Charles University in Prague
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HABILITATION THESIS

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Urban climate in Central Europe

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Contents

Introduction

Cities are home to over 50 percent of the world population, and the urbanization has accelerated in the last decades. The change of natural environment in cities – especially use of artificial materials like concrete, asphalt, glass, metals, etc. leads to change of its atmosphere and even creation of its climate. Traditionally, air pollution has been the main hallmark of the urban atmosphere, as found in antiquity cities. This problem increased in the Middle Ages when coal-burning became widely used in larger cities, London being one of the best examples. And it was London that first appeared in the cornerstone of urban climatology. Luke Howard published the earliest book dealing with urban climate, i.e, with unique features of the city's climate, in 1818. Howard [1818] recognized a significant alteration of meteorological elements. The most important finding of Howard was identification of the warmer temperatures in the urban center compared to the surrounding rural areas. His studies laid the foundations of urban climatology and especially its main feature – the urban heat island. In the next decades of the 19th century, a number of monographic studies dealing with the climate of different cities appeared. This was supported by an increasing number of meteorological stations in city centers and in the countryside. For example, Johann Gregor Mendel is known as an outstanding geneticist. But he was involved in meteorology and climatology, too, and intensely focused on the climate of Brno, the second-largest city of Czechia (see, e.g, Dubec and Orel [1980]).

The rapid increase in urban areas' size after World War II led to deterioration of air quality, meteorological visibility and the alteration of other meteorological parameters. That supported a growing number of studies focussing on urban climate after 1950s. Among them, some remarkable comprehensive monographies can be found, like, e.g, Oke [1979] or Landsberg [1981].

As the cities become more extensive, the impact of urbanized areas on the environment becomes crucial. We can find many ways in which cities influence atmospheric conditions. Urban development modifies the radiative and thermal balance and moisture and aerodynamic properties of the surface. Fluxes and balances of heat, mass, and momentum are influenced by urban surfaces, too, creating a distinct urban boundary layer. This modification of local conditions in metropolitan areas can manifest in many meteorological elements and phenomena, like temperature, humidity, wind, clouds, fogs, sunshine, precipitation.

The main feature of the urban climate is urban heat island (UHI). The concept of the UHI was introduced already some 50-60 years ago Oke and Maxwell [1975]. Different radiative, thermal, hydrological and aerodynamical properties are the reason why city centres have a few degrees higher temperature than the outskirts of the city. This difference can be found in daily average temperatures, but the difference varies throughout the day. The differences are usually larger during the evening and night hours. In the morning, the so-called urban cold island (the situation reversed to UHI, e.g, Goncalves et al. [2018]) can build up for a few hours. The development of the UHI is strongly influenced by synoptic circulation (large-scale atmospheric conditions).

When studying the UHI, we usually talk about the intensity of the UHI, the temperature difference between the city center and the surrounding rural areas – but sometimes it's not easy to compute this parameter since suitable meteorological stations are not always available (both, in the city centers and surrounding (Chapter 1)). The lack of surface observation can be partly solved by using remote measurement techniques, especially the satellite measurements (Chapter 2).

The UHI intensity is greatly correlated with the population of inhabitants and the city size. An increasing UHI intensity can be expected due to increasing number of the population living in the cities in the coming decades. But the UHI can have negative effects on the city's inhabitants, especially older people. For example, we can observe higher night-time temperatures making it difficult to achieve a comfortable temperature for sleeping and resting of inhabitants without air-conditioning. Uncomfortable conditions can occur during hot sunny days in outdoor spaces with artificial surfaces increasing heat stress, especially to vulnerable people. Finally, the higher energy demands caused by higher need of air-conditioning should be considered among the negative effects of UHI.

The adverse effects of the UHI will be very likely amplified during the heat waves that are expected to become more frequent due to global warming (e.g, Founda and Santamouris [2017]). For this reason, many studies and projects have been dealing with counteracting the negative effect of UHI, or generally of the urban climate, in the last few decades (see Chapter 3). To find the best solution for mitigating the UHI effect, modeling its impact in a combination with field measurement campaigns where possible is needed.

The above-mentioned main points of urban climate research, focused on the central Europe region, especially on Prague, are the basis of this thesis. It has been created as a summary and evolution of materials published in selected papers during my research career. The core is built up upon four stand-alone publications with my major or great participation, provided in the appendices and dealing in large part (though not exclusively) with urban heat island and climate and methods of their study:

- Zak, M, Nita, I, Dumitrescu, A, Sorin, C, 2020: Influence of synoptic scale atmospheric circulation on the development of urban heat island in Prague and Bucharest, *Urban Climate*, 34, DOI: https://doi.org/10.1016/j.uclim.2020.100681

  Appendix A (p. 37)

- Zak, M, Miksovsky, J, Pisoft, P, 2015: CMSAF Radiation Data: New Possibilities for Climatological Applications in the Czech Republic, *Remote Sensing*, 7 (11), DOI: https://doi.org/10.3390/rs71114445

  Appendix B (p. 51)

- Zak M, Zahradnicek P, Skalak P, Halenka T, Ales D, Fuka V, Kazmukova M, Zemanek O, Flegl J, Kiesel K, Jares R, Ressler J, Huszar P, 2016: Pilot Actions in European Cities – Prague. In: Musco F. (eds) Counteracting Urban Heat Island Effects in a Global Climate Change Scenario. Springer, Cham, DOI: https://doi.org/10.1007/978-3-319-10425-6_14

  Appendix C (p. 65)

- Karlicky, J, Huszar, P, Halenka, T, Belda, M, Zak, M, Pisoft, P, Miksovsky, J, 2018: Multi-model comparison of urban heat island modelling approaches, *Atmospheric Chemistry and Physics*, 18, DOI: https://doi.org/10.5194/acp-18-10655-2018

Appendix D (p. 94)

Additional supporting materials have been adapted from the following publications, too, though they are not enclosed within the thesis:

- Halenka, T, Belda, M, Huszar, P, Karlicky, J, Novakova, T, Zak, M, 2019: On the comparison of urban canopy effects parameterization, *International Journal of Environment Protection*, 65, 177-194.
- Huszar, P, Karlicky, J, Doubalova, J, Sindelarova, K, Novakova, T, Belda, M, Halenka, T, Zak, M, Pišoft, P, 2020: Urban canopy meteorological forcing and its impact on ozone and PM2.5: role of vertical turbulent transport, *Atmospheric Chemistry and Physics*, 20, 1977–2016

Finally, to provide a complete picture of the discussed topics, selected fragments of yet unpublished analyses or those currently under preparation were also included.

While the topics covered in this thesis vary substantially in terms of used methods, examined datasets, and sometimes even in the purpose of the particular analyses, joint themes can be highlighted. The general subject of urban heat island study pervades in my past research, from connection to synoptic-scale circulations (Zak et al. [2020]) through observing and detecting methods of the UHI, the problem of stations availability including remote sensing methods for climatological analyses (Zak et al. [2015]), to study of the adverse UHI effects on urban inhabitants (Zak et al. [2016], Zahradnicek et al. [2014]). The issue of modeling the UHI effects and its connections to air quality issues also permeates through some of my past work (Huszar et al. [2020], Halenka et al. [2019], Karlicky et al. [2018]).

Despite the obvious topical diversity of the problems addressed here and the resulting specificity of the conclusions reached, general insight regarding the specific features of the urban climate in central Europe can be found. These are provided in the following chapters of this thesis. As already mentioned above, four main themes are discussed in four topically focused (though still partly overlapping and interrelated) segments. Chapter 1 shows the specifics of urban heat island in central Europe, including a discussion of station selection for urban climate study. Chapter 2 deals with remote sensing methods possibilities in climatology, with a focus on UHI analyses. Chapter 3 addresses the adverse effects of the UHI, focusing on thermal comfort, and briefly describes the possibilities of UHI mitigation or counteraction with a description of experiences gained for the city of Prague. The modeling approach of the UHI evolution and its effects on urban weather conditions are explored in Chapter 4. Finally, summarizing and concluding remarks are provided in Conclusion, together with some thoughts on our related ongoing and future research.

1. Urban heat island in Central Europe

Urban heat island (UHI) is relatively common phenomenon of metropolitan areas and a typical feature of their climate. UHI is manifested by significantly higher temperatures in urban areas compare to their surroundings (with either rural or non-urban characteristics). There are many reasons for the UHI occurrence, most of them are relatively well understood (e.g. Landsberg [1981], Oke [1982], Arnfield [2003]).

The main cause is connected with the modified physical characteristics of materials used in the urban areas. The artificial surfaces (of e.g. concrete or asphalt) are absorbing much more solar radiation compared to the natural surfaces. This lead to surplus heating of the surfaces. Therefore surfaces emit long-wave radiation, especially during nocturnal hours. Another factor leading to the increase of temperature is antropogenic heating. It is created by waste heat released during energy consumption (cooling, heating, transportation, industry etc.), called anthropogenic heating. It can be mathematically described through the surface energy balance model (Oke [1988]):

$$R_n + F = H + LE + S + A \tag{1.1}$$

where R_n is the net all wave radiation; F stands for the anthropogenic heating; H stands for sensible heat (that heats the air in the city); LE is the latent heat (i.e. the heat required to convert a solid into a liquid or vapour); S represents heat storage (absorbed e.g., by building materials); and A is the advective heat flux . Heat and energy (left side of 1.1) is mostly stored in materials with low albedo and higher roughness (e.g. asphalt), while lawn, parks, trees etc. act as a heat sink. Therefore, urban areas with artificial materials experience higher temperatures than vegetated areas.

