EPFL

CIVIL-309: URBAN THERMODYNAMICS

Assist. Prof.
Dolaana Khovalyg

Lecture 09:
Human Outdoor Comfort

25 November 2024

Course Schedule

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

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Intermediate presentations on Dec. 2:

Goal: Review the progress of your group work, provide feedback and recommendations on the final part

- Each group will have 15 minutes total: 10 minutes for to present and 5 minutes for Q&A
- Respect the schedule — your presentation must not exceed 10 minutes
- Plan and divide the presentation tasks within your group (decide who presents which part)
- All group members must be present during your assigned time slot
- If you have a problem with your allocated time slot, coordinate with another group to exchange slots
- Attending other groups' presentations is optional, not mandatory

Schedule of presentations:

Time	Group	Time	Group
15:15-15:30	Group 1	16:30-16:45	Group 6
15:30-15:45	Group 2	16:45-17:00	Group 7
15:45-16:00	Group 3	17:00-17:15	Group 8
16:00-16:15	Group 4	17:15-17:30	Group 9
16:15-16:30	Group 5	17:30-17:45	Group 10

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Human - Environment Interaction: Introduction

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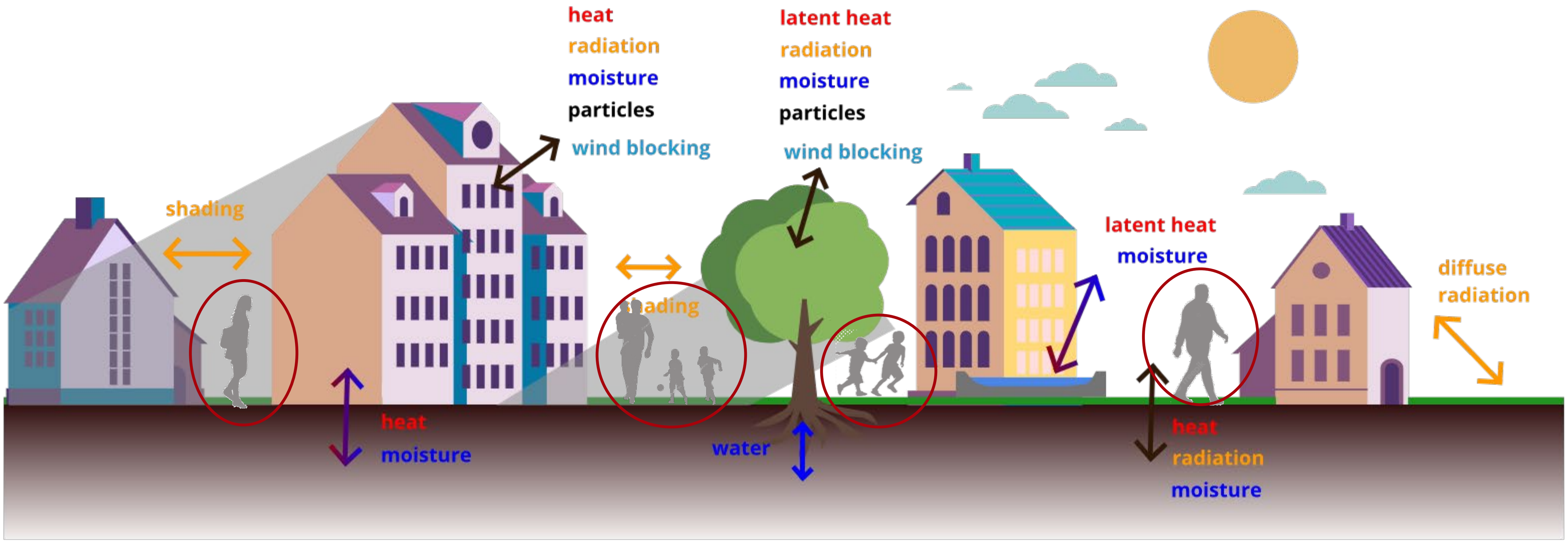
Images from Google

Human - Environment Interaction: Introduction

- **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*



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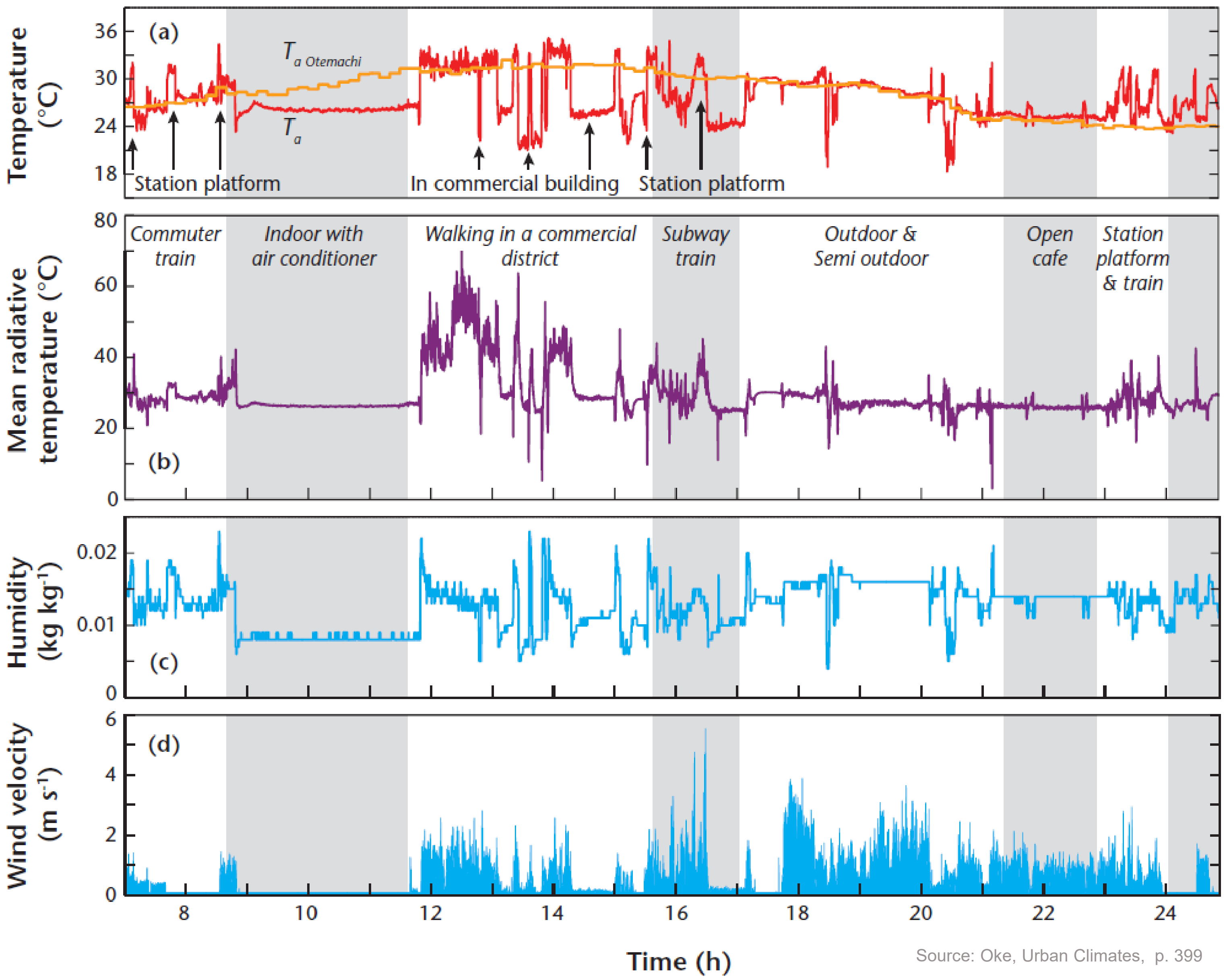
Outdoor Thermal Environment

- **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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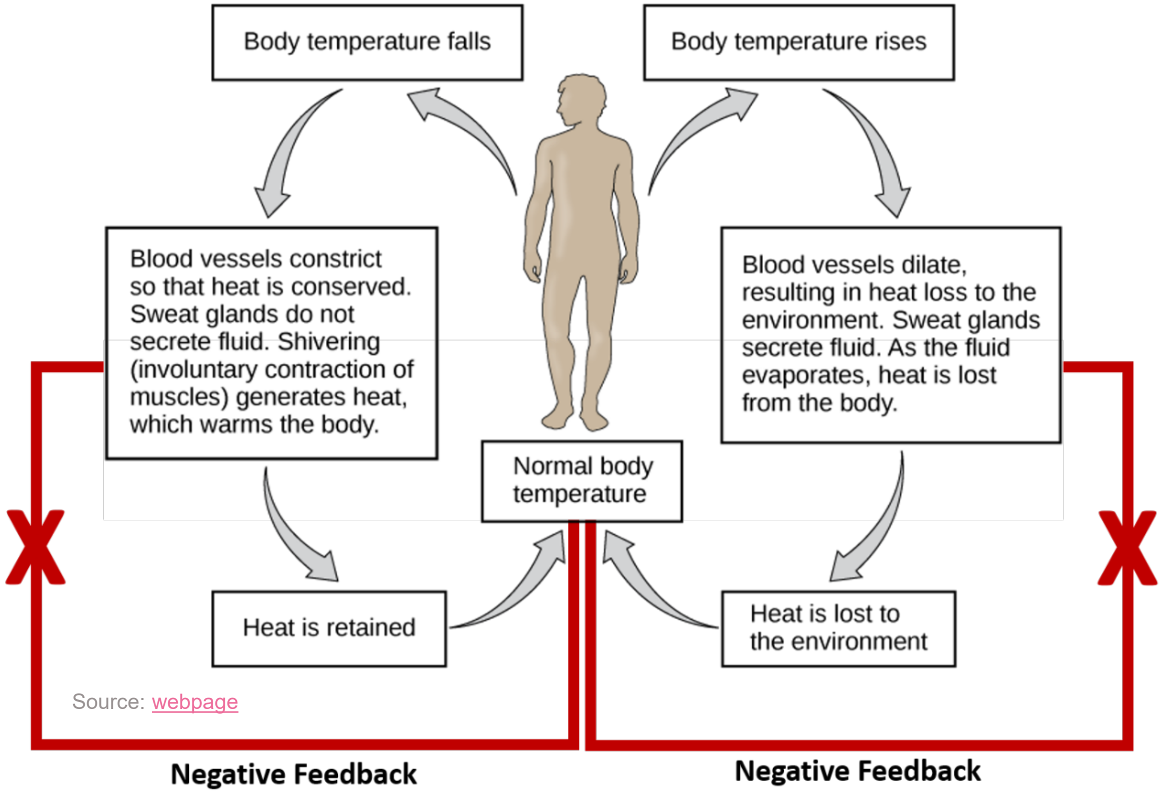
Human Thermoregulation

