Real-time microscale modeling of thermal comfort conditions in Moscow region

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Abstract. Urban climate comfort is an indicator of a set of parameters, such as temperature, humidity, and solar radiation for a person’s sensation of being favorable to being outdoors or indoors. In this study, an attempt to develop a technology of real-time prediction of thermal comfort conditions in urban landscape is described (based on the example of Moscow State University campus). For this, the authors used a RayMan model-based algorithm for calculating three most popular worldwide comfort indexes. In the scripting method, predictive data of the Canadian global model meteorological parameters are automatically transferred to the RayMan-model (with an implementation of the unique thermal and radiation properties of the Moscow State University campus landscape) by using an autoclicker software. For the convenience of perception of the information, the results of calculations are visualized on the basis of a free web mapping service. Thus, the main idea of the work is that any user with minimum expenditure of his time resource and without knowledge of the model’s work can launch the program and receive an individual forecast of comfort conditions for the next few hours in a visually understandable format. It is suggested that the developed methodology will be used for calculations on projected areas to identify the safest construction option. Such real-time forecasting will continue to be of particular importance for urban infrastructure.

1. Introduction and motivation

The health of the urban population is influenced by many factors, among which there are meteorological parameters. Moreover, the impact is not expressed in individual indicators, but in their totality, which is displayed by thermal comfort indices [1]. Basically, they are identified empirically and are presented in the format of the outdoor temperature for ease of perception of information.

Due to the heterogeneity of urban development and urban climate in the Moscow region [17], the thermal comfort conditions at different points in the same territory will differ noticeably with the same meteorological parameters. Thus, it is necessary to study the parameters of comfort on the microscale. Therefore, within the framework of this study, in order to inform the public about the negative impact of weather, and further to minimize the consequences on the human body, an attempt was made to develop an operational system for predicting dangerous conditions of thermal comfort.

By now, more than 100 indices have been developed in world practice to determine the bioclimatic comfort of human life [2]. Such a huge number of indexes developed up to this point is due to the fact that there is no universal indicator due to very different weather conditions in different parts of the planet. Indices that give a more accurate value of cold stress and are based on experiments in a frosty environment are called cold ones. Accordingly, those that better determine heat stress and are based on experiments in a hot environment are called thermal ones. Also, special models have been developed to take into account the individual characteristics of a person when calculating thermal conditions.
Heat balance models take into account many aspects of the heat transfer mechanism. In this study, the authors use three most popular comfort indexes: PET, UTCI, and mPET.

The PET (Physiologically Equivalent Temperature) [3] is a parameter calculated using the Munich Energy-balance Models for Individuals (MEMIs) and defined as the air temperature at which the heat balance for normal room conditions for the human body remains unchanged with the temperature values of the internal organs and skin temperature for this situation. In addition to standard meteorological parameters, such as air temperature, wind speed, and relative humidity, the calculation of PET takes into account the processes of human metabolism, activity, and the thermal insulation properties of clothes. Currently, PET is one of the most commonly used indicators of human comfort and its influence on mortality during heat waves [14].

The mPET is a modified PET [4]. This index represents an improved PET with corrected weaknesses, which were: poor ability to predict thermophysiological parameters and poor response to both clothing insulation and wet conditions.

The parameter UTCI (Universal Thermal Climate Index) is also based on the model of human heat budget [5]. It is expressed as the equivalent ambient temperature of the reference environment providing the same physiological reaction of the reference person in a real environment. In contrast to the PET, when calculating the UTCI not only the heat-insulating properties of clothes are taken into account, but also vapor tightness, insulation of the air surface layers that undergo changes with changing wind speed and the movement of the human body and, as a consequence, affect the physiological reactions. Thus, the modified insulating properties of clothing in a real environment are taken into account.

In 2018, a real-time heat stress forecasting service in Greece was developed based on a thermophysiologically based index. This work is considered in the article “Operational Forecasting of Human-Biometeorological Conditions” [6]. The service is based on an autonomous connection between a model of numerical weather prediction operating at the National Observatory in Athens and a human biometeorological model. The main purpose of the service is to provide information about comfort conditions in a form that will be easily understood by the public. The forecast is provided by the service in 2 forms: table format for settlements and map format. The described service is one of the first of its kind. Thus, in this article the authors show that biometric information about a person can and should be transmitted to the population in an effective and easy to understand way.

In this paper, an attempt is made to develop an operational forecast of thermal comfort indices for the campus of Moscow State University. However, unlike the Greek service, it was planned to write an algorithm based on open forecast data of meteorological parameters. Consequently, it will be possible to implement a real-time prediction based on any other forecast models.

