The influence of anthropogenic heat fluxes on the temperature and wind regimes of the Moscow and St. Petersburg regions

S A Dokukin¹,², A S Ginzburg²,³
¹ Faculty of Physics, Lomonosov Moscow State University, Moscow, 119991, Russian Federation
² A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Pyzhevsky per., 3, 119017, Moscow, Russian Federation
³ Moscow Technological Institute, Moscow, Russian Federation
E-mail: dokukin.sergey@physics.msu.ru

Abstract.
Anthropogenic heat fluxes (AHF) have a significant impact on the weather and climate characteristics of urbanized territories. AHF plays a crucial role in the formation of an urban heat island. The structure of the urban heat island is determined not only by the AHF distribution but also by the location of the city. Moscow and St. Petersburg are the two largest Russian cities located in significantly different climatic conditions with the highest value of the AHF. In this article we compare the influence of the AHF on the temperature and wind regimes in Moscow and St. Petersburg regions.

1. Introduction
Study of the urban climate, its causes and consequences is one of the main research directions of regional climatology and mesometeorology in the 21st century. The main attention in such studies is given to anthropogenic factors, since they play a decisive role in meteorological and climate processes in urban agglomerations. The results of recent studies of the causes and consequences of current and projected climate changes in the world’s largest urban agglomerations are presented in [1]. The climate dynamics of the Moscow agglomeration is described in detail in [2]. The main research results described in this monograph and related to the topic of our work are published in English in [3]. Urban development changes the properties of the underlying surface and the urban boundary layer of the atmosphere, as well as water and heat exchange in the urban atmosphere. Therefore, urban development is the main anthropogenic process that affects the climate of a city.

Anthropogenic heat flux (AHF) is one of the important anthropogenic factors in the formation of an urban heat island. The AHF is determined by the energy consumption of the urban economy. It is widely known that the intensity and the structure of the urban heat island significantly depends on the shape and the size of the urban development, the geographical location of the city and the characteristics of the surrounding territories [1–6]. This article is a development of the previous works of the authors [7, 8]. In previous studies features of the impact of the AHF on the temperature regime of Moscow in winter [7] and the first estimates
of the role of the AHF in the formation of the temperature and wind regimes in a number of megacities in Russia and around the world [8] were discussed. In this article the AHF influence on climate for two biggest Russian cities (Moscow and St. Petersburg) is compared.

Figure 1. Mean annual anthropogenic heat flux spatial distribution for Moscow and St. Petersburg [9].

Figure 2. Impervious surface area spatial distribution for Moscow and St. Petersburg [10].
2. Model description

For numerical simulations of the regional climate the COSMO-CLM\textsuperscript{1} model \cite{11, 12} was used. The COSMO-CLM is the special non-hydrostatic mesoscale numerical weather prediction version of the COSMO model adopted for long-term simulations. Two domains with the same grid sizes were used for simulations in Moscow and St. Petersburg. Size of the domain is 500\times500 km (longitude and latitude grid steps of \sim 0.045°). To obtain initial and boundary condition we used two-step dynamical downscaling procedure. Size of the intermediate domain is 1690\times1690 km (longitude and latitude grid steps of \sim 0.152°). The initial data for the downscaling procedure was the ERA-Interim reanalysis data \cite{13} (with longitude and latitude grid steps of 0.75°). Spectral nudging technique \cite{14} was used to get more reliable results.

To take into account information about the AHF in our simulations the TERRA\_URB bulk urban canopy model was used \cite{15, 16}. The AHF parametrization\textsuperscript{2} is according to \cite{9} (Fig. 1). It is based on the annual-mean value of the AHF considering latitude dependence, diurnal and annual variations. There are two main differences in the Moscow and St. Petersburg AHF maps. Firstly, AHF in Moscow are significantly higher than in the St. Petersburg. Secondly, AHF distribution in Moscow has circular symmetry with maximum approximately in center, while in St. Petersburg there is no symmetry in the AHF distribution and it is more uniform. We would like to note that despite the fact that the AHF data \cite{9} is somewhat outdated, but, nevertheless, it qualitatively correctly reflect the real situation. Lower AHF in St. Petersburg are associated with two main factors: (i) St. Petersburg is a coastal city and, therefore, heating costs in this city are lower and (ii) Leningrad nuclear power plant in Sosnovy Bor makes a big contribution to the heating of this city. Unfortunately, available data is not enough to make estimations. The TERRA\_URB requires information about impervious surface area. These data\textsuperscript{2} are presented in the Fig. 2.

