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COSMO-CLM

The urban land use in the COSMO-CLM model: a comparison of three parameterizations for Berlin

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Abstract

The regional non-hydrostatic climate model COSMO-CLM is increasingly being used on fine spatial scales of 1–5 km. Such applications require a detailed differentiation between the parameterization for natural and urban land uses. Since 2010, three parameterizations for urban land use have been incorporated into COSMO-CLM. These parameterizations vary in their complexity, required city parameters and their computational cost. We perform model simulations with the COSMO-CLM coupled to these three parameterizations for urban land in the same model domain of Berlin on a 1-km grid and compare results with available temperature observations. While all models capture the urban heat island, they differ in spatial detail, magnitude and the diurnal variation.

Keywords: urban heat island, regional climate modelling, urban land use parameterization

1 Motivation and objectives

The increasing resolution of regional climate models over the last two decades has led to an increase in model complexity. Mesoscale regional models currently resolve spatial scales down to ~ 1 km, where the exchange processes of energy and momentum between the surface and the lower atmospheric boundary layer should be captured in detail. This is typically done by parameterizations for different land surface types and often involves a separation between natural and human-made surfaces as the latter differ significantly in their radiative, thermal and morphological characteristics. Ongoing urbanization makes urban space home to more than half the world's population (U.N., 2010) and thus demands more research on urban environments and their vulnerability to climate change. Therefore, the modeling of urban environments and of the urban land surface has gained much attention in the last years as multiple parameterizations for this land use type became available and compared (Grimmond et al., 2011; Grimmond et al., 2010) in "offline-mode" (i.e. forced with observations). This first systematic evaluation of more than 30 different urban parameterizations showed that no individual scheme performs best for all energy fluxes (sensible and latent heat fluxes, long-wave outgoing radiation fluxes), but providing additional information on the urban surface (for example, vegetation fraction) generally improves the performance of most parameterizations. This evaluation study demonstrated that urban parameterizations with higher complexity do not necessarily perform better than simple ones and that a poor choice of model parameters can worsen the performance of parameterizations that would otherwise perform well.

In the present study, we compare three urban parameterizations in "online-mode" (i.e. incorporated directly into the code of the same atmospheric model), a direct coupling which allows an assessment of the impact of each parameterization on the performance of the regional climate model. The mesoscale non-hydrostatic regional climate model COSMO-CLM (CCLM) (Rockel et al., 2008) used in this study was developed by an open international network of scientists of the Climate Limited-area Modelling-Community (CLM-community, www.clm-community.eu) from the original weather predicting model COSMO (Steppeler et al., 2003) of the Deutscher Wetterdienst. CCLM has a standard representation of urban land by modifying soil and vegetation parameters in the Soil-Vegetation-Atmosphere Transfer model TERRA (Doms et al., 2011). Although this implementation allows representing the limited evaporation and warming of urban surfaces, it does not resolve some important urban features such as radiative and thermal properties of urban materials, shadowing effects and thermal regimes of street canyons. The increased attention to the interactions between the urban land cover and the atmosphere within the CLM-Community encouraged further model developments focusing on the parameterization of the urban land (Schubert et al., 2012; Trusilova et al., 2013; Wouters et al., 2012). These developments orig-

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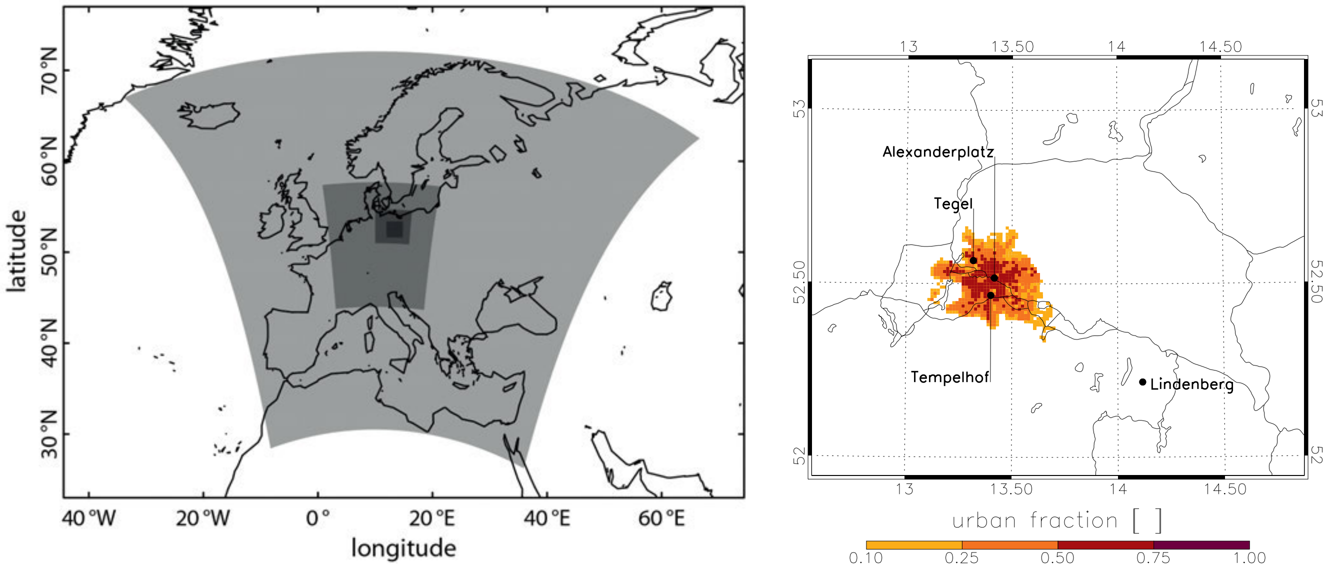

Figure 1: Model domains a) with spatial resolutions of 0.22° (~ 24 km), 0.0625° (~ 7 km), 0.025° (~ 3 km) and 0.009° (~ 1 km); b) the urban fraction within the inner model domain. The solid black line shows water bodies and rivers. The black filled circles indicate the locations of the measurement sites used for the model evaluation.

inated from the need to represent the urban heat island and roughness in climate models and are currently used for various applications ranging from detailed studies of thermal regimes to the modeling of the pollution dispersion in urbanized regions. Up to now, there has not been any synchronization among these implementations and therefore the aim of this study is to compare the three existing urban land use parameterizations in the "online-mode" at the exemplary urban site of Berlin and to identify the key characteristics that guide the choice of each parameterization for a particular type of application.

2 Method

In order to compare three existing implementations of urban land surface parameterization in the CCLM model, a chain of four nested model simulations was performed with the same model configuration with the exception of the urban land parameterization in the inner-most model domain. The simulation for the inner-most model domain is repeated three times – one for each urban land-surface parameterization scheme. The outputs from these model simulations are then compared with the available temperature observations at several chosen sites.

2.1 Setup for CCLM model simulations

We use the non-hydrostatic regional climate model CCLM version 4.8_clm19 and set a chain of four model domains (Fig. 1) for the model simulations. The entire year of 2002 was chosen for simulations based on the availability of the observational data. The year 2002 in Germany was the most humid and one of the warmest since the beginning of the 20th century (Müller-Westermeier and Riecke, 2002). The sunshine duration was in accordance with the reference value of the period 1961–1990. The mean temperature for Germany was 9.6 °C, 1.3 °C higher than the value for the reference period. The year 2002 was the 4th warmest year after 2000, 1994 and 1934, since 1901.