2. Materials and methods
To assess the urban climate in a physiologically significant manner, it is required to use methods of modern human-biometeorology dealing with the effects of weather, climate, and air quality on human organism [7]. The model RayMan [10] estimates the radiation fluxes and the effects of clouds and solid obstacles on short wave radiation fluxes. The model, which takes into account complex structures, is suitable for utilization and planning purposes on local and regional levels. The final output of this model is the calculated mean radiant temperature, which is required in the energy balance model for humans. Consequently, it is also required for the assessment of urban bioclimate and thermal indices, such as the Predicted Mean Vote (PMV), the Physiologically Equivalent Temperature (PET), and the Standard Effective Temperature (SET*).

The development of the model is based on the German VDI-Guidelines 3789, Part II: Environmental Meteorology, Interactions between Atmosphere and Surfaces; Calculation of the Short- and Long Wave Radiation and VDI-3787: Environmental Meteorology, Methods for the Human-Biometeorological Evaluation of Climate and Air Quality for the Urban and Regional Planning at Regional Level. Part I: Climate [8,9]. For the calculation of thermal indices based on the human
energy balance, meteorological (air temperature, wind speed, air humidity, and short and long wave radiation fluxes) and thermo physiological (activity and clothing) data are required \[10,11,12\].

**Sensitivity test.** To test the RayMan model for accuracy, a traditional sensitivity test was performed. The input information includes several meteorological and physiological parameters: air temperature, wind speed, relative humidity, cloud cover, physical activity, which is measured in watts \[13\], and others. The indexes were calculated for data series with one parameter changing and the others stable. Then, based on the values obtained, a graph was constructed, and the regression equation was determined. That is, you can trace how much the indices vary when one of the parameters included in the calculation deviates. The data are presented in Table 1.

**Table 1.** Change in comfort indices (modulo) when changing the parameter by one (for humidity - by 10\%, for activity - by 10 W). The parameters are arranged in decreasing order of influence on the PET index.

| Parameter                  | PET  | UTCI | mPET |
|----------------------------|------|------|------|
| Wind speed (for Δ1 m/s)    | -2.50| -1.65| -1.93|
| Temperature (for Δ1 °C)    | 1.00 | 0.94 | 0.86 |
| Rel.humidity (for Δ10%)    | 0.10 | 0.04 | 0.04 |
| Cloud cover (for Δ1 oct)   | 0.09 | 0.05 | 0.07 |
| Human activity (for Δ10W)  | 0.00 | 0.00 | 0.44 |

On all graphs of the dependence of the index on the parameter, a linear regression was constructed. In almost all cases, it turned out to be positive, which means that with increasing values of the abscissa axis, the values of the ordinate axis also increase. Only for wind the dependence turned out to be negative (the higher the wind speed, the lower the value of the indicator). The dependences of the UTCI and PET indices on physical activity are not observed, which is apparently due to the fact that a certain activity value is included in the calculation models of these parameters and, therefore, activity is not input information.

Table 1 shows that the calculation models for all 3 indices are most sensitive to changes in wind speed. The sensitivity of the parameters to changes in relative humidity, cloud cover, and activity is weakly expressed. In relation to all parameters (except for human activity), the PET is more dependent than the others. On the contrary, the UTCI is the least sensitive to changes in all parameters (except for temperature).

The sensitivity of the UTCI to wind is less than the sensitivity of the PET due to the fact that when calculating the first index heat loss in clothing deformation during strong winds is better taken into account than the PET.

There is no clearly positively distinguished index among the rest; each has its own advantages and disadvantages. Therefore, in relation to the study at the Moscow State University campus, calculations will be performed for all 3 indices considered above.

3. Results

**Development of Real-Time Forecast Technology**

Diagnostic models for calculating comfort indices have already been invented in the biometeorology industry. However, to minimize the harm caused to health, a person must be informed about the conditions of conditional comfort, and so there is a need to create a prognostic model. Nevertheless, the calculation program is hidden from the user. In this paper, an attempt is made to solve this problem. Thus, the main idea of this work is that any user with the minimum expenditure of his time
resource and without knowledge of the model’s work could launch the program and receive an individual forecast of comfort conditions for the next hours in a visually understandable format.

When developing the technology, it was necessary to create several sequentially executed blocks. The flowchart is shown in Figure 1. Further, each of the blocks will be considered in more detail.

**Figure 1.** Flowchart of technology for real-time modeling of thermal comfort indices. Blocks operating in the same environment are indicated by one color.

### 3.1. Download forecast data

For the study, it was decided to use the forecast data of the Canadian GEM global model. The Global Environmental Multiscale Model (GEM) \([15]\) is an integrated forecasting and data assimilation system developed by Environment Canada to meet the operational weather forecasting needs of Canada for the foreseeable future.

These needs include short-range regional forecasting, medium-range global forecasting, and data assimilation; the model is currently operational for the global data assimilation cycle and medium-range forecasting, the regional data assimilation spin-up cycle and short-range forecasting. Overnight mesoscale forecasts are also produced, and are available to operational forecasters. A growing number of meteorological applications now either use or are based on the GEM model.
It was decided to use the forecast data of the Canadian GEM global model because, first, this information is publicly available, and second, the values of different meteorological parameters are located in separate files for easy pumping and processing.

