Anthropogenic elements of heat and water balance of large cities (case study of Moscow)

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Abstract. This paper presents an assessment of the anthropogenic contributions into urban heat and water balance from various sectors - heating, power, and transport. On the basis of data on consumption of various fuels and an analysis of technological processes, monthly amounts of heat and moisture fluxes into the atmosphere are calculated and compared with natural components of heat and water balance. The input data of the study are urban energy statistics data on annual consumption of various types of energy resources (fossil fuels - coal, natural gas, fuel oil, as well as heat and electricity), as well as territorial (by administrative areas) and monthly distributions of production and consumption of heat and electricity. We present a simple technique using a standard energy data count to obtain spatial-temporal distributions of anthropogenic heat and water fluxes in urbanized areas. The case study of Moscow has shown that man-made sources are essential elements of heat and water balance of urban environment, especially in winter. About 30% of the total annual amount of heat distributed over the year almost evenly comes into the ground. The annual anthropogenic heat and water vapor fluxes in Moscow are less by an order of magnitude than the regional norms of solar radiation and natural evaporation, respectively, but in winter the magnitude of anthropogenic and natural fluxes is comparable.

1. Introduction

Growing urbanization and specific features of the microclimate of megacities are of particular interest to specialists in the field of climatic and meteorological modeling [1]-4]. High density of the anthropogenic impact on urbanized territories significantly increases the contribution of anthropogenic (both direct and indirect) factors to meteorological processes [4]-5]. Adequate modeling of heat and mass transfer in urban areas requires realistic assessment of anthropogenic heat and moisture fluxes from different sources [1]-3].

In [6], a generalized approach for estimating season-specific diurnal profiles of urban anthropogenic heating from three components: the building sector, the transportation sector, and metabolism is presented and used for calculations for six large US cities. In [7], the authors developed this method and produced a national database of seasonally and diurnally varying anthropogenic heating profiles for 61 of the largest cities in the United States, and introduced a simple adjustment accounting for different international energy consumption rates relative to the U.S. to generate anthropogenic heating profiles for a range of global cities.

On the basis of the results of [6], the author of [8] developed a global database of anthropogenic heat fluxes (AHF) for 2005 and 2040 calculated from the national energy consumption and population density. The same approach was realised in [9] using a large-scale urban consumption of energy

(LUCY) model from the global to individual city scale at 2.5 × 2.5 arc-minute spatial and seasonal/diurnal temporal resolution.

The authors of [9]-11] calculated the average AHF for Moscow using the mean national per capita consumption and the city population density. This approach produces very rough estimates because, as shown in [5], per capita energy consumption in large cities is usually less than in other areas. For example, per capita energy consumption in Moscow is about 3 tce/yr, and the national mean value for Russia is 7 tce/yr.

This paper presents assessment of the anthropogenic contribution to the heat and water balance of cities from various sectors of urban economy: heating, electricity, and transport. On the basis of data on the consumption of different fuels and an analysis of industrial processes, the amounts of heat and moisture fluxes into the atmosphere are calculated on the monthly basis and compared with the natural components of heat and water balance.

2. Initial data

The information base of the present study comprises urban energy statistics: the quantities of annual consumption of different types of energy resources (fossil fuels – coal, natural gas, fuel oil, heat and electrical energy), as well as territorial (administrative areas) and subannual (monthly) allocation of the production and consumption of heat and electricity. The first group of data is obtained from the Federal Database (www.fedstat.ru), and to generate a second subset an analysis of the regional power grid Mosenergo (http://www.mosenergo.ru/investors/reports/yearly-reports/) and municipal administration (https://www.mos.ru/dgkh/documents/) reports was performed. Figure 1 (left) shows changes in the amount and pattern of energy consumption (external supply) in Moscow in 2000-2015.

