Urban heat island of the Moscow megacity: the long-term trends and new approaches for monitoring and research based on crowdsourcing data

M I Varentsov1,2,3, P I Konstantinov1, N V Shartova1, T E Samsonov1,2,3, P E Kargashin1, A I Varentsov1, D Fenner4, F Meier4

1 Lomonosov Moscow State University, Research Computing Center / Department of Geography, Moscow, Russia
2 A.M. Obukhov Institute of Atmospheric Physics, Moscow, Russia
3 Hydrometeorological Research Center of Russia, Moscow, Russia
4 Technische Universität Berlin, Institute of Ecology, Chair of Climatology, Berlin, Germany

E-mail: mvar91@gmail.com

Abstract. This paper reports on various aspects of the urban heat island (UHI) of the Moscow megacity – its spatial and temporal variability and linkages with human thermal comfort. Firstly, we analyze long-term trends of air temperature, UHI intensity and thermal stress indices based on meteorological observations over the period 1977-2018. We show that the city exhibits 40% higher rates of summertime climate warming than the countryside, as well as higher rates of human thermal comfort deterioration. Secondly, we present a new approach for spatially-resolving urban climate studies and real-time monitoring applications based on the usage of crowdsourced air temperature data from Netatmo citizen weather stations (CWSs). The CWSs provide uncertified and often misrepresented data. However, their quality could be controlled by application of statistically-based algorithms. Additionally, we have experimentally evaluated uncertainties of the Netatmo temperature observations and regard them to be acceptable for UHI studies. Observations from more than 1500 CWSs as well as reference observations were used to analyze spatial patterns of the summertime nocturnal UHI. Both types of data shown an UHI covering the whole city and its suburbs, with a tendency of a temperature decrease with the distance from the city center. As a prototype a monitoring application, based on CWS data, we developed a web-service for real-time temperature mapping in Moscow, which is available at http://carto.geogr.msu.ru/mosclim/.

1. Introduction
The warm temperature anomaly, known as an urban heat island (UHI), is a well-known feature of urban climate. It is caused by several factors, including the thermal properties of urban surface, evaporation differences between urban and rural landscapes, anthropogenic heat emissions, etc. [1].

Nowadays, urban climate studies receive a significant public and scientific attention due to the noticeable impacts of the UHI and other urban climate features on the ecosystems, economy and...
human well-being. The most striking example of such impacts is associated with a deterioration of the thermal comfort, amplification of heat-stress hazards [2,3], and even increase of heat-related mortality in the cities [4,5]. The urban climate issues are strongly linked with climate change problems, because the UHI intensification could speed up the climate warming [6]. Regional climate simulations predict a more rapid increase in the heat stress repeatability in cities compared to rural areas under the expected climate warming of the 21st century [7].

The specific feature of urban environment is the high microclimatic diversity [1]. This determines the need for spatially-resolving urban climate studies, aimed to the investigation of the driving factors shaping the observed temperature heterogeneity. Detailed observational data, which is required for such studies, could be obtained from the so-called urban meteorological networks [8]. Dense urban observations are also needed for verification of numerical models and remote sensing products [9] as well as for monitoring applications. However, deployment of the urban meteorological networks is expensive and complicated, therefore such networks exists only in a few dozens of cities around the world [10]. Many cities are not covered by representative observations at all, because the weather stations of the national weather services are usually located outside of the urban areas [11,12].

Emerging alternative to the specialized observational networks is a concept of crowdsourcing, which proposes using the data generated by amateurs and enthusiasts. In the age of the “Internet of things”, the crowdsourcing concept includes data collection from public sensors and devices, which are connected to the Internet, including the so-called citizen weather stations (CWSs) [13,14]. A significant problem in using the CWS data for scientific and practical applications is inability to explicitly control the quality and representativeness of the observations. This problem still holds back the massive use of the CWS data in meteorology. However, several pioneering studies have already demonstrated effectiveness of statistically-based algorithms to filter out misrepresentative observations [15,16] and to use the quality-controlled CWS data for urban climate studies [15,17,18] as well as for improvement of the numerical weather forecasts [19].

Presented study continues the series of researches, devoted to the investigation of the UHI of Moscow, the biggest European megacity with population of 16-17 million people and built-up area about 1000 km². Due to the size, location within a flat and homogeneous terrain and relatively symmetric city shape, Moscow is almost perfect research object for urban meteorology and climatology. The city has already served as a test-bed for numerous urban climate studies, based on observations, regional climate modelling and remote sensing data, see e.g. [6,9,20–22]. The number of recent studies has revealed the long-term trends of UHI intensification during XX century [21,23] and the so-called urban amplification of climate warming [6]. However, a number of questions about Moscow UHI still require a further research, including the seasonal inhomogeneity of observed climatic trends and their significance for human well-being. As many other cities, Moscow lacks the spatially-resolving urban climate studies and publicly available real-time monitoring services.