- 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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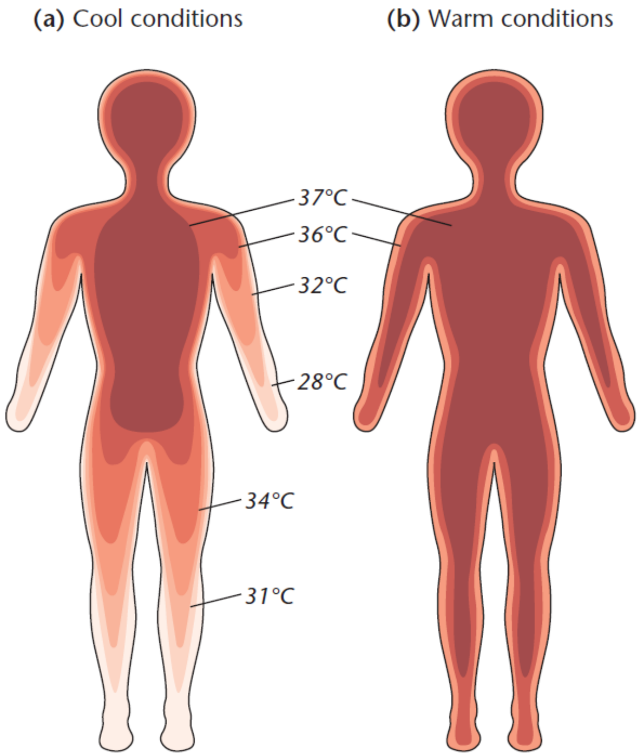

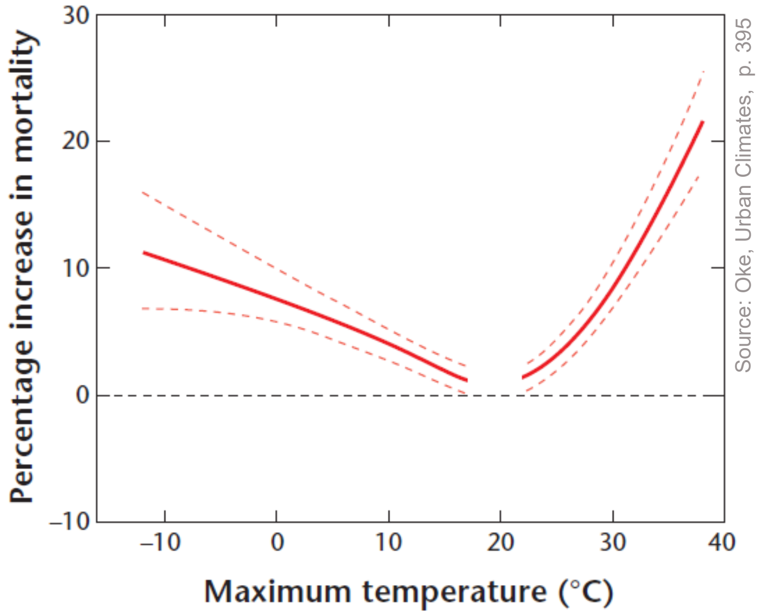

Source: Oke, Urban Climates, p. 395

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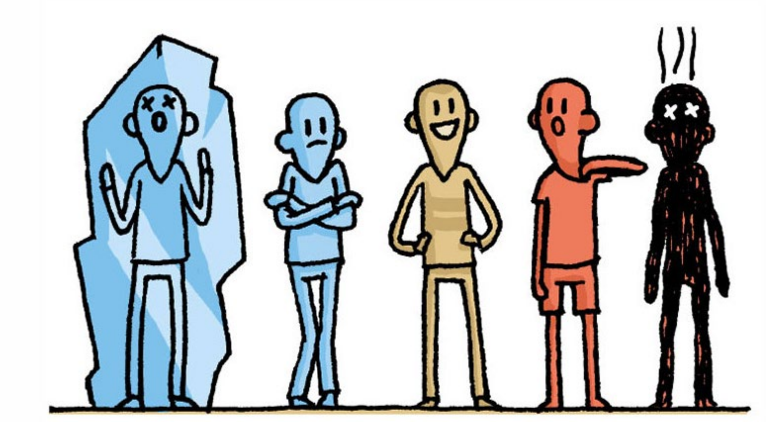
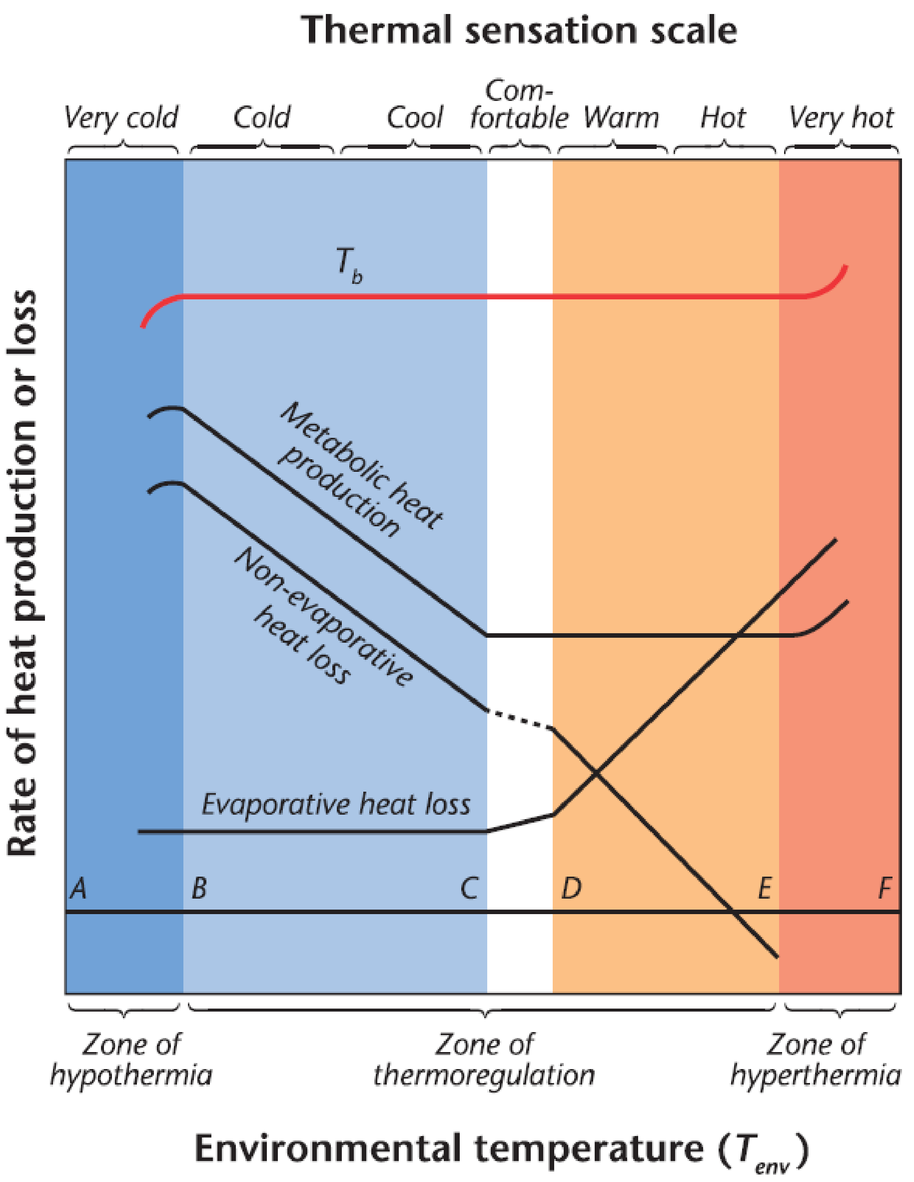
Human Thermal Comfort

- **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

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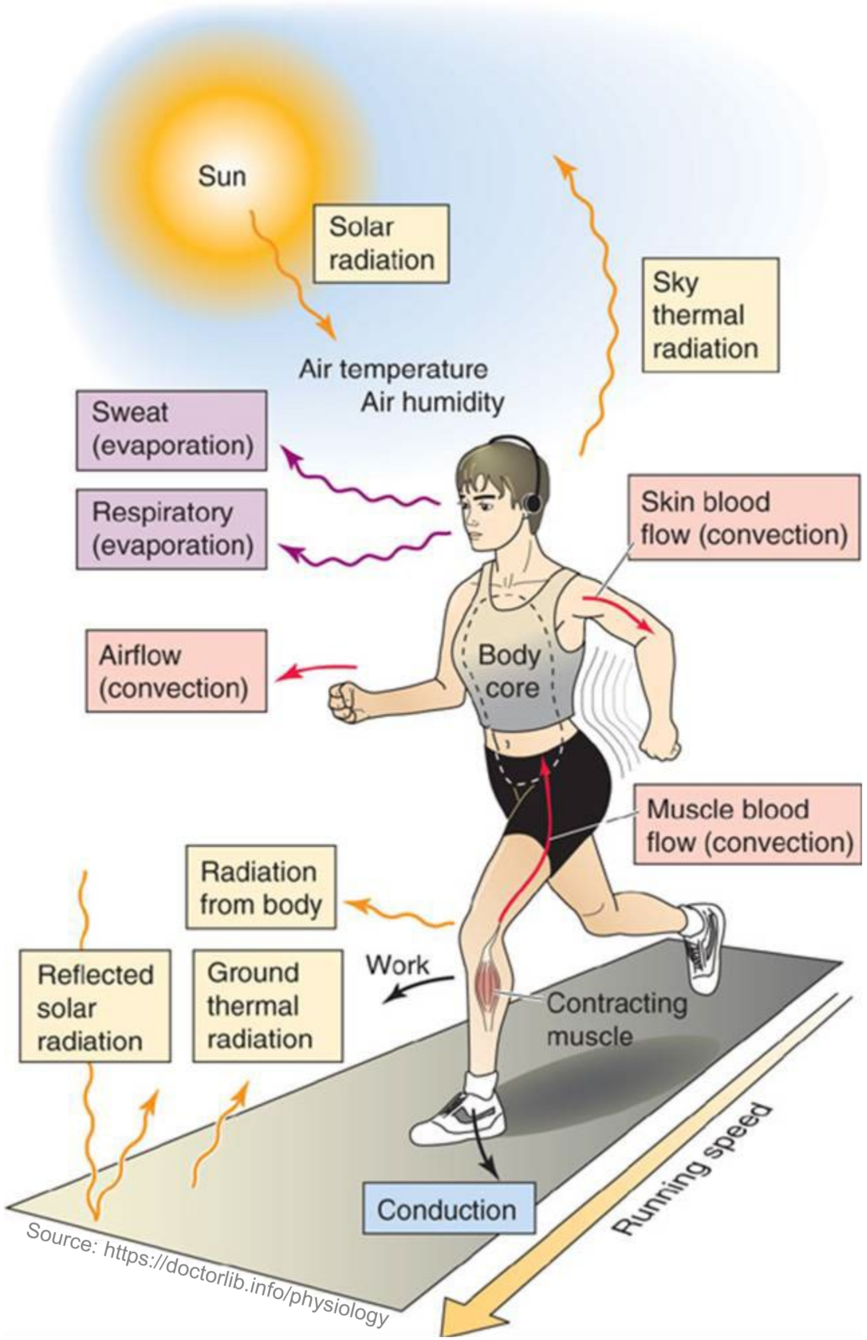
Human Energy Balance

- 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 ($\Delta Q_S \sim 0$).

