Citizen weather stations data for monitoring applications and urban climate research: an example of Moscow megacity

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Abstract. This study considers experience in use of crowdsourced meteorological observations from the world’s biggest network of citizen weather stations (CWSs), Netatmo, for urban climate research and applied monitoring services on the example of Moscow megacity. Crowdsourcing paradigm is an emerging alternative to the development of expensive urban meteorological networks. We have experimentally evaluated the uncertainties of the Netatmo temperature observations and regard them as being acceptable when the stations are shadowed from the sun. In order to filter out the misrepresentative observations, a quality-control algorithm has been developed. Within more than 1500 CWSs in the Moscow region, only about 25% meet this quality control, which is still one order of magnitude higher than the number of official Roshydromet weather stations in the study area. Such amount of data opens new opportunities for spatially-resolving urban climate studies and for applied services. As an example of the latter, we present a prototype of a web-mapping application for a near-real-time temperature monitoring system in Moscow. The application’s backend includes automatic services for downloading of observations from Netatmo and official Roshydromet networks, as well as for database maintaining. The processed data are visualized interactively in a web browser. The application is available on the Internet at http://carto.geogr.msu.ru/mosclim/. It will be further developed to include a real-time thermal comfort assessment based on the contemporary PET and UTCI biometeorological indices, a visualization of the interpolated fields, and other improvements.

1. Introduction

Modern trends in climate change, urbanization, as well as growing demands of the population for a comfortable and safe urban environment determine the growing relevance of applied research in the field of urban meteorology and climatology, including the development of special services that inform city services and the population about environmental conditions.

The urban climate differs significantly from the surrounding rural areas due to the urban heat island (UHI) effect and other micro- and mesoclimatic features [1]. The urban climate features affect the
conditions of thermal comfort and during heat waves may amplify the heat stress and increase associated mortality [2,3]. A specific feature of urban environment is high diversity of local climate and associated thermal comfort conditions [1]. This complicates the intra-city monitoring of meteorological conditions and obtaining of observational data necessary for fundamental urban climate studies, for verification of numerical atmospheric models and remote sensing methods, as well as for informing urban services and the population about environmental conditions. Such data may be obtained by establishing dense urban meteorological networks, but this requires significant financial and labor costs; therefore, such networks exist only in a few dozens of cities around the world [4].

The crowdsourcing paradigm, i.e. solving the problem by a network of volunteers, is an emerging alternative for developing specialized urban observational networks. In the era of the Internet of Things, crowdsourcing allows the use of data generated by Internet-connected devices, including so-called citizen weather stations (CWSs) [5,6]. The key challenge related with the use of CWS data is the inability to control the data quality and representativeness. However, a number of studies have already demonstrated the possibility of successfully applying statistical algorithms for quality control of such data [7,8] and the possibility of their use for studying urban climate [9], high-resolution temperature mapping [10], and improving numerical weather forecasts [11].

Our study aims at revealing the potential of the CWS data from the world’s biggest Netatmo network (https://www.netatmo.com/) for fundamental urban climate studies and applied services using the Moscow megacity as an example. The study considers different aspects of work with CWS data, and is structured as follows. The next section presents a developed software for data collection from the Netatmo network. Section 3 is devoted to the uncertainties of Netatmo CWS observations, a developed quality-control algorithm, and data application for urban climate research. Section 4 presents a prototype of web-mapping application for meteorological monitoring based on the use of CWS data. Section 5 discusses the plans and challenges with respect to further development of the application. The last section outlines conclusions to the paper.

2. Data access
The Netatmo personal weather stations are mass-market gadgets which are typically bought by people to observe weather conditions at their places of living in a smartphone. Netatmo CWSs consist of an indoor module that connects to Wi-Fi and transfers observations to the central server, and a number of wireless outdoor modules. The basic outdoor module measures temperature and humidity, and the indoor module measures atmospheric pressure. Additional modules for wind and precipitation measurements can also be used; however, they are sold separately and are very rare. Nowadays, there are thousands of Netatmo CWSs in big European cities, such as Paris and Berlin, and more than 1500 in Moscow region.

Observations of the Netatmo outdoor modules, if they are shared by their owners, are shown at Netatmo Weathermap (https://weathermap.netatmo.com/) and can be accessed by third-party applications using getpublicata and getmeasure methods of the Netatmo API (Application Programming Interface, https://dev.netatmo.com/). The getpublicata method returns the list of the CWSs for a given area, which are online at the moment of request, including their IDs, coordinates, other metadata, and the last measurements. The getmeasure method returns archived time series of a given station for a given period, but it is necessary to know the ID of this station. Thus, it is impossible to collect the archived data for a CWS which is currently offline when its ID is not known. Hence, the only reliable way to maintain the full archive of the CWS data is to call regularly the getpublicata method.