The UHI effect can be explored in three ways according to their measurement altitudes: boundary UHI, canopy UHI, and surface UHI (Zhang et al. [2009]). Boundary UHI can be understand from the rooftop's level to the atmosphere (Mirzaei and Haghighat [2010]). It investigates the UHI effect at mesoscale point of view (from 1 to 10 000 km^2) and can be for example studied by help of radiosondes (Voogt [2007]).

Canopy UHI is considered from the surface to the rooftop (Krayenhoff and Voogt [2007]). Analyses of the canopy UHI are usually the object of microscale studies and the main input data are obtained from weather stations (Kato and Yamaguchi [2007]). Surface UHI is a feature of the earth's surface level and is usually explored by satellite images (see Chapter 2) to derive the surface UHI effect.

The magnitude of the UHI effect can be expressed in terms of Urban Heat Island intensity. This parameter is obtained as the temperature difference (usually in °C) between urban and rural (or non-urban) temperatures measured simultaneously. The intensity of UHI is greatly influenced by e.g., land-use, population density, vegetation, density of built-up area (e.g., Landsberg [1981], Oke [1982, 1988]). Meteorological conditions can also influence UHI magnitude, as was con-

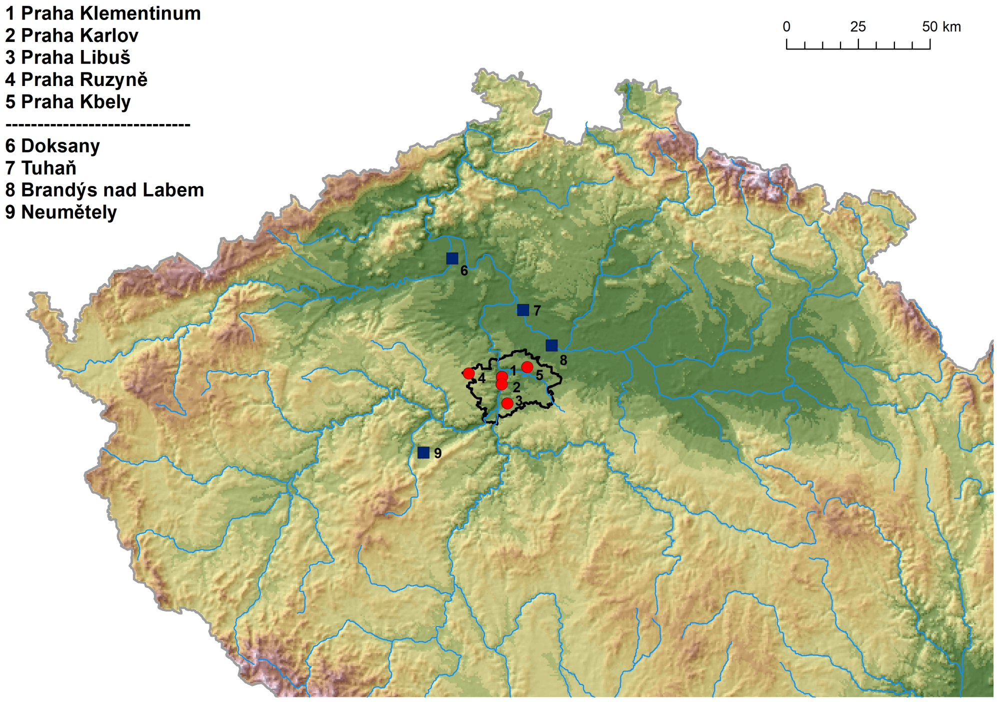

Figure 1.1: Locations of surface climatological stations traditionally used for studying the UHI of Prague.

firmed by many papers (e.g., Sakakibara and Matsui [2005], van Hove et al. [2015]).

Our research focused on central Europe, especially on Prague, the Czech Republic's capital city. Prague's urban heat island has been studied several times, usually using the traditional comparison of urban-rural long-term station pairs. These results have provided information about the UHI of Prague's intensity, its annual course, and long-term changes under climate change. For the city of Prague, such pair of stations usually involves Prague, Klementinum station situated in the very city centre, being one of the stations with the longest continual temperature records in Europe (world), starting in 1775. Of course, as many old urban stations are situated in the heart of a city, its location is not representative of the WMO (World Meteorological Organization) guidelines (placing of the screen with thermometers). But it mirrors the influence of densely built-up area of the city center very well. Before automatization in 2013, only three measurements per day were carried out (7, 14, and 21 o'clock local time); after automatization, 10-minutes observations are available. Another station suitable for UHI study in Prague is the Karlov station, which can be found approximately 2 kilometers from Klementinum (in the building where the office of Dean of the Faculty of Mathematics and Physics of Charles University is situated). This is a so-called synoptic station providing hourly measurement, not only of temperature, but full range of meteorological parameters and phenomena (including wind, cloudiness, sunshine duration, radiation, humidity etc.), i.e., variables needed for calculation of the thermal comfort parameters (see Chapter 3).

As a "rural" station of the stations-pair, either airport stations (typically Ruzyne, sometimes Kbely) are used – both of them being synoptic stations and therefore providing the hourly data with the full range of meteorological parameters; or some of the stations outside of the city of Prague – usually any of the following climatological stations: Dobřichovice, Brandys nad Labem – Stara Boleslav, Tuhaň, Neumětely or Doksany (see Fig. 1.1). All the stations are operated by the Czech Hydrometeorological Institute, that is also responsible for quality checks.

When analyzing the UHI based on station-pairs, it is not always easy to find the best-suited combinations; therefore, more stations have sometimes been used. Besides the question of sufficient data record (full length, all parameters needed), we have to deal with different altitudes of the station used. Another point to be mentioned is the suitability of station selection based on how the UHI effect is mirrored in the measurement. Regarding the effect of the UHI on the day-to-day temperature variability, the Czech Republic area has been (to our best knowledge) for the first time studied in Zak et al. [2019b]. For this purpose, the difference between the day-to-day variation of daytime maximum temperatures and night-time minimum temperatures has been used. Statistical methods based on Anderson et al. [2018] paper were applied, with day-to-day (DTD) temperature variability expressed as follows:

1) absolute difference between the ambient temperatures of adjacent days:

$$DTD = \frac{\Sigma_{i=1}^{N}(T_i - T_{i-1})}{N-1} \tag{1.2}$$

2) the difference between the DTD variation of daytime temperatures and night-time temperatures:

$$\triangle DTD = DTD(T_{max}) - DTD(T_{min}) \tag{1.3}$$

Urban sites are characterized by positive (i.e., daytime DTD(Tmax) exceeds night-time DTD(Tmin)), or less negative values, while rural sites are characterized by negative (i.e., night-time DTD(Tmin) exceeds daytime DTD(Tmax)), or less positive values. DTD values show seasonality with peak for minimum temperature in winter months (when the highest albedo of surfaces occurs, leading to less energy storage) and minimum in July (opposite conditions). When applied to Prague's stations, urban effects can be clearly detected for Karlov and Klementinum stations. On the other hand, some stations usually classified as rural when performing UHI analysis of Prague do not exhibit the $\triangle DTD$ metric's variation expected to be associated with a typical rural station (Fig. 1.2).

The development of the UHI phenomenon is strongly influenced by large-scale (synoptic) circulation. Under high pressure areas, the conditions are generally more favorable due to smaller cloudiness (i.e., higher direct radiation) and usually weak winds (Morris et al. [2001]). The mutual position of the city and anticyclone is important for the UHI development, since it influences the prevailing wind direction. Especially during winter season the low cloudiness under high pressure area conditions can develop and obscure the radiation weather development in the city. This can apply to wind, too. If the wind becomes too strong, the development of the UHI is hindered or suppressed. For Prague, the wind field over the city was simulated with the help of Calmet Modell (Scire et al. [2000]). This simulated wind speed and direction are much more convenient to

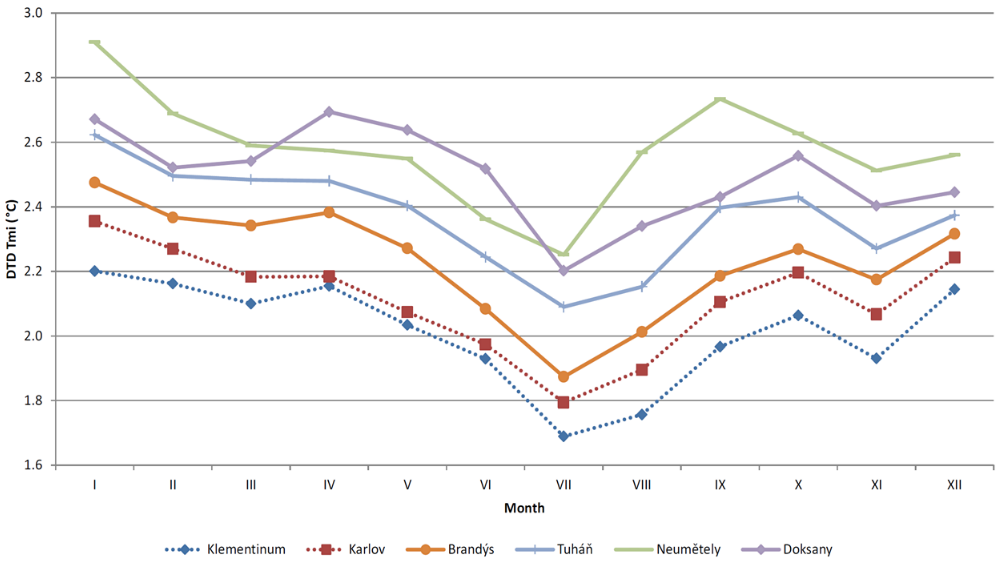

Figure 1.2: Monthly values of DTD for minimum temperatures.

study the connection between UHI development and wind speed because station measurements of wind in the urban area usually suffer from a lack of representativity. Based on these simulations, it was found that Prague's UHI vanishes when windspeed surpass 8 m.s^{-1} (e.g., Zak and Skachova [2010]).

