Implementation of an Urban Parameterization Scheme into the Regional Climate Model COSMO-CLM

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ABSTRACT

As the nonhydrostatic regional model of the Consortium for Small-Scale Modelling in Climate Mode (COSMO-CLM) is increasingly employed for studying the effects of urbanization on the environment, the authors extend its surface-layer parameterization by the Town Energy Budget (TEB) parameterization using the ''tile approach'' for a single urban class. The new implementation COSMO-CLM+TEB is used for a 1-yr reanalysis-driven simulation over Europe at a spatial resolution of 0.11° (~12 km) and over the area of Berlin at a spatial resolution of 0.025° (~2.8 km) for evaluating the new coupled model. The results on the coarse spatial resolution of 0.11° show that the standard and the new models provide 2-m temperature and daily precipitation fields that differ only slightly by from -0.1 to $+0.2$ K per season and ± 0.1 mm day^{-1}, respectively, with very similar statistical distributions. This indicates only a negligibly small effect of the urban parameterization on the model's climatology. Therefore, it is suggested that an urban parameterization may be omitted in model simulations on this scale. On the spatial resolution of 0.025° the model COSMO-CLM+TEB is able to better represent the magnitude of the urban heat island in Berlin than the standard model COSMO-CLM. This finding shows the importance of using the parameterization for urban land in the model simulations on fine spatial scales. It is also suggested that models could benefit from resolving multiple urban land use classes to better simulate the spatial variability of urban temperatures for large metropolitan areas on spatial scales below ~3 km.

1. Introduction

Since the level of world urbanization crossed the 50% mark in 2009 and is expected to reach 69% in 2050 (UN 2009), ever increasing numbers of people are impacted by weather and climate in urban areas. As urban features strongly influence the atmospheric flow, modify the turbulent transport, and determine the microclimate of the local environment (Piringer et al. 2007), there is a growing demand for assessing urban effects on the climate and their feedbacks.

Regional atmospheric models serve as an instrument for studying the climate on spatial scales below 50–80 km. Such models can resolve the atmospheric flow in detail to account for urban-specific processes. The increasing resolution of regional climate models in the last decade lead to the increase of their complexity. On the fine spatial scales of 1–10 km, the parameterization of different land uses requires more discretization between natural and human-made surfaces as they differ greatly in their thermal and morphological characteristics.

The regional model of the Consortium for Small-Scale Modelling in Climate Mode (COSMO-CLM; Rockel et al. 2008), which was developed by the CLM community (www.clm-community.eu) from the weather-predicting model COSMO (Steppeler et al. 2003) of the Deutscher Wetterdienst, is typically run on the spatial resolution of

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1–50 km but does not resolve specifics of urban boundary layers, for example, urban heat island and limited surface evaporation. The growing number of model applications in urbanized regions motivates us to implement a new parameterization for urban land into the COSMO-CLM model to represent urban boundary layers within climate simulations. Such climate simulations are increasingly used for studying feedbacks between the climate and urban environments and as input for impact models on local scales.

Modeling of urban land cover has gained much attention in recent years as multiple parameterizations for urban land use became available for different applications including global climate modeling (Oleson et al. 2008), numerical weather prediction (Masson 2000; Kusaka et al. 2001; Best 2005), and air quality modeling (Martilli et al. 2002). A systematic evaluation of these and other urban parameterizations (Grimmond et al. 2010, 2011) using measurements of surface energy fluxes has shown that no individual scheme performs best for all energy fluxes (sensible and latent heat fluxes, longwave outgoing radiation fluxes), but providing additional information on the urban surface (for example vegetation fraction) generally improves the performance of most parameterizations. This evaluation showed 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 otherwise perform well.

For the implementation into the COSMO-CLM we chose the Town Energy Budget (TEB) scheme—a parameterization of an intermediate complexity for the urban canopy (Masson 2000). The TEB scheme resolves energy and moisture fluxes in a ‘‘typical’’ urban canopy with an explicit differentiation between buildings and street canyons. The TEB parameterization was previously tested and evaluated in offline coupling mode for urban areas of Marseille (Lemonsu et al. 2004), Mexico City, and Vancouver (Masson et al. 2002). The TEB scheme was previously implemented as a parameterization for urban land into the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) by Trusilova et al. (2008, 2009) and used for a study of the climate sensitivity to the urban warming in Europe at the spatial resolution of ~10 km.

In this paper, we present the new version of the regional climate model COSMO-CLM coupled to the TEB scheme. In section 2, we describe the implementation of this coupling. Section 3 presents the model setup and the data used for the evaluation. Section 4 contains results of the model evaluation for two model domains with different spatial resolutions, and section 5 contains the summary and outlook for possible future applications of the new model.

2. Model description

The first steps toward the ‘‘urbanization’’ of the numerical weather-predicting model COSMO were already done by Neunhauserer et al. (2007), who adjusted the existing nonurban surface parameterization of an older two-layer version of the land surface model ‘‘TERRA’’ (Doms et al. 2011) to represent the urban land by modifying radiative and thermal soil parameters and including an anthropogenic heat flux. Although this implementation makes it possible to represent urban-specific temperature forcing at the lower boundary layer, 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; it did not become part of the standard model. With the objective to study interactions between the climate and urban environments, we implement a new, more detailed urban parameterization that accounts for the city-specific surface properties.

Presently, in the operational setup and in climate simulations the land surface model TERRA with 7–9 soil layers (Doms et al. 2011) is used. The surface roughness length, the geometrical height, and the water and vegetation fractions for the TERRA model are calculated from the Global Land Cover 2000 (GLC2000) database (Fritz et al. 2003) at a resolution of 1 km using lookup tables of the operational COSMO setup (Doms et al. 2011). Values of these surface parameters are averaged to the model grid resolution by weighting each contributing land use with its area fraction (composite approach). Although the composite approach to the land use characterization enables accounting for urban land to some extent, there is no differentiation in the parameterization of the surface–atmosphere interactions between the urban and nonurban land. Furthermore, small cities are ‘‘averaged out’’ by the surrounding nonurban land use classes and produce no visible effect on the atmosphere. We couple the TEB (Masson 2000) scheme as a new parameterization for the urban land, leaving other nonurban categories to be resolved by TERRA. The differentiation between the urban and nonurban land is done by introducing a new field ‘‘urban fraction’’ into the model; this field is extracted from the land cover database GLC2000 as for each model grid cell.

a. Implementation of the urban parameterization

We couple the TEB parameterization to the land surface model TERRA of the COSMO-CLM. TEB is a

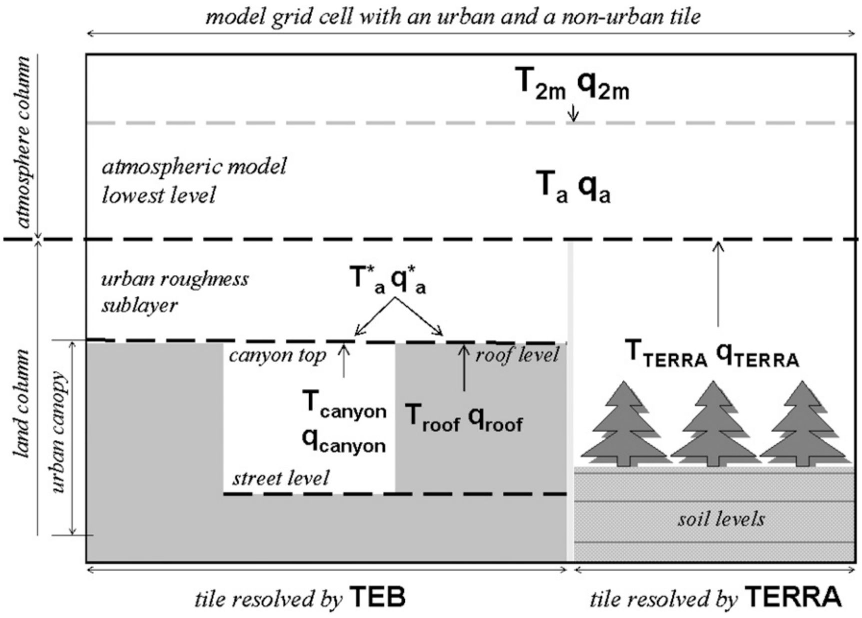

FIG. 1. Scheme of the coupling between the land surface schemes TERRA and TEB to the atmosphere.