Our study follows two aims. The first one is to provide the latest information on the long-term dynamics of rural and urban temperatures and UHI intensity in Moscow region with a focus on summer and winter seasons, and to analyze the significance of the observed trends in terms of the thermal stress repeatability. The second aim is to present the new approaches for investigation and real-time monitoring of the UHI effect and its spatial heterogeneity, based on the use of the CWS data.

2. Data and methods

2.1. Official weather observations in Moscow region

2.1.1. The long-term observations. The Moscow region is covered by a quite dense network of certified weather observations, which are carried out by the Russian hydrometeorological service (Roshydromet) and other agencies. For the assessment of climatic trends, we use the long-term meteorological observations from 12 weather stations, available at 3-hour intervals. Three weather stations represent the urban climate. The Balchug station (WMO ID 27605) is located in a densely
built area just in the city center. The VDNKh station (WMO ID 27612) and the meteorological observatory of Lomonosov Moscow State University (LMSU, WMO ID 27617) represent the urban parks. Location of these three urban stations is given in Figure 3b. To characterize the rural conditions, we used the data for 9 stations surrounding the city following methodology from the previous studies [21], namely Klin (WMO ID 27417), Dmitrov (WMO ID 27419), Pavlovsky Posad (WMO ID 27523), New Jerusalem (WMO ID 27511), Naro-Fominsk (WMO ID 27611), Serpukhov (WMO ID 27618), Kolomna (WMO ID 27625), Maloyaroslavets (WMO ID 27606), Aleksandrovo (WMO ID 27428). Due to the data availability, the period of 1977-2018 was selected for the analysis of climatic trends.

2.1.2. Denser reference observations for recent period. More observational data is available for recent years. New weather stations, including the automatic ones (AWSs) were set up in Moscow region in 2010s. Additionally, the network of automatic air-quality stations (AAQS) of Mosecomonitoring agency is developing since 1990s. The AAQSs do not fully satisfy the meteorological standards, but provide reasonable daily-mean and nocturnal air temperature values [21]. In total, nowadays there are more than 70 sites of the official meteorological observations in the Moscow region, which we use in our study. Further details on the used dataset are given in [9, 21].

2.1.3. The UHI intensity. In the both parts of the study, we define the UHI Intensity (UHI) as a temperature anomaly ($\Delta T$) with respect to the mean rural value, averaged over 9 selected rural stations: $\Delta T = T - \frac{1}{n} \sum_{i=1}^{n} T_i$, where $T$ is temperature at any certain station, $T_i$ is temperature at the each of the rural stations, $n = 9$ is a number of selected rural stations.

2.2. Thermal stress indices
Numerous indices have been developed in order to assess degree of human thermal sensation based on meteorological measurements [24]. In current study, we performed the calculation of two popular empiric indices based on long-term time series in order to estimate, how the observed trends are reflected in terms of thermal comfort conditions. We used the Heat Index (HI) to evaluate the heat stress in summer and the Wind Chill Temperature (WCT) to evaluate the cold stress in winter. The description of these indices and corresponding equations is given e.g. in [24]. The repeatability of hours with different thermal stress gradations according to [24] was calculated for each year and further used for the linear trend analysis.

2.3. Crowdsourced data from Netatmo CWSs
The novel part of our study is an attempt to use a crowdsourcing data from the CWSs to study the UHI spatial patterns and to develop a cartographic web-service for real-time temperature and UHI monitoring. We use CWS observations from Netatmo network (www.netatmo.com). The Netatmo personal weather stations are mass-market devices which are used by people to observe weather conditions at the places of their living. Basically, observations of the atmospheric pressure, temperature and humidity are available. The CWSs are connected to Wi-Fi and transfer observations to the central server. The data could be obtained from the server in real time using Netatmo Weather API (Application Programming Interface). Nowadays, there are thousands of Netatmo CWS in big European cities such as Paris and Berlin, and more than 1500 in Moscow region.