The lowest UHI intensity occurs under cloudy and windy conditions, but not necessarily under cyclonic influence. Many studies focus on UHI development's during clear sky and weak wind, i.e. under optimal conditions. In contrast, the number of papers deeply studying relationship between the UHI intensity and different synoptic conditions is much smaller (e.g., Beranova and Huth [2005] for Prague; Polrolniczak et al. [2017] for Poznan, Poland; Beck et al. [2018] for Augsburg, Germany, or Kircsi and Szegedi [2003] for Szeged, Hungary). These studies are often using special measuring campaign data with high density of observations points but usually with short time period (few years), i.e., not suitable for capturing climate trend of UHI behavior. For Prague, such study was first done in 2005 (Beranova and Huth [2005])) using data from the 1961–1990 period, based on the Bradka synoptic catalog. This catalog distinguishes cyclonic/anticyclonic and directional characteristics (Bradka et al. [1961]). Beranova and Huth [2005] suggested that the North to North-East and South to South-West synoptic flows increase the Prague's heat island. However, it has to be mentioned that subjectivity of Bradka synoptic catalog has to be taken into account.

Therefore, in our research, an objective classification scheme of synoptic (weather) types was used for this purpose, the GrossWetterTypen (GWT) classification scheme of atmospheric circulation based on threshold criteria, like degrees of zonality, meridionality and vorticity of the large scale of MSLP field. This analysis deals with a period of 35 years between 1981 and 2016, i.e. a period greatly influenced by the developing climate change. Details can be found in Appendix A. Based on results of our research, the following points/main features of the UHI of Prague during last 60 years can be found:

1. UHI of Prague is a very pronounced and quite robust all-year-round feature of Prague's climate.

2. The UHI intensity varies between 2 °C and 2.5 °C based on daily minimum temperatures, with the highest values reached in August.

3. The maximum values of UHI intensity can exceed 4 °C (over 6 % of days, based on minimum temperatures).

4. The UHI intensity derived from mean and maximum temperatures is generally smaller (especially for the maximum temperatures) than minimum values.

5. City enlargement, traffic increase and changing of green spaces into buit-up areas have long-lasting magnified the UHI intensity in Prague, with a linear trend of around 0.13 °C / decade for daily minimum temperature.

6. UHI of Prague develops particularly under anticyclonic synoptic types, when south- to southwesterly wind prevail supporting warm air advection.

7. Fewer days of snow cover in the city center during the winter months have contributed to the increasing UHI intensity in winter season.

Although the results about UHI mentioned above are mainly connected with Prague, I also cooperated with colleagues from other countries in Europe, especially during the "UHI" project (Development and application of mitigation and adaptation strategies and measures for counteracting the global Urban Heat Islands phenomenon, 2011-2014), and particularly with urban researchers in Slovakia and Romania. Based on this cooperation, some interesting papers and conference proceedings were produced, dealing with Prague and Bratislava's similarities, and, especially, Bucharest. Despite Bucharest's distance from Prague, some similarities can be found in their physical-geographical background. The similar orographic features (with depression-like structures) partly affecting the synoptic scale circulation make them an interesting pair for comparison from an urban climate research point of view. Finally, both cities have experienced significant changes during the economic and political transition after 1990, which influenced their structure, industry, and transport characteristics.

2. Remote sensing approach

Regardless of its size, every settlement influences the meteorological elements. These influences have been traditionally studied with data from meteorological stations situated in the city and outside of the urban areas to describe the differences between them. Although there can be some difficulties when searching for the representative stations characterizing both areas (see Chapter 1), we usually can find suitable stations for larger (especially capital) cities describing either rural or urban areas. But when attempting to describe spatial features of urban climate and/or urban heat island, we are usually facing a lack of observing stations. Sometimes detailed information can be obtained by unique measuring campaigns (e.g., special rides with instruments investigating the urban environment or engaging a large number of measuring points), but these are usually time-limited and quite expensive. If a broader and more complex view of urban climate is required, remote sensing methods and its data can be used. These data were firstly available in the last decades of the 20th century as the satellite capabilities had developed and the spatial resolution of data provided increased. Further development occurred during the first two decades of the 21st century. Together with extending the length of data records, applicability in climate research has become more and more available.

For the European region, many climate data applicable for climate analyses can be obtained from the Satellite Application Facility on Climate Monitoring (CMSAF); details can be found at the webpage cmsaf.eu. CMSAF is one of eight Satellite Application Facility (SAF) of the EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites). CMSAF provides both operational products and long-term datasets. We have been widely working with these data, and bringing them more into climatological community in the Czech Republic. A general overview and discussion of possibilities of using CMSAF data in the Czech Republic was given in the paper (Zak et al. [2015]). It can be found in Appendix B of this thesis. Based on these experiences, Prague's UHI has been studied from the remote sensing point of view.

Generally, when studying urban climate or UHI from a remote sensing perspective, we have to deal with another approach compared to surface observations. One aspect deals with the limited horizontal resolution, the second one with time resolution, and of course, different parameters are usually available compared to the meteorological station measurements. Horizontal resolution differs according to which type of sensor and satellite is used – in the best case, the resolution in central Europe varies between tens of meters to few kilometers with higher resolution available from polar-orbiting satellites compared to geostationary satellites. The temporal resolution is much higher for data coming from geostationary satellites (usually 15 minutes to 1 hour), while we usually have just a few observations from polar-orbiting satellites per day. This discrepancy between temporal and spatial resolution influences our decision of which data to use. If we focus more on detailed evolution throughout the day then geostationary data would be better for the analysis. If the spatial features are more important polar-orbiting data would be preferred.

Due to its measurement method, satellite data provide different pictures of surface or close-to-surface climate compared to meteorological stations. For urban climate, traditionally, land surface temperature (LST) is the most used parameter. LST is the primary parameter when studying the physical processes of surface energy and water balance both on local and global scale (e.g. Li et al. [2013]). Knowledge of the LST provides information on the surface equilibrium state's temporal and spatial variations and is of a great importance in many urban climate applications. Therefore, LST has become quite popular among urban researchers (see e.g., Yang et al. [2020]) worldwide some years ago.

LST provides information about the thermodynamic temperature of the skin layer of a given surface. It tells us the how cold or hot the Earth's surface would be to the touch. It is a kinetic quantity without wavelength dependence. For ground-based, airborne, and spaceborne remote sensing instruments, LST is the aggregated radiometric surface temperature, i.e., based on a measure of radiance (Norman and Becker [1995]) ensemble of components within the sensor field of view. LST can be described as aggregated radiometric surface temperature obtained from combination of measurement of satellite-remote sensing instruments, airborne and ground based radiometric measurements.

The LST data can be obtained by mechanism described by Guillevic et al. [2018] as follows: *under clear sky conditions, the top of atmosphere radiance measured by a spaceborne sensor ($L_{sat,\lambda}$) includes contributions from the surface emission, the atmospheric upwelling radiance ($L_{\uparrow sky,\lambda}$) and atmospheric downwelling radiance ($L_{\downarrow sky,\lambda}$) reflected by the Earth's surface and attenuated by the atmosphere. Retrieval algorithms rely on one or more top-of-atmosphere spectral measurements to account for atmospheric effects and estimate LST:*

$$L_{sat,\lambda} = [\epsilon_\lambda B_\lambda(LST) + (1 - \epsilon_\lambda L_{\downarrow sky,\lambda})]\tau_\lambda + L_{\uparrow sky,\lambda}, \tag{2.1}$$

where ϵ_λ is the spectral emissivity at wavelength λ or representative of a specific (relatively narrow) domain [λ1, λ2] centred on wavelength λ, $B_\lambda(T)$ is the Planck function describing the radiance of a black body at temperature T, and τ_λ is the atmospheric transmittance.

LST product can be obtained from different instruments, e.g., sensor of Moderate Resolution Imaging Spectroradiometer (MODIS) aboard Aqua and Terra satellites or the Spinning Enhanced Visible Infrared Imager (SEVIRI) flying aboard METEOSAT satellites. These two primary sources were used in our work and analyses.

