Mesoscale modelling of the summer climate response of Moscow metropolitan area to urban expansion

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Abstract. In this paper, the experience of applying a regional climate model to simulating the summer climate features of Moscow metropolitan area is examined. Also, an assessment is made of climate response to the implementation of a scenario of twofold city expansion. The model (COSMO-CLM) was adapted to the conditions of the region under investigation, supplemented by specific urban canopy parameterization and equipped with realistic parameters of urban surface. It was possible to successfully simulate the summer meteorological regime of Moscow region and, specifically, the temporal and spatial variability of the Moscow urban heat island (UHI). First results of the simulation for the city expansion show that the new urbanized areas on the periphery of Moscow have a heating impact on its central part, which leads to an increase of the UHI effect, on the average, of 10% (in the central area). In extreme heat events the temperature response to this scenario is much stronger, which may deteriorate human health and increase thermal stress. The simulation results also show that the city of Moscow is characterized by a positive anomaly of summer precipitation (in the city and its leeward side it increases by 10-30%). The scenario of urban expansion enhances this anomaly by 5-10% and increases its area.

1. Introduction & motivation

Due to the current processes of climate change and urban growth, it is especially important to perform an investigation of local climate modifications caused by expansion of cities and changes in their planning and building features and of the contribution of such modifications to observed or predicted climate changes. It is well known that the features of urban surface strongly influence the atmospheric boundary layer and determine the microclimatic features of local environment, such as urban heat island (UHI) [1,2]. Also, UHI affects the atmospheric processes, such as the precipitation regime [3], mesoscale circulations [4], and the conditions of meteorological comfort of urban dwellers [5].

The Moscow megacity is the biggest monocentric agglomeration in Europe (population: 16-17 million people [6]). Due to its size, location in a zone of continental climate and specific building features, such as the predominance of high-rise block-houses, Moscow forms an intensive UHI with a mean annual intensity value equal to 2 °C (according to the Balchug weather station at the city centre) and with maximum values up to 12-13 °C [7]. Such values of UHI intensity are higher than those for a number of other big megacities including London [8,9], Beijing [10,11], and Shanghai [12]. All these features, in addition to the compact and relatively symmetric shape of the city and its location within a flat and homogeneous terrain makes Moscow a promising and interesting place for urban climate studies [13].

Another reason making such research especially important for Moscow is related to the trend of UHI intensification during the last decades. Since the 1970s, the mean UHI intensity (UHI), defined
as the difference between the temperature in the city and the mean rural temperature (calculated for 9 rural reference weather stations surrounding the city, see Appendix 1), has grown by 0.4 °C (from 1.6 °C to 2 °C), which could be caused both by the population growth (since that time the city population has approximately doubled) and climate change. In other words, urban-induced enhancement of global warming [14] takes place. For instance, warming for 1988-2016 in the city centre (Balchug weather station) is 0.55 °C/10 years instead of 0.36 °C/10 years for the mean rural annual temperature. For the mean summer (JJA) temperature the effect of urban amplification is even more intensive: 0.93 °C/10 years for the city centre instead of 0.55 °C/10 years for the rural area. This pattern seems to be especially dangerous because of increasing repeatability of high air temperatures, which has a negative impact on the citizens’ well-being and health under the conditions of summer heat waves [5,15–17]. It is important that the highest warming rates are observed not at the weather stations located at the edges of the Moscow agglomeration, where active development of new territories has taken place during the last decades, but in the city center, where the land use changes are much smaller.

For these reasons, further investigation of the drivers of the observed climate changes and possible future changes becomes an especially important scientific problem. For the city of Moscow it becomes even more important because of ambitious projects of the further city development, such as plans of development of the so-called “New Moscow” area located to the south-west of the city, which was administratively joined to Moscow in 2011, and the program of renovation of old five-story buildings adopted in 2017 (according to it, more than 5000 buildings all over the city will be demolished and replaced by at least twice as high buildings).

However, more detailed investigation of the city growth and development effect on its climate based on observational data is very complicated because of the small number of stations with long-term datasets and the complicated problem of separating signals from different factors affecting urban-caused climatic anomalies, including the urban growth, local land-use modifications in the stations’ surroundings, and the changes in the repeatability of different weather patterns under the climate change. Very promising for such investigations are mesoscale regional climate models (RCMs), which allow one to simulate changes of selected parameters under invariance of other conditions. This study is devoted to application of such model for understanding of climatic consequences of a possible two-fold expansion of the Moscow city for the summer season.