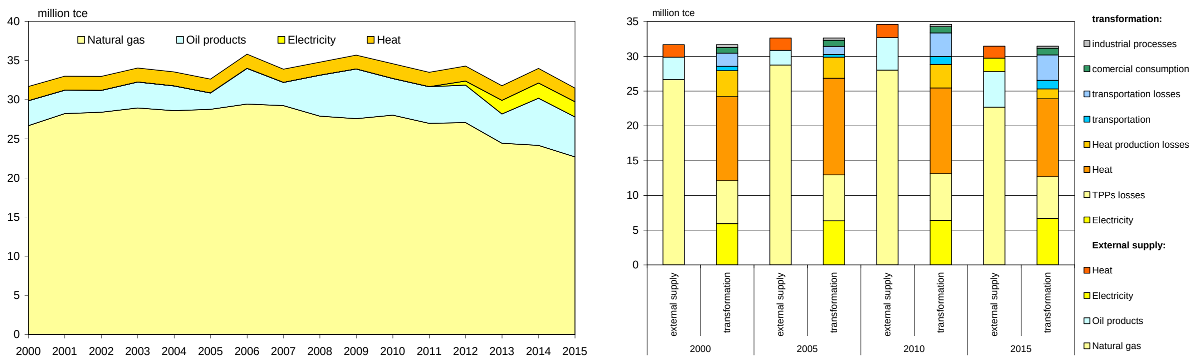
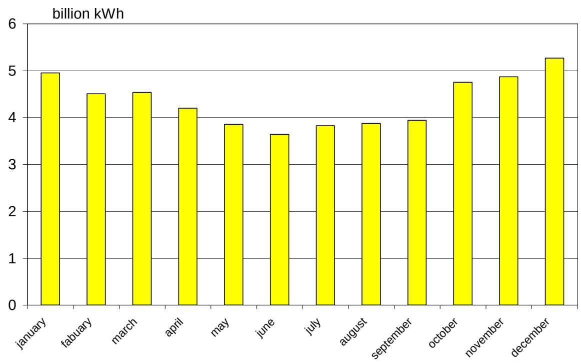


Figure 1. External energy supply (left) and simplified energy balances (right) in Moscow in 2000-2015.

As we can see from Figure 1, the basis of the fuel and energy balance of Moscow is natural gas (approximately 75-80% of the received part), while about 5% of the supply of heat energy is produced outside the city limits, and in the recent years as a result of gradually decreasing urban thermal power plants generation, about 5% of the total energy consumption comes from the outside in the form of electricity. Almost all amount of natural gas coming to Moscow is used for heat and electricity production, and other processes (technological and municipal) constitute less than 5% of the total consumption of energy resources. The residual 10-15% of the total energy supply referring to oil products (gasoline and diesel fuel) are used mostly for transportation.

In the energy transformation sector, significant thermodynamic losses of energy are in cogeneration plants (about 45%) and in transportation (up to 75%).



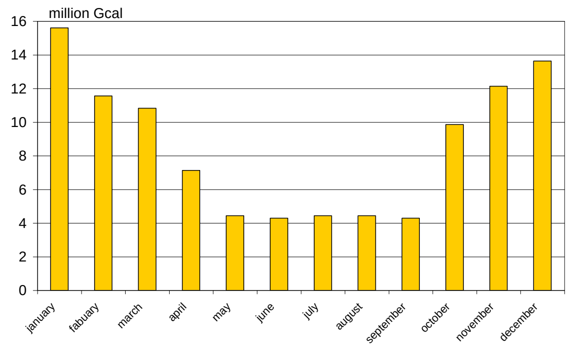


Figure 2. Monthly electricity (left) and heat (right) consumption in Moscow in 2015.

Figure 2 demonstrates substantial seasonal irregularity of electricity and heat consumption: the former during the winter months exceeds the summer level by 30% and the latter, by more than three-fold.

3. Methods

The main sources of anthropogenic heat release into ambient atmosphere of cities are as follows:

1. thermodynamic losses of thermal cycles of power plants and transport engines
2. losses of heat and electricity during transmission and distribution, as well as in the production of heat in boilers
3. energy dissipation from buildings, transportation, and water drainage

Water of technogenic origin enters the atmosphere of cities mainly from burning fuels and by evaporation in cooling towers of thermal power plants (TPPs) and cogeneration heat plants (CHPs).

To assess the heat and moisture flows Q_i from the sources listed above, the following general equation is used:

$$Q_i = \sum_j k_i^j \cdot B_i^j , \tag{1}$$

where B_i^j is the quantitative characteristic of the intensity of the j-th process for the i-th source, and k_i^j is the conversion factor. To generate the coefficients, standard methods of calculation of heat balance and atmospheric emissions in the energy sector were used. The indicators used and the estimated coefficients for Moscow are presented in Tables 1-2.