MODIS LST product from NASA is based on split-window approach and have a spatial resolution of 927 m at nadir. When the scan angle increases up to 65 degrees, the spatial resolution of the sensor degrades to about 6 km. Two bands - 31 (T31) centered on 11.03 μm and 32 (T32) centered on 12.03 μm - of brightness temperatures from MODIS are used to derive LST value by the generalized split-window algorithm (Wan and Dozier [1996]):

$$LST = b_0 + (b_1 + b_2\frac{1-\epsilon}{\epsilon} + b_3\frac{\triangle\epsilon}{\epsilon^2})\frac{T_{31}+T_{32}}{2} + (b_4 + b_5\frac{1-\epsilon}{\epsilon} + b_6\frac{\triangle\epsilon}{\epsilon^2})\frac{T_{31}+T_{32}}{2} \tag{2.2}$$

where ϵ and $\triangle\epsilon$ are the mean and the difference of the emissivity values in bands 31 and 32. The coefficients b_k ($k = 0$ to 6) are influenced by surface air temperature (Tair), viewing zenith angle and water vapor content. They differs for day and nighttime (details can be found in Wan and Dozier [1996]). The spectral emissivity values in bands 31 and 32 is obtained from combination of senescent and green components (Snyder et al. [1997]). Satellites overpass central Europe twice during daytime and twice during nighttime.

CMSAF provide wide range of products from radiation over cloudiness to humidity and surface features, one of them being LST, too, although this variable can be obtained from the Satellite Applications Facility on Land Surface Analysis (LSA SAF), as well. The values are available every 15 minutes and the spatial resolution is 3 km (in nadir). The source for the LST computation in this SAF is Meteosat Second Generation (MSG), that fully covers central Europe. The retrieval algorithm details can be found in the corresponding Algorithm Theoretical Basis Document (Trigo et al. [2008]).

Based on LST remote sensing data, we can detect the so-called surface urban heat island (SUHI). SUHIs are observed using the remotely received spatial patterns of upwelling thermal radiance (Voogt and Oke [2003]).

SUHI can be characterized either by exceedance level or by comparing to prevalent meteorological conditions. Such information can help to identify the hot spots and/or the warmest areas throughout the city and allow for subsequent analysis of their causes. This can eventually lead up to urban planning changes in these overheat-prone areas in order to mitigate the adverse effect on urban inhabitants (see Chapter 3). When using real-time data, hot spots identification can improve heat warning issuing in the cities.

In case of Prague, before 2010s only limited usage of satellite data for UHI analysis can be found. During our research, firstly MODIS data have been used for identifying the SUHI in Prague – the main question was to find the possible limits of UHI. The extents of the UHIs were evaluated based on cross-profiles: the changing points along each profile were identified based on the Rodionov test (Rodionov [2004]) and correlated with land cover (Fig. 2.1).

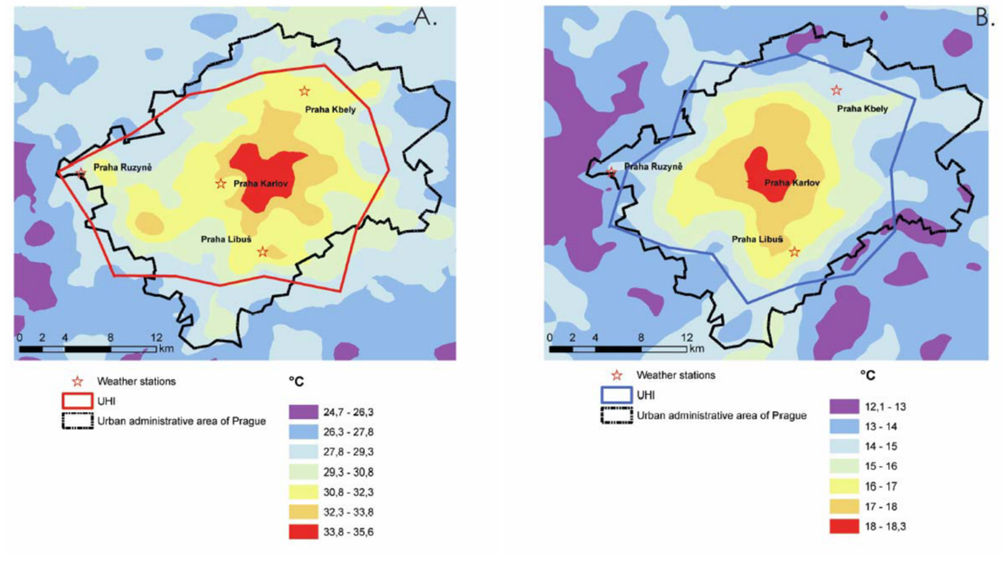

Figure 2.1: Day (A) and night (B) LST for area of Prague derived from only July MODIS images (2000-2006) with limits of UHI indicated (taken from Cheval et al. [2007]).

In order to find a long-term and seasonal characteristics uf SUHI, MODIS data were employed for 18 years long period in 2018 (during solving URBI PRAGENSI project, see Chapter 3). Based on satellite analysis of SUHI (Figs. 2.2 and 2.3), the following features can be found for Prague:

- the warmest part of the city (based on SUHI) is situated in the historical city centre (close to Vltava river) with relatively higher differences during night
- during daytime the warmest region is shifted south-eastward in the densely built-up area with only limited vegetation (see Land use map Fig. 2.4)
- the average intensity of SUHI is 5 to 6 °C for daytime, while being 4 to 5 °C for night-time
- the highest intensity of SUHI for daytime occurs in June (8 to 10 °C), for night-time in July (6 to 7 °C)
- throughout the year, the lowest intensity of SUHI for daytime can be found in November (around 2 °C) and for night-time in December (2 to 3 °C)

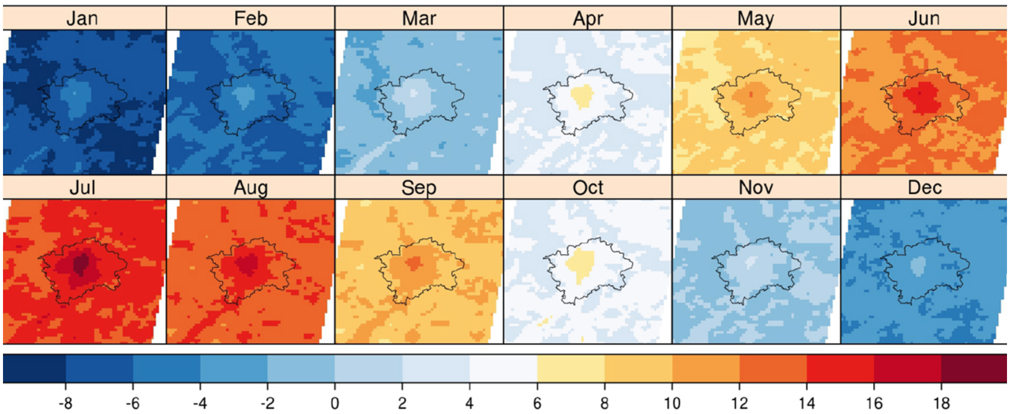

Figure 2.2: Monthly mean of LST based on nighttime MODIS images, period 2000 to 2017 (taken from Zak et al. [2019a]).

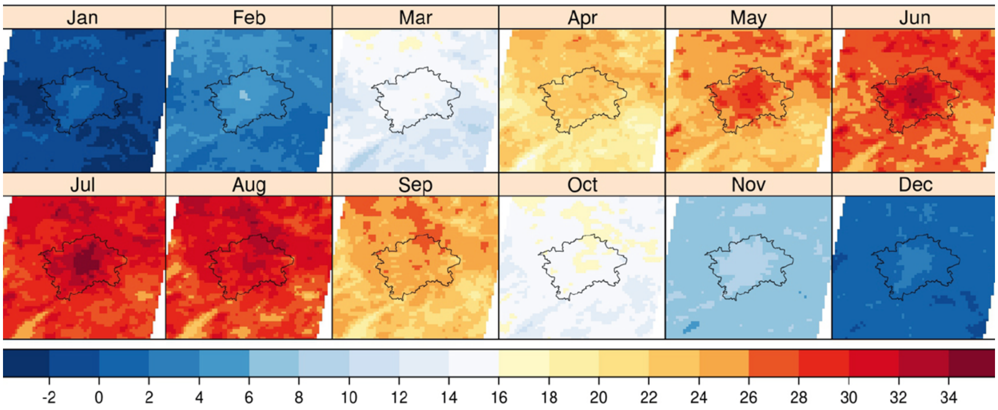

Figure 2.3: Monthly mean of LST based on daytime MODIS images, period 2000 to 2017 (taken from Zak et al. [2019a]).

