

# Chapter 1

## Forecasting Models for Urban Warming in Climate Change

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**Abstract** Defining UHI phenomenon required and interdisciplinary approach using both simulation models and climate data elaborations at regional and metropolitan level. In particular the WP 3 of UHI project provided a detailed survey on the main studies and practices to counteract urban heat islands in different European areas;

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discussed climate models at regional level; simulated the evaluation of urban warming in the different cities involved in the project, providing locally proper measuring and analysis in connection with the specific urban forms.

**Keywords** Forecasting UHI • Climate models • Regional scale • Climate scenario

## 1.1 General Introduction

The working package WP 3 collects technical and scientific definitions and state of the art about the urban heat island phenomenon and further presents strategies to simulate future scenarios by using modelling systems. The knowledge review is a core output of action WP 3.1, giving a complete overview over the problem. It discusses methods to mitigate and adapt to the intensification of the UHI in Central Europe (CE) and beyond and further provides background information for local authorities related to urban planning, building and land use regulations in compliances with EU rules. The review is developed with the contribution of all PPs, scientific and institutional, in order to have main examples of excellences, best practices, innovative regulations and intervention put in act to face the UHI phenomenon.

Working Package WP 3.2 discusses regional climate model simulations and tries to give an estimation of future climate conditions (temperature, humidity, precipitation, wind speed, cloud cover, etc.) which may serve as outer conditions for the assessment of the UHI phenomenon in the cities of CE. The suitable simulations can be made e.g. with WRF or RegCM, especially when urban land use parameterizations involved, and statistical output on means and standard deviations of the meteorological variables can be supplied. The regional climate model uses available boundary conditions provided by existing global climate models. Statistical downscaling techniques can be used as well. Within the city structures, other microscale models are necessary to provide estimates of the local conditions, e.g. in street canyons.

The project partners being involved in this action try to show possibilities to simulate the effect of the Urban Heat Island and analyse its characteristic features for their city of interest. They try to set up models with different backgrounds also to account for simulation of mitigation scenarios counteracting this urban climate

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phenomenon, to work out plans about sustainable strategies for future urban planning together with the local stakeholders. The operators of these models contributing to this report are manifold. On the one hand side there are meteorological services like the HMS (Hungarian Meteorological Service) and research institutes like the KIT (Karlsruhe Institute of Technology). On the other side there are Universities like Prague and Freiburg or territorial alliances like ARPA Emilia Romagna. In the following, the models used by the project partners trying to forecast the UHI are listed.

In the following, a broad range of different tools and studies are presented which have been carried out by the project partners in the course of the activities in working package WP3. The studies range from climate change projections for central European cities with the regional climate model (RCM) WRF, to regional climate modelling with RegCM and statistical downscaling approaches. Further, the microclimatic model RayMan is used to assess climate change on street scale and another study investigates urban effects by coupling a town energy model (TEB) to the surface modelling platform SURFEX.

All the information is collected by the working package leader PP5 – Karlsruhe Institute of Technology and presented according to the requirements introduced in the WP3 methodological document.

## 1.2 Overview of Models and Tools

Collection of models for investigating the extend of Urban Heat Islands and the impact of climate change for Central European urban regions in the course of WP 3 – activities

EnviMet (<http://www.envi-met.com/>)

- Commonly agreed to serve as primary model for simulating urban climatology and mitigation scenarios
- three-dimensional microclimate model designed to simulate the surface-plant-air interactions in urban environment
- typical resolution of 0.5–10 m in space and 10 s in time.
- ENVI-met is a **Freeware program** based on different scientific research projects
- ENVI-met is a prognostic model based on the fundamental laws of fluid dynamics and thermo- dynamics. The model includes the simulation of:
  - Flow around and between buildings
  - Exchange processes of heat and vapour at the ground surface and at walls
  - Turbulence
  - Exchange at vegetation and vegetation parameters
  - Bioclimatology
  - Particle dispersion and pollutant chemistry

- Applied by TU Vienna, University of Friburg and others  
WRF (Weather Research and Forecasting Model)
  - Developed by the National Center of Atmospheric Research (NCAR)
  - Mesoscale, numerical weather prediction model, which also can be used for climate modeling
  - Nested to global circulation model ECHAM5/MPI-OM <http://www.mpimet.mpg.de/en/science/models/echam.html>
  - Open source, code downloadable from the web
  - <http://www.mmm.ucar.edu/wrf/users/>
  - <http://www.wrf-model.org/index.php>
  - Applied by KIT, Germany
- Statistical downscaling approach
  - Using STREAM 1 simulations from ESEMBLES-Project (<http://www.ensembles-eu.org/>)
  - Methodology and forcing that were defined by CMIP3 simulations contributing to IPCC AR4; CMIP3 (Coupled model Intercomparison Project)
  - [http://www-pcmdi.llnl.gov/ipcc/about\\_ipcc.php](http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php)
  - Applied by ARPA-Emilia Romagna, Italy
- Micro-Climatic Model RayMan to assess climate change on city scale
  - Boundary conditions from ENSEMBLE model RT2B (<http://ensembles-eu.met-office.com>) and REMO regional climate model (<http://www.remo-rcm.de>)
  - Calculation of the Physiological Equivalent Temperature (PET)
  - RayMan: calculation of short- and long-wave radiation fluxes affecting the human body and takes complex urban structures into account
  - calculated mean radiant temperature, required for the human energy balance
  - meteorological and thermo-physiological data as input
  - open source: <http://www.mif.uni-freiburg.de/rayman/intro.htm>
  - Applied by University of Freiburg
- SURFEX combined with TEB (Town Energy Model)
  - **SURFEX** (Surface Externalisée) is the surface modelling platform developed by Meteo-France
  - computes averaged fluxes for momentum, sensible and latent heat for each surface grid box → boundary condition for meteorological model
  - input land cover information from ECOCLIMAP database
  - TEB: computes energy balance considering canyon concept
  - ALADIN-Climate RCM as atmospheric forcing
  - <http://www.cnrm-game.fr/spip.php?article145&lang=en>
  - Applied by Hungarian Meteorological Service
- Regional Climate Model RegCM (<http://users.ictp.it/RegCNET/regcm.pdf>)
  - Boundary conditions from GCM CNRM-CM5 (<http://www.enes.org/models/earthsystem-models/cnrm-cerfacs/cnrm-cm5>)

- Community Land Surface Model v3.5 (CLM3.5) as an optional land surface parameterization
- Urban surface treated by coupling with Single Layer Urban Canopy Model linked to SUBBATS surface scheme
- Applied by Charles University, Prague  
CLMM (Charles University Large Eddy Microscale Model)
- LES tool for simulation of the flow in microscales with complex terrain or structures solving CFD problems
- In addition to flow equations it includes transport equation for scalars like temperature, moisture and passive pollutants
- Applied by Charles University, Prague

## 1.3 Case Studies

### 1.3.1 *Projections of Climate Trends for Urban Areas in Central Europe Using WRF*

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#### 1.3.1.1 Introduction

In 2050 the global fraction of urban population will rise to a level up to almost 70 %, which means that around 6.3 billion people are expected to live in urban areas. Next to that development a rise of the global temperature of about 0.2 K per decade for the twenty-first century is projected within the range of the SRES scenarios of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change – IPCC) for Europe (Wagner et al. 2013).

It’s predicted, that extreme events are to increase in the future, which means more and heavier storms, precipitation events and thus increased danger of flooding, occurrence of heat waves or days with high air pollution, especially dangerous in combination with high temperature periods (Beniston et al. 2007).

This note describes how scenario simulations for Central Europe have been performed with a regional climate model based on global climate model scenario simulations.

### 1.3.1.2 Data and Methods

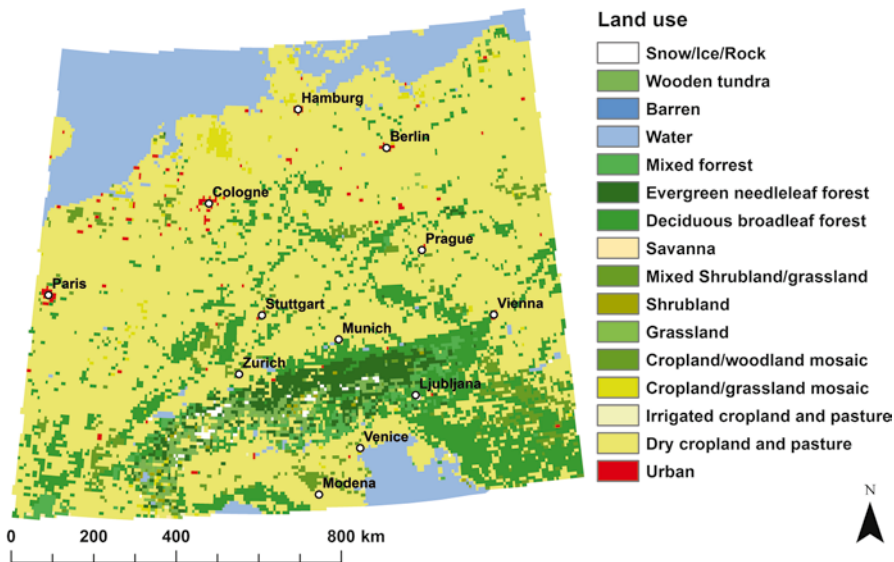
Results from high resolution, multi-ensemble regional climate models are an essential input for many climate impact studies. In the course of the CEDIM (Center for Disaster Management and Risk reduction Technology) project ‘Flood Hazards in a Changing Climate’ (Wagner 2013) a multi model ensemble of high resolution 7 km regional climate simulations for a present (1971–2000) and a near future (2021–2050) time period were conducted. To assess the climate change on regional scales, regional climate models (RCMs) were nested into coarser global circulation models (GCMs). For the bulk of the simulations the ECHAM5/MPI-OM Model in T63 resolution (horizontal grid spacing of approximately  $140 \times 210$  km at mid-latitudes) served as GCM. ECHAM5 is the fifth-generation atmospheric general circulation model developed at the Max Planck Institute for Meteorology, in that case it was coupled to the Max Planck Institute ocean model (MPI-OM). IPCC SRES (Special Report on Emissions Scenario) A1B forcing scenario served as boundary condition.

The spatial resolution of RCM simulations has steadily increased over the last decades. In the past, several larger ensembles were carried out to assess climate change, like for example in PRUDENCE (Christensen and Christensen 2007) with a resolution of 50 km or ENSEMBLES (Hewitt CD 2005) with a spatial resolution of 25 km. To get more information on this, please refer to the respective literature.

Using WRF (Weather Research and Forecasting Model) as regional climate model was one part of the contribution of the Institute of Meteorology and Climate Research (IMK-IFU) to CEDIM. To set up WRF, different steps had to be conducted to make reliable forecasts. Thus three different runs had to be carried out: one past climate run, one validating reanalysis run and the final future climate scenario run. Each of these runs had a calculation time of approximately 3 month (Wagner 2013). Covering Germany and the near surroundings it was possible to extract modeling results for urban areas ( $7 \times 7$  km grid cells) contributing to the CENTRAL Europe Project. Thus, WRF is used in the following to illustrate the effect of climate change on urban regions within the area of central Europe

The regional climate model WRF followed a double nesting procedure, where the coarse nest covered an area of entire Europe with a resolution of about 50 km, whereas the fine nest consisted of Germany and the near surroundings (Fig. 1.1).

