EPFL

CIVIL-309: URBAN THERMODYNAMICS

Prof. Dolaana Khovalyg
Dr. Kun Lyu

Lecture 02:

Overview of physical parameters. Urban environment and urban modeling.

23 September 2024

Course Schedule

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

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

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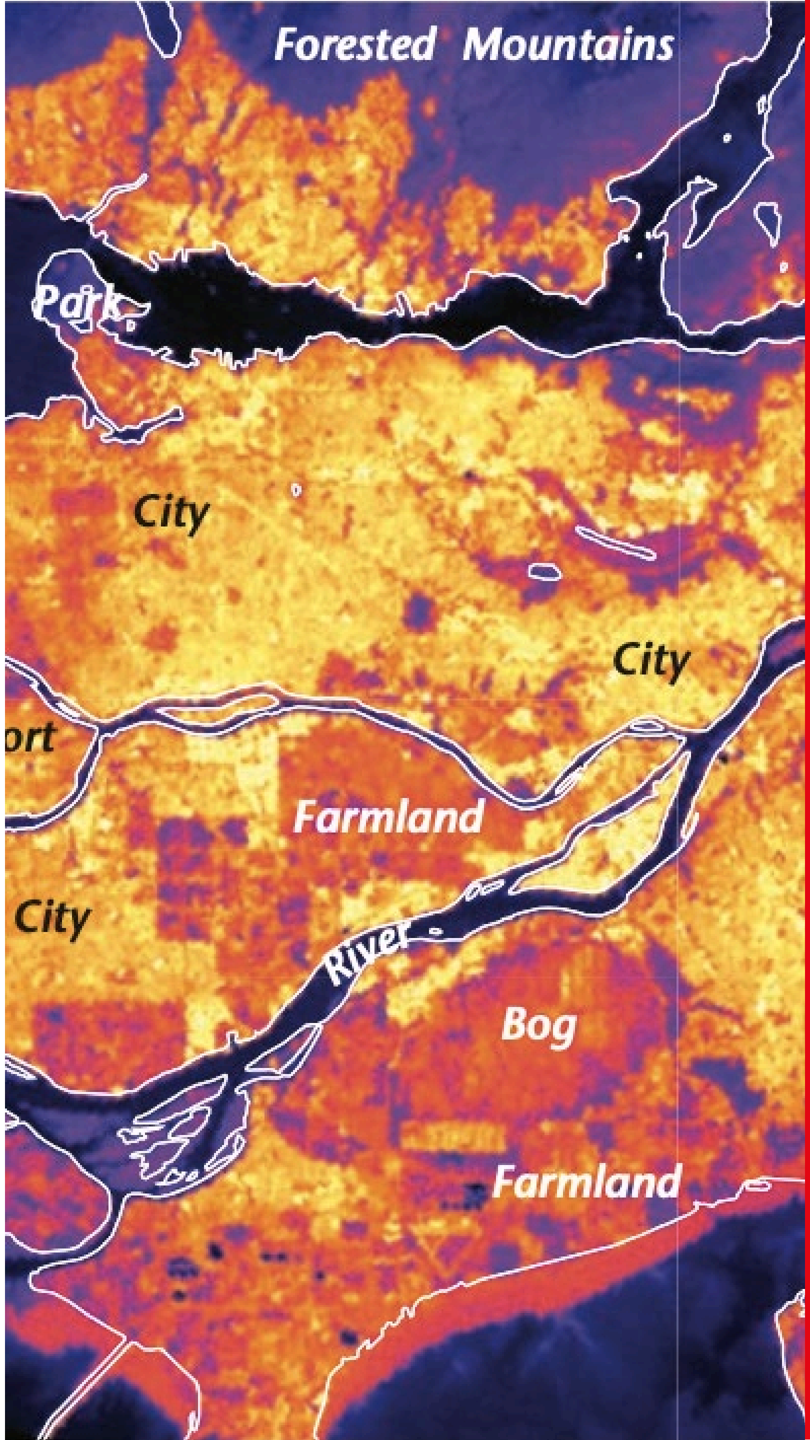

CONTENT:

I. Urban meteorology

- Structure of urban atmosphere
- Micrometeorology
- Winds speed and precipitation

II. Physical parameters

- Temperatures (air, surface, ground)
- Atmospheric pressure
- Water vapor, moist air, air humidity

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IV. Urban modelling

- Physical vs. numerical modelling, CFD
- Overview of numerical software
- Introduction to ENVI-met

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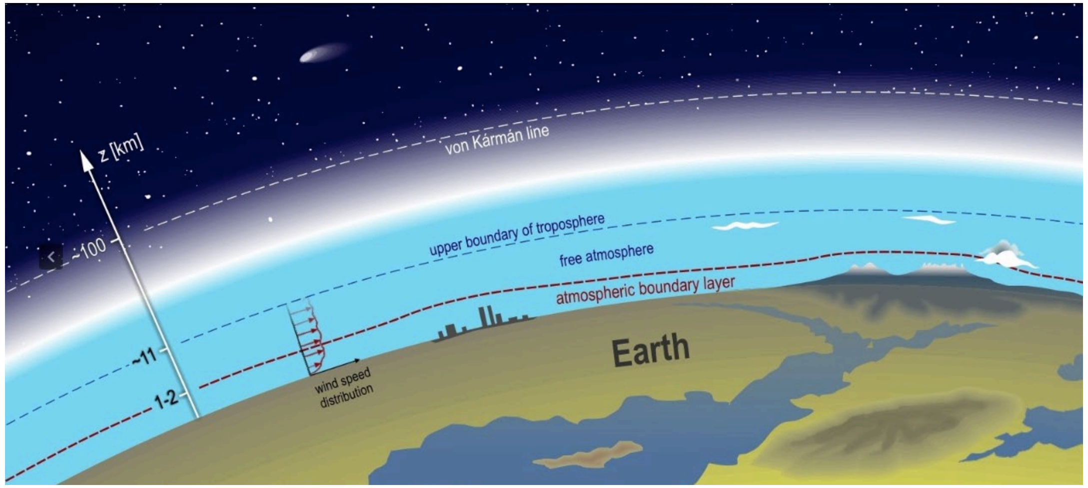
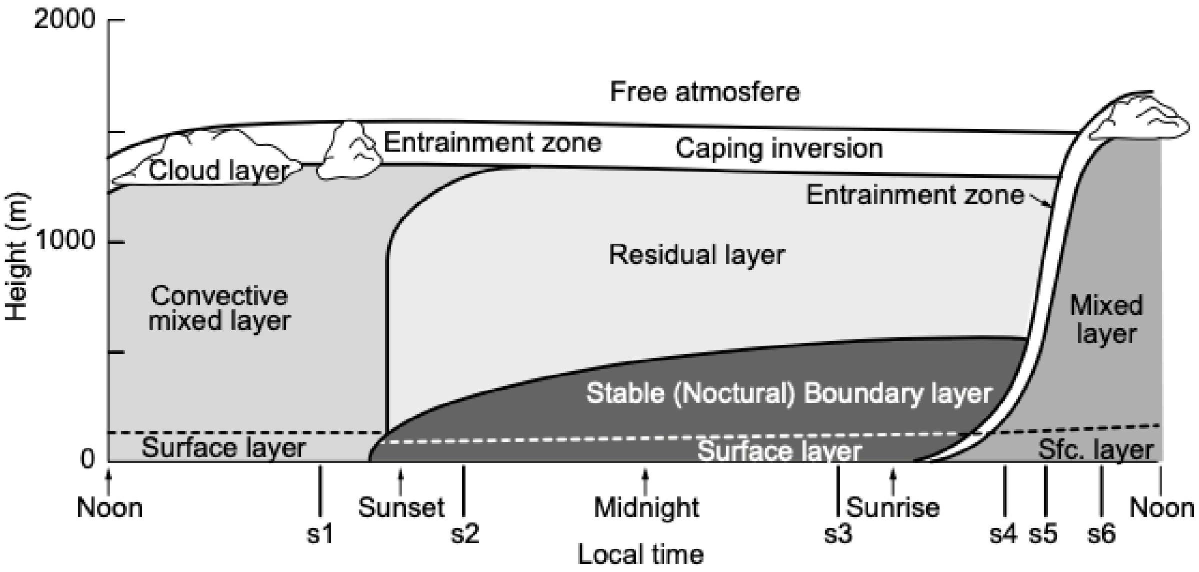
Urban atmosphere: Atmospheric boundary layer

- **Troposphere:** the lowest layer of the *atmosphere*, it constitutes 80% of its mass.
- **Atmospheric boundary layer (ABL):** lowest layer of the *troposphere*. It is directly *influenced by Earth's surface perturbations*. It stretches 1-2 km, above is the **free atmosphere**.
- The *height* and the *structure* of the **atmospheric boundary layer (ABL)** *vary* between *day and night.*
- The atmospheric boundary layer *above urban areas* is called the **urban boundary layer (UBL)**.
- The **urban boundary layer (UBL)** is *higher* than the **rural boundary layer (RBL)** because the *interactions* between the *Earth* and its *atmosphere* are *stronger.*



Source: https://bmeafl.com/the-project-proposal/



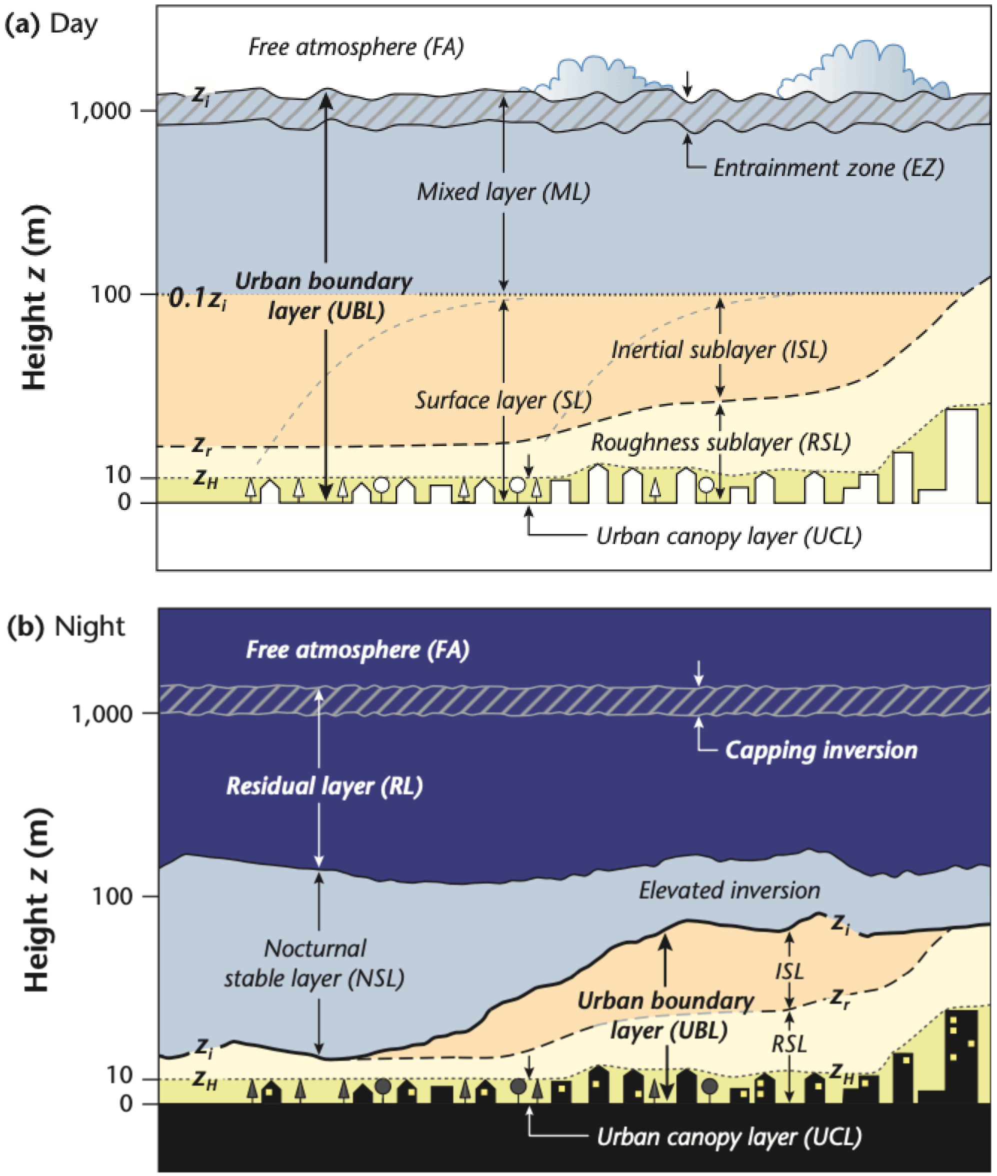
Source: Rodrigues, Fundamental Principles of Environmental Physics, p.2

Urban atmosphere: Atmospheric boundary layer

- The **urban boundary layer** is composed of *two* layers:
  - **Surface layer** (lower 10%)
  - **Mixed layer** (upper 90%)

- **Surface layer**: a layer with *heat* and *mass exchanges* between the Earth and its atmosphere. It is composed of 2 layers:
  - **Roughness sublayer (RSL) -** *lower part* affected by individuals elements, it is turbulent and 3D.
  - **Inertial sublayer (ISL) -** the *upper part* affected by assembles of individual elements, it varies mainly in the horizontal direction.

- **Mixed layer:** heat and mass exchange are *dampened* by turbulent motion; temperature, water vapor, wind speed are almost *uniform* with height



Source: Oke, Urban Climates, p.31

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Urban atmosphere: Wind speed

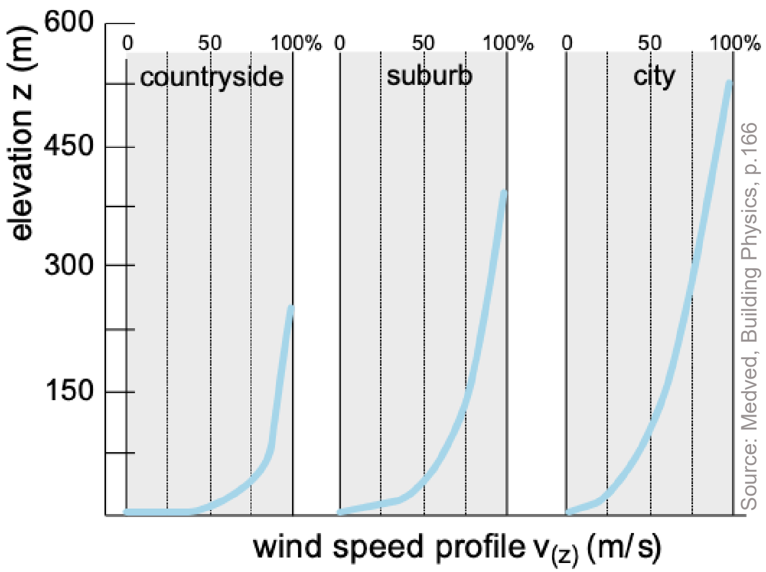
- **Wind speed at the surface** is **zero** and ***increases*** **exponentially** *with the height*:

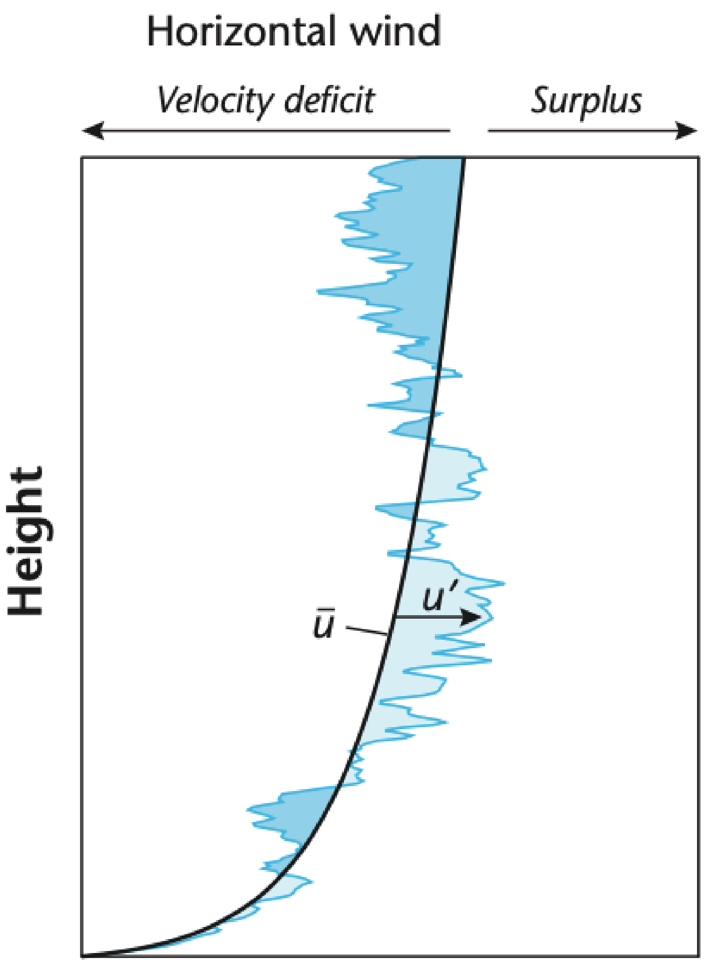
$$u(z) = \left(\frac{z}{z_r}\right)^{\alpha} \cdot u(z_r) \quad (2\text{-}1)$$

z_r - reference height
α - surface roughness coefficient or Hellmann exponent

- In urban areas, wind speeds are *lower* at *lower heights* because of the **surface roughness** effect

Surface type	Surface roughness
Water body	0.10
Meadow	0.13
Forest	0.20
Settlement	0.25
City with tall buildings	0.31





Source: Oke, Urban Climates, p.100

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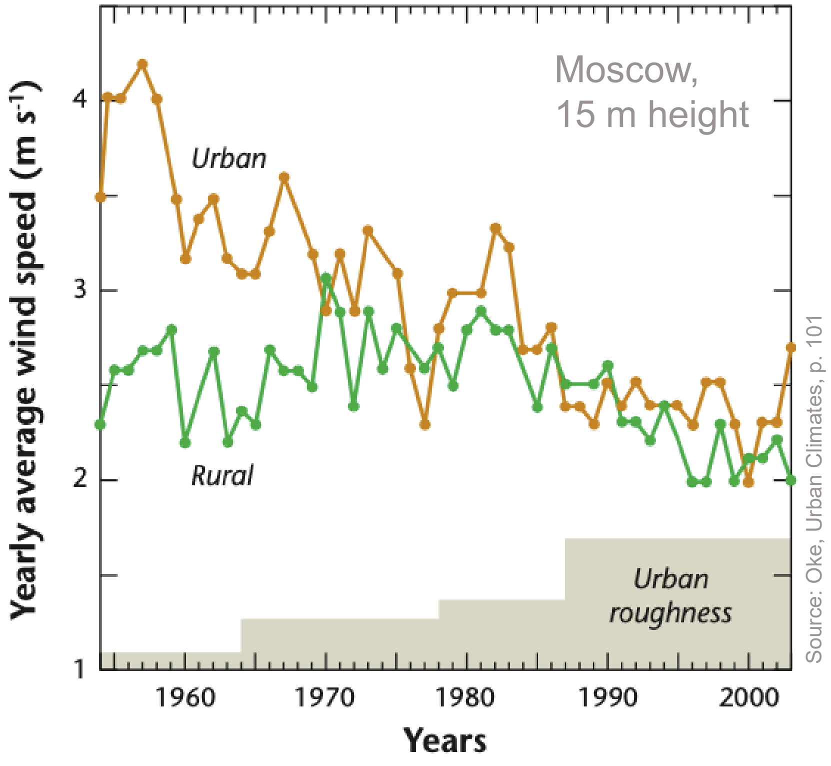
Urban atmosphere: Urban roughness

- **Urban roughness** is characterized by:
  - The **mean height of roughness elements** z_H
  - The **roughness length** z_0
  - The **Hellmann exponent** α
- **Roughness length z_0**: height at which the wind speed theoretically becomes *zero* in *the absence of wind-slowing obstacles*.
- Two approaches to estimate the *roughness parameters*:
  - **Micrometeorological approach:** in-situ measurements of wind to solve the equation of the atmospheric boundary layer profile.
  - **Morphometric approach:** computing the roughness parameters from the dimensions of the urban elements.



