Web-based service for prediction of thermal comfort conditions in large administrative centers of the Russian Federation

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Abstract. This paper discusses the problem of thermal comfort in cities of the Russian Federation. The average person is faced with environmental conditions that are beyond his control. In residential areas associated with permanent population, a more comfortable thermal state is achieved by architectural and urban planning methods. For scientific assessment of thermal comfort, indices have been developed, the Physiological Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI), taking into account many factors. These are completely new indices, and there are no statistical regular data available in Russia during the recent ten years. Calculations are made to obtain bioclimatic indices and characteristics of selected cities for further assessment of the comfort of cities and their comparison. In addition, this paper describes a project http://heat2020.ru «Heat in Russian Cities». The main aim and methods of the project are given, and forecasts of comfort for Moscow in direct sunlight and in shade conditions are compared and analysed.

1. Introduction and motivation

The physiological systems of the human body are very dependent on its thermal state. Any thermal deviations from the norm adversely affect the functioning of the cardiovascular system, the sweating system and, therefore, the water-salt balance, and also affect the work of other organs and systems. Certain thermal states of the body can be assessed as different degrees of tension in the mechanisms of thermoregulation. When standardizing microclimate indicators, the provision of the thermal state of the body can be assessed as different degrees of tension in the mechanisms of thermoregulation. When standardizing microclimate indicators, the provision of the thermal state of the body is taken into account, in which there is no adverse effect on well-being, performance and health by the tension of thermoregulation mechanisms [1].

Nowadays, people have long learned how to regulate the microclimate conditions at home and at work using air conditioning, ventilation, heating systems, and various construction methods. However, going out into the street, a person is faced with conditions that are much less amenable to his control. In residential areas associated with a long stay and rest of the population, a more comfortable thermal state is achieved by architectural and urban planning methods.

In 2019, the share of the urban population in Russia amounted to 75.6%, and administrative centers are the main centralization centers of population in most regions of the country [2], where the presence of not only a tense, and sometimes critical, environmental situation affects the health of the population...
[3], but also urban heat islands. This indicates that the climate assessment of thermal comfort in administrative centers is an urgent issue for bioclimatology.

At the moment, there are no statistical data on modern bioclimatic thermal comfort indices, such as PET and UTCI [4], for the whole of Russia and for recent years. There are statistics only for the traditional, so-called “simple”, bioclimatic indices, which take into account only meteorological environmental variables. For big cities there are only some case studies; for Moscow [6], [7] and for the south of Russia [8].

Due to the sprawl of cities, the meteorological stations which were once outside the city are now located within it. However, not all stations represent the climatic picture of the urban environment [5]. Also, one of the problems is complete lack of data for some administrative centers of Russia, as well as incomplete climatic series for selected cities in the database.

The main goal of the research is to study the bioclimatic indices of environmental comfort for the administrative centers of Russia over a 10-year period from 2009 to 2018. To achieve this goal, the following tasks were set:

1. analyze information on modern indices of environmental comfort for Russia according to various sources;
2. analyze the quality of the data of the series of meteorological parameters for each administrative center for the period from January 1, 2009 to December 31, 2018 from the database (meteo.ru);
3. simulate the thermal comfort conditions of the administrative centers of the constituent entities of the Russian Federation for the selected period using the Rayman Pro 3.1 software package;
4. perform statistical processing of the PET and UTCI bioclimatic indices obtained in the course of modeling, calculating the average annual values of the indices, the values of the seasonal summer and average seasonal winter indices, the average monthly values, and the frequency of occurrence of various gradations of thermal comfort, as well as the variance according to these indicators and present it in cartographic form;
5. analyze the results obtained, classifying these cities according to the degree of comfort and highlighting the most and least favourable cities in Russia.

2. Materials and methods

2.1. General information about comfort calculation

The objects of this study were selected administrative centers of the constituent entities of the Russian Federation. The subject of the study is the bioclimatic comfort index UTCI. For the research, 83 administrative centers of the subjects of the Russian Federation were considered, however, so far, no information has been found for some cities. Below is a map showing the administrative centers, and the amount of information that is available for these cities is marked in color (Figure 1).

![Figure 1. Map of Russia with cities and information.](image-url)
To study the comfort of cities using bioclimatic indices, we took data from a reanalysis of the All-Russian Scientific Research Institute of Hydrometeorological Information – MDC [4] for the period from January 1, 2009 to December 31, 2018 according to the 4 largest administrative centers in Russia. This study examined Moscow, St. Petersburg, Volgograd, and Tyumen, since they are the most representative examples.

The following meteorological parameters were used from the database:
- Air temperature (°C),
- Soil temperature (°C),
- Wind speed (m/s),
- Moisture content of air (%),
- Cloud cover (in octants).