1-layer scheme for simulating the energy and water exchanges between the urban canopy and the atmosphere. TEB includes a detailed representation of a generic street canyon that makes it possible to calculate the turbulent heat and moisture fluxes from the urban canopy toward the atmosphere from two major sources: from the top of the street canyons and from the roofs (Fig. 1). The turbulent fluxes from these two sources are weighted by their area fractions representing the mixing in the urban roughness sublayer.

The calculation of the turbulent heat and moisture fluxes from the street canyon requires a parameterization of the canyon air characteristics. In the TEB scheme the air temperature and humidity are assumed to be uniform in the canyon; for wind the logarithmic law is applied upward from the top of the canyon and the exponential law is used below. TEB resolves the energy balance for three generic urban surfaces—road, wall, and roof—without considering their individual orientations because the averaging is performed over all directions. This feature of the TEB scheme permits its applicability to multiple urban areas.

Although TEB computes momentum fluxes for the entire urban cover with a roughness length formulation and stability coefficients of Mascart et al. (1995), we do not use this part in the coupled model COSMO-CLM+TEB. Instead, to preserve the spatial homogeneity in the calculation of the momentum fluxes, the standard turbulence scheme of COSMO-CLM (Doms et al. 2011) is used for all land use types.

For model validation purposes the 2-m temperature is necessary; it is calculated using the prognostic temperature at the surface and at the lowest layer of the atmosphere. In the COSMO-CLM model the surface layer extends up to the lowest atmospheric level; the roughness sublayer and the laminar sublayer 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 the specific humidity at this level are defined by 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-CLM forecasts because the first atmospheric level lies above ~(10–20) m (there is no need to account for other atmospheric levels above the lowest one).

The surface temperature of the urban tile in the coupled COSMO-CLM+TEB model is defined at the top of the urban canopy (roof level). In this case the vegetated canopy and the urban canopy both lie below the lowest atmospheric level. Such treatment of the urban canopy can be justified if the mean building height is below the lowest atmospheric level, otherwise buildings would protrude into higher model levels. As for the present setup the mean urban canopy height (=building height) is safely below or within the lowest atmospheric model level. Therefore, similarly to the vegetated tile, the 2-m temperature and humidity above the urban tile are defined at the 2-m level above the urban canopy using the same interpolation routine as for the vegetated tile. For the model output, the diagnostic 2-m temperature and humidity fields are calculated as the average between the values from the vegetated and the urban tiles weighted by their area fraction.

b. Turbulent heat and moisture fluxes

In COSMO-CLM the coupling between the atmosphere and the underlying surface is modeled by a stability and roughness-length-dependent surface flux formulation based on the modified Businger relations (Businger et al. 1971). The calculation of the fluxes requires the temperature and the specific humidity at the ground, which are given by the land surface model TERRA. The parameterization of the surface fluxes in the atmospheric part of the model is based on the drag-law formulation. Vertical fluxes are defined at the top of the canopy (and are not resolved within the canopy) and are positive when they are directed toward the atmosphere. For the sensible heat flux H_{TERRA} the following is applied:

$$H_{\mathrm{TERRA}} = -\rho c_{p_d} C_h^d |\mathbf{v}_h| (T_a - T_{\mathrm{sfc}}),$$

$$|\mathbf{v}_h| = (u^2 + v^2)^{1/2},$$

where ρ is the air density, c_{p_d} is the heat capacity of dry air, C_h^d is the aerodynamic transfer coefficient for the turbulent heat exchange at the surface, T_a is the temperature at the lowest atmospheric grid level, T_{sfc} is the ground temperature predicted by TERRA, and u and v are the wind speed components at the lowest model level.

The hydrological section of TERRA calculates the liquid water contents of various reservoirs of water (interception reservoir, snow reservoir) at the surface and in the soil layers. The parametric relation for the surface flux of water vapor F_{TERRA} reads as follows:

$$F_{\mathrm{TERRA}} = -\rho C_q^d |\mathbf{v}_h| (q_a - q_{\mathrm{sfc}}),$$

where C_q^d is the aerodynamic transfer coefficient for turbulent moisture transfer, $C_q^d = C_h^d$, q_a is the specific humidity at the lowest grid level above the ground, and q_{sfc} is the ground level specific humidity predicted by the land surface model TERRA.

The latent heat flux $\mathrm{LE}_{\mathrm{TERRA}}$ is defined accordingly:

$$\mathrm{LE}_{\mathrm{TERRA}} = -\rho L_v C_h^d |\mathbf{v}_h| (q_a - q_{\mathrm{sfc}}),$$

where L_v is the vaporization heat constant.

In TEB the exchange of heat and moisture between the urban canopy and the atmosphere occurs at the top of the canyon and at the roof level (Fig. 1). The turbulent fluxes for urban canyons and roofs are calculated applying classical boundary layer laws that use the aerodynamic resistance.

The correction on the temperature and specific humidity, which is required because of the height difference between the lowest atmospheric level and the top of the urban canopy, is calculated using the Exner function:

$$\Pi = (p/p_0)^{R_d/c_{p_d}},$$

where p is the air pressure, p_0 is the reference pressure, and R_d is the gas constant for dry air. The temperature and the specific humidity at the top of the urban canopy (=roof level = top of street canyon), T_a^* and q_a^*, are defined respectively as

$$T_a^* = T_a \Pi_{\mathrm{sfc}}/\Pi_a \quad \text{and}$$

$$q_a^* = q_a q_{\mathrm{sat}}(T_a^*, p_{\mathrm{sfc}})/q_{\mathrm{sat}}(T_a, p_a),$$

where p_a is the air pressure at the lowest model layer and p_{sfc} is the air pressure at the surface; Π_a and Π_{sfc} are Exner functions that correspond to p_a and p_{sfc}. The temperature T_a^* and the specific humidity q_a^* are used as input forcing to the TEB scheme.

In TEB, the vertical fluxes of heat and water H_{roof}, $\mathrm{LE}_{\mathrm{roof}}$, and F_{roof} between the roof and the atmosphere are

$$H_{\mathrm{roof}} = -\rho c_{p_d} (T_a^* - T_{\mathrm{roof}})/\mathrm{RES}_{\mathrm{roof}},$$

$$\mathrm{LE}_{\mathrm{roof}} = -\rho L_v (q_a^* - q_{\mathrm{roof}})/\mathrm{RES}_{\mathrm{roof}}, \quad \text{and}$$

$$F_{\mathrm{roof}} = -\rho (q_a^* - q_{\mathrm{roof}})/\mathrm{RES}_{\mathrm{roof}}, \quad \text{with}$$

$$\mathrm{RES}_{\mathrm{roof}} = \frac{1}{C_h^d |\mathbf{v}_h|},$$

where T_{roof} is the temperature and q_{roof} is the specific air humidity of the roof predicted by the TEB scheme, $\mathrm{RES}_{\mathrm{roof}}$ is the aerodynamic resistance above the roof, and C_h^d is the aerodynamic transfer coefficient for the turbulent heat and moisture exchange between the roof and the atmosphere computed using the roughness length of 15 cm and the stability functions of Mascart et al. (1995).

The heat and water fluxes between the canyon air and the atmosphere are formulated similarly to those for the roof:

$$H_{\mathrm{canyon}} = -\rho c_{p_d}(T_a^* - T_{\mathrm{canyon}})/\mathrm{RES}_{\mathrm{canyon}} + H_{\mathrm{traffic}},$$

$$\mathrm{LE}_{\mathrm{canyon}} = -\rho L_v(q_a^* - q_{\mathrm{canyon}})/\mathrm{RES}_{\mathrm{canyon}} + \mathrm{LE}_{\mathrm{traffic}},$$

and

$$F_{\mathrm{canyon}} = F_{\mathrm{road}} + F_{\mathrm{wall}} + \frac{\mathrm{LE}_{\mathrm{traffic}}}{L_v},$$

where T_{canyon} is the air temperature and q_{canyon} is the specific air humidity inside the canyon predicted by the TEB scheme; $\mathrm{RES}_{\mathrm{canyon}}$ is the aerodynamic resistance above the canyon computed using the roughness length of $z_{0\mathrm{town}}$ and the stability functions of Mascart et al. (1995). Water vapor fluxes from the road F_{road} and the wall F_{wall} are internally resolved by the TEB scheme. The traffic-related fluxes of sensible heat H_{traffic} and latent heat $\mathrm{LE}_{\mathrm{traffic}}$ are prescribed at the street level and are released into the canyon air. Additionally, the energy fluxes due to the industrial exhaust, H_{industry} and $\mathrm{LE}_{\mathrm{industry}}$, are prescribed directly at the top of the urban canopy. The traffic- and industry-related fluxes do not directly modify the surface energy budgets as they are released into the air. For the present study we set H_{traffic}, $\mathrm{LE}_{\mathrm{traffic}}$, H_{industry}, and $\mathrm{LE}_{\mathrm{industry}}$ to 0.

