Anthropogenic heat fluxes in urban agglomerations and their impact on meteorological processes

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Abstract. One of the main factors of the impact of urbanization on mesoscale atmospheric and climatic processes are the anthropogenic heat fluxes (AHFs) caused by all types of heat sources in urban areas – from industry to metabolism in residents. A calculation of the influence of energy consumption in urban weather and climate made by the COSMO-CLM model with the TERRA-URB scheme shows that anthropogenic heat fluxes have a noticeable effect on urban temperature and wind regime. In Moscow’s agglomeration, the AHF contribution results in an increase of the mean annual temperature by 2˚C and of the mean annual wind speed by more than 1 m/s, while the prevailing wind direction changes only slightly.

1. Background
Since the beginning of the 21st century, more and more attention has been paid to studying the influence of world energy not only on greenhouse gases emissions, but also on thermal pollution of the atmosphere of urban agglomerations.

The scales of the urban atmospheric processes are in the middle of the time and horizontal length scales of the meteorological processes \cite{1, 2} and for understanding and modeling of the anthropogenic impact on meteorological and climatic characteristics within large urban agglomerations it is necessary to consider a wide range of atmospheric processes.

Anthropogenic heat fluxes (AHFs) arising from the energy consumption in urban areas strongly affect the mesoscale atmospheric processes in densely populated regions of the world. AHFs are one of the main factors in the formation of the urban heat island and have a significant impact on the city’s wind regime, humidity, and cloud cover.

Estimates of anthropogenic heat fluxes in different countries and specific urban agglomerations vary greatly due to different methods for their determination and significant uncertainty and initial statistical data. The AHFs are responsible for a significant part of the urban heat island intensity \cite{3, 4}. Regional atmospheric advection also significantly affects the intensity and shape of the urban heat island. To describe the features of the urban heat island dynamics and assess the energy needs of urban economy, it is necessary to consider the feedbacks between the temperature regime and the urban energy consumption.

The anthropogenic heat fluxes within large urban agglomerations could be estimated by empirical assessment based on reliable data on the population and energy consumption of the urban economy. Another approach to the AHF estimation is inventory and summation of all consumers of the heat and electric energy in the city.

These two main approaches to the determination of anthropogenic heat fluxes and methods for their assessment are described in detail in \cite{5, 6}.

A series of studies on the empirical assessment of anthropogenic heat fluxes in the largest urban agglomerations of the world was performed at the Laboratory of Mathematical Ecology of the A.M. Obukhov Institute of Atmospheric Physics (IAPh) RAS. The method of this empirical assessment is based on the most reliable data on the population and energy consumption of the urban economy of.
megalopolises. Calculation of the influence of energy consumption in urban areas on mesoscale atmospheric processes was carried out using the COSMO-CLM [7] model with a TERRA-URB scheme [8-12].

2. Methods
It is well known that large cities create their own climate and anthropogenic heat fluxes play a crucial role in the formation and dynamics of the urban climate. However, obtaining reliable data on the magnitude and spatiotemporal distribution of anthropogenic heat fluxes in megacities of various countries of the world is associated with many difficulties.

One of them is the inclusion of different anthropogenic heat sources which exist on urban territories: electric and heat production energy consumption, transport, boilers, and even human metabolism. Electric energy is usually generated outside urban territories, and this AHF source is not included in city statistical data. Another difficulty is that the administrative boundaries of a city often include not only downtowns, business and residential blocks, but also industrial and suburban territories.

The main useful method for the estimation of the AHFs is the inventory and summation of all consumers of heat and electric energy in the city taking into account the population size and the influence of transport, the length of roads, and the engineering communications (see, for example, [13]):

\[ Q_a = Q_V + Q_b + Q_m, \]  \hspace{1cm} (1)

where \( Q_a \) is the total AHF, \( Q_V \) is the heat generated by vehicles, \( Q_b \) is the heat from buildings, and \( Q_m \) is the human metabolism. The COSMO consortium team is using a similar approach.

An alternative method of the AHF estimation was proposed in [5, 6]. It is based on the most reliable data on the population and energy consumption of the urban economy. In this case

\[ Q_a = k \times PD \times EC, \]  \hspace{1cm} (2)

\( PD \) is the population density within the urban administrative boundaries, \( EC \) is the energy consumption per capita for the country where this urban agglomeration is located. If \( Q_a \) is in \( \text{W/m}^2 \), \( PD \) in people per sq. km, and \( EC \) in kg o.e., the coefficient will be \( k = 1.325 \).

3. Results
In [5, 6] the available data provide estimates of the mean annual AHF for several world megacities and capitals, such as New York, London, Beijing, Tokyo, Seoul, Jakarta, as well as Moscow within the 2011 borders and after the city borders expansion in 2012.