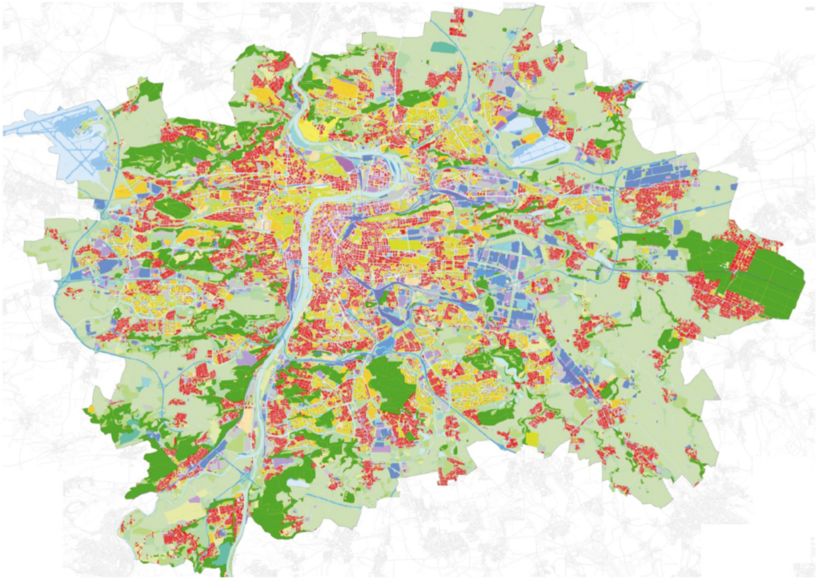

Figure 2.4: Land use map of Prague (blue - traffic infrastructure, red - housing, orange - public services, violet - industrial buildings, green - trees and green infrastructure, dark green - dumps, mining (source: http://app.iprpraha.cz).

3. Thermal comfort in cities and mitigation of the urban heat island effects

Urban Heat Island (UHI) is supposed to become on the main problems during this century due to increasing rate of urbanization of the human civilization (Rizwan et al. [2008]). UHI intensity for many cities around the world (including cities in central Europe such as Prague) has generally been increasing in the last decades. The main reason is the increasing density of built-up areas and changing brownfields and green spaces into areas with high-density buildings (usually having more floors, too). Also, the artificial sources of heat (air-condition, heating, transportation, industry) have been gradually contributing to this UHI intensity increase. This UHI intensification leads to urban overheating, generally negatively affecting the urban inhabitants. This overheating is causing substantial increase in energy demand for air-conditioning purposes. As shown by Santamouris et al. [2015]), the corresponding rise of the peak electricity load varies between 0.45% and 4.6% for each degree of temperature increase. The overheating also leads to the increase of harmful pollutants concentration, e.g., near-surface ozone.

Rising urban temperatures are causing increased thermal discomfort levels and generally influencing the health of the urban inhabitants. Heat exposure can have many negative effects. Firstly, it reduces occupational performance, it can worse minor illnesses, increase the risk of hospitalization, and eventually can increase risk of death. These health risks are probably to increase as the result of climate change and growing degree of urbanization in the future throughout many countries (Heaviside et al. [2017]). It takes its toll on the animal populations within cities, too. Some animal populations are more likely to struggle to find food, water, and shelter in hotter cities. But there is the other side of the coin, where some animal species may find cities more attractive than the wilderness and turn into urban pests that carry disease and become a nuisance (Kaiser et al. [2016], Tryjanowski et al. [2013]). Generally, increasing UHI intensity has negative effects worsening the city's economy and influencing, e.g., tourism.

These adverse effects have led to efforts to reduce the UHI. Various measures can be implemented to achieve this reduction, but generally, the modification of urban structures, surfaces, and materials are the most important. These include especially highly reflective materials (with high albedo) applied to buildings (e.g., in the form of cool roofs) as well as to urban surfaces. Based on the paper of Macintyre and Heaviside [2019], the largest temperature drop caused by cool roofs can be achieved when this method is applied to extensive industrial and commercial buildings, when reduction of temperature maxima above these surfaces can reach up to around 3 °C during the hottest days when the sun is in the highest position. Another possibility to mitigate UHI is using green measures – like green roofs and facades, or perhaps incorporating blue infrastructure measures, like increasing of the extent of areas with cooling water bodies (they need to be deep enough in order to maintain their function even during long heat waves). Sometimes the combination of blue and green features can be incorporated, or even some changes in the structure of blocks of buildings or city quarters. Many studies can be found dealing with this topic (e.g., Yuan et al. [2017], Ambrosini et al. [2014], Fikfak et al. [2020], Lai et al. [2019], Macintyre and Heaviside [2019]), usually focusing on aspects of the energy budget of the urban areas and concentrating on air temperature reduction. For this aim, various models having different spatial resolutions are used. If possible, their results together with local measurements are used for case studies evaluation the benefits of the proposed solution. But when health-related effects of urban conditions are investigated, not only air temperature should be used as the human body cannot perceive individual climatic parameters like an instrument.

One possible approach for the thermoregulatory response is to use the human energy balance equation (Thompson and Perry [1997]):

$$(M + W) + Q + R + C + E + S = 0 \tag{3.1}$$

where M represents the metabolic heat (internal energy production), W the physical work output, Q short-wave solar radiation income, R the long wave radiation, C the convective heat flow, E is latent heat flow (to evaporate water diffusing through the skin, for heating and humidifying inbreathed air and for evaporation of sweat), and S the storage heat flow for heating or cooling the body mass. The terms in this equation are positive when they result in energy gain for the body, and are negative for energy loss of the body. M is always positive, W and E (except of part for humidifying and heating the inbreathed air) are always negative.

To quantitatively describe the thermal effects of UHI the inhabitants really feel, we need to use thermal indices based on the human energy balance. These indices provide detailed information on the effect of complex thermal environment on humans (Hoppe [1999]). They are influenced by all climatic parameters. Some of these parameters are being partly interrelated (i.e., affecting each other).

Frequently used thermal indices (based on the human energy balance) are Predicted Mean Vote (PMV, Fanger [1972]), Physiologically Equivalent Temperature PET (Matzarakis et al. [1999]), Standard Effective Temperature SET* (Gagge et al. [1986]) or Outdoor Standard Effective Temperature Out_SET* (Spagnolo and de Dear [2003]), Perceived Temperature pT (Staiger et al. [2012]) and Universal Thermal Climate Index UTCI (Jendritzky et al. [2012]).

Computation of the thermal indices is quite demanding on meteorological data. Usually, it requires the following meteorological elements: air temperature, air humidity, wind speed, short and longwave radiation fluxes (or sunshine duration and/or cloudiness). It has to be mentioned, that these parameters can have a large spatial and temporal variability and thus influence the thermal indices values. Temperature and wind speed usually have the highest variability since they are greatly influenced by the obstacles in the complex urban areas. This has to be taken into account, and use high quality measurement for calculating these parameters. Representativeness of the measuring point/station should be deeply reflected in the following analysis of the computed indices.

In the Czech Republic, using of thermal indices was not widely popular until 2010s when during the so-called ”UHI ”Project (”Development and application of mitigation and adaptation strategies and measures for counteracting the global Urban Heat Islands phenomenon"), these quantities have started to be used more often (see Zahradnicek et al. [2014]), including in our research. Especially UTCI and PET have become quite popular in the Czech Republic in the last decade, the second one later used in the modified version of mPET (modified Physiologically Equivalent Temperature, an improvement of PET using the multi-node model defining UTCI, see e.g., Chen et al. [2011] and Matzarakis et al. [2014]). PET can be described as *"the air temperature at which, in a typical indoor setting (without wind and solar radiation), the energy budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed"* (Hoppe [1999]). It has become one of the most commonly used indices in bioclimatology, because the computed values can be easily compared to those from other studies (Matzarakis et al. [2014]). Another important advantage of (m)PET is the use of °C as a unit, making the results easier to interpret to the wider public without deeper knowledge of human biometeorology.

During our research, the PET index was calculated using the numerical model RayMan developedat the Meteorological Institute of the Albert-Ludwigs University Freiburg (Matzarakis et al. [2007]). This model requires hourly input data of air temperature, air humidity, wind speed and radiation or cloudiness. Based on our computation, the first pictures of PET values throughout the year as well as during the heat waves were obtained for the city of Prague (and other cities in Czechia, too). It should be noted that values between 18 °C and 23 °C are described as comfortable thermal perception, 23 °C to 29 °C as slightly warm, 29 °C do 35 °C as warm, 35 °C to 41 °C as hot, and over 41 °C as very hot thermal perception.

It's not a surprise that the highest values (partly over 30 °C) in Prague occur during summer months, July and the first half of August (Fig. 3.1), quite similar to the annual course of air temperature, but PET values during the afternoon/evening hours are about 3 °C to 6 °C higher than the air temperature. When comparing PET values in the city center with those in the urban outskirts, an interesting picture can be found – the largest difference over 4 °C occurs just after sunset during the summer season. A bit lower difference between PET in the city center and PET in the suburbs is detected during afternoon, especially in the summer. The smallest difference was found shortly after the time of sunrise in the summer half-year with values than 1.5 °C and in some days and shorter periods nearly approaching 0 °C – this is caused by less sunshine in the city center due to building obstacles during morning hours and connected to the urban cold island that can shortly develop during these periods. For the rest of the year and parts of the day, the difference between PET in the city center and the city suburb is usually about 2 to 3 °C. PET values can be used for computation of characteristics similar to those used for air temperature, like summer and tropical days, including the number of hours with PET above given threshold. E.g., the number of PET tropical days in Prague's center is about 2.5x higher than according to regular air temperature. Another interesting picture can be obtained if we look at the hottest days. The PET values are 5 °C to 8 °C higher during these extremely hot days, i.e., with PET values over 40 °C, making them days with very hot thermal perception. This highlights the potential hazard of these heatwaves, especially for elderly people and children.