The total sensible and latent heat fluxes into the atmosphere are calculated by averaging these fluxes from the nonurban land (resolved by TERRA) and from the urban canopy (resolved by TEB) proportionally to their area fractions:

$$\begin{aligned} H_{\mathrm{total}} &= a_{\mathrm{natural}}H_{\mathrm{TERRA}} + a_{\mathrm{urban}}[a_{\mathrm{bld}}H_{\mathrm{roof}} \\ &\quad + (1 - a_{\mathrm{bld}})H_{\mathrm{canyon}} + H_{\mathrm{industry}}], \end{aligned}$$

$$\begin{aligned} \mathrm{LE}_{\mathrm{total}} &= a_{\mathrm{natural}}\mathrm{LE}_{\mathrm{TERRA}} + a_{\mathrm{urban}}[a_{\mathrm{bld}}\mathrm{LE}_{\mathrm{roof}} \\ &\quad + (1 - a_{\mathrm{bld}})\mathrm{LE}_{\mathrm{canyon}} + \mathrm{LE}_{\mathrm{industry}}], \quad \text{and} \end{aligned}$$

$$\begin{aligned} F_{\mathrm{total}} &= a_{\mathrm{natural}}F_{\mathrm{TERRA}} + a_{\mathrm{urban}}\left[a_{\mathrm{bld}}F_{\mathrm{roof}}\right. \\ &\quad \left. + (1 - a_{\mathrm{bld}})F_{\mathrm{canyon}} + \frac{\mathrm{LE}_{\mathrm{industry}}}{L_v}\right], \end{aligned}$$

where a_{urban} is the urban fraction of a model grid cell, $a_{\mathrm{natural}} = (1 - a_{\mathrm{urban}})$ is the fraction of the natural land, a_{bld} is the fraction of the urban canopy occupied by buildings, and $(1 - a_{\mathrm{bld}})$ is the building-free fraction (i.e., street fraction) of the urban canopy.

c. *Momentum fluxes*

Within COSMO-CLM the momentum fluxes at the surface are parameterized by the drag-law formulation:

$$M_{\mathrm{sfc}}^u = -\rho C_m'^d|\mathbf{v}_h|u \quad \text{and}$$

$$M_{\mathrm{sfc}}^v = -\rho C_m'^d|\mathbf{v}_h|v,$$

where u and v are velocity components and $C_m'^d$ is the drag coefficient for the momentum exchange at the surface. The drag coefficients are calculated for the roughness length averaged using the area weighting over the grid cell according to the "composite approach." Model variables of COSMO-CLM are staggered on the Arakawa-C/Lorenz grid with scalars (temperature, pressure, humidity, and transfer coefficients) defined at the center of a grid box and the normal velocity components are defined on the corresponding box facets. The drag coefficient at the box facet $C_m'^d$ is calculated by interpolating the drag coefficients C_m^d of the two adjacent grid cells, i, and $i+1$:

$$C_m'^d = \frac{(C_m^d)_{\mathrm{sfc},i} + (C_m^d)_{\mathrm{sfc},i+1}}{2}.$$

TEB resolves the momentum fluxes for the entire urban cover within a module that is very similar to the one of COSMO-CLM. Therefore, for calculating the drag coefficients and the corresponding momentum fluxes in a uniform way for all land use classes, the standard module (Doms et al. 2011) of the COSMO-CLM model is used. The application of the tile approach to the computing of the drag coefficients still remains a challenge for future model implementations.

3. Model setup and data

We use the nonhydrostatic regional climate model COSMO-CLM, version 4.8_clm17. As a limited-area model it must receive forcing data for the initial state of the atmosphere at the boundaries of the model domain. In the present setup we use two model domains: domain Europe (EU) (Fig. 2a) with the spatial resolution of 0.11° (~12 km) and 40 vertical levels and domain Berlin (BER) (Fig. 2b) with the spatial resolution of 0.025° (~2.8 km) and 50 vertical levels. The forcing data for the initialization and constraining the EU domain at the lateral boundaries are the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim) dataset (Dee et al. 2011). The domain BER is nested into the domain EU and is constrained at its boundaries by the EU simulation. The model is run with time steps of 100 and 25 s for the EU and BER domains, respectively, for a 1-yr simulation of 2009 preceded by a 3-month spinup simulation. This simulation period was chosen because 2009 was a typical

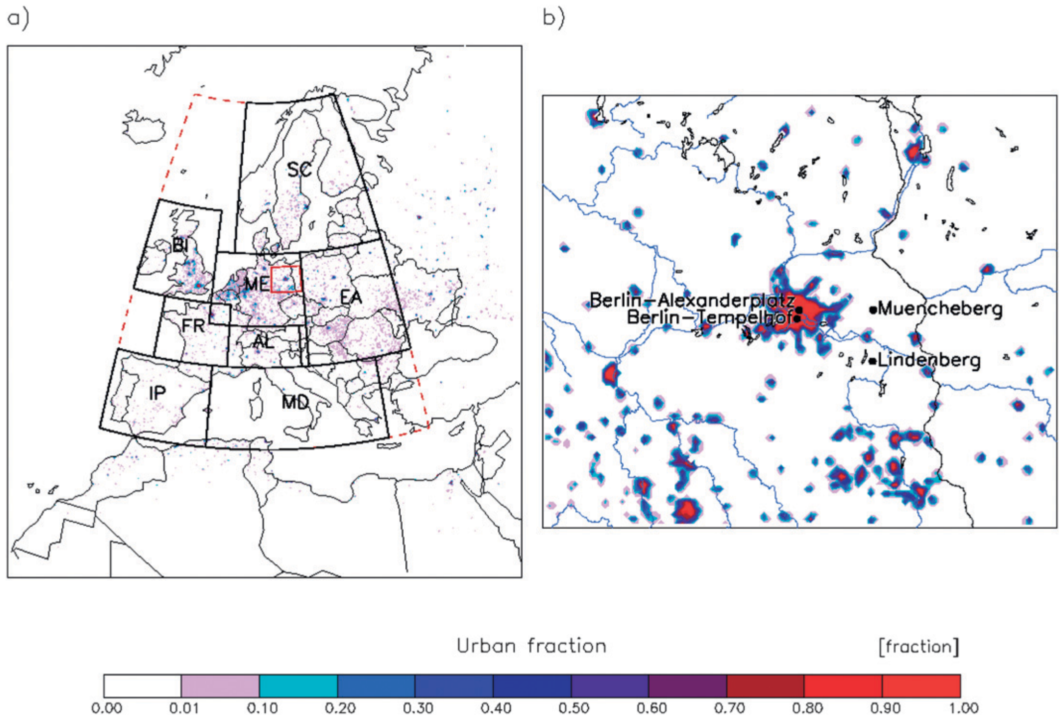

FIG. 2. Urban fraction in (a) the model domain EU with the spatial resolution of 0.11° and (b) the model domain BER with 0.025°. Maximum urban fraction of a grid cell is 1.0 in both model domains. Panel (a) shows eight European PRUDENCE regions, outlined by the black solid line, defined for the analysis of integrative climate variables: BI—British Isles, IP—Iberian Peninsula, FR—France, ME—middle Europe, SC—Scandinavia, AL—Alps, MD—Mediterranean, EA—eastern Europe. An additional area outlined by the red dashed line defines the integrated PRUDENCE region. The solid red line shows the place of the domain BER nested into the domain EU. The black filled circles in (b) indicate the measurement sites used for the model evaluation.

year of the warmest decade 2000–09 for Europe with an average mean temperature being 0.5°–2°C above the climatological mean of 1961–90 and nearly normal or above-normal precipitation in central, northern, and eastern Europe and in Iberia, with some excessive precipitation in southeastern Europe and the British Isles (Arndt et al. 2010). In Germany the mean temperature of 2009 was by ~0.9°C above the climatological mean, the mean total precipitation was 785.5 mm (equal to the climatological mean), and the sunshine duration was 1683.5 h—10% higher than the reference in the period 1961–90 (DWD 2009). Parameterizations include the two-time level Runge–Kutta split-explicit scheme for both model domains. For the domain EU the convection parameterization scheme (Tiedtke 1989) and the parameterization for the subgrid-scale orography (Schulz 2008) are used. The land surface model TERRA is used with nine soil layers between 0.5, 2.5, 7, 16, 34, 70, 142, 286, 574, and 1150 cm. The TEB scheme is applied for each model grid cell with the urban fraction greater or equal than 0.1 in both model domains; the largest urban fraction in both model domains is 1.0.

a. *Parameters for the urban scheme*

The parameterization TEB requires several parameters that describe the shape of the generic street canyon and the radiative and thermal properties of the buildings (Table 1). Values for these parameters are adopted from Mayer (2004).