$$Q^* + Q_M = Q_H + Q_E + Q_G + \Delta Q_S \quad (9\text{-}1)$$

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



Source: https://doctorlib.info/physiology

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

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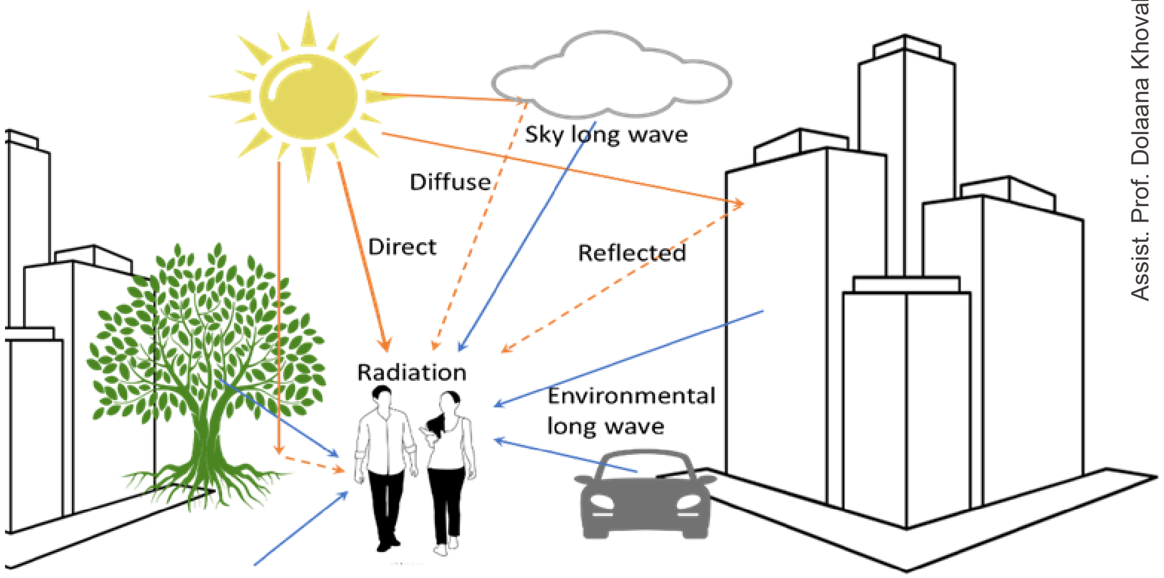
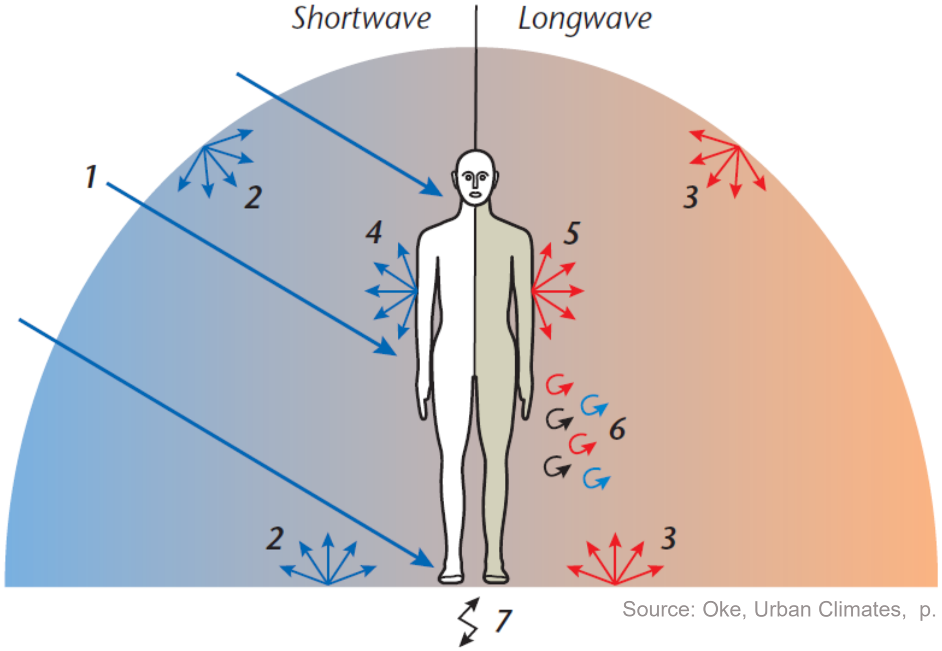
- The **radiation budget** for **an individual** is the same as that for **the surface radiation budget** of any naturals surface (its application to humans is *more complicated* due to *the human shape*):

(3−35) → (9-2) $$Q^* = K^* + L^* = (K_\downarrow - K_\uparrow) + (L_\downarrow - L_\uparrow)$$

(9-3) $$Q^* = (S + D) \cdot (1 - a) + (L_\downarrow - L_\uparrow)$$





Source: Oke, Urban Climates, p. 390

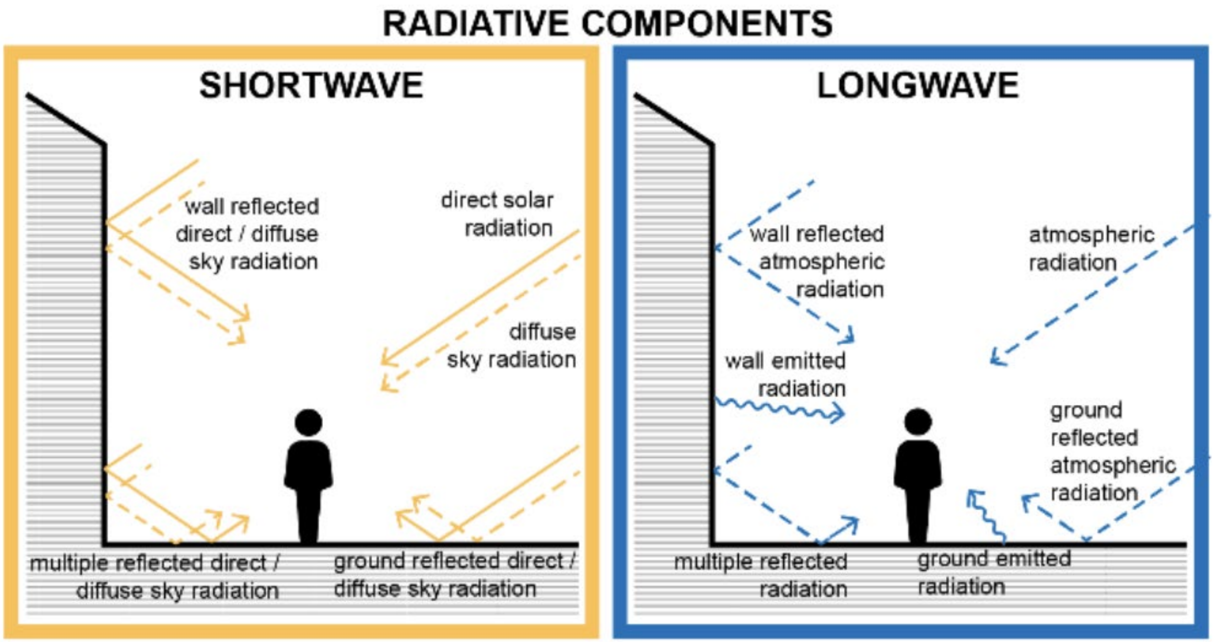
(1) direct shortwave radiation S that impinges on the sunlit part of the body;
(2) diffuse shortwave radiation D that originates from the sky as a result of scattering and from the ground as a result of reflection;
(3) diffuse longwave radiation $L_\downarrow$ that is emitted from the sky vault and from 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.

Mean Radiant Temperature

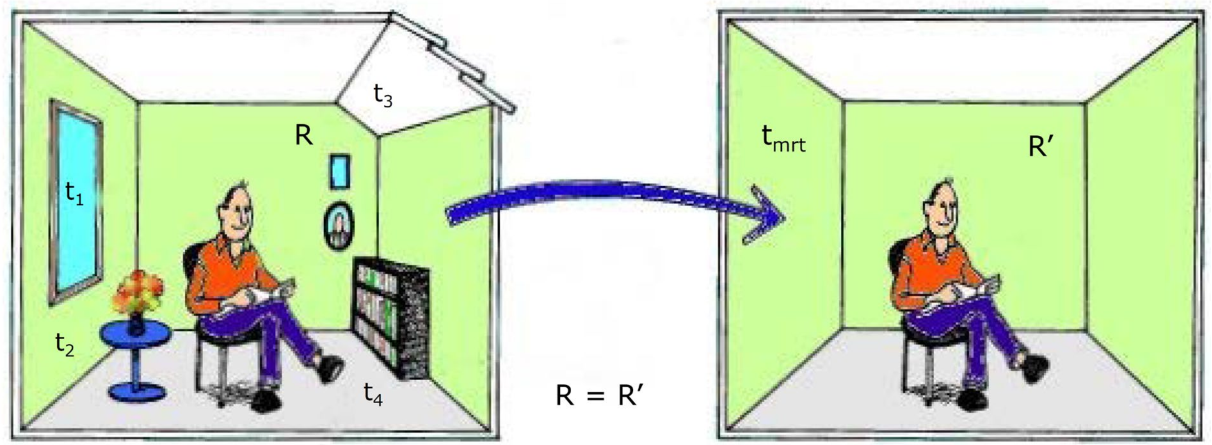
- **Actual radiant environment** around a person is **very diverse**. Thus, to numerically represent how human beings experience radiation, a parameter T_{MRT} is defined.
- **Mean Radiant Temperature T_{mrt}** (K) - *a surface temperature* of a *blackbody* (perfect emitter) that generates *the same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

$$T_{mrt} = \sqrt[4]{\frac{K_{\downarrow} \cdot a + L_{\downarrow} \cdot \varepsilon}{\sigma}} \quad (9\text{-}4)$$

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



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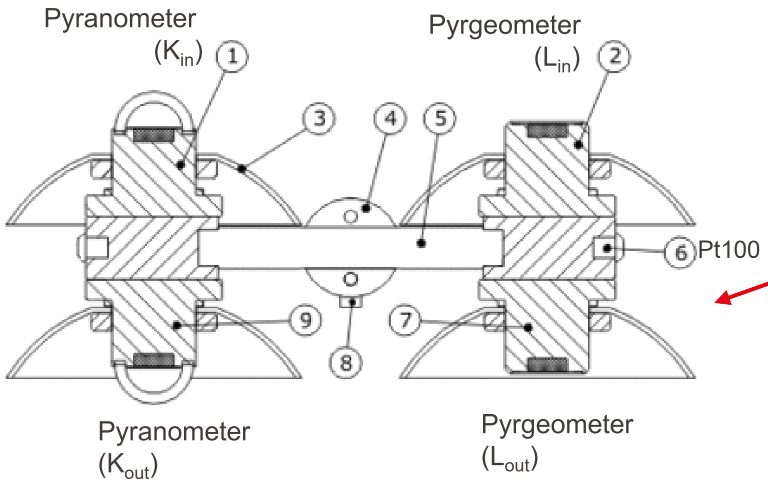
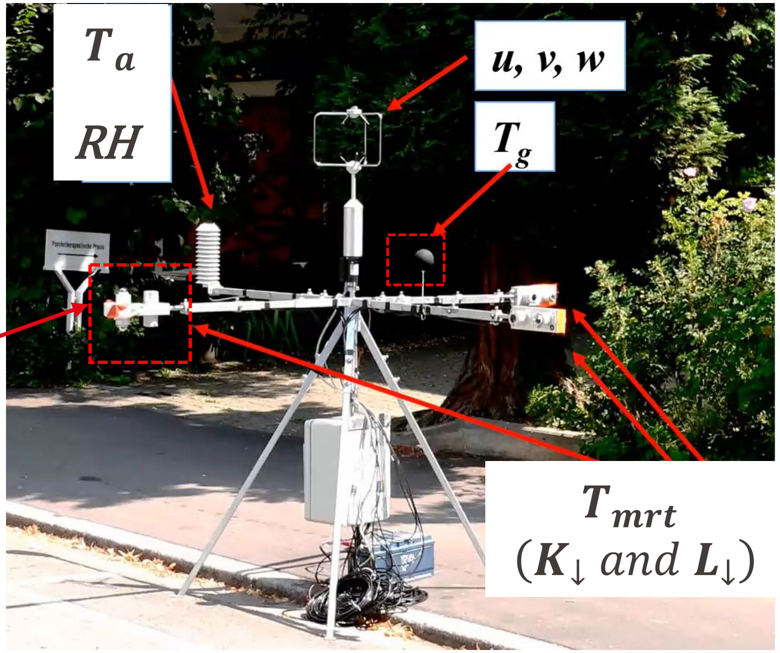
Mean Radiant Temperature: Measurements

- 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*).





