Influence of global warming and climate continentality on the Moscow urban heat island

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Abstract. The intensity of an urban heat island depends on the location, layout and development of the city, the number and density of its population, and the energy consumption of the urban economy. These dependencies can vary greatly from city to city. In recent years, more and more attention has been paid to the dependence of the city's climate characteristics on global and regional climate processes, their trends and variations. At present, there is no clear answer to the question of how climate changes affect the evolution of an urban specific city, since modern climate changes in different cases can both increase and decrease the intensity of the urban heat island. This work discusses the reasons some stabilization of the intensity of the Moscow heat island, observed in the second half of the XX century and early XXI century, and the relationship of this phenomenon with the weakening of continentality climate in the Moscow region.

1. Background
The temperature of atmospheric air in cities is simultaneously affected by local and regional meteorological processes, global climate change and its regional manifestations, as well as the size, layout and construction of the city, population density and energy consumption of the urban economy.

At present, the role of regional manifestations of modern climate change on the climate characteristics of specific cities is becoming more and more obvious. To study this impact, it is not enough to consider only the anthropogenic effects of urbanization. It is also necessary to consider the dynamics of the city's climate against the background of regional climate changes, changes in the climate continentality of the region where the city is located.

The previous publications described a negative correlation between the continentality index and the average annual air temperature in the Moscow region and the influence of the North Atlantic oscillation on changes in the continentality of the climate in Moscow. It is clear that the relationship between changes in urban, regional and global climate is fundamentally different at different time scales. It is also well known that the dynamics of the temperature regime in the first decades of the XXI century, not only in Moscow, but on a regional and even global scale, differs in a number of features compared to the second half of the XX century.
The recent meta-analysis of urban heat island (UHI) trends [1] detected positive trend in the most of 30 largest cities of the world during the period of 1960-2009. In contrast, the study of UHI trend in 54 US cities during the period of 2000-2015 [2] show that the difference in daily-minimum temperature between urban and rural stations tends to decrease with increasing temperature. Besides, simulations made by using an urban boundary layer climate model [3] coupled with output fields of global climate models show no significant difference in the air temperature changes in urban and rural areas [4]. The study of UHI trend in Moscow [5] show no significant difference between UHI intensity in 1954-1955 and in 1991-1997 in contrast to the positive trends during the period of 1960-2009 reported in [1], and show a sharp increase in UHI intensity in 2000-2014 compared to UHI intensity in 1991-1997 in contrast to the study of UHI trends reported in [2].

The results of these studies shown that there is no general answer to the question about the climate change impact on the UHI intensity. It could be either positive or negative depending on the city under study. Since UHI quantifies warming in a relative sense -- as the difference between urban area and its surroundings –the geophysical properties of the city surroundings may determine UHI response to climate change.

The most noticeable changes in the Moscow heat island intensity, that is, in the difference between the air temperature in the city and in its surroundings, were manifested in the second half of the XX century, when there was a stabilization of the intensity of the urban heat island due to the transition to less continental regional climatic conditions.

Recent studies of the centennial changes of the Moscow heat island intensity, among which should be noted the works of the Geographical faculty of M.V. Lomonosov Moscow State University, describe the phenomenon of "quasi-stabilization" of the intensity of the Moscow heat island in the second half of the XX century. In detail this phenomenon discussed in [5]. In this article, as well as in other studies (see for example [6]), the problems of a clear assessment of the average city (urban) and surrounding area (background) air temperature, which occurs in connection with various conditions for the placement of meteorological stations in the city and beyond, are discussed in detail.

This challenge is addressed in this paper by comparing the air temperature changes in Moscow to the changes in the surface air temperature averaged over the central part of Russian plain surrounding the Moscow. Considering Moscow’s UHI evolution from this new perspective hopefully stimulates the discussion of the physical mechanisms staying behind the UHI response to climate change.

2. Methods

To represent the climate changes in the Moscow’s urban area, the time series of monthly temperature in Moscow (WMO code: 27612) was taken from the GHCN dataset [7]. The time series of the mean annual temperature (MAT) calculated from these data were transformed into the time series of 30-year MAT moving average (MAT$_{30}$) to highlight the urban MAT trend (Fig. 1).

