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Nina V. Dudorova, Boris D. Belan, "The role of evaporation and condensation of water in the formation of the urban heat island," Proc. SPIE 11208, 25th International Symposium on Atmospheric and Ocean Optics: Atmospheric Physics, 112088J (18 December 2019); doi: 10.1117/12.2547941

Event: XXV International Symposium, Atmospheric and Ocean Optics, Atmospheric Physics, 2019, Novosibirsk, Russian Federation

The role of evaporation and condensation of water in the formation of the urban heat island

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ABSTRACT

The effect of the latent heat flux on the urban heat island formation is estimated for Tomsk as an example. It is shown that the latent heat flux is close to zero in winter and takes negative values in summer, reducing the urban heat island intensity.

Keywords: Urban heat island, evaporation, latent heat flux, temperature, humidity

1. INTRODUCTION

According to works [1–3], one of the most significant factors which form an urban heat island (UHI) is a decrease in the heat consumption for water evaporation in a city as compared to background region. The heat flux associated with phase transitions of water is often called the latent heat flux (Q_E) in the literature. The presence of water on the underlying surface and the water vapor content in the atmosphere are the determining factors for Q_E formation. According to Landsberg G.E. and Oke T.R. [1, 2], the daytime Q_E value which characterizes the heat consumption for evaporation is very high in vicinities of a city and is negligible in the city. During the nighttime, there is no difference between Q_E in a city and its suburbs. Christen A. [3] have shown that average daytime Q_E values amounted to 22% of the expenditure part of the heat balance in a city, and 60%, in adjacent territories.

The aim of this work is estimation of the effect of latent heat flux on the formation of the urban heat island.

2. MATERIALS AND METHODS

The study was carried out in 2004-2005 on the territory of Tomsk, Russia. Tomsk is an administrative center of the Tomsk region, located in the south of Western Siberia, on the right bank of the Tom river. The area of the city is 294.6 km²; the population is 490 000 people (2004-2005) [4]. Tomsk is a typical city of central Russia in terms of its physical-geographical and social-economical characteristics. The time period 2004-2005 was quite typical for Tomsk climate in terms of meteorological parameters [5].

The heat flux from water evaporation and water vapor condensation was calculated by the equation [0, 0]:

$$Q_E = -L \rho k \frac{\partial s}{\partial z} \quad (1)$$

Here L is the specific heat of evaporation, [J/kg]; ρ is the air density, [kg/m^3]; k is the turbulence factor, [m^2/s]; ∂s/∂z is the vertical gradient of the specific air humidity, [g/kg].

The turbulence factor is calculated by the equation [0]:

$$k = \chi^2 z \frac{\Delta u}{ln\frac{z_1}{z_2}} \left[1 - \frac{hg}{T} \frac{\Delta\theta}{(\Delta u)^2} \frac{(ln\frac{z_1}{z_2})^2}{\ln(\frac{z_3}{z_4})} \right] \quad (2)$$

where Δu is the difference in the wind speed at altitudes z_1 and z_2; $\Delta\Theta$ is the difference in the potential temperatures at altitudes z_3 and z_4; z is the altitude between z_1 and z_4, where k is calculated; h = 30 m is the surface air layer height; g is the gravity acceleration; T is the absolute air temperature; χ = 0,38 is the dimensionless Karman constant.

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25th International Symposium On Atmospheric and Ocean Optics: Atmospheric Physics, edited by
Gennadii G. Matvienko, Oleg A. Romanovskii, Proc. of SPIE Vol. 11208, 112088J

Meteorological parameters (air temperature and humidity and wind speed) in the surface air layer usually change with altitude in proportion to the altitude logarithm [0]. Therefore, the potential air temperature gradient can be expressed as

$$\frac{\partial\theta}{\partial z} = \frac{1}{z}\frac{(\theta_1-\theta_2)}{\ln(z_1/z_2)} \tag{3}$$

where Θ_1 and Θ_2 are the potential temperatures at altitudes z_1 and z_2, respectively; z is the altitude between z_1 and z_4, where the gradient Θ is calculated.