The CCLM-simulations include different spin-up periods. The coarse-scale simulation with a spatial resolution of 0.22° (~ 24 km) starts on January 1st 2001 and includes a 1-year spin-up time. The simulation with 0.0625° resolution (~ 7 km) has a spin-up time of 3 months starting on October 1st 2001. The simulations with resolutions of 0.025° (~ 3 km) and 0.009° (~ 1 km) start on January 1st 2002 and, therefore, have no spin-up time. The initialization and constraining of the outermost model domain at the lateral boundaries is done with the ERA-Interim Reanalysis dataset (Dee et al., 2011) from the European Centre for Medium-Range Weather Forecasts (www.ecmwf.int). For all model domains, the two-time level Runge-Kutta split-explicit scheme and the land surface model TERRA (Doms et al., 2011) with nine soil layers between 0.5, 2.5, 7, 16, 34, 70, 142, 286, 574 and 1150 cm are used. More details on the configuration of the model simulations over all domains are listed in Table 1.

For model validation we use the 2-m temperature which is calculated using the prognostic temperature at the surface and at the lowest layer of the atmosphere. In the CCLM model, the surface layer extends up to the lowest atmospheric level. The roughness sub-layer and the laminar sub-layer of the surface layer are defined as "skin" layers without resolving their vertical extension. The 2-m level (for 2-m temperature, humidity, etc.) is defined above the canopy (above the effective canopy height) and below the lowest atmospheric level. The temperature and humidity at this level are defined by

Table 1: Configuration for the model simulations.

Model simulation setting	Domain 1 (outermost)	Domain 2	Domain 3	Domain 4 (inner-most)
Spatial resolution (degrees/km)	0.22 °/~ 24 km	0.0625 °/~ 7 km	0.025 °/~ 3 km	0.009 °/~ 1 km
Number of grid points	190 × 90 × 40	180 × 220 × 40	150 × 150 × 50	195 × 195 × 50
Time step (sec)	150	40	25	10
Convection parameterization (Tiedke, 1989)	Yes	yes	Shallow convection	Shallow convection
Sub-scale orography parameterization (Schulz, 2008)	Yes	yes	no	no
Urban parameterization	No	no	no	yes (various)

Table 2: Characteristics of urban land cover resolved in the model simulations.

Process/parameter	Sim_MLUCM	Sim_SLUCM	Sim_BULKM	Sim_BULKM$_0$
description of buildings	detailed, multi-layer; uses a statistical distribution for the building height in each model grid cell	detailed, 1-layer; uses the mean building height for each model grid cell	bulk	bulk
vehicles Q_{Fv}	No	no	yes (statically prescribed)	no
buildings Q_{Fb}	yes (dynamically modelled)	yes (dynamically modelled)	yes (statically prescribed)	no
human metabolism Q_{Fm}	No	no	no	no
industry Q_{Fi}	No	no	yes	yes
snow cover on urban land	No	yes	no	no

the interpolation along a logarithmic profile between the corresponding values at the surface and the lowest atmospheric level.

This definition is used in most COSMO/CCLM forecasts. As the first atmospheric level lies 10–20 m above the ground, the canopy "interacts" with only the lowest atmospheric layer.

2.2 Parameterizations for urban land

For the inner-most model domain, three CCLM simulations are performed. Each simulation uses one of the following parameterizations for urban land:

1) Sim_MLUCM with the multi-layer (ML) urban canopy model (UCM) of high complexity using the coupled model CCLM-DCEP (Schubert et al., 2012),

2) Sim_SLUCM: with the single-layer (SL) urban canopy model of intermediate complexity using the coupled model CCLM-TEB (Trusilova et al., 2013),

3) Sim_BULKM: with the bulk parameterization (BULK) scheme using the extended model CCLM-TERRA-URB (Wouters, et al., 2012) with a prescribed anthropogenic heat flux (Flanner, 2009).

3a) Sim_BULKM$_0$: similar to Sim_BULKM but without the anthropogenic flux. This simulation is used to demonstrate the impact of anthropogenic heat on urban temperatures.

Each urban canopy model accounts for one or several sources of anthropogenic heat, Q_F, which can be divided into four components (Table 2):

$$Q_F = Q_{Fv} + Q_{Fb} + Q_{Fm} + Q_{Fi} \quad (2.1)$$

The subscripts v, b, m and i refer to vehicular, building, human metabolic and industrial heat emissions, respectively. Metabolic heat is often assumed negligible relative to vehicle and building heat production (Smith et al., 2009).

For the simulation Sim_SLUCM, the heat flux Q_{Fb} is calculated dynamically by heat transfer through building walls while setting the inner building temperature to a fixed value. For Sim_MLUCM, urban surfaces are resolved in multiple layers and a zero-flux condition is used for the heat flux at the inner-most layer. Thus, the innermost layer temperature varies in Sim_MLUCM throughout the simulation. This approach does not yield the additionally dynamically created anthropogenic heat and only the previously stored heat is released by buildings in Sim_MLUCM. For the simulation Sim_BULKM, an anthropogenic heat flux derived according to the methodology presented by Flanner (2009) is prescribed at the lowest atmospheric model level. For the additional simulation Sim_BULKM$_0$, no anthropogenic flux is prescribed.

The urban canopy parameters – building fraction, height and width – used in Sim_MLUCM and Sim_SLUCM are derived from a data set of impervious surfaces and a digitalized 3-D building data set of Berlin as described in the work of Schubert and Grossman-Clarke (2013) and illustrated in Fig. 2 of their work.

2.2.1 Parameterization 1: simulation Sim_MLUCM

The Double Canyon Effect Parameterization (DCEP) scheme (Schubert et al., 2012) is based on the Building

Effect Parameterization, BEP (Martilli et al., 2002) and thus inherits its underlying principles: both describe the urban surfaces with effectively two-dimensional street canyons characterized by orientation, building and street width as well as the building height distribution. The surface energy balance is simulated for road surfaces as well as for walls and roofs at different heights within the urban canopy in order to account for radiative and sensible heat fluxes between urban surfaces and the atmosphere. Thereby, the DCEP scheme is coupled to CCLM through the surface fluxes into the lowest atmospheric model layer as well as the energy and momentum fluxes from roof and wall surfaces in numerical layers above. In such a way, the DCEP scheme accounts for tall buildings that protrude through multiple layers of the atmosphere model. Each model grid cell containing urban land use is separated into two fractions covered by urban street canyons and natural surfaces, respectively. The DCEP scheme is applied on the urban fraction and the natural land surface types are resolved by the original COSMO land surface scheme TERRA. In contrast to BEP, DCEP considers the radiative exchange of roofs with other urban surfaces, treats diffuse and direct solar radiation separately and closes the radiative energy balance (Schubert et al., 2012).

In CCLM-DCEP, additional parameters that describe buildings must be specified for each grid cell based on available urban building data sets or urban land use classes as described in the work of Schubert and Grossman-Clarke (2013).

The heat flux from buildings Q_{Fb} is calculated dynamically by heat transfer through building walls resolved in 10 layers as in the work of Schubert and Grossman-Clarke (2013) given the zero-flux condition for the heat flux inside buildings, so that the temperature of the inner-most layer varies through the simulation. The heat diffusion equation and an energy budget for every surface are solved at each level in the urban material for computing the surface temperatures of roofs, walls and streets. Details of these calculations are given in the Appendix A of the work by Martilli et al. (2002). The heat from vehicles, Q_{Fv} and the industrial waste heat fluxes, Q_{Fi} can be prescribed in the model at the respective levels. For the model simulation Sim_MLUCM we set $Q_{Fv} = Q_{Fi} = 0.0\,\mathrm{W m^{-2}}$ as no estimate of these fluxes in Berlin is available to the authors. The anthropogenic moisture fluxes (from industry and traffic) as well as the moisture from evaporation of rain water from the urban surfaces are not captured by DCEP. Due to the iterative calculation of the energy transfer through multiple wall layers, the computational cost of the CCLM-DCEP is up to 15 % higher than that of the standard CCLM model.