In order to collect the CWS data for a real-time web-mapping application and maintain the data archive for urban climate studies, an original software package (Python script) was developed. It sends requests to the API, processes responses, updates the catalogue of unique CWSs in the study area, and archives the data for each CWS in the *.csv format. The software is running on regular time intervals (30 minutes) by using the Windows Task Scheduler. The first version was based on the patatmo Python library (https://pypi.org/project/patatmo/). However, we further found that patatmo is not
sufficiently flexible for the required tasks, and developed a second version of the software, which does not use external libraries to communicate with Netatmo API. The recent version of the software package is freely available for downloading and usage at the GitHub (https://github.com/pavelkargashin/LoadNetatmoData).

Data collection with the developed software started in August 2019 for the Moscow region with its first version, and the second version was launched in May 2020 for Moscow and other selected cities in Russia and neighboring countries (Saint-Petersburg, Ekaterinburg, Novosibirsk, Minsk, Nur-Sultan). For each region, data are collected for an area of about 200 × 200 km around the city (for Moscow it is limited by 36.4 and 39 °E, 54.8 to 56.6 °N). Both versions demonstrated stable work during the period of operation. As expected, the largest amount of data is collected for Moscow, where almost 2000 unique CWSs have been discovered in total and 1200-1400 CWSs are active each day (Figure 1a). Surprisingly, the number of active CWSs experienced a noticeable decrease in summer, which may be related to seasonal patterns of human activity (citizens may move to vacations and switch off their CWSs). Among the other cities, the largest number of active CWSs (250-300 per day) is in Saint-Petersburg (Figure 1b), 60-70 in Minsk, Belarus (Figure 1c), 30-40 in Ekaterinburg and Novosibirsk, and only 5-10 in Nur-Sultan, Kazakhstan.

![Figure 1](https://example.com/figure1.png)

(a) Moscow  
(b) Saint-Petersburg  
(c) Minsk

**Figure 1.** Number of active CWSs whose data were collected by the Netatmo download software for each day in Moscow (a), Saint-Petersburg (b), and Minsk (c). The black and red lines indicate the first and second software versions, correspondingly.

3. **CWS accuracy, quality control, and applications for urban climate studies**

The Netatmo CWSs provide uncertified observations which can be misrepresentative for many reasons. For example, outdoor modules may be installed at the overheated walls or even inside buildings [7]. Beyond these extreme cases, other typical ways of CWS installation could be far away from the standards of meteorological observations.

An experimental study of Netatmo uncertainties was carried out at the meteorological observatory of Lomonosov Moscow State University. Its first part was aimed at the evaluation of instrumental uncertainties. Ten outdoor modules were placed inside a Stevenson screen for 19 days in May-June
2019 (Figure 2a). A comparison with reference measurements by Vaisala AWS310 has shown that the instrumental uncertainties of Netatmo temperature observations correspond to their declared accuracy (±0.3 °C), with a near-zero bias and a RMSE of 0.45 °C. For relative humidity, a systematic bias was found, that linearly depends on humidity values and varied from overestimation by 5-10% for dry conditions to similar underestimation for humid conditions. Such bias may be easily corrected in postprocessing. The second part of the experiment was aimed at the evaluation of the uncertainties induced by the outdoor module placement. Ten modules were placed for two months at different sites within the territory of the observatory in order to simulate the typical ways of their installation by users, including a 15-meters tower (1), four building walls (2-5), a building roof (6), a branch of a small tree (7), a metal pole (8), the shadowed outer side of the Stevenson screen (9). Module no. 10 was kept inside the Stevenson screen. This experiment revealed that unshaded outdoor modules are strongly overheated in the daytime (Figure 2b). At night the mean biases of the majority of modules converge to zero, which increases the reliability of Netatmo data for urban climate studies in nocturnal conditions, when the magnitude of urban temperature anomalies becomes much higher than CWS biases. More details on this experiment are given in [12], and extended results will be published in further studies.

Despite the huge biases revealed for the unshaded Netatmo CWSs, previous studies have already shown the opportunity to filter out misrepresentative data using quality-control (QC) algorithms. We developed a QC algorithm based on ideas from the previous studies [7,8] with some modifications, which allow more intensive use of reference observations in Moscow region. Since the reference network covers both rural and urban areas, we assume that it resolves the major part of variability of local climates within the study area. The algorithm consists of 5 levels, L1-L5. For now, it is tested for air temperature, but in could be further adopted for humidity and, likely, to other parameters.