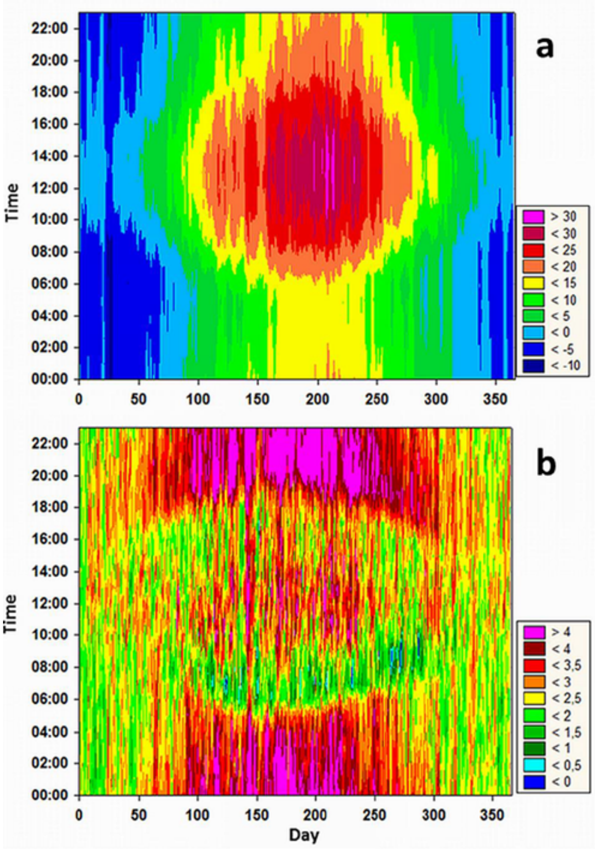

Figure 3.1: Example of the annual course of physiological equivalent temperature, PET (°C), at the Prague Karlov station (a) and difference between Karlov and Ruzyne station, period 2005-2013. 200th day is 19th July (taken from Zahradnicek et al. [2014]).

Compared to studies based only on air temperature, results using thermal indices ((m)PET or UTCI) produce different results. For example, using high reflective materials for the pavements or roads have an effect of greater shortwave reflection - this leads to increase of (m)PET values, although the air temperature is decrease since there is less energy stored in the surface. The green wall has different thermal characteristics, leading to lower (m)PET and, thus, more comfortable conditions. This is important not only from the thermal comfort point of view, but the aesthetic respect influences the use of the public space in cities by citizens and their choosing of places for spending time outdoors. Finally, easy understandable graphs and figures can be provided for better transfer of knowledge between researchers (climatologists) and end-users (urban planning, general public). The above-mentioned adverse effects of urban climate have gained more and more attention among urban planners and city stakeholders in the last decades, including the city of Prague. The era of changing climate leading to more intense heat waves, irregularities in precipitation regime, etc. contributes to the necessity of adaptation plans and/or cities' strategies. This planning is a complex matter where climatological inputs are very important and represent the first step. Therefore, cooperation between urban planners and climatologists is very desirable. To decide which adaptation measure is the best one, the climatological expertise and/or modeling approach is needed. This has become apparent to Prague's urban planners, too, especially during the solving of the "UHI" project, when the issues of of urban climate and urban heat island has gained large attention among the wider public. As a first step, the so-called pilot areas were selected to find the answer to the question "what happens when...".

For this reason, microclimatic simulations were performed for these pilot areas. Various types of simulations were used, from the quite simple one for a street corridor (Legerova) with heavy traffic using RayMan model, over a city quarter of typical brownfield (Bubny-Holesovice) using EVNI-met software, to green belt around the city using WRF (for meteorology) and CMAQ (for air quality) model. The results are described in Appendix C. Experiences gained during these simulations and the "UHI" project solving helped prepare the adaptation strategy of the city of Prague.

Experiences from the computations mentioned above were used and further improved during the implementation of another project, URBI-PRAGENSIS, solved between 2018 and 2020, where I have been involved, too. Some of the results of this project are discussed in Chapter 4.

4. Urban heat island modelling approaches

Adverse effects of urban climate, especially overheating due to exposure to extreme temperatures during heat waves can lead to thermal stress, hyperthermia, circulatory collapse or dehydration, and eventually even to death. The UHI phenomenon can be responsible for amplification of these dangers making mitigation strategies of great importance, as already mentioned in the previous chapter.

A wide variety of mitigation strategies can be found in urban planning to reduce UHI, as was mentioned in Chapter 4. These strategies when applied are good not only for reduction of thermal comfort in urban areas but can have quite complex influence on urban climatological conditions. And it is not always easy to evaluate the real response of these strategies. Therefore, numerical modelling of urban climate can be very helpful in answering the question what adaptation (or mitigation) strategies are the most suitable for the selected city or its part.

The urban climate models are diverse depending on the purposes of the study - we can e.g. explore the impact of the UHI on thermal comfort of citizens (on the scale of buildings), but also the effect of large-scale winds on urban ventilation (Mirzaei [2015]). Three levels/types of models can be distinguished: building scale models, micro-scale models and city-scale (that are actually mesoscale) models.

The building scale (or energy) models are mainly limited to an isolated building envelope and the influence of the buildings in the neighbourhood on its energy performance is neglected. They are constructed in order to investigate the impact of the future climate change scenario on the building envelope.

The micro-scale, or microclimate models are focused on interaction of a building with its surrounding environment in the surface layer. Urban canopy layer models (UCM) investigating the energy budget of an urban canopy layer belongs to this type of models, too (for details, see e.g. Mirzaei [2015])).

In the last decade, the urban boundary layer (UBL) have been increasingly studied by the mesoscale models with the urban canopy schemes coupled. Special impulse was provided after the widespread use of the mesoscale Advanced Research Weather Research and Forecasting (ARW-WRF) model (Liao et al. [2014]). UCM have a simplified urban geometry, like infinitely-long street canyons, and involves also 3-D urban surfaces (roofs, walls, roads). These models are, e.g., able to compute temperature profiles within the street canyon and include the important factor of an anthropogenic heat increasing the UHI intensity.

The influence of building surface material, orientation of buildings and street canyon configuration, vegetation including trees on inhabitants in the streets and on street ventilation can be investigated using UCM models. It has to be noted they have quite limited domain size due to high computational cost. City-scale models are very useful tool when investigating variation of UHI in a wider area of the whole city and its surroundings. These models are able to compute wide range of meteorological fields changes caused by urbanization, from temperature and moisture to cloudiness and radiation.

Very important question when modelling the UHI is how to parameterize the

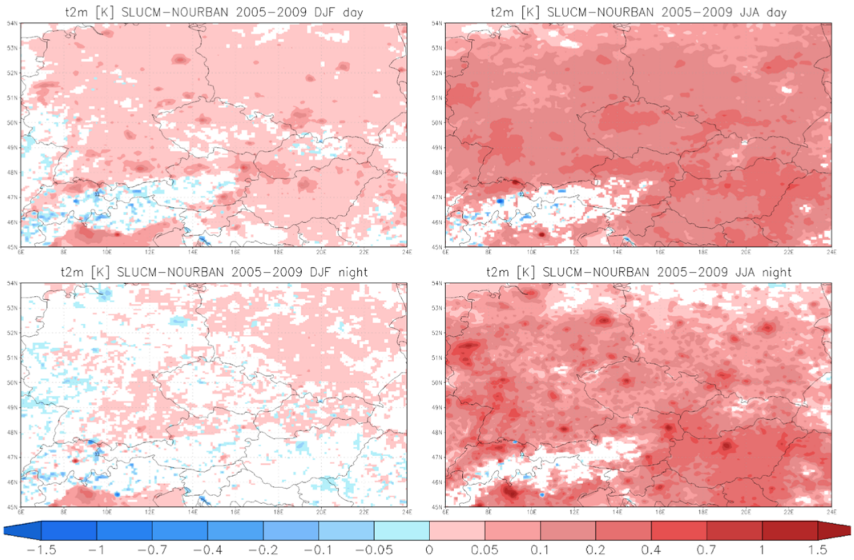

Figure 4.1: The impact of urbanized surfaces on the winter (left) and summer (right) near surface temperature for day (top) and night-time (bottom) conditions in K averaged over years 2005–2009 (reprint from Huszar et al. [2014]).

urban meteorological phenomena. This can be done simply by replacement of the surface parameters by an average value corresponding to the urban surface – so-called bulk parameterization (described, e.g. in Chen et al. [2011]). Another group of models have typically a single urban layer and an idealized street canyon (e.g. Single-Layer Urban Canopy Model - SLUCM; Kusaka et al. [2001]). The third type of models consider more layers of the urban environment with possibility of including different heights of the buildings and vertical structure of the urban canyon (e.g. Building Environment Parametrization - BEP; Martilli et al. [2002]).

It is important to mention that not only averaged values, but also the extremes and variability of meteorological parameters are crucial in assessing the urban impact including poorly observed or immeasurable parameters in the urban and suburban areas, like wind profile or boundary layer height. Generally, long-term simulations (the longer the better) are necessary if we want to evaluate the quality of computed variables against the measured parameters.