2. Data and methods

2.1. Configuration of numerical experiments with RCM

This study is based on numerical simulations with a regional climate model called COSMO-CLM (Climate Limited-area Modeling community). It is a nonhydrostatic model of the atmosphere and soil active layer based on the COSMO model (COnsortium for Small scale MOdelling) and adopted for long-term numerical experiments [18]. This model was applied for three-step dynamic downscaling of ERA-Interim reanalysis [19] data (with a long. and lat. grid step of 0.75°), which was used as the initial and boundary conditions for running the model for a “basic” domain D1. During the calculations the boundary conditions were undated 4 times per day to keep meteorological fields in the model close to reality. In addition, to ensure a more reliable binding of the internal model mode to the real atmospheric dynamics, the spectral nudging technique [20] was used. The importance of its use in such applications is shown in [21,22]. It should be noted that the dynamic downscaling method used in this study is the most complicated and computationally expensive one among all methods of downscaling used in meteorology and climatology. However, instead of others it provides not only statistical information for selected variables, but detailed 4-dimensional (spatio-temporal) fields of all meteorological variables (available in the model) calculated with consideration of all possible processes and their interactions, which could be reproduced within the framework of the model’s physics and numerics.
Domain D1 covers the central part of European Russia with a size of approx. 1700x1700 km and a 12-km horizontal grid step (140x140 grid cells). Modelling results for D1 were used as the initial and boundary conditions for intermediate domain D2 with a size of 600x600 km (200x200 grid cells) and a 3-km grid step covering the Moscow region and the neighboring regions of Russia. Then the same procedure was repeated for domain D3 with a size of 180x180 km with a 1-km grid step. The final 1-km step was selected to explicitly resolve large features of the urban landscape and the urban-caused mesoscale circulations and avoid the problems of parameterization of atmospheric turbulence for smaller grid steps [23]. For D2 and D3 domains, the spectral nudging was not used, the boundary conditions were updated more often (every hour), and a shallow convection scheme was used instead of a deep convection parametrization [24] used for D1. The time step was defined as 120 sec. for D1, 40 sec. for D2, and 10 sec. for D3. For all domains, 50 vertical levels in the atmosphere and 11 levels in soil were used. Surface features such as albedo, leaf index, soil type, etc. were set according to Globcover database [25].

Model options were tuned to fit the modelled meteorological regime to observations based on a large number of preliminary test experiments (details are not shown). In general, the procedure of model tuning was aimed to solve the problem of significant overestimation of nocturnal temperatures and underestimation of its diurnal variations by the model, which is also reported in [26–28], as well as the problem of temperature overestimation for hot and dry summer seasons [29]. Details are listed in appendix 2.

The numerical experiments configured as described above were initialized on the 1st of May and were run until the 31st of August. The first month (May) was considered as a spin-up period required for adaptation of the model to the meteorological regime. Such experiments were performed for five summer seasons: 2009, 2013–2015, and the extremely hot summer of 2010 [29,30]. 2014 was also rather hot and dry, and the other three years were close to the climate mean (Table 1).

2.2. Description of urban surface features for modern city and scenario of its extension

A bulk urban canopy model (UCM) called TERRA_URB [31,32] coupled to COSMO-CLM was used to simulate the urban climate features. To take into account the features of heat balance of the urban surface including the influence of “street canyons” [33], TERRA_URB provides semi-empirical corrections of surface parameters (roughness length, albedo, emissivity, etc.), parameterizes the moisture balance of impervious surface, and realizes the so-called tile approach, which assumes the existence of urbanized and natural parts within each model cell. The anthropogenic heat flux (AHF) was calculated according to a parameterization in [34] which takes into consideration its “typical” diurnal and annual variation and the dependence of its annual amplitude on the latitude.

Running of this UCM requires the definition of parameters describing the urban surface: urban area fraction $F_{urb}$, mean annual value of AHF, building height $H$, building area fraction within urban fraction $F_{urb}$, and the aspect ratio of street canyons $H/W$, where $W$ is the mean street width. Such parameters for modern city were obtained with the use of GIS-processing of OpenStreetMaps data according to [35]. Mean values of $H$ and $H/W$ within each model cell were explicitly calculated by GIS algorithm with a 1-km grid step. It should be noted that $H$ values were calculated from the number of buildings’ stories available in OpenStreetMaps, with an assumption that height of one story is 3 m and the height of basement and roof is 2 m. For buildings with unknown heights, typical values were used. The urban fraction $F_{urb}$ was calculated as a combination of output parameters of OpenStreetMaps data GIS-processing:

$$F_{urb} = \min\{1 - F_{nat}, \max\{F_{bud} + F_{road} + k_{ind}F_{ind} + k_{res}F_{res}; F_{bud} + F_{can}\}\},$$

where $F_{nat}$ is the known fraction of natural surfaces (open water and vegetation), $F_{bud}$ and $F_{road}$ is the buildings and roads fraction, $F_{ind}$ and $F_{res}$ is the fraction of industrial and residential areas, and $F_{can}$ is the fraction of street canyons identified by GIS. The ratio of artificial and impervious surfaces within the industrial and residential (usually the courtyard) areas was controlled by $k_{ind}$ and $k_{res}$ coefficients, which were set to 0.5. The annual mean value of AHF was defined according to [36],
which gives an estimate of its mean value for Moscow as 75 W/m² for urbanized area in agreement with [37,38]. According to the approximation of its annual variation [34] used in the model the mean value for the summer season is about 30 W/m². To take into account the dependence of AHF on the building height and density, the following formula was used for its calculation for a certain model grid cell:

$$AHF = \min (\bar{AHF} \cdot F_{urb} \cdot \frac{F_{urb} \cdot L_{bld}}{M}, AHF_{max}),$$

where $F_{urb}$ is the building fraction within the urban fraction, $L_{bld}$ is the mean number of building stories, $\bar{AHF} = 75 \text{Wt/m}^2$ is the adopted estimate of annual mean AHF averaged over the urbanized area within Moscow, $M = \frac{\sum (F_{urb} \cdot F_{urb} \cdot L_{bld})}{\sum F_{urb}}$, $AHF_{max} = 150 \text{Wt/m}^2$ is the adopted maximum value of AHF for a model cell.

The considered scenario of urban expansion was developed according to the assumptions of a twofold increase in the population of the Moscow agglomeration, preservation of the current pattern of its development, keeping unchanged the building and planning features of the “old” city part within the Moscow Automobile Ring Road (MKAD), and development of new areas outside this road. The urban surface parameters required for the model and representing this scenario were obtained by a developed iterative algorithm. During each step of this algorithm new built model cells are created near previously built cells with a prescribed probability, which models gradual growth of the city. The work of the algorithm continued until the sum of the product of the area of buildings by the number of stories doubled (it was assumed that the population is proportional to this parameter). The spatial distribution of the urban fraction and building height for the modern city and the considered scenario of its expansion is shown in Figure 1. It should be noted that the proposed scenario of urban expansion does not pretend to be realistic, but it is convenient for studying the effect of urban growth on local climate.

The TERRA URB scheme was used only for the “final” domain D3, for which numerical experiments with a realistic modern city (URB) and a double city (URBx2) were performed for each summer season. In addition, an experiment without the TERRA URB scheme (noURB) assuming the replacing of urban areas by natural landscapes was also calculated to compare the climate response to city expansion with climatic anomalies caused by the influence of modern city within the same modelling framework.

![Figure 1](image1.png)

Figure 1. Spatial distribution of urban fraction (a, b) and building height (c, d) defined for model cells for URB (a, c) and URBx2 numerical experiments.
2.3. **Observations used for model verification**

The use of the model to study the phenomenon-induced response to some changes requires checking the ability of the model to simulate this phenomenon (i.e., verification of the model). For this purpose we used observations at meteorological stations located in the Moscow region, including new automatic meteorological stations (AWS) and automatic air-quality stations (AAQS) of MosEcoMonitoring (in total, more than 70 measurement points in the city and its 100-km neighborhood). A more detailed description of the meteorological observations used to verify the model can be found in [7, 39–41]. Despite the fact that the AAQSs do not fully correspond to the meteorological standards, a comparison of the observation data of such stations installed at the same points as the standard meteorological stations showed satisfactory results for the mean daily and mean nocturnal air temperatures [39].

The main WMO stations that characterize different parts of the Moscow city are Balchug station in the city center (600 meters from the Kremlin) and the Meteorological Observatory of Moscow State University (MSU campus) and the VVC weather station located in park zones (see Appendix 1 and Figure 3a).