The pre-processing step, L0, removes CWSs with exactly the same location (assuming that the location was wrongly defined by using the IP address). Three first steps, L1-L3, depend on statistics calculated over a period Δt = 14 days before the i-th moment for which the QC is applied. L1 is passed if the missing data ratio for the j-th CWS over the Δt period is lower than a threshold (Rmiss = 0.5). L2 is passed when the temperature mean value $T_{j}^{CWS}$ and the standard deviation $\sigma(T_{j}^{CWS})$ for the j-th CWS for the Δt period are within an acceptable range determined by min/max values within a set of n reference stations in the study area with an additional $k_1$-sigma tolerance (for now, $k_1$ is set to 1.5):

$$
\begin{align*}
\text{L2:} & \min(T_{1...n}^{ref}) - k_1 \cdot \sigma(T_{1...n}^{ref}) \leq T_{j}^{CWS} \leq \max(T_{1...n}^{ref}) + k_1 \cdot \sigma(T_{1...n}^{ref}) \\
& \min(\sigma(T_{1...n}^{ref})) - k_1 \cdot \sigma(\sigma(T_{1...n}^{ref})) \leq \sigma(T_{j}^{CWS}) \leq \max(\sigma(T_{1...n}^{ref})) + k_1 \cdot \sigma(\sigma(T_{1...n}^{ref})).
\end{align*}
$$

This approach rejects CWSs if the outdoor module is located indoor and partially eliminates cases when the outdoor module is not shaded properly. The L3 step checks the correlation coefficient $R$ between the data for the j-th CWS and the mean temperature over all reference stations over the Δt period, it is passed if $R > 0.9$. Levels L4 and L5 depend on the data for the i-th time moment only. The L4 step checks whether the CWS temperature value is within an acceptable range determined by min/max values within a set of reference stations with an additional $k_2$-sigma tolerance (for now, $k_2$ is also set to 1.5):

$$
\begin{align*}
\text{L4:} & \min(T_{1...n}^{ref}) - k_2 \cdot \sigma(T_{1...n}^{ref}) \leq T_{j}^{CWS} \leq \max(T_{1...n}^{ref}) + k_2 \cdot \sigma(T_{1...n}^{ref}).
\end{align*}
$$

Finally, an L5 step is proposed to remove too high spatial variability within closely-located CWSs within a 3-km distance following an idea of “buddy check” from [11]. The need for L5 is debatable and will be further analyzed in subsequent studies.

The QC algorithm was tested based on CWS data archived in the Technical University of Berlin by using a similar approach to that described in Section 2 [7], but for a longer period. The data for May-June 2019 were used. Observations from Roshydromet weather stations, the weather observatory of Lomonosov Moscow State University, and automatic air quality stations (AAQSs) of
Mosecomonitoring agency were used as a reference data set (in total about 70 sites within 100 km around Moscow, see more details in [12,13]). Figure 2c demonstrates the time series of air temperature according to CWS data for different QC levels. As can be seen, the L0 data may be indeed misrepresentative due to overheating of the outdoor modules, placing them indoors or even in a fridge. Only about 25% of data pass through the strictest QC levels L4 and L5 which is, however, still a lot in comparison to the number of official weather stations in Moscow region.

Figure 2. Set-up of 10 Netatmo outdoor modules in a Stevenson screen in the first part of experiment (a); diurnal variation of mean temperature bias ($\Delta T_{\text{netatmo-reference}}$) for 10 outdoor modules during the second part of experiment (b); time series of air temperature according to CWSs data for different QC levels together with min/max reference values in June 2019 (c), temperature anomaly values with respect to mean value over 9 rural stations around Moscow averaged over selected nocturnal cases with intense UHI, for weather stations (big circles), AAQSS (squares), and L5 CWS data (small circles) (d).
Figure 2d shows the spatial distribution of the temperature anomaly with respect to 9 rural weather stations around Moscow for the selection of 97 nocturnal cases with an intense UHI in May-June 2019 according to reference observations and quality-controlled CWS data (L5 level). Both types of data clearly demonstrate a persistent warm anomaly over the whole Moscow city and its suburbs, as well as intra-urban temperature heterogeneity, which is discussed in more detail in [12]. The presented results open opportunities for further spatial studies on a linkage between urban temperature heterogeneity and urban canopy parameters. Such analysis is currently under development and will be published later.