2.2.2 Parameterization 2: simulation Sim_SLUCM

The Town Energy Budget (TEB) scheme (Masson, 2000) is a single-layer urban canopy model for simulating the energy and water exchanges between the urban canopy and the atmosphere. The scheme includes a detailed representation of a generic street canyon for calculating the turbulent heat and moisture fluxes from the urban canopy to the atmosphere. The TEB scheme was coupled to the CCLM model (Trusilova et al., 2013) using the tile-approach: each grid cell has a fraction of urban land resolved by TEB and a fraction of non-urban land resolved by TERRA. There is no vegetation allowed inside the street canyons as in the latest version of TEB (Lemonsu et al., 2012) and the top of the urban canopy is placed at the base of the atmospheric model. The canyon air temperature and humidity are assumed to be uniform, the logarithmic law for wind is applied at the top of the canyon and an exponential law is used below. The scheme resolves the energy balance for three generic urban surfaces (road, wall and roof) without considering their individual orientations as the averaging is performed over all directions. The thermal and radiative parameters for urban materials in this scheme are listed in Table 1 in Trusilova et al. (2013). The heat flux from buildings Q_{Fb} is calculated dynamically by heat transfer through building walls and roofs resolved in three layers given the constant inner building temperature of 19 °C for roofs and walls and the zero-flux condition for roads. The temperature evolution of urban materials and the heat flux through the multiple layers are described by equations 2–4 in the work by Masson (2000). The heat from vehicles Q_{Fv} and the industrial waste heat fluxes Q_{Fi} can be prescribed at the bottom of street canyons and at the top of the urban canopy, respectively. For the model simulation Sim_SLUCM, we set $Q_{Fv} = Q_{Fi} = 0.0\,\mathrm{W m^{-2}}$ as for the simulation Sim_MLUCM. TEB resolves the moisture flux from the water reservoir limited to 1 kg $\mathrm{m^{-2}}$ and the snow cover on roofs and roads. This allows applicability of CCLM-TEB in any weather conditions such as rainy periods and periods with snow cover allowing heat island cooling by water evaporation after rainfall and snow effects. Due to the iterative calculation of the energy transfer through walls and roofs in three layers, the computational cost of the CCLM-TEB scheme is of the order of 5–10 % higher than of the standard model.

2.2.3 Parameterization 3: simulation Sim_BULKM

The parameterization scheme TERRA-URB is an extended version of the land surface scheme TERRA that includes the urban surface energy balance and the urban-specific calculation of the surface layer transfer coefficients for momentum and heat determined in a non-iterative way (Wouters et al., 2012). Urban land cover is characterized by a specific thermal inertia (Demuzere et al., 2008), roughness length, albedo and emissivity (Sarkar and De Ridder, 2010; Wouters et al., 2013) and accounts for surface layer stability and the roughness sub-layer (Ridder, 2009). A bluff-rough thermal roughness length parameterization for the urban land-cover from Brutsaert (1982) is adopted using pa-

Table 3: Meteorological stations used for the evaluation of the model simulations.

Station name	Coordinates	Ground height [m]	Site description
Berlin-Alexanderplatz	52 ° 31 ′ 19 ″ N 13 ° 24 ′ 44 ″ E	37	Urban site: densely built up area of the Berlin city center with scarce vegetation patches of grass and shrub
TV-tower (at Alexanderplatz)	52 ° 31 ′ 15 ″ N 13 ° 24 ′ 34 ″ E	37	Urban site: densely built up area; temperature measurements at heights of 135 m, 260 m and 365 m above ground
Berlin-Tempelhof	52 ° 28 ′ 07 ″ N 13 ° 24 ′ 14 ″ E	48	Semi-urban site: grass field at the southern side of a former airport, free space in the north of the station and densely built up city in the south
Berlin-Tegel	52 ° 33 ′ 52 ″ N 13 ° 18 ′ 32 ″ E	36	Semi-urban site: grass field at the eastern side of the Belin-Tegel airport, free space in the south of the station, densely built up city in the east and in the north, airport runway at the south-west from the station
Lindenberg	52 ° 12 ′ 35 ″ N 14 ° 07 ′ 13 ″ E	98	Rural site: vegetated park-like area, ~ 65 km south east from the city center of Berlin

rameter values from Kanda et al. (2007). Two simulations with TERRA-URB are used in this comparison: 1) Sim_BULKM with the pre-calculated cumulative anthropogenic heat flux $Q_{Fv} + Q_{Fb} + Q_{Fi}$ (Flanner, 2009), which accounts for country-specific data of energy consumption calculated based on the population density and the latitude-dependent diurnal and seasonal distributions, prescribed at the lowest atmospheric model level; 2) Sim_BULKM$_0$ with the anthropogenic flux $Q_{Fv} = Q_{Fb} = Q_{Fi} = 0.0\,\mathrm{Wm}^{-2}$. The evaporation from urban impervious surfaces is not modeled in TERRA-URB in this study, although the model has an option to account for the evaporation by means of a new water-interception parameterization (Wouters et al., 2015). Due to the simple representation of the urban land as a bulk and non-iterative solution for the transfer coefficients, TERRA-URB is computationally inexpensive and only requires up to 3 % more computational cost as compared with the simulation with the default scheme TERRA.

2.3 Data for the model evaluation

In order to examine the ability of each model simulation Sim_MLUCM, Sim_SLUCM and Sim_BULKM to reproduce the urban and rural temperatures, as well as the urban heat island (UHI) of Berlin, the modelled temperature is compared with 2-m temperatures observed at four meteorological stations and temperature time series at three heights of the TV-tower at the city-center of Berlin (Fig. 1 and Table 3). All temperature time series are available at a 1 hour resolution from the database of the German Meteorological Service (Deutscher Wetterdienst).

The simulated temperature time series are corrected to fit the same height above ground as the observations by adding the standard atmosphere gradient 6.5 K/km to the original simulated temperature values. For calculating the UHI values from the time series of each station pair, the height correction is also applied. The latter is especially important when the time series from Lindenberg station at 98 m (higher than other stations) is used for calculating the UHI.

3 Results

3.1 Mean daily temperatures in Berlin

We evaluate the time series of mean daily 2-m temperatures from the model simulations Sim_MLUCM, Sim_SLUCM, Sim_BULKM, and Sim_BULKM$_0$ at the four chosen sites (Table 3). The differences among the model simulations are small at the rural site Lindenberg and are largest at the urban sites (Fig. 2) (as expected because of the different parameterizations for the urban land use). The largest inter-model differences occur in winter and reach up to 4.6 K per day (Fig. 2). At the rural and urban sites, all models have a similar RMSE of 1.52–1.70 K compared with the observations (Fig. 2, numbers to the left of the panel). All models overestimate the temperature variance calculated for the daily time series over the entire year at the stations: as the observed temperature standard deviation varies within 7.9–8.1 °C, the models give estimates within 8.4–8.8 °C. These estimates of the standard deviation, as the measures of how far a set of numbers is spread out, indicate that the modelled temperature data are more spread out from the mean value and from each other than the observed temperature data. In this respect, all three models provide a similarly larger spread of values as compared with the observations.