The times series of MAT$_{30}$ highlighting the trend “background climate” changes, was derived from the Global Soil Wetness Project phase 3 data set (GSWP3; http://hydro.iis.u-tokyo.ac.jp/GSWP3/). The GSWP3 data set, which is widely used in the analysis of regional climate processes (see, for example, [8, 9]), is based on reanalysis data from the Climate Research Unit (http://www.cru.uea.ac.uk/data), and provides the information about monthly air temperature, monthly precipitation, and some other climate variables in a well-structured way on a 0.5 by 0.5° grid for the period of 1901-2010.

The GSWP3 data on monthly air temperature at 0.5° grid are used in this research. Averaging MAT$_{30}$ values that fall within a rectangle surrounding the Moscow and covering the central part of the Russian Plain located between 51 - 59°N and 31 - 42°E gives the time series of MAT$_{30}$.

Since the time series of MAT$_{30}$ represents the background MAT trend with accuracy to a constant, the difference between the MAT$_{30}$ and MAT$_{30}$ represents the UHI trend ($\Delta$T) also with accuracy to a constant.
3. Results and discussion

The time series of $\Delta T_{u,30} - \Delta T_{b,30} + c_0$, where $c_0$ is set 0.5°C, show the course of $\Delta T$ increase above some reference level (Fig. 2). Since the reference level is arbitrary, the absolute values of $\Delta T$ are also arbitrary. The curve representing the time series of $\Delta T + c$, where $c$ is an arbitrary constant show only stabilization of $\Delta T$ in the second half of the XX century, not the absolute value $\Delta T$. Strictly speaking, the absolute value of $\Delta T$ cannot be known for sure, because the information about Moscow’s pre-urban climate is lacking.

The information presented at Fig. 2 tells that $\Delta T$ increased by 0.5°C approximately during the XX century, that the major part (0.3°C) of this increase happened between 1920 and 1965, that the rate of $\Delta T$ growth had dramatically reduced after 1965, and that $\Delta T$ growth seemingly has stopped.

These results agree, in general, with the results of the study carried out by Lokoshchenko [5], who did not find significant difference between UHI intensity in 1954-1955 and in 1991-1997 and arrived at a similar conclusion about $\Delta T$ stabilization by the end of the XX century. The reported sharp increase in UHI intensity in 2000-2014 compared to UHI intensity in 1991-1997 [5] may possibly manifests itself in the rising tail of the $\Delta T$ curve (Fig. 2): the mean value of $\Delta T$ for the period of 1981-2010 exceeds the mean value of $\Delta T$ for the period of 1971-2000 by 0.07°C.

The novelty of this research is the use of a large region for estimating the background MAT. This makes it possible to discuss $\Delta T$ stabilization with respect to the changes in the large-scale atmospheric circulation.

It seems very natural to explain $\Delta T$ rise and stabilization by the rise and stabilization of urbanization processes, but one cannot simply ignore the shift towards less continental climate observed in Moscow after 1950 [10]. This shift is partly explained by the positive phase of North Atlantic Oscillations (NAO), which in its turn is an indicator of intensified heat exchange between the Atlantic Ocean and European continent [11]. Another mechanism is the radiative forcing induced by the rise of the atmospheric carbon dioxide concentration in the atmosphere [12-13]. Both mechanisms are capable to reduce the UHI intensity.
The UHI intensity depends on the depth of urban boundary layer [14]. The heat emitted by urban surfaces is trapped inside the urban boundary layer and increase its temperature. The increase in temperature depends on the heat capacity of the urban boundary layer which is largely determined by its depth. Due to this reason, the UHI intensity is also sensitive to the large-scale atmospheric phenomena that influencing the depth of planetary boundary layer and the frequency of forming a stable stratification within the boundary layer.

4. Conclusions
This study further highlights the Moscow’s UHI stabilization, reported earlier by Lokoshchenko [5] using an independent method for calculating the changes in the Moscow’s UHI intensity. The novel element of this study is the use of a large region, the central part of Russian plain surrounding the Moscow, for calculating historical changes in the Moscow’s background climate. Defining the background climate is a starting point for any assessment of the climatic effects of urbanization. The use of such a large region for calculating the changes in the background climate facilitates the discussion of the possible effects of climate change and natural variability in atmospheric circulation on the evolution of Moscow’s UHI and leads to some hypothesis for testing with climate models.

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