Urban Climatology

1. Motivation to study urban climates, historical overview
2. Main factors controlling urban climate (UC), UC scales, layers, energy balance
3. Climate of Brno as an example (data, methods, main outcomes)
4. Urban heat Island (UHI), UHI types, atmospheric UHI, UHI intensity
5. Urban Remote Sensing, surface UHI
6. Precipitation in urban areas
7. Spatio-temporal variability of other meteorological elements in urban areas
8. Local climate zones
9. Urban Climate Modelling
10. Urban adaptation to climate change

Part I Motivation to study urban climates, historical overview

- Is it an actual problem to study urban climates?
- What do you know about history of urban meteorology and climatology?
- What is the difference between "descriptive" and "physical" urban climatology?
- What are the main topics of urban climatology in the near future?

Part II Main factors controlling urban climate (UC), UC scales, layers, energy balance

1. Thermal properties of the surface materials
2. Surface geometry
3. Surface waterproofing
4. Anthropogenic heat
5. Air pollution

Role of local geography

Table U2 Urban climate effects for a mid-latitude city with about 1 million inhabitants (values for summer unless otherwise noted)

Variable	Change	Magnitude/comments
Turbulence intensity	Greater	10–50%
Wind speed	Decreased	5–30% at 10 m in strong flow
	Increased	In weak flow with heat island
Wind direction	Altered	1–10 degrees
UV radiation	Much less	25–90%
Solar radiation	Less	1–25%
Infrared input	Greater	5–40%
Visibility	Reduced	
Evaporation	Less	About 50%
Convective heat flux	Greater	About 50%
Heat storage	Greater	About 200%
Air temperature	Warmer	1–3°C per 100 years; 1–3°C annual mean up to 12°C hourly mean
Humidity	Drier	Summer daytime
	More moist	Summer night, all day winter
Cloud	More haze	In and downwind of city
	More cloud	Especially in lee of city
Fog	More or less	Depends on aerosol and surroundings
Precipitation		
Snow	Less	Some turns to rain
Total	More?	To the lee of rather than in city
Thunderstorms	More	

Urban climate – main meteorological elements and their climatological characteristics show typical features of their temporal and spatial variability

- **Urban climate scales**

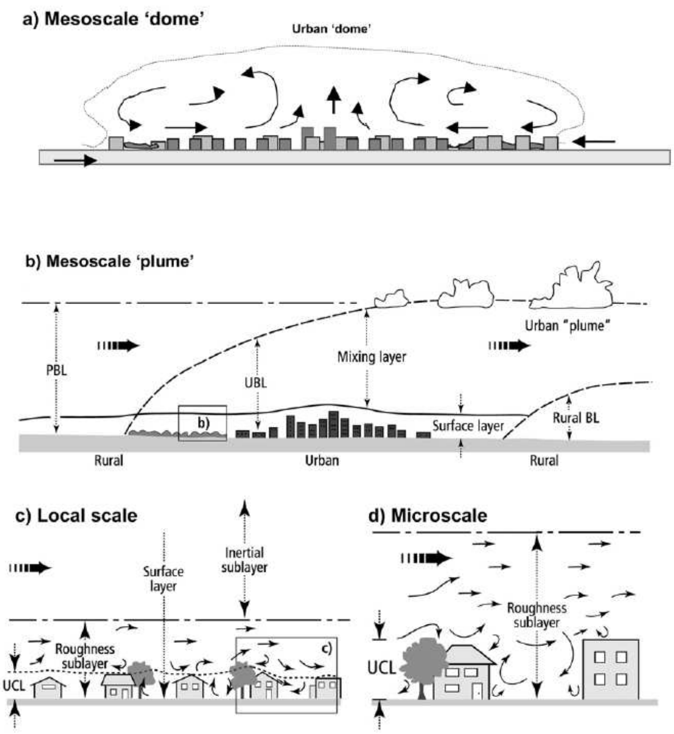
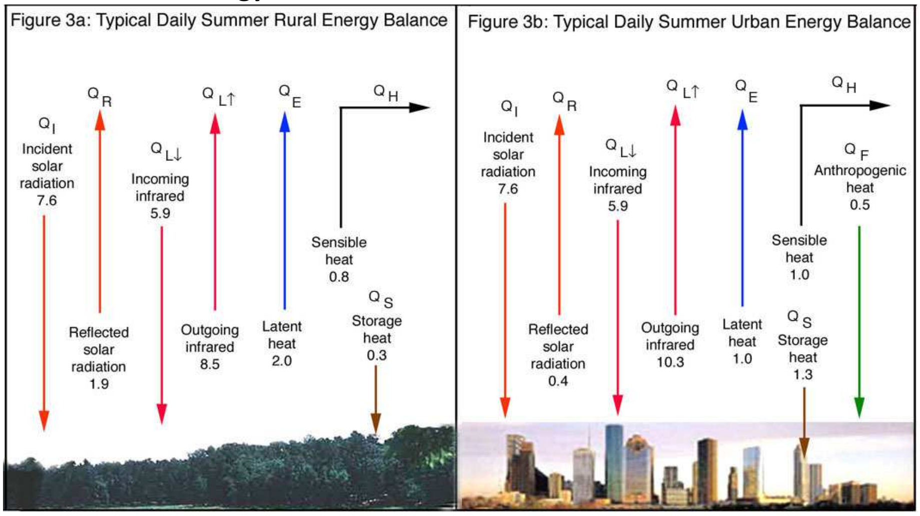