4. A prototype of the web-based monitoring application

Dense coverage in world’s biggest cities and high data update frequency (data are updated with a frequency of about 5-10 minutes almost in real-time regime) make the Netatmo CWSs a prospective data source not only for climatological studies, but also for applied tools aimed at informing the population and urban services about actual environmental conditions. However, the authors do not know any successful example of such a service that involves the CWS data. For example, the Netatmo Weathermap service has a lot of limitations: it does not include observations at official weather stations; the built-in QC algorithm is not documented and seems to be misrepresentative in some cases; the number of shown CWSs decreases with decrease of scale; archived data are not available.

In order to demonstrate the opportunity of implementing the monitoring service with CWS data, we are developing a prototype of the web-mapping application Mosclim aimed at real-time monitoring of meteorological and thermal comfort conditions in Moscow region. The application workflow is schematically shown in Figure 3. The application backend combines software modules written in Python and R programming languages for automated collection of Netatmo data (see Section 2), automated collection of official Roshydromet data from open-access sources (currently, http://www.pogodaiklimat.ru/ website is used), updating the PostgreSQL database, data preprocessing (temporal interpolation), and QC. Since raw Netatmo measurements are collected at arbitrary timestamps, they are interpolated at regularly spaced timestamps (every 30 minutes). Each interpolated value is then checked by the QC procedure. The application frontend is based on the OpenLayers web mapping library. The database is accessed by using the supplementary Node.js server application.

Figure 3. Workflow scheme of the Mosclim web-based application including modules that are under development (shown by light gray color).
The current version of the Mosclim application allows mapping of air temperature observed by Netatmo CWSs and Roshydromet weather stations in a near-real-time mode. Near-real-time means suggest a possible delay from 1 to 4 hours determined by the update frequency of the Roshydromet data in open-access data sources. This limitation may be eliminated in the future by accessing Roshydromet data using official protocols with a higher update frequency or by modifying the QC algorithm allowing an opportunity to use Netatmo data independently from reference data if the latter are not updated. Archived data for a given moment in the past can be also visualized. Other meteorological variables available from the CWS and Roshydromet data flows are also processed and stored in the database; an opportunity for their mapping will be added in the future.

The user interface of the application includes a panel to select date and time (the data for the last available moment are shown by default), switch controls to show/hide Netatmo and Roshydromet data, and a menu for selecting the shown QC level. The QC algorithm in the application follows the same ideas as those described in Section 2 with minor differences since it is still under development and testing. Levels L1-L4 are currently supported. Level L0 in the application is different from the L0 described in Section 2: it is introduced for testing purposes and corresponds to a stand-alone level L4 (applied without criteria for the previous levels). An option called standardization allows showing a temperature anomaly defined with respect to the mean value over 9 rural stations around the city, instead of absolute temperature values.

Screenshots in Figure 4 demonstrate the Mosclim application on the example of two cases. The first one is a typical summer nocturnal case with an intense UHI observed on June 25, 2020, with a temperature anomaly reaching up to 7-9°C in the city center. The second one is even more interesting, because it shows a daytime “cold island” in the southern part of Moscow, which is up to 10°C cooler than the surrounding areas. Such a temperature pattern was caused by a mesoscale convective system that passed over Moscow on the 20th of June 2020 and resulted in an intense rainfall (the registered precipitation sums were 20 mm for the city center (Balchug) and 35 mm in Vnukovo Airport) and flooding of the Varshavskoye Highway in the southern part of the city. Thick clouds and rainfall cooled the area under the convective cell, while the other territory was not affected and experienced typically high daytime temperatures.

5. Further developments and challenges
In addition to the minor improvements listed above, two major developments are also planned for the Mosclim application, namely the geospatial interpolation and thermal stress assessment based on the CWSs and Roshydromet data (Figure 3). It is planned to convert scattered data to 2D fields on a regular grid with a step of 250 m and to use interpolated data for real-time assessment and mapping of the thermal stress conditions. It is also planned to involve a detailed information on the urban canopy parameters in both of these tasks. A gridded data set on urban canopy parameters was compiled from three different data sources, namely the OpenStreetMap vector-formatted data on buildings, Sentinel-2 space imagery and Copernicus Global Land Cover data (CGLC), and include information on impervious area fraction, built up area fraction, mean building height, aspect ratio of street canyons (H/W), and other parameters on 250, 500, and 1 km regular grids [14].