The fraction of urban land a_{urban} is not directly a parameter of the TEB scheme but is used to average the output TEB fluxes with those computed with TERRA for the vegetation fraction of the model grid box. The value of a_{urban} varies throughout the model domain; this fraction is extracted from the database GLC2000 at the preprocessing step and is included as an additional input field into the COSMO-CLM model.

The fraction of buildings (to the total urban area of a grid cell) everywhere in the model domain EU is set to $a_{\mathrm{bld}} = 0.43$, and the mean height of buildings is set to $h = 17$ m. These values are calculated by averaging the values published for three cities—London, Toulouse, and Berlin—by Ratti et al. (2002) and represent surface properties of a typical European city. For the model

TABLE 1. Parameters of the TEB scheme.

Symbol	Designation of symbol	Value for EU/BER domain	Unit
a_{urban}	Fractional area of urban land	variable 0.0–1.0	—
a_{bld}	Fractional artificial area occupied by buildings	0.43/0.35	—
h	Building height	17.0/19.9	m
h/w	Height to width ratio of buildings	0.67/0.66	—
z_0	Roughness length for the building–canyon system	1.0	m
a_{roof}	Roof albedo	0.25	—
a_{road}	Road albedo	0.18	—
a_{wall}	Wall albedo	0.30	—
e_{roof}	Roof emissivity	0.90	—
e_{road}	Road emissivity	0.96	—
e_{wall}	Wall emissivity	0.92	—
$d_{\text{roof},i}$	Thickness of the roof layer $i = 1$	0.05	m
	$i = 2$	0.40	
	$i = 3$	0.05	
$d_{\text{road},i}$	Thickness of the road layer $i = 1$	0.05	m
	$i = 2$	0.10	
	$i = 3$	1.00	
$d_{\text{wall},i}$	Thickness of the wall layer $i = 1$	0.02	m
	$i = 2$	0.15	
	$i = 3$	0.02	
$\lambda_{\text{roof},i}$	Thermal conductivity of the roof layer $i = 1$	0.83	$\mathrm{W\,m^{-1}\,K^{-1}}$
	$i = 2$	0.09	
	$i = 3$	0.27	
$\lambda_{\text{road},i}$	Thermal conductivity of the road layer $i = 1$	0.75	$\mathrm{W\,m^{-1}\,K^{-1}}$
	$i = 2$	1.51	
	$i = 3$	0.042	
$\lambda_{\text{wall},i}$	Thermal conductivity of the wall layer $i = 1$	0.81	$\mathrm{W\,m^{-1}\,K^{-1}}$
	$i = 2$	0.08	
	$i = 3$	0.27	
c_{roof}	Heat capacity of the roof layer $i = 1$	1372.5	$10^3\,\mathrm{J\,m^{-3}\,K^{-1}}$
	$i = 2$	454.4	
	$i = 3$	1491.0	
c_{road}	Heat capacity of the road layer $i = 1$	1941.2	$10^3\,\mathrm{J\,m^{-3}\,K^{-1}}$
	$i = 2$	2112.0	
	$i = 3$	1344.0	
c_{wall}	Heat capacity of the wall layer $i = 1$	1372.5	$10^3\,\mathrm{J\,m^{-3}\,K^{-1}}$
	$i = 2$	281.6	
	$i = 3$	1491.0	

domain BER $a_{\text{bld}} = 0.35$ and $h = 19.9$ m were set as suggested by Ratti et al. (2002) for Berlin. Urban surfaces—roofs, roads, and walls—are resolved in three layers in depth; the values of thickness, thermal conductivity, and heat capacity are specified for each layer $i = 1, \ldots, 3$ (Table 1), where the layer $i = 1$ is the outermost. The inner building temperature is set to 20°C and kept constant throughout the simulations. For the roughness length we use the value $z_{0\text{town}} = 1.0$ m suggested by Ratti et al. (2002) for European cities.

b. Data for the model evaluation

First, we evaluate the model performance for eight large regions of Europe (Fig. 2a) in the model domain EU. These regions were defined within the project Prediction of Regional Scenarios and Uncertainties for Defining European Climate Change Risks and Effects (PRUDENCE; http://prudence.dmi.dk/) for the evaluation of regional climate models and roughly correspond to different climate zones in Europe. As reference for this evaluation we choose data fields of the mean temperature at 2 m above ground and the total precipitation of the European land-only daily high-resolution gridded dataset ‘‘EOBSv5.0’’ (Haylock et al. 2008) for the entire year 2009. The dataset EOBSv5.0 includes the effect of the urbanization on the temperature by adding a Gaussian distributed random error with standard deviation increase of 0.0055°C decade^{-1} since 1900. The rainy day in this observation-based data is defined by the threshold of 0.5 mm day^{-1} (Haylock et al. 2008) so that precipitation totals less than this threshold are not represented. We perform two model simulations: simulation ‘‘EU-STD’’ with the standard model COSMO-CLM (urban surface is described by standard model surface

TABLE 2. Meteorological stations used for the evaluation of the model simulations BER-URB and BER-STD in the area around Berlin.

Station name	Coordinates	Ground height (m)	Site description
Alexanderplatz	52°31′19″N, 13°24′44″E	37	Densely built up area of the Berlin city center with scarce vegetation patches of grass and shrub
Tempelhof	52°28′07″N, 13°24′14″E	48	Southern side of a former airport, free space at the north of the station and densely built up city at the south
Lindenberg	52°12′35″N, 14°07′13″E	98	Vegetated parklike area, ~65 km south east from the city center of Berlin
Muencheberg	52°31′08″N, 14°07′30″E	63	Vegetated parklike area, ~50 km east from the city center of Berlin

parameters given by lookup tables) and simulation "EU-URB" with the coupled model COSMO-CLM+TEB. We compare the model output of both simulations with the observational data ("EU-OBS") of the EOBSv5.0 dataset.

Second, we analyze the model simulations on the fine spatial resolution in the area around Berlin (Fig. 2b). We use time series of daily average 2-m temperature at four stations (Table 2) to examine the ability of the new model to reproduce the mean urban heat island (UHI) of Berlin. As for the coarse-scale model domain, we perform two model simulations—BER-STD and BER-URB—without and with the TEB parameterization, respectively. Both simulations are nested into the EU-STD. The modeled 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^{-1} to the original modeled temperature values.

The variability of temperature and precipitation fields and the discontinuity of precipitation patterns require the integration of the data in time and space to extract the large-scale trends in the variables and to avoid miscalculations such as "double penalty." The double penalty problem appears when traditional point-matching categorical and continuous verification measures are applied to discontinuous model fields such as precipitation. Small displacements in space or time between modeled and observed precipitation events penalize twice when the modeled and the observed data fields are compared by direct overlaying: 1) when the model produces precipitation and the observation does not and 2) when the model produces no precipitation and the observation indicates some. To avoid the double penalty, which is common in evaluation of high-resolution models, a statistical postprocessing is applied to the model output. In this study we calculate climate variables integrated over seasonal, monthly, and daily intervals. For the EU-domain the temperature and precipitation data are integrated over eight PRUDENCE regions (Fig. 2a). For the BER domain we compare time series of the daily mean 2-m temperature extracted from the corresponding model grid cells at two urban and two rural stations (Table 2) with station-based observations. Using these time series we calculate and compare the magnitude of the modeled and observed mean urban heat island in Berlin. The precipitation analysis of these finescale simulations is left out of the scope of this study.

4. Results

a. Coarse-scale simulations for Europe

1) MONTHLY VALUES

The biases characteristics for COSMO-CLM temperature/precipitation were previously discussed in detail by Jaeger et al. (2008) and, therefore, we do not further analyze them in the present study. We rather focus on the temperature/precipitation changes introduced into the model by its new component—the urban land parameterization.