Figure U1 The idealized vertical structure of urban-modified air. **(a)** The whole city (mesoscale) in near-calm conditions with its "dome", and **(b)** in a steady regional air flow with its urban "plume". **(c)** A single urban terrain zone (local scale) showing the internal layering of the urban canopy (UCL) and lower portion of the urban boundary (UBL) layers. **(d)** A single street canyon (microscale) and building elements (after Oke, 1998).

- **Urban climate energy balance**



source: http://www.ruf.rice.edu/~sass/UHI.html

Short and long-wave radiant energy terms as energy is transferred back and forth between the Earth and space:

- QI = Incident (direct and diffuse) solar radiation,
  QR = Reflected solar radiation,
  QLu = Upward surface emission of long-wave length radiation,
  QLd = Downward atmospheric emission of long-wave length radiation,
  Q* = Net solar energy (positive or zero) = QI - QR, and
  QL = Net infra-red energy = QLd-QLu (generally negative or zero)

Energy terms identify energy moving about the Earth and between the surface and the atmosphere:

- QF = Anthropogenic energy such as from industry, transportation, heating and AC
  QE = Latent heat from evaporation of water from trees, soil, bodies of water, etc.
  QH = Sensible heat carried by vertical and horizontal air motion, including wind
  QS = Storage heat flux within the system (ground, buildings, etc.)

Questions:

1. What are the main factors controlling urban climate?
2. How we can define urban climate scales?
3. What are the main terms of urban climate energy balance?

To read:

02_urban_climatology.pdf (from page 766)

02_Hart_Sailor_TAC_2009.pdf

Part III. The Climate of Brno

Main aim: What are typical features of spatial and temporal climate variability in Brno?

1. Local geography character
    a. Land use distribution
    b. Complex relief
2. History of meteorological measurements
    a. No typical urban station
    b. Compiled series of air temperature and precipitation. Air temperature is rising continuously (since 1960s) while precipitation demonstrate high inter-annual variability without any long term trend.

    Q1: Is it useful to have a long term measurements?