The potential temperature is calculated by the standard formula [0]. In the lack of pressure measurements at required altitudes, the following equation was used:

$$P = P_0\, exp\left(-\frac{gz}{R_c T}\right) \tag{4}$$

where P_0 is the surface air pressure.

To estimate the amount of moisture released during the combustion of all fuel in the city, the following technique was used. As is known, a certain amount of water vapor is emitted into the atmosphere during combustion of all fuel types in the city. The hydrocarbon combustion reaction can be generally written as [0]:

$$\mathrm{C_m H_n} + \left(\mathrm{m}+\frac{\mathrm{n}}{4}\right)\mathrm{O_2} = \mathrm{nCO_2} + \frac{\mathrm{n}}{2}\mathrm{H_2O} + heat \tag{5}$$

where *m and n* are the numbers of carbon and hydrogen atoms in a molecule.

The relative contents of different hydrocarbons in different fuel types (benzene, natural and liquefied gas) are given in Table 1, along with the mean fuel composition found based on reference sources (equivalent fuel).

Table 1. (Mass) percentage of different hydrocarbons in different fuel types

Hydrocarbon	**Chemical formula**	**Equivalent fuel, %**	**Petrol,%**	**Natural gas, %**	**Liquefied gas, %**
Methane	CH_4			94	
Ethane	C_2H_6			2	
Ethylene	C_2H_4				
Acetylene	C_2H_2				
Propane	C_3H_8				90
Propene	C_3H_6			2	
Butane	C_4H_{10}	4		2	10
Pentane	C_5H_{12}	23			
Hexane	C_6H_{14}	28			
Heptane	C_7H_{16}	11	10		
Toluene	$C_6H_5CH_3$	10			
Octane	C_8H_{18}	12			
Xylene	$C_6H_4(CH_3)_2$	8			
Nonan	C_9H_{20}	2.5			
Decane	$C_{10}H_{22}$	1.5			
Isooctane	C_7H_{15}		90		

If the hydrocarbon percentage in fuel is known, the amount of water evaporated during combustion of a fuel mass unit can be calculated using Eq. (5) (Table 2).

Table2. Average molar mass of different fuel types and the amount of water vapor W_Z released from combustion of a fuel mass unit.

	Equivalent fuel, %	**Petrol,%**	**Natural gas, %**	**Liquefied gas, %**
Average molar mass	90.65	99.1	17.68	47.6
W_Z, mass unit of fuel	1.33	1.37	2.16	1.97

Based on data in Table 2, it was found that 2.16 mass units of water vapor are released from combustion of a mass unit of natural gas; this amount is equal to 1.97 for liquefied gas and 1.37 for benzene. The amount of water evaporated from the combustion of other fuel types was taken equal to 1.33 mass units.

The data on the amount of fuel consumed by small and large enterprises and motor transport in Tomsk were provided by Tomskoblstat [0].

The absolute moisture released air from the combustion of all fuel types in Tomsk (a_{fuel}) was calculated on the basis of the above technique and data on horizontal and vertical sizes of UHI in Tomsk [0].

The absolute air humidity in the city (a_{urb}) and in a background region (a_{rur}), as well as the heat flux from the water evaporation and water vapor condensation (Q_E) were calculated on the basis of meteorological parameters measured at the TOR station [0], with an AKV-2 mobile station [0], and at the BEC observatory [0].

3. RESULTS AND DISCUSSION

Figure 1 shows the heat flux from water evaporation and condensation calculated for Tomsk suburbs. The monthly average maximum of the heat flux is 90–100 W/m^2; it falls to the warmest month July, which is characterized by maximal specific air humidity. Data of the similar study for Lodz (Poland) [0] are also given in Fig.1 for the comparison