3. **Results and discussion**

3.1. **Results of model verification**

Comparison of the observational data at meteorological stations, AWS, and AAQS with the modeling results show that COSMO-CLM simulations for conditions of the modern city adequately reproduce the meteorological regime of the Moscow region and the features of the UHI including the mean rural temperature and UHII in the city center and urban parks, which is confirmed by the model vs observations plots (Figures 2a-c). The simulated spatial variability of the temperature within the city is also in good agreement with the observations, which is confirmed by the scatter plots for the mean values during the summer of 2014 to observation (at all available meteorological stations, AWS, and AAQS) and modeling data (Figures 2d-e). Details of the methodology for comparing observations and modeling data are described in [39]. In addition, the results from [39] show that the model adequately simulates the vertical extent and structure of the UHI for the other considered summer seasons.
Figure 2. Temporal variations of modeled and observed values of mean rural temperature (a), UHII for city center (b) and urban park (MSU) (c) during 11 June – 11 August 2014; scatterplots for mean (d) and mean nocturnal (at 0 UTC) (e) temperatures for 2014 summer season at different points within 110 km from city center according to observations (weather stations, AWSs, and AAQSs) and modeling results. In (d, e) the color of the markers represents the urban fraction for corresponding model cell, square markers are used for points within 25 km from the center, and circles, outside this distance.

For the other summer seasons considered the model also adequately simulates the temperature regime, UHII and precipitation amount, which is confirmed by statistics of the model-to-observation comparison in Table 1 (mean error ME, root mean square error RMSE, and correlation coefficient R). It should be noted that for precipitation sums only the mean error, ME, was calculated, because more detailed verification of mesoscale precipitation fields based on observations at weather stations is a complicated problem. The ME was calculated as the difference between the modelled precipitation sum averaged over D3 domains (P3 value from Table 2) and its mean values over the weather stations within this area (see Appendix 1). These results allow us to use this model in this configuration for the investigation of climate response to the scenario of urban expansion being considered.

Table 1. Observed mean rural temperature (T), observed mean summer precipitation sum (P), averaged over weather stations located within domain D3, and statistics of comparison between modelled and observed values for T, P, and UHII: mean (ME) and root-mean-square (RMSE) errors and correlation coefficients (R).

| Year | Mean rural T, °C | Mean P, mm | Statistics of comparison between modelled and observed values |
|------|-----------------|------------|-------------------------------------------------------------|
|      | Mean rural T    | UHII (Balchug st.) | UHII (MSU st.) | Mean P |
|      | ME, °C | RMSE, °C R | ME, °C | RMSE, °C R | ME, °C | RMSE, °C R | ME, mm | ME, % |
| 2009 | 16.7 | 215 | 0.2 | 1.4 | 0.96 | 0.2 | 1.3 | 0.73 | 0.4 | 1.2 | 0.55 | 55 | 25.4 |
| 2010 | 21.5 | 158 | 0.1 | 1.6 | 0.97 | 0.1 | 1.4 | 0.78 | 0.4 | 1.5 | 0.56 | 6 | 4.0 |
| 2013 | 18.2 | 240 | 0.0 | 1.2 | 0.97 | 0.1 | 1.3 | 0.77 | 0.2 | 1.3 | 0.63 | 28 | 11.8 |
| 2014 | 18.0 | 144 | 0.3 | 1.4 | 0.97 | 0.0 | 1.3 | 0.83 | 0.4 | 1.3 | 0.75 | 7 | 4.9 |
| 2015 | 17.1 | 197 | -0.1 | 1.3 | 0.96 | 0.2 | 1.2 | 0.81 | 0.1 | 1.1 | 0.71 | 2 | 1.2 |

3.2. Model response to city expansion in terms of temperature and precipitation
The model response to the expansion of the city was considered as the temperature difference between URBx2 and URB experiments for temperature and precipitation. To compare it with the
meteorological anomalies created by the existing city, the model response to the emergence of modern city (switching on the UCM) was also estimated in the same way as the difference between URB and noURB experiments.

The response in the air temperature field shows that the city expansion to the suburbs not only leads to a significant local warming (more than 1°C) in these areas, but also has a heating effect on the surrounding areas, including the old city core and the city center. During the summer season, the average daily temperature within most of the city increased by 0.2-0.4°C (Figure 3a), the average night temperature (measured at 0 UTC) is 0.5-0.6°C. At first glance, these values are small enough. However, they correspond to an increase in an average UHI intensity for the city center by about 10%, and even more for the other parts of Moscow. For comparison, during 1977-2017, due to a combined effect of various factors, the UHI intensity for the city center increased by 0.7°C, and for the MSU campus region by 0.4°C. Therefore, these values are comparable.