    Q2: What do we need for analysis of urban climate?
3. Meteorological data (dependent, target variables)
    a. Standard measurements at professional stations (Met-service)
    b. Special-purpose measurements
    c. Mobile measurements
    d. Measurements from remote sensing systems (satellite imagery)
4. Geographical database (independent, explanatory variables) in the form of 300 x 300 m grid cells
    a. Altitude
    b. Density of buildings
    c. Density of vegetation
    d. Density of roads
    e. Sky view factor

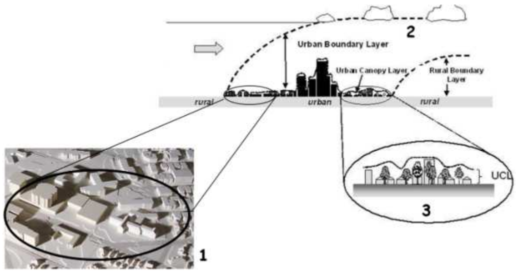
    Q3: Do they reflect all main factors that control urban climate?
5. Two examples of air temperature variability analysis
    a. Land surface temperatures (LSTs) derived from thermal satellite images
        i. We quantified to what extent different land use categories increase/decrease LSTs
        ii. "Hot-spots" occur in typical parts of the city
        iii. Amount of vegetation (in the form of NDVI) explains more than 2/3 of LST variability

        Q4: What parts of the city are most susceptible to higher temperatures?
    b. Nocturnal air temperature field analyzed from mobile measurements
        i. The same explanatory variables, but used for air temperature analysis
        ii. Design of traverses through the city
        iii. Amount of air temperature variability explained – the best result for density of vegetation and density of buildings. Weak influence of altitude.
        iv. Typical air-temperature spatial distribution – **Urban heat island (UHI)**

        Q5: Why it is important to study temperatures at night?

        Q6: Compare positive/negative features of the two methods?

Part IV. Urban heat Island (UHI), UHI types, atmospheric UHI, UHI intensity



1. **Surface UHI**
2. **Atmospheric boundary layer UHI**
3. **Atmospheric canopy layer UHI**

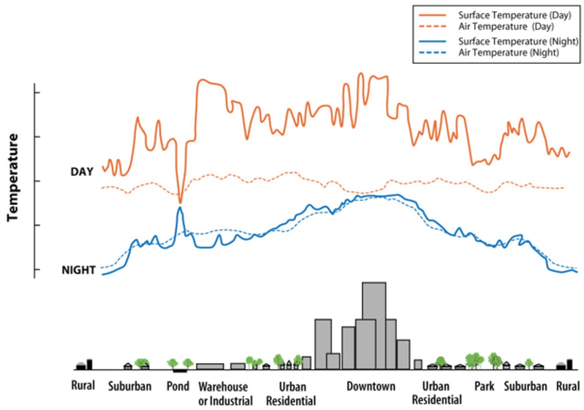
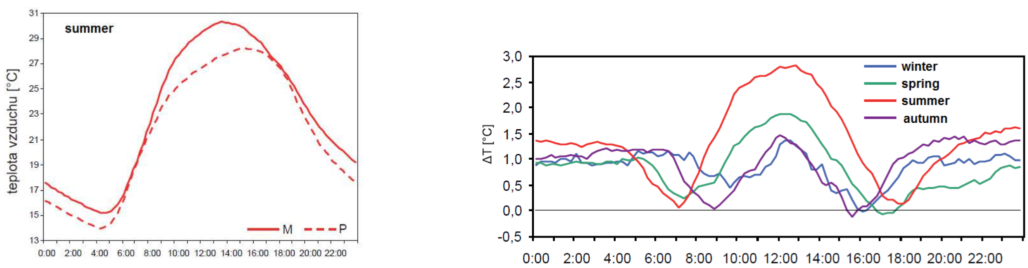


Table 1: Basic Characteristics of Surface and Atmospheric Urban Heat Islands (UHIs)[4]