2.3.1. Experimental study on the temperature observation uncertainties of Netatmo CWS. The Netatmo CWSs provide uncertified observations which could be misrepresentative due to many reasons. For example, the CWSs could be installed by the users at the overheated roofs or walls or even inside the buildings [15]. Beyond these extreme cases, other typical ways of CWS installation could be far away from the standards of meteorological observations. Additionally, the sensors could be affected by instrumental biases and drifts. In order to investigate the possible uncertainties of Netatmo observations, a special experiment was carried out at the LMSU meteorological observatory. The description and results of the experiment are given in section 3.2.
2.3.2. Data collection. To obtain the CWS data for Moscow region, we use the software packages, developed in Technische Universität Berlin (TUB), and in Lomonosov Moscow State University (LMSU). The both packages are based on sending the regular repeated requests to the ‘getpublicdata’ method from Netatmo API [15]. The data set, collected by TUB, was used for the analysis of the UHI spatial patterns (see section 3.3). It was obtained for the area, limited by 36.4 and 39 °E, 54.8 to 56.6 °N, for a warm and hot period of June 2019, and includes the data for 1730 unique CWSs. The CWS data was collected with 1-hour temporal resolution, but we further use the data on same 3-hour time intervals as for the reference data. The software, developed by LMSU, is running since the October 2019 and collects the data which is further used by the web-service for a real-time temperature and UHI monitoring and mapping (see section 3.4).

2.3.3. Quality-control and filtering the CWS data. The quality-control and filtering out the misrepresentative data are the essential parts of the work with CWS data. We used a quality control algorithm, based on the ideas from the previous study for Berlin [15] with some modifications. The algorithm is still under development and testing, so we present only a short description here and will publish a complete one in the next studies. At the first stage, the algorithm removes the CWSs with exactly same location (assuming that the location was wrongly defined using the IP address). At the second stage, the CWSs with the missing data ratio over a given value are removed, which gives us L0 data. At the third stage, the mean temperature \( \overline{T} \) and temperature standard deviation \( \sigma(T) \) are calculated for all CWSs as well as for reference observations (weather stations and AAQs). The ranges of acceptable \( \overline{T} \) and \( \sigma(T) \) values are defined based on the reference observations within the study area. Next, CWSs are rejected for which \( \overline{T} \) or \( \sigma(T) \) values are outside the acceptable range, which gives us L1 data. Such approach allows rejecting the CWSs with the outdoor module located inside as well as partially eliminate cases when the outdoor module is not shaded properly. At the fourth stage, the CWS temperature observations are analysed for each time step, and the values outside the acceptable range (defined according to reference data) are rejected. Finally, the CWS with too high ratio of rejected values are completely excluded from the data set, and L2 data is obtained.

3. Results and discussion

3.1. Long term trends of air temperature, UHI intensity and thermal heat stress repeatability

Long-term observations for 1977-2018 period show the warming trends both for summer (June-August) and winter (December-February) seasons (Figure 1a,b), which is consistent with numerous previous studies. For the countryside, the warming speed, characterized by a linear trend coefficient, is higher in winter than in summer (0.65 °C/decade vs 0.54 °C/decade). However, the winter temperature trends are less significant than summer ones due to a higher inter-annual variability in winter.

The urban weather stations exhibit the UHI effect, which is most pronounces at the city center. The annual-mean UHII for Balchug weather station for the recent decade since 2010 is 2.05 °C, the mean summer value is 2.53 °C and mean winter value is 1.84 °C. The UHII for urban parks is more than twice lower in comparison to the city center, which is consistent with results from [23]. The trend of UHI intensification is clearly observed in summer (Figure 1c). It amplifies the summer warming for the city center by additional 0.23 °C/decade or by 42% in comparison to rural areas. The urban parks also exhibit amplified warming, however the rates of UHI intensification are much lower in comparison to the city center. The rates of the UHI intensification in the center of Moscow are the same order of magnitude as in Beijing [25] and are higher than in London [26] and New-York [27]. However, the winter UHII does not exhibit noticeable trends (Figure 1d).
Figure 1. The variation of the mean summer (a) and winter (b) temperature, mean summer (c) and winter (d) UHII, the repeatability of hours with moderate or stronger heat stress in summer according to HI index (e) and the repeatability of hours with high or stronger cold stress in winter according to WCT index (f) for rural and urban weather stations in Moscow region during 1977-2018. The linear trends are shown by dotted lines for each urban weather stations and for the mean rural value, averaged over 9 rural stations. The liner trend coefficients (k, °C/decade or %/decade) and trend determination coefficients (R^2) are given in the legend for each plot.

A detailed analysis, presented in [21], suggested that the observed UHII trends are caused by the combined effect of the urban growth and the climate change. The population of the city has almost doubled during the analyzed period (only the population of the Moscow city has increased from 7.8 to 12.5 million people, excluding the population of satellite cities and labor migrants). The urban sprawl
mostly took place outside the historical city center, where Balchug station is located, however the recent modelling study suggested that such development has also the non-local effects in the city center [22]. The repeatability of calm and clear weather conditions, which are favorable for the UHI appearance [1], has increased in summer under the climate change processes, which has additionally amplified the UHI. In winter, on contrary, the repeatability of favorable conditions has decreased, which has compensated the effect from urban growth.