The fine model domain of 174 by 174 grid cells covers an area between 1.5 to 17.5° E and 44.5 to 54.5° N. The model resolution of 7 km implies that every urban area of interest is covered by at least one grid cell 40 vertical levels where used for both nests. For further specifications on model physics and modeling proceedings refer to Berg et al. (2013) and Wagner et al. (2013).



**Fig. 1.1** WRF nested domain with 7 km horizontal resolution, showing USGS 2006 classified land use, projected on a LAT/LON grid with the coordinate system WGS 84 Zone 32 N. The urban areas of interest are marked

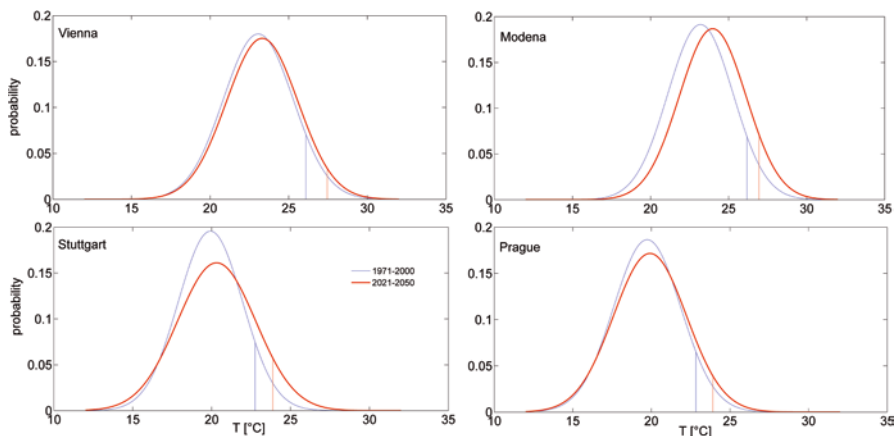
### 1.3.1.3 Results

All simulation results project a significant warming throughout the model domain between 0.8 and 1.1 K. All ECHAM5 driven regional climate models predict an increase of annual precipitation in the range of 2 to 9% (average of 3% for Germany), with higher values in winter and autumn months. Using WRF as RCM reveals changes of temperature and precipitation (Wagner 2013). Differences in 2 m temperature between future and past regional climate model run, extracted for certain urban areas located in the model domain and in the project region Central Europe reveal the following trends (Table 1.1).

Monthly mean temperatures are extracted for one grid cell in the centre of a selected urban region to create probability density functions in order to statistically compare the modelling results. By calculating the values to fall below the 5% confidence interval, the tendency towards extreme values is to be analysed on the basis of the comparison of the future (2021–2050) with the reference period (1971–2000). Probability density functions (PDF) for 4 selected cities are presented in Fig. 1.2. Following the expectations given by the IPCC AR4, temperatures will develop in direction to the extremes (Beniston et al. 2007). The PDFs indicate a compression and widening of the future curve compared to that one of the past. The shift in the 95th percentile reflects the climate change signal.

**Table 1.1** Projected fine nest seasonal and annual temperature changes [°C] between 1971 and 2000 and 2021–2050 for the WRF simulation averaged for urban area

	DJF	MAM	JJA	SON	Annual
Ljubljana	1.47	0.66	0.66	1.35	1.03
Modena	1.11	0.61	0.75	1.24	0.93
Padua	0.86	0.26	0.29	0.9	0.58
Vienna	1.92	1.04	1.13	1.91	1.5
Prague	1.43	0.05	0.07	1.13	0.67
Stuttgart	2.05	1.36	1.86	2.31	1.89



**Fig. 1.2** Probability density functions (PDFs) extracted for the central  $7 \times 7$  km pixel of a selected urban area. The *blue line* indicates the probability density curve for extracted monthly mean temperatures in the past (1971–2000), the *red line* shows the same for the future (2021–2050) period. The *vertical lines* illustrate the 95th percentile for each plot and time frame

### 1.3.1.4 Conclusion

Delivering climate runs with higher resolution, which may fit better to the urban scale will be very cost intensive. Nevertheless, results from projects like the above-mentioned one can be used as boundary conditions for high resolution city-scale models to conduct scenario runs (e.g. different urban planning strategies) for future climate conditions and region of interest. For further studies on impact of climate change on urban settlements please refer also to the project Ensembles-Based Predictions of Climate Changes and Their Impacts – ENSEMBLES (Hewitt CD 2005). This study can be used for other working packages dealing with mitigation and adaptation strategies, with the background that climate change will amplify Urban Heat Islands and future problems for urban inhabitants coming along with that phenomenon. Specific measures like urban greening, changing radiative properties of building materials or restructuring of city quarters, are not discussed in this report, rather should the results serve as basis for referring the problem of UHI's to a more to raise public awareness on a different level.



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### ***1.3.2 Human-Biometeorological Assessment of Changing Conditions in the Region of Stuttgart in the Twenty-First Century***

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### 1.3.2.1 Data and Methods

Regional climate simulations of the ENSEMBLE RT2B model (for more information see <http://ensembles-eu.metoffice.com/>) with daily resolution are used as the data basis for the analysis of climate change in the greater region of Stuttgart for 1960–2100. The RT2B model focuses on the SRES A1B scenario. The regional climate model REMO (for more information see <http://www.remo-rcm.de/>) in hourly resolution and 10 km spatial resolution focusing on SRES A1B and B1 scenario is used to analyze the human thermal comfort conditions.

Therefore, the thermal index Physiologically Equivalent Temperature (PET; Höppe 1993; Mayer and Höppe 1987; Matzarakis et al. 1999) is calculated with the help of the micro-climate model RayMan (Matzarakis et al. 2007, 2010). PET is used to quantify especially the frequency and intensity of heat stress. Thereby, PET between 18 °C and 23 °C was assessed to be comfortable, while PET above 35 °C (Nastos and Matzarakis 2012) stands for strong heat stress (Matzarakis and Mayer 1996).

The dataset is used to calculate the number of climatologically event days and their change until the end of the twenty-first century.

### 1.3.2.2 Results

Table 1.3 shows the frequency of climatological event days. The frequency of hot days ( $T_{\max} \geq 30$  °C) and summer days ( $T_{\max} \geq 25$  °C) will increase to 174 % and 140 % in the period 2021–2050 and 280 % and 157 % until end of the twenty-first century. On the other hand the number of frost ( $T_{\max} \leq 0$  °C) and ice days ( $T_{\max} \leq 0$  °C) per year will decrease to 33 % in the period 2071–2100.

The average annual air temperature might rise by 1.5 °C from 1961–1990 to 2021–2050 and 3.5 °C until the end of the twenty-first century (Table 1.3). Thereby, the increase in air temperature is strongest during summer and winter and weakest in spring.

The number of days per year with heat stress ( $PET > 35$  °C) at 14:00 MEZ will increase by 6 days from 1961 to 1990 to 2021–2050 and by 28 days until the end of the twenty-first century according to the REMO data A1B scenario. The B1 data shows no increase until the mid of the twenty-first century, but an increase of 4 % (16 days) until 2071–2100 (Table 1.2).

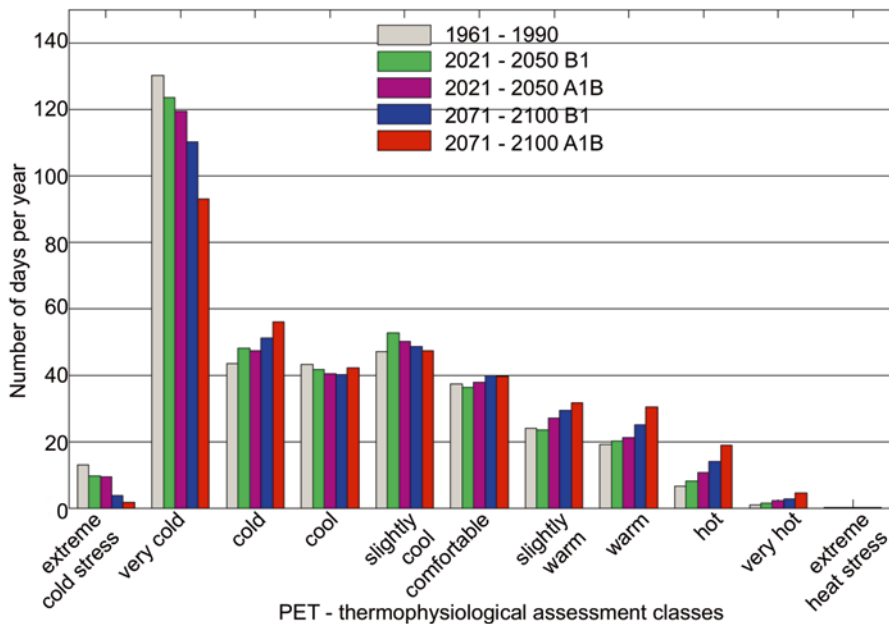
In the early morning (6:00 MEZ), the number of days with (extreme) cold stress will significantly decrease by 15 (10) days according to the A1B (B1) scenario until 2021–2050 and by 48 (29) days until 2071–2100 (Fig. 1.3). In contrast, the number of days with  $PET > 29$  °C will rise by 5 (15) days until the mid (end) of the twenty-first century according to the A1B scenario.

**Table 1.2** Analysis of the number of climatological event days in the greater area of Stuttgart using the ENSEMBLE model RT2B for three different time periods 1961–1990, 2021–2050 and 2071–2100

Event		1961–1990	2021–2050	2071–2100
Extreme hot days	$T_{max} \geq 39 \text{ }^\circ\text{C}$	$0 \pm 1$	$1 \pm 2$	$3 \pm 5$
Hot days	$T_{max} \geq 30 \text{ }^\circ\text{C}$	$7 \pm 9$	$12 \pm 14$	$20 \pm 24$
Summer days	$T_{max} \geq 25 \text{ }^\circ\text{C}$	$27 \pm 19$	$37 \pm 22$	$42 \pm 38$
Frost days	$T_{min} \leq 0 \text{ }^\circ\text{C}$	$104 \pm 29$	$79 \pm 27$	$35 \pm 30$
Ice days	$T_{mix} \leq \text{ }^\circ\text{C}$	$30 \pm 13$	$18 \pm 10$	$7 \pm 8$
Extreme cold days	$T_{max} \leq -10 \text{ }^\circ\text{C}$	$1 \pm 1$	$\pm 0$	$\pm 0$

**Table 1.3** The average annual air temperature simulated by the ENSEMBLE models RT2B and the standard deviation in the greater region of Stuttgart from 1961–1990 to 2021–2050 and 2071–2100

Air temperature	1961–1990	2021–2050	2071–2100
Yearly	$7.9 \pm 1.7$	$9.4 \pm 1.8$	$11.4 \pm 2.1$
Spring	$6.7 \pm 2.0$	$7.8 \pm 2.3$	$9.6 \pm 2.0$
Summer	$16.5 \pm 2.5$	$18.0 \pm 2.7$	$20.5 \pm 3.4$
Autumn	$8.3 \pm 1.8$	$9.7 \pm 1.8$	$11.8 \pm 2.4$
Winter	$0.1 \pm 2.1$	$1.8 \pm 2.1$	$3.8 \pm 2.1$



**Fig. 1.3** Number of days with PET assessment classes in the climate normal period 1961–1990 compared to the frequency in 2021–2050 and 2071–2100 at 6:00 a.m. Data basis: REMO A1B and B1 scenario

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### ***1.3.3 Urban Climate Modelling with SURFEX/TEB at the Hungarian Meteorological Service***

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#### **1.3.3.1 Introduction**

Half of the world's population lives in cities nowadays, which are continuously growing and have significant effects on local climate. Moreover, consequences of climate change in cities might be enhanced by the impact of urban surfaces. Thus, to make adaptation strategies to climate change, investigating these impacts is especially important. Therefore urban climate modelling activity started besides regional climate modelling at the Hungarian Meteorological Service (HMS) in 2010. To

portray the interactions between the atmosphere and the urban areas, SURFEX surface model is applied. Main objective of using SURFEX is downscaling the regional projections for the future over Hungarian cities, and this paper is focusing on the first step of this, i.e. the validation of the surface model.