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Human Skin: Radiation Properties

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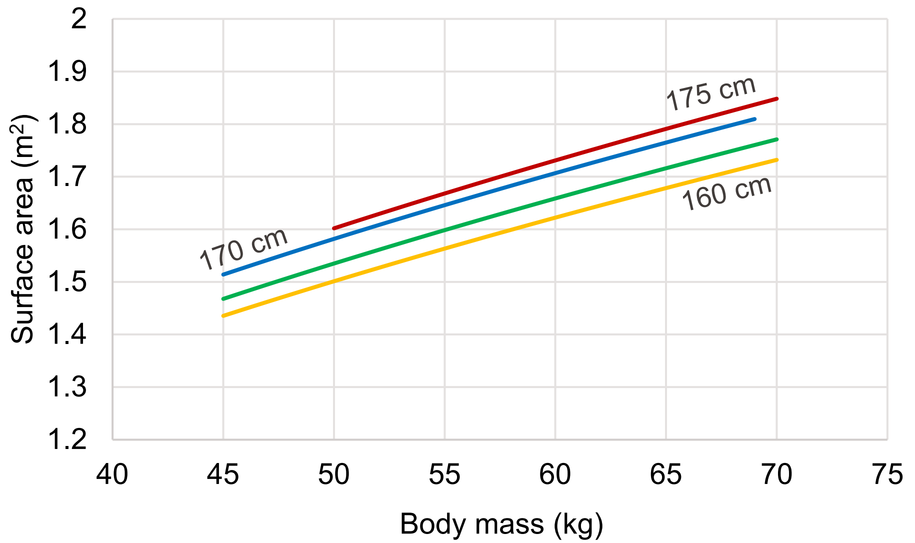
- **Surface area of the body A_{body}** in **m²** (DuBois formula):

$$A_{body} = 0.007184 \cdot M^{0.425} \cdot H^{0.725} \quad (9\text{-}5)$$

M (kg) – human body mass, H (cm) – human height

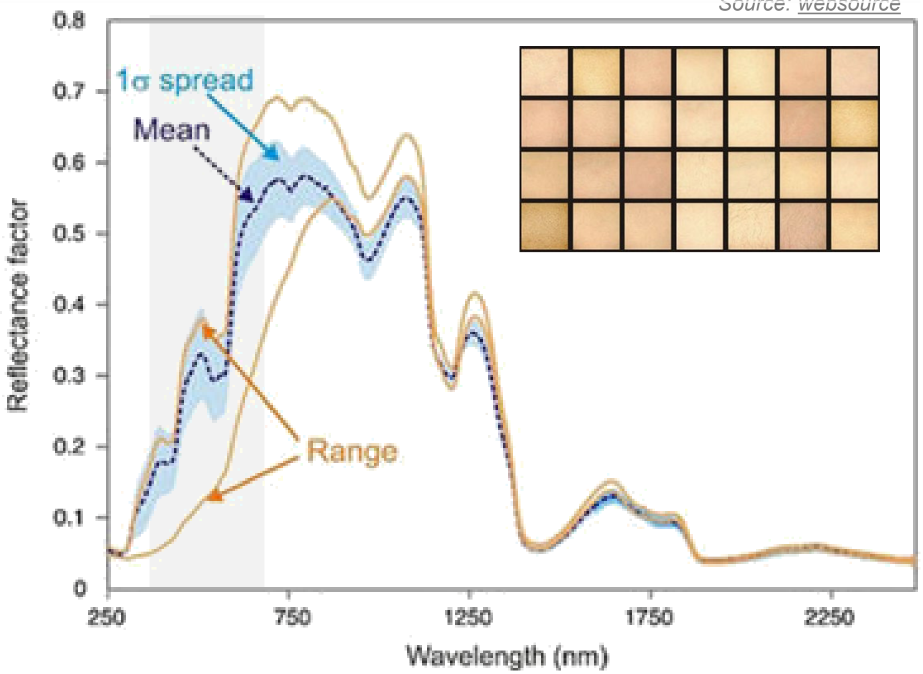


- **"Average" human body parameters:**

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)

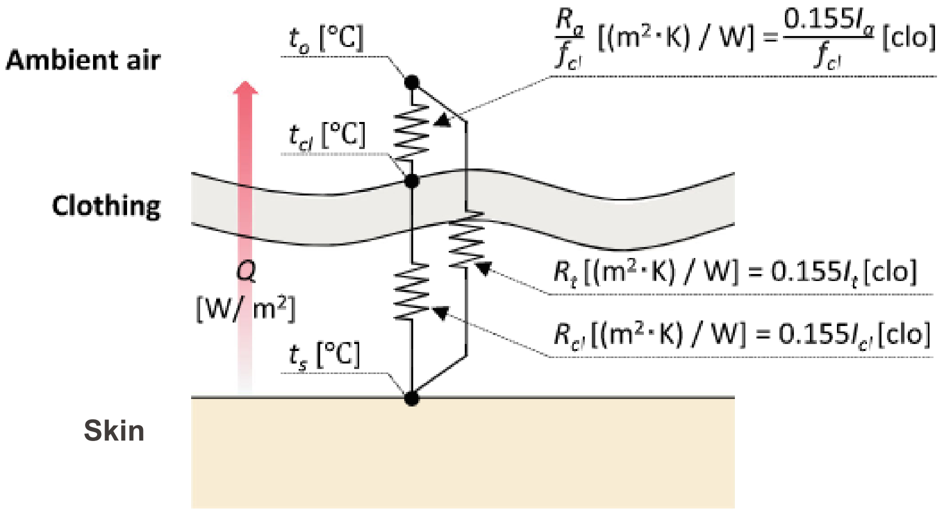
Source: websource



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":

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



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.

$$f_{cl} = \frac{A_{cl}}{A_{body}} \quad (9\text{-}6)$$

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

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

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

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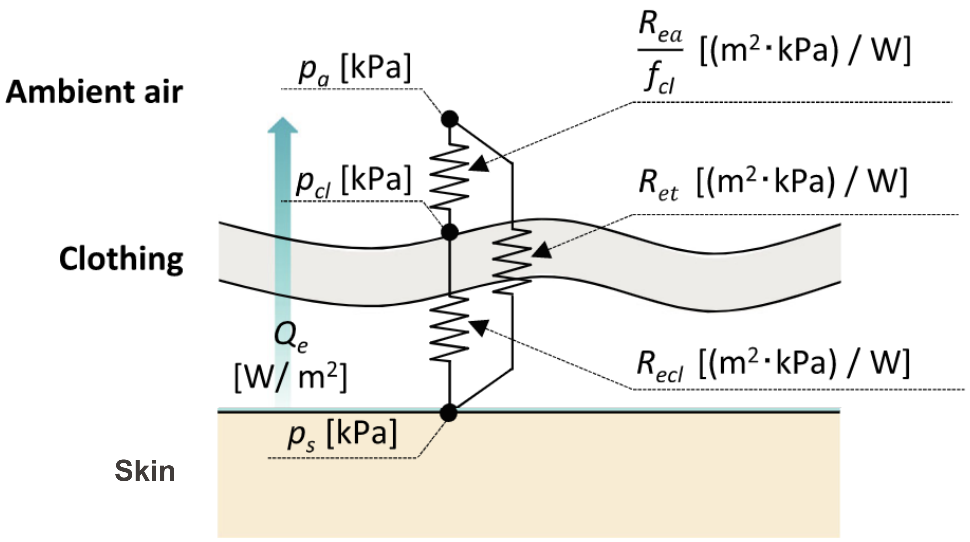
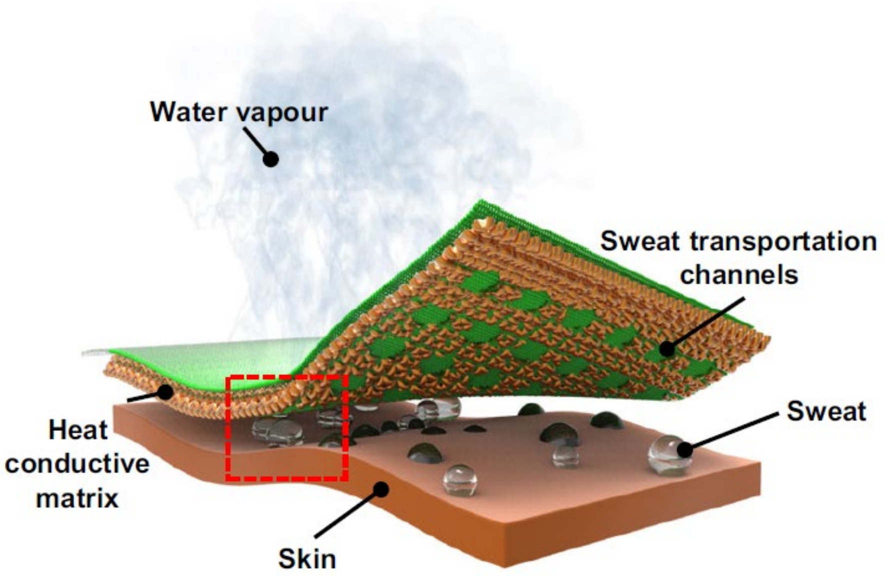
Clothing: Vapor Resistance

- 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



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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).