The time series of the daily UHI are calculated as the difference in 2-m temperature between the urban station Alexanderplatz and the rural station Lindenberg (Fig. 3). The daily UHI time series are calculated from the available hourly observational and modeled data. The mean annual UHI (Fig. 3, see the values on the left from the

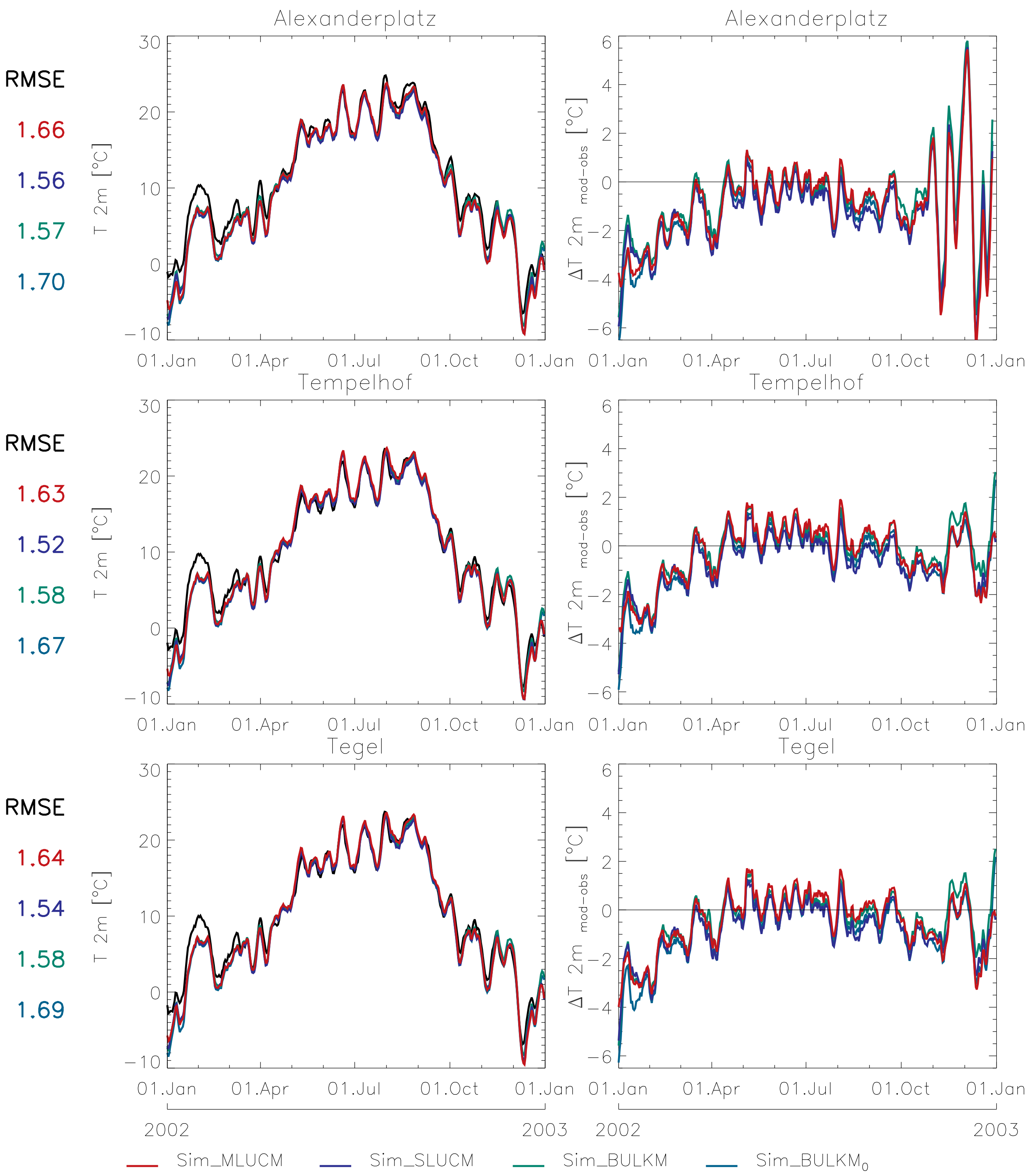

Figure 2: Time series of the daily mean 2-m temperature (left panels) at three urban stations: observed (black line) and modeled (colored lines) 2-m temperatures and the annual RMSE, which was calculated from the mean daily data, for each simulation (shown on the left from the corresponding panel in color); differences of each model to observations (right panels). For clarity, only the weekly running mean is shown for each time series. The time series at the rural station Lindenberg are not shown as all models produce a very similar signal (the color lines overlap).

panels) is overestimated by all models and ranges between 1.33–1.95 °C, whereas the observed mean UHI is 0.99 °C. All models tend to overestimate the UHI magnitude in all seasons. These overestimations originate from the setting of thermal parameters for urban materials in Sim_MLUCM and Sim_SLUCM (given in Table 1 of the work by Trusilova et al., 2013), the prior estimate for the anthropogenic heat flux in Sim_BULKM, as well as the way the 2-m temperature is calculated by each model. However, the further investigation of these rea-