The data on the geographical coordinates of cities and their average height above sea level were also introduced to account for radiation flows. Modeling was performed in the RayMan software [4] package to obtain bioclimatic indices UTCI and PET.

The PET and UTCI, which are based on the human energy balance and describe the effects of the meteorological conditions (which were given above) and of the thermo-physiological conditions (clothing and activity) on humans, are used [10]. Specific categories for the assessment of thermal stress and thermal comfort are given in Tables 1 and 2. The main difference between the PET and UTCI is that the PET always uses standard clothing (clo = 0.9), while the UTCI adjusts clothing based on the existing outdoor conditions. Therefore, extreme cold stress is reached in the PET index already at 4 °C, while at the UTCI equal to 4 °C only mild cold stress is achieved. In this regard, the PET index is used to analyze the summer season, and the UTCI can be used to analyze the comfort class of any season.

### Table 1. Gradations of PET and UTCI indices [10].

| PET value, (°C) | UTCI value, (°C) | Physiological class   |
|----------------|------------------|-----------------------|
| –              | UTCI≤-40         | Extreme cold stress   |
| PET<+4         | -40≤UTCI<-27     | Very high cold stress |
| 4≤PET<+8       | -27≤UTCI<-13     | High cold stress      |
| 8≤PET<+13      | -13≤UTCI<0       | Moderate cold stress  |
| 13≤PET<+18     | 0≤UTCI<+9        | Slight cold stress    |
| 18≤PET<+23     | +9≤UTCI<+26      | No thermal stress     |
| 23≤PET<+29     | +26≤UTCI<+32     | Moderate heat stress  |
| 29≤PET<+35     | +32≤UTCI<+38     | High heat stress      |
| 35≤PET<+41     | +38≤UTCI<+46     | Very high heat stress |
| +41≤PET        | +46≤UTCI         | Extreme heat stress   |

The physiological Equivalent Temperature is based on the Munich Model of Energy Balance for Individuals (MEMI), which simulates the thermal conditions of the human body in a physiologically appropriate way. The PET is defined as the air temperature at which, in a typical indoor environment (without wind and solar radiation), the human body’s thermal balance is balanced with the same internal body and skin temperatures as in the difficult external conditions that need to be assessed. Compared to other thermal indicators, it has the advantage of a unit that is clear to everyone, degrees Celsius [6].

The UTCI is defined as the air temperature of a reference condition (50% humidity and no wind) that produces the same model response as actual conditions. The UTCI was developed in 2009 thanks
to international collaboration between leading experts in human thermophysiology, physiological modeling, meteorology, and climatology [7].

Various bioclimatic models are available today, but they are of limited strength due to a narrow range of environmental conditions. The general idea behind the UTCI results was to fill in the gaps and create an index that reflects the overall comfort picture. The new generation of multi-node human thermal balance models allows full consideration of heat transfer and exchange both inside the human body and between the skin and the surrounding air layer, and a new air temperature is obtained, which ensures the thermal balance. The UTCI tends to be a one-dimensional quantity that adequately reflects the physiological response of a person to an actual thermal state determined in a multidimensional manner.

2.2. Project «Heat in Russian Cities»

At the beginning of August 2020, a demonstrational project ‘Heat in Russian Cities’ was launched by a team of professional meteorologists and experts in the field of studying the impact of weather on human health from Moscow and Tomsk (with the support of the Center for Smart Technologies for Sustainable Development of the Urban Environment in the Context of Global Changes, RUDN University).

This project aims to familiarize the media and the population of Russia with the first test system in the Russian Federation for predicting the danger of heat for urban residents. Due to limited computing resources, forecasting is currently being carried out for the 30 largest cities in Russia and two resort

Figure 2. Website of the project “Heat in Russian Cities” (http://heat2020.ru ).
cities - Sochi and Yalta. The calculation of the forecast of meteorological parameters is made for the day ahead. Next, the data are used to calculate the PET comfort index and uploaded to the site of this project. In this project, indices are calculated for 32 cities for the conditions of a person being in direct sunlight, and for Moscow and Tomsk conditions are also calculated when a person is in the shade (Figure 2).

The necessary data on temperature, relative humidity, wind speed, and cloud cover were obtained for each city under consideration sequentially using a specially developed bash-script. For each forecast hour, using the NOMADS interface [13], this script downloads the available temperature and relative humidity for 2 m, the u- and v- components of the wind for 10 m, as well as the total percentage cloudiness for the entire atmosphere; using the u and v components, it calculates wind speed at 2 m; converts units of measurement; and outputs the result in tabular form to a text file. Most commonly, the coordinates of the cities under consideration do not coincide with the GFS grid points. Thus, to determine the values of the necessary meteorological parameters for a city, data for four nearby points were downloaded and linearly interpolated to a given point (city). The altitude of the city above sea level (elevation), also required for further calculations, was determined by using the GLOBE map from NOAA with a horizontal resolution of 1 km [14]. In the case when the elevation is known, it defines directly for the bash-script. This setting significantly reduces the script's running time. Thus, the map is accessed only once during the first data processing for a new city. Further, since the coordinates of the city are unchanged, as well as its elevation in the time scales we are considering, this value is specified directly. The speed of the script performing is mainly determined by the speed of the data downloading, which depends on the Internet connection speed. Mathematical processing (calculation of the necessary meteorological parameters and conversion of units) accomplishes almost instantly.