$$Q_H = h_{conv} \cdot f_{cl} \cdot (T_{cl} - T_a) \quad (9\text{-}7)$$

- **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:

$$h_{conv} = 8.3 \cdot U_a^{0.6} \quad (9\text{-}8)$$

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

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* $\boldsymbol{T_{op}}$

(9-9) $$\boldsymbol{Q^* + Q_H = h \cdot f_{cl} \cdot (T_{cl} - T_{op})}$$

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

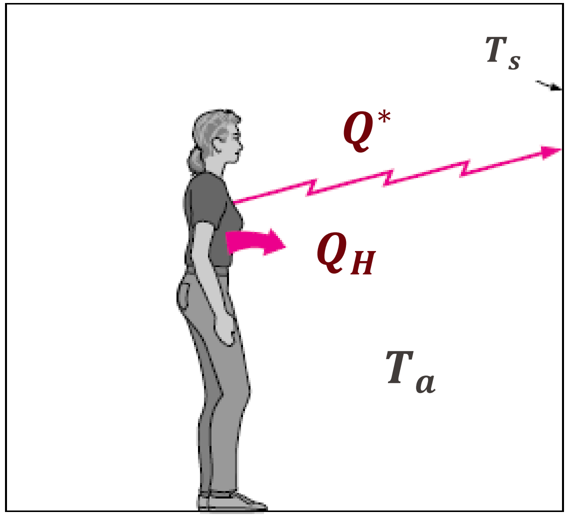
- **Operative temperature** $\boldsymbol{T_{op}}$ is the **uniform temperature** of **an enclosure** in which *an occupant* would exchange *the same amount of heat* by **radiation** plus **convection** as *in the actual non-uniform environment.*

$$\boldsymbol{T_{op}} = \frac{h_{conv} \cdot T_a + h_{rad} \cdot T_{mrt}}{h_{conv} + h_{rad}} \quad (9\text{-}10)$$

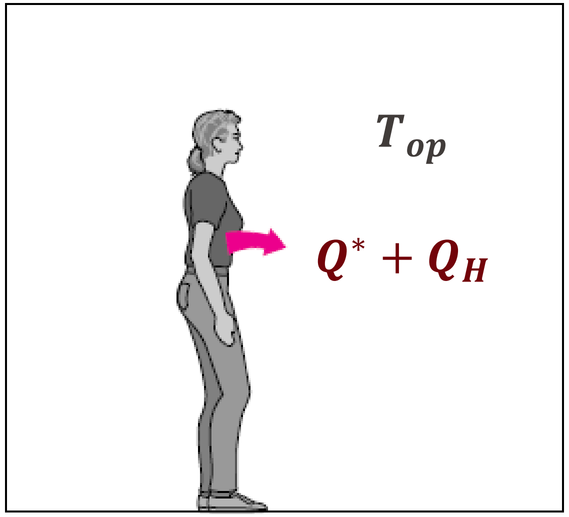
  - Radiative heat transfer coefficient:

$$\boldsymbol{h_{rad} = \varepsilon} \cdot \sigma \cdot f_{eff} \cdot (T_{cl}^2 + T_{mrt}^2) \cdot (T_{cl} + T_{mrt}) \quad (9\text{-}11)$$

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



(a) Convection and radiation, separate



(b) Convection and radiation, combined

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 ($t_{cr} \sim 37^oC$)

$$Q_{E,rsp} = \dot{V} \cdot \rho_{a,in} \cdot (q_{a,out} - q_{a,in}) \cdot L_v / A_{body} \quad (9\text{-}12)$$

- $\dot{V}$ (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

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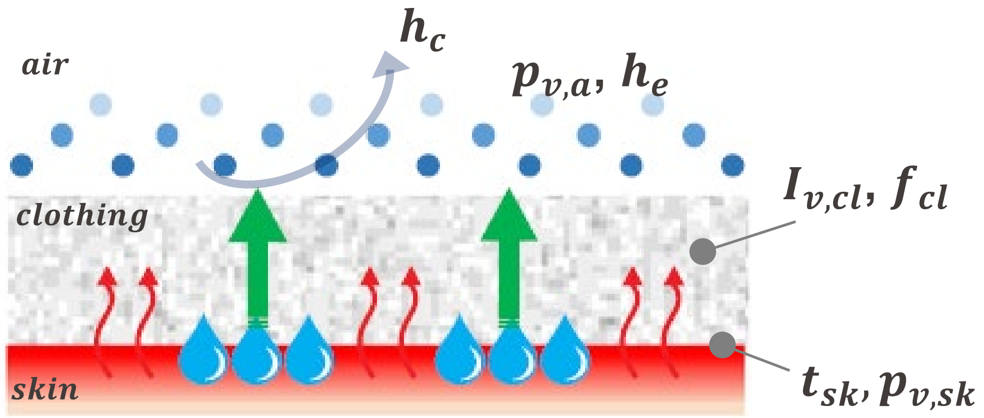
Evaporative Heat Flux: Skin

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

$$Q_{E,sk} = \frac{w \cdot (p_{v,skin} - p_{v,a})}{(I_{v,cl} + \frac{1}{f_{cl} \cdot h_e})} \quad (9\text{-}13)$$

- 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, $LR = 16.7\ K/kPa$)

$$h_e = LR \cdot h_{conv} \quad (9\text{-}19)$$



$$w = 0.06 + \frac{Q_{E,rsw}}{Q_{E,max}} \quad (9\text{-}14)$$

$Q_{E,rsw}$: Actual regulatory sweat evaporation

$Q_{E,max}$: Maximum evaporation (Eqn. 9-18 at w=1)

$$Q_{E,rsw} = M_{rsw} \cdot L_v \quad (9\text{-}15)$$

$$M_{rsw} = 4.7 \cdot 10^{-5} \cdot (t_b - 36.18) \cdot e^{(\frac{t_{sk} - 33.7}{10.7})} \quad (9\text{-}15a)$$

$$t_b = \alpha \cdot t_{sk} + (1 - \alpha) \cdot t_{cr} \quad (9\text{-}15b)$$

- L_v (kJ/kg)- heat of vaporisation of water (2430 kJ/kg at 30°C)
- M_{rsw} (kg/s*m²) - 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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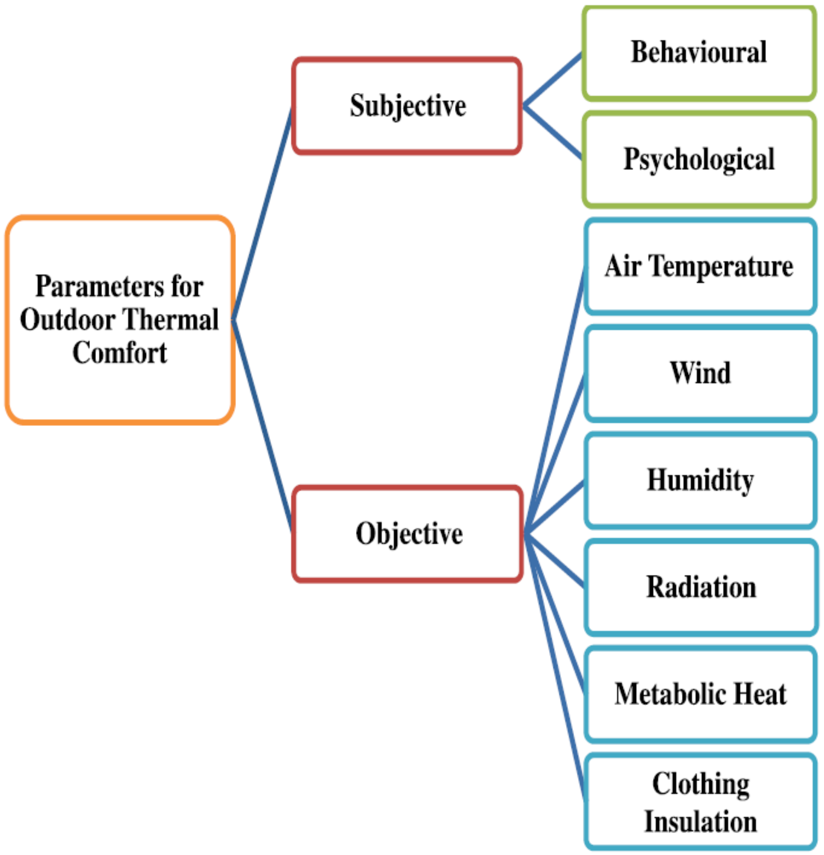
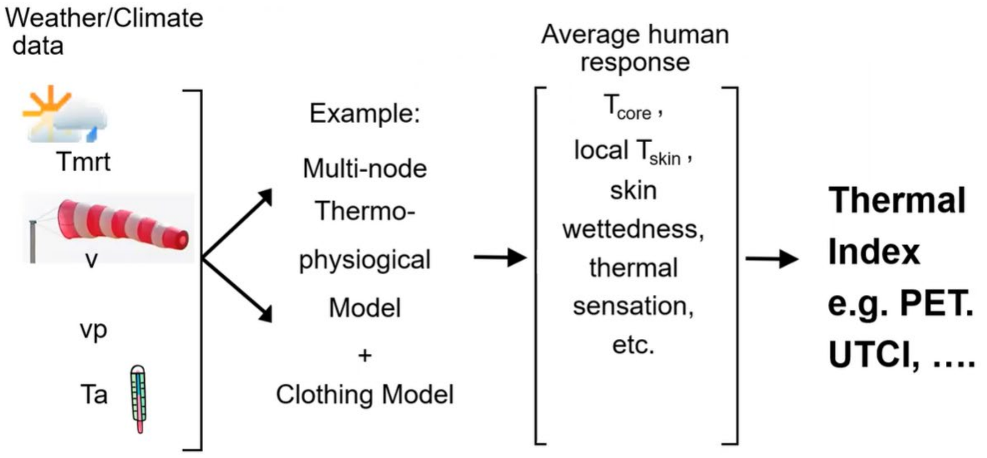
CONTENT:

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**.





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Outdoor Thermal Comfort Indices: Overview

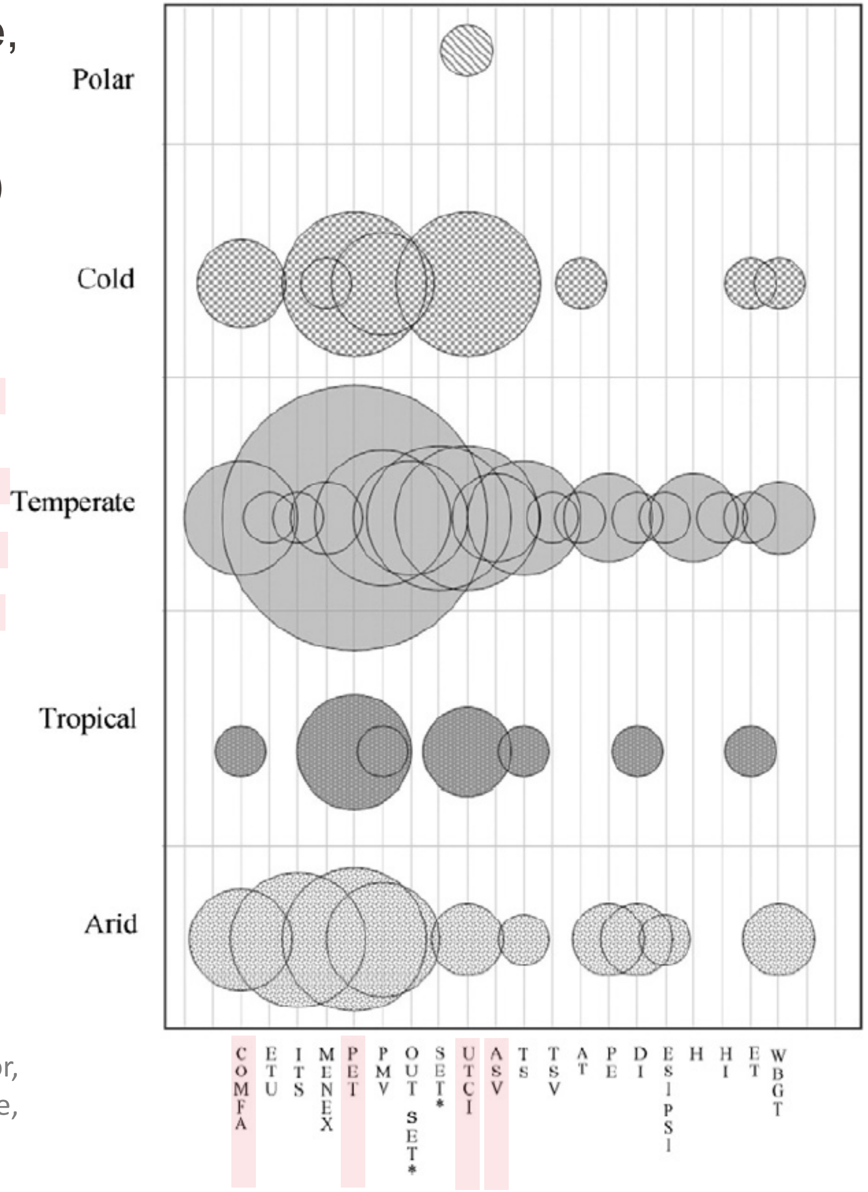
- Indices vary in their ability to analyze the **climate**, **microclimate,** and **human characteristics**.
- Many of them are **validated** only for specific regions (climates)

	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.