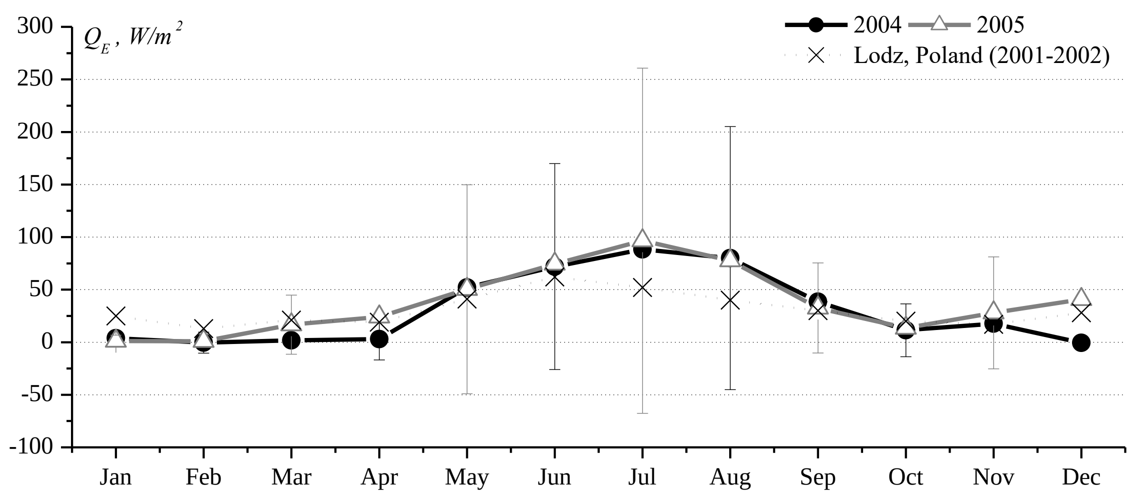

Figure 1 – Annual variation in the latent heat flux near Tomsk in 2004-2005

To estimate the effect of Q_E on the UHI formation, it is necessary to subtract the value of the latent heat flux near Tomsk Q_E^{rur} from that in the city Q_E^{urb}:

$$\Delta Q_E = Q_E^{urb} - Q_E^{rur} \tag{6}$$

It was impossible to calculate the latent heat flux inside the city. Therefore, we used an approximate equation based on the calculation of the absolute air humidity using direct measurements of meteorological parameters in Tomsk and in a background region. Then,

$$\Delta Q_E = Q_E^{rur}((\mathrm{a}_{\mathrm{rur}} - \mathrm{a}_{\mathrm{urb}}) / \mathrm{a}_{\mathrm{rur}}) \quad (7)$$

Figure 2 shows the annual variations in the absolute air humidity in the background region near Tomsk, the difference between the air humidity in Tomsk and in the background region, and the moisture released in air from the combustion of all fuel types in Tomsk. All the parameters were averaged over two year (2004 and 2005). It is seen that the difference in the air humidity is always positive in the warm season. Therefore, it is possible to assume that the amount of heat consumed for water evaporation in Tomsk is larger than out of the city. This is confirmed by the difference between the latent heat fluxes in the city and in the background region shown in Fig. 3.

