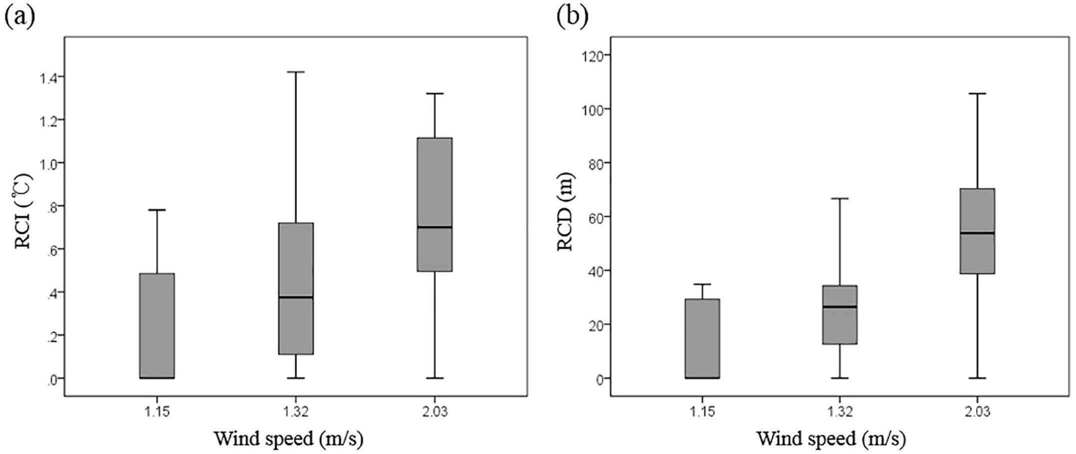
Urban ventilation enhances water cooling effects (intensity and distance).

Open streets and squares perpendicular to water.

Land cover:

Synergies between urban green space and blue space. Positive relationship between water cooling effect and urban vegetation cover.





Source: (Park et al., 2019) Influence of urban form on the cooling effect of a small urban river

Urban water bodies

- Which water body has better cooling effect? Why?

1.

Water body A

Water body B

2.

Water body A

Water body B

3.

Water body A

Water body B

EPFL

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Thank you for your attention