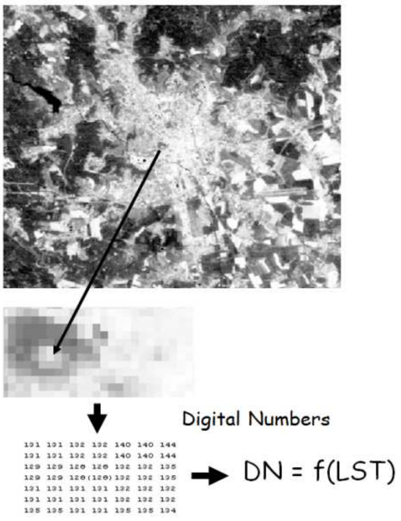
Feature	Surface UHI	Atmospheric UHI
Temporal Development	• Present at all times of the day and night • Most intense during the day and in the summer	• May be small or non-existent during the day • Most intense at night or predawn and in the winter
Peak Intensity (Most intense UHI conditions)	• More spatial and temporal variation: ▪ Day: 18 to 27°F (10 to 15°C) ▪ Night: 9 to 18°F (5 to 10°C)	• Less variation: ▪ Day: -1.8 to 5.4°F (-1 to 3°C) ▪ Night: 12.6 to 21.6°F (7 to 12°C)
Typical Identification Method	• Indirect measurement: ▪ Remote sensing	• Direct measurement: ▪ Fixed weather stations ▪ Mobile traverses
Typical Depiction	• Thermal image	• Isotherm map • Temperature graph



Mean daily variations of summer air temperature at urban (M) and rural (P) stations during clear and calm days in Brno region (left) and daily variation of urban heat island intensity (ΔT); UHI intensity is expressed as a difference between mean air temperature at urban and rural stations (right)

1. How do Urban Heat Islands form?
2. How we can estimate UHI intensity depending on available data?
3. What are the main problems related to UHI?
4. Can be there any benefits of UHI?

Part V. Urban Remote Sensing (URS), surface UHI



Principle – Stefan-Boltzmann law:

The thermal energy radiated by a **blackbody** is proportional to the fourth power of the absolute temperature:

$$M = \sigma T^4$$

M – thermal energy

T – absolute temperature

σ - the Stefan–Boltzmann constant

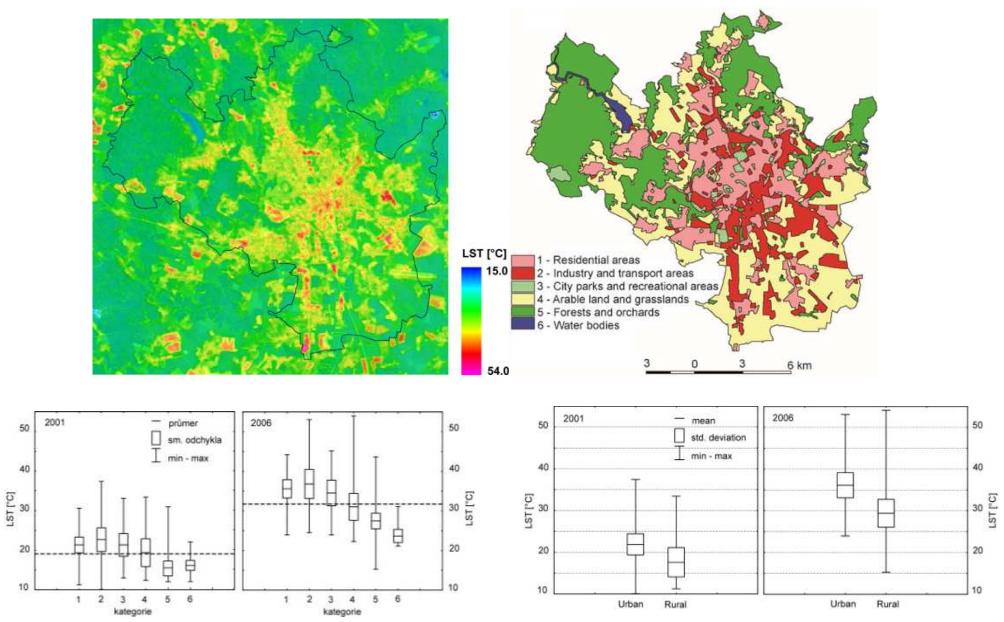
Real surfaces:

$$M = \varepsilon \sigma T^4$$

ε - emissivity

There are at least **two problems** in urban remote sensing:

