Numerical modeling of anthropogenic heat flux impact on air temperature in Moscow in wintertime

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Abstract. The difference between air temperatures in a city and the countryside - urban heat island intensity - depends primarily on the type and density of the buildings and energy consumption in municipal economy. There are many ways and methods for urban heat island intensity assessment: from empirical formulas to numerical simulation. One of the most useful numerical models for such purposes is COSMO-CLM. Various modifications of the COSMO model are now widely used in scientific research of mesoscale meteorological and climatic processes, as well as in weather forecast operational practice. The goal of this paper is to show the role of anthropogenic heat fluxes caused by urban energy consumption in Moscow’s urban heat island in wintertime nights under various weather conditions. Numerical simulations are performed using the COSMO-CLM model and a scheme called TERRA-URB with and without anthropogenic heat fluxes. Meteorological characteristics of the Moscow agglomeration are calculated using computational capacity of the A.M. Obukhov Institute of Atmospheric Physics RAS.

1. Introduction

The problem of urban energy supply is getting more and more important due to an acceleration of the urbanization processes. The energy demand for heating, ventilation, and cooling depends upon the local climate conditions. The climate of megacities is impacted not only by the global processes manifested on their regional scale, but also by some local interactions like “heat islands” appearing due to a city impact on the environment. Accounting for the feedback between the climate and the energy system is still quite a challenge.

One of the main goals of the Russian Science Foundation project “Analysis of the Impact of Regional Climate Change on Residential and Commercial Energy Consumption of Russian Megacities” is to implement regional models of urban climate and city energy demand for better understanding of the influence of climate parameters trends and changes in energy consumption of megacities.

Energy consumption during the heating season creates significant anthropogenic heat fluxes that have a significant effect on the temperature of the atmospheric air within Moscow as well as within other Russian megacities.

This paper presents the first experience of IAP team on the adaptation of the COSMO-CLM model for assessing the impact of energy consumption on the city climate and some preliminary results of numerical modeling of the anthropogenic heat flux impact on the air temperature in Moscow in the wintertime using the COSMO-CLM model coupled with TERRA-URB for the Moscow region.

2. Model, energy balance scheme, and computational capacities

Among the numerous mesoscale atmospheric and climatic models developed around the world, we chose the non-hydrostatic regional model of the Consortium for Small-Scale Modelling in Climate Mode (COSMO_CLM). This model was chosen for many reasons: excellent guide and documentation,
a possibility to become a Consortium member organization, and a more than a decade experience of using the COSMO model in Russia.

The COSMO model has been designed for both operational numerical weather prediction and various scientific applications [3]. The COSMO_CLM version of COSMO [2, 4, 5] is the most useful model in Europe for studying the effects of urbanization on the regional climate. The urban heat island in Berlin, Moscow, and some other large European cities and regions has been successfully simulated by the COSMO_CLM with different surface energy balance schemes. As initial input weather data for COSMO modelling are used the ERA-Interim reanalysis [6].

The COSMO model describes the meso-β scale meteorological processes (from 20 to 200 km) and meso-γ processes (from 2 to 20 km) [7] within different size domains up to a few thousand km. According to Figure 1, urban effects are located in the middle of the characteristic time and horizontal length scales of atmospheric processes, and for better understanding and modeling of energy consumption effects within large urban agglomeration it is necessary to consider a wide range of atmospheric (meteorological and climatic) processes.

![Figure 1. Scale definitions, characteristic time and horizontal length scales of a variety of atmospheric processes (adapted in [8] from [7]).](image)

Various modifications of models of the COSMO family are now widely used both in scientific research of mesoscale and practice and of using models in Russia is described in detail in works of the staff of the Russian Hydrometeorological Center, M.V. Lomonosov Moscow State University (see, for example, [3], 15, [17] and many other publications).

The IAP Laboratory of Mathematical Ecology passed the registration in the COSMO association in the COSMO-CLM and SOILVEG groups, which allowed beginning work on adaptation of the COSMO-CLM model and energy balance calculation schemes on the urban surface of the TERRA_URB type to the capabilities of the IAP cluster.

The IAP cluster consists of two logical parts. The first one has 8 servers SR1435VP2, each of which contains two dual-core Xeon processors with a frequency of 3 GHz. The peak performance of this part of the cluster is 3.7 Gflops. The second part is a single Intel® S5520UR server consisting of two quad-core Intel Xeon E5530 processors with a frequency of 2.4 GHz. The peak performance of this part of IAP cluster is 4.8 Gflops. The cluster has a 64-bit operating system CentOS 5.2 Linux, as well as the necessary utilities and compilers.

From the COSMO-CLM launch package we selected and successfully reproduced the test corresponding to the capabilities of the IAP computational cluster. The COSMO-CLM version is similar to the one used at the Geographic Faculty of Moscow State University. It turned out to be too cumbersome for the IAP computational cluster, and to use the model to estimate the impact of energy consumption on the city climate the number of grid cells horizontally and the layers in the vertical were reduced. Test calculations were successfully carried out on three nested domains in the European part of Russia. Each of these domains contains 10,000 cells of a horizontal grid corresponding to a size
of 17x17 km, 5x5 km, and 1x1 km, 40 layers in the atmosphere and 9 layers in the underlying layer. Calculating a day for these domains using two quad-core processors of the IAP cluster takes approximately 10, 30, and 180 minutes of computational time, respectively. The long calculation time for the smallest domain is associated with the need to use a small time step.