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

Number of references 2000-2016:



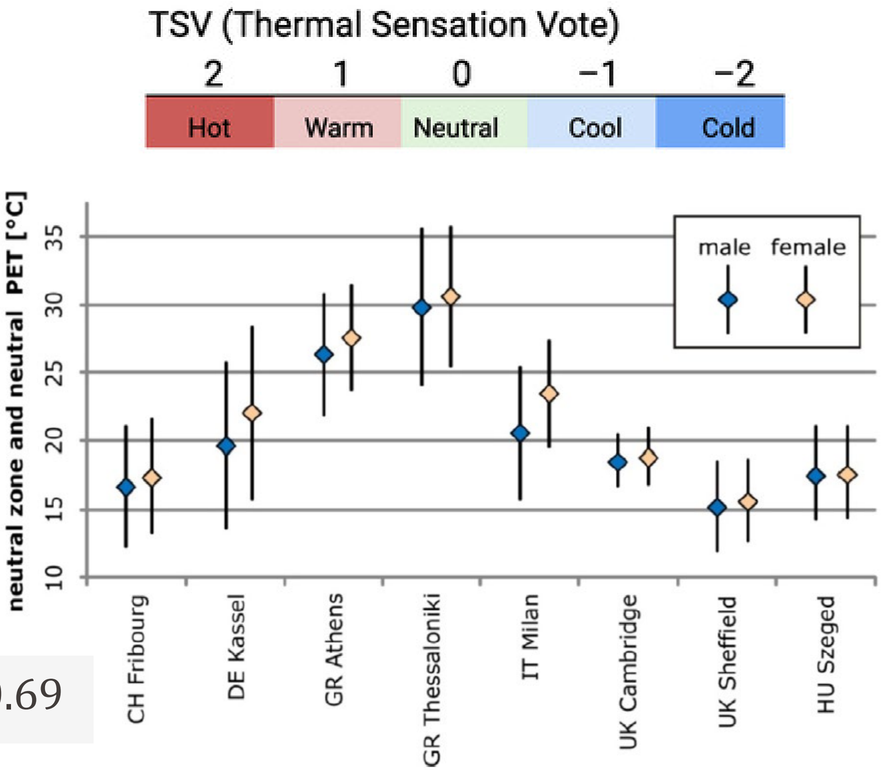
Empirical Models: Actual Sensation Vote

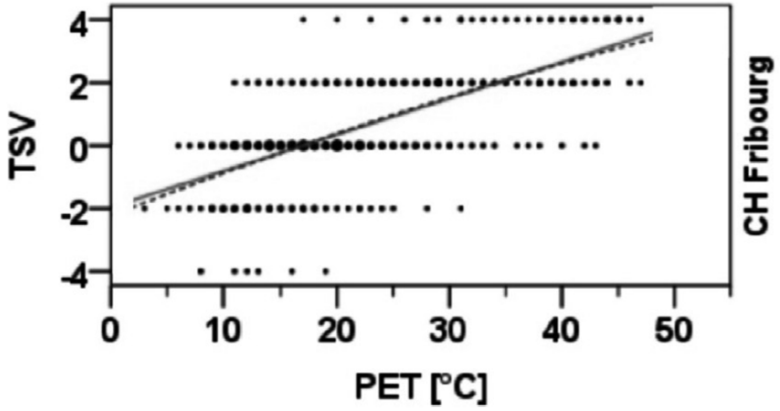
- **Actual Sensation Vote** is expressed as *a linear equation* based on *onsite monitoring* and questionnaire results (surveying people outdoors).
- Environmental factors (air temperature, global radiation, wind speed, and relative humidity) are *multiplied* by *a numerical coefficient* that *varies*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

(9-16a) $$ASV = 0.068 \cdot T_a + 0.0006 \cdot K_{\downarrow} - 0.107 \cdot U_a - 0.002 \cdot \varphi_a - 0.69$$

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

(9-16b) $$ASV = 0.049 \cdot T_a + 0.001 \cdot K_{\downarrow} - 0.051 \cdot U_a - 0.002 \cdot \varphi_a - 2.079$$





- 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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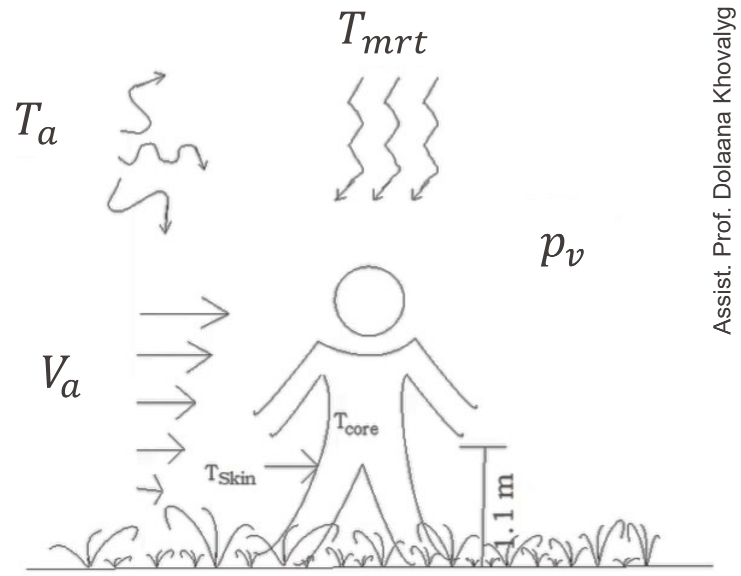
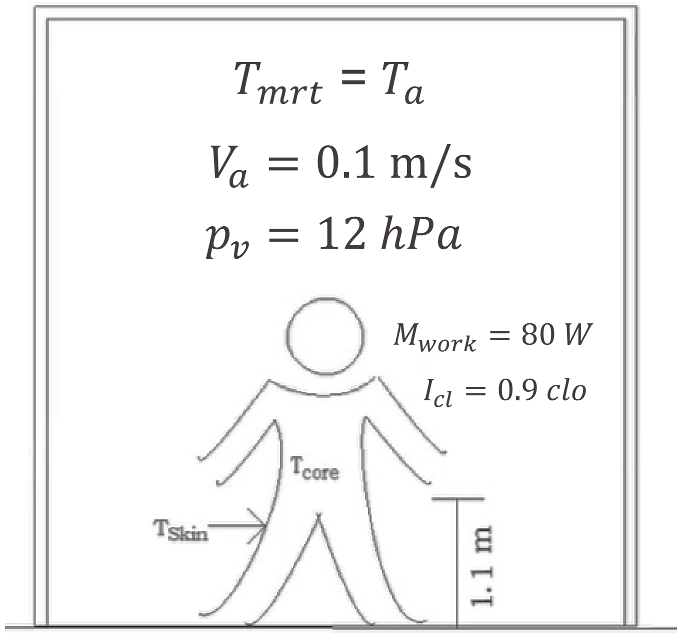
Outdoor Thermal Comfort Indices: PET

- **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: $T_{mrt} = T_a$
  - 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 $I_{cl} = \mathbf{0.9}\ clo$





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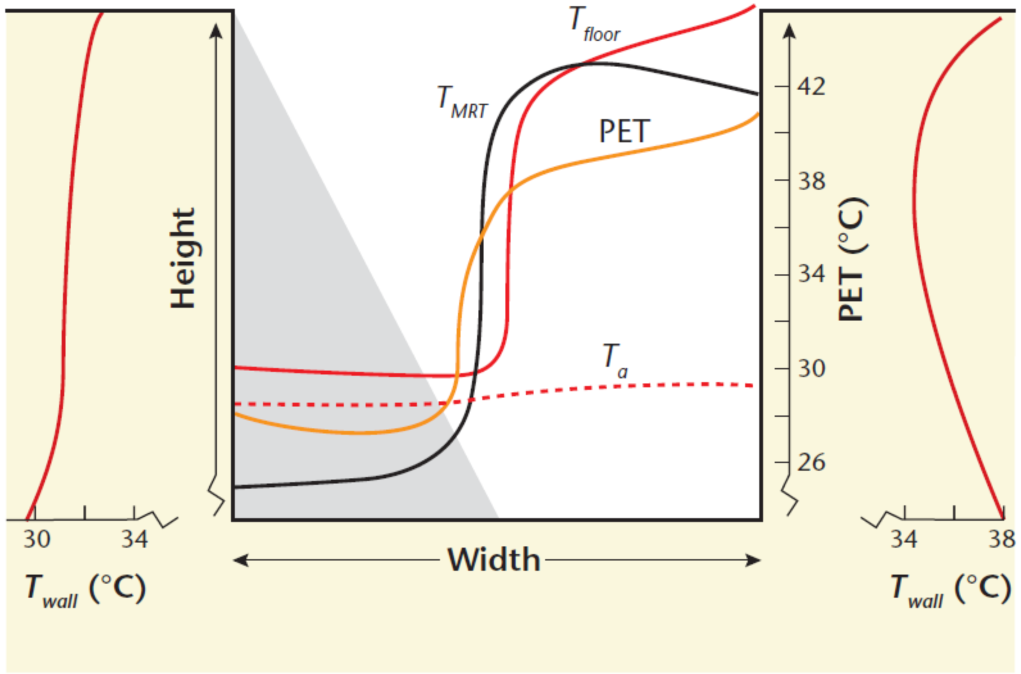
Outdoor Thermal Comfort Indices: PET

- 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.