3. Results

![Graph of changes in summer seasonally average values of UTCI for 2010-2019 in Moscow, St. Petersburg, Volgograd, and Tyumen.](image)

**Figure 3.** Graph of changes in winter seasonally average values of UTCI for 2010-2019 in Moscow, St. Petersburg, Volgograd, and Tyumen.
Within the framework of the project of comparison of thermal comfort conditions in the largest administrative centers, initial statistical processing of the indices in selected cities was performed. In order to obtain the average annual values of the indices, the values of the average seasonal summer and average seasonal indicators of the winter indices, the average monthly values, for the 4 selected cities – Moscow, St. Petersburg, Volgograd, and Tyumen, the following graphs were constructed (Figures 3 – 4).

By comparing the graphs of changes in winter and summer mean seasonal values of the UTCI index for 2010-2019 in 4 cities, it can be seen that the most comfortable city both in winter and in summer is Moscow, where in summer for 10 years the seasonal average UTCI values did not fall below 12.2 °C and did not rise above 15.6 °C; these values correspond to the absence of thermal stress, and in winter it is between -5.1 °C and -11.4 °C; these values are within the range of moderate cold stress.

In St. Petersburg, the values are very close to those in Moscow, but still lower due to increased wind speeds, which affect the perception of cold by a person. In summer, the maximum value is 13.1 °C and the minimum value is 8.9 °C in 2017, this is the only year in which the UTCI has dropped to slight cold stress. In winter, the maximum value is -8.5 °C and the minimum value is -13.4 °C. Thus, there was moderate cold stress every year, except for 2010, there was high cold stress.

Volgograd has the smallest amplitude of summer UTCI values, in contrast to the other cities, it has an amplitude of 14.2 °C to 16.2 °C. But the city has a large amplitude in winter, it has an amplitude of -18.5 °C to -9.7 °C, it means classes from moderate cold stress to high cold stress. It is also one of the hottest cities in Russia in summer, but due to its location in a temperate continental climate, there is a more pronounced difference between the winter and summer indicators. Thus, in 2010-2012 and in 2017 the average annual values dropped to high cold stress, and in 2013-2016 and 2018-2019, to moderate cold stress.

Tyumen is located in a sharply continental climatic zone, which is shown, where in winter in all 10 years there is a high cold stress, from -23.8 °C to -16.2 °C, and in summer temperatures are on the verge between 6.8 °C and 12 °C, it has no stress in 2010-2013 and 2016-2018, and slight cold stress in 2014, 2015, and 2019.

![Figure 4. Graph of changes in winter seasonally average values of UTCI for 2010-2019 in Moscow, St. Petersburg, Volgograd, and Tyumen.](image-url)
After running the project «Heat in Russian Cities», the authors got a new thermal comfort database. Additional comparative analysis of comfort was carried out in conditions of direct sunlight and in conditions of shade in Moscow for the period from August 5 to September 5, 2020 (Figure 5).

The data were taken for the period from 9 to 21, since at this time a person is most likely to be outside.

For 30 days (390 hours), most often in natural open air conditions, there was lack of thermal stress (30%) and slight cold stress (26%). The lack of thermal stress occurred within 28 days out of 30 days. Slight cold stress was marked for 29 days. High heat stress was observed 9 times a month (9%).

In shaded area conditions, slight cold stress was more often observed (39%), which was marked 25 times out of 30. No stress was observed 20 days out of 30. Moderate cold stress and moderate heat stress were observed within 10 days, but moderate cold stress was more prolonged during the day; therefore, in the diagram it exceeds moderate heat stress. High heat stress was observed for only 1 day.

Comparing the diagrams, we can say that colder conditions were observed under shade conditions than under open air conditions, which is logical.

4. Conclusions
It is planned to calculate complete statistics of the PET and UTCI indices for all administrative centers of the Russian Federation and thus obtain for the first time a complete climatology of thermal comfort conditions over the past 10 years on the territory of Russia.

According to the above graphs, after complete statistical processing, an analysis of all results will be carried out, a description of regions in terms of comfort in their administrative centers will be compiled, the cities will be classified according to degrees of comfort, the most comfortable and uncomfortable cities will be highlighted and, to complete the study, a map of comfort of Russia's regions will be created.

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