EPFL

CIVIL-309: URBAN THERMODYNAMICS

Assist. Prof. Dolaana Khovalyg, Dr. Jaafar Younes

Lecture 10: Human Outdoor Comfort

05 December 2025

Course Schedule

7	24.10		**BREAK**	
8	31.10	1 x 45'	**Urban modeling and computational tools**	JY
		1 x 45'	Introduction to the web tool **CityTherm** (part II)	JY
		1 x 45'	**Introduction to the course project II**	JY
9	07.11	2 x 45'	**Building-environment interaction:** thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
10	14.11	2 x 45'	**Ground-environment interaction:** ground properties, thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
11	21.11	2 x 45'	**Water body - environment interaction**: thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
12	28.11	2 x 45'	**Vegetation – environment interaction:** characteristics of vegetation, evapotranspiration, aero- and thermal interaction	DK
		1 x 45'	**Supervised group work - course project II**	JY
13	05.12	2 x 45'	**Human Outdoor Comfort:** Parameters affecting human comfort and comfort indices (UTCI, PET)	JY
		1 x 45'	**Supervised group work - course project II**	JY
14	12.12	1 x 45'	**Climate-Sensitive Urban Design**: complex interaction of all urban elements and their effect on UHI and outdoor comfort	DK
		2 x 45'	**Supervised group work - course project II**	JY
15	19.12	3 x 45'	Supervised group work on the course project II **Course project II submission deadline: 16:00 on December 19**	DK, JY

CONTENT:

Human - Environment Interaction: Introduction

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Images from Google

Human - Environment Interaction: Introduction

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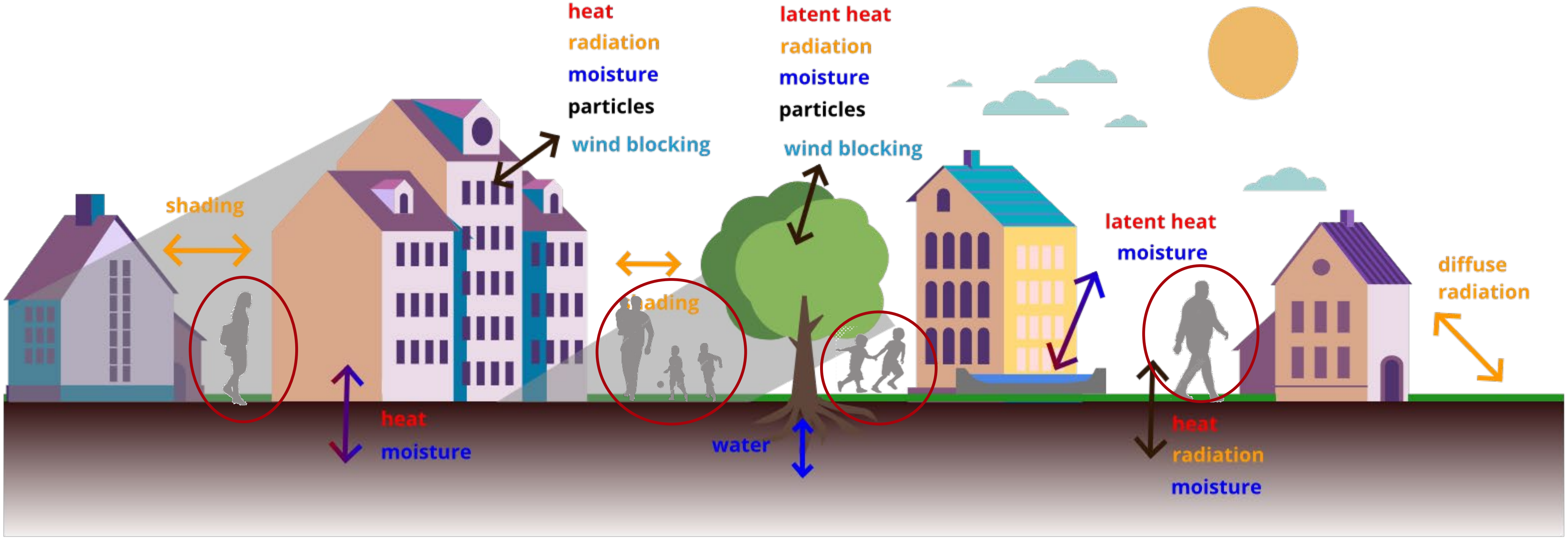
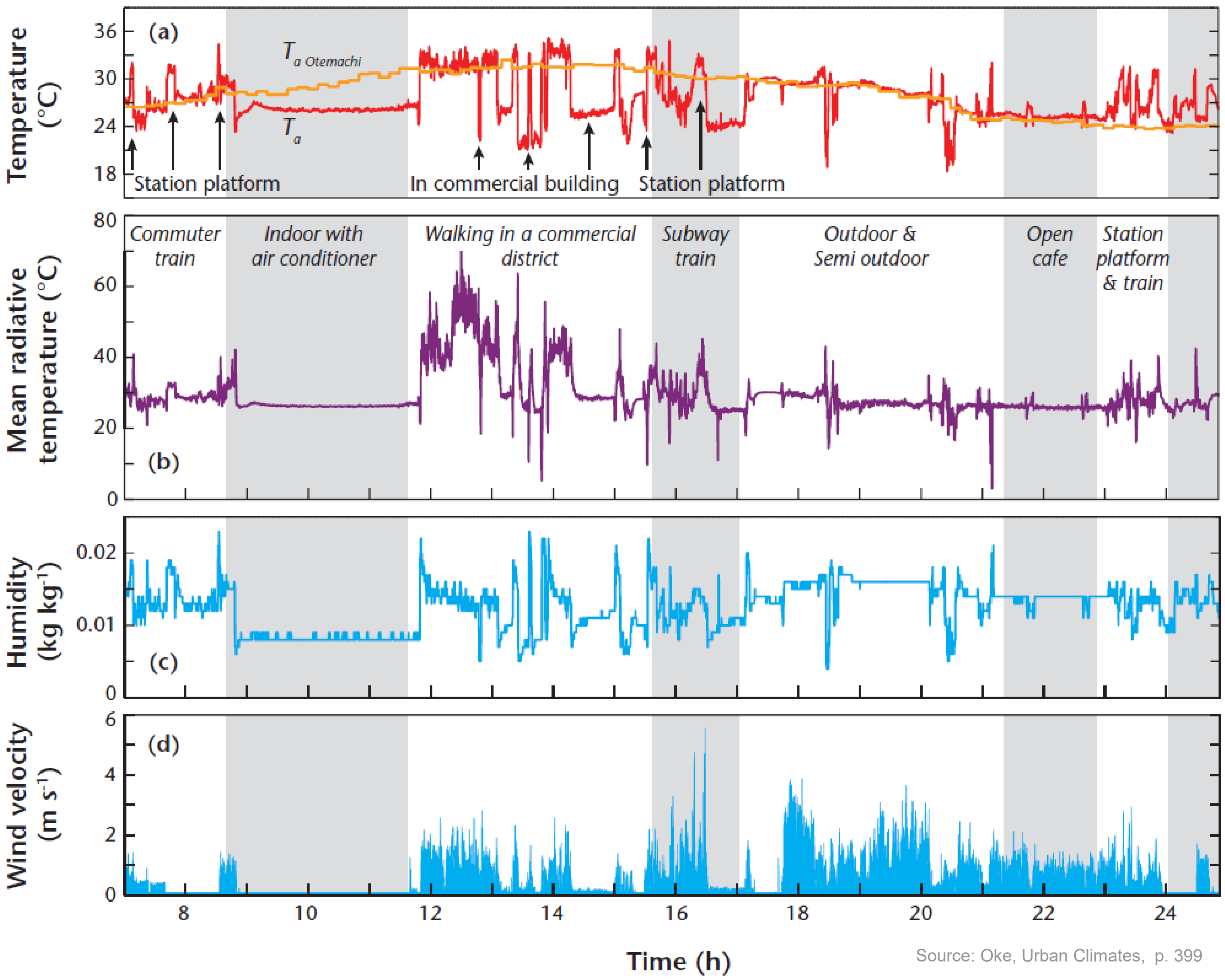
- **Cities** are *designed*, *shaped*, and *occupied* by humans → should provide comfort and well-being
- **Outdoor human comfort** is an *essential parameter* to access **the quality** of **urban microclimate**
- **Human body** *interacts* with outdoor environment via *all modes* of *heat transfer*
- The **uniqueness** of **humans**, as urban elements, in their **adaptability**, and **transient** *behavior*



Outdoor Thermal Environment

- **Greatly influenced by the built environment** (e.g., anthropogenic heat, evaporation, and evapotranspiration of plants, shading by trees and man-made objects, and ground surface cover such as natural grass and artificial paving, etc.)
- People *experience* **different thermal sensation** while carrying out the outdoor activities in streets, plazas, urban parks, etc.



Source: Oke, Urban Climates, p. 399

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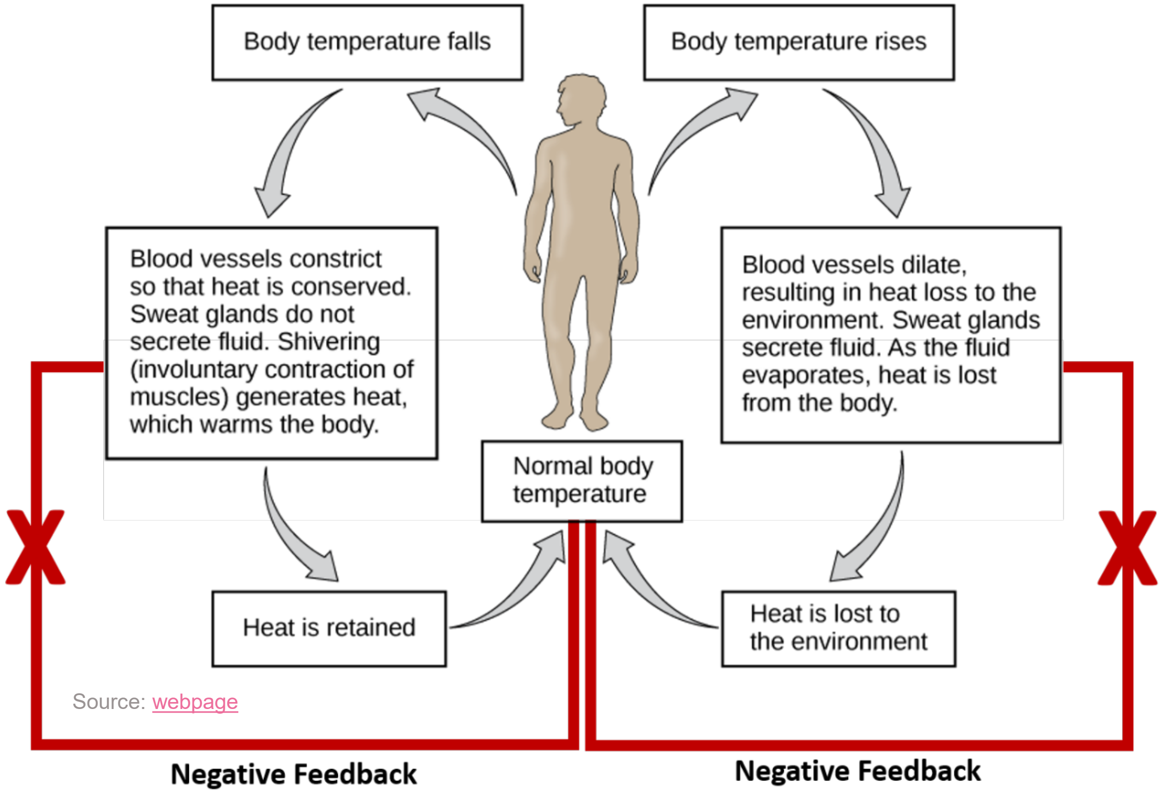
Human Thermoregulation

- The human beings are homeotherms therefore the body tries to maintain an internal temperature **~ 37°C**.
- The mechanism of heat balance and temperature control is regulated by the **hypothalamus**
- The human body temperature can be used as an indicator of its thermal condition.



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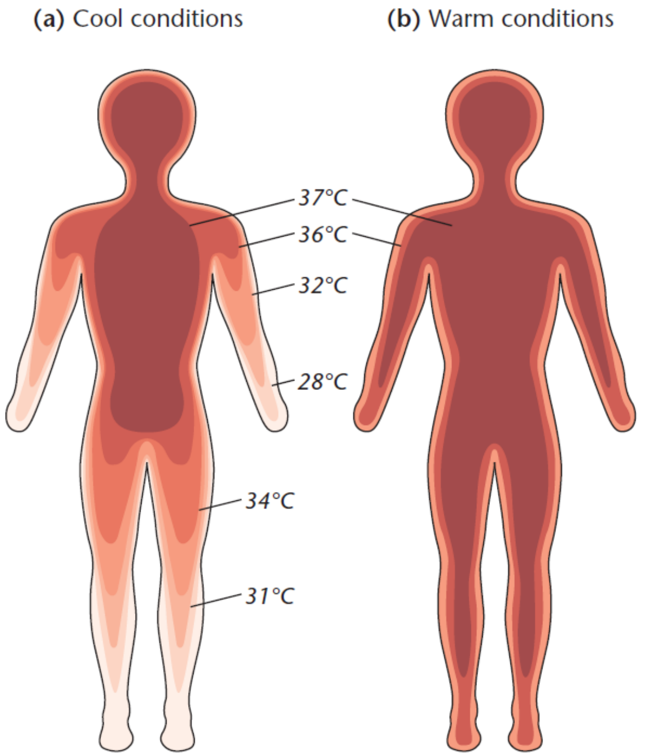