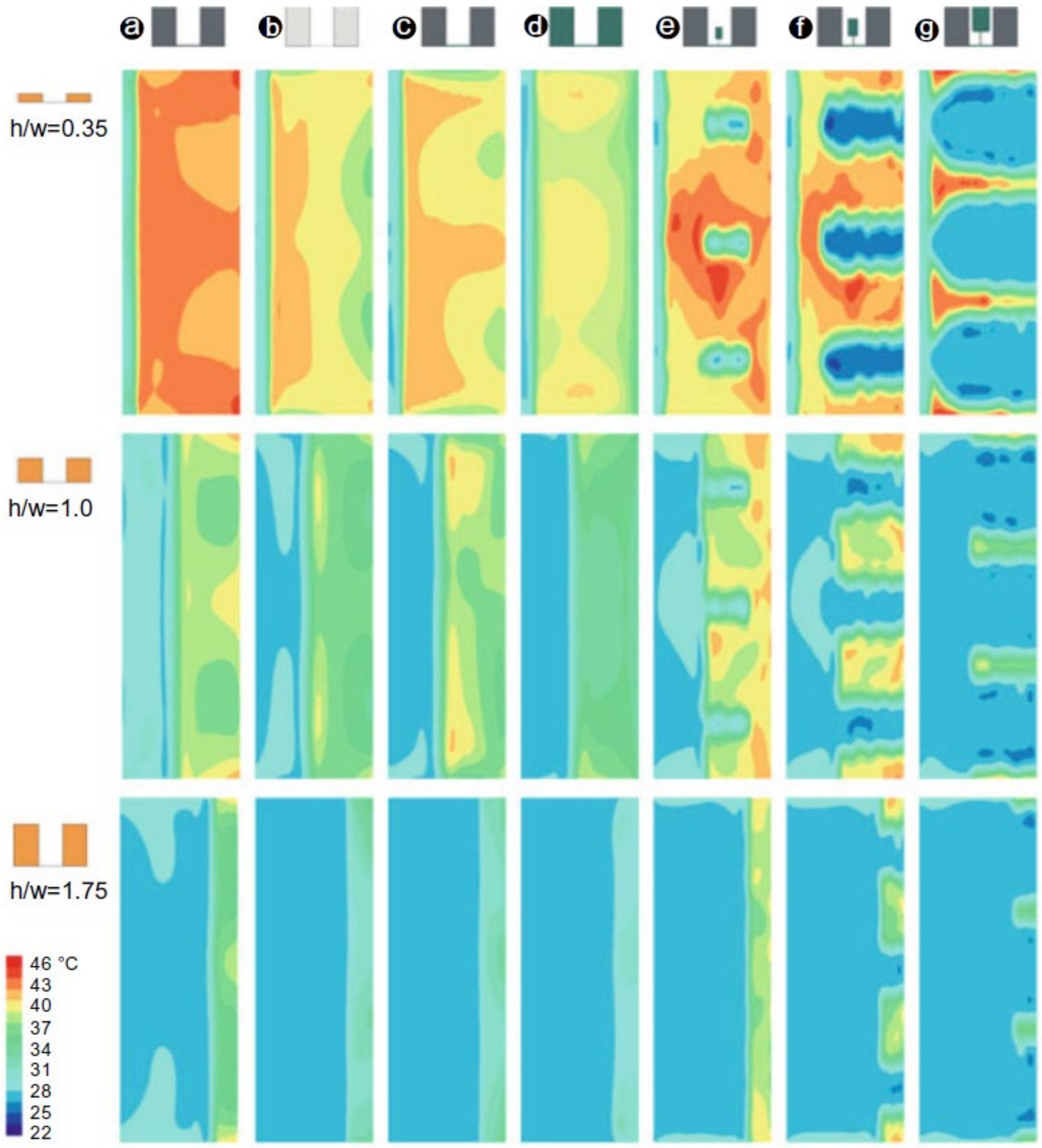
A cross-section of an urban canyon showing simulated variations in wall T_{wall} and floor T_{floor} temperatures, air temperature (T_a) and mean radiant temperature (T_{mrt}). Effect of the shade on PET is demonstrated.

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):

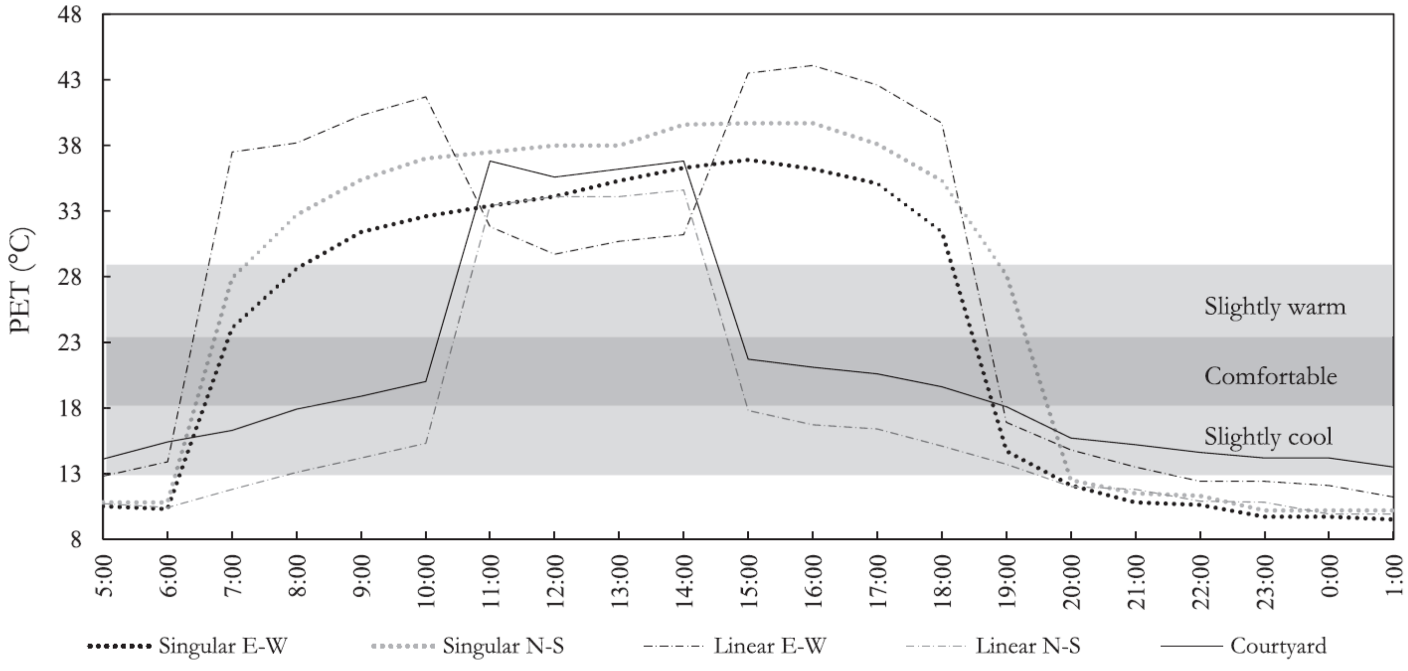
a. Dark canyon surfaces (albedo 0.3)
b. Bright canyon surfaces (albedo 0.7)
c. Dark canyon surfaces and grassy ground
d. Total vegetated surfaces (albedo 0.4)
e-f. Dark canyon with grassy ground and trees of different size planted in the middle of canyon

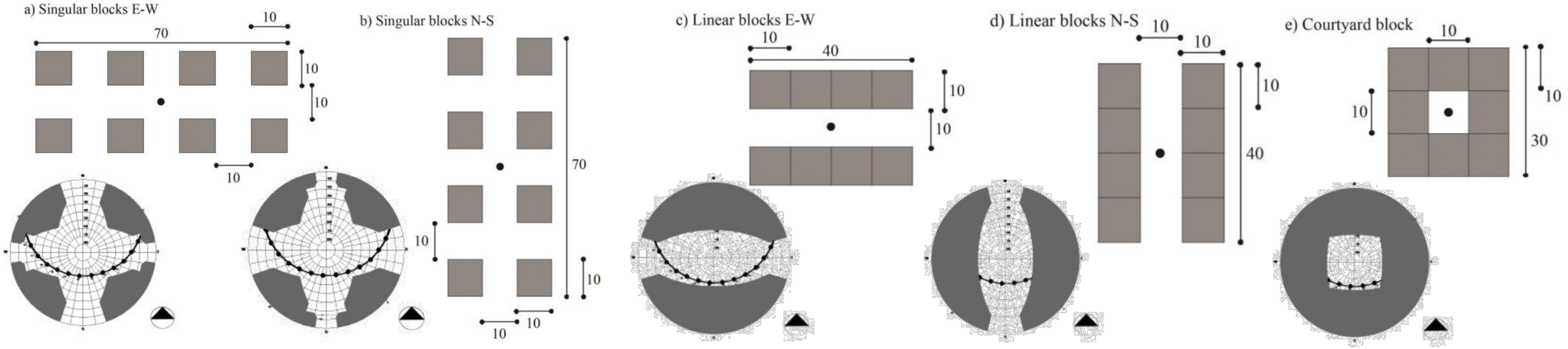


Source: Medved, Building Physics, p. 468

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

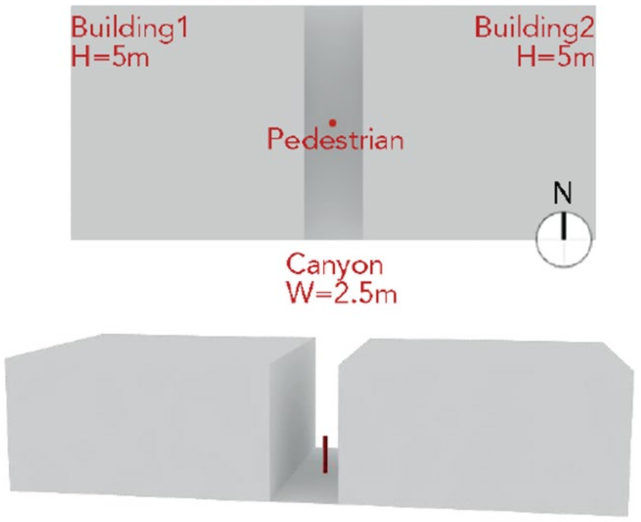
Outdoor Thermal Comfort Indices: COMFA

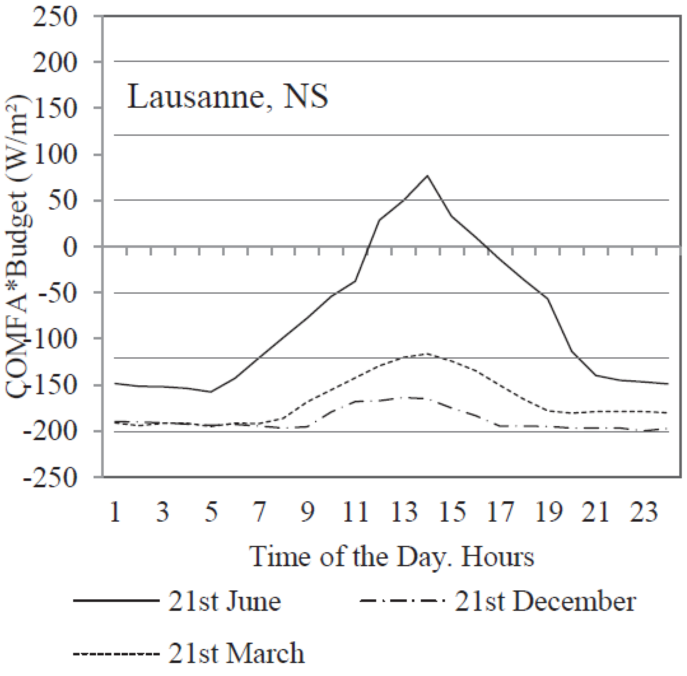
- **COMfort FormulA (COMFA) model** determines **the human energy balance B** (W/m^2) based on 4 elements (**net radiation budget**, **metabolism**, **latent** and **sensible heat flux**). Heat flux due to conduction and heat storage are ignored.