Source: Oke, Urban Climates, p. 103

Local climate zone type	Mean height of roughness elements z_H (m)	Roughness length z_0 (m)	Hellmann exponent α
Lawn	0.2 – 0.5	0.03 – 0.06	0.11 – 0.13
Compact low-rise	5 – 8	0.3 – 0.8	0.2 – 0.25
Compact mid-rise	7 – 14	0.7 – 1.5	0.23 – 0.27
Compact high-rise	11 – 20	0.8 – 2	0.26 – 0.29
High-rise	> 20	> 2	0.29 – 0.35

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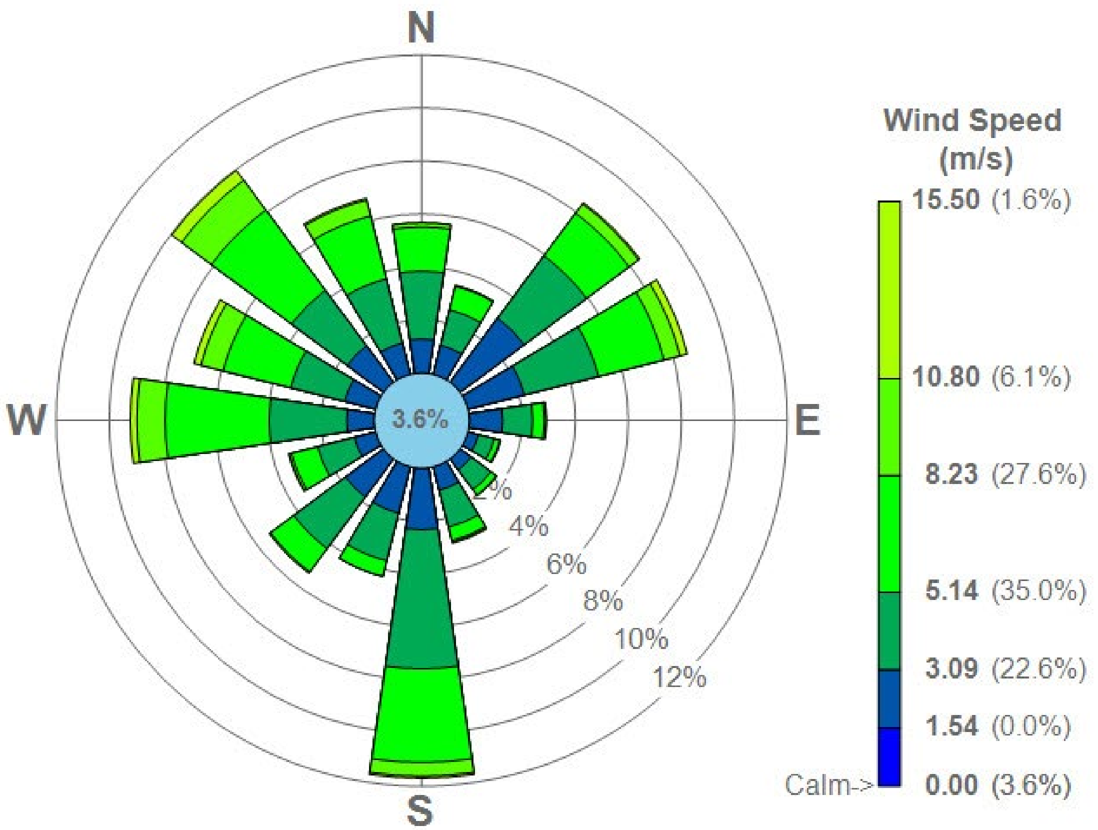
Urban meteorology: Wind speed and direction

- **Wind** is driven by a **pressure difference in the air** due **to different air density**. It describes the *movement of air.*
- **Wind speed** or **magnitude** $\bar{u}$ $\left(\frac{m}{s}\right)$ is the resultant norm of the wind components u, v, w in the main direction

$$\bar{u} = \sqrt{u(x)^2 + v(y)^2 + w(z)^2}$$

- The **wind** *above the urban canopy* is considered to be **two-dimensional**
- **Wind rose - a graphical representation of the *repartition* of the wind speeds according to the wind direction**. It gives *statistical information* on the wind direction and allows to determine the *predominant* wind speeds
  - The wind direction is typically shown between 0 and 360° (North = 0°, East = 90°, South = 180°, West = 270°)

La Guardia Airport, New York, 2008



Source: https://en.wikipedia.org/wiki/Wind_rose

Wind animation in real time:

[Weather Maps | Live Satellite & Weather Radar - meteoblue]

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Urban atmosphere: **Micrometeorology**

- **Meteorology** – **science** dealing with the **atmosphere** and **its phenomena** (varies on the *spatial*- and *time*- scale).
  - Spatial scales: *micro, meso, synoptic, global*
- **Micrometeorology** is applied at the ***local* scale.** It studies *small-scale* (< 1km) *atmospheric processes*, associated with the short-term (< 1h) *interaction* of the atmosphere and the Earth's surface.
- **Micrometeorology considers:**
  - *Turbulence phenomena* present at space scales of a few meters
  - *Surface transport* and *energy exchange*
  - *Heat* and *humidity* at the ground layer of the atmosphere

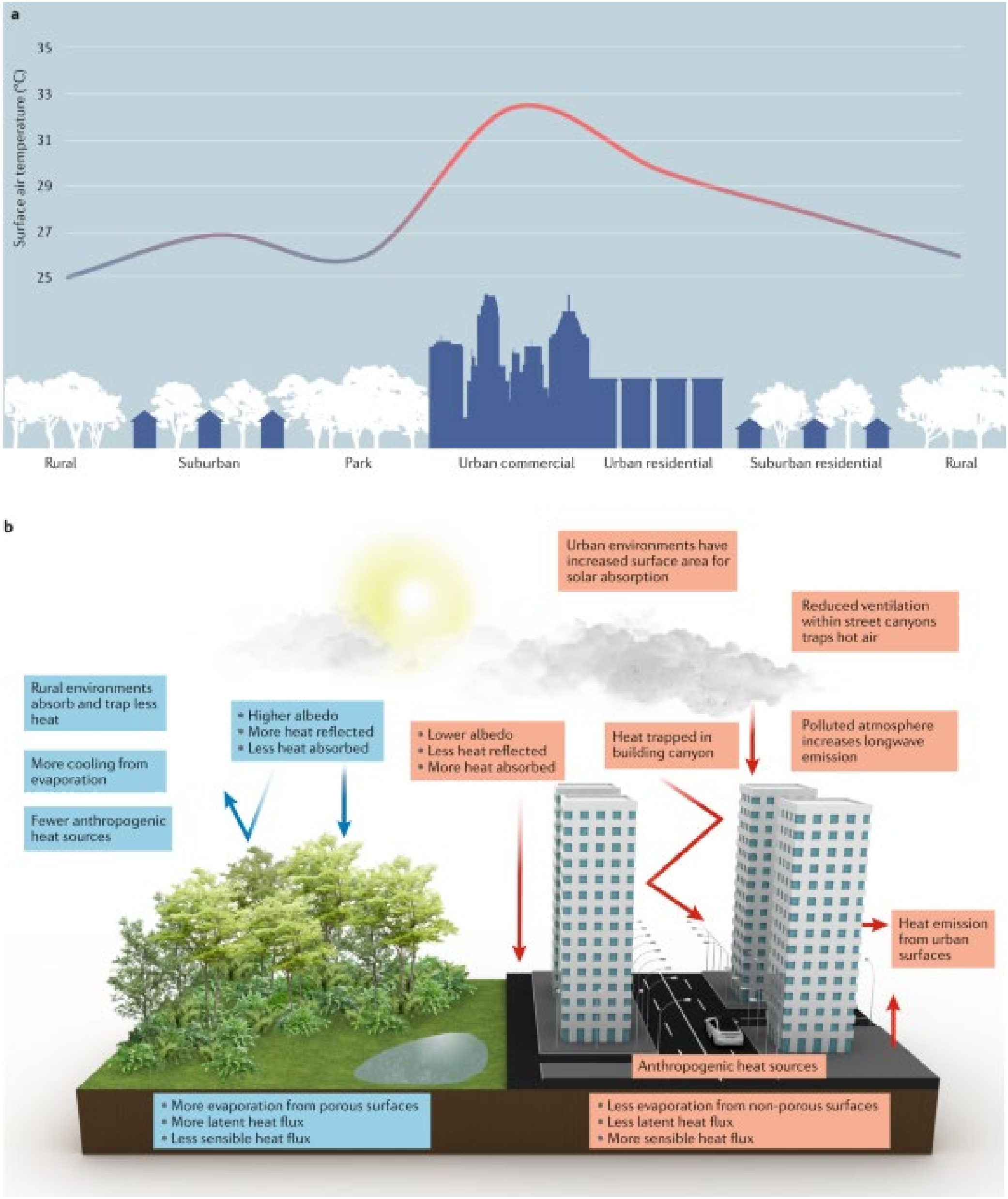
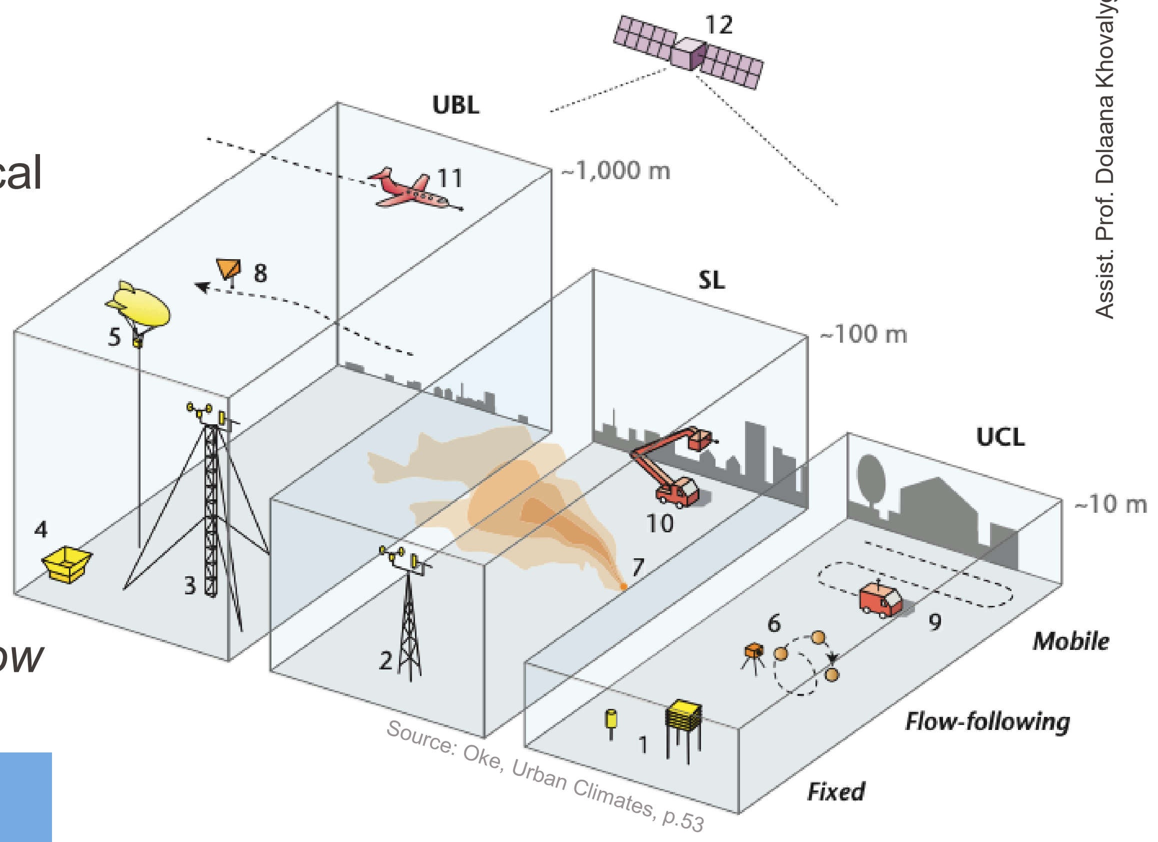


Image from: https://www.nature.com/articles/s43017-020-00129-5

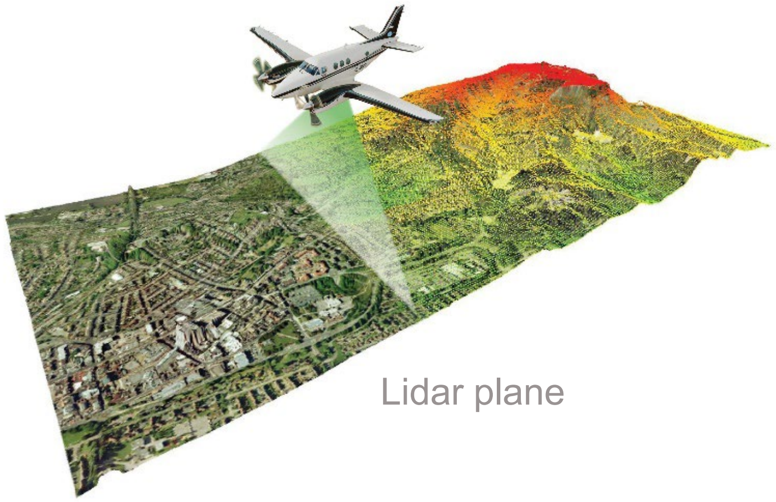
Urban meteorology: Measurements

- Two types of measurements:
  - **Long-term routine** urban meteorological information (e.g., weather forecast)
  - **Field campaigns** (e.g., to answer specific research questions)
- They can use sensors that are used
  - **In situ**
  - Remotely (**remote** sensors)
- … and that can be *fixed, mobile* or *following the flow*



Ground-based, aerial and remote-sensing platforms

1. Stevenson screen
2. Meteorological tower
3. Tall tower
4. Ground-base sensing platform
5. Tehered ballon with intrusments winched up and down
6. Small-scaled ballon traced by camera
7. Tracer release experiment
8. Tetroon ballon
9. Vehicle
10. Mobile crane platform
11. Helicopter, airplane and drone
12. Satellite remote-sensing



Lidar plane

Portative weather station

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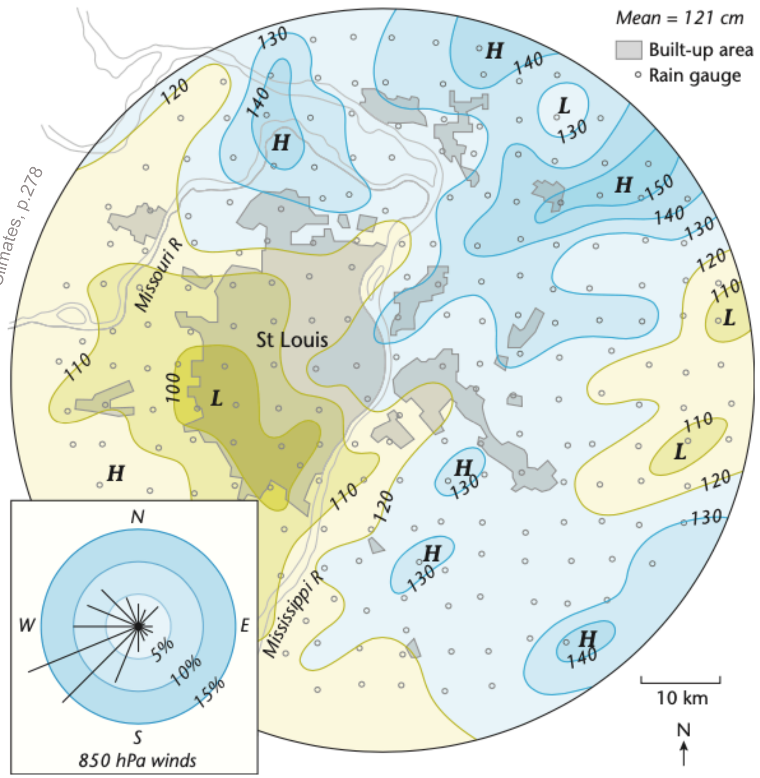
Urban meteorology: Precipitation

- **Precipitation**: **amount of rainfall on the ground** whether in the form of **water drops**, **snow flakes**, or **droplets of mists**
- It is expressed in *water depth*, *snow water* or *equivalent of snow thickness* **in mm**
- Precipitation is characterized by its **intensity** and its **occurrence**.
- **Precipitation intensity** is expressed in $\frac{mm}{h}$
- Precipitation is *higher* in *some* urban areas because cloud condensation is *stimulated* by the presence of air pollutants, the urban boundary layer structure and the presence of the urban heat island.