In this paper, we for the first time attempt to estimate how the temperature and UHII trends in Moscow are reflected by thermal stress repeatability. For summer, we consider the repeatability of hours with moderate or stronger heat stress according to HI index (HI > 27 °C), which shows positive trends during the analyzed period (Figure 1e). The urban weather stations exhibit a higher heat stress repeatability and higher rates of its growth. For the city center, the heat stress repeatability for the recent decade (2010-2018) is almost twice higher than mean rural value (13.0% vs 7.3%) as well as the linear trend coefficient (2.36 vs 1.38 %/decade). For winter season we consider the repeatability of hours with high or stronger cold stress according to WCT index (WCT < -28 °C), which shows decreasing trends. The cold stress repeatability in the city center is more than twice less than in the countryside, however the urban-rural difference is decreasing (1.6% vs 4.0% for 1977-1986 period; 0.5 vs 1.4% for the 2010-2018 period). Since the potential of the UHI to mitigate the winter cold stress is weakening, while the urban-induced amplification of the summer heat stress is further growing, the overall UHI impact on the human thermal comfort is worsening. In future studies we will further investigate the revealed trends using more comprehensive biometeorological indicators.

3.2. Uncertainties of temperature observations by the Netatmo CWSs
Threatening results from the previous sub-section highlight the need for more comprehensive spatially-resolving urban climate studies as well as for improvements of the monitoring systems which are responsible for warning the heat stress danger. We consider an opportunity to use the crowdsourcing data from Netatmo CWS for both of these tasks and start with experimental assessment of the uncertainties of the Netatmo temperature observations.

The first part of the experiment was aimed to the evaluation of the instrumental uncertainties. Ten outdoor modules were placed inside the Stevenson screen at the observational ground of the LMSU meteorological observatory (Figure 2a) for 19 days in May-June 2019. The Netatmo temperature observations were compared with reference measurements by Vaisala AWS310. The comparison has shown that the instrumental uncertainties of Netatmo temperature observations correspond to the accuracy declared by the manufacturer (±0.3 °C). The mean temperature bias was almost zero (0.02 °C) and the mean RMSE was 0.45 °C. The RMSE did not exceed 0.6 °C for each among 10 CWSs and the bias did not exceed 0.3 °C.

The second part of the experiment was aimed at the evaluation of the uncertainties induced by outdoor module placement conditions. Ten modules were placed at different sites within the territory of the meteorological observatory in order to simulate the typical ways of their installation by users (Figure 2b). The first one was placed at the top of fifteen-meter tower. Modules 2 to 5 were installed at the building walls. Module 6 was installed at the building roof. Modules 7 and 8 were attached to a branch of a small tree and to a metal pole correspondingly, at the 2-meter height. Module 9 was installed at the shaded (northern) side of the Stevenson screen, and module 10 was kept inside the screen. Netatmo-produced observations in 10 sites were compared with reference data for the period from 7th of June to 3rd of August 2019. Results revealed that the unshaded outdoor modules are strongly overheated at the daytime (Figure 2c). The highest daytime biases are observed for the modules installed at the walls (no. 2 – 5), on the roof (no. 6) and at the metal pole (8). However, at night the mean biases converge to zero with only exception for the module no. 8. There is no dependence between nocturnal Netatmo temperature biases and the UHII (Figure 2d), which means that for the cases with a pronounced UHI the uncertainties of Netatmo temperature observations become less significant in comparison to the magnitude of the analyzed phenomenon.
Figure 2. Set-up of 10 Netatmo CWS in the Stevenson screen during the first part of the experiment (a); the scheme of the CWS location in the LMSU meteorological observatory during the second part of the experiment (b); diurnal variation of mean temperature bias ($\Delta T_{\text{netatmo-reference}}$) for 10 outdoor modules during the second part of the experiment (c); the boxplot, which shows the temperature biases for the CWSs no. 1 – 9 for the nocturnal hours (21-03 UTC), separated by the groups according to UHII values for the Balchug weather station (d).

3.3. Investigation of the spatial patterns of the Moscow UHI using the CWS data

We attempted to use the CWS data for the analysis of the spatial patterns of the Moscow megacity UHI with a principally new level of detail. We performed the analysis for June 2019, when the prevailing weather conditions were hot, dry and when there was a lot of days with intensive UHI. Among the 1720 CWSs available for this period, only 500 or 29% passed through the quality-control routine as L2 data (Figure 3a). The observations from 42 weather stations and 48 AAQS within the study area were used as reference data.