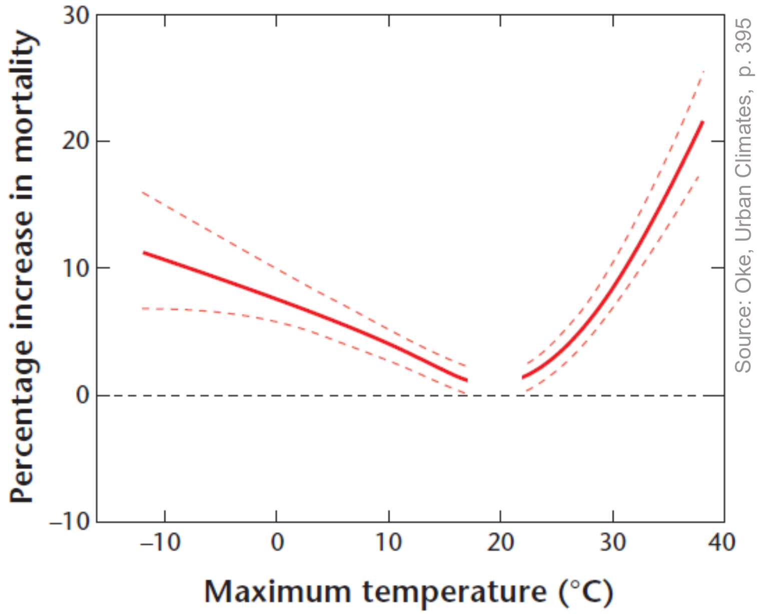

Source: Oke, Urban Climates, p. 395

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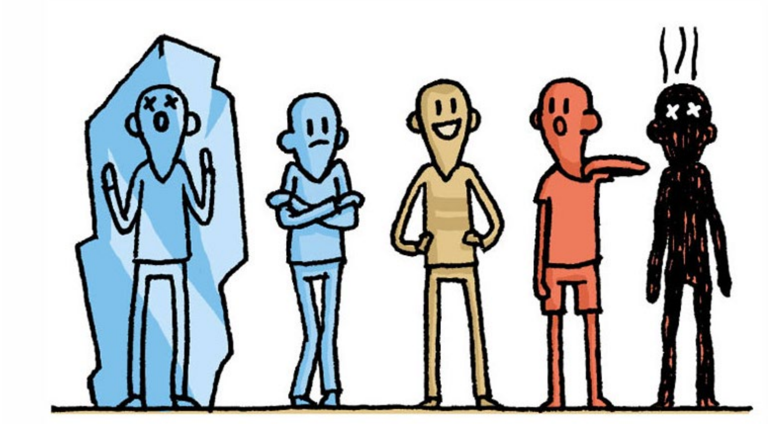
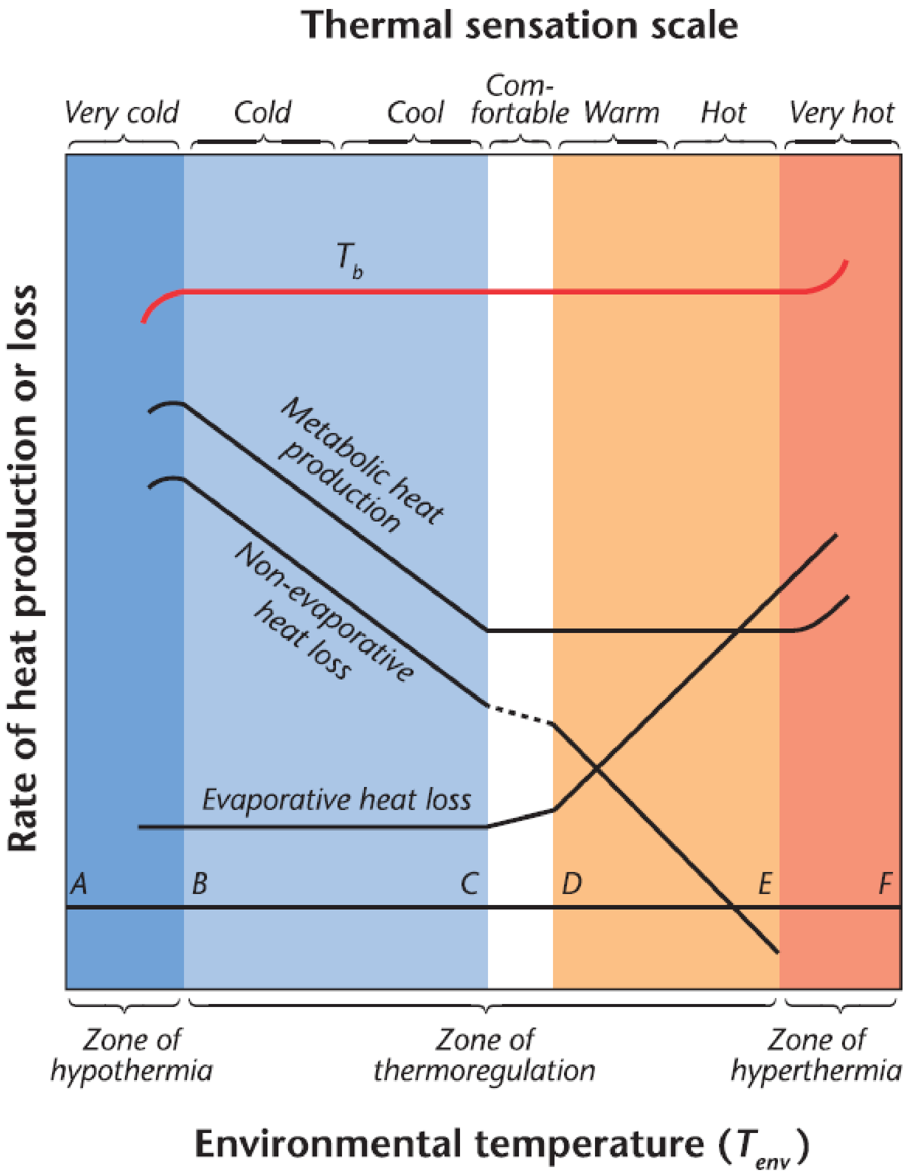
Human Thermal Comfort

- **COMFORT** – a state of ***physical ease*** and ***freedom*** from **pain** or **constraint**
- **THERMAL COMFORT** "…***the condition of mind*** *that* ***expresses satisfaction*** *with the* ***thermal environment*** *and is assessed by* ***subjective evaluation***" (ISO 7730)



- **Thermal comfort** is mainly achieved when **there is a balance** between **the generation of metabolic heat within the body** and **the loss of heat from the body** (via the mechanisms of *conduction*, *convection*, *radiation* and *evaporation)*.



Source: Oke, Urban Climates, p. 394

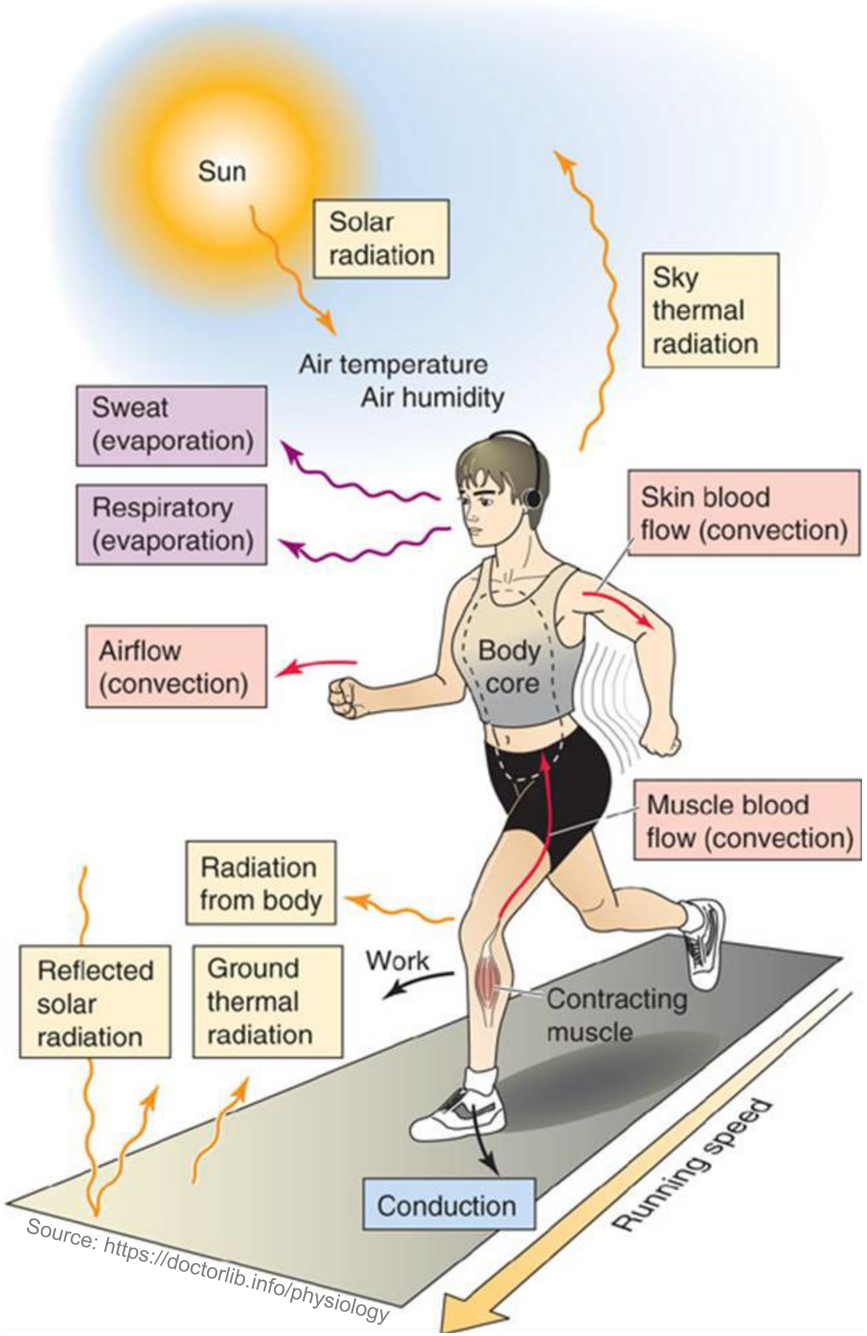
CONTENT:

Human Energy Balance

- The **energy exchange** with the ambient environment occur across the outer surface of the body.
  - **Metabolic rate** Q_M is *internal energy* required to *sustain functioning* of *the human body*, generated from the food. It contains two parts, M (metabolic activity) + W (physical work output)
  - Heat exchange via **conduction** Q_G is normally *relatively small* as typically just a small proportion of the body's surface area is in contact with a solid surface.
  - The *healthy body* (e.g., non-obese) regulates heat fluxes so that **heat storage** is minimal ($\Delta Q_S \sim 0$).

$$Q^* + Q_M = Q_H + Q_E + Q_G + \Delta Q_S \quad (10\text{-}1)$$

Radiation budget, Human metabolism, Sensible heat, Latent heat, Ground heat, Stored heat



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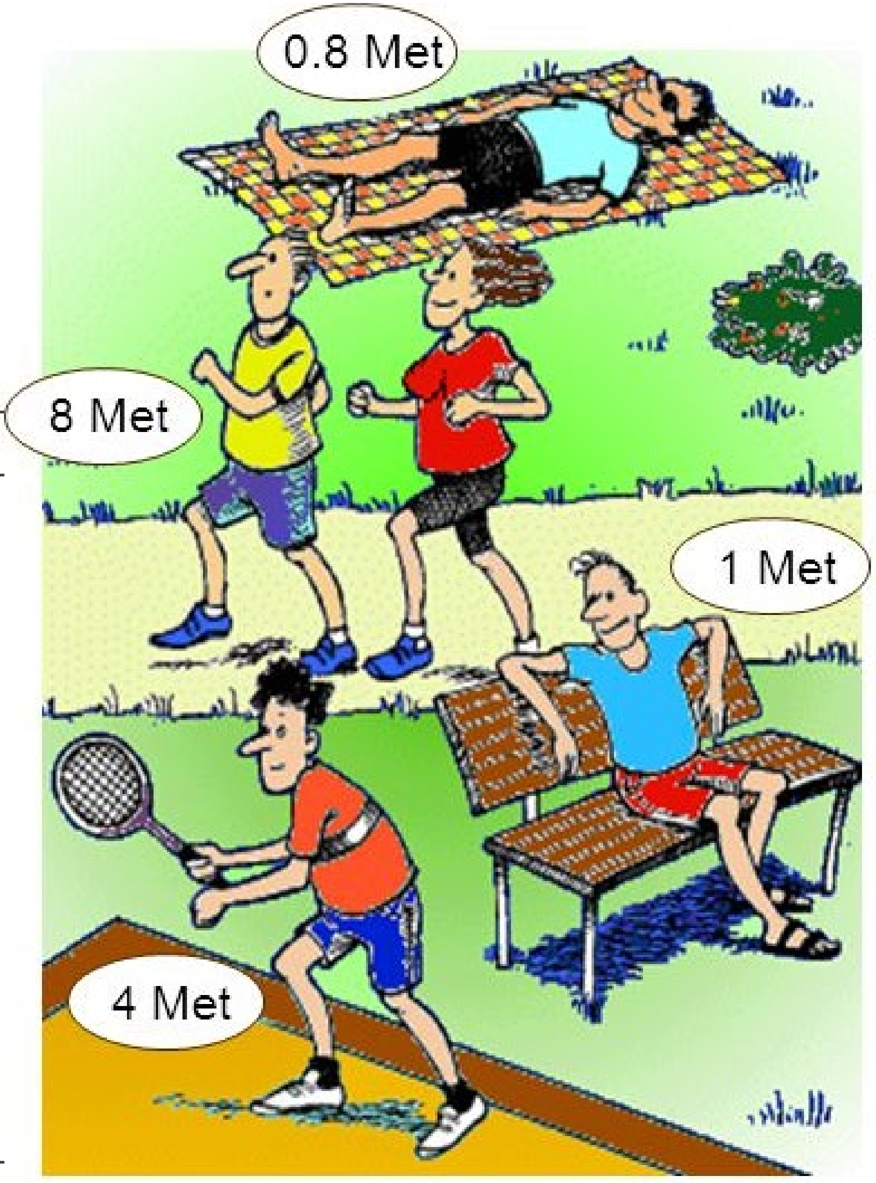
Human Metabolic Rate (M)

- **The rate** of **transformation** of **chemical energy** into ***heat*** and **mechanical work** by **metabolic activities of an individual**, per **unit** of **skin surface area** (expressed in units of *Met*) equal to **58.2** W/m^2 (the energy produced per unit skin surface area of an *average person* seated at rest).