1) How to determine emissivity of real surfaces in highly heterogeneous urban environment. Emissivity can be estimated from land cover maps (systems with a single thermal band - LANDSAT) or can be calculated directly from thermal imagery (systems with several thermal bands systems - ASTER)
2) How to recalculate LST - Land Surface Temperature, T_{2m} – air temperature in 2 meters above the ground as the relation between LST and T_{2m} strongly depends on land cover types

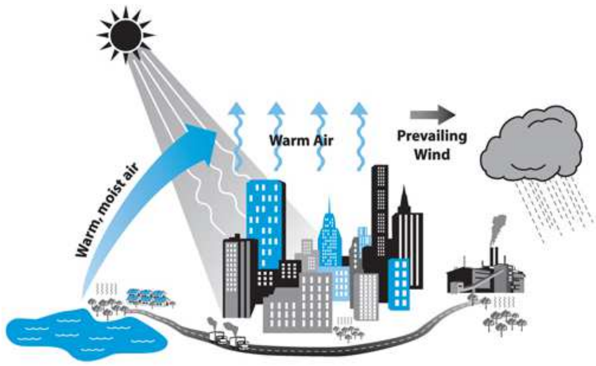


Land surface temperatures (top left) and main land cover types (top right); contribution of the main land cover types to surface UHI (bottom left) and estimation of surface UHI intensity (bottom right) in Brno area

1. What are limitations of URS in terms of spectral, spatial and temporal resolution?
2. What are the main benefits of URS for heat wave studies compared to air temperature analysis?
3. How can be URS used for practical urban planning, regional development and for better adaptation to climate change?

Part VI. Precipitation in urban areas

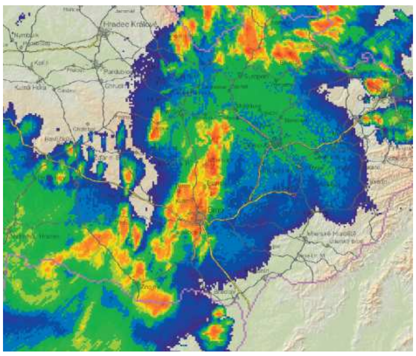
- precipitation is not continuous in time and space
- empirical studies sometimes show contradictory results
- it is not clear whether urban environments initialize new precipitation events or whether they just intensify existing precipitation
- most studies proved that precipitation totals in cities and in their leeward side are 5–15% higher compared to rural areas



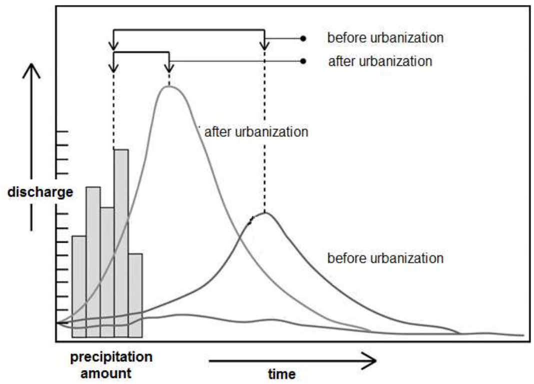
Modification of precipitation regime in urban environment; a general model adopted from http://www. ucar.edu/communications/staffnotes/0603/cities.shtml)

Precipitation in urban areas is modified due to three different effects:

- **thermal effect** (UHI and stronger convection in summer -> more showers and thunderstorms)
- **mechanical effect** (higher roughness -> lower velocity of atmospheric fronts -> more precipitation)
- **pollution effect** (more condensation nuclei)



Spatial distribution of radar reflectivity (maximum values in vertical direction) measured at meteorological radars at 15 July 2009, 19:25 hours of central European summer time



Before and after urbanisation hydrograph (adopted from Christopherson 1997)

1. What are the main impacts of changed precipitation regime on people living in cities?
2. How we can define extremity of precipitation regime?
3. What is the role of other factors such as relief, position, land use etc.?
4. How can be negative effects mitigated in urban-planning design?