3. Results and discussion

Meteorological characteristics were simulated from December 2015 to January 2018. Fig. 3 shows several simulation results at 0 a.m. GMT. The simulation results were compared in two regimes: with AHF and without AHF. It is worth noting that in regime without AHF only AHF field was equal to zero but all the other TERRA\_URB functions were activated. Two days were chosen for the greatest difference: one day in winter and one day in summer. Air temperature within the cities is higher when the AHF are used in simulations. Formation of urban heat island in Moscow is clearly observed. Our results are in a qualitative agreement with previous simulations of the weather in Moscow region \cite{2, 3, 6}. Unfortunately, we could not find any scientific publications about St. Petersburg to compare our simulation results. Urban heat island in St. Petersburg is much less pronounced than in Moscow. The reasons are as follows. Firstly, the AHF in St. Petersburg are much less than in Moscow \cite{8}. Secondly, the AHF distribution in Moscow has radial symmetry and, therefore, is more pronounced. Thirdly, the temperature over the Baltic sea is significantly higher than over the city. Area with high temperature near the city makes it difficult to detect the urban heat island. Finally, the wind speed over the Baltic sea is high. The temperature increase under the AHF influence is inversely proportional to the wind speed \cite{7} and, therefore, high wind speed results in weak influence of the AHF on temperature.

Temperature increase under the AHF influence is inversely proportional to the wind speed in Moscow and St. Petersburg (Fig. 4). When the wind speed is not very high the increase in temperature is higher in Moscow. This is primarily due to the fact that in Moscow the AHF is higher and, therefore, when the wind speed is the same the temperature increase is higher in Moscow. When the wind speed \gtrsim 6 m/s the influence of the wind speed on the temperature increase is almost the same in Moscow and St. Petersburg.

\textsuperscript{1} int2lm version is 2.00_clm4 and cclm version is 5.00_clm9.

\textsuperscript{2} Data for figures is obtained using the WebPEP utility. WebPEP is the web interface for the EXTPAR \cite{17} program.
Figure 3. Temperature and wind fields in the Moscow and St. Petersburg regions from the COSMO_CLM simulations (left pictures without AHF, right pictures with AHF).
Figure 4. Dependence of the temperature increase $\Delta T$ under the AHF influence on the wind speed $W$ in the region in winter period. Temperature increase $\Delta T$ is the difference of the temperature in the simulation with and without the AHF accounting. Points in plot present $\Delta T$ and $W$ values at 0 a.m. GMT averaged over the area with size 250×250 km. The dependencies are approximated with the equation $\Delta T = a \cdot W + b$, where $a = -0.047$, $b = 0.397$ for Moscow and $a = -0.012$, $b = 0.119$ for St. Petersburg.

Figure 5. Dependence of the wind speed increase under the AHF influence on the temperature increase under the AHF influence in a city in winter period. Wind speed increase $\Delta W$ is the difference of the wind speed in the simulation with and without the AHF accounting. Temperature increase $\Delta T$ is the difference of the temperature in the simulation with and without the AHF accounting. Points in plot present $\Delta T$ and $\Delta W$ values at 0 a.m. GMT averaged over the area with size 25×25 km. The dependencies are approximated with the equation $\Delta W = a \cdot \Delta T + b$, where $a = 0.180$, $b = 0.607$ for Moscow and $a = 0.275$, $b = 0.058$ for St. Petersburg.
An increase in temperature leads to an increase in wind speed (Fig. 5). Therefore, the influence of the AHF indirectly leads to an increase in wind speed. The same effect was previously observed in the simulations of the AHF influence on the climate over Hangzhou City [5]. We observe stronger influence of the temperature increase on the horizontal wind speed increase in Moscow than in St. Petersburg. This is due to the following reasons: (i) the mean wind speed in Moscow is significantly lower than in St. Petersburg and (ii) the structure of the urban heat island over Moscow is much more precise than over St. Petersburg.

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