We aggregate time series of monthly mean 2-m temperature and total precipitation from the model and observational data for the eight PRUDENCE regions (Fig. 2a). The absolute bias between each model simulation and the observations EU-OBS we calculate as the difference between the monthly values for each region. Figure 3 shows similarities in simulated 2-m temperature between the two model simulations EU-STD and EU-URB that have essentially the same bias to the observations (Fig. 3b) with the maximum difference between the two models from −0.9 to +1.5 K per month per region and the average difference from −0.1 to +0.2 K per season. Both models show a typical for COSMO-CLM "cold bias" of 0.5–2.5 K to the observations during winter months and a "warm bias" up to 1.75 K in southern Europe [regions Mediterranean (MD), Iberian Peninsula (IP), and France (FR)].

The modeled monthly precipitation time series have the largest bias in the region of the Alps (AL; Fig. 4b) and very similar distributions throughout the year (Fig. 4a) with the difference between the two models varying between −32 and +40 mm month^{-1} per region. Both simulations EU-STD and EU-URB tend to slightly underestimate total precipitation in the region of the

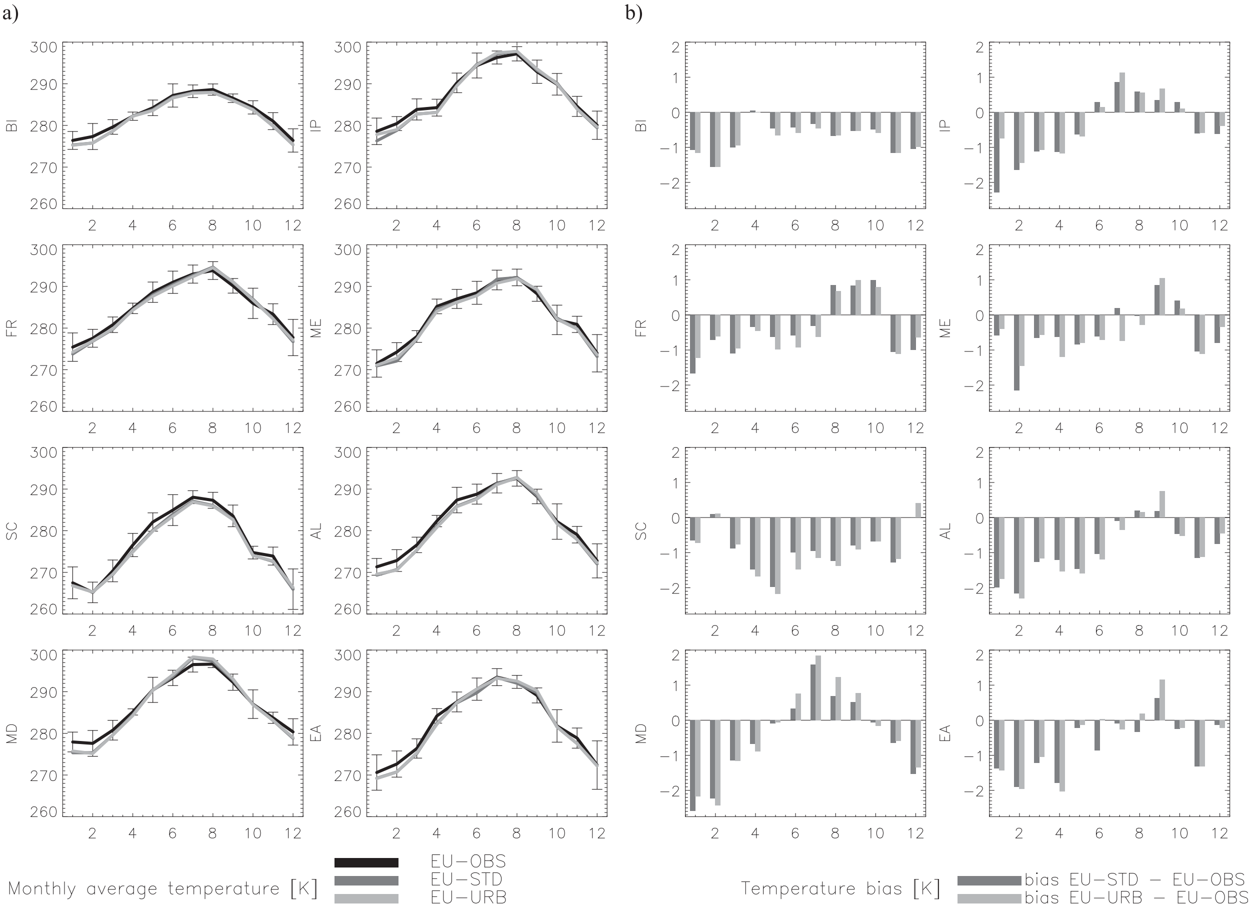

FIG. 3. Air temperature (K) at 2-m level: (a) monthly mean values and (b) the bias for the PRUDENCE regions. The error bars in (a) show the monthly standard deviation calculated from the daily observational data.

British Isles by 4–8 mm month^{-1} on average and to overestimate it in other regions: by 8 mm month^{-1} in France, 4–8 mm month^{-1} in middle Europe, 14–16 mm month^{-1} in Scandinavia, 30 mm month^{-1} in the Alps, 12–17 mm month^{-1} in the Mediterranean region, and 4–9 mm month^{-1} in eastern Europe.

Although the models differ from each other, their biases do not show any persistent offset or trend that can be attributed to the presence of urban land parameterization, that is, no increase or reduction of precipitation by this new parameterization. To check the significance of the differences between the two models the statistical properties of these differences need to be analyzed.

2) DO THE MODELS HAVE STATISTICALLY SIGNIFICANT DIFFERENCES?

With the help of statistical significance tests we investigate the differences between the simulation EU-STD and the simulation EU-URB as well as the differences between the simulations and the observations over the integrated PRUDENCE region (Fig. 2a). On the daily data of the entire integrated PRUDENCE region we apply two nonparametric statistical significance tests:

1) the Wilcoxon rank-sum test for equal sample sizes (Wilcoxon test) and
2) the two-sample Kolmogorov–Smirnov test (KS test) for distributions of observations and model values of daily 2-m temperatures and precipitation.

The Wilcoxon test determines whether two data samples have different medians. The KS test makes it possible to identify differences in the shape of the empirical cumulative distribution functions of two data samples. For the statistical analysis we built three data samples for the 2-m temperature and daily cumulative precipitation from the observations EU-OBS and model simulations EU-STD and EU-URB. We apply the Wilcoxon test and the KS test to the pairs of data series {EU-OBS, EU-STD}, {EU-OBS, EU-URB}, and {EU-STD, EU-URB} for four seasons: winter [December–February (DJF)], spring [March–May (MAM)], summer [June–August (JJA)], and autumn [September–November