Part VII. Spatio-temporal variability of other meteorological elements in urban areas

Besides air temperature and precipitation **wind field** and **humidity** are modified in urban climate

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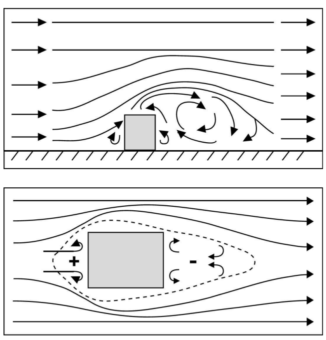
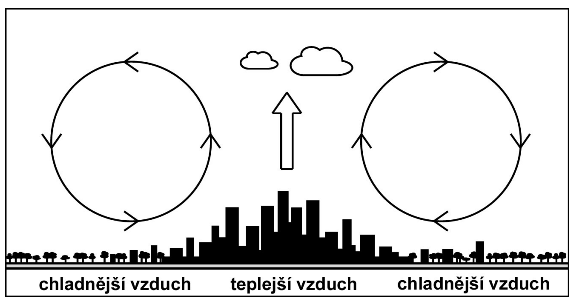
- Spatial and temporal variability of air humidity in urban areas is the result of evapo-transpiration, condensation and advection processes. There are several positive and negative feedbacks.
- Higher temperature -> higher intensity of evapotranspiration (that is however low due to lack of vegetation
- No consumption of latent heat -> rising temperature
- Fast runoff -> les intensity of evaporation
- **Urban dry island**

Wind filed in urban environment is modified due to **mechanical** (left figure) and **thermal** (right figure) effects



Wind field modification in urban environment in vertical (above) and horizontal direction (below)



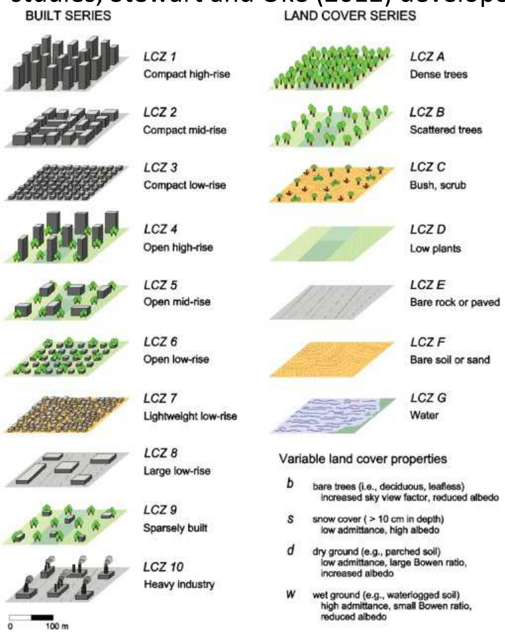
Local circulation resulting from temperature differences between rural and urban areas (modified after Munn 1968)

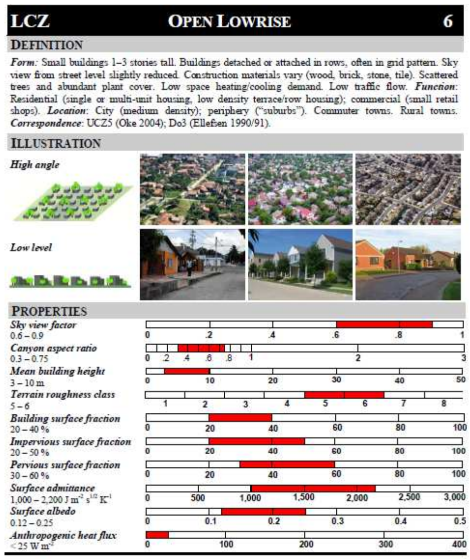
The ratio between *Fmax* (maximum daily wind speed) and *Favg* (mean daily wind speed) may be used as a simple measure of intensity of turbulence. The ratio is clearly higher at the urban station.

1. How does the vegetation in urban areas influence humidity?
2. What can be the most important negative effects of wind field modification in urban areas?