$$B = Q^* + Q_M - Q_H - Q_E \quad (9\text{-}18)$$

- 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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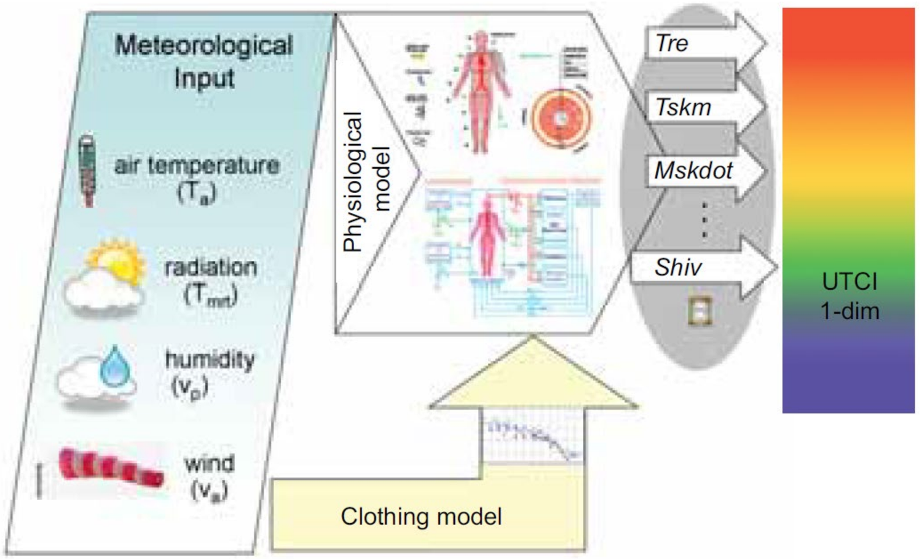
Outdoor Thermal Comfort Indices: UTCI

- **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*



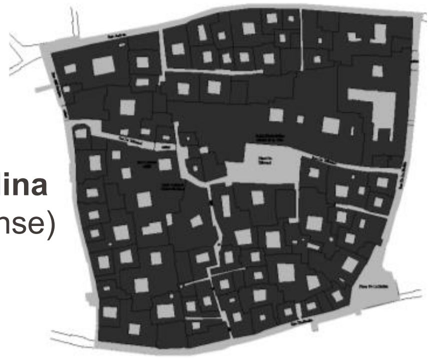
$$UTCI(T_a, T_{mrt}, U_a, p_a) = \boldsymbol{T_a} + \boldsymbol{Offset}\,(T_a, T_{mrt}, U_a, p_a) \quad (9\text{-}17)$$

UTCI (°C)	Thermal Stress category
≥ +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 $I_{cl} = \mathbf{0.9}\ clo$

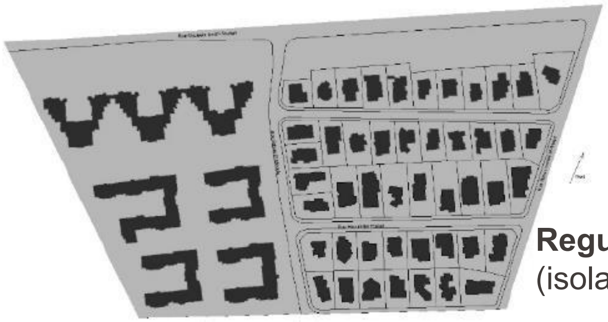
Outdoor Thermal Comfort Indices: UTCI

- **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)

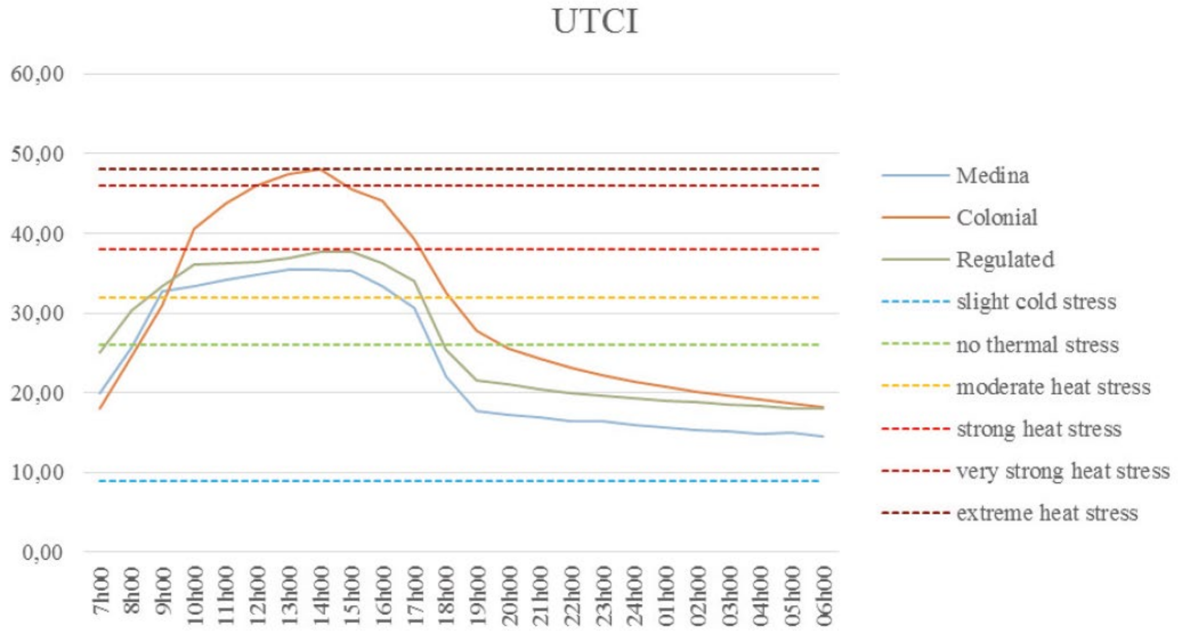
Colonial
(EU city model)



Regulated
(isolated habitats)

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

Medina		**Colonial**		**Regulated**	
Fish-eye	SVF	Fish-eye	SVF	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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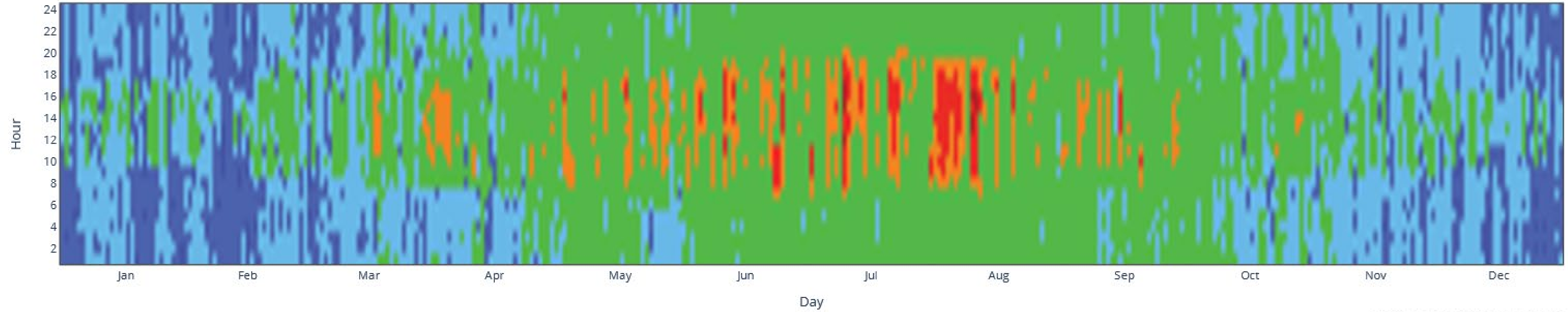
EPFL

Case study site: Outdoor thermal comfort

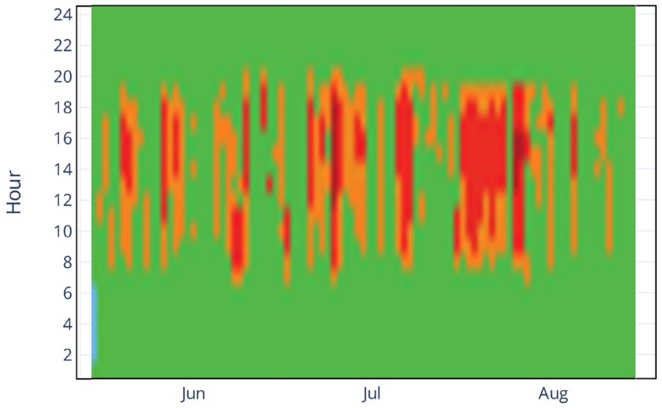
From Lecture 2

Dr Kun Lyu

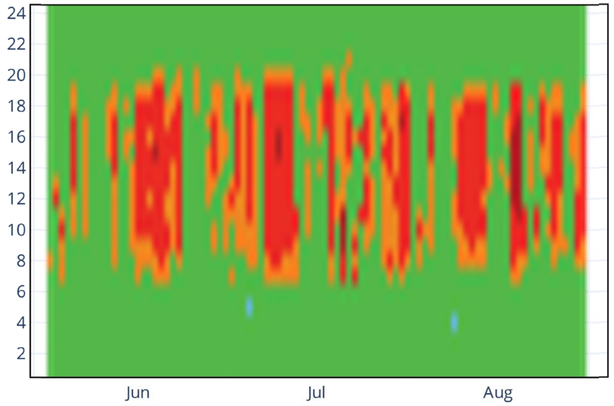
UTCI thermal stress: **sun & wind 2000-2010**



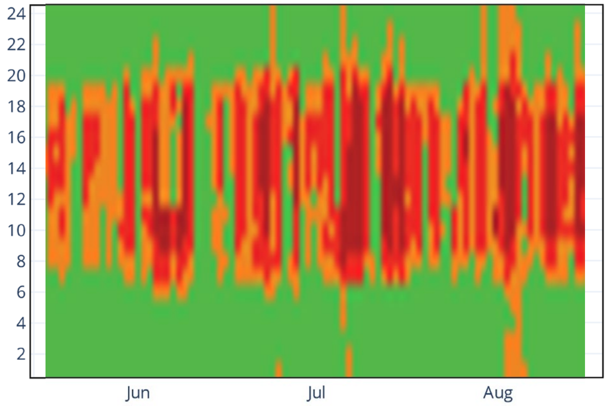
UTCI thermal stress:
2000-2010 sun & no wind



UTCI thermal stress:
2050 sun & wind



UTCI thermal stress:
2100 sun & wind



The **percentage of time** under **thermal stress** if we follow the **RCP 85** pathway:

- in **2050**: will increase by **10.6%** in June, **15.8%** in July, **20.5%** in August
- in **2100**: increase by **30.6%** in June, **42%** in July, and **57.1%** in August

Thank you for your attention!

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