Modelling of UHI and/or urban climate specifics of Prague has started in the early 2010. An important stimulus appeared during solving the “UHI” project between 2011 and 2014 (see also Chapter 4). Regional climate model RegCM4.2 with coupled SLUCM was used in 2014 (Huszar et al. [2014]) of urbanization on conditions throughout the day and night in different seasons. The largest impacts were found during summer nights with up to 1.5 °C higher temperatures (Fig. 4.1) in the city centre than without considering urban surfaces, i.e. the results consistent with the values from the station observations. Another interesting findings derived from the simulations include the so called urban-breeze circulation (wind speed increase during nocturnal hours) (Fig 4.2), connected with convergent motions towards the city centre. This situation forms under the presence of thermally induced surface pressure gradient (Hidalgo et al. [2010]), or height increase of planetary boundary layer over most of time.

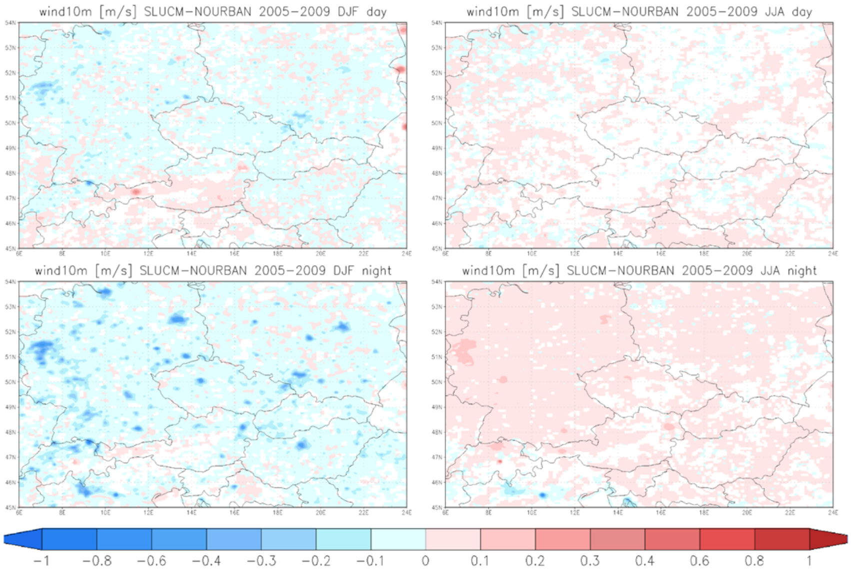

Figure 4.2: Same as 4.1 but for the wind velocity at 10 m in m.s-1 (reprint from Huszar et al. [2014]).

The question of different UHI modeling approaches was widely solved and discussed in the paper Karlicky et al. [2018], and the details can be found in Appendix D. Based on our results, all urban schemes captured the main features of urban meteorological conditions, not only UHI. No real difference between various models was discovered, and the anthropogenic heat influence on UHI was satisfactorily represented. Greater variance among different model approaches was found to impact the urban environment on the planetary boundary layer height and the surface wind speed. The investigation of pollutant dispersion modeling has shown slightly improving dispersion in the urban areas due to wind cleansing effect and convection and turbulence dispersion effect.

Later, the urban canopy meteorological forcing was studied (Huszar et al. [2020]), where the effect of the numerical model's sensitivity to grid resolution was investigated. A number of model simulations was carried out to answer the question what is the urban canopy meteorological forcing - this was realized by considering of the urban canopies or of the rural ones. These simulations were done primarily for Prague, but as can be seen from Fig. 4.3, the UHI of Berlin is also very well represented. The expected, well-pronounced effect on temperature (increase up to 2 °C, see Fig. 4.3) and wind (decreases by up to 2 m.s^1) was found, including similarities in the diurnal cycle of the urban canopy temperatures (with maximum warming over urban areas of Prague around 2.4 °C, see Fig. 4.4).

The question of impact of the urban land surface on extreme values was investigated in the paper by Huszar et al. [2020]). The results can be found in Tab. 4.1. Larger influence was found on the lowest temperatures compared to the average ones during winter (larger release of anthropogenic heat during cold days). Summer days with low temperatures and limited sunshine are affected less (radiation is trapped only limitary). In contrast, hot summer days with plenty of sunshine behave oppositely (much larger heat accumulation due to multiple reflections and trapping in street canyons). These results are similar to those shown by Zha et al. [2019]), who found that events with high and extreme temperatures

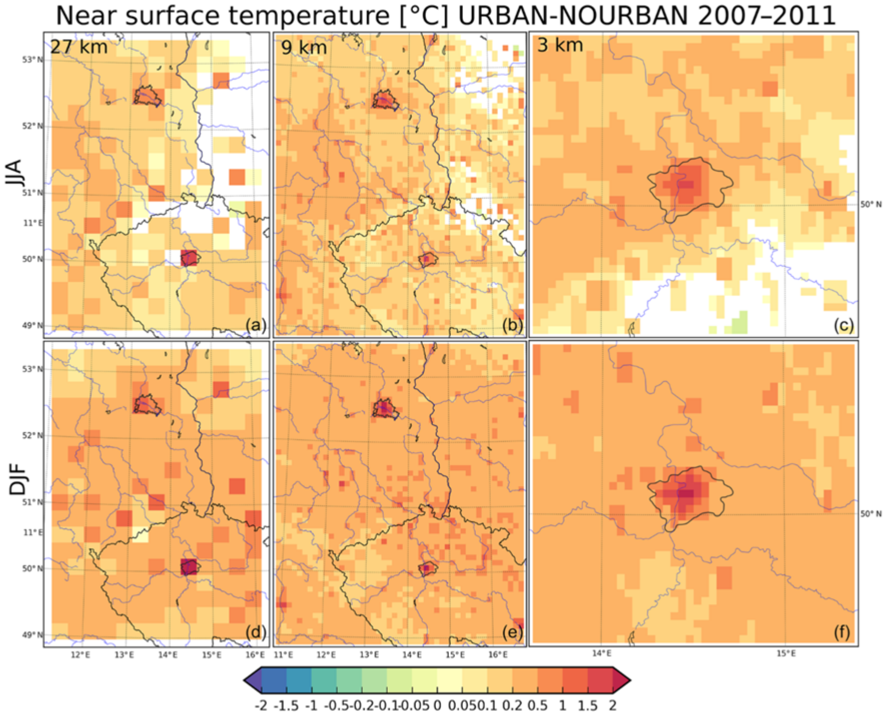

Figure 4.3: Impact of urban surfaces on near-surface temperature in °C for JJA (a, b, c) and DJF (d, e, f) for the three resolutions (27, 9 and 3km). Shaded areas represent statistically significant changes over the 98% threshold using a two-tailed t test. The geographic locations of Berlin and Prague are indicated by their administrative boundaries. (reprint from Huszar et al. [2020]).

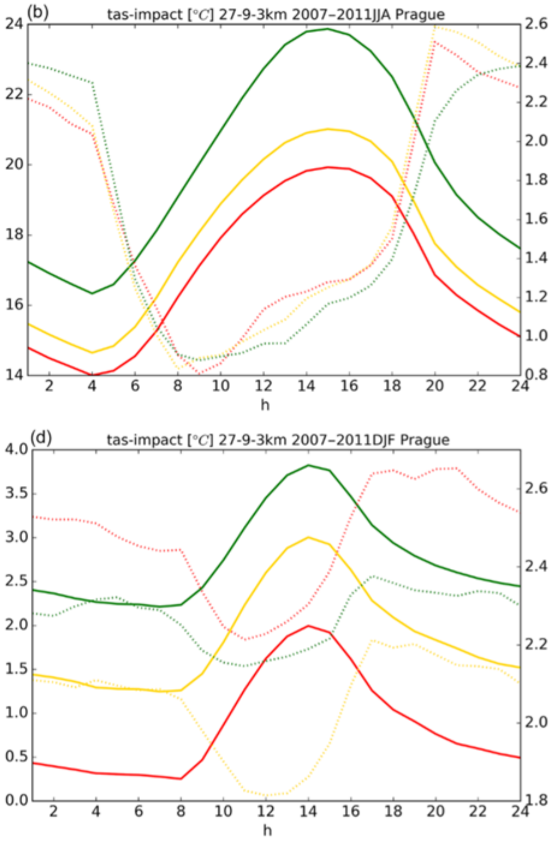

Figure 4.4: Impact of urban surfaces on near-surface temperature diurnal cycle in °C for JJA (b) and DJF (d) for the three resolutions (27km – red, 9km – orange and 3km – dark green). Solid lines are the absolute values (left-hand y axis) from the URBAN model experiment; dashed lines represent the urban impact (right-hand y axis). (reprint from Huszar et al. [2020]).