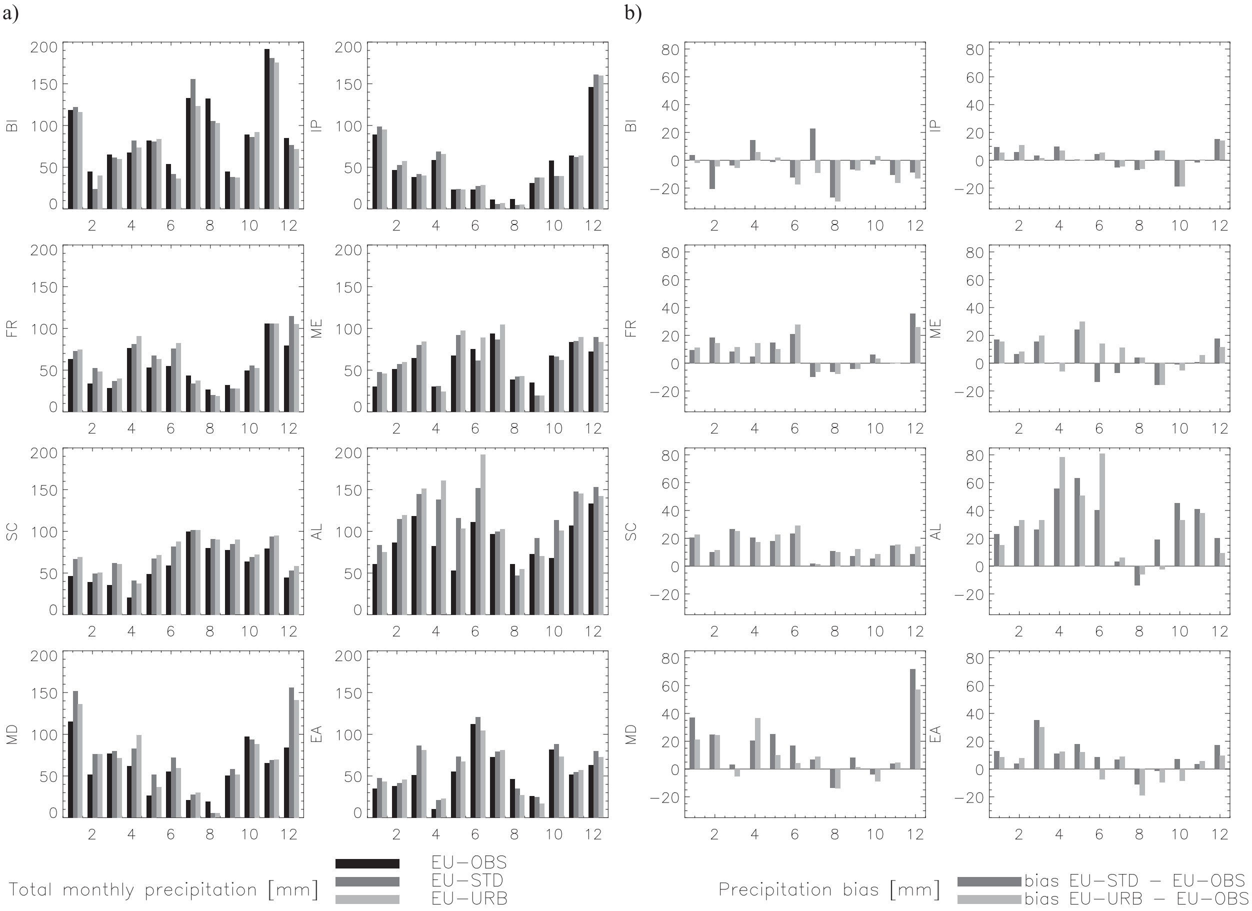

FIG. 4. Total precipitation at the surface (mm): (a) total monthly sum and (b) bias for the PRUDENCE regions.

(SON)]. The significance level for both tests is set to $p = 0.05$. For a better illustration of the model-to-observation differences we show histograms from the daily values of temperature and precipitation (Fig. 5).

The Wilcoxon test indicates that the medians of the 2-m temperature of EU-OBS, EU-STD, and EU-URB data samples differ from each other for all seasons with one exception in spring (MAM) when both models EU-STD and EU-URB have the same median. The medians of EU-STD and EU-URB are ~1 K lower than the median EU-OBS indicating the model's cold bias, whereas the medians EU-STD and EU-URB differ from each other only by from −0.1 to +0.2 K from season to season. The KS test on the temperature data shows that in each season model datasets EU-STD and EU-URB belong to the same distribution. However, both models do not capture the extreme temperatures: the lowest in winter (Fig. 5, DJF) and the highest in summer (Fig. 5, JJA). The results of these statistical analyses support the finding from the evaluation of the monthly data in the previous chapter: the inclusion of the urban parameterization into the regional climate model COSMO-CLM may help to reduce the cold bias locally but overall the regional climate model retains the same shape of the distribution of the seasonal temperature values that miss the extremes of the observations.

As with the temperature data, we apply the Wilcoxon test and the KS test to the precipitation data. The Wilcoxon test applied on precipitation data greater than or equal to 0.5 mm day^{-1} suggests that medians of modeled data differ to the median EU-OBS. For all seasons except winter (DJF) the medians of both models do not differ. The model datasets EU-STD and EU-URB have similar differences to the observations and overestimate the number of days with precipitation totals under 1 and over 20 mm day^{-1} (Fig. 5); both models overestimate winter and spring precipitation and slightly underestimate the summer precipitation of magnitude 2–12 mm day^{-1}. The medians of EU-STD and EU-URB differ from each other only by from −0.1 to +0.1 mm day^{-1} from season to season. According to the KS test the precipitation

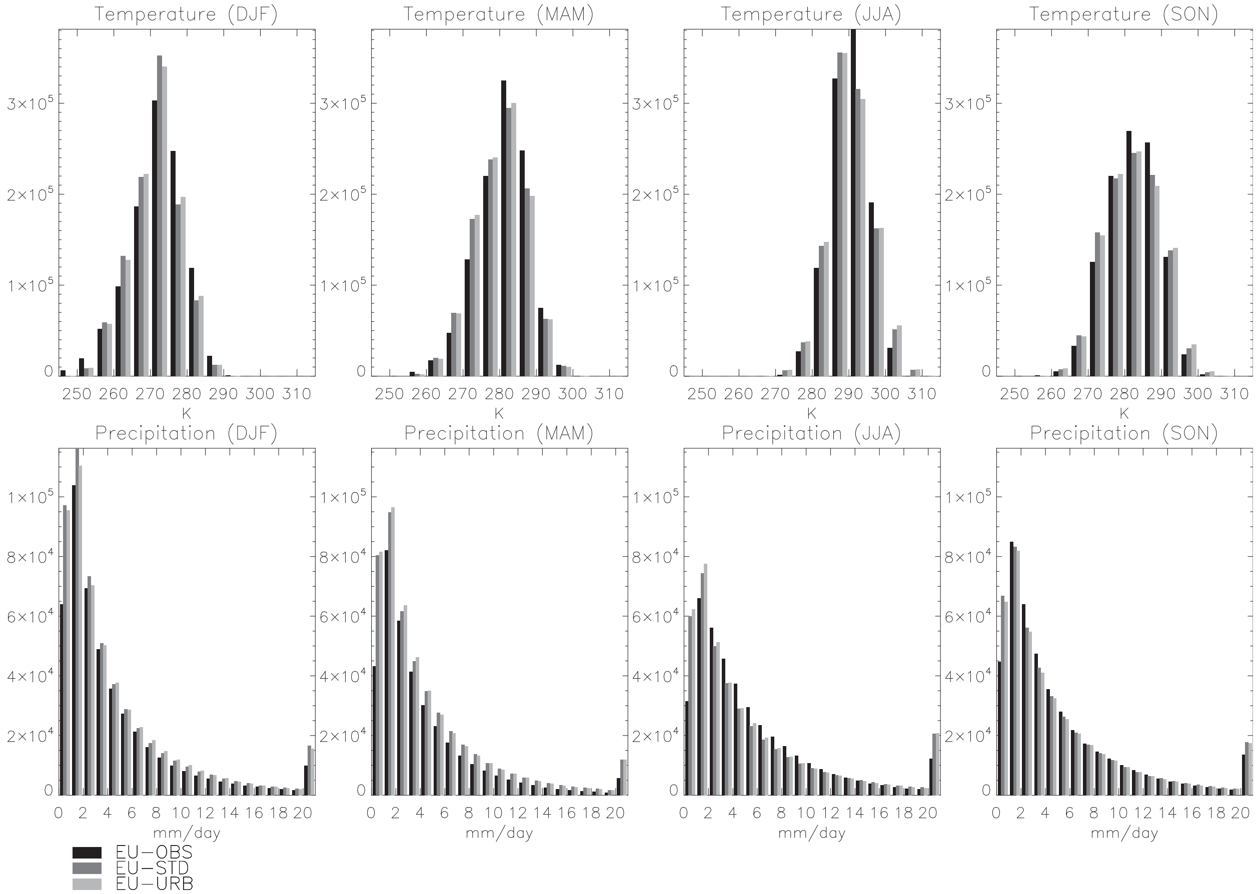

FIG. 5. Histograms of (top) the daily 2-m temperature and (bottom) total daily precipitation from EU-OBS, EU-STD, and EU-URB data for (left to right) the four seasons. The vertical axis has units of number of days. Rainy days in histograms for precipitation are defined by the threshold 0.5 mm day^{-1} as in the database of observations EOBSv5.0 (Haylock et al. 2008).

distributions of the EU-STD and EU-URB data have the same statistical distributions (the same shape of the distribution). This means that the frequencies of the same daily precipitation total are similar.