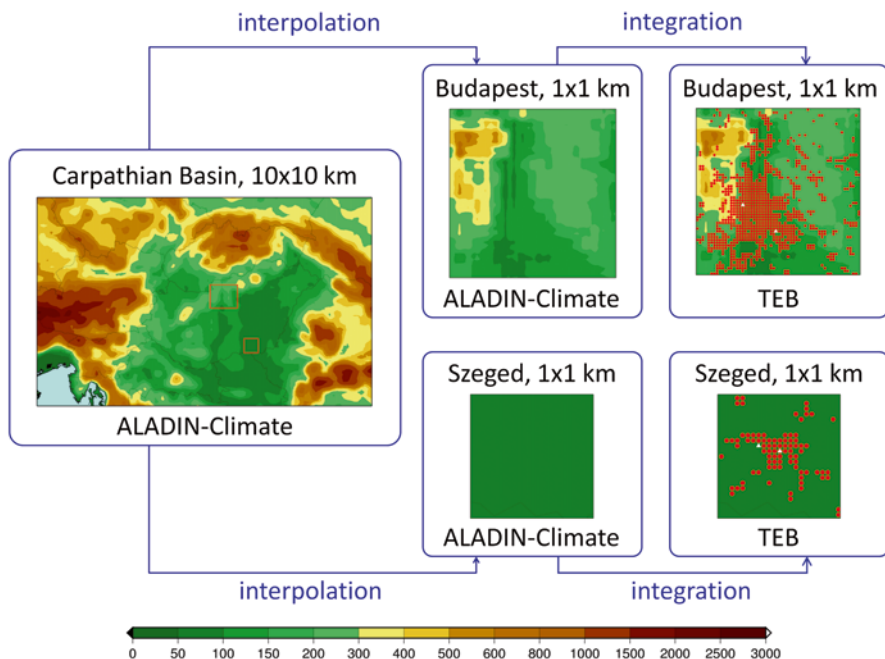
### 1.3.3.2 Methodology

The SURFEX (SURFace EXternalisée; Le Moigne 2009) surface model consists of four schemes for urban surface, sea, inland water and nature. Amongst these schemes the Town Energy Balance (TEB) model (Masson 2000) describes interactions between urban surface and atmosphere by simulating turbulent fluxes. It follows local canyon approach, where canyon represents the road with buildings on the sides. TEB considers three surfaces (roof, wall, road) with different energy budgets. It takes several processes into account which are important in urbanized areas, e.g., it treats water and snow interception by roofs and roads, fog, runoff, radiative trapping, momentum and heat fluxes. The anthropogenic heat and moisture fluxes derived from traffic, industry and domestic heating are also considered.

As input, SURFEX needs information about the atmospheric conditions, i.e. the atmospheric forcing, which can be supplied either by measurements or an atmospheric model. The atmospheric model may be coupled with SURFEX and thus it can get feedback from the surface scheme, but SURFEX running in offline mode (i.e., without feedback) is feasible as well. It is noted that advection is not taken into account in SURFEX, thus there is no interaction between grid points in offline mode, which is only possible through the atmospheric model.

At HMS, the SURFEX studies started in 2010 (Vértesi 2011) for modelling urban heat island (UHI) effect in Budapest. Some 10-year long experiments were achieved over Budapest and Szeged. The atmospheric forcing was obtained from ERA-40 re-analysis (Uppala et al. 2005) produced by ECMWF (European Centre for Medium-range Weather Forecast). Re-analyses are three-dimensional climate databases, which are created with data assimilation technique using as many observations as possible plus short-range weather forecasts. ERA-40 is a global dataset at ca. 125-km horizontal resolution, which was downscaled by ALADIN-Climate regional climate model (Csimas and Horányi 2008) to a 10-km resolution domain covering the Carpathian Basin for 1961–2000. These results were interpolated by a special configuration of the model to two smaller areas around Budapest and Szeged at 1 km resolution (Fig. 1.4) for the investigated periods. These served as inputs for SURFEX, which was run in offline mode at also 1 km resolution. The information for the fine surface coverage and physiography was derived from the ECOCLIMAP database (Masson et al. 2003).

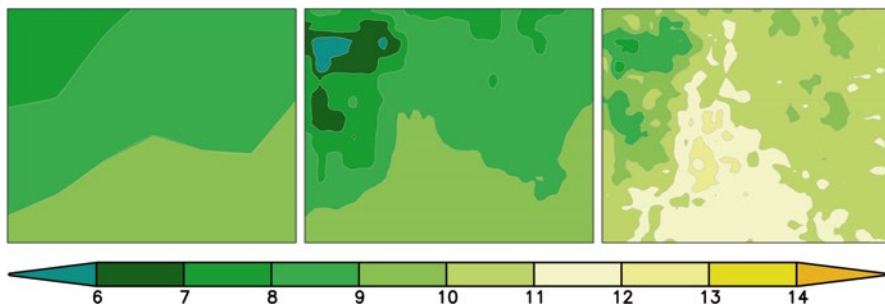
The first experiment was conducted over Budapest for 1961–1970. ECOCLIMAP was created in 2006, thus it might not describe the surface characteristics of the given period realistically, as several houses have been built since the 60s, especially in the outskirt. Therefore, the experiment was repeated for 1991–2000 to see



**Fig. 1.4** Flow chart about the use of SURFEX with topography [m] and the gridpoints that include urban surface (*right panels; red*); white dots indicate the observational stations in the *right panels*

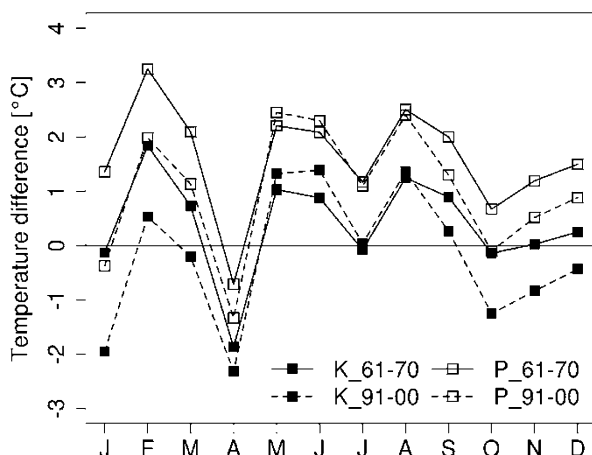
whether these changes modify the results. For this latter period a simulation was achieved over Szeged as well to investigate the effect of urbanization in another location.

The results were validated against observations of HMS stations. In both cities two stations were selected: one in the centre and one in the outer part of the town. In case of Budapest the inner station is situated in Kitaibel Street, close to the Buda Hills, the other one operates in Pestszentlőrinc, in the outskirts (Fig. 1.4). However, ECOCLIMAP considers both points as temperate suburban (it is composed of 60 % town and 40 % nature). Szeged is located in the Southern Great Plain region, where higher elevated orographic objects (hills or mountains) cannot be found in the vicinity of the town. The surroundings of its inner observational site are also categorized as temperate suburban in ECOCLIMAP, while the outer point is actually a rural point without buildings. This paper summarizes the performance of the SURFEX model for these three experiments. Climate change assessment is not the aim of this study, since 10-year periods are insufficient for such investigations.



**Fig. 1.5** Spring 2-m mean temperature ( $^{\circ}\text{C}$ ) of ALADIN-Climate (at 10 and 1 km resolution – *left and middle panel*) and SURFEX (at 1 km resolution – *right panel*) over Budapest for 1961–1970 (Vértesi 2011)

**Fig. 1.6** Difference of monthly mean temperature ( $^{\circ}\text{C}$ ) between SURFEX and observation in Kitaibel street (*filled squares*) and Pestszentlőrinc (*open squares*) for 1961–1970 (*solid lines*) and 1991–2000 (*dashed lines*)



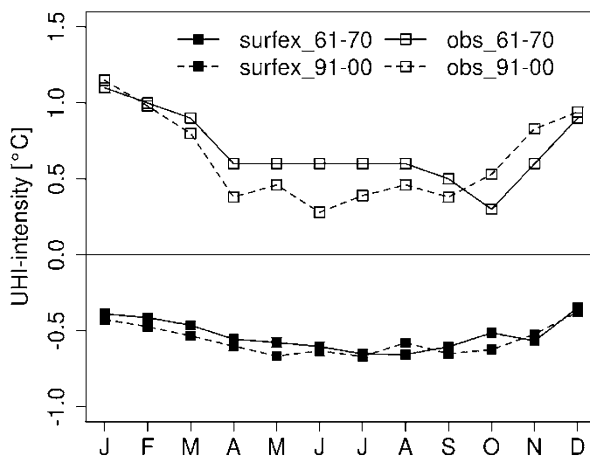
### 1.3.3.3 Results

#### 1.3.3.3.1 Budapest

Figure 1.5 shows how the interpolation and SURFEX integration modify the original temperature field of ALADIN-Climate. The applied interpolation takes into account the 1-km resolution topography, therefore, some new orographic features appear in the middle panel, like the cooler Buda hills. As a result of the sophisticated surface schemes in SURFEX, its temperature field (right panel) shows much more detailed information, Danube becomes slightly visible and temperature excess appears over the heart of the city.