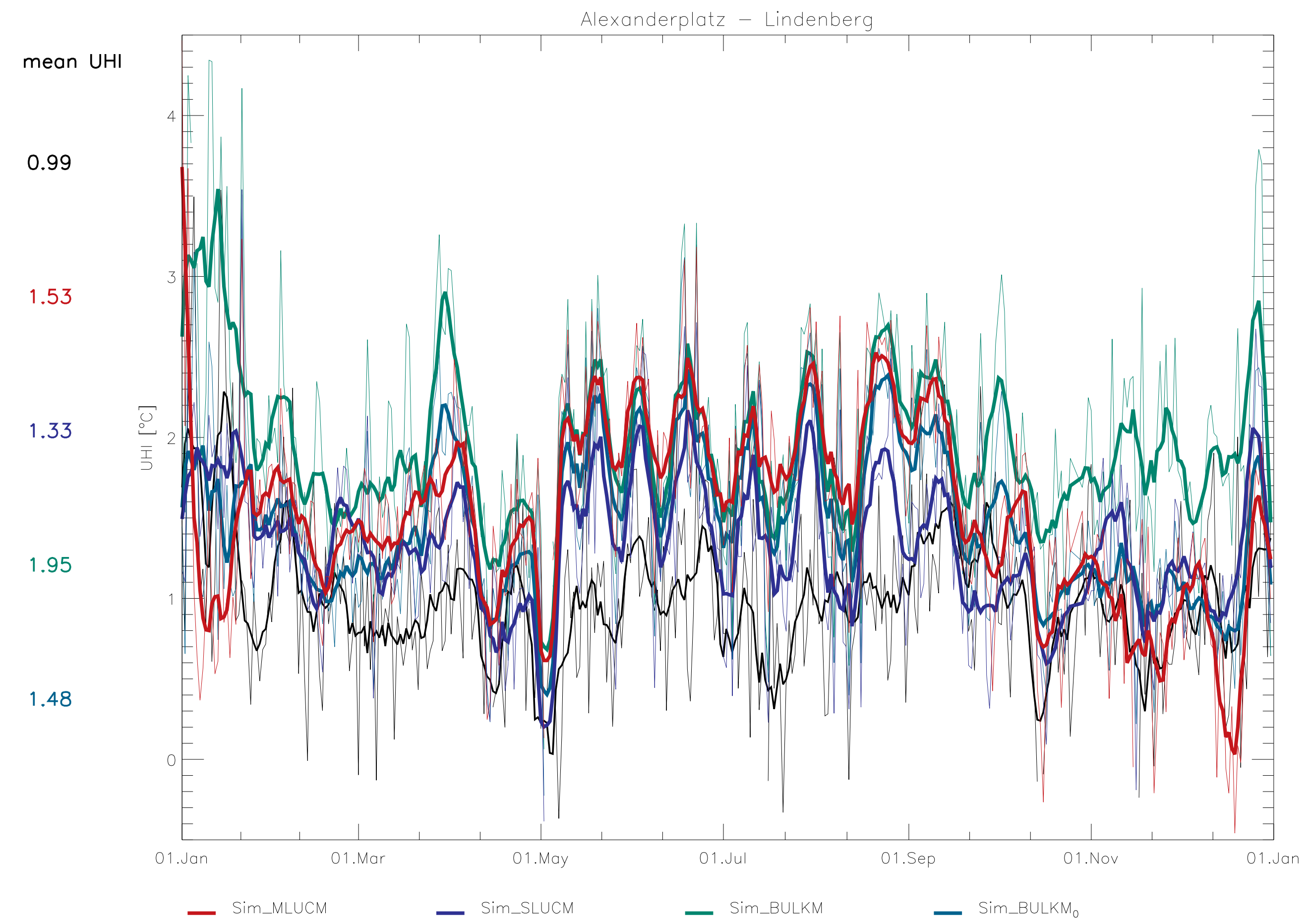

Figure 3: Time series of the daily mean UHI: observed (black line) and modeled (colored lines). UHI is calculated as the difference of the 2-m temperature between the stations Berlin-Alexanderplatz and Lindenberg. The mean annual UHI for observations and each model simulation is shown on the left in each panel in corresponding color. The weekly running mean is shown by the thick line for each time series.

sons and evaluation of each model are beyond the scope of this paper.

The mean annual difference in UHI between simulations Sim_BULKM and Sim_BULKM$_0$ is 0.47 °C (with daily differences up to several degrees in winter), a difference which originates from the anthropogenic heat flux added in Sim_BULKM and shows the importance of the correct estimate for this flux. Although the magnitude of the anthropogenic heat flux added in Sim_BULKM varies throughout the seasons with Q_F of $\sim$ 20 Wm^{-2} in summer and $\sim$ 60 Wm^{-2} in winter, its relative contribution to the surface energy budget (dominated by the input of the solar energy) in winter is higher than in summer (not shown).

3.2 Mean diurnal temperature variation in Berlin

We compare the time series of the mean diurnal temperature from three model simulations – Sim_MLUCM, Sim_SLUCM, and Sim_BULKM – at three heights of the TV-tower in Berlin (Fig. 4) and at 2-m above ground (Fig. 5). The temperature data for this comparison are averaged for four seasons: winter (JFD), spring (MAM), summer (JJA) and autumn (SON).

At the lowest 135 m-level of the TV-tower, the discrepancies among the simulations reach up to 2 °C /day (not shown). At the levels of 260 m and 365 m, all three models agree suggesting a weak effect of the different urban parameterizations on the temperatures in the higher altitudes. The temperature time series at 2-m (Figs. 2 and 5) and the temperatures at the TV-tower (Fig. 4) show that all models underestimate the observed temperature values in winter and autumn. This underestimation originates from the common "cold bias" coming from the boundary data of the coarser model simulation (throughout the atmosphere) as illustrated in Fig. 4. The time series from the coarse-scale model also underestimates the winter temperatures at all three heights.

The time series of the mean diurnal 2-m temperature variation from the four simulations Sim_MLUCM, Sim_SLUCM, Sim_BULKM, and Sim_BULKM$_0$ at the four measurement sites are compared in Fig. 5. In winter, the 2-m temperature is strongly influenced by the anthropogenic heat flux as seen by comparing Sim_BULKM with Sim_BULKM$_0$. The daily average difference between Sim_BULKM and Sim_BULKM$_0$is 0.46–1.06 °C in winter, 0.14–0.56 °C

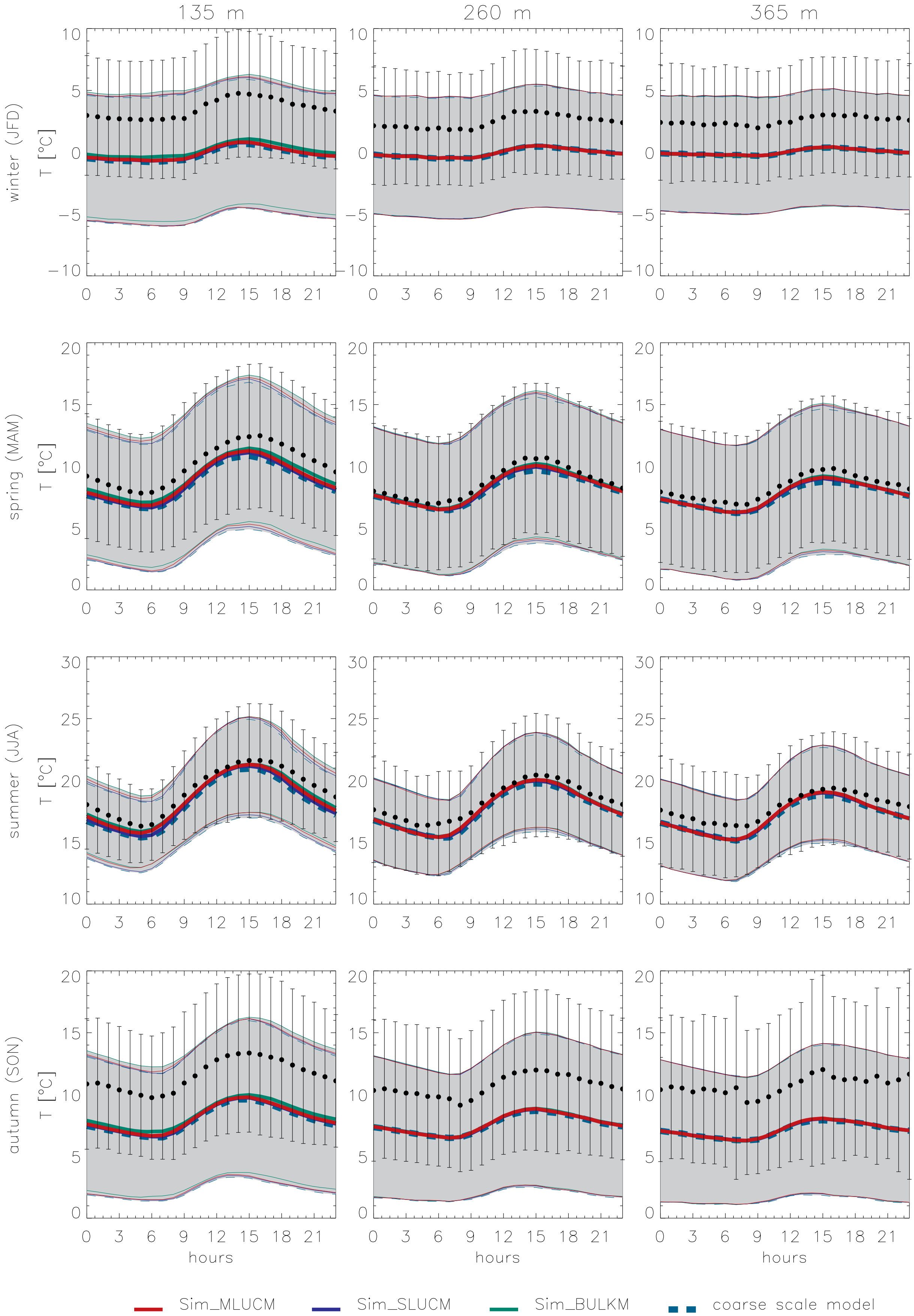

Figure 4: Time series of the daily mean temperature variation at the TV-tower at Alexanderplatz at three heights: 135 m, 260 m and 365 m above ground. The values calculated from observations are shown by black filled circles with one standard deviation range (vertical black lines) for each hour. The model values are shown as color lines with one standard deviation range (grey shaded area). The dashed line shows the time series derived from the model domain with a coarser spatial resolution of 0.025 ° (~ 3 km).