Part VIII. Local climate zones

- Until recently, there was no universal approach to describe and characterize the physical nature of cities for urban climatologists.
- Much of the existing terminology was not transferable across cultural and geographical regions.
- To help standardize methods of observation and documentation in urban heat island studies, Stewart and Oke (2012) developed the Local Climate Zone (LCZ) classification scheme.





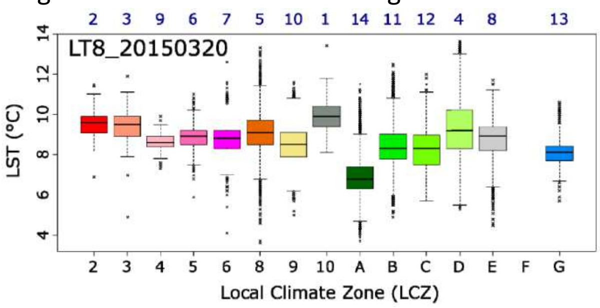
Local climate zones are formally defined as regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometers in horizontal scale.

Each LCZ exhibits a characteristic geometry and land cover that results in characteristic screenheight temperature regime that is most apparent over dry surfaces, on calm, clear nights, and in areas of simple relief.

LCZ scheme consists of 17 standard LCZs, of which 15 are defined by surface structure and cover and 2 by construction materials and anthropogenic heat emissions. The standard set is divided into “built types”(1–10), and “land cover types”(A–G)

There are several methods how to define LCZ:

- Bechtel method based on automatic classification of satellite imagery
- GIS method using GIS database and a set of logical rules in the form of decision tree



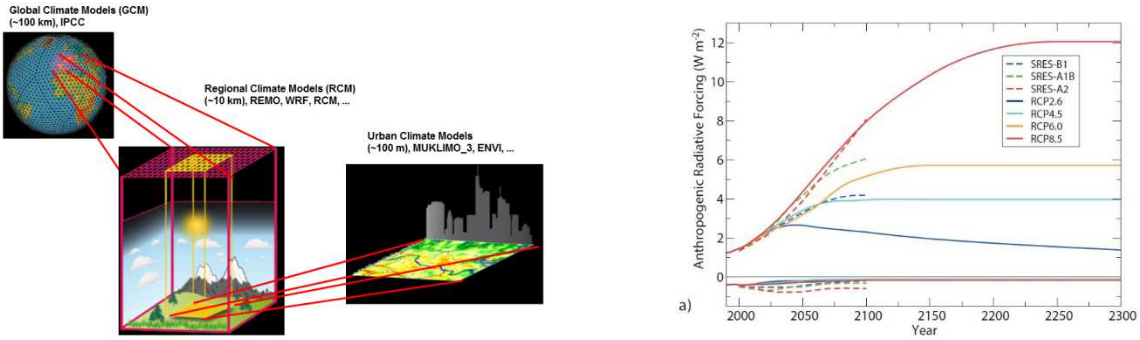
Box-plots with typical LSTs derived from satellite imagery in individual LCZ classes in Brno.

1. Why is simple Urban – rural division insufficient in urban climatology?
2. What were the main reasons to create LCT classification scheme in urban climatology?
3. How can be LCZs used for mitigation negative effects of UHI and heat waves?
4. How can be LCZ useful e.g. to architects, planners, ecologists, and engineers?

PART IX. Urban Climate Modelling

Climate projections indicate that the frequency, intensity, and duration of heat waves is very likely to increase. In the future cities may become more often exposed to extreme heat stress.

Over the past decades, numerical models of varying complexity have been developed to represent urban surface physics in atmospheric models.