Source: Oke, Urban Climates, p.278

Characterization of the rain	Intensity of precipitation ($\frac{mm}{h}$)
Very weak	< 0.25
Weak	0.25 – 1.0
Moderate	1.0 – 4.0
Heavy	4.0 – 16.0
Very heavy	16.0 – 50.0
Extreme	> 50.0

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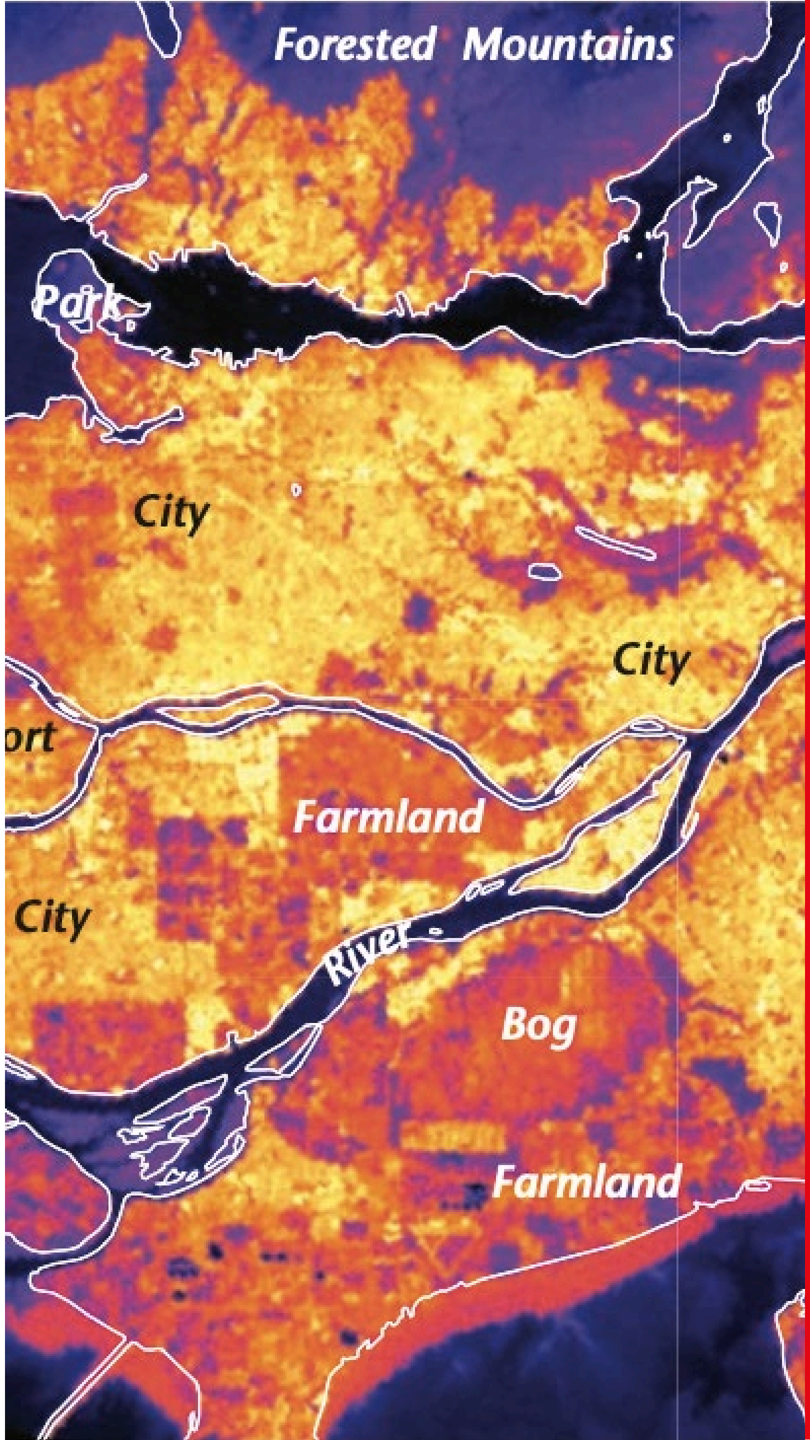

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Overview of temperatures: Definitions

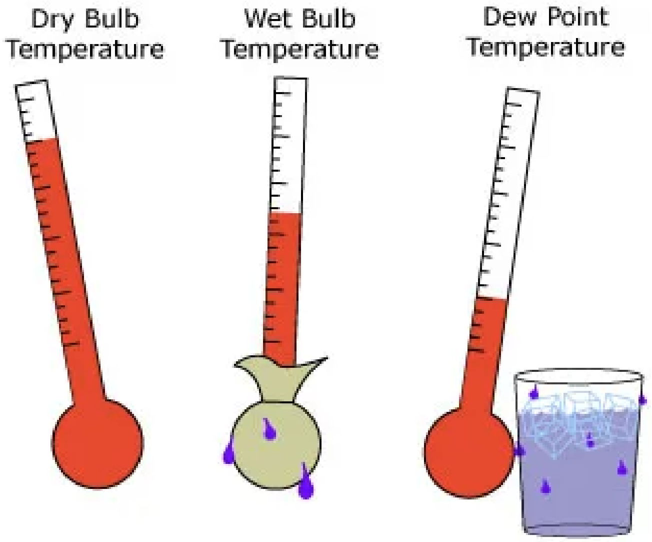
- **Dry bulb temperature T_{db}** (K or °C): the **air property** that is most commonly used.

  By referring to "**air temperature**", we normally refer to **dry bulb temperature** affected by the *moisture* present in the air.

- **Dewpoint temperature T_d** (K or °C): the temperature the air needs *to be cooled* to (at constant pressure) in order to achieve *a relative humidity* of 100%.

- **Wet bulb temperature T_{wb}** (K or °C): the *lowest* temperature that can be reached under given ambient conditions *by the evaporation of water only*.

  Theoretical limit to human survival for more than a few hours is a wet-bulb temperature of 35°C.

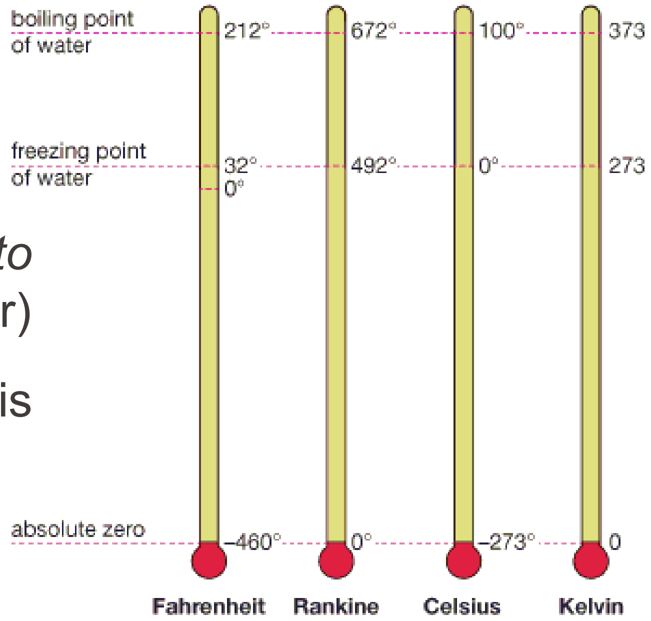


- **Temperature scales:** measurement of temperature *relative to* easily reproducible states (e.g., *freezing* and *boiling* points of water)

- **Kelvin scale** – *thermodynamic (absolute) temperature scale* that is independent of properties of any substance or substances

$$0°C = 273.15\ K$$

* Important to pay attention when the absolute temperature in [K] is used



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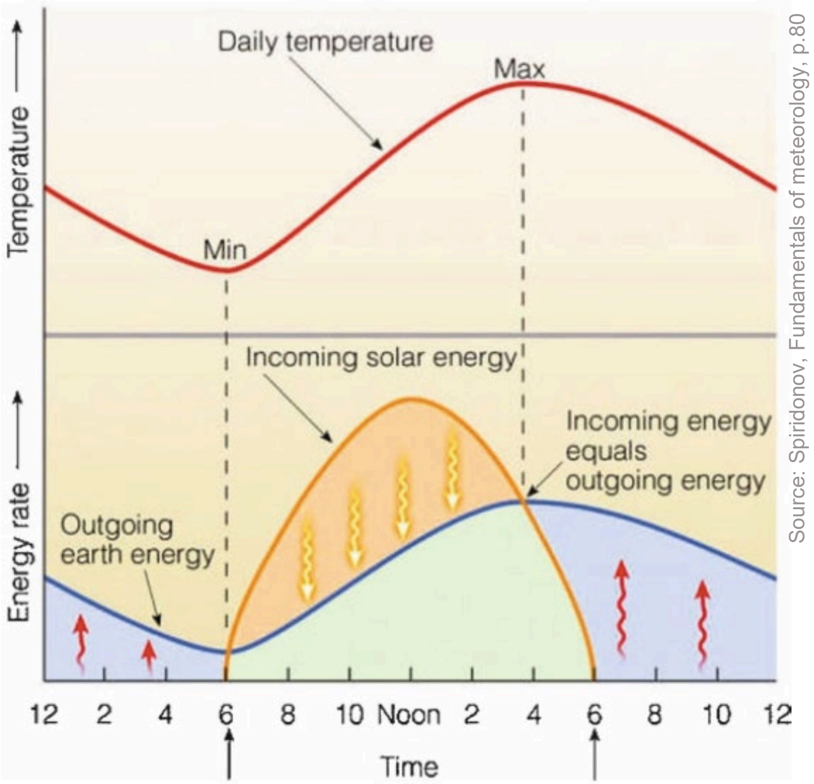
Air temperature

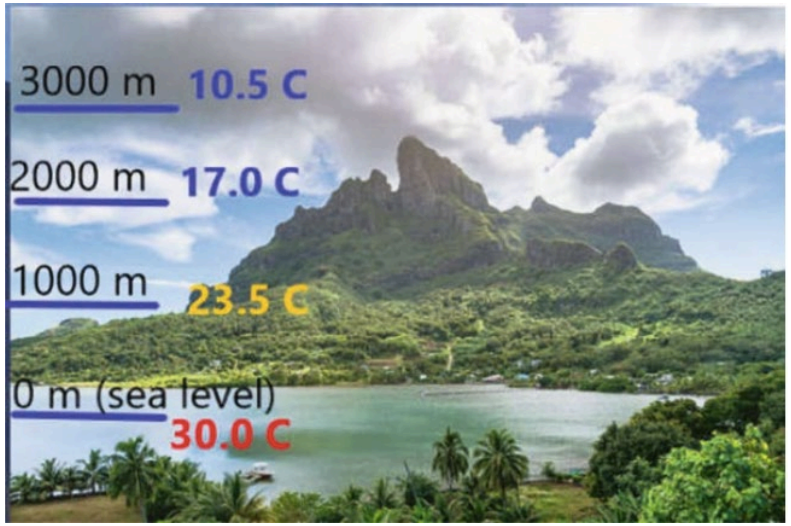
- **Air temperature $T_a = T_{db}$** (K or °C): **measure** of the **atmospheric heat content** as **a response** to ***combined effects of:***
  - *absorbed solar radiation* by the Earth's surfaces,
  - the *vertical fluxes* of *sensible* and *latent heat* released to the air due to convection
  - *horizontal advection* (movement) of *warm* and *cold air* masses

- As **air** temperature above ground is *highly affected* by *solar radiation*, it follows a **daily** and **seasonal variation**:
  - *Minimum daily temperature*: usually happens early morning, shortly after sunrise
  - *Maximum daily temperature*: 2-4 hours after the solar noon (with some delay compared to the maximum of solar radiation)

- Air temperature is *higher* closer to the surface and *decreases* with height. The *distribution of temperature along the height* varies locally with the local climate and topography.



Source: Spiridonov, Fundamentals of meteorology, p.80



Spiridonov, Fundamentals of meteorology, p.81

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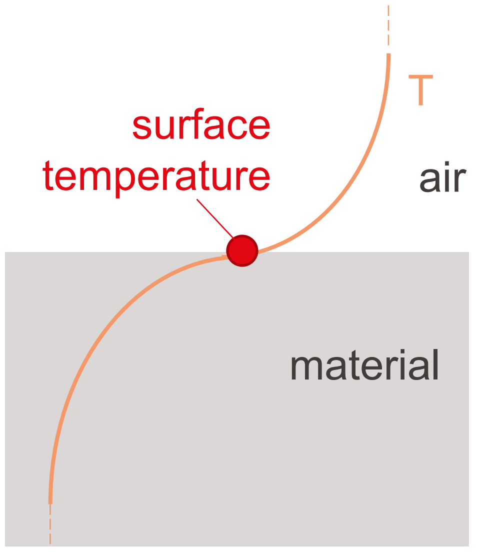
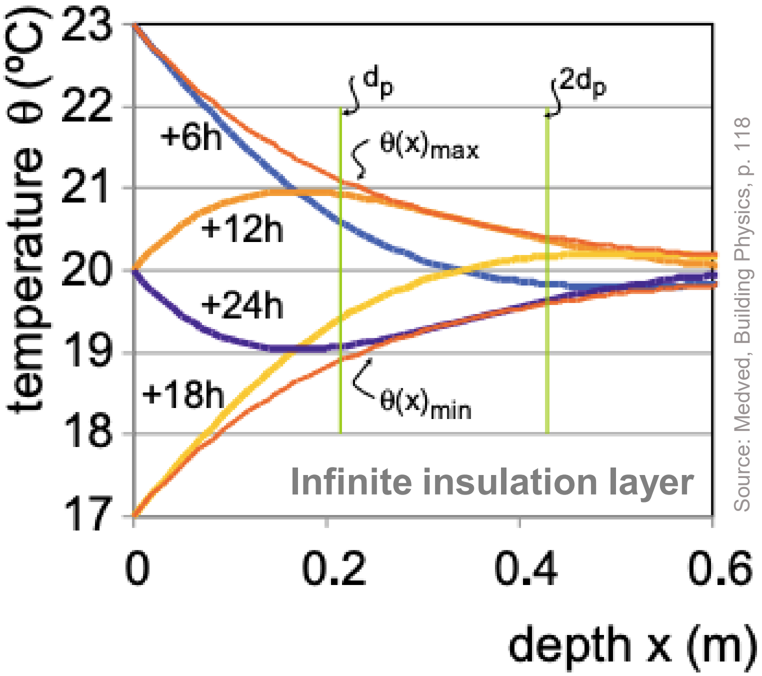
Surface temperature

- **Surface temperature T_s** (K or °C): **temperature** of a **material** (artificial matter) **at its outer limit**, at its surface *in contact* with another solid, liquid or gas.
    - Surface temperature is determined with **the surface energy balance**
    - It depends of the **temperature** of *materials in contact* and the *solar radiation* reaching the surface.
    - It follows a *daily* and *seasonal* variation delayed with respect to the *variation of solar variation*.
- **Dynamics of surface temperature:**
    - **Maximum surface temperature** is reached *1-2 hours after maximum solar radiation* and **minimum temperature - *1-2 hours before the first direct sunlight***.
    - The **amplitude of the variation** depends on the *material's properties.*
    - **Temperature** on *both sides of the surface* **varies exponentially.** Air temperature could have 20 K difference over 1 mm next to a heated surface.

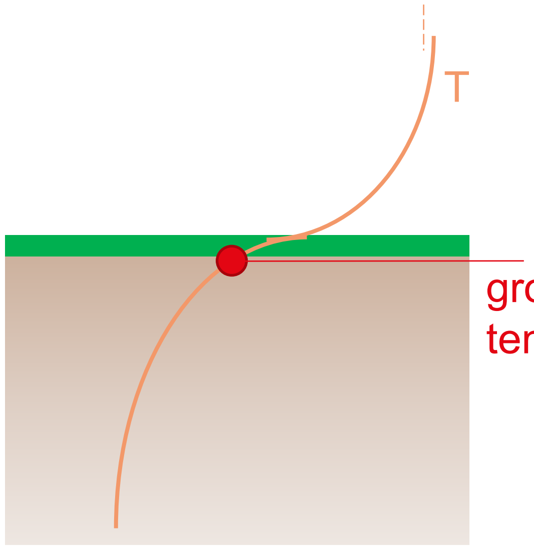


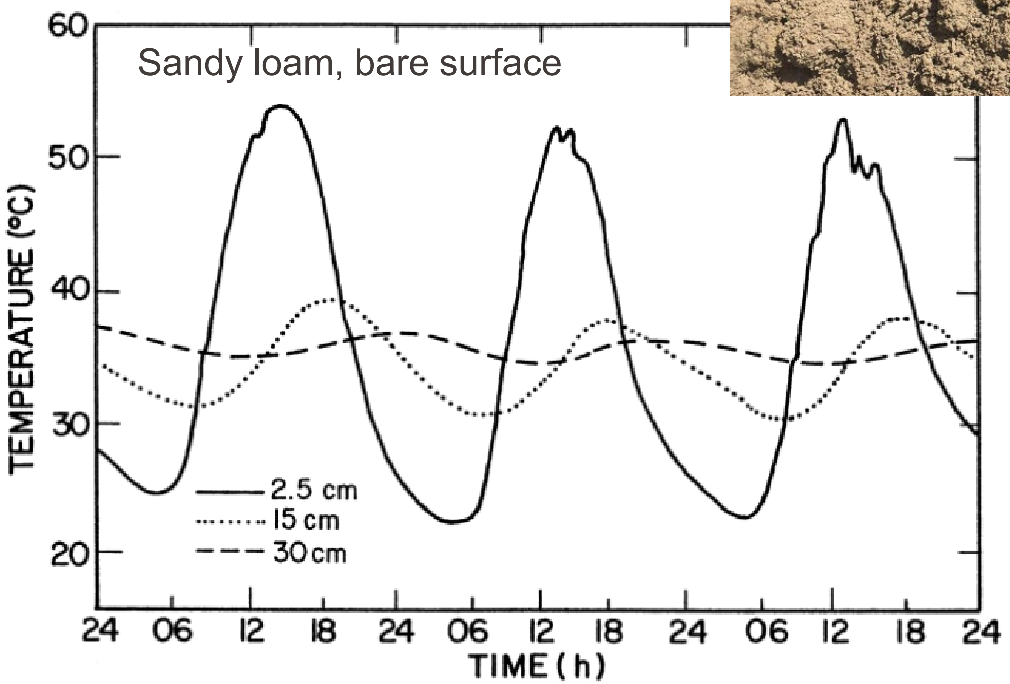


Source: Medved, Building Physics, p. 118

Ground temperature

- **Ground temperature next to the surface** is *affected by the physical processes* of the **upper environment**
- Major difference **between ground** and **other material** temperature: only the *outer surface temperature changes* while the *bottom temperature remains constant* after a certain depth (the thickness of ground is considered infinite)
  - Ground temperature next to the surface *varies daily* and *with season* with *time lag* depend on *solar radiation* and *air temperature*
  - The **ground thermal properties** and **deep temperature** depend on *soil composition* and *structure*