Activity type	*Met*	W/m^2
Reclining	0.8	45
Seated, relaxed	1.0	58
Sedentary activity (office, dwelling, school, laboratory)	1.2	70
Standing, light activity (shopping, laboratory, light industry)	1.6	93
Standing, medium activity (domestic work, machine work)	2.0	116
Walking on level ground:		
2 km/h	1.9	110
4 km/h	165	2.8
5 km/h	200	3.4

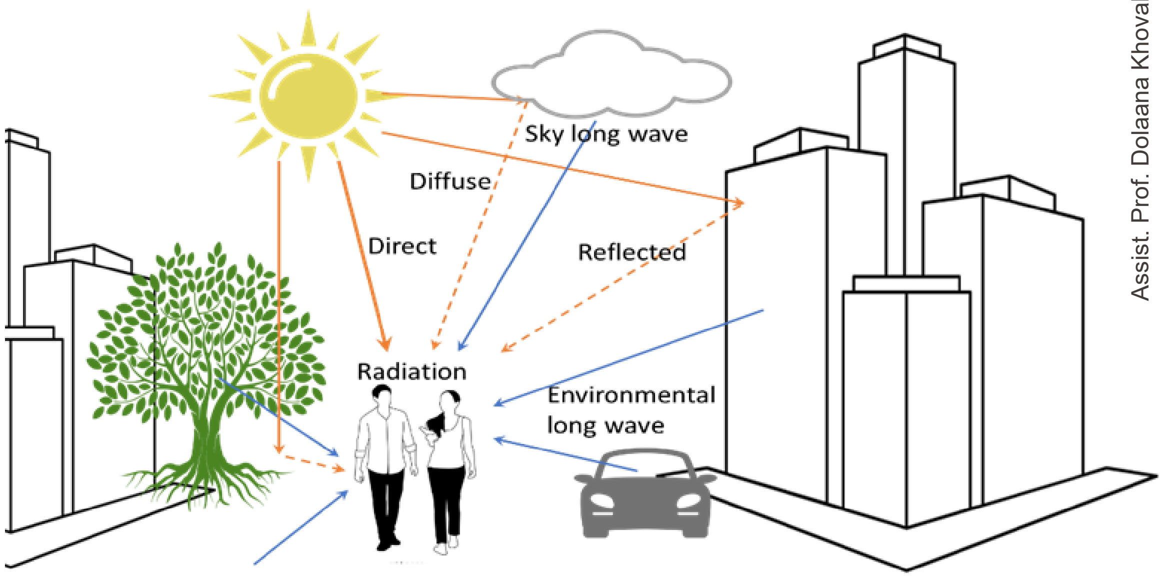


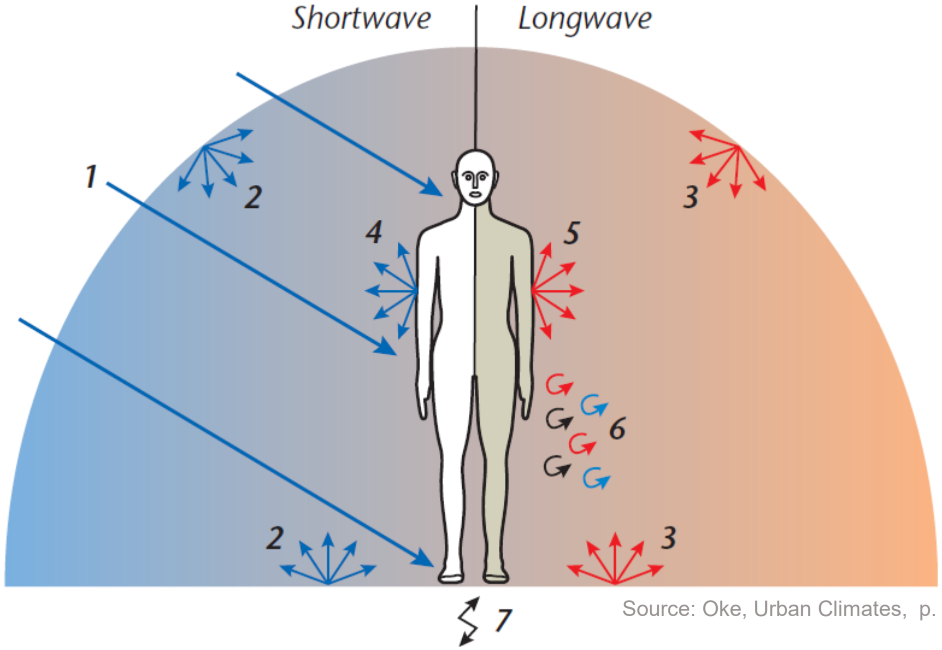
Human-Environment: Radiation Budget

- The **radiation budget** for **an individual** is the same as that for **the surface radiation budget** of any naturals surface (its application to humans is *more complicated* due to *the human shape*):

(3−35) → (10-2)
$$Q^* = K^* + L^* = (K_{\downarrow} - K_{\uparrow}) + (L_{\downarrow} - L_{\uparrow})$$

(10-3)
$$Q^* = (S + D) \cdot (1 - a) + (L_{\downarrow} - L_{\uparrow})$$





Source: Oke, Urban Climates, p. 390

(1) direct shortwave radiation S that impinges on the sunlit part of the body;
(2) diffuse shortwave radiation D that originates from the sky as a result of scattering and from the ground as a result of reflection;
(3) diffuse longwave radiation $L_{\downarrow}$ that is emitted from the sky vault and from the ground;
(4) reflected shortwave radiation $(S + D) \cdot (1 - a)$ controlled by the albedo of the clothed body;
(5) emitted longwave radiation $L_{\uparrow}$ which is a function of surface temperature;
(6) convective heat loss Q_H by sensible and latent heat exchange with the ambient air that is partly a function of wind speed and;
(7) conductive heat exchange Q_G with the ground through physical contact.

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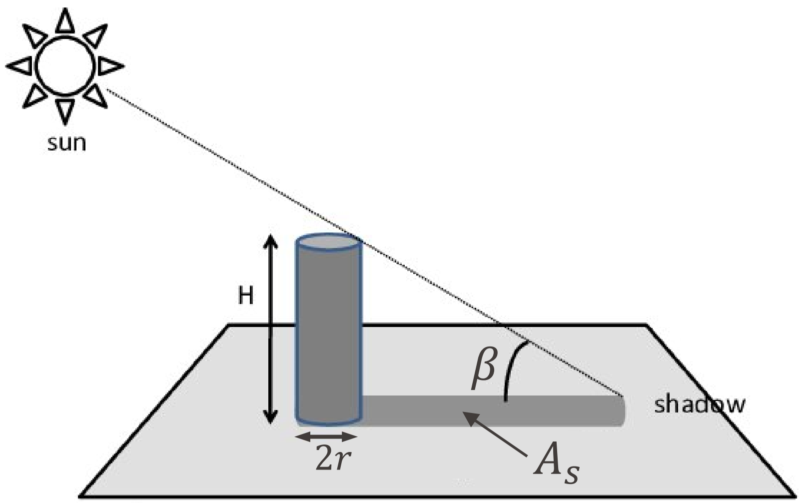
Human-Environment: Shortwave Radiation Exchange

- **Direct solar radiation** ***S*** (W/m^2) received by a person depends on the area of the body *as viewed* from *vantage point* of *the Sun*:
  - Varies through the day and year due to the Earth's rotation
  - Depends on the body posture and orientation
  - The **intercepted solar radiation** on an *upright* individual can be estimated by calculating *the shadow area* A_s generated by a cylinder that has the appx. dimensions of the human body:



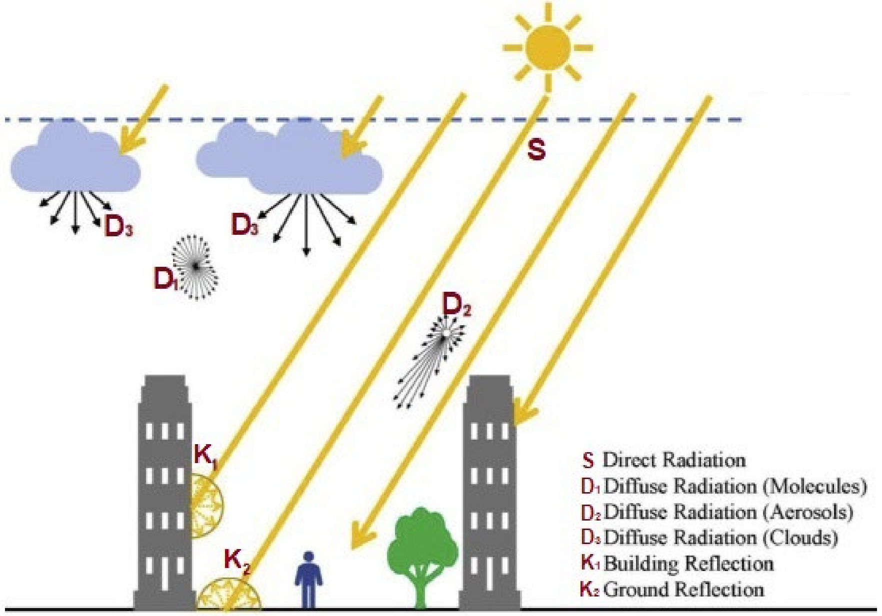
$$A_s = (2 \cdot r \cdot H) \cdot cot(\beta) + \pi \cdot r^2 \quad (10\text{-}4)$$

β (deg) – solar altitude (varies with latitude, time of year and day)
H (m) – height of the cylinder (= human), r (m) – cylinder radius (= human torso)

- **Diffuse irradiance** ***D*** (W/m^2) is a function of the *strength* of the radiation source and *the proportion of the flux* leaving that source *incident on the body surface* (considered by ψ):

$$D = D_{sky} + D_{env} = D_0 \cdot \psi_{h\rightarrow sky} + K_{\uparrow} \cdot \psi_{h\rightarrow env} \quad (10\text{-}5)$$

D_0 (W/m^2) – diffuse radiation received on a flat surface (ψ_{sky}= 1)
$K_{\uparrow}$ (W/m^2) – reflected radiation from the environment that impinges on the body
$\psi_{h\rightarrow sky}$, $\psi_{h\rightarrow env}$ – view factors between the human body and the sky/environment



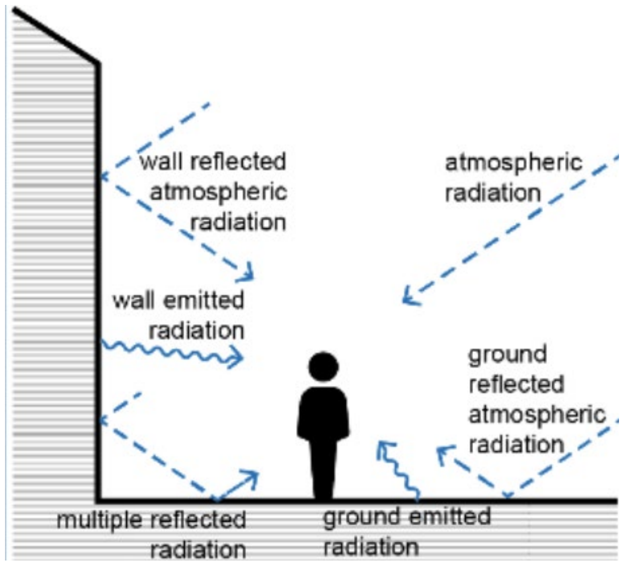
Source: 10.1016/j.buildenv.2018.10.025

Human-Environment: Longwave Radiation Exchange

- Longwave radiation exchange can be treated in the same way as for other urban surfaces:

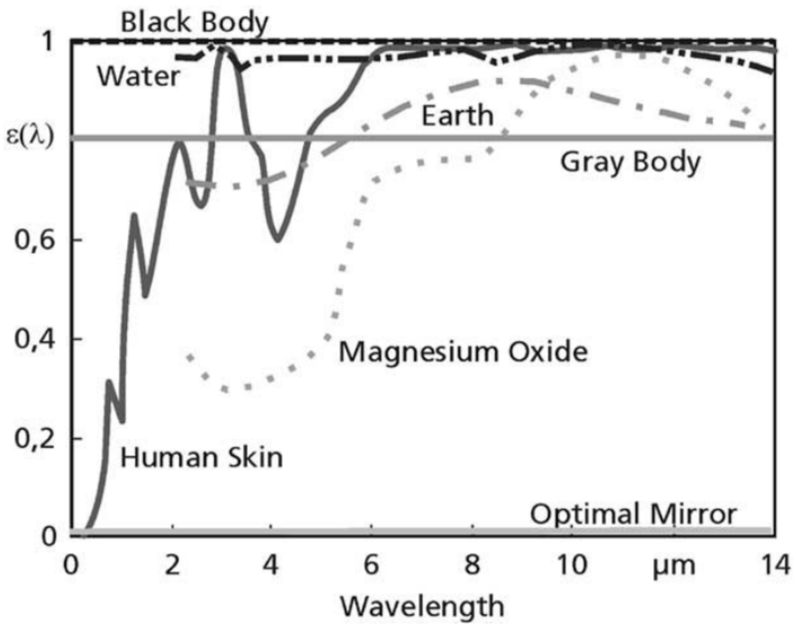
(10-6) $$L_{\downarrow,h} = L_{\downarrow,sky,0} + L_{\downarrow,env} = L_{\downarrow,0} \cdot \psi_{h\to sky} + \sum_{j=1}^{N} (L_{\uparrow,j} \cdot \psi_{h\to j})$$

$L_{\downarrow,0}$ (W/m^2) – longwave radiation received on a flat surface (ψ_{sky}= 1)
$L_{\uparrow,env}$ (W/m^2) – radiation emitted by surrounding facets
$\psi_{h\to sky}$, $\psi_{h\to j}$ – view factors between the human body and the sky/environment



- The human skin reflects *a very small proportion* of $L_{\downarrow}$ (less than 5% due to emissivity of ~ 0.95) and consequently is near a perfect emitter at long wavelengths.
  - Reflectivity of the human's outer surface can be altered using reflective clothing.

(10-7) $$L_{\uparrow} = \underbrace{\varepsilon_h \cdot \sigma \cdot T_h^4}_{emission} + \underbrace{(1-\varepsilon_h) \cdot L_{\downarrow}}_{reflection}$$



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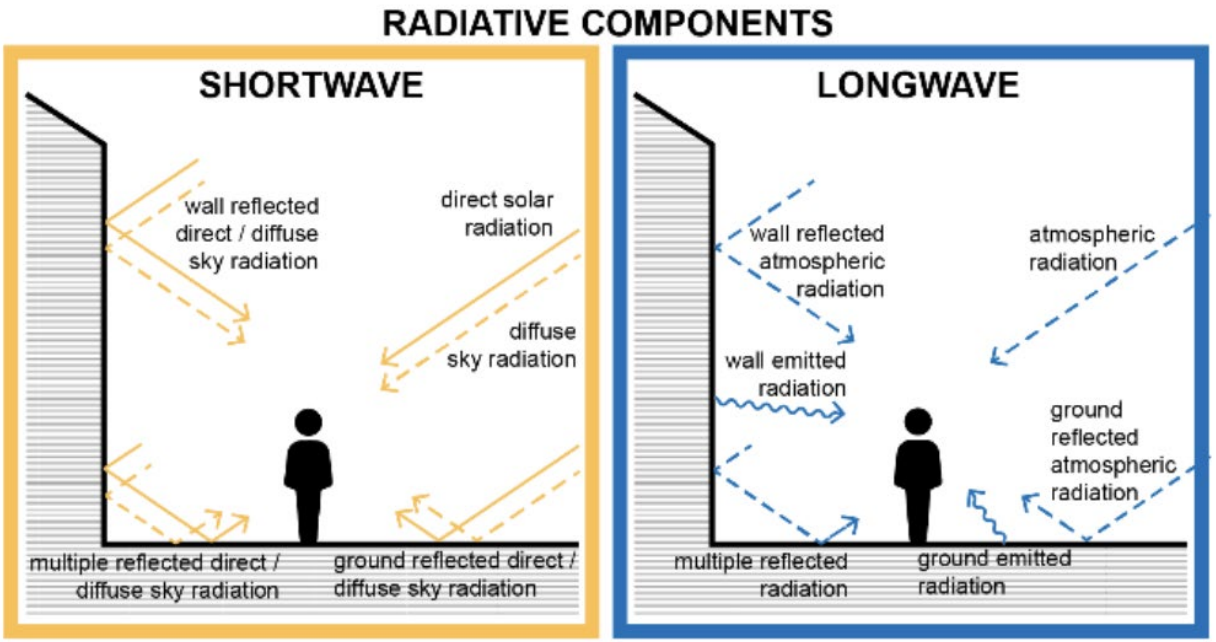
Mean Radiant Temperature