Following the results from the section 3.2, we selected 60 nocturnal cases (21-3 UTC) with the pronounced UHI, when UHII for the Balchug weather station exceeded 4 °C. The spatial distribution of the mean temperature anomaly, calculated with respect to the mean rural value (see section 2.1) and averaged over selected cases, is shown in Figure 3b. Both types of data clearly demonstrate the persistent warm anomaly over the whole Moscow city and its suburbs as well as the intra-urban temperature heterogeneity. For example, the urban parks (e.g. VDNKh and MSU sites) are cooler than surrounding built-up areas but still warmer than the countryside. With rare exceptions, the highest temperatures are found in the city center. Further, a tendency of temperature decrease with distance from the center is observed against the background of local heterogeneity, which explains the one half of the observed spatial variation (Figure 3c). Similar dependency was previously revealed for other summer and winter seasons based only on the reference data [21]. In further studies the CWS data will allow more detailed analysis of the factors producing the observed UHI spatial patterns.
Figure 3. The time-series of the air temperature according to the Netatmo observations in Moscow and surroundings at the quality levels L0, L1 and L2 together with minimum and maximum reference temperatures (a); the mean temperature anomaly, averaged over selected nocturnal cases, for weather stations (big circles), AAQSSs (squares) and CWSs (small circles) (b); the dependence between the temperature anomaly and the distance from the city center (c).

3.4. The web-service for real-time temperature monitoring and mapping using the CWS data

In addition to the theoretical studies, the crowdsourced data from Netatmo network could be used for practical applications, including the real-time monitoring services. In order to demonstrate such possibility, we developed a prototype of the web-service for real-time temperature monitoring and mapping for the Moscow region. The service combines the software for the automated collection of the Netatmo and Roshydromet observations (the later are obtained from the website www.pogodaiklimat.ru), the SQLite database; pre-processing tools including the module for the quality control of Netatmo data; visualisation tools based on Geoserver software and a user interface. The service is available in the Internet at http://carto.geogr.msu.ru/mosclim/. The current version shows the air temperature. Further developments will include mapping of the other meteorological parameters and the real-time thermal comfort assessment, more sophisticated quality-control algorithms, spatial interpolation of the visualized variables, etc.

4. Conclusion and outlook

The presented work expanded the knowledge about the urban climate features of the Moscow megacity, presented the new approaches for urban climate research and monitoring based on the crowdsourced data and outlined the further research directions.

The analysis of the long-term trends was performed for air temperature and UHII based on the observations at urban and rural weather stations for period 1977-2018. The results revealed the tendency of UHI intensification in summer, which additionally increases the speed of climate warming.
in the city center by 0.23 °C/decade or by 42% in comparison to rural areas. In winter, on contrary, the UHII trend is not expressed. For the first time, we evaluated the temperature and UHII trends in terms of the thermal stress repeatability using the Heat Index for summer and Wind Chill Temperature for winter. We revealed the tendencies of increasing heat stress repeatability in summer and decreasing cold stress repeatability in winter. The summer excess of heat stress repeatability in the city further increases, the mitigating effect the UHI on cold stress in winter is weakening, which worsens the overall UHI impact on human thermal comfort.

The novel part of our study is the attempt to use the crowdsourcing data from the Netatmo CWSs to study the UHI spatial patterns. The CWSs provide uncertified and often misrepresentative data, however their quality could be controlled by statistically-based algorithms. Additionally, we have experimentally evaluated the uncertainties of the Netatmo temperature observations. We show that instrumental uncertainties correspond to the manufacturer’s specifications, but different typical ways of the outdoor module placement could result in huge biases at the daytime. However, such biases converge to zero at night, so the CWS data could be used for the spatially-resolving UHI studies in nocturnal conditions, especially for the cases with a pronounced UHI. We attempted to use the data from 1720 CWSs in Moscow region, as well as the high-quality reference observations to study the spatial patterns of the Moscow UHI for the summer conditions of June 2019. Both types of data have shown that UHI covers the whole city and its suburbs, with a tendency of a temperature decrease with a distance from the city center. Further investigations are needed in order to explain the driving factors of the observed temperature spatial inhomogeneity. In order to demonstrate a possibility to use the CWS data for monitoring applications, we have developed a prototype of cartographic web application for real-time temperature monitoring over the Moscow region, which shows observations at Roshydromet weather stations and Netatmo CWSs.

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