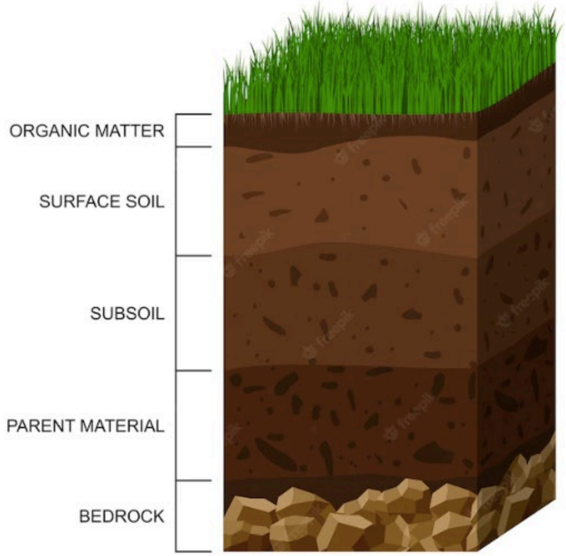




Source: Arya, Introduction to micrometeorology, p. 48

Ground vs. Soil

- **Ground** is the **surface of the Earth**. Ground is used indifferently to describes the *surface* and the *volume* of matter below it (i.e. soil).
- **Soil** is **a mixture of organic matter**, **minerals**, **gases**, **liquids** and **organisms**. Soil is *a three-state system* composed of solids, liquids and gases. It is usually *structured into layers* of different composition.
- Ground surfaces can be:
  - **Artificial**: pavement
  - **Natural**: bare soil or soil with vegetation



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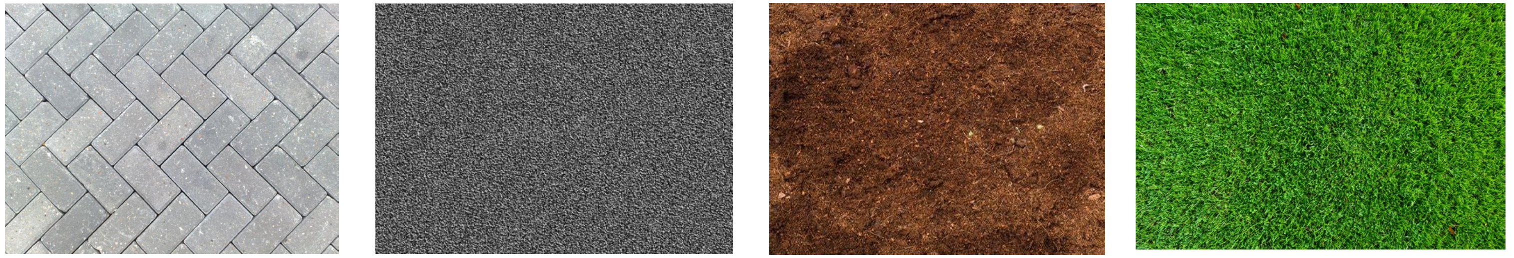

Soil

Ground

Picture from: web link

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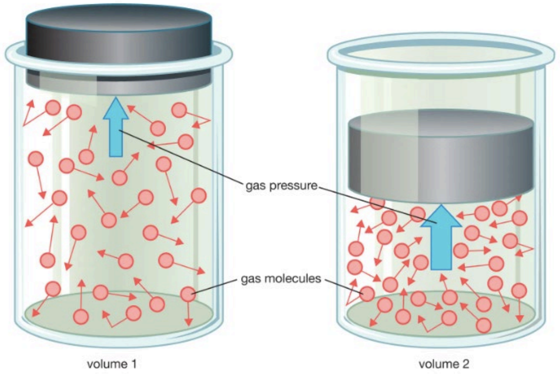
Atmospheric pressure

- **Atmospheric pressure** p_a $(Pa = \frac{N}{m^2})$: **weight** *exerted by* **the overhead atmosphere** on **a unit area of surface**

$$p_a = \frac{V_a \cdot \rho_a \cdot g}{A} \quad (2\text{-}2)$$

$$1\ bar = 10^5\ Pa \quad (2\text{-}3)$$

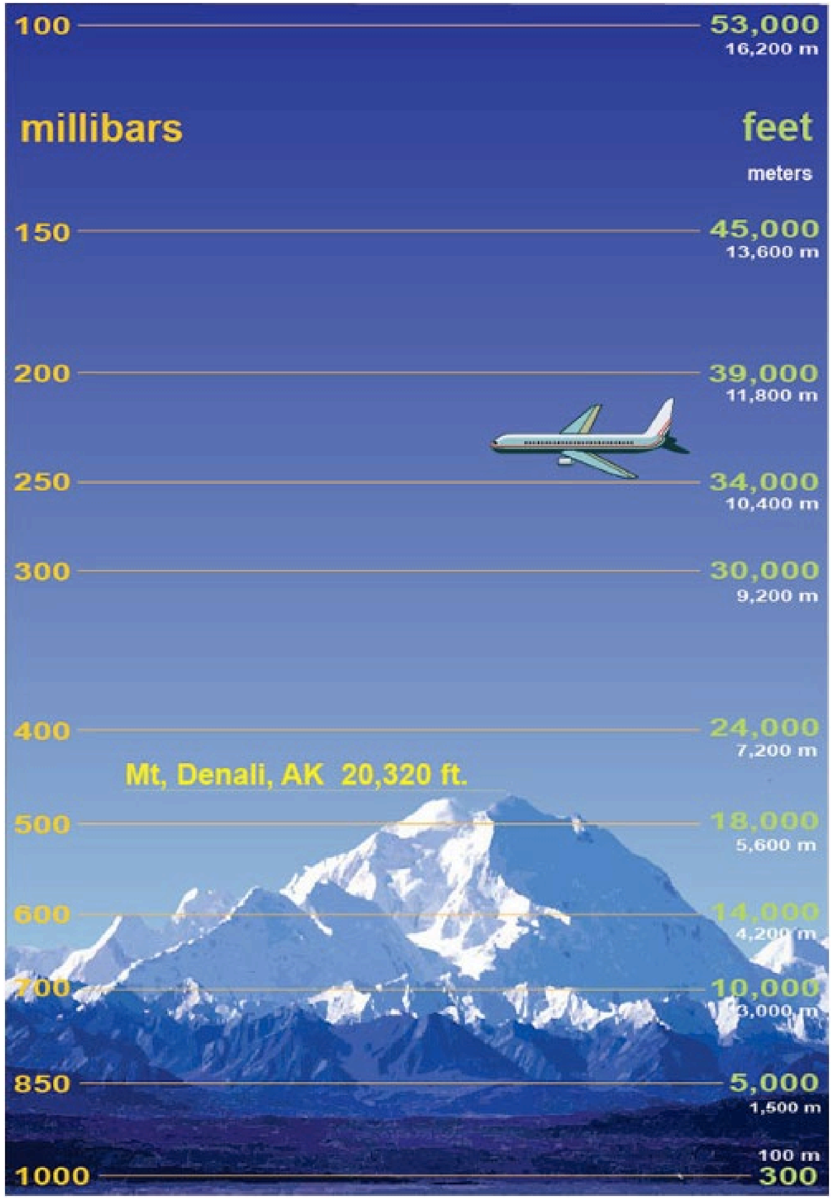


Source: https://www.britannica.com/science/pressure

- Air pressure decreases with the altitude (around $10\ \frac{Pa}{m}$)
- Pressure is exerted *equally in all directions*
- Air (dry) pressure is related to air density and temperature through **the Ideal Gas Law:**

$$p_a \cdot V_a = n \cdot R \cdot T \quad (2\text{-}4a) \longrightarrow p_a = \rho_a \cdot R_a \cdot T \quad (2\text{-}4b)$$

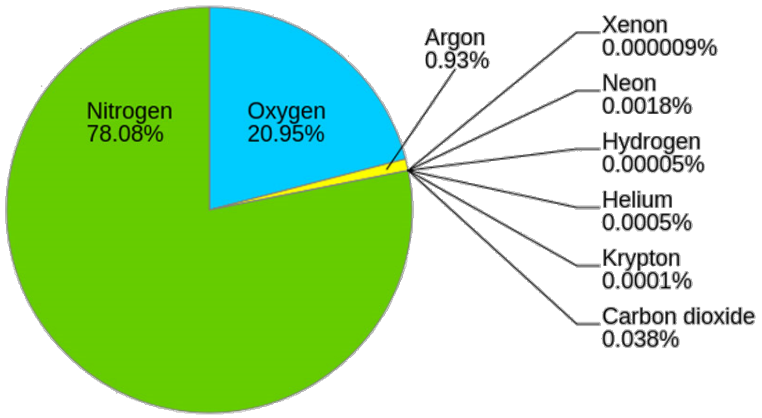
R_a - *specific gas constant* for dry air $(287.04\ \frac{J}{kg \cdot K})$



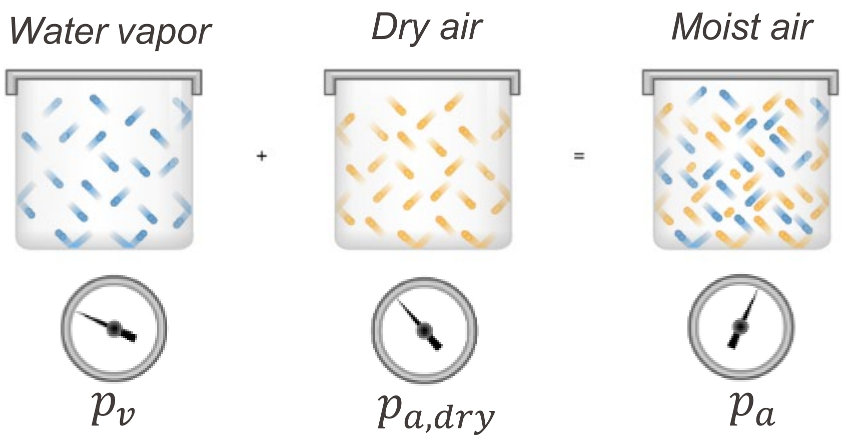
Source: https://www.weather.gov/jetstream/pressure

Water vapor

- **Standard air** or **barometric pressure** p_a 1013 mbar (=101.3 kPa) is defined *at sea level*
- Air is a mixture of gases, predominantly N_2, O_2, Ar, and CO_2. Important to consider that air *always* contains **water vapor**
- **Humidity** or **moisture** – the amount of **water vapor** *present* in the air



- **Partial pressure of water vapor** p_v (Pa): the pressure that would be exerted *by water vapor* if it occupied the same volume as the moist air on its own
  - **Partial pressure of water vapor** in the air p_v is between 0.1-12 kPa, depending on air temperature and humidity



- Moist air behaves according to **the Dalton's law** – the *total air pressure* p_a is equal to *the sum of the partial pressure* p_i of the i-th gas present in the air (i.e., $p_{a,dry}$), and *the partial pressure of water vapor* p_v.

$$p_a = \sum_i p_i + p_v = p_{a,dry} + p_v \qquad (2\text{-}5)$$

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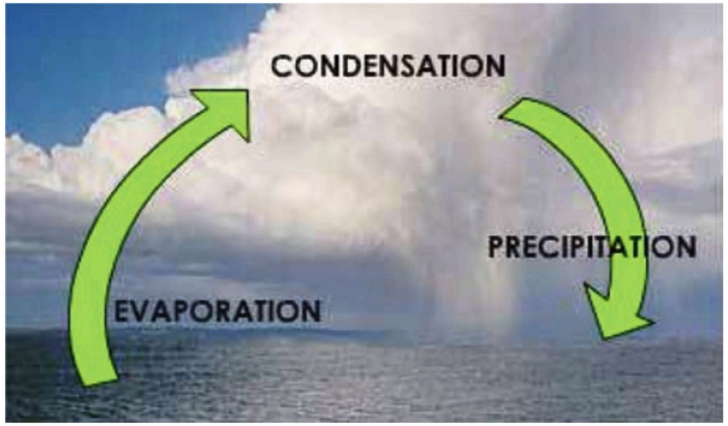
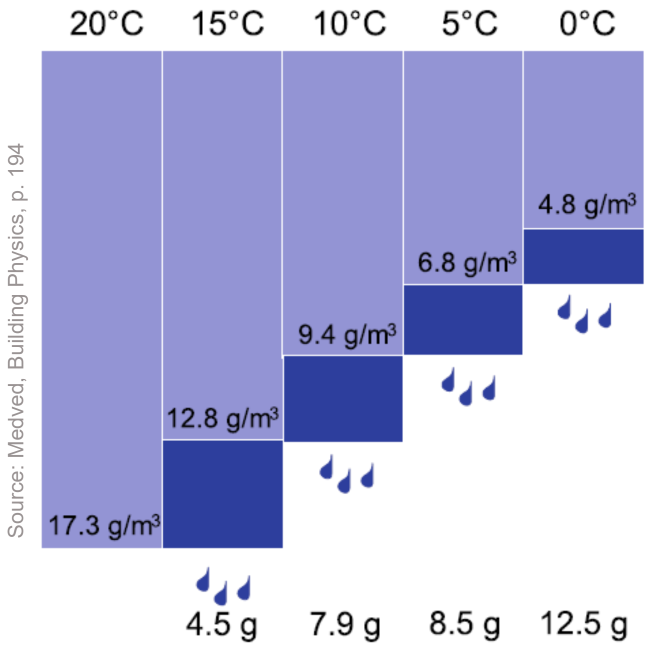
Moist air

- **Source of humidity:** evaporation process from surfaces:
  - An <u>increase</u> in moisture caused by **evaporation**
  - A <u>decrease</u> in moisture caused by **condensation**
- Depending on the *moisture ratio* between the air and the surface and their respective *temperatures*, **evaporation** or **condensation** happens
- Air is **saturated with water vapor** when *another water input* would lead to *condensation*
- A state of **saturation** is achieved *by moistening the air* (by evaporation from the water surfaces, by spraying the water droplets) or by cooling it to the saturation temperature (= dew point temperature T_{dew})
- **The water content** in the air is highly ***dependent on air temperature.*** Hot air can hold more water-vapor molecules than cold air due to the increase in **water-vapor saturation pressure $p_{v,sat}$** with **an increasing air temperature**

Source: Spiridonov, Fundamentals of meteorology, p. 133





Quantity of liquid water condensing from 1m³ of saturated air as the air is cooled from 20°C to lower dew point temperature

Psychrometric Properties: Moist Air

- **Water vapor saturation pressure $p_{v,sat}$ (Pa)** – the **pressure** at which **water vapour** is ***in thermodynamic equilibrium* with its *condensed state***.
  - At higher pressures ($p > p_{v,sat}$), water *condenses*
  - At lower pressures ($p < p_{v,sat}$), water *evaporates*
  - Relationship between $p_{v,sat}$ and T is approximated by *the Clausius-Clapeyron eqn*:

(2-6) $$p_{v,sat} \approx p_o \cdot e^{\frac{L}{R_v}\cdot\left(\frac{1}{T_0}-\frac{1}{T}\right)}$$

R_v - water-vapor gas constant (461 $J/K \cdot kg$), T_o =273.15 K, p_o = 611 Pa, L – latent heat (2.5 $\cdot 10^6$ J/kg for vaporization, and 2.83 $\cdot 10^6$ J/kg for sublimation)

  - Simplified $p_{v,sat}$ (Pa) formulas (t - air temperature in °C):

For t > 0°C:

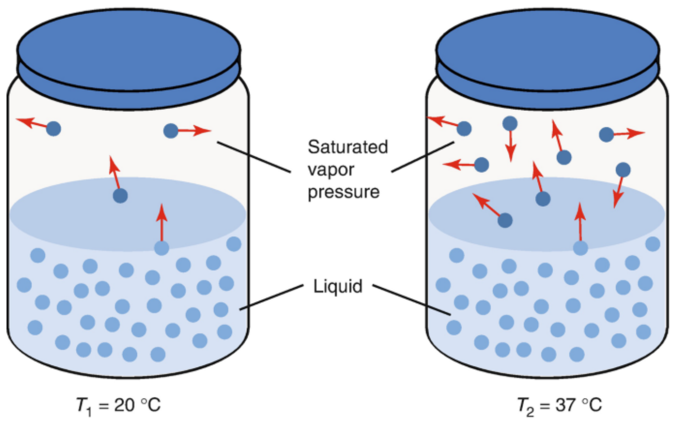
$$p_{v,sat} = 611 \cdot e^{\frac{17.08 \cdot t}{234.18+t}}$$ (2-6a)

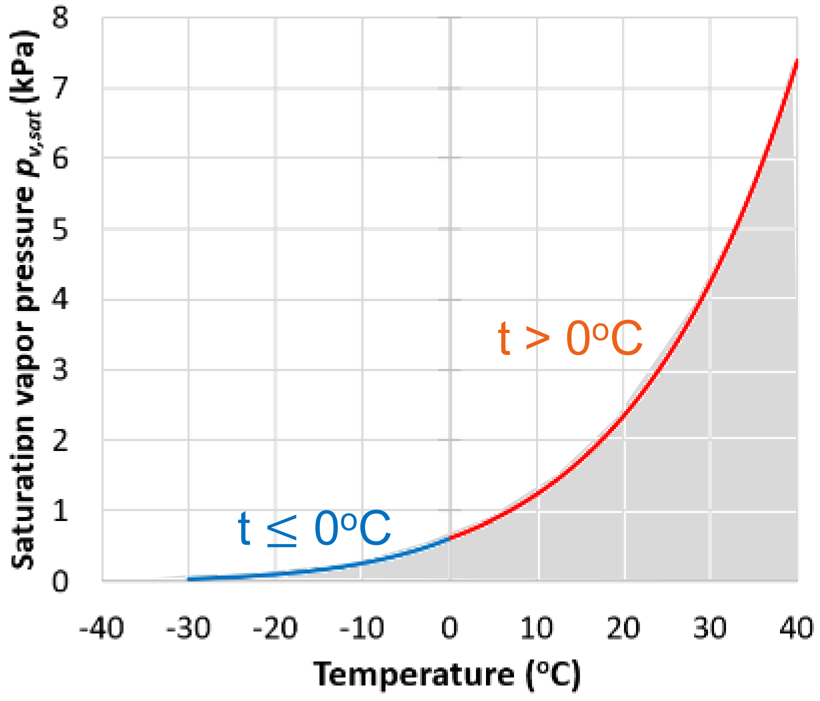
For t ≤ 0°C:

$$p_{v,sat} = 611 \cdot e^{\frac{22.44 \cdot t}{272.44+t}}$$ (2-6b)

- **Water vapor pressure deficit Δp_{vd}** (Pa) is defined as how much more partial pressure can be taken up before saturation occurs:

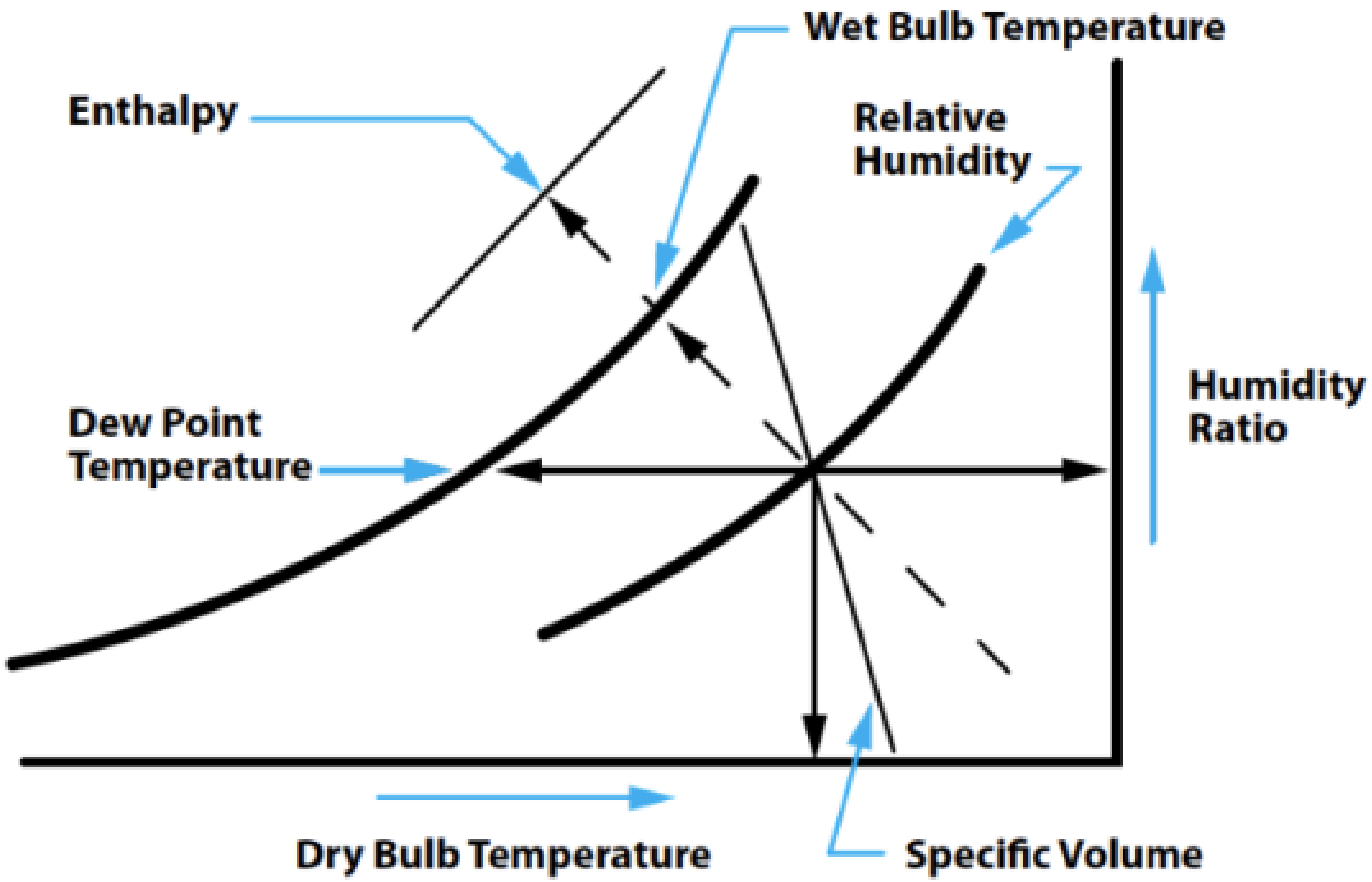
$$\Delta p_{vd} = p_{v,sat} - p_v$$ (2-7)





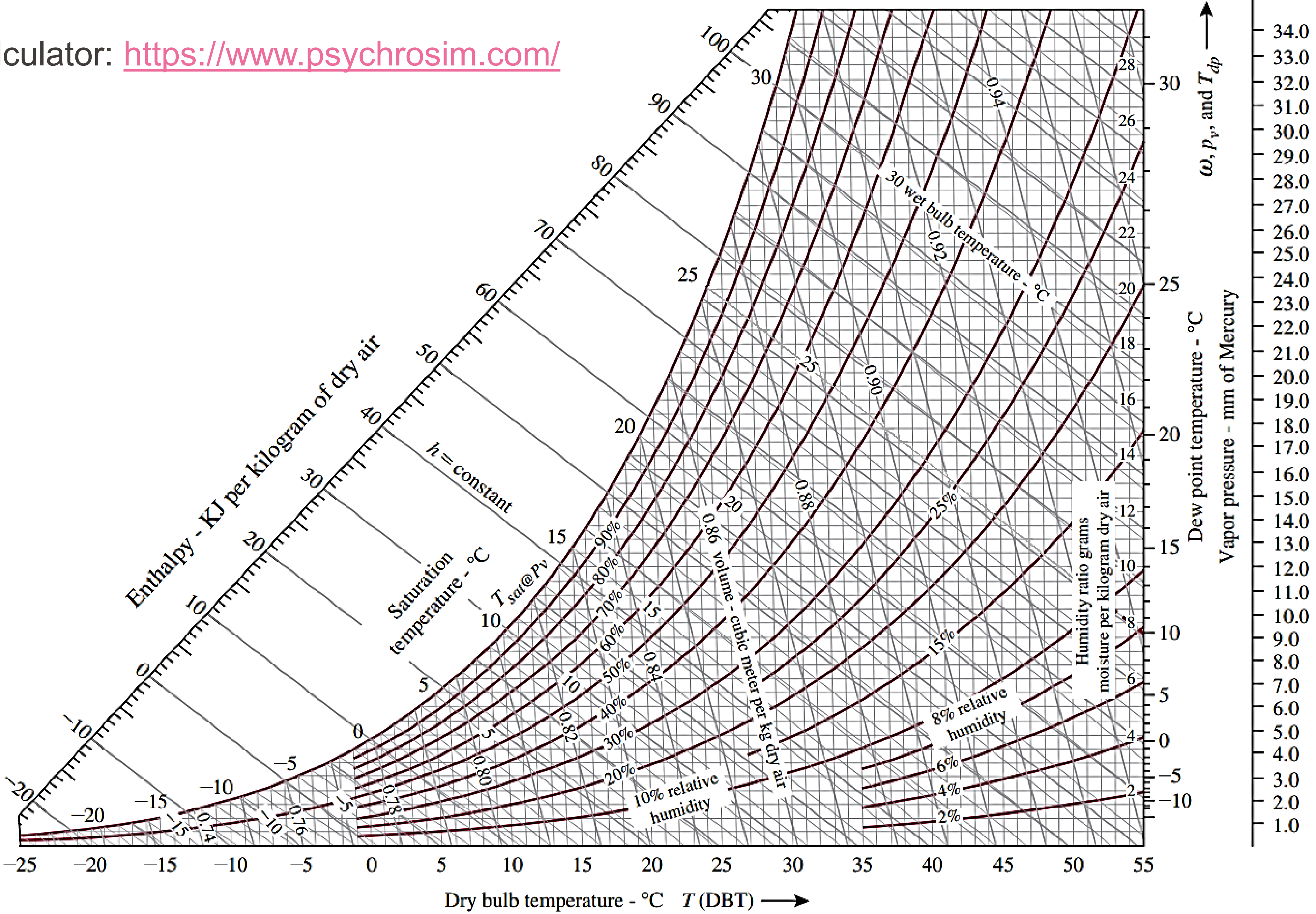
Psychrometric Properties: Moist Air

- **Psychrometric chart** presents *physical* and *thermal properties* of *moist air* in a graphical form (**at standard atm. pressure 101.3 kPa**)
- **Parameters displayed:**
  - Dry bulb temperature T_a
  - Wet bulb temperature $T_{wb,a}$
  - Dew point temperature T_{dew}
  - Specific enthalpy h_a (*internal energy of air measured relative to a reference temperature* 0 °C)
  - Relative humidity φ or *RH*
  - Absolute humidity x
  - Vapor pressure p_v
- Absolute humidity ranges:
  - *in nature:* 2-20 g/kg
  - *indoor air:* 4-12 g/kg



Psychrometric Properties: Moist Air

Online calculator: https://www.psychrosim.com/



Assist. Prof. Dolaana Khovalyg

Psychrometric Properties: Air humidity

- **Specific humidity q ($\frac{kg}{kg}$)**: the **mass ratio** between **the mass of water vapor** and **the mass of moist air** (does not change with the change of temperature and pressure)

$$q = \frac{m_v}{m_a} \quad \text{(2-8a)} \qquad q = \frac{p_v \cdot M_v/M_{a,dry}}{p_a - (1 - M_v/M_{a,dry}) \cdot p_v} = 0.622 \frac{p_v}{p_a - 0.378 \cdot p_v} \quad \text{(2-8b)}$$

- **Absolute humidity x ($\frac{kg}{kg}$)**: **mass of water vapor** *per* **1 kg of dry air**

$$x = \frac{m_v}{m_{a,dry}} \quad \text{(2-9a)} \qquad x = \frac{p_v \cdot M_v}{p_{a,dry} \cdot M_{a,dry}} = 0.622 \frac{p_v}{p_a - p_v} \quad \text{(2-9b)}$$

- **Relative air humidity φ (- or %)**: **ratio** of **the actual partial pressure of water vapour p_v** to the **water vapour saturation pressure $p_{v,sat}$** at *a specific air temperature* (often labeled as "RH", air is saturated at $\varphi = 1\ or\ 100\%$)

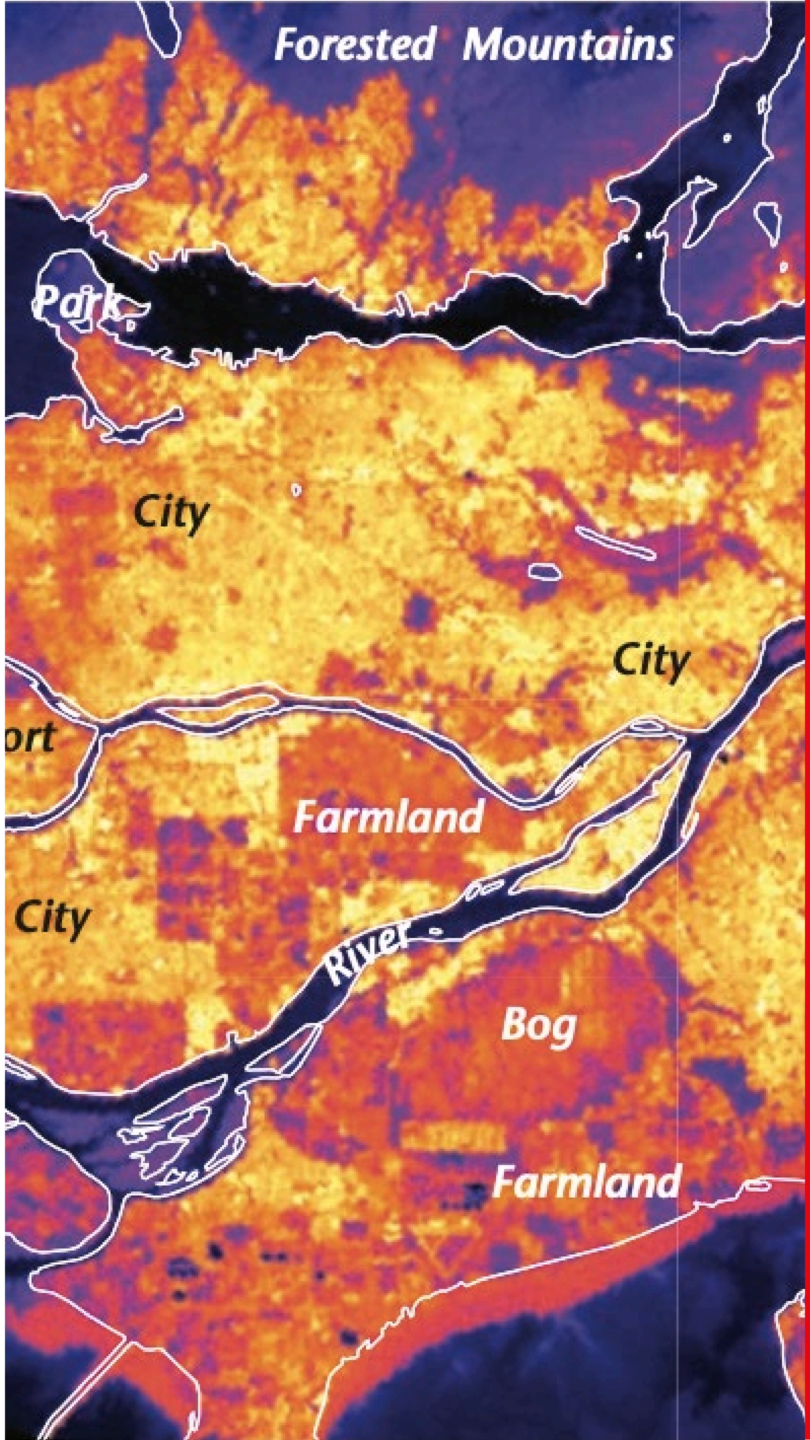
$$\varphi = \frac{p_v}{p_{v,sat}} \ (\text{-}) \quad \text{(2-10a)} \qquad \varphi = \frac{p_v}{p_{v,sat}} \cdot 100\ (\%) \quad \text{(2-10b)}$$

- **Humidity by volume v ($\frac{kg}{m^3}$)**: **water vapour mass** per unit **volume of air**

$$v = \frac{p_v}{R_v \cdot (t + 273.15)} = \frac{p_{v,sat} \cdot \varphi}{462 \cdot (t + 273.15)} \quad \text{(2-11)}$$

- t – air temperature (^oC),
- M_v - molar mass of the water vapour (18 $kg/kmol$),
- $M_{a,dry}$ - molar mass of dry air (28.9 $kg/kmol$),
- R_v - gas constant of water vapor ($462\ J/kg \cdot K$)

EPFL

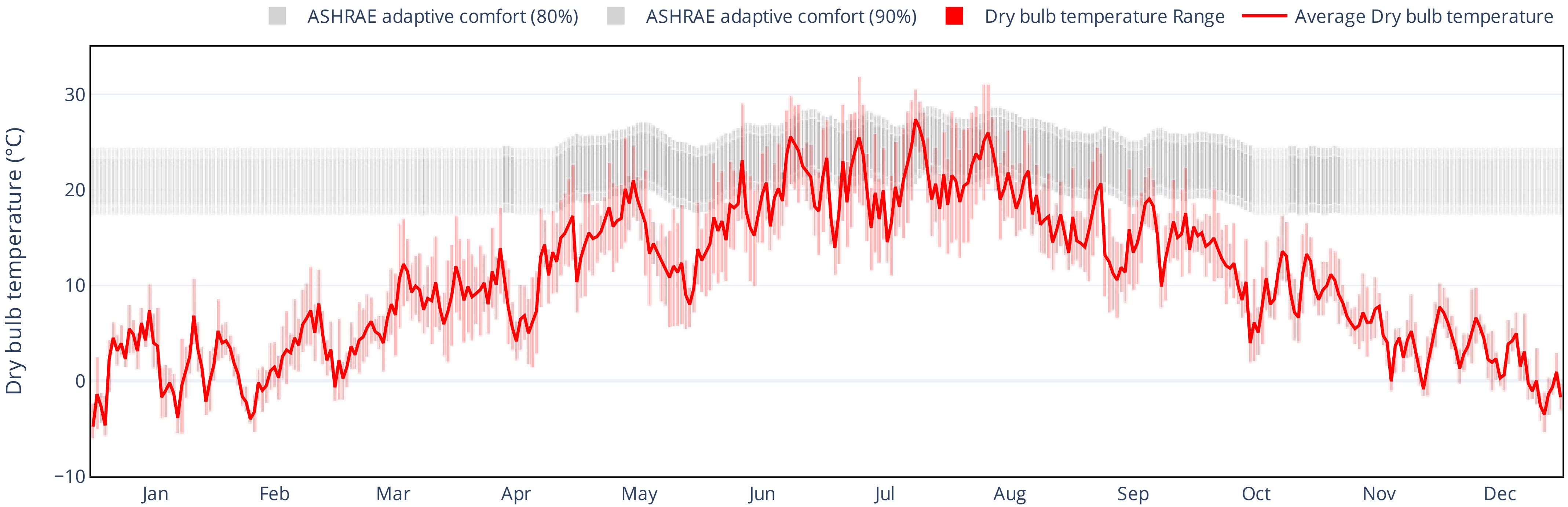


CONTENT:

Case study site: Dry bulb (air) temperature

Measurement location: Esplanade

- Longitude: 6.566, Latitude: 46.52
- Elevation above sea level: 398 m
- Period: **2000 – 2010, 2050 RCP 8.5, 2100 RCP 8.5**
- Köppen–Geiger climate zone: Cfb.
- Marine west coast, warm summer.