The largest values of the temperature response to the city expansion in its center are observed in the evening, night, and early morning (Figure 4a), their maximum values exceed 1°C and are observed under conditions of anticyclonic weather. It is interesting that the daily course of such response is shifted forward by several hours in comparison with the daily course of UHI for a modern city (Figure 4c). This could be caused by the remoteness of the areas of city expansion from the center of Moscow. In addition, the dependence of the temperature response to the city expansion on rural temperature values (Figure 4b) and a similar dependence for modern-city UHI (Figure 4d) were clearly identified. The highest values of modern-city UHI and temperature response to the city expansion are observed under conditions of hot weather, which agrees with the results given for some other cities in [42–44]. This emphasizes the importance of such dependence in the context of the urban effects on the conditions of meteorological comfort, because human health study is most important in hot weather conditions, when relatively small changes in meteorological conditions can make a significant impact on people's health and well-being [5].

**Figure 3.** Spatial distribution of model response to city expansion in the field of mean air temperature ($\Delta T_{URBx2} = T_{URBx2} - T_{URB}$) averaged over considered summer seasons (a); relative model response to city expansion in the field of precipitation sum ($\Delta P_{URBx2} = 100\% \cdot (P_{URBx2} - P_{URB})/P_{URB}$) (b); relative model response to switching on the UCM in the field of precipitation sum ($\Delta P_{URB} = 100\% \cdot (P_{URB} - P_{noURB})/P_{noURB}$) (c). Model cells changed by the city expansion are shown by gray color in (a), and blue markers show the location of the main urban weather stations used in this study (1 – Balchug, 2 – VVC, 3 – MSU).
The modeling results also show that relatively small temperature changes in the central part of the city due urbanization at its periphery under conditions of extreme heat may significantly change the meteorological indices important for human thermal comfort assessment. For example, we analyzed this effect using the number of so-called "hot nights" (days with minimum temperature higher than 24 °C), which is a popular index of heat stress used in some studies, e.g. in [45, 46].

During the hot summer of 2010, the number of “hot nights” according URBx2 experiment was significantly higher than according URB experiment: it increased by 3 for the Balchug station area (21 for URBx2 vs. 18 for URB), by 6 for VVC (10 vs. 4), and by 4 for MSU (8 instead of 4). It should be noted that for Balchug these numbers were calculated for the temperature representing the urban tile within the corresponding model cell, and for MSU and VVC the temperature for natural tile was used. In reality, according to the observational data for Balchug, VVC, and MSU, 25, 3, and 4 “hot nights” were observed, which is similar to URB experiment. And according to noURB experiment, “hot nights” were not observed at all, as well as at rural stations according to observations.

**Figure 4.** Whiskers diagrams representing the dependence of modelled temperature response to urban expansion (temperature difference between URBx2 and URB experiments) (a, b) to switching on the UCM for modern city (temperature difference between URB and noURB experiments) (c, d) the time of the day (a, c) and mean rural temperature (b, d). Diagrams (a, c) are constructed for hourly temperature values in the city center (Balchug station surroundings) and (b, d) for daily-mean temperature values in the city center (Balchug) and urban park (VVC station surroundings) for considered summer seasons.

A positive response to the city expansion is identified in the field of summer precipitation sum (Figure 3c), as well as an urban-caused precipitation anomaly for the modern city (Figure 3d). In both cases fields of the difference between the precipitation sums for the corresponding pairs of experiments (URBx2 – URB and URB – noURB) are rather noisy and spotty, which could be explained by the stochastic nature of summer convective showers. The spotting is even higher if we
consider the same responses for certain summer season, and it decreases with increasing of the averaging period. 5-year averaging period is sufficient for clear identification of a positive urban-caused precipitation anomaly of the modern city located over its center and to the east of the city (Figure 3c) on its leeward site in relation to the prevailing western wind. This pattern agrees with the results of a number of investigations covering the problem of urban effect on precipitation [3, 47, 48].

The precipitation response to the scenario of urban expansion being considered is not so intensive, but it could be identified over a wider area (Figure 3c). Its maximum values are observed outside the “old” part of the city and it is also more intensive in the eastern (leeward) part of the region. If we consider the mean precipitation sum over the whole area of “final” domain D3 (180x180 km), the effect of the city expansion is approximately equal to the urban-caused anomaly for the modern city: in the both cases the precipitation sum increases approximately by 1.5% (see \( \Delta P_1 \) values in Table 2).