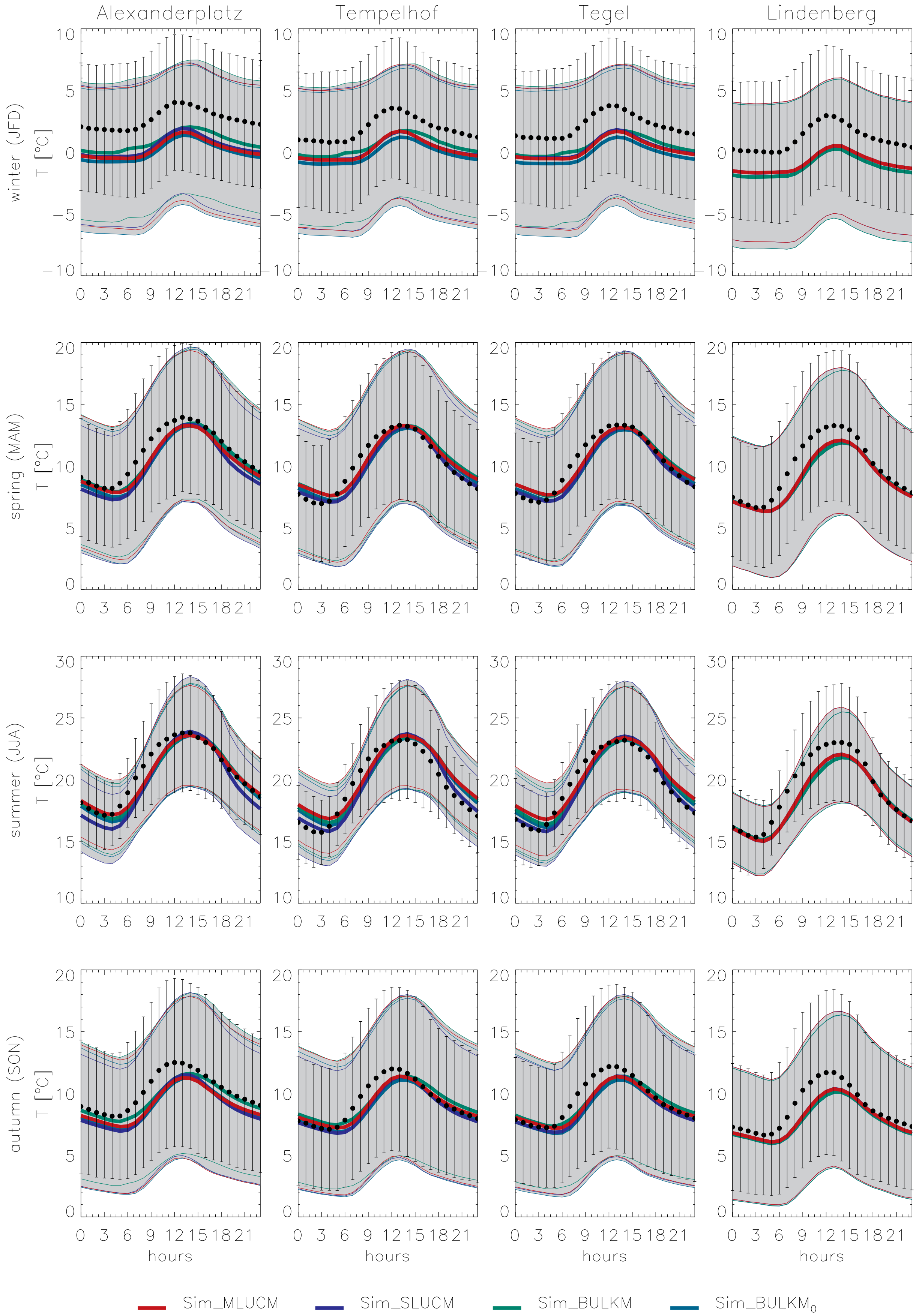

Figure 5: Averaged daily variation of 2-m temperature at four stations for four seasons. The observations are shown by black filled circles with one standard deviation range (vertical black lines) for each hour. The model values are shown as color lines with one standard deviation range (grey shaded area). Model lines overlap for the station Lindenberg.

in spring, 0.01–0.30 °C in summer and 0.24–0.81 °C in autumn. These temperature effects show the importance of the anthropogenic heat flux contribution to the surface energy budget in winter when the incoming solar radiation flux is the lowest in the year. In winter, all three models underestimate the 2-m temperatures by up to ∼ 2 °C (Fig. 5) because of the "cold bias" propagated from the coarse-scale model as discussed earlier. In spring and summer, there is a better agreement between the models and the observations, but all models show a delay of 1–2 hours in reaching the highest daily temperature compared with the observations. The largest discrepancies of 0.45–1.19 °C/season among models are found in night hours at the station Alexanderplatz, while the smallest difference of 0.05–0.34 °C/season is found at the station Lindenberg (as expected because this station is rural).

For a closer look at the inter-model differences, we define the UHI as the difference between the 2-m temperature of the urban sites – Berlin-Alexanderplatz, Berlin-Tempelhof, Berlin-Tegel – and the rural site Lindenberg (Fig. 6). All models overestimate the day-time UHI, especially in spring and summer, and perform very differently in terms of the diurnal variation of the UHI. The largest discrepancies among models are in day-time UHI in winter and in night-time UHI in summer. The observations of the vegetated airport sites Tempelhof und Tegel show, on average, a lower temperature than the modelled values (by all models). This is explained by the high fraction of urban land (more than 0.25, see Fig. 1) in the model at these sites, whereas both measurement stations are situated on the grassland fields away from buildings.