In both reference points and periods mean intra-annual temperature differences between the SURFEX results and observations are very similar (Fig. 1.6), and mainly reflect the behaviour of the bias of ALADIN-Climate (not shown). From May to September the model exaggerates the temperature, and in April very strong

**Fig. 1.7** Observed (*open squares*) and modelled (*filled squares*) urban heat island intensity (°C) in Budapest for 1961–1970 (*solid lines*) and 1991–2000 (*dashed lines*)

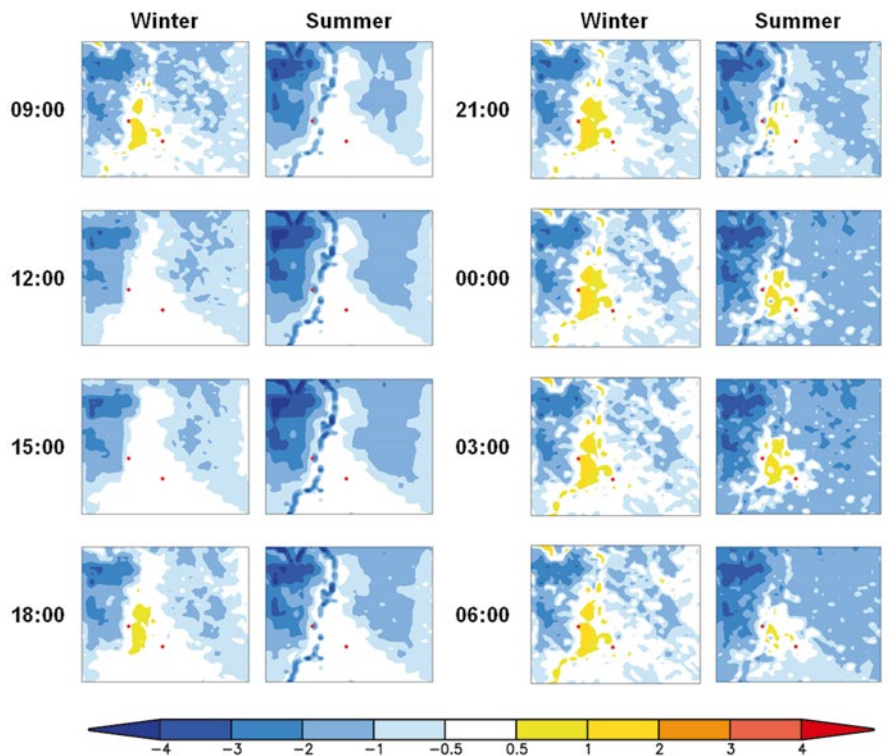


underestimation can be seen. In the concordantly overheated months, the results of Kitaibel Street are better, while in the rest of the year (except for April) this statement is valid only for the earlier period. Since ECOCLIMAP database provides information about recent surface characteristics, the reduced overestimation in Pestszentlőrinc in 1991–2000 compared to the results of 1961–1970 might be caused partly by the more realistic coverage description. (However, the fact that the improvements cannot be detected in every months indicates the key role of different atmospheric forcings in the two periods, especially in summer.)

In contrast with the temperature measurements, urban heat island cannot be noticed in any periods of the year (Fig. 1.7), which means that the inner point is colder than the outer one in the model. This already appears in the ALADIN-Climate results, and SURFEX cannot improve this, especially because the two points are characterised with the same cover type in the ECOCLIMAP. Moreover, Kitaibel Street locates on higher elevation than Pestszentlőrinc, and the neighbouring of the Buda Hills to the inner site might cause too strong cooling in ALADIN-Climate compared to the observations (recall that SURFEX does not simulate interactions between the neighbouring grid cells).

In the two reference points the results does not indicate good performance, but if a larger area is taken, SURFEX captures the daily cycle of UHI (Fig. 1.8). In daytime the air temperature of the city centre does not differ from the reference point in the suburban area; however after dusk (in winter already at 18:00, in summer at 21:00 UTC) UHI appears and its maximum intensity can be seen 5–6 h after sunset. The physical reason is that energy supply by solar radiation ends after sunset and upward longwave radiation is much more effective over natural surfaces than in the densely built-in urban area due to the smaller heat capacity of soil and the trapping of radiation in urban canyons (Basically the same conclusions were drawn for 1991–2000).





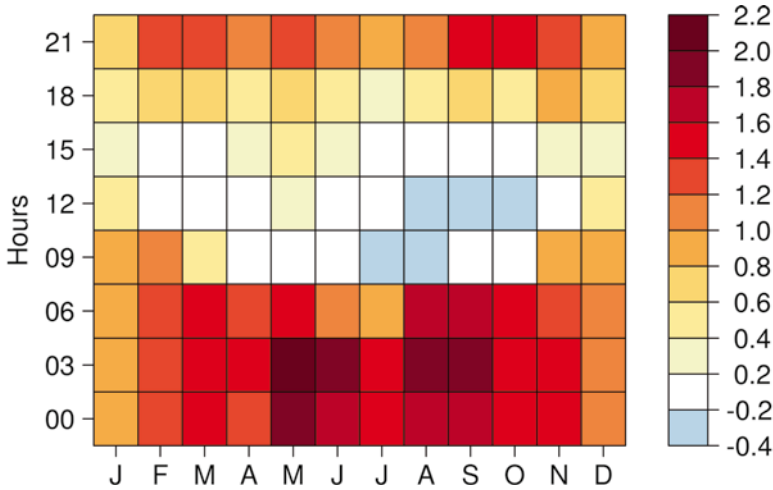
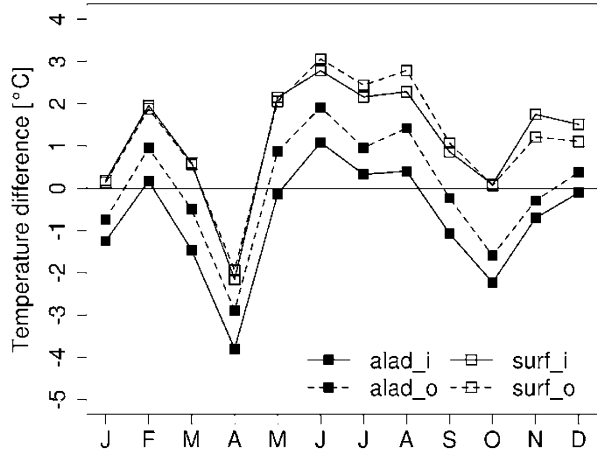
**Fig. 1.8** Difference of simulated mean temperature ( $^{\circ}\text{C}$ ) from the value at Pestszentlőrinc (the outskirts point) in winter and summer for 1961–1970 (the two *red points* represent the selected stations in Kitaibel Street and Pestszentlőrinc)

### 1.3.3.3.2 Szeged

The meteorological measurements in the inner site of Szeged have started in May 1998, thus the validation was limited for 1999–2000. Figure 1.9 presents the monthly average biases of ALADIN-Climate and SURFEX in the two reference points in this period. The annual cycles of the biases are similar to the result for Budapest. In general, SURFEX is giving more heat to the temperature fields of ALADIN-Climate, and due to the representative locations of the reference points (being in a flat area, and the outer point is situated in natural environment), the inner site gains larger warming to the extent that the difference between the bias of the two points almost diminishes. This implies that the monthly average UHI intensity is positive in all months (Fig. 1.10) and the magnitudes are represented adequately, as well.

The average annual and daily cycle of UHI simulated by SURFEX in 1991–2000 (Fig. 1.10) follows the theoretical pattern, namely the largest intensity occurs in the nocturnal hours from May to September with a peak of 1.8–2.2  $^{\circ}\text{C}$ . In contrast, in the late mornings of summer and autumn the outer point can be warmer than the inner one, since they warm slowly due to the larger heat capacity of urban surfaces

**Fig. 1.9** Monthly mean temperature bias (°C) of ALADIN-Climate (filled squares) and SURFEX (open squares) compared to observations in the inner (solid lines) and outer site (dashed lines) of Szeged for 1999–2000



**Fig. 1.10** Annual and daily cycle of UHI intensity (°C) in 1991–2000 between the two selected points in Szeged simulated by SURFEX

and the urban canyons form obstacles against low sun-rays. In December and January UHI feature can be seen all day, however the maximum intensities are lower than in summer.

### 1.3.3.4 Summary

At HMS SURFEX dynamical scheme is applied to describe interactions between the atmosphere and the urban surfaces. Some 10-year long test simulations were accomplished with the model over Budapest and Szeged. In this paper preliminary results of these validation experiments are performed. Based on the results, SURFEX captures the main characteristics of the urban climatology: temperature excess in

the heart of the city and daily cycle of the urban heat island. However, the evaluation indicated also some discrepancies: in the reference points SURFEX overestimates temperature in most months and in Budapest the central point is colder than the outer one, contrary to the observations. These errors derived partly from the atmospheric forcings and the inaccurate coverage description of ECOCLIMAP. Some additional investigations and test experiments are planned in order to examine the behaviour of the model in detail and develop its performance. Further goal with SURFEX is the dynamical downscaling of climate projections over towns, furthermore, supplying a reliable basis for impact studies in the cities for the future.

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### ***1.3.4 Regional Climate Modelling Considering the Effect of Urbanization on Climate Change in Central Europe***

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### 1.3.4.1 Introduction

Big cities or urban agglomerations can significantly impact both climate and environment. The emissions of large amount of gaseous species and aerosols, which affect the composition and chemistry of the atmosphere (Timothy et al. 2009), can have adverse effect on the environment in the cities and their vicinity. Moreover, this can negatively impact the population (Gurjar et al. 2010). In addition, this pathway can result in indirect impact on the meteorology and climate as well, due to radiation impact of the atmospheric composition on the thermal balance and thus affect the temperature as well. Especially within the canopy layer in the cities, the changes can be quite significant.

However, the primary reason for temperature increase within the cities or urban agglomerations with respect to the rural vicinity, is the effect of so called urban heat island (UHI, Oke 1973), which is mainly due to construction elements within the urban environment. This is extensively covered by artificial objects, buildings, using by large stone, bricks or concrete, and by quite large spaces often paved. This kind of surface clearly differs from natural surfaces (e. g. grassland, forest) by mechanical, radiative, thermal, and hydraulic properties, therefore, these surfaces represent additional sinks and sources of momentum and heat, affecting the mechanical, thermodynamical, and hydrological properties of the atmosphere (Lee et al. 2010). Nevertheless, the changes of meteorological conditions within the urban areas due to UHI can further affect the air-quality. This has been studied recently by e.g. Ryu et al. (2013), they found significant impact on the ozone day and night-time levels especially due to circulation pattern changes for the Seoul metropolitan area.

For WP3 we have focused on the aspects of climate conditions changes in urban environment, yet especially on those with strong potential to impact the air-quality, based on the experiment setup described below. For the region of Central Europe, we investigate the impact of the urban environment by means of its introducing into the regional climate model. As the spatial scale of the meteorological influence due to the cities is much smaller than the scale resolved by the mesoscale model, inclusion of urban land-surface requires additional parameterizations. The most common parameterizations considering the urban effects are the slab models (bulk parameterization), where the urban surface constants (e.g., surface albedo, roughness length, and moisture availability) can vary to better describe those of the urban surfaces. This treatment however ignores the three-dimensional character of the urban meteorological phenomena, moreover, in feasible resolutions the urban environment cannot be well resolved. Therefore, a more accurate approach is provided using urban canopy models (single layered – SLUCM, or multi-layered MLUCM) coupled to the driving mesoscale model (Chen et al. 2011). Our study describes in

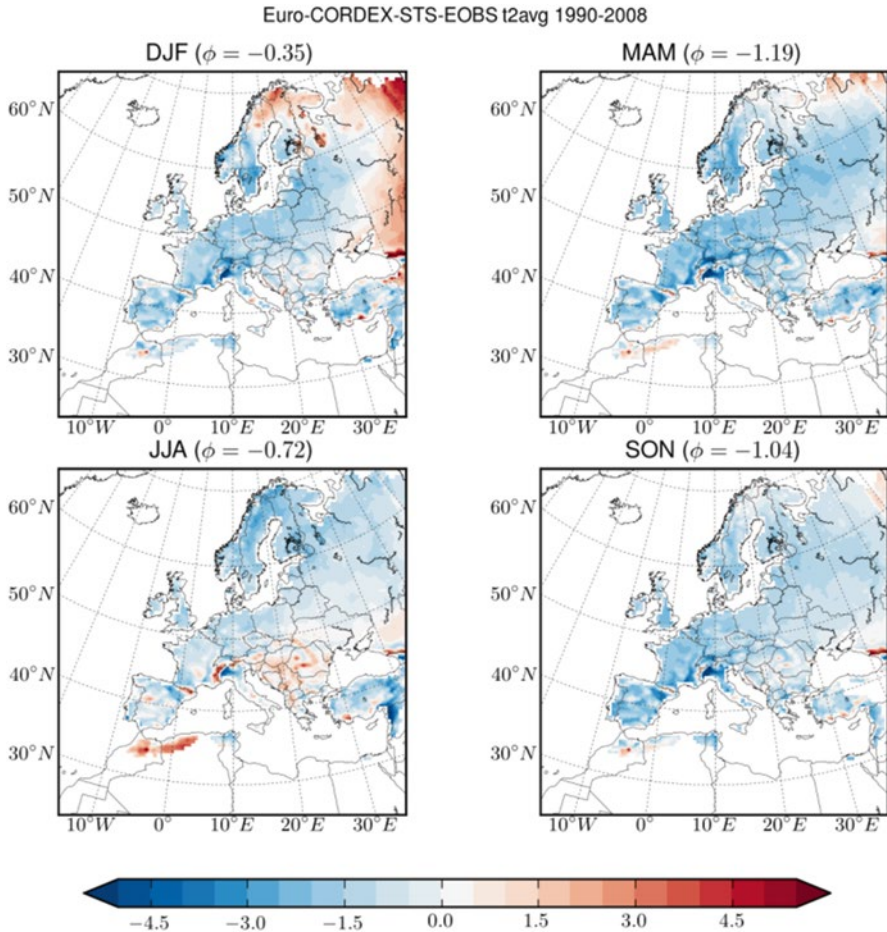
more details the implementation of such a SLUCM into our regional climate chemistry modelling system.