The comparison of the model simulations at the coarse spatial scale of ~12 km demonstrates very small differences between the standard and the urbanized models that do not change the model climatological fields strongly. In accordance to our prior expectations, the urban parameterization reduces a systematic underestimation of the near-surface temperatures (cold bias) locally. However, similarities of the statistical distributions of the 2-m temperature and daily precipitation sums showed a very small effect from the urban parameterization on the model's climatology at this coarse scale. Finally, we conclude that an urban parameterization makes a rather small contribution to the climate variables at the chosen spatial resolution of ~12 km and, thus, may be omitted in model simulations at this scale.

b. *Simulations for Berlin*

1) THE UHI OF BERLIN

For the high-resolution model domain BER we evaluate the time series of the 2-m temperature at the four chosen sites (Fig. 6): two rural stations at Muencheberg and Lindenberg and two urban stations in Berlin at the Alexanderplatz and at the Tempelhof (a former airport). The mean difference between the modeled and observed time series at the two rural stations is very similar for both models: at Lindenberg the annual mean observed temperature is 283.0 K and the annual mean estimated temperature is 282.4 K in BER-STD and BER-URB simulations, at Muencheberg observations and models show the same annual mean temperature of 282.4 K. The root-mean-square error (RMSE) for both models at rural sites is 2.2 K. Although at Lindenberg both simulations BER-STD and BER-URB underestimate the 2-m temperature by 0.6 K, this bias may potentially be explained by the representation of land

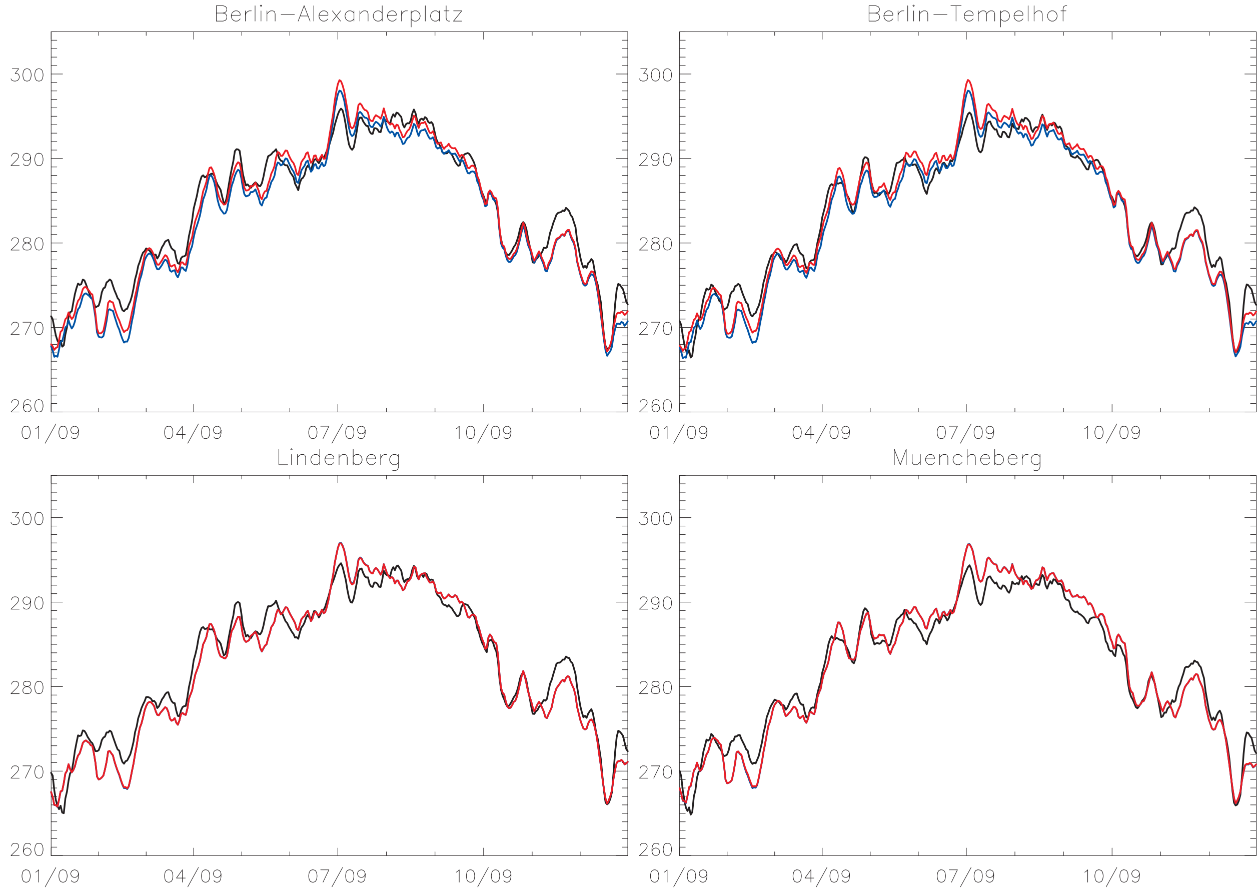

FIG. 6. Time series of the weekly running mean of daily mean 2-m temperature observed (black line) and modeled with standard model (blue line) and model with the urban parameterization TEB (red line) at the four chosen measurement sites. The two sites Berlin-Alexanderplatz and Berlin-Tempelhof are located within Berlin and have the fraction of urban land equal to 1.0 in model simulations; sites Lindenberg and Muencheberg are rural stations with fraction of urban land equal to 0.0 (at rural stations the red line overlays the blue one).

surface characteristics (Meißner 2008). At urban stations, Berlin-Alexanderplatz and Berlin-Tempelhof, the simulation BER-URB represents the annual mean 2-m temperature better than the standard model. For the station Berlin-Alexanderplatz the observations yield the annual mean average of 283.9 K, whereas BER-STD and BER-URB simulations underestimate this value by ~1.3 K and by ~0.5 K, respectively. At the station Berlin-Tempelhof with the measured mean temperature of 283.5 K, the BER-STD simulation underestimates this value by ~1.1 K (with the RMSE of 2.2 K) and the BER-URB simulation by ~0.2 K (with the RMSE of 2.3 K). The comparison of the two modeled time series with the observations (Fig. 6) confirms that the simulation BER-URB better represents the observations at the urban sites than the simulation BER-STD.

From the available data at the four stations we calculate the mean UHI as the difference between the mean daily temperature in the city and its rural surroundings (Fig. 7). The average magnitude of the mean urban heat island (Fig. 7, numbers to the left of the panels) is better captured by the BER-URB simulation than by the one with the standard model. However, there are some discrepancies in the UHI between the BER-URB and BER-OBS time series (Fig. 7b) that indicate an overestimation of the UHI by the simulation BER-URB in spring and summer months. This overestimation results from the underestimation of temperatures at the Lindenberg site during the winter–spring time (Fig. 6) in combination with the vegetationless representation of the Berlin-Tempelhof site in the model (urban fraction = 1.0). This error indicates the importance of the correct representation of the land cover and soil characteristics within the model and can possibly be corrected by an adjustment of these model parameters.

2) SPATIAL DISTRIBUTION OF DAILY AVERAGE UHI

We analyze and compare temperatures in the area of Berlin simulated by the standard model COSMO-CLM

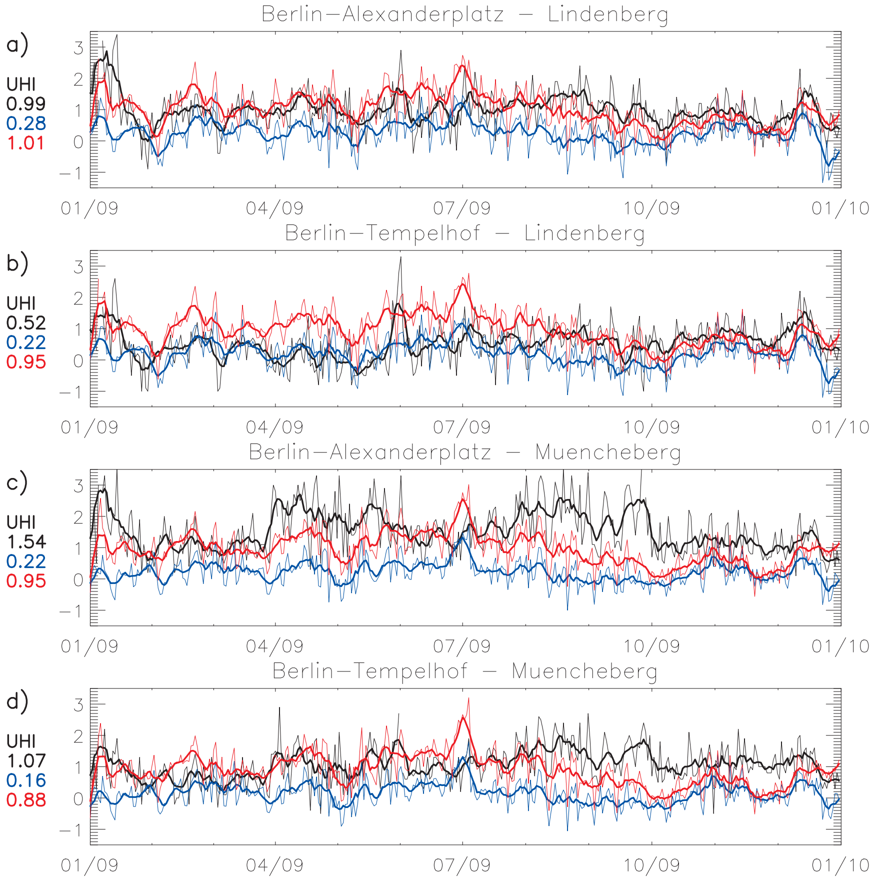

FIG. 7. Time series of the daily mean UHI for four Berlin stations calculated from observations BER-OBS (black line), from the simulation BER-STD (blue line), and from the simulation BER-URB (red line). The weekly running mean is shown in solid thick lines for each time series. The average value of each time series is shown on the left from each panel in corresponding color.