The observations at the "truly urban" site Berlin-Alexanderplatz show a small day-time UHI and a much larger night-time UHI that peaks at about 18 UTC. The two other urban sites – Berlin-Tempelhof and Berlin-Tegel – have a more complex UHI diurnal variation with two pronounced peaks in the morning and in the evening hours. This kind of diurnal evolution resembles a diurnal variation of the traffic intensity, with peaks during the intensive traffic flow and domestic energy use, and is neither captured by Sim_SLUCM nor Sim_MLUCM because the corresponding heat flux components were set to 0.0 Wm^{-2} in these simulations; these two simulations only resolve dynamically the heat transfer from buildings. The two peaks in the UHI diurnal cycle are captured by Sim_BULKM because the anthropogenic flux, which includes the traffic component and forms these two peaks, is directly prescribed in the simulation. This argument is supported by Sim_BULKM_0 that uses no anthropogenic flux and does not capture the UHI peaks. Sim_BULKM provides the highest UHI estimate throughout the winter, spring and autumn, which we attribute to a possible overestimation of the anthropogenic heat flux used in this simulation. Sim_MLUCM gives the highest UHI estimate in summer with the diurnal variation closest to the observations. In the "cold" seasons (winter and autumn) when anthropogenic heat makes a large contribution to urban temperatures, Sim_MLUCM underestimates the UHI as the anthropogenic heat is set to 0.0 Wm^{-2} in this simulation. Sim_SLUCM gives the lowest estimate of the night-time UHI at Alexanderplatz in all seasons with the strongest underestimation in summer. One of the reasons for this underestimation is the fast cooling conditioned by the heat transfer coefficients of the TERRA model. At Berlin-Tempelhof and Berlin-Tegel, the day time UHI is overestimated by Sim_SLUCM (as by other models), something that is partly conditioned by the setting of the building's thermal parameters too generally (this we cannot prove within this study). The lowest UHI estimate among the three models is given by Sim_SLUCM, which is explained by the definition of the 2-m level temperature used in this simulation (the 2-m temperature is defined above the canopy in TERRA and, consequently, above the building roofs in TEB) and by accounting for the evaporative cooling. For an alternative definition of the 2-m temperature, the temperature in street canyons – a variable of the TEB scheme – is also provided by the model. However, the definition of the 2-m temperature in non-urban areas has to be considered as well by taking into account the canopy structure and thickness. At the moment, the vegetation canopy is an infinitely thin "skin" layer and its vertical profiles of atmospheric variables are not resolved in the standard COSMO-CLM model.

At Alexanderplatz – the truly urban built-up site – Sim_MLUCM captures the daily evolution of the UHI best with the exception during winter. However, the daily mean magnitude is overestimated. Sim_BULKM captures the daily evolution of winter-time UHI best. At the two airport sites – Tempelhof and Tegel – Sim_SLUCM gives the closest estimate of the UHI magnitude but none of the models capture well the daily variation of UHI in all seasons. This conclusion must be considered with care because of the discrepancies between modeled and observed temperatures. A grid of 1-km may not represent the local temperature variability governed by the heterogeneity of urban environments. Often patches of grassland, tree parks and water surfaces are not resolved in models but influence the observations. However, besides the assumptions made in each of the urban parameterizations, the model errors could originate from other reasons as well. For instance, model errors and uncertainties in the atmospheric part of the regional climate model CCLM may deteriorate the overall model performance in terms of the urban heat island. For instance, the nocturnal boundary-layer structure and processes strongly influence the formation of UHI (Wouters et al., 2013). Additionally, inconsistencies in the measured temperatures among the sites could lead to errors in the UHI-estimate derived from observations. For example, biases in the measured temperature series may add up (or cancel out each other) when calculating UHI, which may lead to an overestimation (or underestimation) of the overall urban heat island in the measurements.

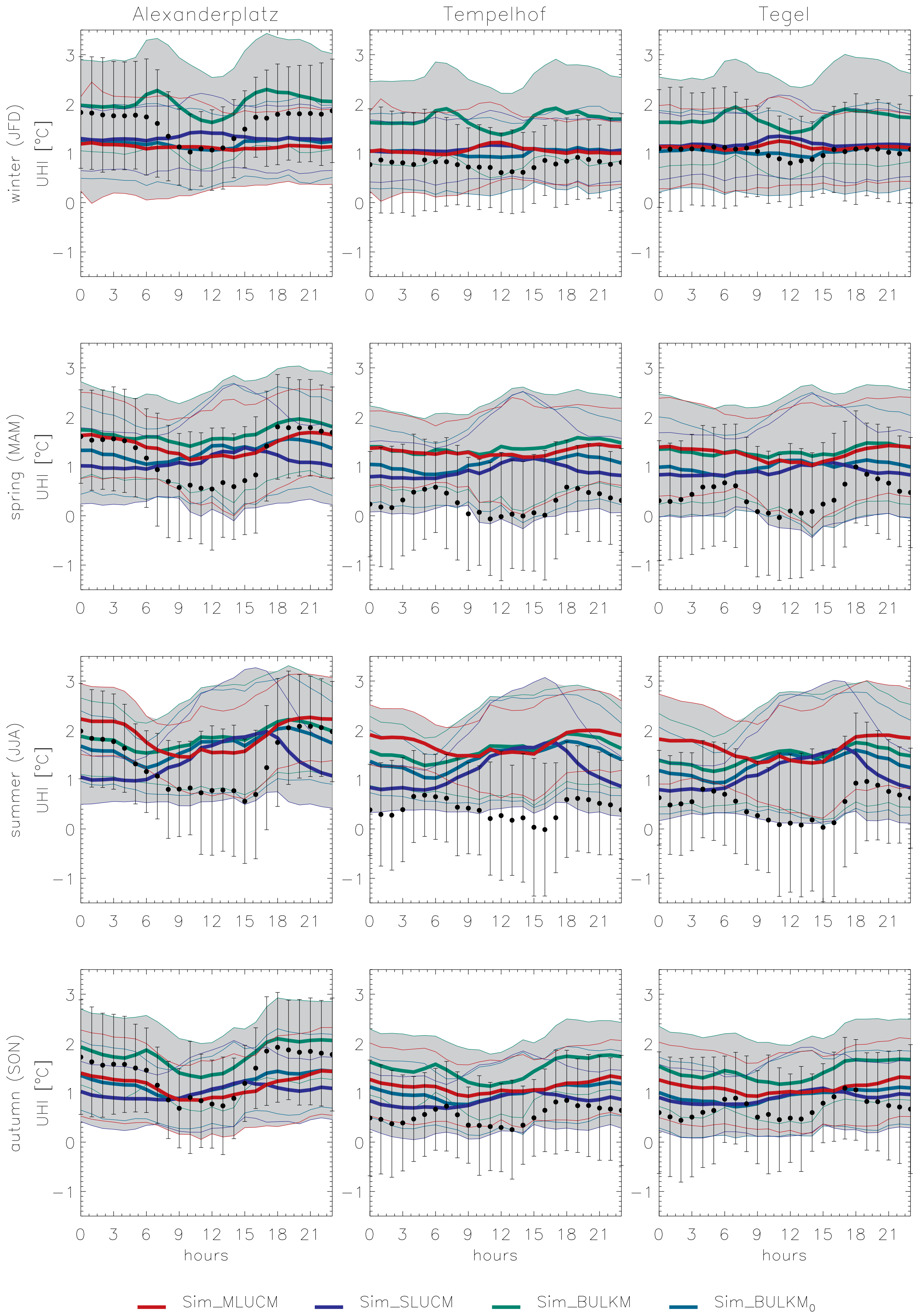

Figure 6: Averaged daily variation of UHI calculated as the difference in 2-m temperature between each urban station and the station Lindenberg. The UHI from the observations is shown by black filled circles with one standard deviation range (vertical black lines) for each hour. The modeled UHI values are shown by color lines with one standard deviation range (grey shaded area).