The following assumptions were used:

- motor fuel consumption, as well as the heat consumption for hot water supply are distributed across the year evenly;
- electricity and thermal energy used for mechanical work finally dissipates in the form of heat into the ambient air;
- heat fluxes from losses in the transmission and distribution of heat, as well as in the sewage, are accumulated in the ground, and the others go directly into the atmosphere.

To calculate the heat release into the city atmosphere through thermodynamic losses of TPPs, CHPs, and transportation, as well as from heat production in boilers, a database on the energy efficiency of power industry and car inventory was used. For the energy losses from transmission and distribution, statistical data were also applied. The energy dissipation from buildings, transportation, and water drainage was calculated as the residual value.

Table 1 Characteristics of the man-made elements of thermal balance of Moscow.

Heat sources	B_i		k_i	
	Name	units	value	units
(1) thermodynamic losses of TPPs and CHPs	(a) TPP fuel consumption	tce	$2.9 \cdot 10^{-4}$	PJ/tce
	(b) electricity production	kWh	$3.6 \cdot 10^{-9}$	PJ/kWh
	(c) heat supply from CHP	Gcal	$4.2 \cdot 10^{-6}$	PJ/Gcal
(2) thermodynamic losses in transportation	gasoline and diesel fuel consumption	tce	$2.2 \cdot 10^{-4}$	PJ/tce
(3) heat losses in transmission and distribution	total heat supply	Gcal	$5.0 \cdot 10^{-7}$	PJ/Gcal
(4) electricity losses in transmission and distribution	electricity consumption	kWh	$3.6 \cdot 10^{-10}$	PJ/kWh
(5) losses in heat production in boilers	heat supply from boilers	Gcal	$7.4 \cdot 10^{-7}$	PJ/Gcal
(6) energy dissipation from buildings	(a) total heat supply	Gcal	$3.6 \cdot 10^{-6}$	PJ/Gcal
	(b) electricity consumption	kWh	$3.2 \cdot 10^{-9}$	PJ/kWh
(7) energy dissipation in transportation	gasoline and diesel fuel consumption	tce	$7.3 \cdot 10^{-5}$	PJ/tce
(8) energy dissipation from sewage	heat consumption for hot water supply	Gcal	$4.2 \cdot 10^{-6}$	PJ/Gcal

Note: 1 tce = 29.3 MJ; 1 Gcal = 4.2 GJ; 1 kWh = 3.6 MJ

To calculate the moisture release from fuel combustion, a standard hydrogen content [12] was used. For evaporation in cooling towers of TPP and CHP, the typical values of water losses from [13] were applied.

Table 2 Characteristics of the man-made elements of water balance of Moscow.

Water sources	B_i		k_i	
	Name	units	Name	units
(1) stationary fuel combustion	(a) natural gas consumption	tce	1.4	t/tce
	(b) coal consumption	tce	0.45	t/tce
	(c) fuel oil consumption	tce	0.8	t/tce
(2) mobile fuel combustion	gasoline and diesel fuel consumption	tce	0.9	t/tce
(3) evaporation in cooling towers of TPP and CHP	electricity production	kWh	0.022	t/kWh

4. Results and discussion

In Figure 3, the structure of the heat flux from anthropogenic sources into the environment (soil and air) in Moscow for 2015 is presented. The seasonal irregularity is clearly pronounced: the winter heat flow exceeds the summer one almost twofold. The main sources of anthropogenic heat and the reason of its unevenness are the district heating and electricity consumption, while the energy flows from transport are practically constant throughout the year and account for about 15% of the annual amount. Heat flows into the soil formed from the heat transmission and distribution losses and hot water drainage account for less than 30% of the total volume and are fairly independent of the season.