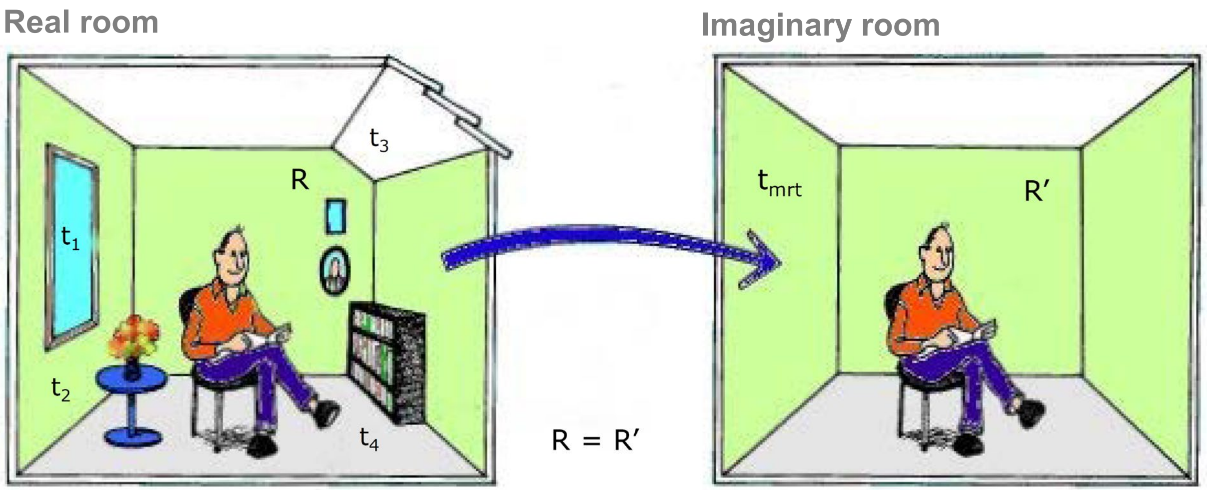
- **Actual radiant environment** around a person is **very diverse**. Thus, to numerically represent how human beings experience radiation, a parameter T_{MRT} is defined.
- **Mean Radiant Temperature T_{mrt}** (K) - *a surface temperature* of a *blackbody* (perfect emitter) that generates *the same radiation* as that *absorbed* by the body

$$T_{mrt} = \sqrt[4]{\frac{K_{\downarrow} \cdot a + L_{\downarrow} \cdot \varepsilon}{\sigma}} \quad (10\text{-}8)$$

a , ε – albedo and emissivity of the outer surface of the body (clothed surface)
σ – Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W/m^2K^4)



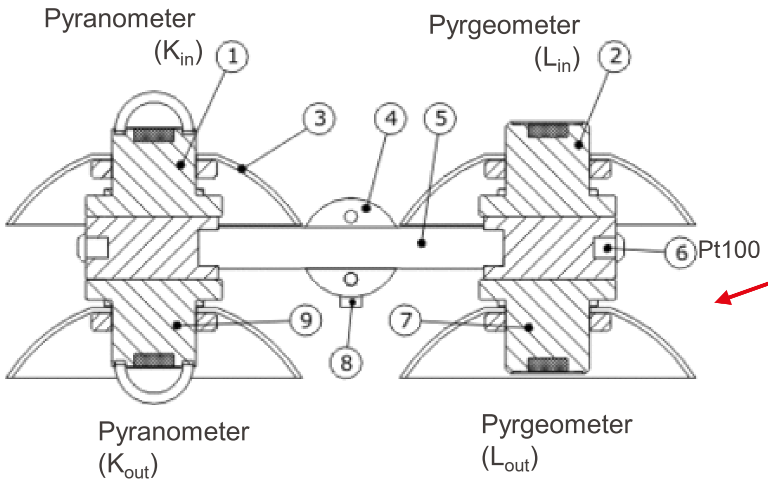
Source: 10.1088/1742-6596/2069/1/012186

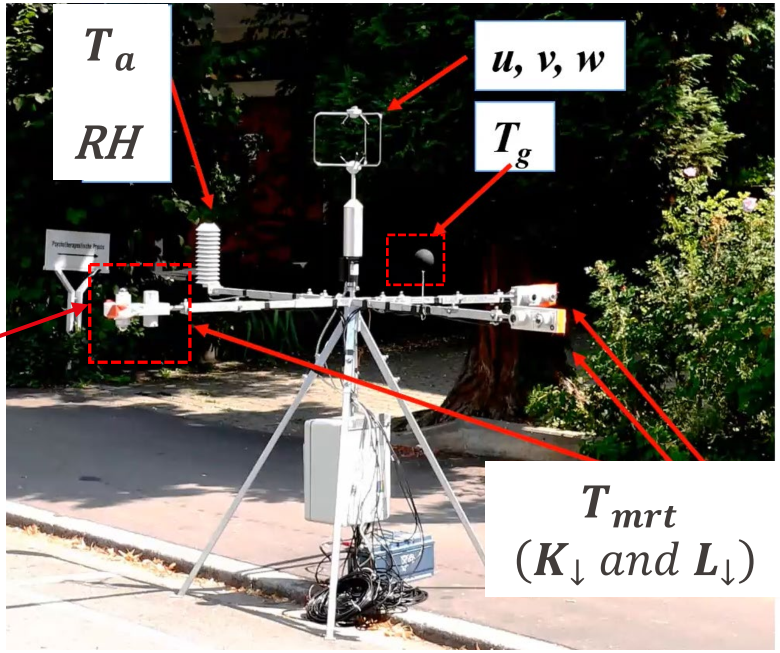


Mean Radiant Temperature: Measurements

- T_{mrt} (K) can be estimated from the **globe temperature measurements**:
  - **Globe thermometer** – a blacked hollow sphere with a diameter D with a temperature sensor in the center (a standard diameter is 6 inch, 0.15 m)
  - *Assuming the globe thermometer is in equilibrium*, its reading from internal thermometer reflects the **convective** and **(longwave) radiative heat exchange** around the globe thermometer.

- T_{mrt} (K) can be estimated based on **the plane radiant temperature** in **six opposite directions** measured using **a set of radiometer** (measuring *radiant heat*).





CONTENT:

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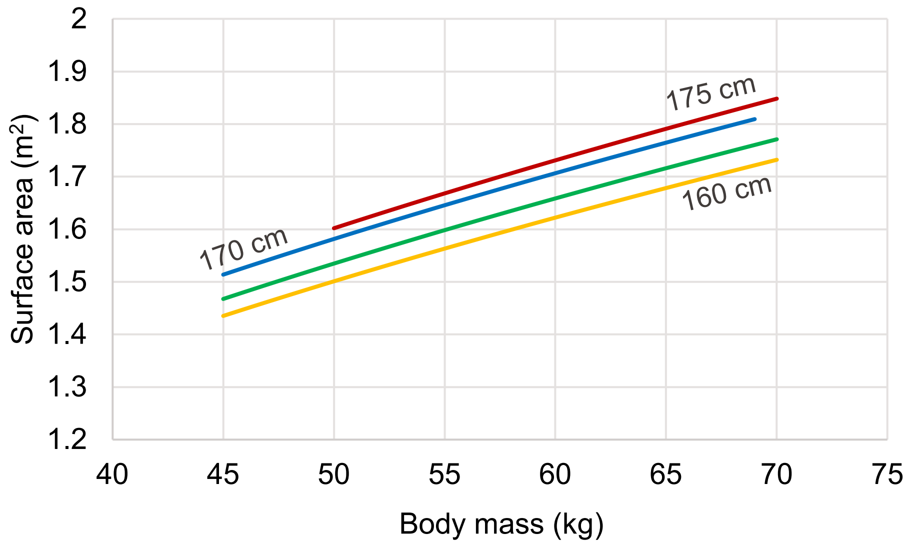
Human Skin: Radiation Properties

- **Surface area of the body A_{body}** in **m²** (DuBois formula):

$$A_{body} = 0.007184 \cdot M^{0.425} \cdot H^{0.725} \quad (10\text{-}9)$$

M(kg) – human body mass, $\boldsymbol{H}$ (cm) – human height

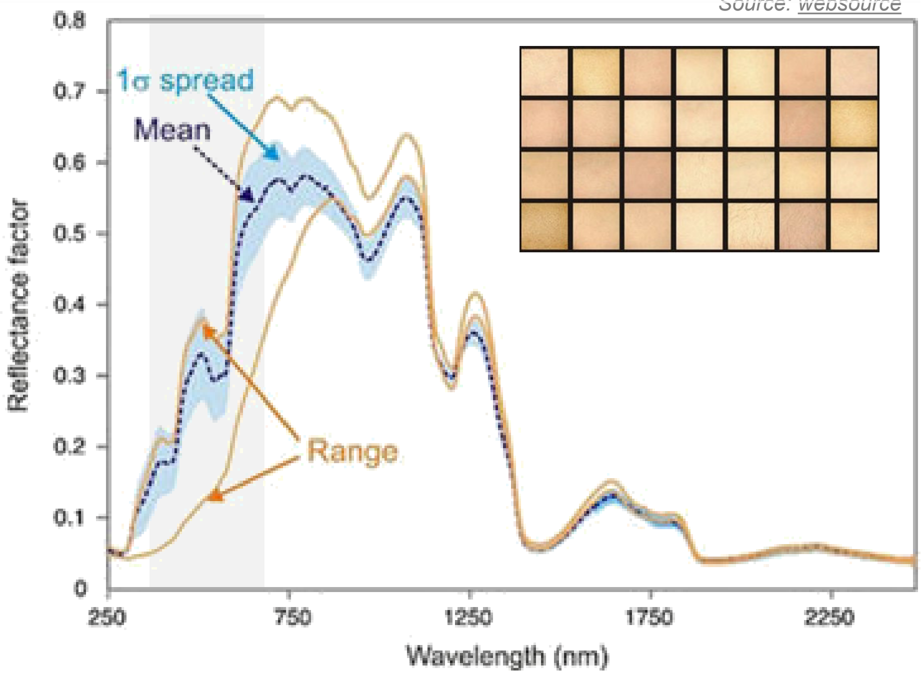


- **"Average" human body parameters:**

  70 kg, H = 165 cm, r_{body}= 0.12 m, A_{body} = 1.8 m²

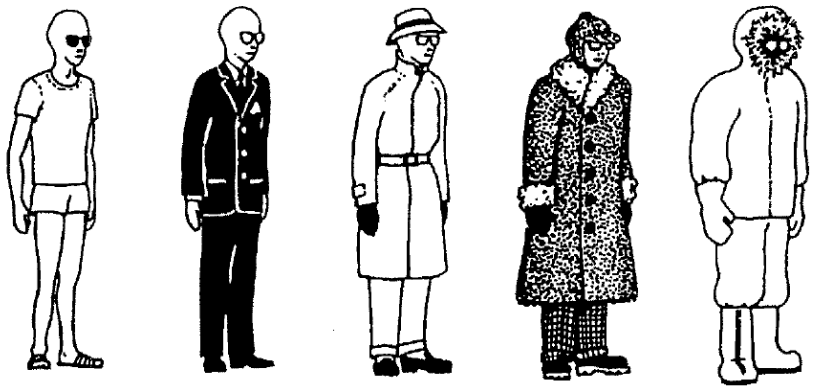
- **Reflectivity** of **human skin,** depending on pigmentation (melanin) and skin blood flow (hemoglobin), **regulates *absorption* of radiation**:
  - Varies from 0.15 (dark) - 0.35 (light) at 0.4-0.7 μm (visible wavelength)
  - Increases sharply to 0.6 between 0.8-1.2 μm
  - Drops at longer wavelengths (> 1.2 μm)

Source: websource



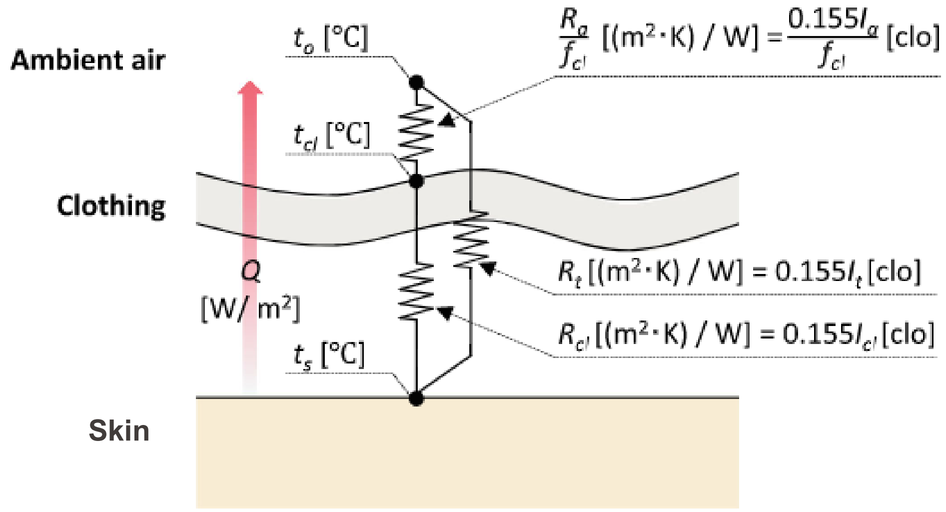
Clothing: Thermal Resistance

- Clothing is *an interface* between *body* and *environment*.
- Various types of clothing vary in their **thermal resistance** I_{cl} (*insulative capacity*) measured in "*clo*":



$0.5\ clo$ | $1\ clo$ | $2\ clo$ | $3\ clo$ | $6\ clo$

$$1\ clo = 0.155\ \frac{m^2 {}^\circ C}{W}$$



Garment	Insulation I_{cl} ($K\ m^2\ W^{-1}$)	Depth of still air (mm)
Individual clothing layers		
Underwear (e.g. underpants, T-shirt, slip)	0.03–0.10	0.15–0.52
Footwear (e.g. socks, slippers, boots)	0.02–0.10	0.10–0.52
Shirts/Blouses (e.g. short and sleeve shirt, sweatshirt)	0.15–0.30	0.78–1.55
Trousers (e.g. shorts, trousers, overalls)	0.06–0.28	0.31–1.45
Sweaters/Jackets	0.20–0.35	1.03–1.81
Dresses/skirts	0.15–0.40	0.78–2.07
Outdoor clothing (coat, parka)	0.55–0.70	2.84–3.62

Source: Oke, Urban Climates, p. 393

- **Clothing factor** f_{cl} - a ratio of the clothed surface area to that of the nude body.