A difficulty of such estimates, apart from the uncertainty (and not always reliability) of energy consumption data, lies in the fact that in various cases sparsely populated (essentially, suburban) areas are included or not included in the administrative boundaries of cities. For example, until 2012 the administrative area of St. Petersburg was almost twice as large as Moscow, while the population of St. Petersburg was less than twice as large as that of Moscow. Similar situations are in New York, London, and Beijing, where there is a “city core” comparable to Seoul or Moscow (until 2012), and the suburbs administratively subordinate to the city authorities, comparable to new Moscow (territories annexed in 2012).
Table 1. Administrative area, population, energy consumption, and mean AHF for several world cities.

| City            | Administrative area, km² | Population, millions | Mean energy consumption in the country, kg o.e. per capita | Mean anthropogenic heat flux, W/m² |
|-----------------|--------------------------|----------------------|------------------------------------------------------------|-----------------------------------|
| New York        | 1215                     | 8.4                  | 6949                                                       | 63.7                              |
| Moscow (June 2012) | 1081                    | 11.3                 | 4943                                                       | 68.5                              |
| Moscow (July 2012)   | 2510                    | 11.6                 | 4943                                                       | 30.3                              |
| London          | 1572                     | 8.9                  | 2777                                                       | 20.8                              |
| Beijing         | 1288                     | 11.1                 | 2237                                                       | 25.5                              |
| St. Petersburg  | 1439                     | 5.4                  | 4943                                                       | 24.6                              |
| Novosibirsk     | 503                      | 1.6                  | 4943                                                       | 20.8                              |

In Table 1, the data are taken from Wikipedia [14-19] for the city area and population and from the UN Little Green Data Book [20] for the national mean energy consumption per capita. The AHF values are calculated by equation (2).

In numerical climate models, the databases created at the beginning of the 21st century and most fully presented in [21] are usually used to describe the AHF field. This work uses statistics from 2005. It should be noted that over the past decade data on the energy consumption per capita in many countries have changed significantly. Thus, in the UK this value has decreased by a quarter and in China, by three quarters. In Russia and the USA this indicator has not changed so much over the past decade.

To study the influence of the AHF on mesoscale atmospheric processes, we use the regional climate model COSMO-CLM [7], where the initial average annual AHF fields are set based on data [21] with additions and corrections based on NOOA and EEA datasets. Figure 1 shows the average annual AHF fields used in the COSMO-CLM for New York, London, and Beijing, as well as for the three largest cities in Russia - Moscow, St. Petersburg, and Novosibirsk. A comparison of the AHF values given in Table 1 and presented in Figure 1 shows good agreement between the estimates obtained by various methods.

We performed a numerical simulation of the anthropogenic heat flux impact on the air temperature and wind within Moscow region using the COSMO-CLM model coupled with a TERRA-URB surface energy balance scheme. The model and the energy balance scheme were adapted to the capabilities of the IAPh cluster (see [22, 23]). The calculations were carried out on two 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 and 5x5 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 IAPh cluster takes approximately 10 and 30 minutes of computational time, respectively.

Figure 2 shows some results of temperature and wind fields for several days at UTC 0 from simulations during 2016 and 2017. The air temperature over Moscow is higher when considering the AHF. It means that the formation of an urban heat island is observed. We can see that the wind speed is higher in the figures with the consideration of the AHF (especially on January 5, 2016 and July 6, 2017).
Figure 1. Mean annual anthropogenic heat flux spatial distribution for selected large world and Russian cities (data from [21] accessed using WebPEP tool of CLM-Community).
Figure 2. Temperature and wind fields in Moscow region from COSMO-CLM simulations (left figures – without AHF, right figures – with AHF).
Table 2. Mean annual air temperature and wind velocity in Moscow region during 2017 calculated with COSMO-CLM model.

| Parameter               | Without AHF | With AHF |
|-------------------------|-------------|----------|
| Air temperature, °C     | 1.3         | 3.1      |
| Wind velocity, m/s      | 2.9         | 3.9      |

Table 2 presents the average annual air temperature and wind velocity in Moscow region in 2017. The air temperature in the model with the consideration of the AHF is higher than in the model without the consideration of the AHF because, according to the Fourier law, heat fluxes increase the temperature. The average wind speed is also higher in the model with the consideration of the AHF because, as shown previously, the consideration of the AHF results in strengthening of the urban breeze circulation [24-25].

4. Discussion and conclusions
Anthropogenic heat fluxes are major factors in the formation of an urban heat island. AHFs also significantly affect the wind regime of a megalopolis. In Moscow’s agglomeration, the average wind speed increases by more than 1 m/s, while the prevailing wind direction changes slightly. A similar effect is described in [24] and some other publications.
In turn, regional atmospheric advection significantly affects the intensity of an urban heat island, by strengthening or weakening the feedback between the temperature regime and the energy consumption of urbanized territories.

The feedback is negative during the heating season and positive during the indoor air conditioning period [26, 27]. The significance of such feedbacks substantially depends on the climate and relief of the region in question, the heat and power supply systems of the city, and other factors. Anthropogenic heat fluxes are very strongly interconnected with the characteristics of the heating season [28] and with the carbon footprint of large cities [29].

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