Prague	DJF			JJA		
	mean	5 %	95 %	mean	5 %	95 %
Δtas (°C)	2.4/1.3*	5.0/1.9	1.2/1.1	2.2/2.2	0.6/1.9	3.1/2.9
ΔPBLH (m)	384/128	294/45	450/248	480/265	248/195	491/353
Δwind10m (m s^{-1})	−1.1/ − 0.5	−0.34/ − 0.26	−2.57/ − 1.6	−0.64/ − 0.15	−0.25/ − 0.29	−1.45/ − 0.35
Berlin						
Δtas (°C)	1.44/1.46	1.6/1.6	0.5/1.3	2.2/2.2	0.6/1.9	3.1/2.9
ΔPBLH (m)	238/170	142/70	227/279	307/337	162/279	280/433
Δwind10m (m s^{-1})	−0.80/ − 0.74	−0.38/ − 0.28	−1.86/ − 2.1	−0.46/ − 0.32	−0.27/ − 0.30	−0.80/ − 0.58
Munich						
Δtas (°C)	1.33/1.82	2.89/2.65	0.59/2.19	1.12/2.2	0.53/1.96	1.76/2.83
ΔPBLH (m)	132/106	65/29	144/157	244/270	122/201	362/367
Δwind10m (m s^{-1})	−0.46/ − 0.26	−0.25/ − 0.21	−0.77/ − 1.01	−0.32/ − 0.11	−0.21/ − 0.33	−0.52/ − 0.36
Budapest						
Δtas (°C)	1.13/1.37	2.60/1.02	0.54/1.74	1.2/2.4	0.71/2.16	1.40/2.97
ΔPBLH (m)	132/122	106/67	268/248	265/336	132/225	236/509
Δwind10m (m s^{-1})	−0.91/ − 0.17	−0.33/ − 0.24	−1.92/ − 1.00	−0.59/ − 0.20	−0.39/ − 0.32	−0.83/ − 0.69

Table 4.1: Mean and 5% and 95% quantiles of the urban canopy impact for models RegCM and WRF on near-surface temperature (tas), the height of the boundary layer (PBLH) and 10m wind speed (wind10m) averaged over DJF and JJA 2015–2016 for centers of four different cities. For Prague, values are taken from the 1km simulations and 9km for the rest. (reprint from Huszar et al. [2020]).

(in terms of the number of summer days, i.e. days with maximum temperature over 25 °C) are becoming more often with increasing urbanization.

For the wind speed changes, strong winds are the modified in a most manner (almost twice to average wind speed). This is caused by the additional drag (due to urban surfaces) that is slowing the large-wind speed relatively more compared to the slow winds.

Relatively large difference in the impact on the average and extreme (low/high percentiles) values have been identified between cities. These differences can by explained by their different sizes, fractional urban land cover and population (e.g. Berlin has almost twice the population of Munich and is twice as large). Another reason can be connected to different climate in which the urban canopy meteorology forcing acts.

5. Conclusion

Throughout this text, the individual pieces of analysis have demonstrated a few examples of our contribution to the urban climate knowledge, focusing on Prague and especially (but not limited) to its urban heat island. The results and methods used are quite wide, and it is not easy to summarize them in a simple conclusion. But there are, of course, some points worth highlighting. Finally, some information about the related research's ongoing works with our participation is given in this section.

First, our results have brought more details about knowledge of the UHI of Prague. Based on the careful analyses, more information about the intensity has been gained and the UHI's behavior under various synoptic conditions. Of course, it is no surprise that the warming is the strongest in the city center and indirectly points out the UHI amplification. The reoccurrence of extremely hot days and especially nights is growing statistically significantly in the city center and faster than at suburban stations. Due to the presence and increasing intensity of the UHI, Prague's center has become the warmest place in the Czech Republic since the '1980s. We can conclude that Prague's center is about 1.0-1.5 °C warmer (based on daily means of temperature) thanks to the existence of UHI, but for minimum temperatures, the UHI intensity exceeds 2 °C. From a synoptic perspective, the UHI of Prague develops especially under anticyclonic synoptic types with south- to southwesterly flow. The UHI greatly vanishes when the wind speed exceeds 6 to 8 metres per second.

The study and analysis of UHI traditionally based on surface stations measurement can generally lead to results that are strongly influenced by the stations localization and exposure. For Prague this is not a big issue since the location of central stations is virtually exemplary in the sense of their proximity to the geometric centre of Prague. But the exposure should be taken into account where needed for certain analyses - especially for precipitation and snow. This influences the study of drought occurrence in Prague, where new interesting results have been found in Kveton and Zak [2021]). With method exploring the continuous days with daily precipitation totals not exceeding given threshold and continuous days with cumulative precipitation average not exceeding given threshold. The long-term analysis showed a small increase in drought duration since 2002.

Another picture of UHI (and other urban climate features) can be obtained by satellite measurement. Generally, more information about size and shape and even UHI magnitude can be obtained when using satellite data. But in this case, we should rather talk about Surface Urban Heat Island (SUHI) since we are usually working with land surface temperature (LST) data. MODIS LST data have been used for the first detailed analysis of Prague's SUHI, already in the '00s of 21st century, showing the first image of its shape. CM SAF LST data used in thesis Dolezalova [2020] studying the SUHI of Prague has confirmed the previous results of lower daytime SUHI intensity in winter compared to summer (4-5 °C vs. 8-10 °C). When using satellite data, some issues have to be taken into account. Certainly, limited spatial resolution (and for polar-orbiting satellite temporal resolution, too), as well as confinement to cases without cloudiness, can influence the obtained results. The second point is especially important in winter season, when generally larger cloudiness is observed in central Europe, and especially the low stratiform clouds are often occurring. Another important issue is the presence of snow cover in winter months. It greatly influences the city center's albedo for such days, making the SUHI less expressed compared to UHI based on station measurement (Dolezalova [2020]). However, the UHI can be manifested thanks to important anthropogenic heat sources.

Urban climate and especially urban heat island can have adverse effects on urban inhabitants. It is therefore important to study possibilities of mitigation of these effects. Especially during prolonged heat waves increased risk of health complications occurs, mainly for elderly people and babies. Still, worse sleeping quality during warm nights can finally contribute to enhanced lassitude and decreased attention even for young people. The question of mitigating these adverse effects come to attention at the end of the last century. However, in the case of the Czech Republic, the urban planners and stakeholders become to deal with it not until the end of 00's of 21st century, when the importance of UHI becomes more apparent to the wider public. This activity has been partly supported by projects focused on UHI mitigation.

Although there was a large concern about the UHI of Prague (and perhaps other cities in the Czech Republic) in the scientific community, the question of thermal perception has become widely popular not before the last decade, partly due to studies of our team made during solving the European "UHI" project. Parameters like (m)PET and UTCI have started to be used to describe thermal comfort not only be climatologists but also by urban planners and stakeholders. Among the first works using these parameters were the pilot actions investigating the effects of diverse mitigating strategies for areas with deeply pronounced UHI effect, especially in the summer months. Since then, these quantities are now widely accepted and used to evaluate various mitigation and/or adaptation strategies in the city of Prague.

Last but not least, the modeling of urban influences gradually gains more and more attention. The first urban climate models were used during solving the MEGAPOLI (https://cordis.europa.eu/project/id/212520) project at the Department of Atmospheric Physics. By that time, more details the air quality issues were more prioritized to urban climate. But this has changed under increasing climate change impacts combined with the deepening UHI effects and when need of deepening our knowledge about Prague's climate arose.

Nowadays, UHI models can cover a wide spectrum of scales with respect to the study's aim or analysis. In this thesis, the modeling works have been focused on urban canopy layer models with limited domain size used to study the urban boundary layer's dynamic and thermal properties. These models are able to represent most features typical for the urban areas, like street canyons, walls, roofs, and roads, including sources of anthropogenic heat, increasing the UHI intensity. The representation of the "real weather" in the city and its surroundings is of great importance. Based on our results (mostly for Prague), the urban schemes could capture the typical urban weather modification features, especially the temperature (including the typical diurnal cycle). But not all parameters are simulated properly. For example, there can be found discrepancies between real and model-simulated wind speed and planetary boundary layer height, with the simulated values showing greater variance (although it is not easy to evaluate the model values to the measured ones due to scarce station measurements).

Meteorological forcing of the urban canopy was underlined by (Huszar et al. [2020]), where model simulations were carried out either with rural or urban canopies. The models can be expected to become more and more powerful instruments when studying various effects of mitigation and adaptation strategies, but we are still lacking in the judgment of how correct they are when going into microclimate. Although there can be found several comparisons (e.g. Antoniou et al. [2019])) dealing with this matter in scientific literature, for Prague only limited measuring campaigns have been realized (some of them during URBI PRAGENSI project) focused mostly on small areas (typically with extent of hundreds of meters).

A bit more knowledge is expected to be gained during solving two-year project "Urban Heat Island in the Czech Republic" finishing by the end of this year (2021), which investigates Prague and other large cities in Czechia. As a part of the project solution, there are special measuring campaigns done by air-borne and car measurement – ways that have been implemented only a few times. In the case of car-rides for Prague, such an approach was applied only some decades ago.

Urban climate has become very important part of climatology in the Czech Republic since the end of the last century. Many projects and studies focused on this topic were solved during last two decades, mostly focused on urban heat island, although the issue of air quality is of a big importance, too. The question of UHI mitigation and adaptation to worsening conditions under the era of climate change is another topic being studied in the current and ongoing projects as well in student thesis at our Department of Atmospheric Physics.

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