$$f_{cl} = \frac{A_{cl}}{A_{body}} \quad (10\text{-}10)$$

$$f_{cl} = 1 + 1.29 \cdot I_{cl} \quad for\ I_{cl} \le 0.5$$

$$f_{cl} = 1.05 + 0.645 \cdot I_{cl} \quad for\ I_{cl} > 0.5$$

A_{cl} (m²) – area of the human body covered with clothing

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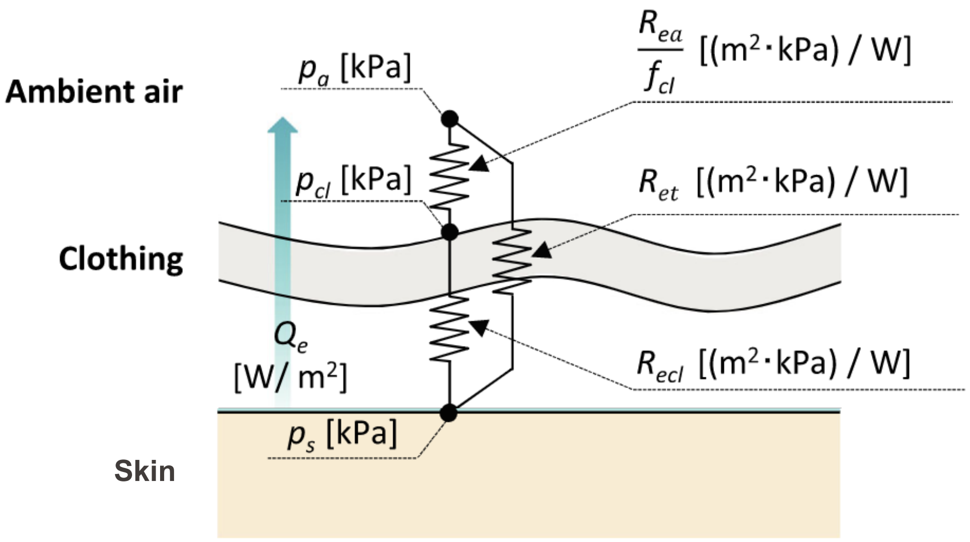
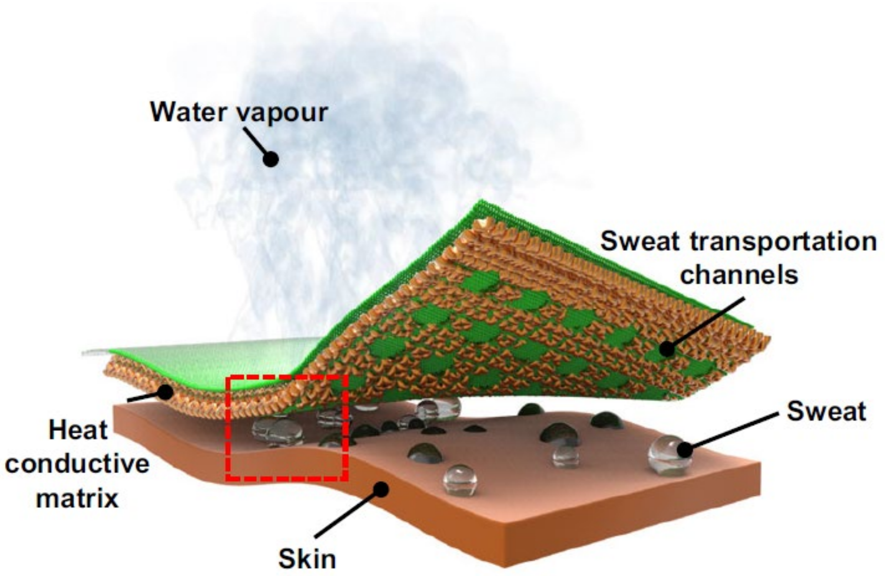
Clothing: Vapor Resistance

- Various types of clothing vary in their **vapor resistance** $I_{v,cl}$ $(\frac{m^2 \cdot Pa}{W})$, in material's reluctance to let water vapor pass through.

$I_{v,cl}$ $(\frac{m^2 \cdot Pa}{W})$	Performance
0–6	Very good or extremely breathable. Comfortable at higher activity rate
6–13	Good or very breathable. Comfortable at moderate activity rate
13–20	Satisfactory or breathable. Uncomfortable at high activity rate
20–30	Unsatisfactory or slightly breathable. Moderate comfort at low activity rate
30+	Unsatisfactory or not breathable. Uncomfortable and short tolerance time



Source: Nomoto et al. (2019) 10.1002/2475-8876.12124



CONTENT:

Humans-Environment: Sensible Heat Flux

- **The sensible heat flux density Q_H** (W/m^2) occurs by **breathing** and by **convective exchange** at **the skin surface**
  - The breathing rate is a function of activity. For moderate activities, *less than 5%* of heat loss by breathing from metabolic rate generated.
  - The *majority* of sensible heat transfer *occurs* via **the outer surface** (mostly covered by clothing).

$$Q_H = h_{conv} \cdot f_{cl} \cdot (T_{cl} - T_a) \quad (10\text{-}11)$$

- **Convective heat transfer coefficient** $h_{conv} (W/m^2K)$:
  - for a standing or walking pedestrian, represented as a vertical cylinder, can be determined using a simplified correlation:

$$h_{conv} = 8.3 \cdot U_a^{0.6} \quad (10\text{-}12)$$

Validity range:

$0.2 < U_a < 4\ m/s$

$U_a\ (\frac{m}{s})$ - horizontal wind speed averaged over the height of the body

Speed (m/s)	Effects
0–1.5	Calm, no noticeable wind
1.6–3.3	Wind felt on face
3.4–5.4	Wind extends light flag; hair is disturbed; clothing flaps
5.5–7.9	Raises dust, dry soil and loose paper; hair disarranged
8.0–10.7	Force of wind felt on body; drifting snow becomes airborne; limit of agreeable wind on land
10.8–13.8	Umbrella used with difficulty; hair blown straight; difficult to walk steadily; wind noise on ears unpleasant; airborne snow above head height
13.9–17.1	Inconvenience felt when walking
17.2–20.7	Generally impedes progress; great difficulty with balance in gusts
20.8–24.4	People blown over by gusts

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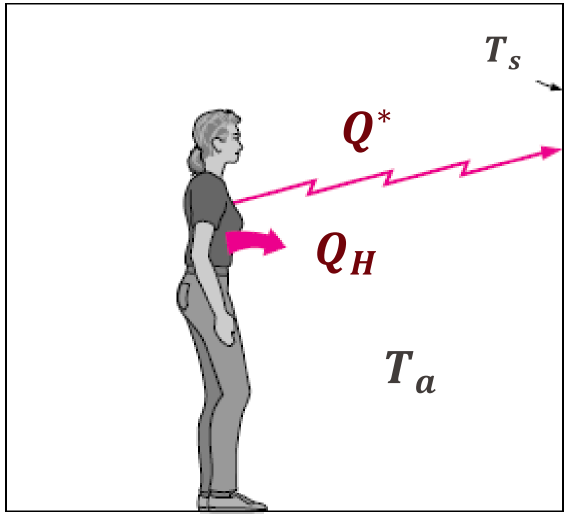
Humans-Environment: Sensible Heat Flux

- **Net allwave radiation** and **sensible heat fluxes** at the exterior of clothing *can be combined* by *summing heat transfer coefficients* and introducing *the operative temperature* $\boldsymbol{T_{op}}$

(10-13) $$\boldsymbol{Q^* + Q_H} = h \cdot f_{cl} \cdot (\boldsymbol{T_{cl}} - \boldsymbol{T_{op}})$$

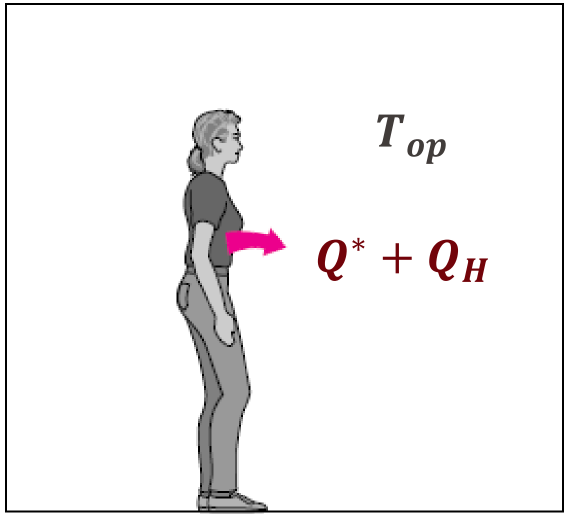
$\boldsymbol{h} = h_{conv} + h_{rad}$ - combined heat transfer coefficient



(a) Convection and radiation, separate

- **Operative temperature** $\boldsymbol{T_{op}}$ is the **uniform temperature** of **an enclosure** in which *an occupant* would exchange *the same amount of heat* by **radiation** plus **convection** as *in the actual non-uniform environment.*

$$\boldsymbol{T_{op}} = \frac{h_{conv} \cdot T_a + h_{rad} \cdot T_{mrt}}{h_{conv} + h_{rad}} \quad (10\text{-}14)$$



(b) Convection and radiation, combined

  - Radiative heat transfer coefficient:

$$\boldsymbol{h_{rad}} = \boldsymbol{\varepsilon} \cdot \sigma \cdot f_{eff} \cdot (T_{cl}^2 + T_{mrt}^2) \cdot (T_{cl} + T_{mrt}) \quad (10\text{-}15)$$

  - The effective radiation area factor f_{eff} is 0.7 for a sedentary person, and 0.77 for a standing person

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Evaporative Heat Flux: Respiration

- **Latent heat exchange** (Q_E) occurs via **respiration** and via **the skin** (water vapor diffusion).
- **Latent heat flux via respiration** $Q_{E,rsp} (W/m^2)$:
  - Exhaled air is close to saturation ($\varphi \approx 100\%$) at body's core temperature ($t_{cr} \sim 37^oC$)

$$Q_{E,rsp} = \dot{V} \cdot \rho_{a,in} \cdot (q_{a,out} - q_{a,in}) \cdot L_v / A_{body} \quad (10\text{-}16)$$

- $\dot{V}$ (m^3/s) – breathing rate [can be found from tables]. Alternatively, can be determined from the metabolic rate as $\dot{V}\left(\frac{kg}{h}\right) = 0.006 \cdot M\left(\frac{kcal}{hr}\right)$ as the breathing rate is mainly a function of metabolism.
- $\rho_{a,in}$ (kg/m^3) – inhaled air density at $t_{a,in}$ and humidity
- $q_{a,out}$ (kg/kg) – specific humidity of exhaled air (at $p_{v,sat}$ and t_b, see Eqn. 9-21b)
- $q_{a,in}$ (kg/kg) – specific humidity of inhaled air (considering temperature and relative humidity of inhaled air)
- L_v (kJ/kg) – heat of vaporisation of water (e.g., 2418 kJ/kg at 35°C)
- A_{body} (m^2) – body surface area

Example: If the inhaled air is **20°C** and **50% RH**, and a breathing rate is **2.1** m^3/h (moderate activity, average adult), latent heat flux via respiration is **59** W/m^2 (106.4 W).

Human breathing rates by activity level

Level of exertion	Resting ($m^3\ h^{-1}$)	Light ($m^3\ h^{-1}$)	Moderate ($m^3\ h^{-1}$)	Heavy ($m^3\ h^{-1}$)
Adult female	0.3	0.5	1.6	2.9
Adult male	0.7	0.8	2.5	4.8
Average adult	0.5	0.6	2.1	3.9
Child 6 years	0.4	0.8	2.0	2.4
Child 10 years	0.4	1.0	3.2	4.2

Source: Oke, Urban Climates, p. 387

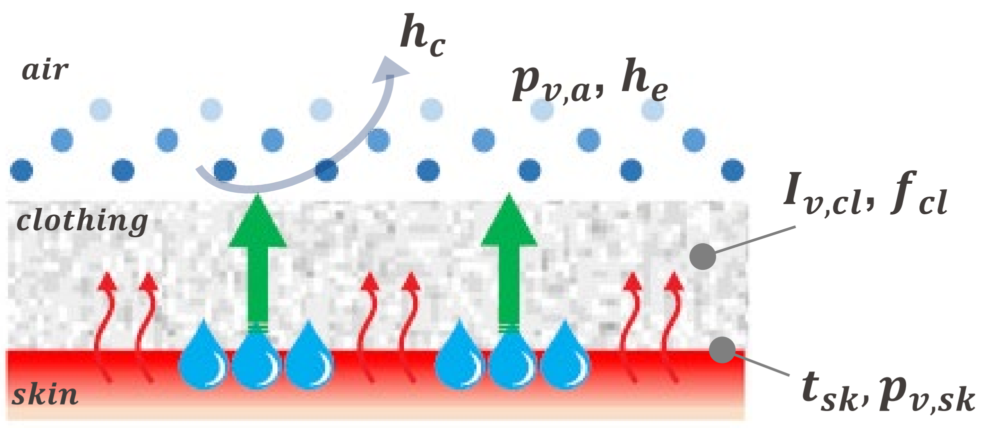
Evaporative Heat Flux: Skin

- **Evaporative heat loss** at the **skin surface** (W/m^2):

$$Q_{E,sk} = \frac{w \cdot (p_{v,skin} - p_{v,a})}{(I_{v,cl} + \frac{1}{f_{cl} \cdot h_e})} \quad (10\text{-}17)$$

- w (-) - skin wettedness (the fraction of wet skin), varies from 0.06 (natural diffusion of water) to 1 (completely wet skin)
- $p_{v,a}$ (kPa) - water vapour pressure in the ambient air temperature
- $p_{v,skin}$ (kPa) - water vapour pressure at the skin (normally assumed to be saturated water vapour pressure $p_{v,sat}$ at the skin temperature t_{sk})
- $I_{v,cl}$ $(\frac{m^2 \cdot kPa}{W})$ – vapour resistance of clothing (typically 0.015 $\frac{m^2 \cdot kPa}{W}$ for regular clothing)
- f_{cl} (-) – clothing factor
- h_e $(\frac{W}{m^2 \cdot kPa})$ - *evaporative heat transfer coefficient*, linked with convective heat transfer coefficient h_{conv} via the Lewis number LR (for typical conditions, $LR = 16.7\ K/kPa$)

$$h_e = LR \cdot h_{conv} \quad (10\text{-}22)$$



$$(10\text{-}18) \quad w = 0.06 + \frac{Q_{E,rsw}}{Q_{E,max}}$$

Actual regulatory sweat evaporation

Maximum evaporation (Eqn. 9-18 at w=1)

$$(10\text{-}19) \quad Q_{E,rsw} = M_{rsw} \cdot L_v$$

$$(10\text{-}20) \quad M_{rsw} = 4.7 \cdot 10^{-5} \cdot (t_b - 36.18) \cdot e^{(\frac{t_{sk} - 33.7}{10.7})}$$

$$(10\text{-}21) \quad t_b = \alpha \cdot t_{sk} + (1 - \alpha) \cdot t_{cr}$$

- L_v (kJ/kg)- heat of vaporisation of water (2430 kJ/kg at 30°C)
- M_{rsw} (kg/s*m^2) - rate at which sweat is secreted
- t_b , t_{sk}, t_{cr} (°C) – average *body*, *skin*, and *core* temeprature
- α - weighting number (0.2 for thermal equilibrium while sedentary, 0.1 for vasodilation and 0.33 for vasoconstriction)