At the same time, the urban-caused precipitation anomaly for the modern city is more intensive within 20 km from its center, its mean value over this area is 10%, and in the city center and to the east of the city it reaches 30% (Figure 3c). The urban expansion scenario causes an approximately equal increase of precipitation over the “old” part of the city (within 20 km from its center) and over the area of new development lying mostly within 20-40 km from the center, for both of these areas the mean precipitation sum increases approximately by 5% (see \( \Delta P_2 \) and \( \Delta P_3 \) values in Table 2). It should be noted that the inter-annual variability of these responses is rather high. However, for each of the 5 considered summer seasons they are positive for each of the three considered areas (Table 2).

| Year | \( P_{URB} \), mm | \( \Delta P_{URB} = P_{URB} - P_{URBx2} \) | \( \Delta P_{URBx2} = P_{URBx2} - P_{URB} \) |
|------|------------------|------------------|------------------|
|      | \( P_1 \) | \( P_2 \) | \( P_3 \) | \( \Delta P_1 \) | \( \Delta P_2 \) | \( \Delta P_3 \) | \( \Delta P_1 \) | \( \Delta P_2 \) | \( \Delta P_3 \) |
| 2009 | 270 | 297 | 289 | 3 | 1.0 | 18 | 6.3 | 9 | 3.2 | 3 | 1.0 | 20 | 6.8 | 12 | 4.3 |
| 2010 | 164 | 175 | 177 | 2 | 1.5 | 14 | 8.4 | 5 | 2.9 | 2 | 1.4 | 4 | 2.2 | 7 | 4.0 |
| 2013 | 268 | 263 | 267 | 8 | 2.9 | 71 | 27.1 | 15 | 5.6 | 9 | 3.2 | 5 | 1.5 | 29 | 10.3 |
| 2014 | 151 | 154 | 164 | 3 | 1.8 | 19 | 12.2 | 6 | 3.5 | 3 | 1.6 | 10 | 5.7 | 7 | 4.0 |
| 2015 | 200 | 191 | 202 | 1 | 0.5 | 1 | 0.5 | 6 | 2.9 | 2 | 0.9 | 10 | 5.5 | 6 | 2.9 |
| Mean | 211 | 216 | 220 | 3 | 1.5 | 24 | 10.9 | 8 | 3.6 | 4 | 1.6 | 10 | 4.3 | 12 | 5.1 |

4. Conclusions

The main result of this study is the demonstration of possibilities to simulate the meteorological regime over large urban agglomerations with high spatial resolution within the framework of regional climate modelling and its application to the investigation of climatic responses to various urban developments. The numerical experiments with such model (COSMO-CLM) adapted to the conditions of Moscow region, supplemented with TERRA_URB urban canopy model, and supplied with realistic parameters of urban surface show its ability to successfully reproduce the summer meteorological regime of the research area, including the features of Moscow UHI.

The scenario of doubling of the city size by its expansion on the periphery was considered as a testing case for the investigation using this modelling approach to evaluate the climatic effect of urban developments. The simulations for this scenario show that it leads not only to a local temperature increase in the area of new developments, but also provides a heating effect on the central part of the city and increases the UHII in the city center by 10% or higher (the average daily temperature increases by 0.3 °C, and the average nocturnal temperatures, by 0.6 °C). This result shows the good
agreement with the urban amplification of global warming diagnosed for Moscow according to meteorological observations over the past 40 years [14] and partly explains its causes. At the same time, the temperature response to the city expansion is maximal in conditions of extreme heat and could impair the meteorological comfort and cause increased heat stress, which is shown by the example of the frequency of "hot nights" events during the summer of 2010.

In addition, the simulation results show that Moscow can be characterized by a positive urban-caused anomaly of total summer precipitation (in the city and at its leeward side it increased by 10-30% by the influence of modern city). The scenario of city expansion reinforces this anomaly by 5-10% and enlarges its area. Understanding the physical mechanisms of this anomaly formation, as well as its more detailed characteristics (such as its dependence on the precipitation type and intensity) require more detailed studies. However, the fact of its existence and sensitivity to urban expansion is an important result.

Appendix 1
The mean rural temperature was calculated according to observations at 9 stations located within 110 km from Moscow and surrounding it: Naro-Fomisk (WMO id 27611), and P. Konstantinov) was supported by the grant program of Russian Science Foundation (project no. 17-77-20070 "An initial assessment and projection of the bioclimatic comfort in Russian cities in XXI century against the context of climate change"). The human thermal comfort assessment in Moscow (performed by P.I. Konstantinov) was supported by the Russian Foundation for Basic Research (grant no.15-35-70006-mol_a_mos).

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