*Climate models hierarchy (left) and **Radiation concentration Pathway** scenarios (right)*

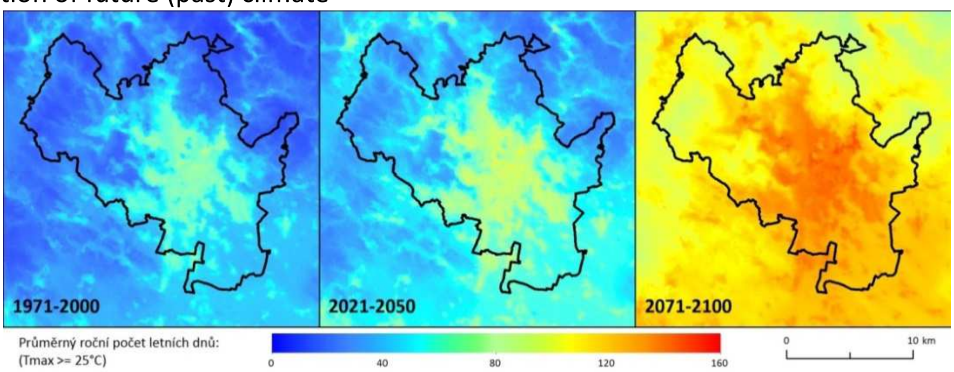
RCPs are scenarios of future climate. They are four greenhouse gas concentration trajectories adopted by the IPCC. They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. RCPs are named after a possible range of [radiative forcing] values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively).

MUKLIMO_3 - an example of urban climate model, typical input data

- Elevation model and land use in the form of Local Climate Zones (LCZ)
- Land Use Table – descriptive attributes of individual LCZs
- Meteorological data – initial state of the atmosphere

Model runs:

- Control run (validation) – ability to simulate present climate
- Simulation of future (past) climate



Období	MIN	MAX	AVG
1971-2000	10,5	83,4	37,2 (100 %)
2021-2050	17,8	93,2	52,3 (140 %)
2071-2100	40,7	121,3	81,4 (220 %)

Mean number of summer days (T_{max} ≥ 25°C) in Brno area in different periods. Future climate based on RCP8.5 scenario

1. What aspects of urban climate would be useful to simulate?
2. What is the main purpose of urban climate models?
3. Are there any other method how to do projections of future climate? What is a difference between “projection” and “prediction”?

Part X. Urban adaptation to climate change

In cities climate change is strongly intertwined with other socio-economic changes: demographic trends, higher proportion of older people, urbanization, competing demand for water, etc. These socio-economic changes **increase the vulnerability of people**, property and ecosystems under current climate conditions as long as no adaptation measures are taken.

Negative impacts of climate change in cities (higher temperatures, changing precipitation patterns, sea level rise, …) require various actions, strategies, technologies that help inhabitants to adapt or mitigate.

Adaptation to climate change is the adjustment in urban areas in response to actual or expected climatic stimuli or their effects. It moderates harm or exploits beneficial opportunities of climate change.

Adaptive capacity is the ability of urban areas to adjust to climate change to moderate potential damages, to take advantage of opportunities or to cope with the consequences.

Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes.

Mitigation of climate change is an anthropogenic intervention to reduce the anthropogenic forcing of the climate system. It includes strategies to reduce greenhouse gas sources and emissions and enhancing greenhouse gas sinks.

Resilience is the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization and the capacity to adapt to stress and change.

Green city

Blue city

White city (cool roofs)

Resilient cities

Adaptation options

- **'Grey' infrastructure approaches** - physical interventions or construction measures and using engineering services to make buildings and infrastructure essential for the social and economic well-being of society more capable of withstanding extreme events.
- **'Green' infrastructure approaches -** contribute to the increase of ecosystems resilience and can halt biodiversity loss, degradation of ecosystem and restore water cycles. At the same time, green infrastructure uses the functions and services provided by the ecosystems to achieve a more cost effective and sometimes more feasible adaptation solution than grey infrastructure.
- **'Soft' approaches** - include policies, plans, programs, procedures, information dissemination and economic incentives to reduce vulnerability, encourage adaptive behavior. They are related to behavioral changes, emergency systems and the adequate provision of information to vulnerable groups.

Further possibilities: Energy saving and passive houses
Warning systems and disaster risk management programs

Urban adaptation relies on action beyond cities' borders (flooding due to inappropriate land use and flood management in upstream regions) and incudes reducing cities' dependency on external services

1. How to persuade politicians or local authorities that some adaptations are needed?
2. What is the role of climatologists (geographers) in the adaptation process of cities to climate change?