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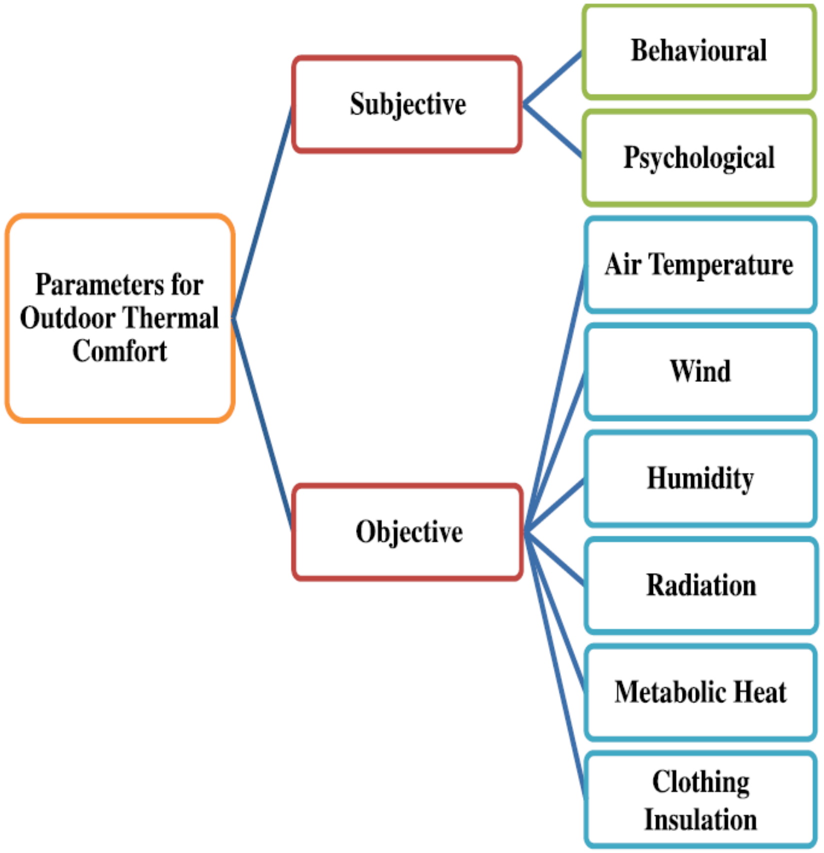
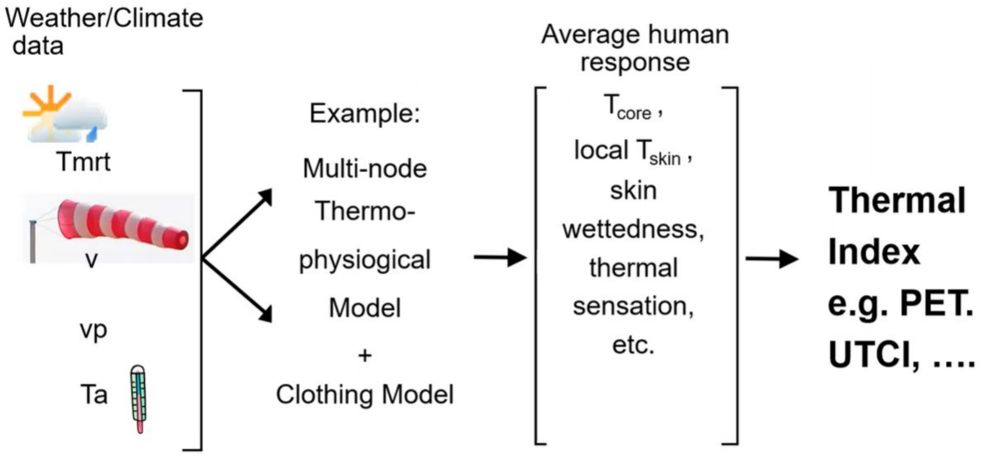
CONTENT:

Outdoor Thermal Comfort: Indices

- Multiple indices *linking* **thermal responses** to measures of **ambient stress** and **body strains** are developed (e.g., PET, WCI, UTCI, etc.)
- **Categories of Indices**:
  1. **Empirical**, based on **readily available meteorological data** (easy computation)
  2. Based on **measures of thermal strain** such as *skin temperature* and *sweat rate* (challenging to measure)
  3. Based on **the human energy balance** (the most comprehensive, requires computational tools and input of actual measured parameters)
- Most of the indices determine **the "equivalent" air temperature** that would exert *the same stress* (or cause *the same strain*) as the conditions to which the body is exposed to providing **a single measure** of **the thermal environment**.





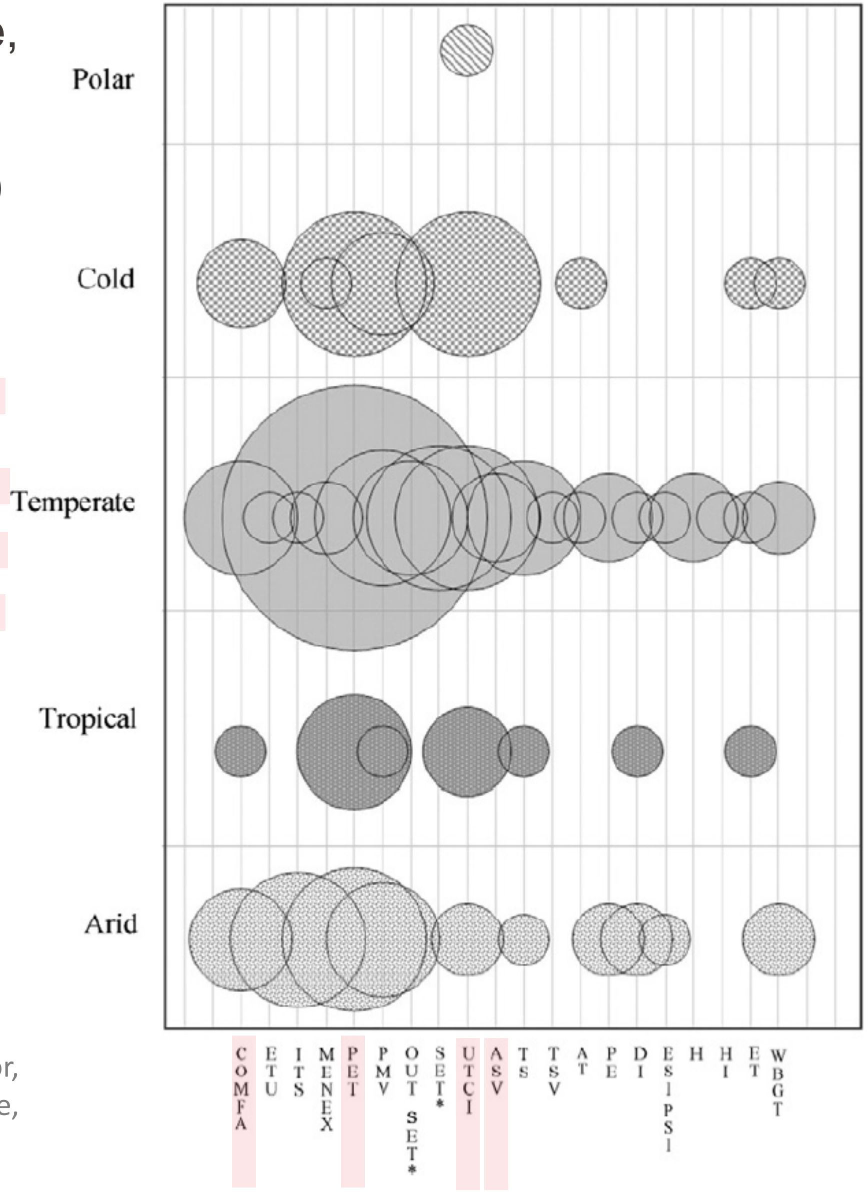
Outdoor Thermal Comfort Indices: Overview

- Indices vary in their ability to analyze the **climate**, **microclimate,** and **human characteristics**.
- Many of them are **validated** only for specific regions (climates)

	Climate				Microclimate								Human	
Model	Gr	Ta	RH	Ws	SVF	Dr	Dfr	MRT	St	Gt	Ba	Ga	Ma	Cl
COMFA*	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓[1]
ETU	✓	✓	✓	✓	✓			✓			✓	✓	✓	✓
ITS	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
PET[2]	✓	✓	✓	✓				✓					✓	✓
PT	✓[3]	✓	✓[3]	✓		✓[3]	✓[3]	✓						✓
UTCI		✓	✓	✓				✓						✓[1]
PMV		✓	✓	✓				✓					✓	✓
ASV	✓	✓	✓	✓										
AT	✓	✓	✓[4]	✓										
DI		✓	✓[5]											
ESI	✓	✓	✓											
ET		✓	✓	✓										
HI		✓	✓											
H		✓	✓											
PE		✓		✓										
RSI		✓	✓[4]											
THI		✓	✓											
TS	✓	✓	✓	✓						✓				
TSV	✓	✓	✓	✓										
WBGT	✓[6]	✓	✓[6]	✓[6]									✓[7]	
WCI		✓		✓										

Gr – global radiation, **Ta** – air temperature, **RH** – relative humidity, **Ws** – wind speed, **SVF** – sky view factor, **Dr** – direct radiation, **Dfr** – diffuse radiation, **MRT** – mean radiant temperature, **St** – surface temperature, **Gt** – ground temperature, **Ba** - Building's albedo **Ga** – ground albedo, **Ma** – metabolic rate, **Cl** – clothing.

Number of references 2000-2016:



Source: Soccolo et al. (2016) http://dx.doi.org/10.1016/j.uclim.2016.08.004

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Empirical Models: Actual Sensation Vote

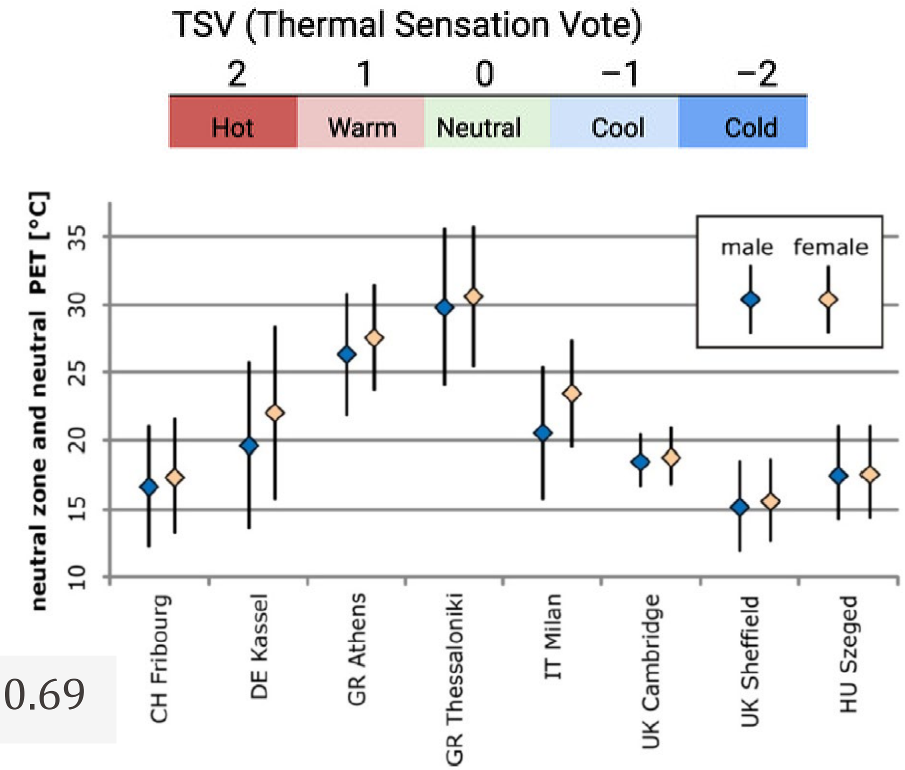
- **Actual Sensation Vote** is expressed as *a linear equation* based on *onsite monitoring* and questionnaire results (surveying people outdoors).
- Environmental factors (air temperature, global radiation, wind speed, and relative humidity) are *multiplied* by *a numerical coefficient* that *varies* according to *climate*.
- RUROS project (**R**ediscovering the **U**rban **R**ealm and **O**pen **S**paces, 2004):
  - **ASV equation for Fribourg (Switzerland)**

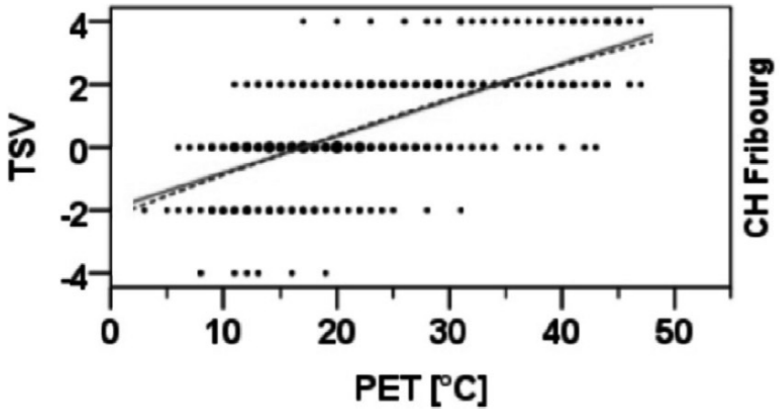
$$ASV = 0.068 \cdot T_a + 0.0006 \cdot K_{\downarrow} - 0.107 \cdot U_a - 0.002 \cdot \varphi_a - 0.69$$

  - **ASV model for Europe (combined from 7 EU cities)**

$$ASV = 0.049 \cdot T_a + 0.001 \cdot K_{\downarrow} - 0.051 \cdot U_a - 0.002 \cdot \varphi_a - 2.079$$

- Empirical models are influenced by *subjectivity* of respondents and by the *transient effect* (response of the person might be based on the thermal exposure prior to the survey), can *become outdated* (due to the local climate change)