### 1.3.4.2 Background of Modelling for Europe

For the purpose of the climate simulations for UHI we follow two lines. First one aims to prepare up-to-date background information on the changing conditions in Europe using Euro-CORDEX rules. Euro-CORDEX is European part of the CORDEX initiative under WCRP which intend to provide downscaled information on climate change for individual continents around the world. It supposes to perform the coordinated simulations (i.e. for coordinated domains and periods), which results in creating large ensemble of model simulations, both for validation based on ERA-Interim reanalysis and/or historical runs with a GCM from CMIP5 driving an RCM. Especially for the historical runs, as well as the subsequent transient future runs, the matrix of GCMs and RCMs is expected to be quite large. While the resolution  $0.44^\circ$  (50 km) has been selected as standard for the CORDEX, for Europe the resolution of  $0.11^\circ$  (12 km) is emphasised as well. We participate in this activity with the model RegCM, both in evaluation experiment driven by ERA-Interim for 1989–2008 and transient historical and future run covering the period 1960–2100, at 50 km resolution, using scenario RCP4.5 for the future changes. As driving GCM, CNRM-CM5 is used. Figures 1.11 and 1.12 show the validation of temperature for the simulations driven by ERA-Interim and CNRM model, respectively. Further, Figs. 1.13 and 1.14 present climate change temperature signal for near future (2021–2050) and far future (2071–2100), respectively.

The regional climate model we use is the model RegCM version 4.2 (hereafter referred to as RegCM4.2) from The International Centre for Theoretical Physics (ICTP), which is a three-dimensional mesoscale model. In terms of physical parameterizations it is based on RegCM3 (Pal et al. 2007) with many additional options. Major changes in the model from version 3 to version 4.2 include the following: the inclusion of the Community Land Surface Model v3.5 (CLM3.5) as an optional land surface parameterization, a new optional parameterization for diurnal SST variations, and a major restructuring (modularization) of the code base. RegCM4.2 and its evolution from RegCM3 is fully described by Giorgi et al. (2012).

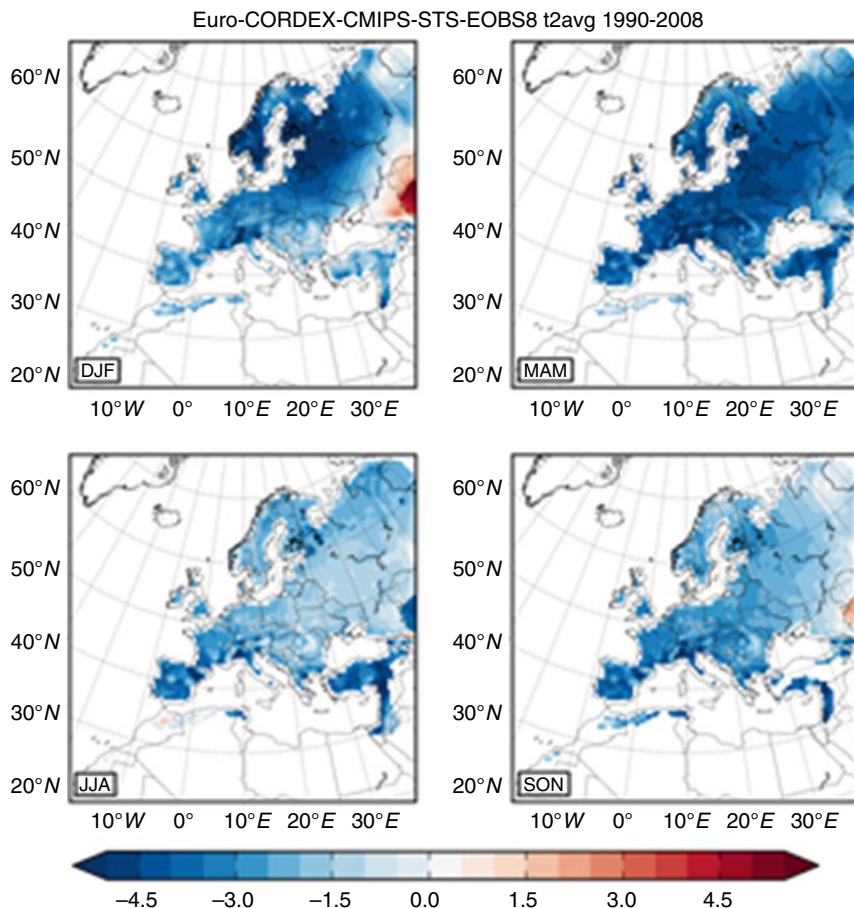
RegCM4.2 includes a two land-surface models: BATS and the CLM model. Both land-surface models can work in mosaic-type mode where the model grid is divided into sub-grid boxes for which the calculation of fluxes is carried out separately and the fluxes are then aggregated back to the large scale model gridbox (for BATS scheme referred as SUBBATS, see Pal et al. 2007). While in Europe scale we used standard BATS scheme, for the second line aiming to get high resolution downscaling with effect of urban parameterization included we have selected the SUBBATS on 1 km grid, which enable to identify clearly urban and suburban types of the land-use.



**Fig. 1.11** The validation of model mean temperature in terms of the difference of the ERA-Interim driven simulation against E-OBS data, for temperature and individual seasons

### 1.3.4.3 Urban Parameterization and Experimental Setup

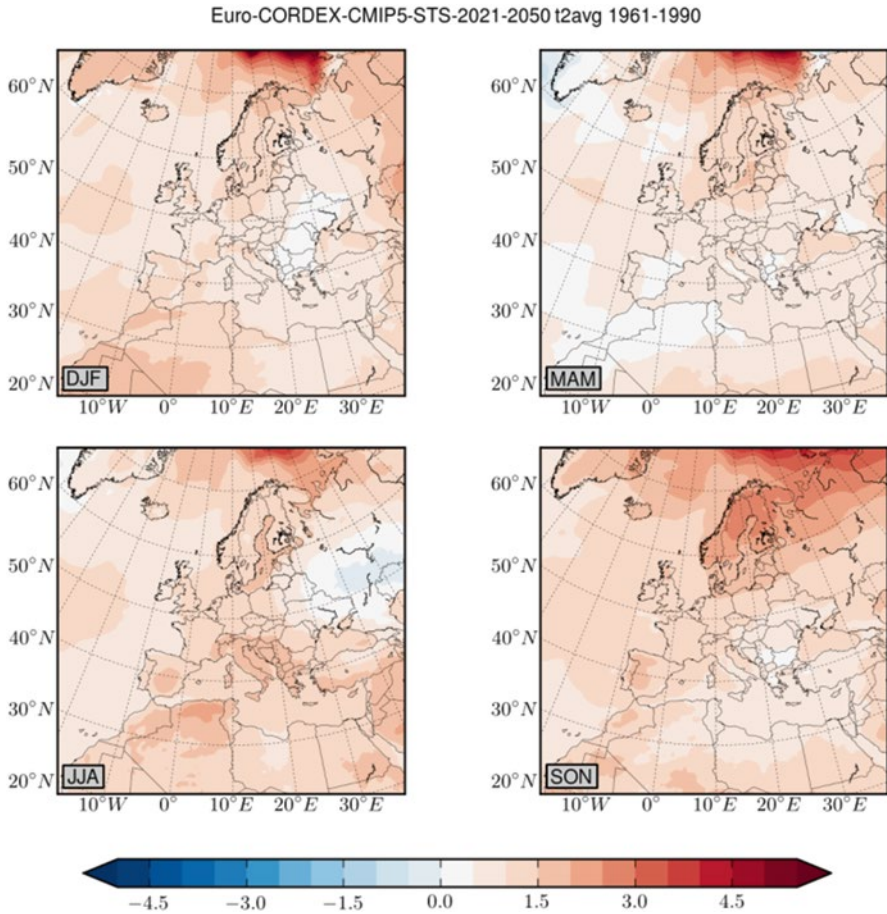
Cities affect the boundary layer properties thus having direct influence on the meteorological conditions and therefore on the climate. The urban surface is covered by large number of artificial object with complex 3 dimensional structure and considerable vertical size. Specific characteristics in urban morphology can be involved in complicated physical processes such as increased momentum drag, radiation trapping between buildings (effect of vertical surfaces), and heat conduction by the artificial surfaces. There had been many field measurements in cities that found characteristic features of mean flow, turbulence and thermal structures in the urban boundary layer (e.g. Allwine et al. 2002; Rotach et al. 2005).



**Fig. 1.12** The validation of model mean temperature in terms of the difference of the CNRM-CM5 driven simulation against E-OBS data, for temperature and individual seasons

Although there is a trend (enabled by the faster computational resources) to increase the spatial resolution of the mesoscale models, regional weather prediction and climate models still fail to capture appropriately the impact of local urban features on the mesoscale meteorology and climate without special sub-grid scale treatment. This accelerated the implementation and application of urban canopy sub-models (Chen et al. 2010 or Lee et al. 2010). For the regional climate model RegCM4 we have chosen the Single Layer Urban Canopy Model (SLUCM) developed by Kusaka et al. (2001) and Kusaka and Kimura (2004); this scheme is proven to perform well in simulating the urban environment and it is less demanding in computational resources unlike its multi-layer counterparts (Lee et al. 2010).