The initial fields for a grid with a step of 16.9 km are taken from the reanalysis, for a grid with a step of 5 km, the results of the calculation of the domain with a grid spacing of 16.9 km, and for a grid with a step of 1 km, respectively, the results of the calculation of the domain with a grid spacing of 5 km. The air temperature fields in Moscow and its nearest surrounding calculated within the different domains, as shown in Figure 2, are very similar one to another.

Figure 2. Example of air temperature modelling on three nested domains for December 2, 2009.

Figure 3 shows that the average air temperatures over Moscow practically do not depend on the size of the domain and cells.

Figure 3. Simulated daily mean temperature for December 2-9, 2009 over Moscow and its neighborhood (100x100 km) calculated with different domains and grid spacing.
For studying the effect of energy consumption on the climatic and weather characteristics of urban agglomeration and the influence of climatic variations and trends on the energy needs of urban economy, a correct description of the energy fluxes within different urbanized areas is very important.

Various approaches to urban and rural surface energy fluxes parameterization can be found in COSMO_CLM guide and scientific papers [2, 9, 10, 11, 12, 13]. There are several schemes for surface energy fluxes parameterization: TEB (Town Energy Balance), BEP (Building Energy Parameterization), and others [9, 10, 11]. The international COSMO team developed the TERRA_ML scheme for multilayer soil description. Later, especially for urban climate and weather studies, the TERRA_URB scheme was created. The TEB to TERRA schemes are shown in Figure 4 from [11]. Recently, some simulations for Belgium, Berlin, and Moscow were presented at international scientific events and published [13, 14, 15, 16, 17].

To study the Moscow agglomeration urban heat island, the Moscow State University team uses two versions of urban surface parameterization [15, 17]: a more complete urban development model based on the concept of urban canyon, TEB, and a simpler one, TERRA_URB (Figure 4), which is a modification of TERRA_ML.

The TERRA-URB scheme provides a possibility to consider anthropogenic heat fluxes, AHF (“heat emission” in Figure 5). Different approaches to the AHF value estimation are presented in [18, 19, 20, 21, 22] and some other papers. At the next stage of this study the main attention will be paid to urban climate modeling considering the energy consumption impact on the urban heat island intensity using different methods of anthropogenic heat fluxes parameterization, as well as positive and negative feedbacks between the energy demand and climate changes within large urban agglomerations.

Figure 4. Land surface schemes TERRA and TEB schemes.
3. Results
The Moscow regional meteorological characteristics were simulated for the period from December, 2016 to February, 2017. The air temperature field dynamics during the winter of 2016-2017 within Moscow and suburb area calculated by the COSMO-CLM model with the TERRA-URB energy balance scheme is presented in the Appendix.

Calculations show a significant effect of AHF on the air temperature within Moscow region. This influence depends not only on the AHF value, but also on the weather conditions and, first of all, on the wind velocity. In the situation with a weak wind, the difference between the simulated temperature in the Moscow downtown with and without the AHF impact is larger than under strong wind.

Sometimes, under special weather conditions like in the case of January 12, 2017, the anthropogenic heat flux “stopped” a north cold air invasion, and the difference between the temperature with and without the AHF reached approx. 7 C. Excluding this special case, the remaining calculation results show a clear interdependence between the wind velocity and the magnitude of the influence of anthropogenic heat fluxes on the intensity of the urban heat island in Moscow in winter. This dependence is shown in Figure 6.

4. Conclusions
The above-presented results of numerical modeling showed the computational capacities of the COSMO-CLM model with the TERRA-URB scheme and the IAP-type cluster to simulate daily and
seasonal meteorological characteristics of the Moscow agglomeration. The dependence of the intensity of urban heat island on the presence of anthropogenic heat fluxes due to the energy consumption of Moscow's municipal economy in winter was shown. The influence of wind speed in the formation of urban heat island was also shown.

Acknowledgments
The authors wish to thank the Russian Science Foundation for financial support (project no. 16-17-00114 "Analysis of the Impact of the Regional Climate Change on Residential and Commercial Energy Consumption of Russian Megacities") and the COSMO consortium team for information and technical support. The authors also wish to acknowledge the assistance and encouragement received from their colleagues - G Rivin, A Kislov, V Platonov, M Varentsov, D Blinov, I Belova, and L Maximenkov (Hydrometeorological Center of Russia, Moscow State University, and the Institute of Atmospheric Physics).
Appendix. The simulated air temperature field dynamic during winter 2016-2017 within Moscow city and suburb area (Left column - calculation without AHF, right column - with AHF)

December 15, 2016

December 22, 2016

December 29, 2016
January 05, 2017

January 12, 2017

January 19, 2017
January 26, 2017

February 02, 2017

February 09, 2017
February 16, 2017

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