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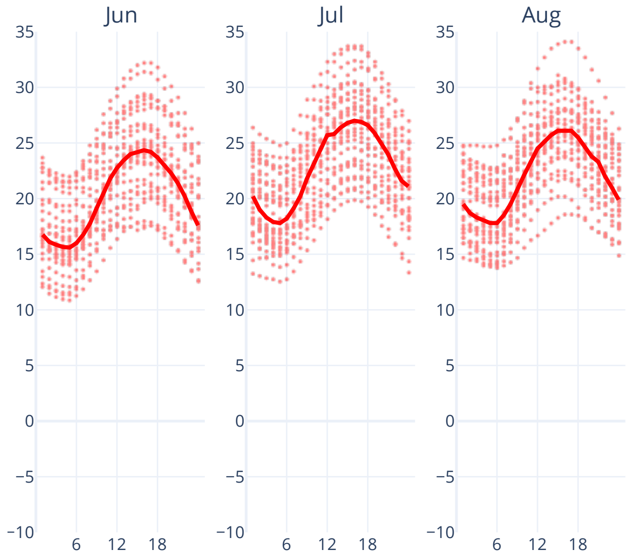
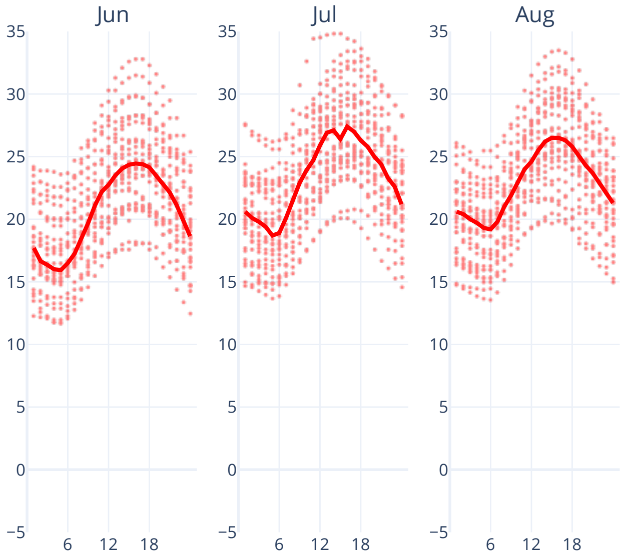
Case study site: Dry bulb (air) temperature

- Air temperature variation during summertime (past and future projection)

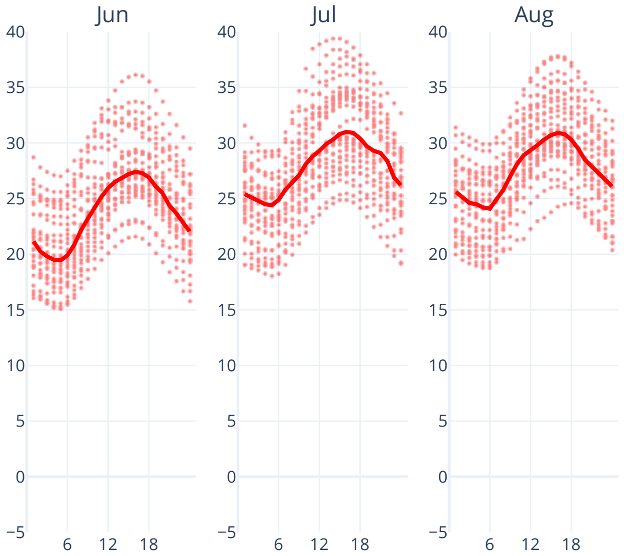
2000-2010



2050 RCP 8.5



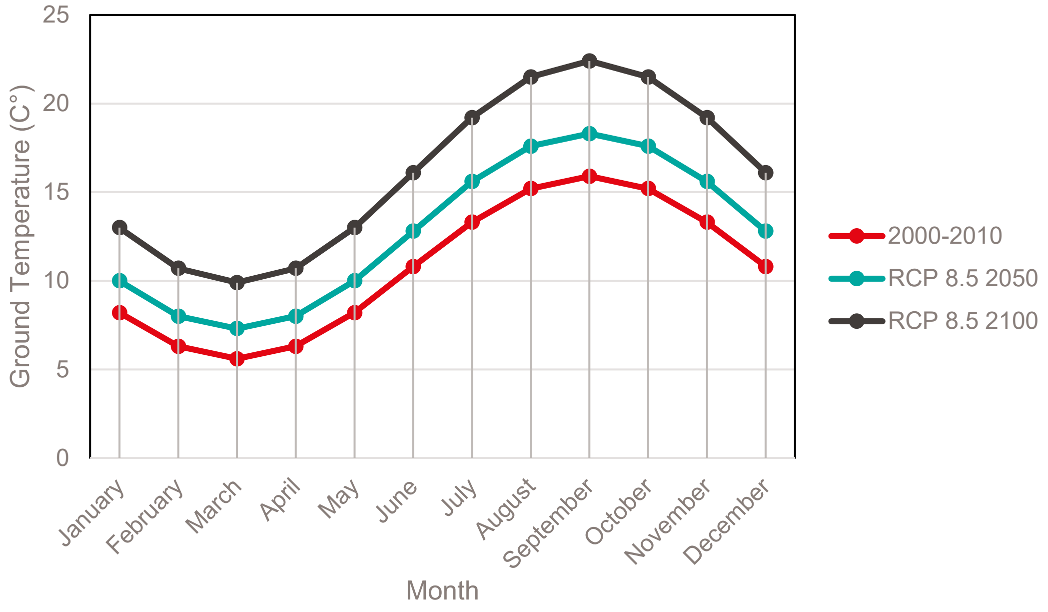
2100 RCP 8.5



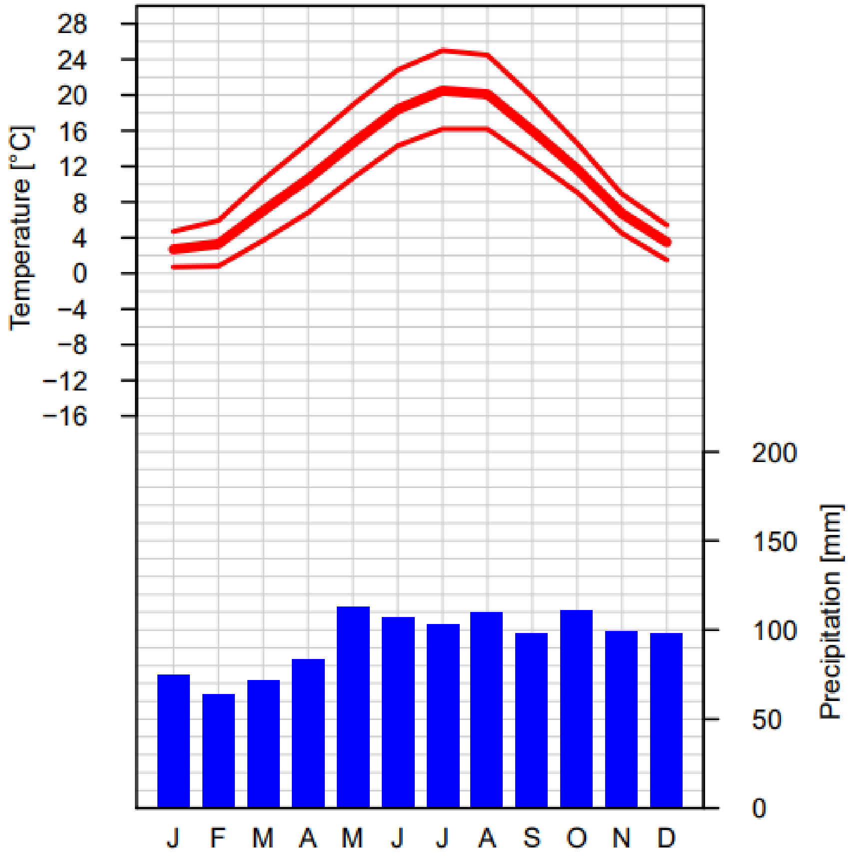
Scenario	2000 – 2010			2050 RCP 8.5			2100 RCP 8.5		
Month	June	July	August	June	July	August	June	July	August
Mean	18.8±4.6	20.7±4.7	19.8±4.3	21±4.4	23.4±4.5	22.9±4.1	24.3±4.4	28.0±4.4	27.7±4.1
Maximum	29.9	31.9	31.1	32.8	34.8	33.5	36.1	39.4	37.8
Minimum	8.0	11.0	11.5	11.7	13.7	13.6	15.1	18.1	18.8

Case study site: Ground temp. and Precipitation

Monthly **ground temperature** in different scenarios

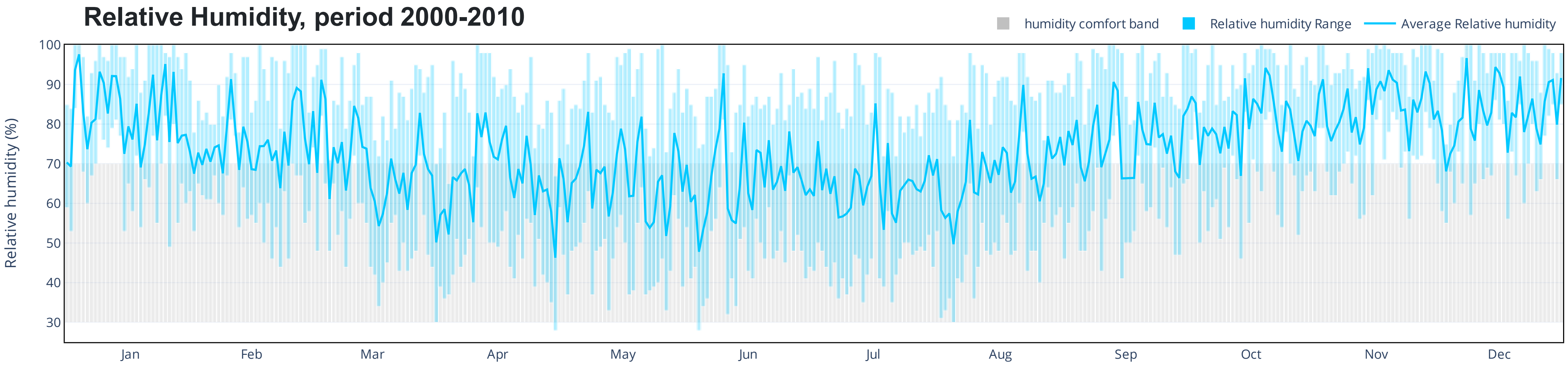


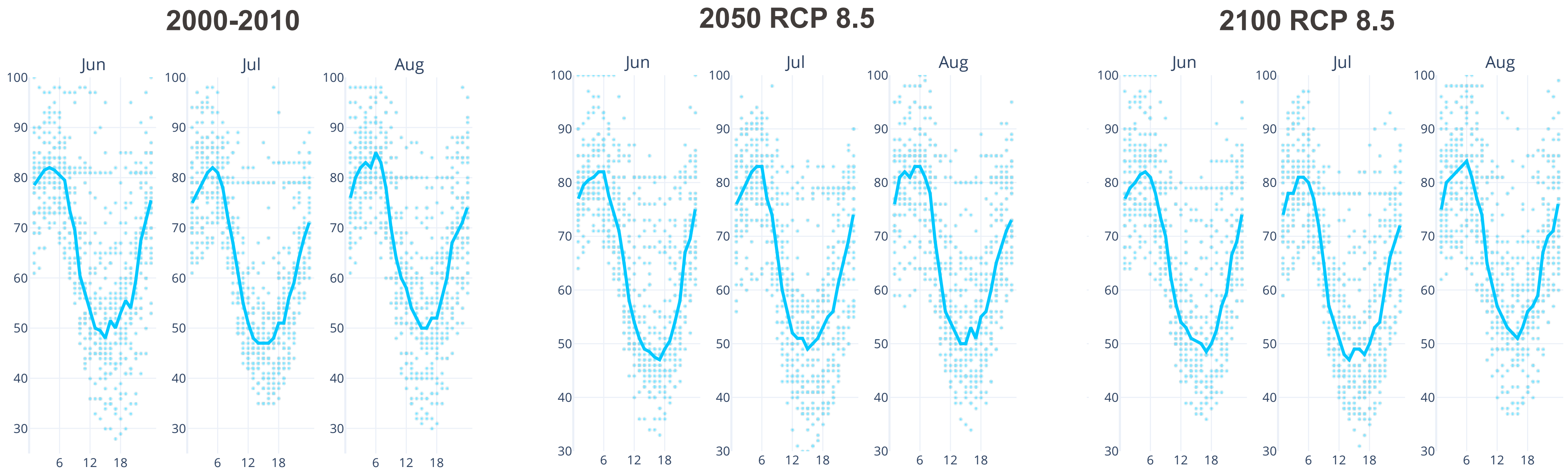
Monthly sum of **precipitation depth**
Lausanne Pully, **1991 - 2020**



Source: Swissmeteo

Case study site: Relative Humidity





Case study site: Solar radiation

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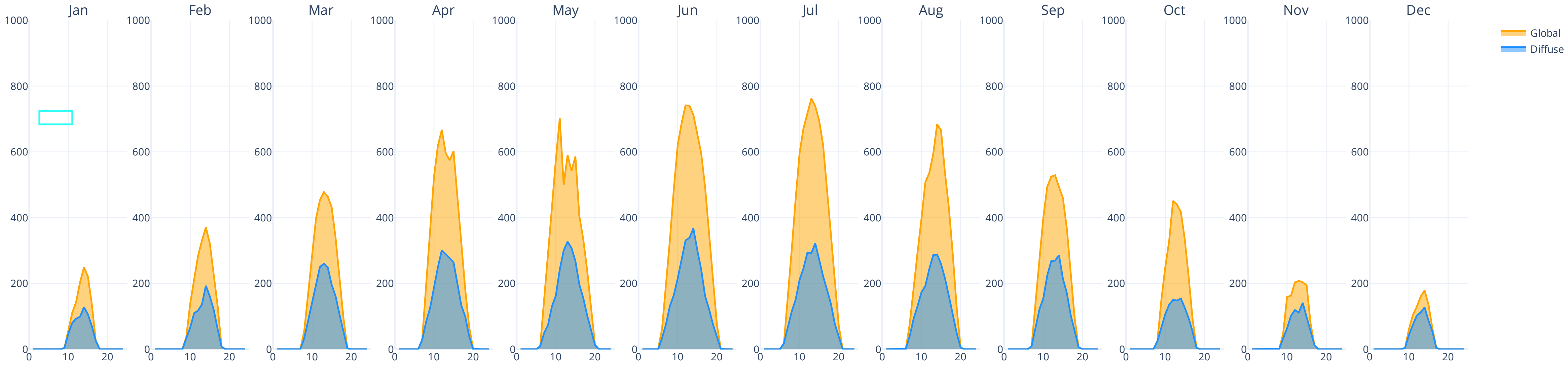
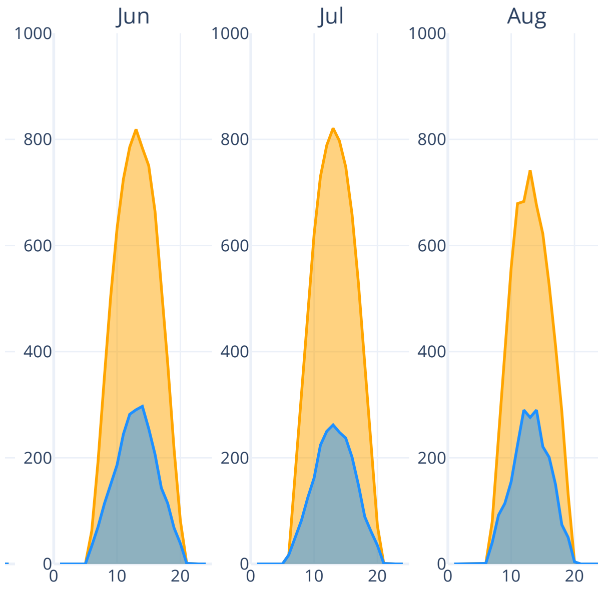
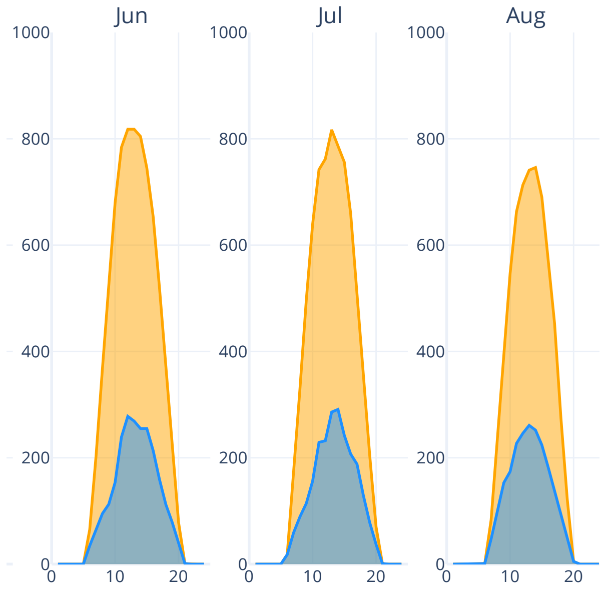
Global and Diffuse Horizontal Solar Radiation (Wh/m²), period 2000-2010



Global and Diffuse Horizontal Solar Radiation during summer (Wh/m²), future projection RCP 8.5 2050

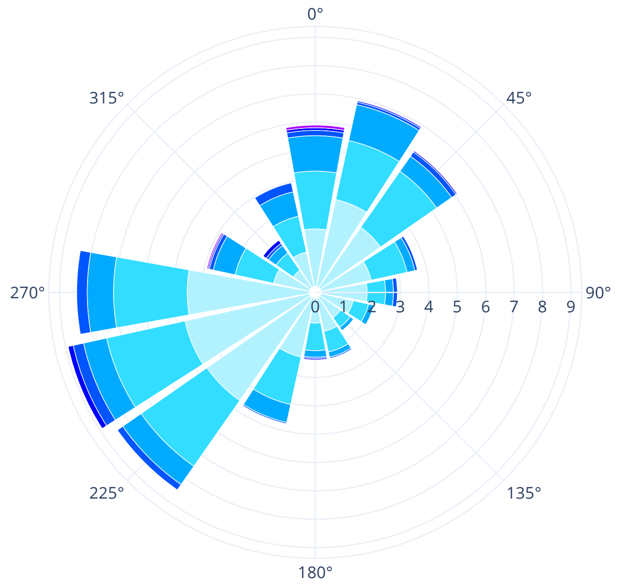


Global and Diffuse Horizontal Solar Radiation during summer (Wh/m²), future projection RCP 8.5 2100