SLUCM considers the urban surface in a realistic way: it assumes street canyons with a certain width; in the street canyon, shadowing, reflection and trapping of

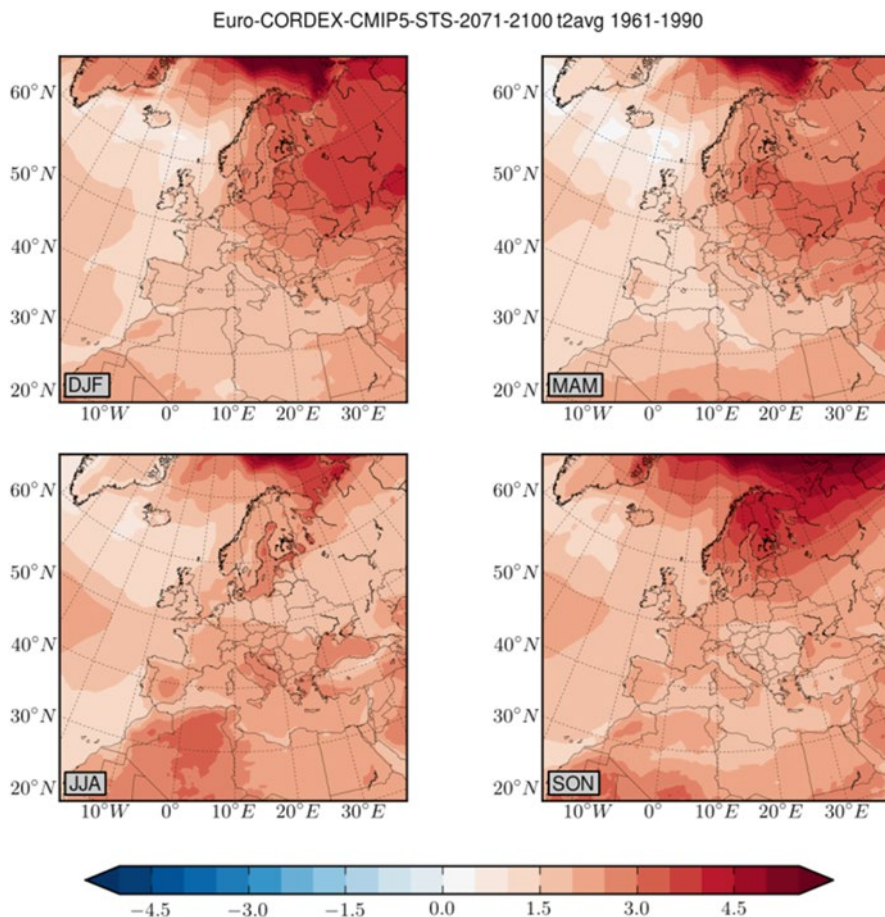


**Fig. 1.13** The climate change signal for near future in terms of the difference of the CNRM-CM5 driven simulation 2021–2050 against 1961–1990, for temperature and individual seasons under RCP4.5

radiation are considered. An exponential wind profile is prescribed. SLUCM treats surface skin temperatures at the roof, wall, and road and temperature profiles within roof, wall and road layers as prognostic variables. The heat fluxes from each surfaces are calculated using the Monin-Obuchov similarity theory and finally the canyon drag coefficient and friction velocity is computed using a similarity stability function for momentum. Figure 1.15 presents the conceptual design of SLUCM with the fluxes between street canyon air and the surrounding surfaces (road and walls) and the fluxes from/to the building roofs.

For high resolution downscaling with dynamic resolution of 10 km for the Central Europe we use SUBBATS scheme at 1 km resolution as already mentioned above. However, as the parameterization used till now in RegCM4 did not recognised the urban effects, an improvement can be achieved by implementing more

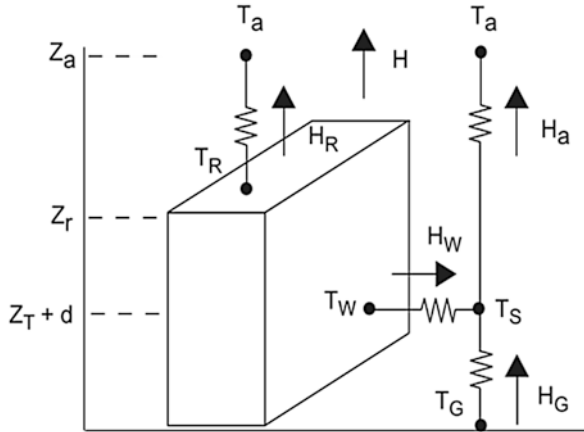




**Fig. 1.14** The climate change signal for near future in terms of the difference of the CNRM-CM5 driven simulation 2071–2100 against 1961–1990, for temperature and individual seasons under RCP4.5

sophisticated urban parameterizations lying under these land-surface models that better represent for the urban land-use type most urban features like building morphology, street geometry, variability of the properties of artificial surfaces, as well as the description of radiation trapping in the street canyon. For this purpose, Chen et al. (2010) provide a Single Layer Urban Canopy Model (SLUCM), originally developed by Kusaka et al. (2001) and applied in Kusaka and Kimura (2004).

This SLUCM model has been implemented into RegCM4.2 by linking it to the BATS surface scheme, applying SUBBATS with 1 km×1 km sub-grid resolution. SLUCM is called within SUBBATS wherever urban land-use categories are recognized in the land-use data supplied. The scheme returns the total sensible heat flux from the roof/wall/road to BATS, as well as the total momentum flux. The total friction velocity is aggregated from urban and non-urban surfaces and passed to



**Fig. 1.15** Energy fluxes in the SLUCM between the street canyon and the road and walls and from the buildings roof ( $T_a$  – air temperature at reference height  $z_a$ ,  $T_R$  – building roof temperature,  $T_W$  – building wall temperature,  $T_G$  – the road temperature,  $T_S$  – temperature defined at  $z_T + d$ ,  $H$  – the sensible heat exchange at the reference height,  $H_a$  is the sensible heat flux from the canyon space to the atmosphere,  $H_w$  – from wall to the canyon space,  $H_G$  – from road to the canyon space,  $H_R$  – from roof to the atmosphere) (following Kusaka et al. 2001)

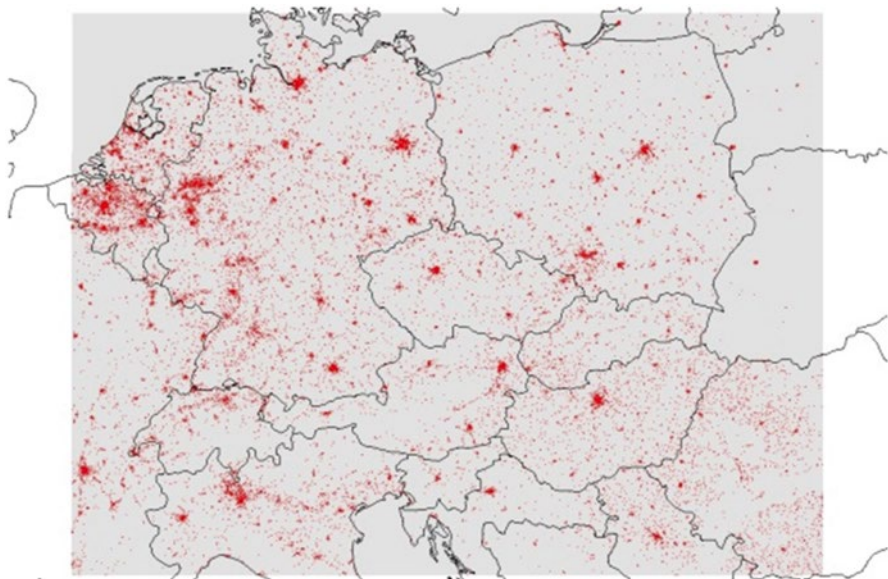
RegCM’s boundary layer scheme. However, as RegCM4.2 by default does not consider urban type land-use categories, we extracted the urban land-use information from the Corine 2006 (EEA 2006) database and we have added this information to the RegCM4.2 land-use database. In those parts of the domain where this was not available in Corine data, the GLC2000 (GLC 2000) database was used. We considered two categories, urban and suburban. See Fig. 1.16 for the urban land-use coverage for the SUBBATS 1 km  $\times$  1 km subgrid module.

The domain for the present study has been selected to cover most of Central Europe with a spatial resolution of 10 km  $\times$  10 km. It is divided into 23 vertical levels reaching up to 5 hPa. For convection, we have used the Grell scheme (Grell 1993). RegCM4.2 is initialized and driven by the ERA-Interim reanalysis (Simmons et al. 2007). The time step for the integration is 30 s.

### 1.3.4.4 Results

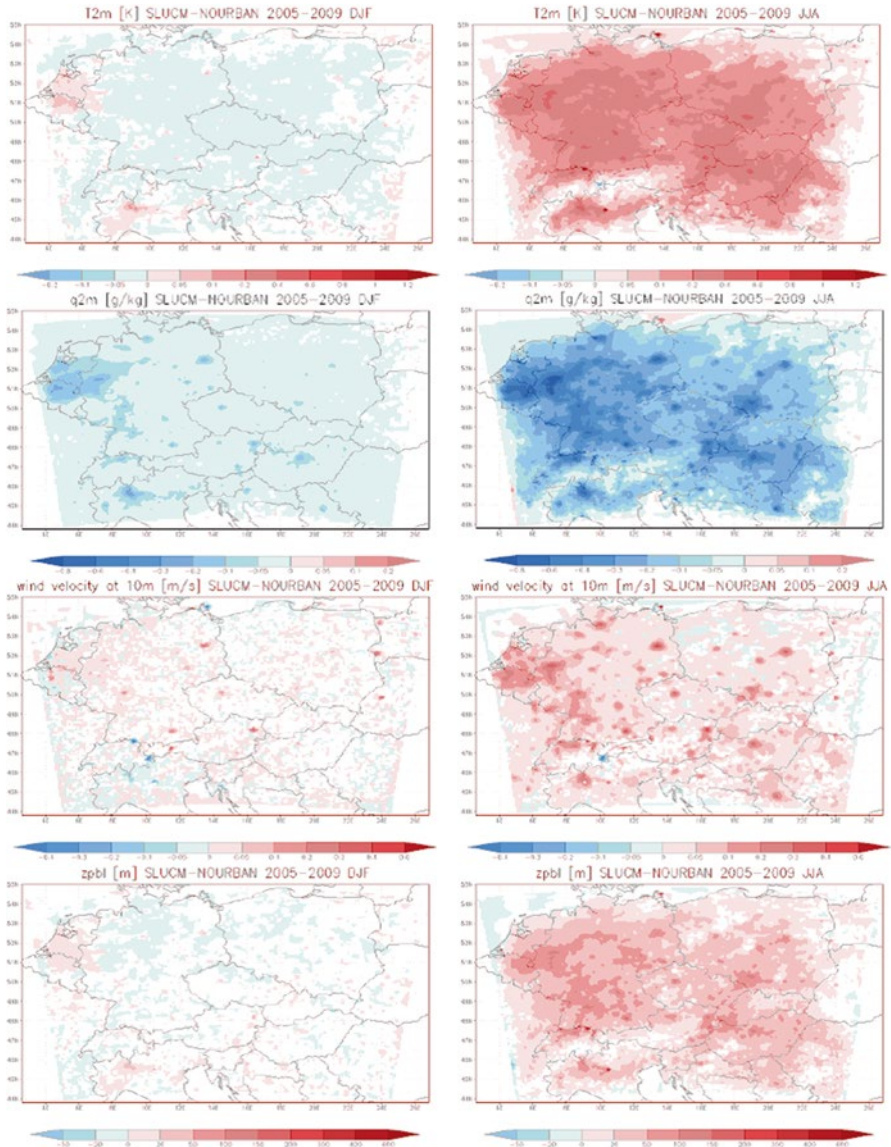
Figure 1.17 presents the change of selected meteorological parameters between experiments SLUCM (the urban canopy model turned on) and NOURBAN (urban canopy not considered) averaged over years 2005–2009. Shaded areas represent significant changes on the 95% confidence level. We show only winter (left panels) and summer (right panels) seasons, actually, the effect is well expressed in spring and autumn as well, but summer signal is stronger.