and the urbanized model COSMO-CLM+TEB for winter and summer seasons (Fig. 8). The simulation BER-STD does not produce any visible UHI in Berlin in winter, whereas the BER-URB shows the urban temperatures 0.5–1.0 K higher than in the rural surroundings (Fig. 8). The average temperature difference between the two simulations shows the contribution of the urban parameterization up to 1.0 K in winter in the area of Berlin. This influence of the urban warming spreads by up to ~40 km into the surroundings of Berlin in the northeastern direction governed by the prevailing winds from the west direction. In summer, the contribution of the urban parameterization to the 2-m temperatures in Berlin is generally higher than 1.0 K and is more restricted to the densely built urban cover than in winter. The comparison of the 2-m temperature fields from the BER-STD and BER-URB simulations for Berlin demonstrates the superior capability of the coupled model COSMO-CLM+TEB to simulate the UHI of Berlin and its influence on the temperatures of the city's surroundings. The simulation BER-STD captures the UHI of Berlin only to some extent (Fig. 7) and produces no visible urban-to-rural temperature differences. Therefore, for investigating urban effects on the atmosphere and their feedbacks, we suggest using the coupled model COSMO-CLM+TEB, although some tuning of model parameters is needed to capture specifics of the morphology of Berlin and physical properties of a building's materials.

Figure 8 shows a rather homogeneous UHI that is closely correlated to the urban fraction in the model (Fig. 2b). This illustrates the importance of the correct representation of the urban land cover in models: on fine spatial scales, for example, below 3 km, when urban areas can be sufficiently resolved, the uniform representation of the urban land cover could be refined to improve the spatial pattern of the modeled UHI. Such refinement is essential for urban planning and estimating its impacts of future climate changes.

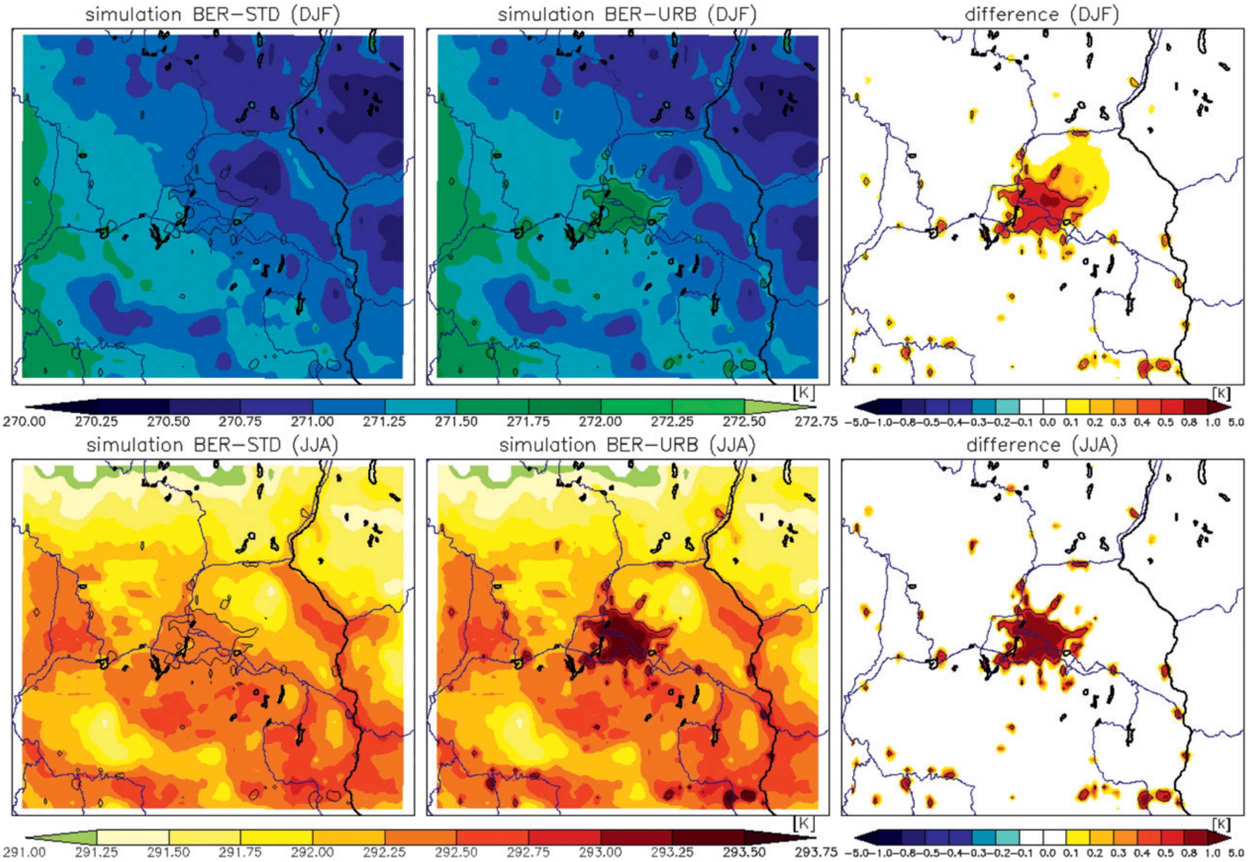

FIG. 8. Absolute mean daily 2-m temperature of simulations BER-STD and BER-URB and their difference in (top) winter and (bottom) summer 2009. The thin black solid line shows the boundaries of areas with the fraction of urban land greater than 0.5.

5. Summary and outlook

In this study we presented a new version of the regional climate model COSMO-CLM+TEB that was extended from the standard COSMO-CLM by a parameterization for urban land [TEB scheme by Masson (2000)]. We performed model simulations at a coarse spatial resolution of ~12 km and a fine spatial resolution of ~2.8 km with and without the urban parameterization and compared the modeling results to available observations. This comparison helped us to identify differences in the model behavior in the European domain due to the urban parameterization. On the coarse scale, in accordance with our prior expectations, the urban parameterization helped to reduce a systematic underestimation of the near-surface temperatures (cold bias) only locally. It showed only a relatively small effect on the climatological fields of the temperature at 2 m above ground level (from -0.1 to $+0.2$ K per season) and the total daily precipitation ($\pm 0.1\,\mathrm{mm\,day^{-1}}$). We conclude that on the spatial resolution of ~12 km the comprehensive urban parameterization included into the mesoscale regional climate model COSMO-CLM does influence the modeled temperature and precipitation fields by a negligible offset in the 2-m temperature and winter precipitation without a generally seen trend (such as warming/cooling or increase/reduction of precipitation that could be universally attributed to the presence of urban land). As for the chosen European domain, the urban parameterization neither disturbs nor improves the modeled climatological fields, and it can be omitted on this spatial resolution to save the computing time. However, we must note here that for some model applications that focus on the large-scale impacts of urbanization on the climate under different projections of city growth and development, the urban parameterization may be included for quantifying these effects, as in the work of Georgescu et al. (2013).

The model simulations on the fine spatial resolution showed that the effect of the urban parameterization is no longer negligible. The model COSMO-CLM+TEB was able to better simulate the magnitude of the urban heat island in Berlin than the standard model COSMO-CLM. We noted that, on the spatial resolution below

~3 km, the large metropolitan area of Berlin can be resolved in sufficient detail that an introduction of multiple urban land use classes may become effective for a better spatial representation of the urban heat island. We leave for the future the investigation of the model performance on finer spatial resolutions with more sophisticated urban land classifications as well as the analysis of urban effects on precipitation.

Our future research plans focus on the multiyear climate simulations with the new model COSMO-CLM+TEB. Possible applications of the long-term climate simulations with the new model will focus on the evolution of the urban heat island, its spatial heterogeneity and changes in the spatial–temporal distribution of precipitation under the changing climate.

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