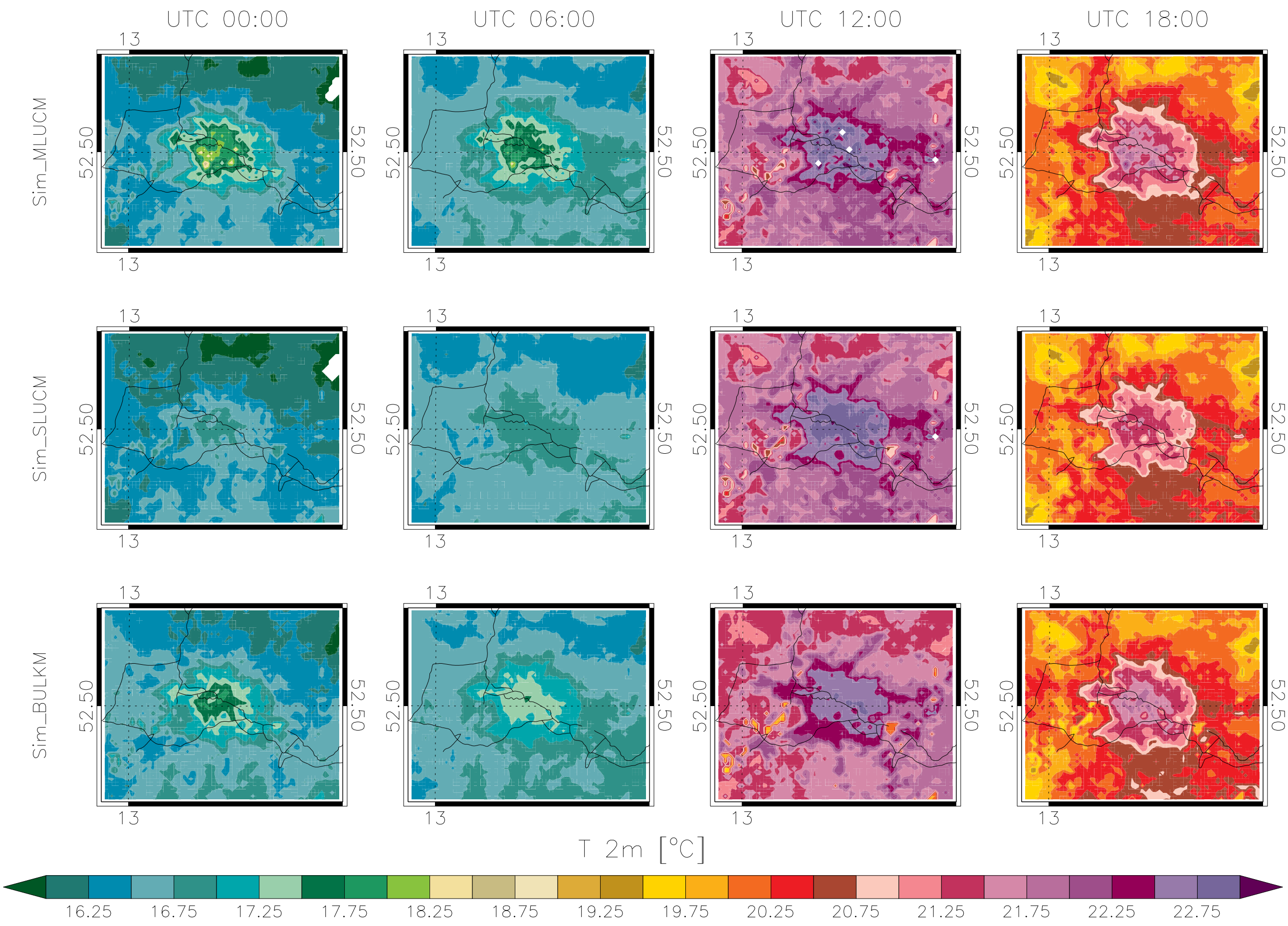

Figure 7: Mean 2-m temperature in July 2002 at 00:00, 06:00, 12:00 and 18:00 UTC.

Additionally to the 2-m temperature time series, we compared the spatial extent of the temperatures simulated with the different models (Fig. 7) for July 2002. According to Fig. 7, all models capture higher urban temperatures but estimate its magnitude differently. These discrepancies appear for several reasons: 1) different assumptions for representing the thermal properties of buildings, 2) differences in calculating the 2-m temperature, 3) differences in parameterizing heat transfer from the roughness layer into the atmosphere. All models agree well at 12:00 UTC and 18:00 UTC but differ for night and early morning (as was previously discussed and shown in Fig. 5 and 6).

Sim_MLUCM provides a 2-m temperature estimate with the highest heterogeneity within the city (Fig. 7, 12:00 UTC). Such a heterogeneous pattern results from the fact that Sim_MLUCM accounts for individual street orientations and building height distributions in each model grid cell. The model also provides the highest estimate of urban temperatures at night (Fig. 6, Sim_MLUCM in summer). Sim_SLUCM shows less spatial detail in the estimated temperature field than Sim_MLUCM. This is expected because the Sim_SLUCM uses the concept of the generic street canyon without differentiation of street directions (in the calculation of the sky-view factor for the building walls) and building morphology. Generally, Sim_SLUCM provided the lowest estimate of UHI in July 2002, taking into account 12 days with more than 1 mm/day total rainfall. The simulation Sim_BULKM gives an estimate of the urban 2-m temperature of a magnitude comparable with the other two models, but with less spatial variability at midday (when other schemes capture shadow-effects in streets and different volume of buildings) due the simplified representation of the urban land use.

4 Summary and outlook

We compared simulations from the non-hydrostatic regional mesoscale climate model CCLM coupled to three different urban land parameterizations of different complexity. We performed three high-resolution (~ 1 km) model simulations using these coupled models for the larger area of Berlin for one year and compared model outputs.

The multi-layer urban canopy model CCLM-DCEP (Schubert et al., 2012) accounts for street orientation and various building heights in each model grid cell. This multi-layer structure resolves temperature and moisture gradients within street canyons and the influence of buildings on the air flow. The interaction between the atmosphere, the air in the urban canopy and buildings is resolved in detail and suggests the favorable model applicability on spatial scales of 1 km and possibly finer provided that the required data on street and building morphology is available. The model represents well the daily variation and magnitude of the urban heat island in summer. However, as the model does not resolve the evaporation from urban surfaces, it should best be used for simulating rain-free periods and for estimating extremes of urban temperatures.

The single-layer urban canopy model of the intermediate complexity CCLM-TEB (Trusilova et al., 2013) parameterizes the generic street canyon, chosen as the representative for the city and described by the mean building height and street width, with the simple parameterization of canyon air characteristics (as homogeneous) that only interacts with the atmosphere through the top of the street canyon. This simplification suggests the model applicability on the spatial scales where the shape of individual buildings and streets can be averaged, such as 1–5 km. The model matches the mean daily temperature at Berlin-Tempelhof and Berlin-Tegel (Fig. 5) in all seasons except winter (due to the cold bias propagated from the model forcing fields). The model overestimates the night urban temperature at the site Berlin-Alexanderplatz, most probably because the input data contain only sealed surfaces without any vegetated land. The parameterization of the water evaporation from urban surfaces makes the model CCLM-TEB suitable for “all-weather” simulations, i.e., climate simulations when the interaction between the urban canyon air and the atmosphere needs to be resolved.

The simple bulk-model CCLM-TERRA-URB (Wouters et al., 2012) parameterizes the effects of buildings on the air flow without resolving the energy budgets of the buildings themselves, but using the externally calculated anthropogenic heat flux. This approach allows representing effects of multiple cities on the atmosphere without requiring additional data on the building structure. The use of the previously estimated anthropogenic heat flux, modified thermal and radiative parameters and a modified surface-layer transfer scheme, provides the urban heat island with the correct diurnal phase. The magnitude of this flux can potentially be revised to fit the mean measured signal. Such an implementation is computationally fast and is recommended for studies with large spatial and temporal scales when the interactions between the urban canyon air and the atmosphere, as well as the building temperatures, do not need to be resolved in detail, but rather the effect of the urban canopy on the atmosphere is to be represented (for example, for studies on the pollution dispersion in the boundary layer).

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