For temperature, there is an evident increase with urban canopy introduced in summer, for winter only slight signal can be seen – for big cities like Berlin and

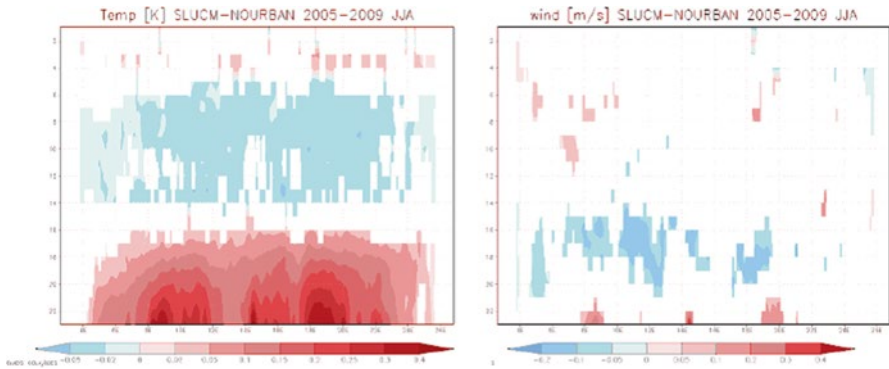


**Fig. 1.16** Urban and suburban land-surface categories at  $2\text{ km} \times 2\text{ km}$  resolution

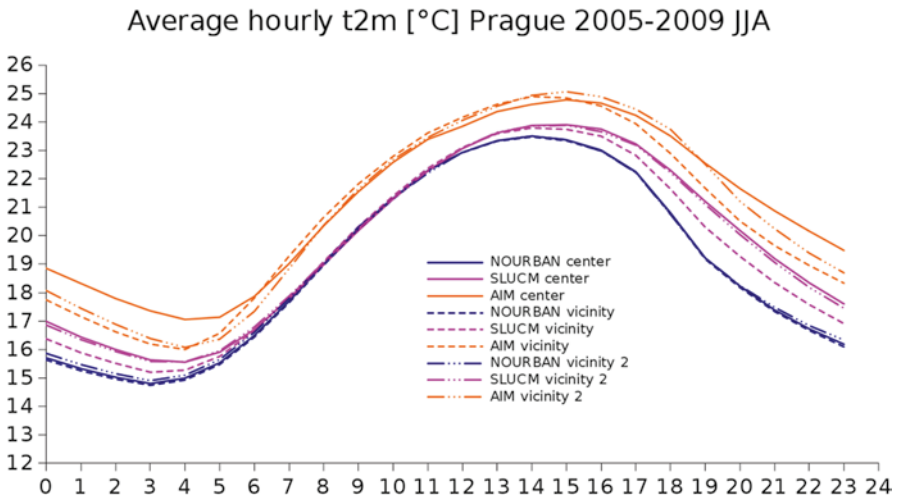
Vienna, similarly for urban and industrial areas like Rhine-Ruhr region and Po-valley. In summer, this temperature increase can be of 1 K over urbanized areas (effect of cities like Budapest, Vienna, Prague, Berlin are well seen), but it is statistically significant elsewhere with up to 0.4 K increase even over non-urban areas. Opposite effect can be seen for specific humidity. Urban surfaces can absorb less water vapor than other surfaces and they represent a sink for the precipitated water as well. Therefore the evaporation from the urban surfaces is reduced as well which leads to the lower humidity over urban areas as seen in Figure 1.17. Again, this decrease is highest above cities (up to  $-0.8\text{ g/kg}$ ), but significant decrease is simulated over non-urbanized areas as well, up to  $-0.3 - -0.4\text{ g/kg}$ . Signal is quite strong in summer, but similar patterns, although much slighter, can be seen in winter. For wind speed, introducing the urban canopy parameterization leads to stronger wind over the surface (Fig. 1.13). This increase is limited mainly over urban areas where it can reach  $0.4-0.6\text{ m.s}^{-1}$  in summer, much less it is expressed in winter, when for Po-valley there is even decrease. However, the signal is rather small in winter and not so much significant in all the domain. The increase above the cities in summer has to be further studied, one possible reason might be support of convection above the city with stronger winds in the bottom. Finally, we assess the effect of urban canopy parameterization on the height of planetary boundary layer from the model, which leads to statistically significant increase in summer above most of the domain, with quite strong signal above the cities and industrial regions (Fig. 1.17) of about 100–150 m, mostly negligible and not significant in winter.



**Fig. 1.17** The mean differences of meteorological parameters between experiments with SLUCM against NOURBAN averaged over 2005–2009 for winter (*left panels*) and summer (*right panels*): from the top – temperature at 2 m (K), specific humidity at 2 m ( $\text{g}\cdot\text{kg}^{-1}$ ), wind speed at 10 m ( $\text{m}\cdot\text{s}^{-1}$ ), and planetary boundary height (m). *Shaded areas* represent significant changes on the 95 % level of confidence



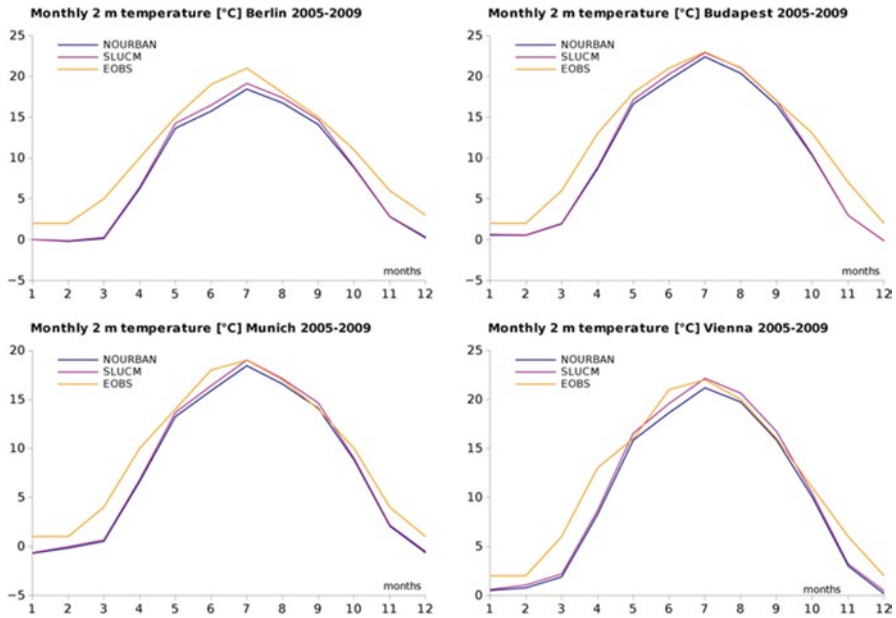
**Fig. 1.18** The mean differences in summer between experiments with SLUCM against NOURBAN averaged over 2005–2009 for vertical cross-section on 50°N of temperature (K, left panel) and wind speed ( $\text{m}\cdot\text{s}^{-1}$ , right panel). Shaded areas represent significant changes on the 95% level of confidence



**Fig. 1.19** Daily course of 2 m temperature for Prague city center and two points in vicinity, where number 2 is rather suburban. The simulation without urban effect included is shown in blue, with the effect included in violet and observations are in orange. Summer season is shown

Figure 1.18 presents the more detailed analysis of significant patterns of vertical structure of the urban parameterization effects in summer. The increase of temperature in the boundary layer is accompanied with temperature decrease above, concerning the humidity there is no effect in the free atmosphere (not shown). Stronger wind can be seen only at surface level, the effect throughout the boundary layer is rather negative.

In Fig. 1.19, the daily courses of surface temperature (2 m) are shown for Prague, with more detailed analysis of the simulations with respect to the observation data.



**Fig. 1.20** Annual course of 2 m temperature for selected cities based on the simulation without urban effect included (*blue curve*) and with the effect included (*violet*), compared to observations (*orange*)

In summer the strongest effect is shown, with clear extension of high temperature in evening hours both in city center data and in the simulation with urban effect included, to some extent as well in case of the second vicinity point, which has rather suburban character and it seems to be interpreted by the model with similar patterns as urban. Underestimation of the temperature in both simulations is evident, but especially during afternoon and night hours the urban effect contribute toward the bias reduction. Similar effect is clearly seen in comparison of simulations for other selected cities of the Central Europe in Fig. 1.20 in annual course, with E-OBS data shown as well. Again, introduction of the urban effect results in bias reduction in warm part of a year.

### 1.3.4.5 Conclusions

We have prepared the modelling stream for the assessment of the urban environment patterns and their changes due to both climate and other land-use or city structure changes. We have completed the decade 2021–2030 high resolution downscaling with respect to the pilot action in Prague, where city authorities are interested rather in closer future. Having both only BATS and SUBBATS results we can assess the effect of the urban environment. The analysis of other Euro-CORDEX results can

provide the information on the uncertainty or the spread of the local changes. Finally, we are running the CTM CAMx coupled with the RegCM4 to assess the impact of the changes on air-quality. The changes of emissions will be taken into account as well. Moreover, CLMM model is used to get effects in street canyons.

We successfully implemented a single layer urban canopy parametrization into the regional climate model RegCM4.2. Preliminary assessment is based on present day conditions simulation for 5 year long period with and without urban canopy parameterization included. Our simulations have shown that the impact on meteorological parameters is significant not only over urbanized areas but also over rural ones far from cities. The most important impact is the increase of surface temperature (up to 1 K), decrease of humidity, increase of surface wind speed, decrease of precipitation (not shown here) and increase of boundary layer height.

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### ***1.3.5 Statistical Downscaling Techniques Applied to ENSEMBLES GCMs: Bologna-Modena Case Study***

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#### **1.3.5.1 Introduction**

Another tool used by the scientific community in order to construct future climate projections is the statistical downscaling techniques (SDs). One of the main advantages of this technique is that it produces information at local scale, station or grid points and it is not expensive in terms of computational time. One major problem for all tools that produce climate change scenario is to quantify and reduce the uncertainties that appear in modelling processes. Particular attention has been paid on this problem and many projects have been focused on this issue. One of this is Ensembles project (<http://www.ensembles-eu.org/>), where it was recommended use of a range of models over the same area and construction of an ensemble mean (EM). This technique has been applied in the present work, in order to produce climate change scenario over Bologna-Modena case study selected in the project.