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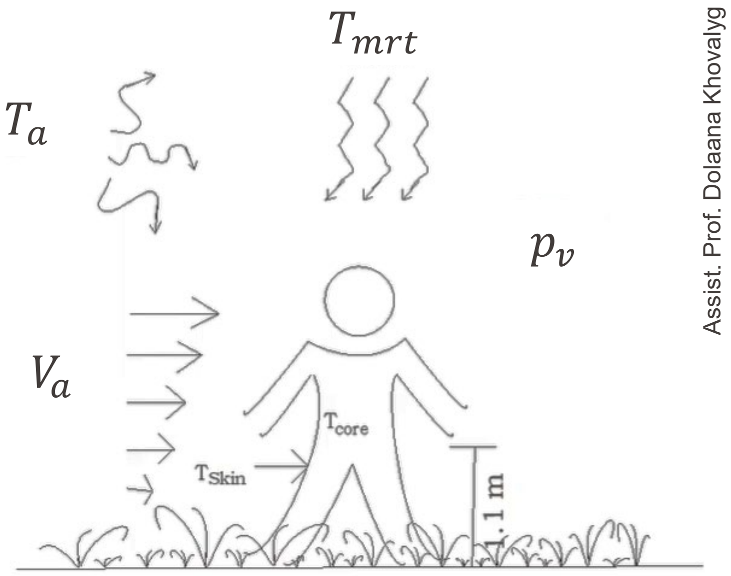
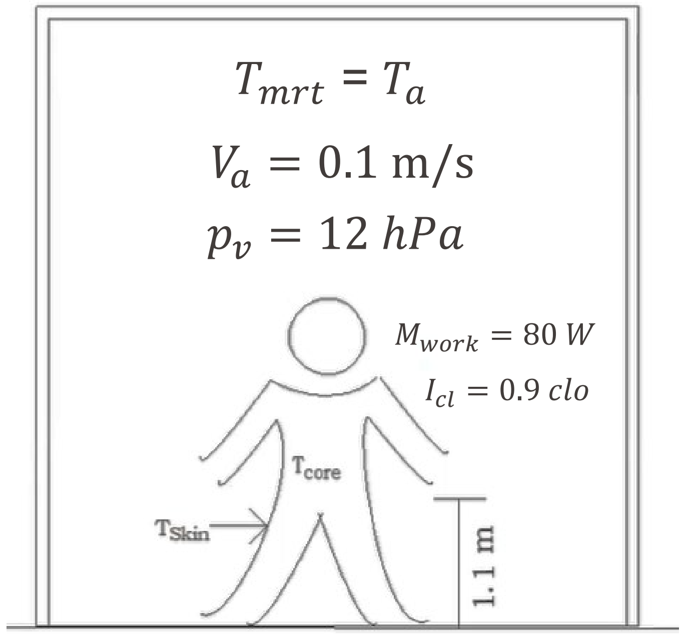
Outdoor Thermal Comfort Indices: PET

- **Physiologically Equivalent Temperature PET** (°C) – air *equivalent air temperature* at which the energy balance for the *assumed indoor conditions* is balanced by ***the same mean skin temperature*** and ***sweat rate*** as calculated for *the actual outdoor conditions*.

PET (°C)	Thermal Perception	Grade of physical stress
$>$ 41	Very hot	Extreme heat stress
35 – 41	Hot	Strong heat stress
29 – 35	Warm	Moderate heat stress
23 – 29	Slightly warm	Slight heat stress
18 – 23	Comfortable	No thermal stress
13 – 18	Slightly cool	Slight cold stress
8 – 13	Cool	Moderate cold stress
4 – 8	Cold	Strong cold stress
$\leq$ 4	Very cold	Extreme cold stress

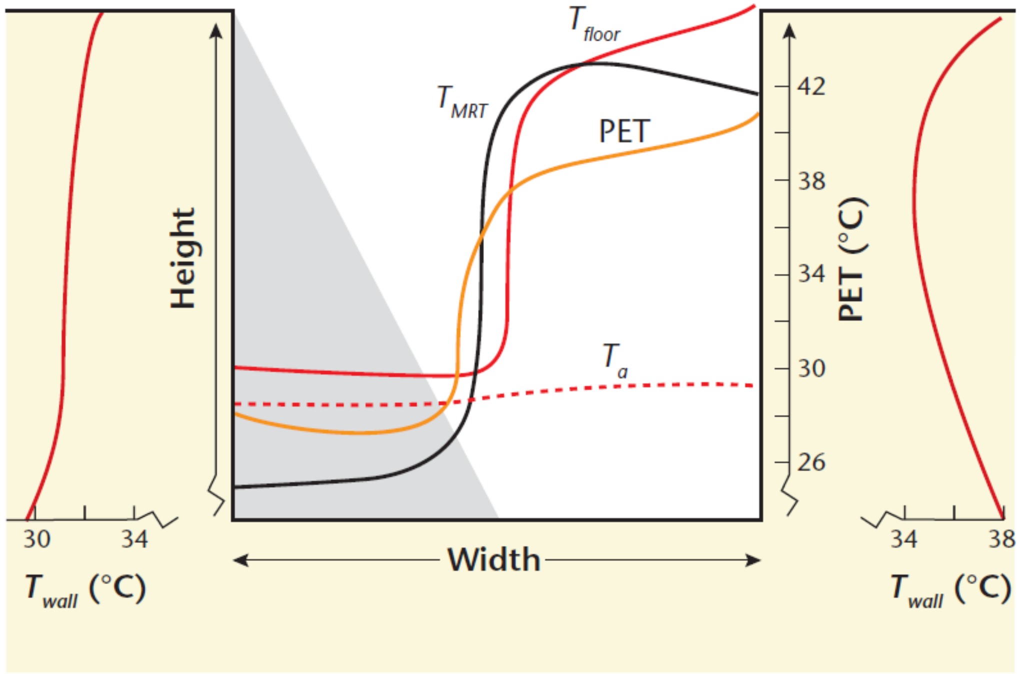
- **Reference indoor conditions (at 1.1 m)**:
  - Temperatures: $\boldsymbol{T_{mrt} = T_a}$
  - Air velocity: $V_a = \mathbf{0.1}\ \mathrm{m/s}$
  - Water vapour pressure: $p_v = \mathbf{12}\ hPa$ (appx. $\varphi = 50\%$ at T_a= 20°C)
  - Human: 1. 75 m, 75 kg, 35 y.o.
  - Light activity (metabolism $M_{work} = \mathbf{80}\ W$)
  - Human clothing $I_{cl} = \mathbf{0.9}\ clo$





Outdoor Thermal Comfort Indices: PET

- Street geometry affects the climate experienced by pedestrians
- **Shaded side of the street:** no direct SW radiation, and the bulk of the intercepted LW radiation is sourced from the shaded side of the street, which occupies the larger view factor.
- **Sunlit side of the street**: a pedestrian receives direct-beam irradiance and intercepts more radiation emitted by warm walls.
- **Tmrt** captures the radical change in the radiation environment, and **PET** *follows the path of Tmrt*, illustrating the importance of the radiation environment on human (dis)comfort outdoors.



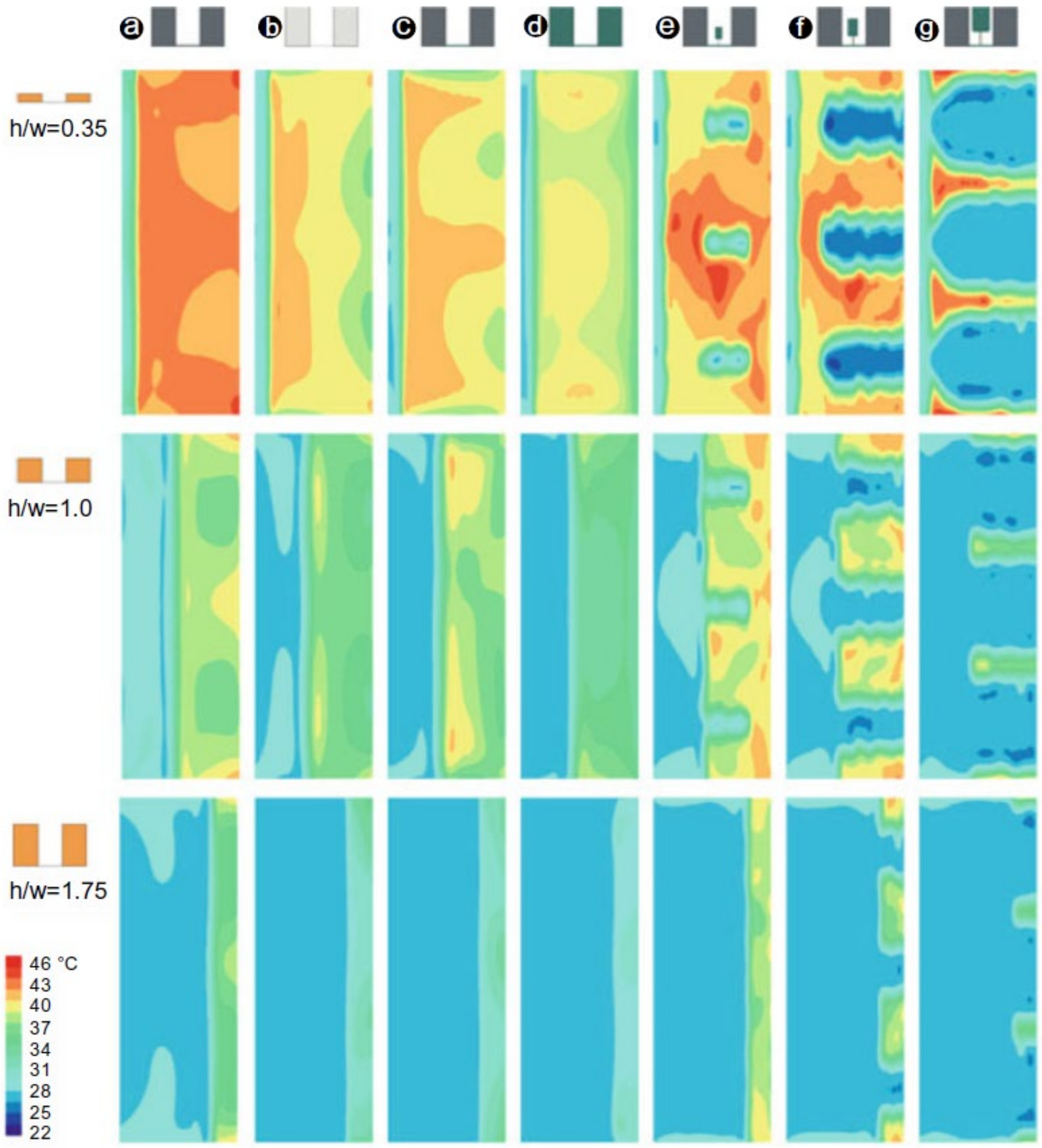
A cross-section of an urban canyon showing simulated variations in wall T_{wall} and floor T_{floor} temperatures, air temperature (T_a) and mean radiant temperature (T_{mrt}). Effect of the shade on PET is demonstrated.

Outdoor Thermal Comfort Indices: PET

- Outdoor comfort depends on the materials of the urban street canyon (*albedo*), and the presence of vegetation
- Effect of trees:
  - Trees planted in the street canyons decrease the perceived temperatures as they block the solar irradiation.
  - Airing of the canon is weaker, the concentration of air pollutants may increase.

PET in the strip-like street canyons on a clear summer day (1.5 m above the ground):

a. Dark canyon surfaces (albedo 0.3)
b. Bright canyon surfaces (albedo 0.7)
c. Dark canyon surfaces and grassy ground
d. Total vegetated surfaces (albedo 0.4)
e-f. Dark canyon with grassy ground and trees of different size planted in the middle of canyon



Source: Medved, Building Physics, p. 468

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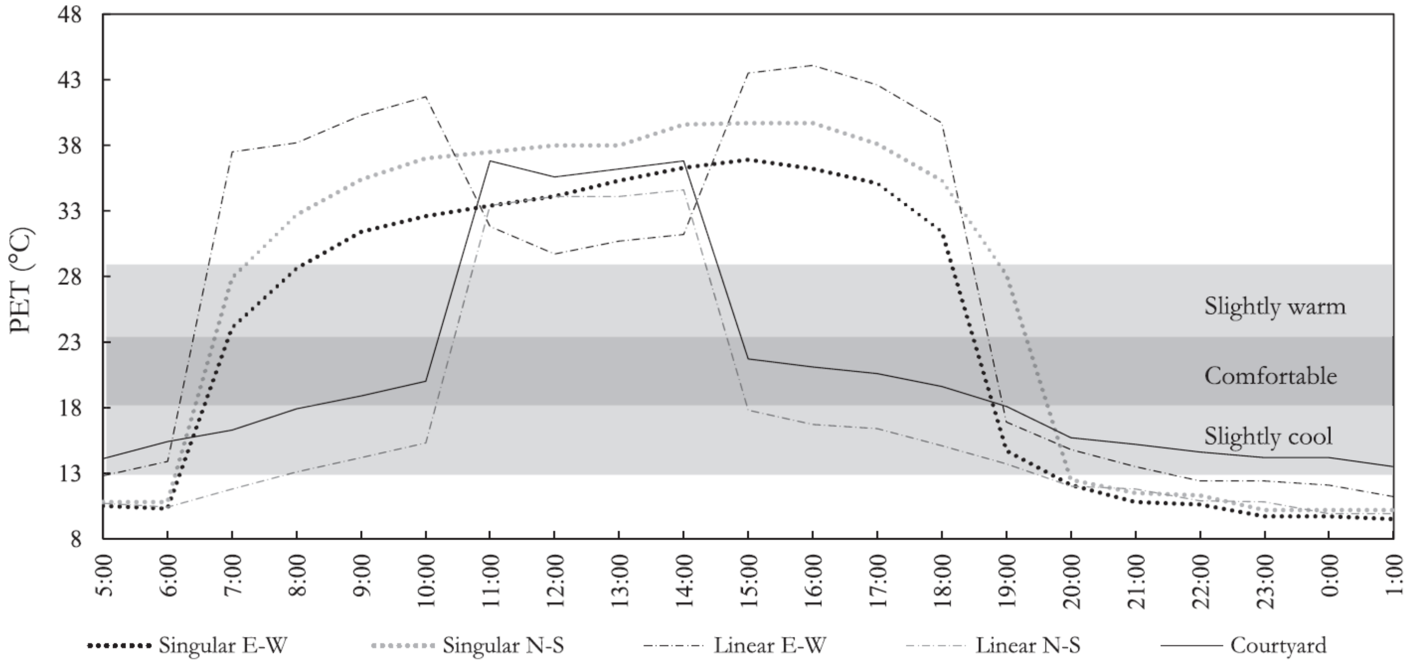
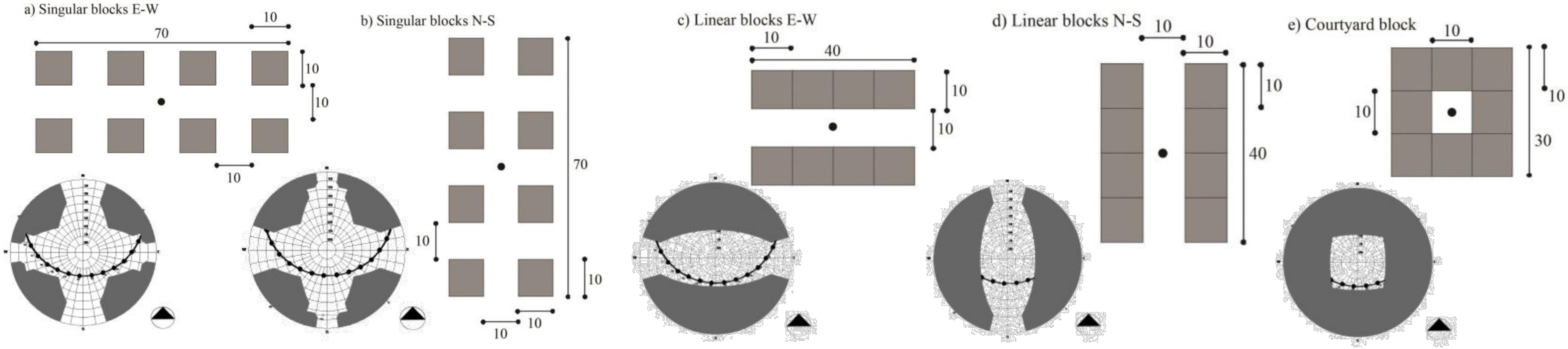
Outdoor Thermal Comfort Indices: PET