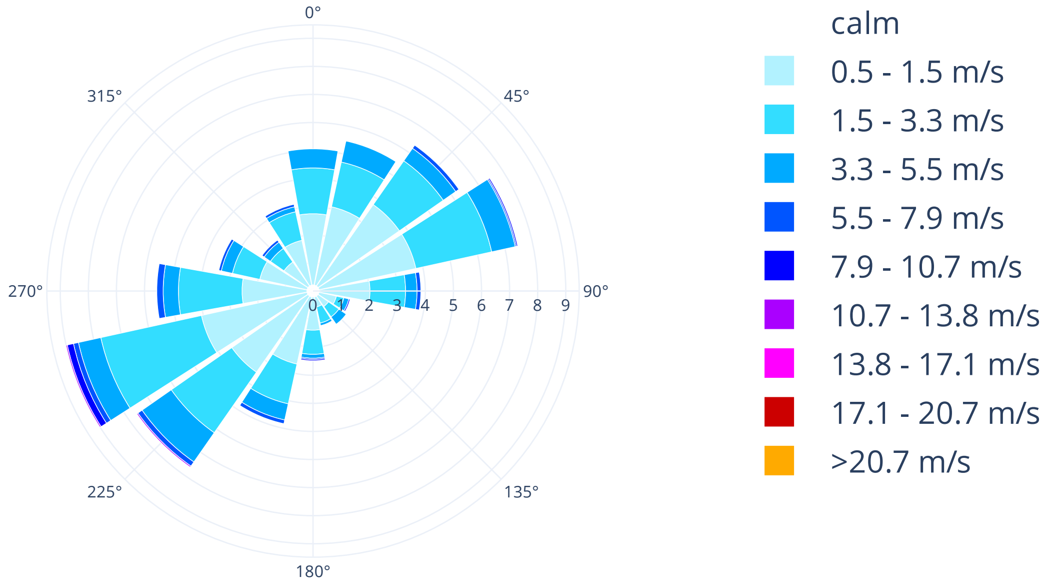


Case study site: Wind speed

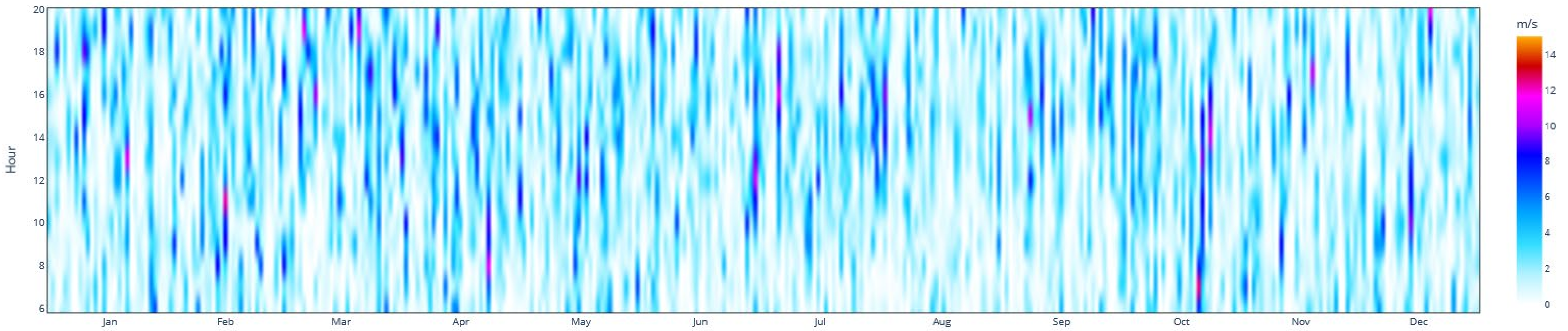
Wintertime wind rose 2000-2010
(Dec – Feb 01:00-24:00)



Summertime wind rose 2000-2010
(Jun – Aug 01:00-24:00)



Heat map of daily wind speed for an average year in 2000-2010 during 6:00 to 20:00



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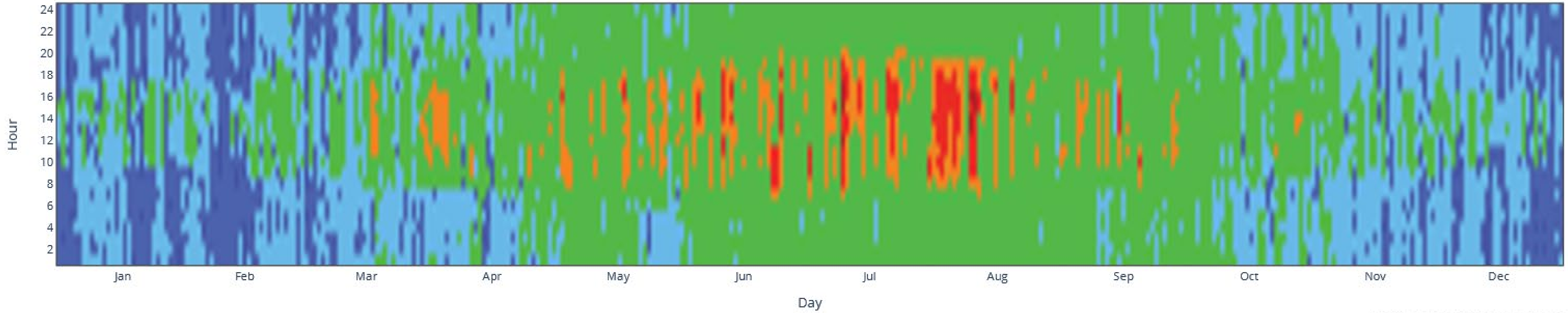
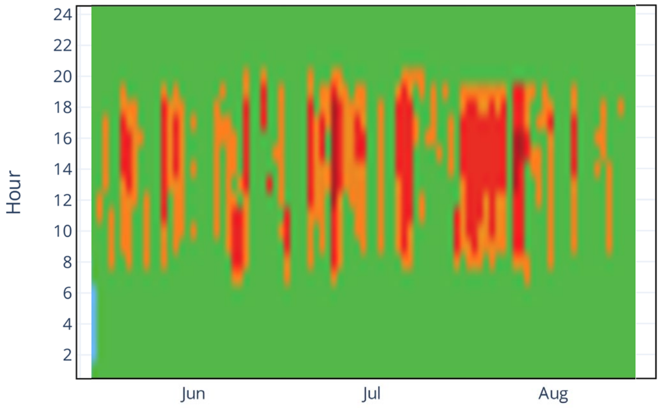
Case study site: Outdoor thermal comfort

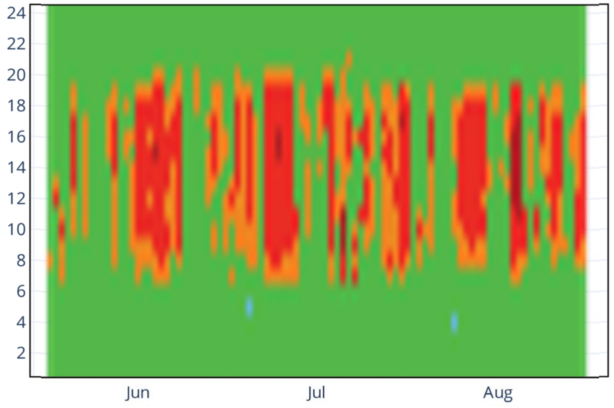
UTCI thermal stress: **sun & wind 2000-2010**



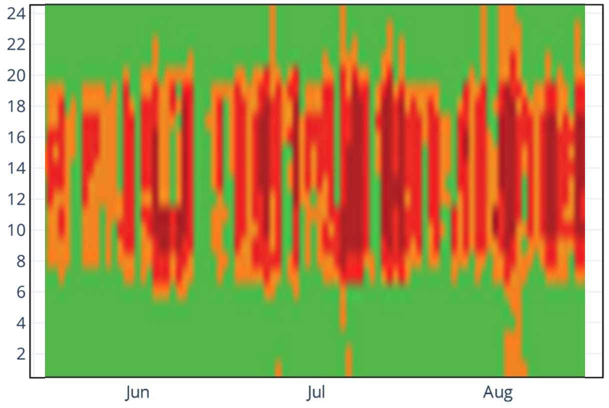
UTCI thermal stress:
2000-2010 sun & no wind



UTCI thermal stress:
2050 sun & wind

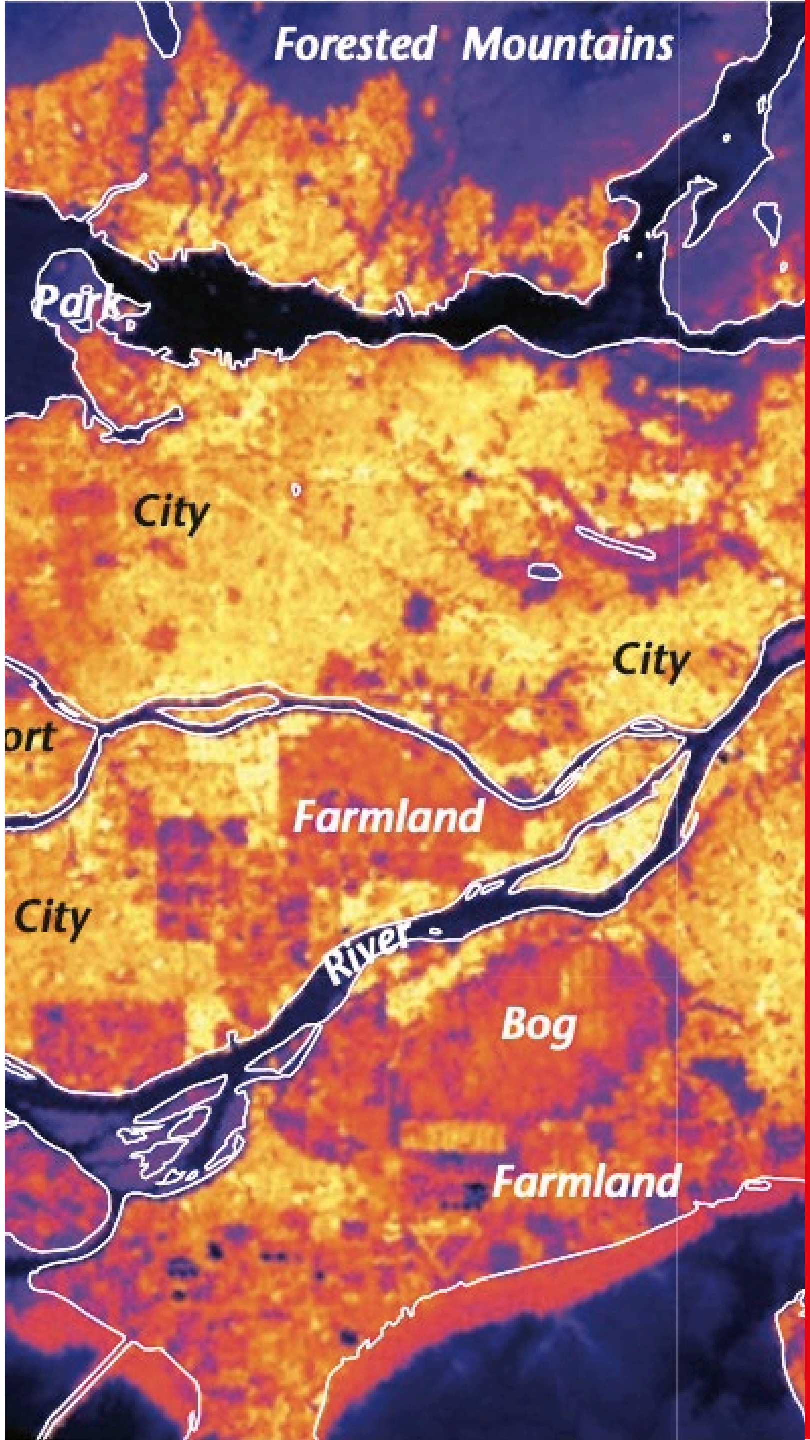


UTCI thermal stress:
2100 sun & wind



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



CONTENT:

I. Urban meteorology
- Structure of urban atmosphere
- Micrometeorology
- Winds speed and precipitation

II. Physical parameters
- Temperatures (air, surface, ground)
- Atmospheric pressure
- Water vapor, moist air, air humidity

III. Case study parameters overview

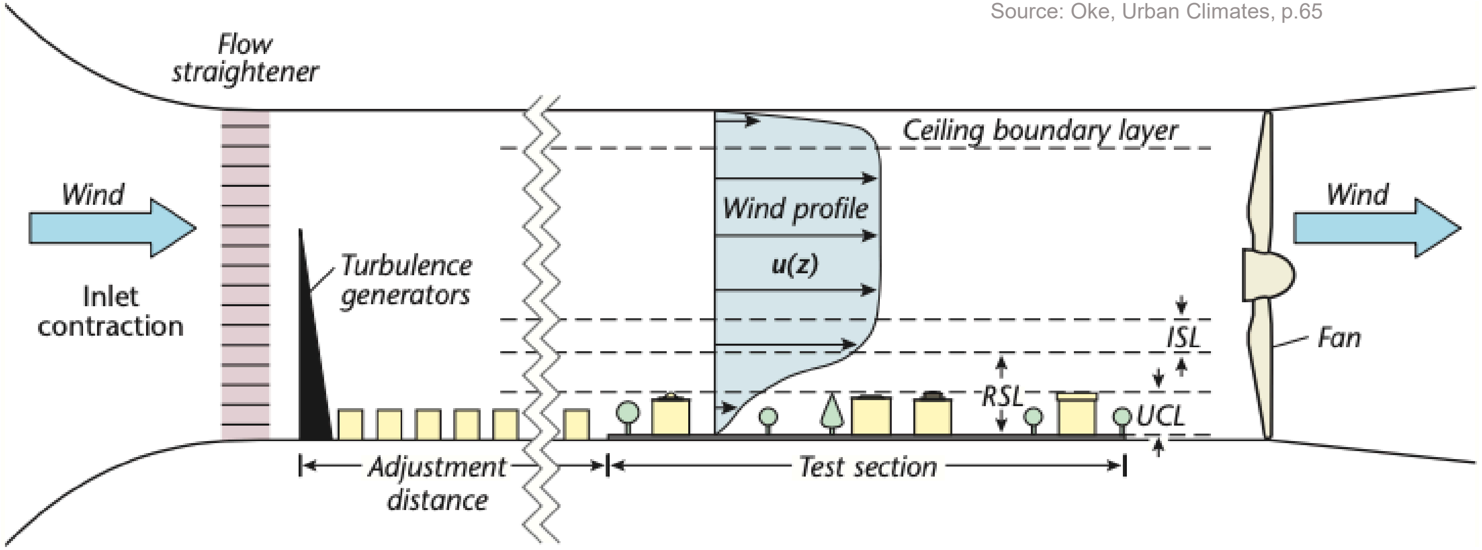
IV. **Urban modelling**
- **Physical vs. numerical modelling, CFD**
- **Overview of numerical software**
- **Introduction to ENVI-met**

Urban modelling: Physical modelling

- A **physical model** is a surrogate of a real-world system that is simplified and scaled.
- Scaling can trigger *modelling problems* and the similitude is kept by conserving the geometric ratio and the **physical adimensional numbers**
- It can be built:
  - Indoors with *controlled* meteorological conditions
  - Outdoors under *real* meteorological conditions

Source: Oke, Urban Climates, p.65

- A **wind tunnel, water flume** or **water tank** can be used to model the urban airflow

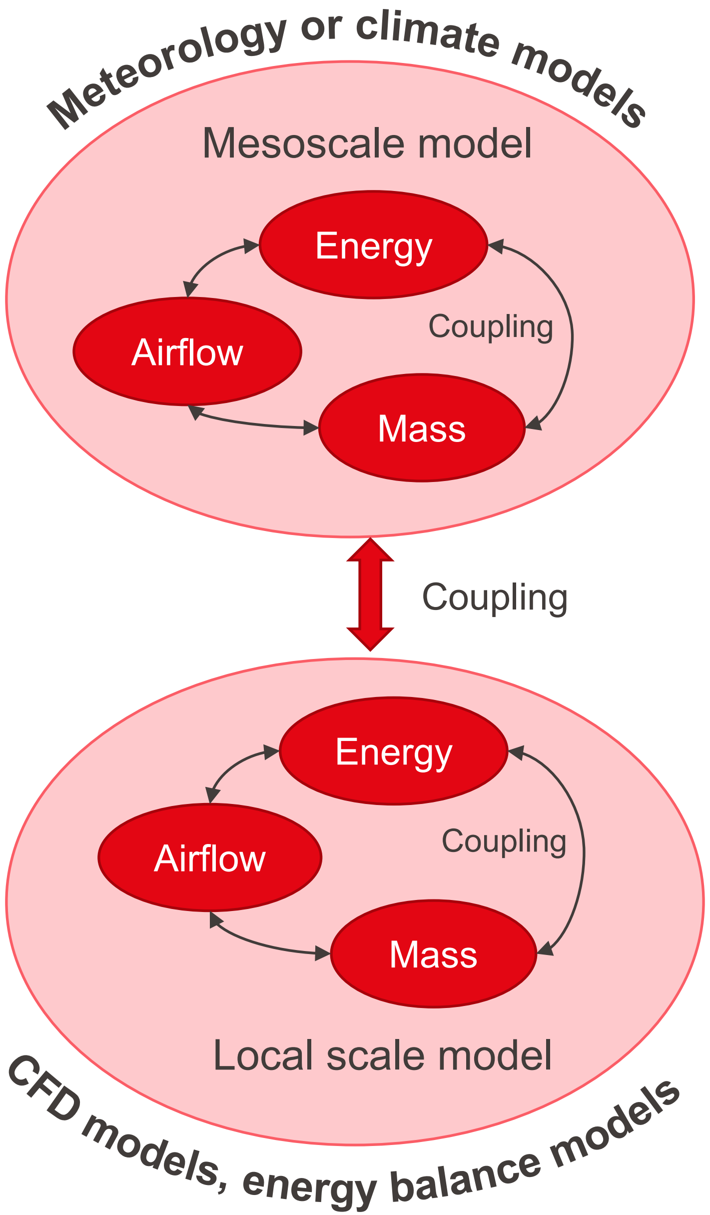


Source: Oke, Urban Climates, p.63

About the wind tunnel at EPFL: https://www.epfl.ch/labs/wire/facilities/wind-tunnel/

Urban modelling: Numerical modelling

- The numerical models have for object air flow, energy or mass and can be **coupled** together to *simultaneously* simulate these objects
- For the same object to model, different models exist depending on the scale of modelling. These models can be coupled together to encompass broader scales of the urban environment.
- **Urban climate model**: numerical model of the urban atmosphere and surface that evolve together in response to exchanges with the surface and atmosphere domain.
- The scales of numerical models:
  - **micro** or **local scale**
  - **mesoscale**