#### **1.3.5.2 Data and Methods**

The SDs model developed by ARPA-SIMC, is a multivariate regression based on Perfect-Prog approach, built using observed local fields at station level, and large scale fields derived from re-analysis data set. A set of 75 stations distributed over N-Italy, including Bologna station, that measure minimum and maximum



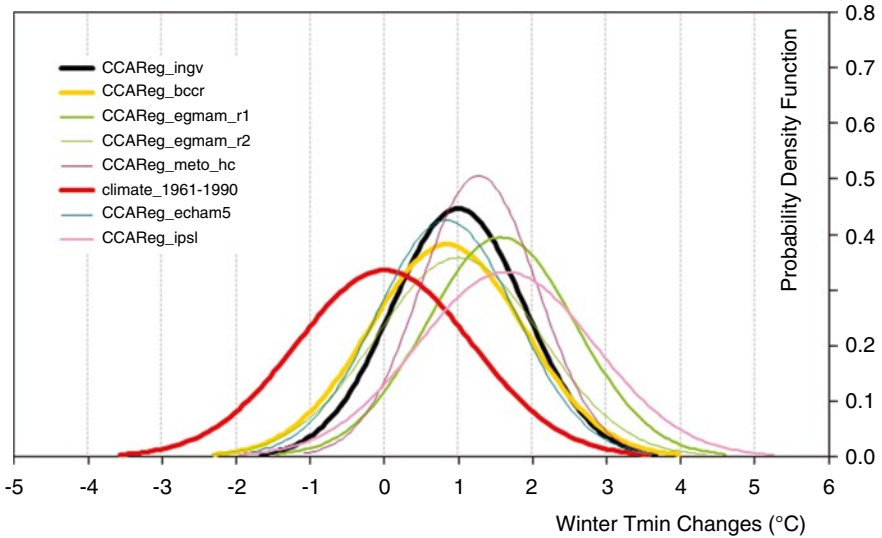
temperature and the large scale fields from ERA-40 reanalysis, over the period 1960–2002 has been used in order to set-up SDs model. Once the most skilful model is selected for each season and predictand, this is then applied to the predictors simulated by AOGCMs experiments in the framework of A1B emission scenario, such as to evaluate the local future scenarios of seasonal temperature. The SDs scheme here proposed use as predictors a selection of fields between mean sea level pressure (MSLP), 500 hPa geopotential height (Z500), and temperature at 850 hPa (T850), already tested over Emilia-Romagna and N-Italy region (Tomozeiu et al. 2013). These fields (predictors) derived from ERA40 re-analysis (<http://www.ecmwf.int/products/>) have a spatial resolution of  $1.125^\circ \times 1.125^\circ$ , cover the window  $90^\circ\text{W}–90^\circ\text{E}$  and  $0^\circ–90^\circ\text{N}$  and are referred to the period mid-1957 (September) to mid-2002 (August). As regards the AOGCMs predictors from the ENSEMBLES –STRAEM1 (Van der Linden and Mitchell 2009) runs had been used, over the period 1961–1990 (control-run) and 2021–2050 (A1B scenario). These fields are archived in the Climate and Environmental Retrieval and Archive (CERA data base) of the World Data Center System for Climate (WDC) and the access at the data is given by <http://ensembles.wdc-climate.de>. The STREAM1 simulations (<http://www.ensembles-eu.org/>), used in the present work have been performed with the methodology and the forcing that were defined for the CMIP3 simulations contributing to the IPCC AR4 assessment. Thus, the experiments were done using a common set of agreed forcing for historical simulations over the period 1860–2000, and for the three IPCC scenario A1B, A2, B2, over the twenty-first century. The scenarios were started from an initial condition obtained for year 2000 in the historical simulation. Several runs, produced by the following modelling groups have been take into account in the present work: INGV, NERSC, FUB, IPSL, METOHC (2 runs), MPIMET+DMI. The statistical downscaling scheme (CCAReg scheme) was applied to each seasons and each predictands (seasonal minimum and maximum temperature). The presence of different AOGCMs gives the opportunity to construct an Ensemble Mean (EM) of climate projections. The results obtained by applying the outputs of the AOGCMs to the CCAReg scheme at Bologna station are presented below.

### 1.3.5.3 Results

The future changes are presented in terms of probability density functions (PDFs) of seasonal minimum and maximum temperature, which provide a good estimation of changes not only in the mean but also in the extreme values. As could be noted from Fig. 1.21, that presents the PDFs of changes in winter minimum temperature as projected by the CCAReg scheme applied to each AOGCM, all the outputs emphasizes an increase in the winter T<sub>min</sub> between 0.7 (BCCR and ECHAM5 models) up to 1.8 °C (IPSL and EGMAM run2), over the period 2021–2050 with respect to 1961–1990.

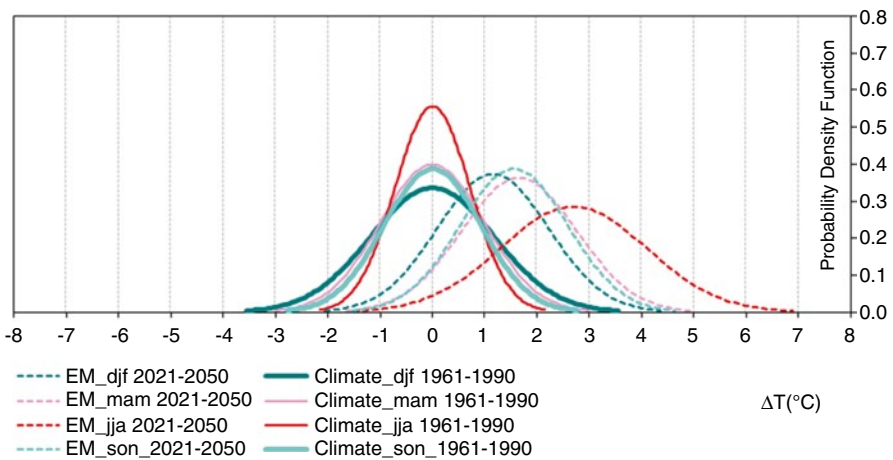
As concerns the other seasons, the Ensemble Mean of changes in minimum temperature computed taking into account all runs, reveals an increase of temperature in all seasons (see Fig. 1.22), around 1.5 °C during spring and autumn and 2.5 °C during summer.

**PDFs of winter Tmin changes projected by CCAReg model applied to 7AOGCMS-Bologna station, scenario A1B (2021-2050 respect to 1961-1991)**



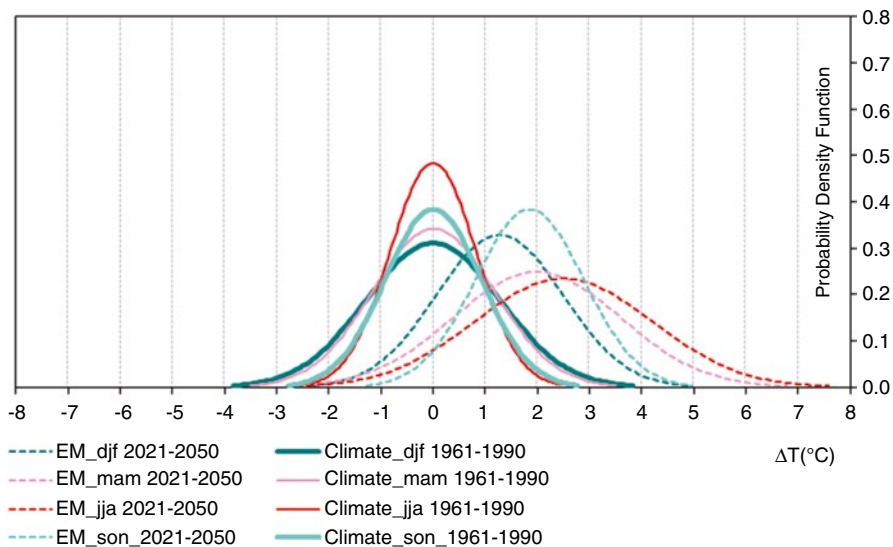
**Fig. 1.21** Climate change projections of winter minimum temperature-Bologna station, scenario A1B, 2021–2050

**Ensemble Mean (EM) of climate change projections of: winter(DJF), spring (MAM), summer (JJA) and autumn (SON) minimum temperature -Bologna station; scenario A1B (2021:2050-1961:1990) - output of SDs**



**Fig. 1.22** Ensemble Mean (EM) of seasonal changes of minimum temperature projected at Bologna station (CCAReg model), scenario A1B, 2021–2050 with respect to 1961–1990

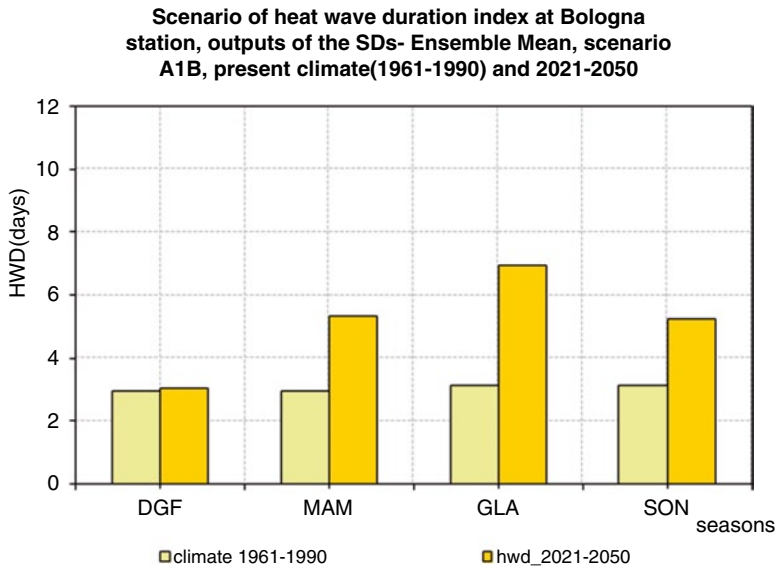
**Ensemble Mean (EM) of climate change projections of: winter(DJF), spring (MAM), summer (JJA) and autumn (SON) maximum temperature -Bologna station; Scenario A1B (2021:2050-1961:1990)-output of SDs**



**Fig. 1.23** Ensemble Mean (EM) of seasonal changes of maximum temperature projected at Bologna station (CCAReg model), scenario A1B, 2021–2050 with respect to 1961–1990

A similar signal of warming has been projected in seasonal maximum temperature. As it could be noted from Fig. 1.23, that presents the Ensemble Mean of changes in seasonal maximum temperature, the projected warming is around 1 °C during winter, similar with those projected in minimum temperature. During spring and autumn the maximum temperature is projected to increase with 2 °C (central moment of the distribution) with respect to 1961–1990. The peak of warming is projected to appear during summer season when the changes will be around 2.5 °C (central moment of the distribution).

Analyzing the PDFs of changes in seasonal minimum and maximum temperature (Figs. 1.22 and 1.23) it could be noted that all projected distributions (dashed curves) tend to shift to warm values with respect to present distributions (continuous curves). In addition significant changes could be noted not only in the central moment of the distribution but also in the tails, more significant in the upper tails of summer minimum and maximum temperatures when the 90th percentile could reach changes of 5 °C. A signal of increasing could be noted also in 10th percentile of minimum temperature, especially during summer. This could connect to an increase in the heat waves (days with  $T_{max} > 90$ th percentile of  $T_{max}$ ) and number of tropical nights ( $T_{min} > 20$  °C) over Bologna during the period 2021–2050 with respect to 1961–1990. In fact, the downscaling of the heat wave index for each season emphasizes a possible increase in the future 2021–2050 with respect to 1961–1990. Fig. 1.24 presents the climate scenarios of seasonal heat wave at Bologna, present



**Fig. 1.24** Ensemble Mean (EM) of seasonal heat waves projected at Bologna station (CCAReg model), scenario A1B, 2021–2050 and present climate (1961–1990)

and future climate. As could be noted significant increase is projected during summer season, followed by spring and autumn.

### 1.3.5.4 Conclusion

The future scenarios constructed through the statistical downscaling scheme applied to several GCMs show a possible increase in the seasonal minimum and maximum temperature over Bologna, around 2 °C over the period 2021–2050 with respect to 1961–1990. The signal is more intense during summer (around 2.5 °C the central moment of the distribution) when an increase of the frequency of heat waves is projected. The results are in agreement with those obtained by the regional climate models (Van der Linden and Mitchell 2009).

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