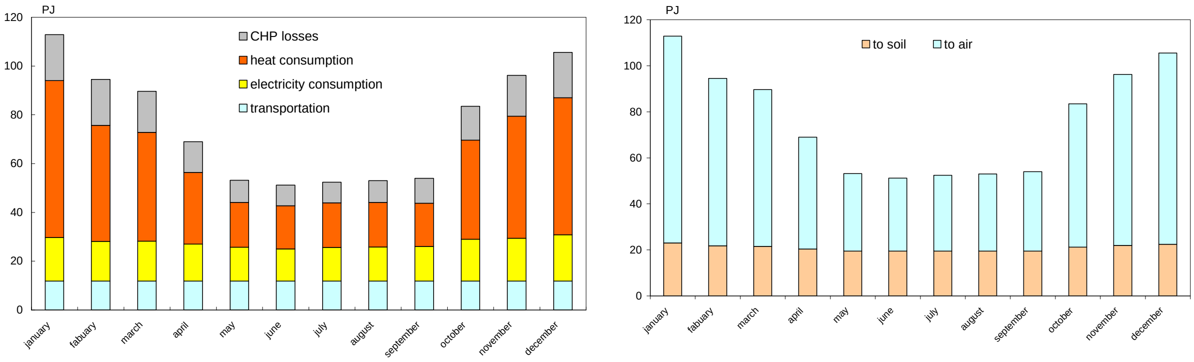


Figure 3. Anthropogenic heat flows in Moscow in 2015 by source (left) and direction (right).

As shown in Figure 4, the main man-made source of water vapour into the atmosphere of Moscow is fossil fuel combustion (88% of the annual flow comes from the stationary combustion of gas and about 10% – from burning of motor fuels for transportation); evaporation from the cooling towers represents only 2%. The man-made water vapour flows in winter surpass the summer ones about two-fold.

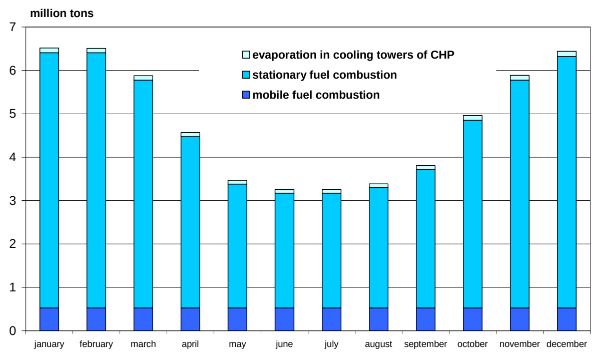


Figure 4. Anthropogenic moisture flows in Moscow in 2015 by source.

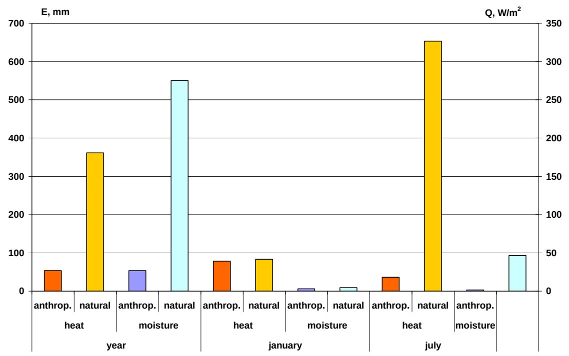


Figure 5. Total anthropogenic heat and moisture flows in Moscow in 2015 as compared to natural evaporation *E* and solar radiation *Q*.

A comparison of the anthropogenic and natural components of heat and water balance in the urban atmosphere (Figure 5) shows that on the annual scale the anthropogenic heat accounts for only 15% of the mean solar radiation Q, and the evaporation of water from the technological sources accounts for less than 10% of the natural evaporation E calculated according to [14] from the mean monthly values of air temperature T_m and humidity w_m [15] by the equation

$$E = 0.0018 \cdot (25 + T_m)^2 \cdot (100 - w_m)\,. \qquad (2)$$

However, for January these shares reach 95% and 67%, respectively. In summer the direct impact of the urban technosphere on the heat and water balance is negligibly small (3-5% of the natural components).

5. Conclusions

A simple technique for the calculation of spatial-temporal distributions of anthropogenic heat and water flows in urbanized areas using standard urban energy information is presented. The case study of Moscow has shown that man-made sources are essential elements of heat and water balance of urban atmosphere, especially in winter. About 30% of the total annual heat flux that is distributed almost evenly over the year comes to the soil. The annual anthropogenic heat and water vapour fluxes in Moscow are nearly an order of magnitude less than the regional norms of solar radiation and natural evaporation, respectively, but in winter the magnitude of anthropogenic and natural fluxes is comparable.

Acknowledgments
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