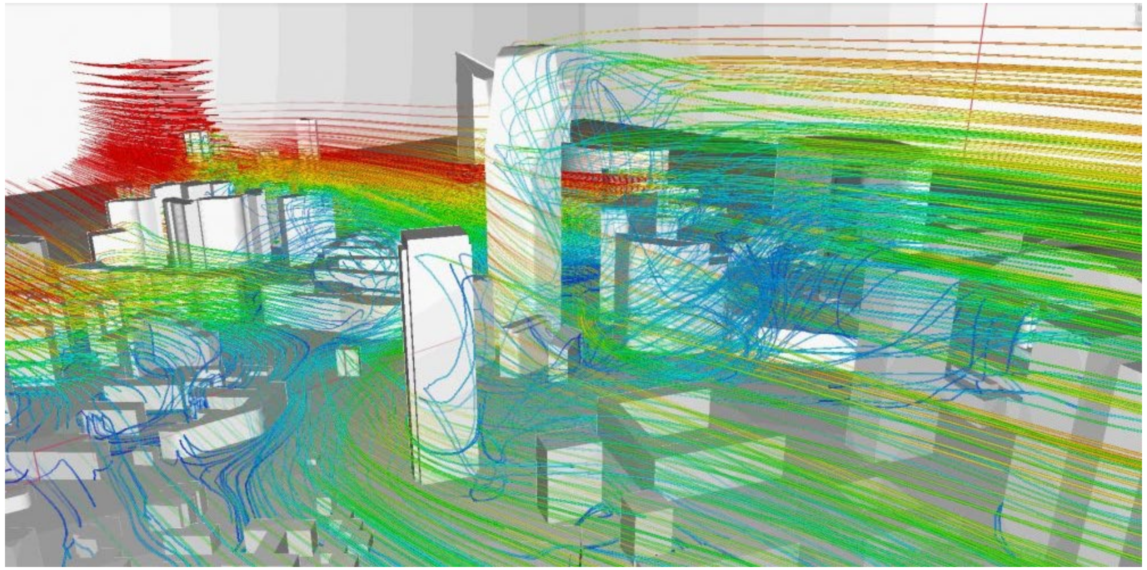
Urban modelling: Modelling choice

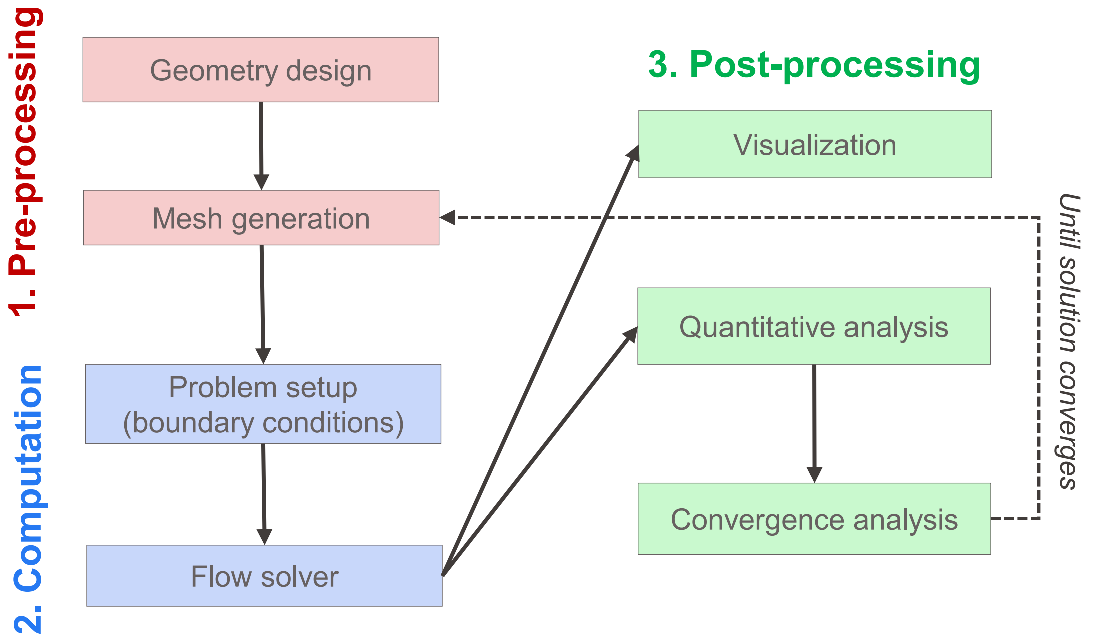
- **Physical modelling** is preferred in the case of studies related to *a very specific location* with a delimited research question.
- **Numerical modelling** is preferred in the case of *generic studies*, *parametric studies*, *optimization problems* and *predictions*.

Method	Advantages	Disadvantages
Physical modelling	Provides experimental control and detailed observation of urban effects	Requires careful design to ensure similitude. Requires access to specialized facilities (e.g. flume, wind tunnel). Expensive. Requires testing against field observations or numerical results.
Numerical modelling	Gives complete experimental control and can account for all climate scales. Can give predictions for an existing setup.	Assumptions can be restrictive, unrealistic or too theoretical. Requires testing against field observations to establish confidence. Output can be extensive.

Urban modelling: CFD

- **Computational Fluid Dynamics** (CFD) is a very common **numerical method** used **to simulate flow dynamics**. It covers a wide range of problems from fluid dynamics, aeroacoustics to thermo-physical problems.
- **CFD relies on the finite volume method**: the continuous flow is discretized in order to be numerically solved
  - 3 steps of CFD analysis: *pre-processing*, *computation*, and *post-processing*
- CFD is an efficient tool to replace *expensive* and *time-consuming experiments*, that gives physical information on the entire computed domain and that is *useful to perform* **parametric studies** and **optimization**





Urban modelling tools: Overview

MESO-SCALE

- Aims at atmospheric research and operational forecasting applications.
- Multiscale from large-eddy to global simulations.
- Applications include real-time weather forecasting, data assimilation, parameterized-physics research, regional climate simulations, air quality modeling, atmosphere-ocean coupling, and idealized simulations

Weather Research and Forecasting (WRF)

Australian Community Climate and Earth System Simulator (ACCESS)

MICRO-SCALE

Specialised Microclimate CFD Tool

Comprehensive model for urban surface-plant-air interactions, such as building physics, radiation exchange, and the cooling effects of vegetation, air pollutant dispersion

ENVI-met
- Paid
- Closed source
- GUI
- Neighbourhood scale

PALM4U
- Free
- Open source
- No GUI
- Neighbourhood and city scale

General CFD Tool

General purpose CFD for a wide range of physical phenomena, including chemical reactions, turbulence and heat transfer.

ANSYS FLUENT

OpenFOAM

Other

CITYSIM
Energy performance and neighborhood.

CITY ENERGY ANALYST
Urban energy system planning and sustainability analysis

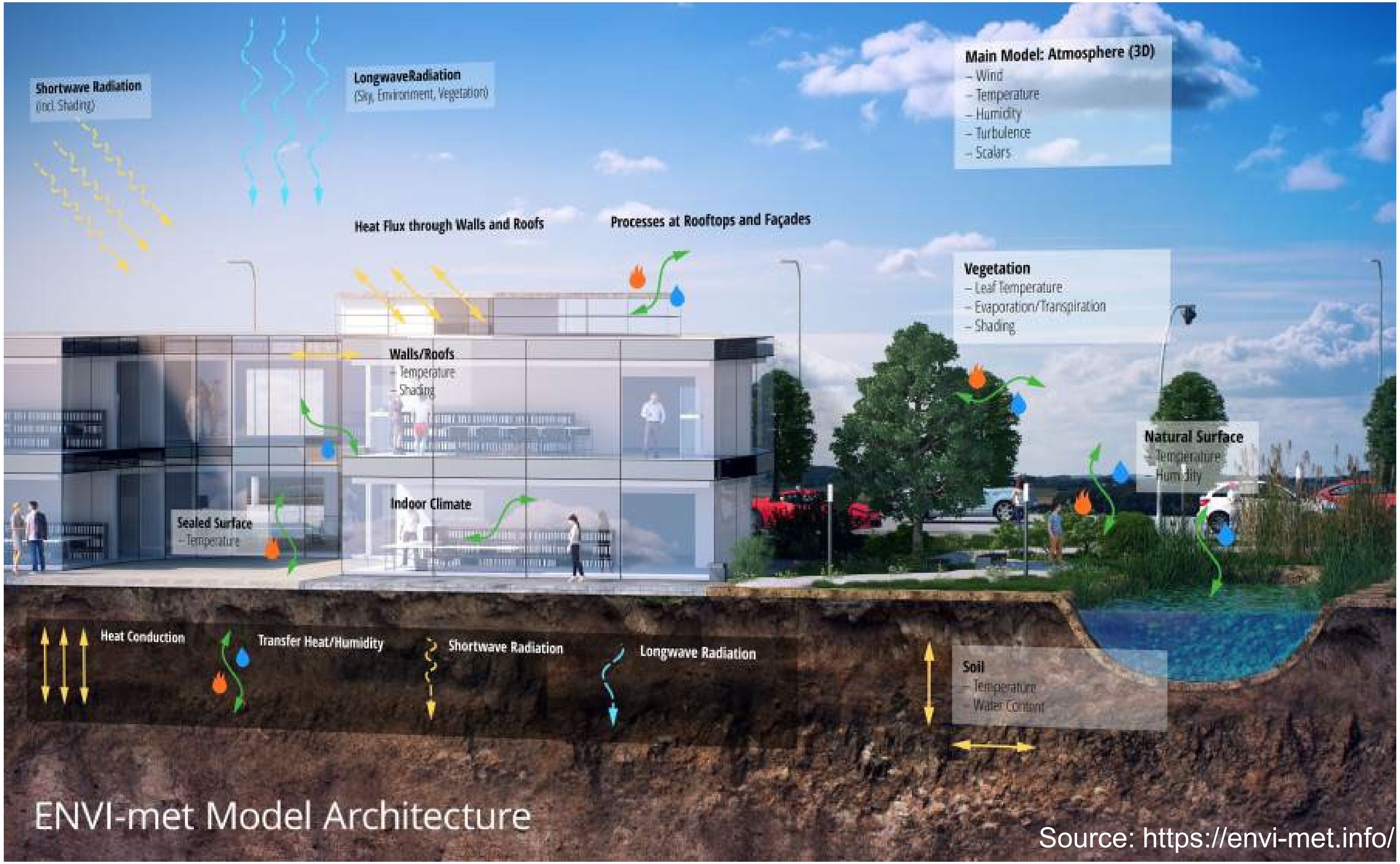
UMEP
Urban climate modelling and environmental prediction, for large scale application

and more…

EPFL

Urban modelling tools: ENVI-met

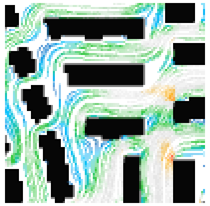
- **ENVI-met:** prognostic model based on the fundamental laws of *fluid dynamics* and *thermodynamics*



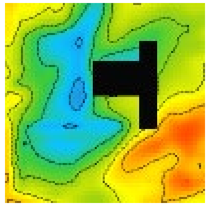
Source: https://envi-met.info/

ENVI-met: Models & Capacity

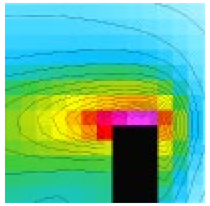
▪ Atmospheric model



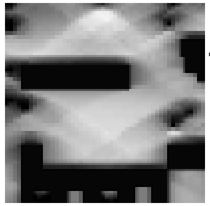
CFD wind field: 3D CFD model for each grid and time step



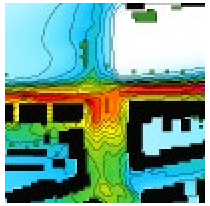
Air temperature & humidity: heat exchange between elements, advection and diffusion through air movement



Turbulence

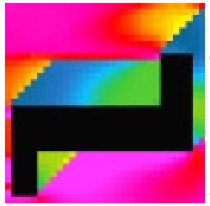


Radiative fluxes

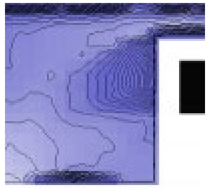


Pollutant dispersion

▪ Soil model

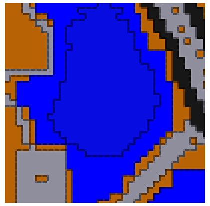


Surface & soil temperature: surface temperature of soil and artificial seal material down to -4m



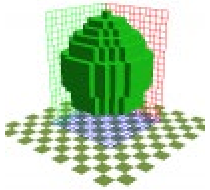
Soil water content: water balance of ground based on Darcy's law

Vegetation water supply

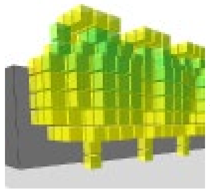


Water bodies and pounds: radiation transmission and absorption, heat convection

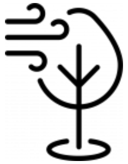
▪ Vegetation model



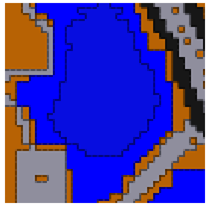
3D plant geometry: simple and complex 3D plants



Foliage temperature: energy balance of leaf surface in relation to weather, plant physiology, water supply, etc.

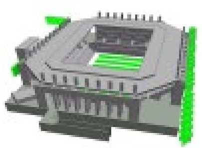


Vegetation water supply

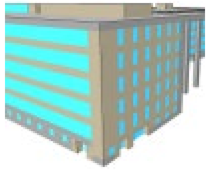


Water bodies and pounds: radiation transmission and absorption, heat convection

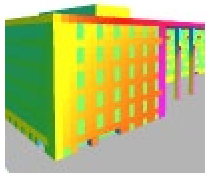
▪ Atmospheric model



3D building geometry & Single walls



Detailed building materials



High resolution building physics

Building energy performan ce

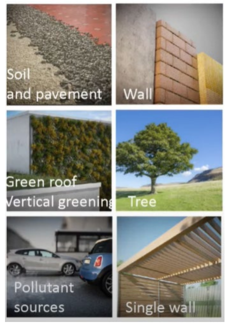
Green roof and walls

Source: https://envi-met.info/

ENVI-met: Simulation workflow

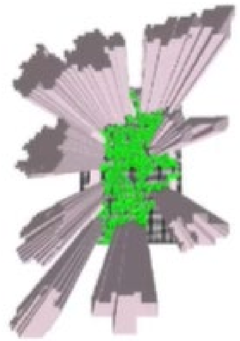
Design concept

- 2D scaled sketch;
- Digital geometry in other 3D modelling software



Material database

- Create material and specify thermal properties (heat absorption, transmission, reflection, emissivity, specific heat, thermal conductivity, density).
- Create wall, roof constructions (3 layers)

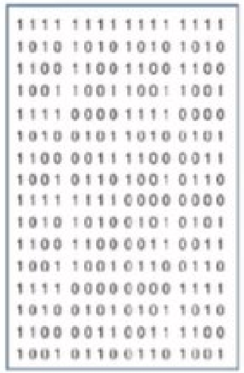


Digitise 3D model

Create model area, import background pic from step 1, model the study site (buildings with materials assigned, ground, vegetation, etc.)

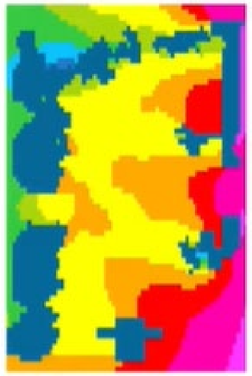
Meteorological condition

- Download weather data (e.g., epw file)
- Create forcing files in *forcing manager*, inspect weather conditions of specific days and choose simulation period (drastic change of wind speed and direction can lead to simulation issues).



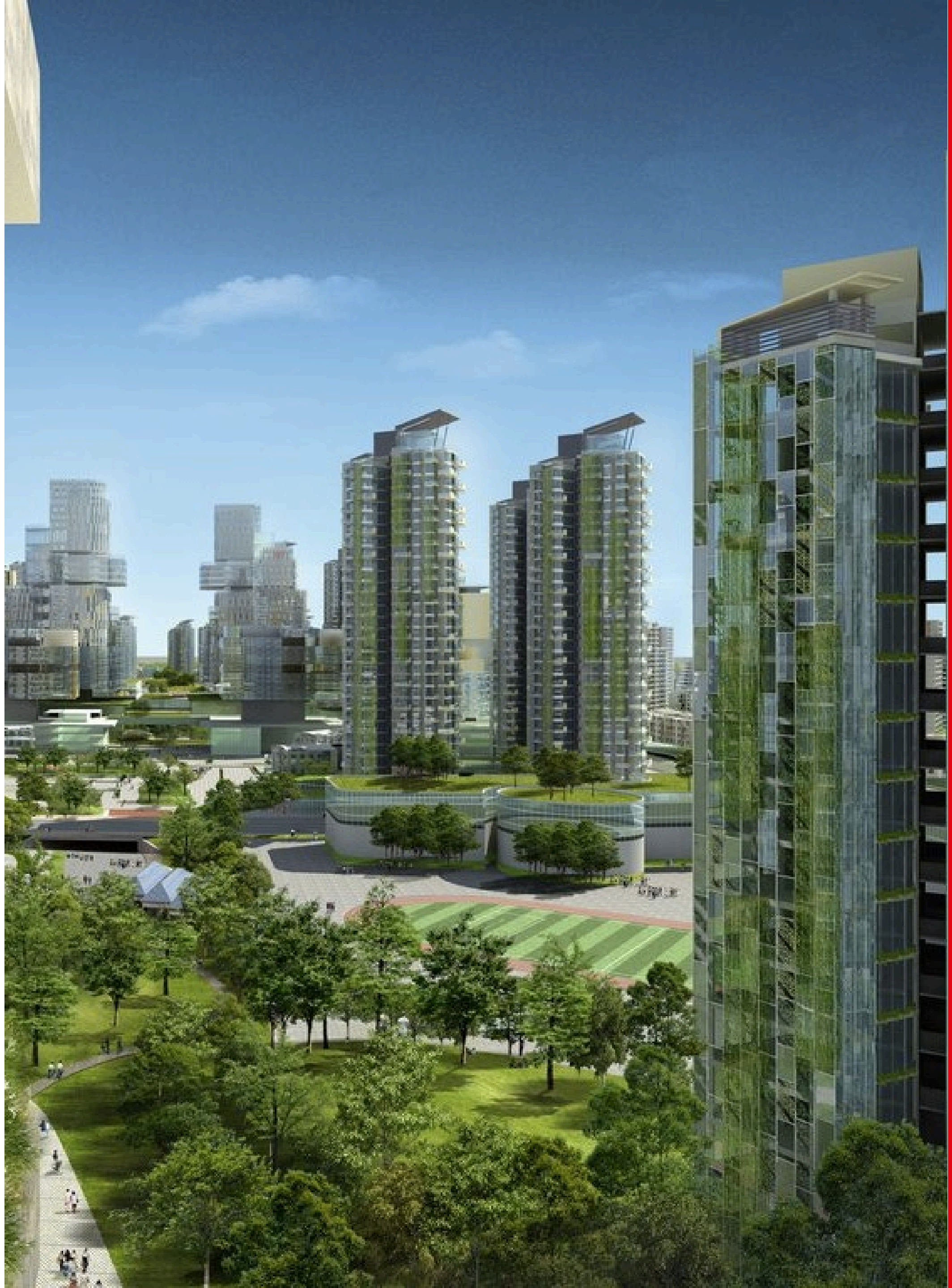
Simulation

- Create *SIMX* file in *envi-guide*, specify simulation settings.
- In *envi-core*, run simulation.



Visualisation

- Data exploration in *Leonardo*, or *QGIS, or import data – net CDF format to other data analytical tools (Python, R, excel…)*



Thank you for your attention

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