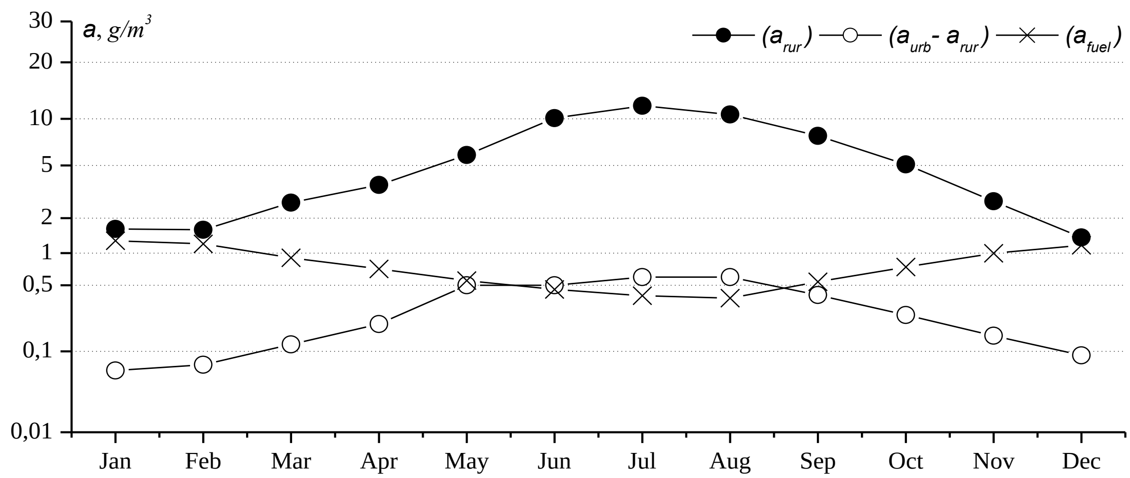

Figure 2 – Annual variations in the absolute air humidity in the background region near Tomsk (a_{rur}), the difference between the absolute air humidity in Tomsk and in the background region ($a_{urb} - a_{rur}$), and absolute moisture released in air from combustion of all fuel types in Tomsk (a_{fuel}).

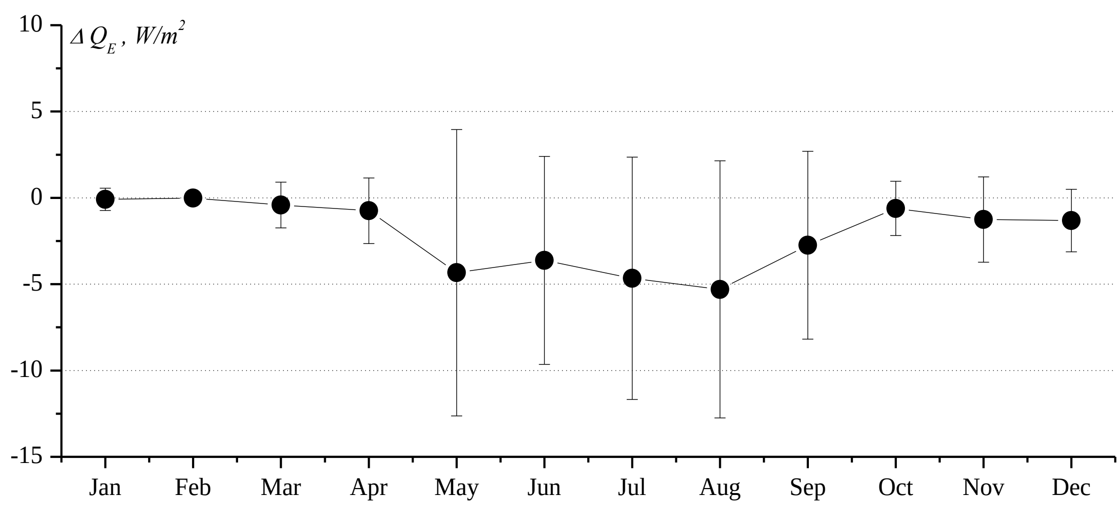

Figure 3 – Dynamics of the difference in the latent heat fluxes in Tomsk and its suburbs.

The heat consumed for water evaporation in Tomsk is greater than outside in the warm season, which produced the cooling effect and somewhat reduces the UHI temperature in Tomsk. An increase in the air humidity inside the city relative to the background region in summer can be explained, first, by the presence of natural water bodies in the city, and second, by poor disposal of water.

The absolute difference in the air humidity between the city and its suburbs ($a_{urb} - a_{rur}$) is close to zero in winter (Fig. 2); the absolute humidity in the background region of Tomsk (a_{rur}) is almost equal to the moisture released during the combustion of all fuel types in the city (a_{fuel}) (Fig. 2). This is confirmed by the fact that there is no difference in heat consumption for evaporation between Tomsk and its suburbs in winter (Fig. 3).

4. CONCLUSIONS

Thus, the study performed allows a conclusion that the latent heat flux in the city, typical for central Russia, is not decisive, which is often noted in the literature; moreover, it can inversely affect, that is, it reduces the UHI intensity, though insignificant.

This work was supported by the Russian Science Foundation (Grant No. 17-17-01095 to 10.05.2017).

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