However, the proposed developments of the Mosclim application face significant technical and methodological challenges that are still not completely resolved. The technical challenges are related to the computation of the thermal stress indices within the framework of the automated workflow. We plan to use advanced state-of-the-art biometeorological indices, namely, PET (Physiologically Equivalent Temperature) and UTCI (Universal Thermal Climate Index) that are based on human energy balance models [15]. These indices account for air temperature, humidity, wind speed, solar radiation, and human-related parameters (activity level, clothing) and provide more comprehensive and relevant assessment of the human thermal perception than the so-called simple indices. A generally accepted tool for calculating these indices is the RayMan software, which combines human energy balance models with a model of radiation transfer in built environment, and can take into account shading from buildings [16]. However, the RayMan tool is developed as a closed-source
application for Windows and does not support operation in automated workflow. This limitation can be eliminated in different ways. First, RayMan can be executed by using external software, e.g. an autoclicker, as proposed in [17] or more advanced packages such as pywinauto. Such solutions have been already developed, however their computational speed is strongly limited, and further work is needed to ensure their stable automated operation on a server. A more convenient and promising solution seems to rewrite the calculation model used in RayMan relying on the existing model documentation or to use open-source tools that are available for UTCI calculation.

Figure 4. Screenshots of the Mosclim web-based application for two cases: an intense nocturnal UHI on 25\textsuperscript{th} of June 2020 (top) and a convective cell passing over the southern part of Moscow on 20\textsuperscript{th} of June 2020 (bottom). Digits and colors indicate the temperature anomaly calculated with respect to mean temperature for 9 rural Roshydroment weather stations around Moscow. Big and small circles indicate Roshydroment weather stations and Netatmo CWSs, correspondingly.
The methodological challenge is related to accounting for the properties of built environment in the calculation of the meteorological indices and in geospatial interpolation. The geometry of buildings strongly affects the radiation regime, as well as the wind flow inside the urban canopy on a microscale [1]. Features of the shortwave radiation balance may be accounted for by using the so-called sky-view factor (SVF). SVF can be calculated for a specific point within a real building geometry or for an idealized street canyon based on the mean H/W ratio over a grid cell [18]. Preliminary sensitivity studies with the RayMan software have already shown high sensitivity of the PET and UTCI indices to the SVF, with a decreasing heat stress repeatability as the SVF is decreasing (because the shadowing repeatability is increasing). Long-wave radiation balance is a more complicated story, because it depends on the surface temperature of building facets, which is unknown. It is important to estimate the sensitivity of the thermal stress indices to the lack of such information in the further studies. Another challenge is related to accounting for the urban canopy parameters in geospatial interpolation of the meteorological parameters. Possible solutions include regression-based geospatial modelling [10,19], with application of the urban canopy parameters as additional predictors. Alternatively, the results of high-resolution numerical weather forecast for urban areas may also be involved. In either case, there is a wide field for further research.

6. Conclusions
The above-presented study has demonstrated a potential of using the crowdsourcing meteorological data from the Netatmo CWS network for urban climate studies and monitoring applications, and introduced key workflow elements required to work with the CWS data. For collecting the CWS data for a given area, we developed a software that communicates with the Netatmo API and archives the data. This tool is now freely available at the GitHub (https://github.com/pavelkargashin/LoadNetatmoData). The thus developed software has collected the CWS data for Moscow since August 2019 and for five other selected cities since May 2020. The uncertainties of the Netatmo CWS were experimentally evaluated at the meteorological observatory of Lomonosov Moscow State University. Instrumental uncertainties were found to be within a given accuracy for air temperature, and a systematic bias was found for relative humidity. The uncertainties that appear in popular ways of CWS installation by the users (e.g. on walls or in gardens) were also evaluated, and huge daytime biases were found for cases when the outdoor modules are not shaded properly. However, at night such biases converge to near-zero values in most of the cases.

A multi-level quality-control algorithm was suggested for filtering out the misrepresentative CWS observations. The algorithm follows ideas from some previous studies, but more extensively uses reference data from the official weather stations. Among more than 1500 CWSs that are available for Moscow, the above-proposed algorithm rejects about 75% of the data, however, the number of the remaining CWSs is still much larger than the number of the official weather stations in the study area. Such amount of data opens new opportunities for spatially-resolving urban climate studies and for applied services.

In order to demonstrate an opportunity to implement the monitoring service with CWS data, we presented a prototype of a web-mapping application for near-real-time temperature monitoring in the Moscow region, which is called Mosclim. The application’s backend includes automatic services for downloading observations from the Netatmo and official Roshydromet networks, as well as for database maintaining and quality control with the above-proposed algorithm. The processed data are visualized interactively in a web browser. The application is available on the Internet at http://carto.geogr.msu.ru/mosclim/. The application is still under development, and its current version can only show air temperature from the Netatmo and Roshydromet observations for a recent available moment or for a given moment in the past. However, even the current version can be useful for weather- and climate-related scientific research, for operational weather forecasting, education, and mass media. The application will be developed further to include mapping of other meteorological
variables, geospatial interpolation, heat stress assessment, and mapping based on the available meteorological data and modern biometeorological indices.

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