- **Case study:** Netherlands
- **Simulation tool:** ENVI-met
- Typical 5 building typologies
- **Simulation day:** 19/06/2000
- Clear sky (no clouds)
- Analysis of different urban forms on thermal comfort of pedestrians using PET index over 24 hours





Source: Taleghani et al. (2015) http://dx.doi.org/10.1016/j.buildenv.2014.03.014

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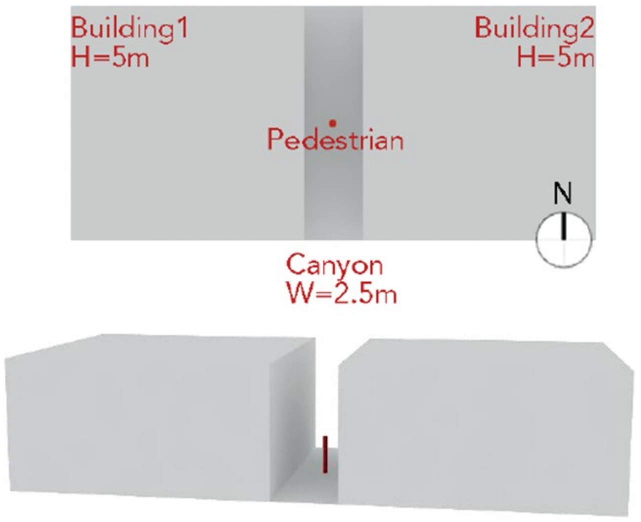
Outdoor Thermal Comfort Indices: COMFA

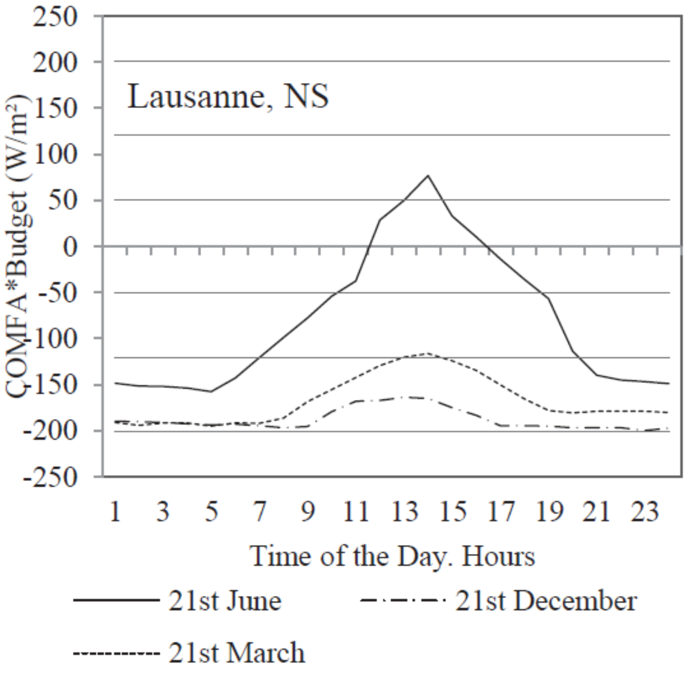
- **COMfort FormulA (COMFA) model** determines **the human energy balance B** (W/m^2) based on 4 elements (**net radiation budget**, **metabolism**, **latent** and **sensible heat flux**). Heat flux due to conduction and heat storage are ignored.

$$B = Q^* + Q_M - Q_H - Q_E \quad (10\text{-}23)$$

- Considers **adaptive clothing model** (based on outdoor conditions)
- Considers **the impact of building forms** (BVF and GVF)

Sensation ratings	Budget (Wm^{-2})	Description
−3	≤−201	Cold
−2	−200 to −121	Cool
−1	−51 to −120	Slightly cool
0	−50 to +50	Neutral
1	51 to +120	Slightly warm
2	+121 to +200	Warm
3	≥+201	Hot





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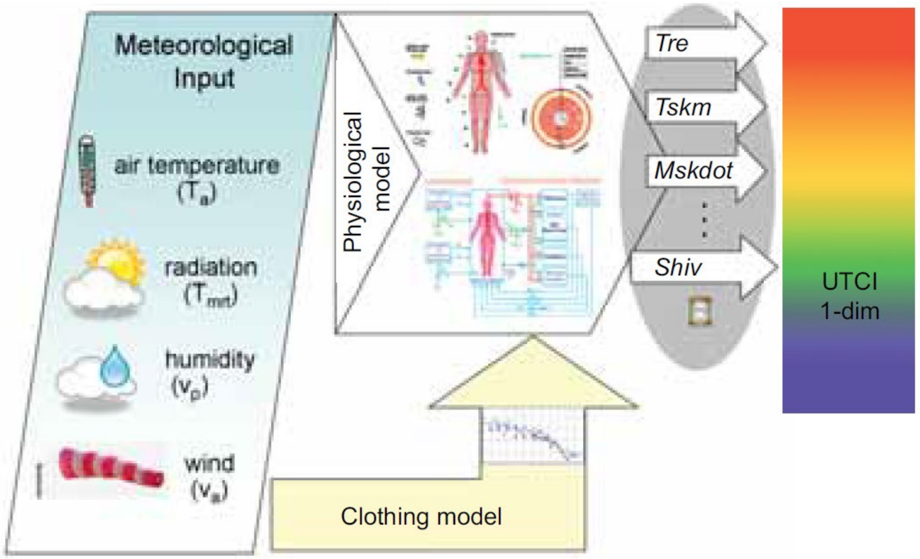
Outdoor Thermal Comfort Indices: UTCI

- **Universal Thermal Climate Index UTCI** (°C) – *equivalent air temperature* of the reference condition yielding the same dynamic physiological response.
- Human response is computed using a multi-node human thermo-physiology model by Fiala' model
- Adaptive clothing model (based on outdoor env.)
- Developed by the *Int. Society of Biometeorology*



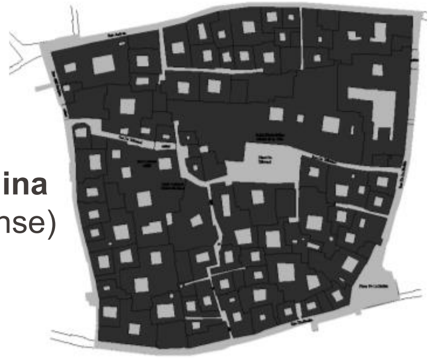
(10-25) $$\boldsymbol{UTCI}(T_a, T_{mrt}, U_a, p_a) = \boldsymbol{T_a} + \boldsymbol{Offset}\,(T_a, T_{mrt}, U_a, p_a)$$

UTCI (°C)	Thermal Stress category
$\geq$ +46	Extreme heat stress
+38 – +46	Very strong heat stress
+32 – +38	Strong heat stress
+26 – +32	Moderate heat stress
+9 – +26	No thermal stress
0 – +9	Slight cold stress
-13 – 0	Moderate cold stress
-27 – -13	Strong cold stress
-40 – -27	Very strong cold stress
< -40	Extreme cold stress

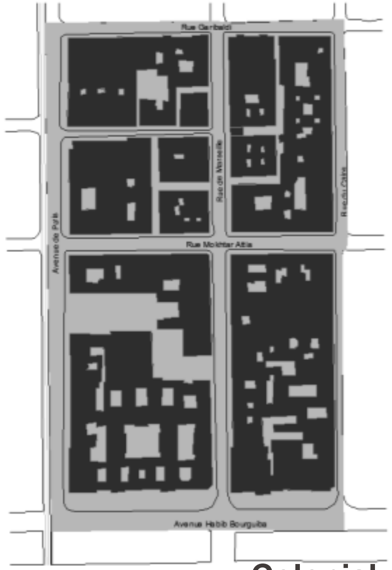
- **Reference conditions**:
  - Temperatures: $\boldsymbol{T_{mrt}} = \boldsymbol{T_a}$
  - Air velocity (at 10m): $V_a = \mathbf{0.5}$ m/s
  - Relative humidity: $\varphi = \mathbf{50\%}$ ($T_a < 29$°C)
  - Air pressure: $p_a = \mathbf{2}\ kPa$ ($T_a > 29$°C)
  - Activity: walking at **4** km/h ($135\ W/m^2$)
  - Human clothing $I_{cl} = \mathbf{0.9}\ clo$

Outdoor Thermal Comfort Indices: UTCI

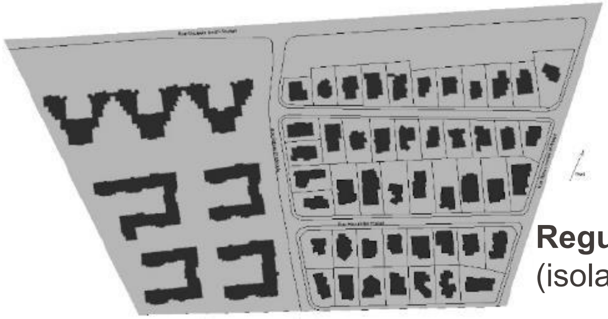
- **Case study:** Tunis, Tunisia
- **Climate:** subtropical Mediterranean
- **Simulation tool:** ENVI-met
- Study of the impact of the geometry of an urban street canyon on outdoor thermal comfort
- Types of fabric studied:



Medina
(old, dense)



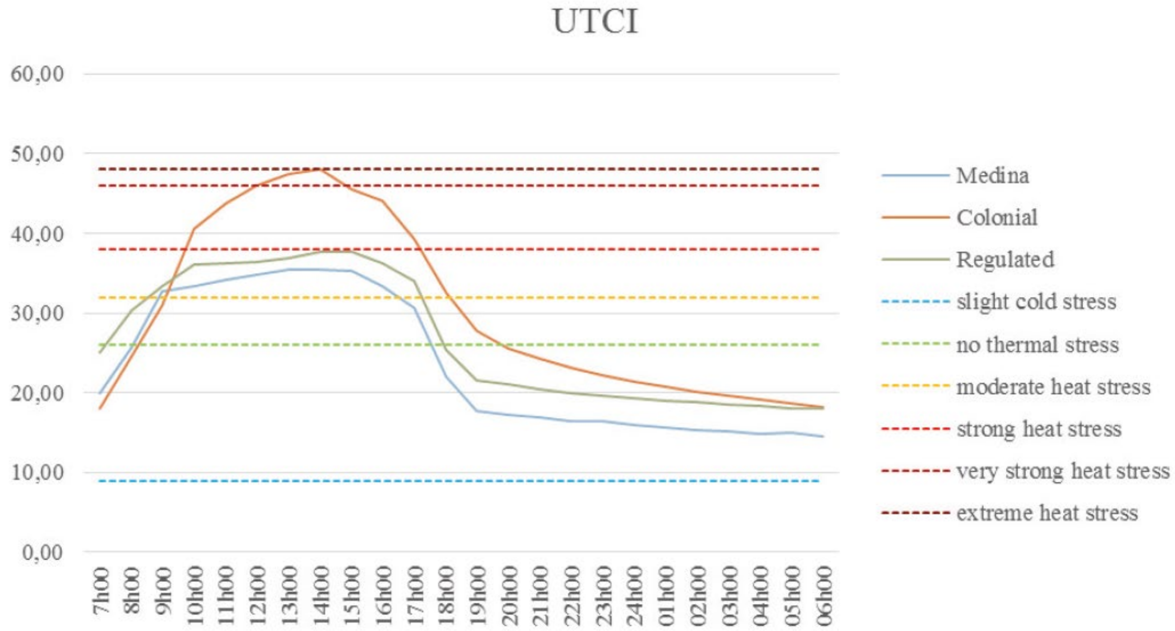
Colonial
(EU city model)



Regulated
(isolated habitats)

Medina Prospect	Ratio	Colonial Prospect	Ratio	Regulated Prospect	Ratio
	3.40		1.71		0.56

Medina Fish-eye	SVF	Colonial Fish-eye	SVF	Regulated Fish-eye	SVF
	0.09		0.18		0.59



Source: Achour-Younsai et al. (2015), 10.1016/j.sbspro.2015.12.062

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Correlation between PET and UTCI

Thermal perception	Indices				
	UTCI	WBGT	SET	PMV	PET
Very cold[1] (Extreme cold stress[1,2])	< -40			-3	<4
(very strong cold stress[2])	-40 to -27				
Cold[1] (Strong cold stress[1,2])	-27 to -13			-2.5	4-8
Cool[1,3] (Moderate cold stress[1,2]/ Moderate Hazard[3])	-13 to 0		<17	-1.5	8-13
Slightly cool[1] (Slight cold stress[1,2])	0 to +9			-0.5	13-18
Comfortable[1,3] (No thermal stress[1,2]/ No Danger[3,4])	+9 to +26	<18	17-30	0	18-23
Slightly warm[1] (Slight heat stress[1])				0.5	23-29
Warm[1,3,4] (Moderate heat stress[1,2]/ Caution[3,4])	+26 to +32	18-23	30-34	1.5	29-35
Hot[1,3,4] (Strong heat stress[1,2]/ Extreme caution[3,4])	+32 to +38	23-28	34-37	2.5	35-41
(very strong heat stress[2])	+38 to +46				
Very hot[1,3,4] (Extreme heat stress[1,2]/ Danger[3,4])	> +46	28-30	>37	3	>41
Sweltering[4] (extreme danger[4])		≥30			

[1] PET and PMV   [2] UTCI   [3] SET   [4] WBGT

Source: Zare, S., Hasheminejad, N., Shirvan, H. E., Hemmatjo, R., Sarebanzadeh, K., & Ahmadi, S. (2018). Comparing Universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year. Weather and climate extremes, 19, 49-57.

Thank you for your attention!

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