Downloading is performed using the “cmd.exe” interpreter in the Windows environment, after installing the wget utility on the hard disk. For further calculations, it is necessary to download data on surface temperature, surface atmospheric pressure, total cloud cover, wind speed 10 meters above surface level, and specific humidity.

3.2. File conversion
The need for this module was that the GEM global model provides its information in grib2 format, and the RayMan model which calculates comfort indices works with text files.

Conversion is also performed in the cmd.exe interpreter in the Windows environment using the wgrib2 utility. First you need to set the path to the folder in which this utility is located, and then connect it. The next step is to retrieve the value at the desired point. The resolution of the Canadian model is 0.6 degrees. After preliminary calculating the number of the cell in which the values of the meteorological parameters for Moscow are located, the required information is obtained using the “-ij” option. This operation must be performed 5 times for each of the downloaded files. After extraction, the forecast meteorological variables are written to separate text files. Description information is also recorded.

3.3. Data formatting
The next stage of the program is data formatting and combining all necessary information into one file using the computer language “Fortran 90” in the “Developer studio” environment. Correction of the data is required to conform to the format requested by the RayMan model. In this block, specific humidity is converted to relative one, the cloud units are converted from percent to octants, the wind speed is reduced from 10 m to 2 m, the temperature is converted from degrees Celsius to degrees Kelvin. Then all formatted data are combined into one text file, which will serve as input to the RayMan model. As a result, a file with a program of the .exe format is downloaded to include the module in a common file.

3.4. Calculation of comfort indices
The file obtained at the previous stage is loaded into the model using the “AutoClickExtreme” auto clicker [18]. Autoclickers are a type of software or macro that can be used to automate clicking. They can be triggered to generate input that was recorded earlier or generated from various current settings.

Comfort indices are calculated based on the heat-energy balance model. All formulas are embedded in the RayMan model and are hidden from an ordinary user, which makes it difficult to include the calculation stage in a common script. This was the need to use the autoclicker. It recorded mouse movements: using the file obtained at the previous step, as well as the obstacle file and marking the location of the point on it as input; ticking the used weather data; start of index calculation. After completing all necessary actions, it is possible to deflate the autoclicker record in a separate file, so that later it can be included in the technology.

The choice of the clicker was ensured by its advantages: the ability to run from the command line, tracking and recording computer mouse movements, typing on the keyboard, and playing back actions almost without errors.

To calculate the comfort conditions, 10 points were chosen on the Moscow State University campus. The points are located on all 4 sides of the main building, in the botanical garden, and on the open football field, and so at each moment of time they are in a different exposure due to the shading conditions. This fact gives reason to consider a representative picture made up of selected points to be representative, as it was made for Moscow-2010 heat wave conditions [16].
The comfort indices were calculated for a conventional person with standard physiological parameters (male, height - 180 cm, weight - 75 kg, age - 35 years) using one file with the values of meteorological elements and 3 obstacle files.

3.5. Formatting a file with calculated values
The next step is formatting again. At this point the result file changes, in which there is a large amount of information that is unnecessary for visualization and complicates it. Using the “Fortran 90” language, a program was implemented to extract the desired value from the file.

3.6. Visualization
After receiving the results, there is a need to display them in an easily perceptible format. For visualization, the calculated values were plotted on the campus map of Moscow State University in the form of punsons at the studied points. At this stage, the multifunctional mapping library “Leaflet” was used, working on the basis of the computer language “JavaScript”. The result (Figure 2) is displayed on the website [http://urbanreanalysis.ru/PET_forecast.html](http://urbanreanalysis.ru/PET_forecast.html).

![Figure 2. Visualization of calculated PET-values.](image)

The last step in creating the technology was to combine all modules into one script for better usability. This stage was carried out using the “Bash” language in the Windows environment. The result of the work is the ability of the user to launch the finished bat-file with two clicks without a detailed study of the essence of the technology and in a few minutes to receive the spatial distribution of the predicted comfort indices in the area of interest.

4. Technology approbation and discussion
Climatic calculations of thermal comfort indices on the campus of Moscow State University
To track the differences in the comfort conditions on a climatic scale on the university campus, the indices were calculated from 1980 to 1999, provided by the Moscow State University Meteorological Observatory. The selected period was 20 years, since the calculation time is limited in the RayMan model. To search for maximum discrepancies, only the July period was taken from a series of climatological data. The authors also analyzed two points that were different in terms of shading: the first is located on the football field (open), and the second in the botanical garden (covered by tree
crowns). The obtained values of the PET index were distributed according to the repeatability of stress levels and are illustrated in pie charts (Figure 3).

![Figure 3.](image)

**Figure 3.** Frequency of PET Thermal Comfort Index values distributed across various comfort levels. *repeatability of cases of mild, moderate, and severe heat stress (28°C <PET <41°C).

In Figure 3 one can see that on the football field in July the cases of weak, moderate, and severe heat stress (28°C <PET <41°C) are repeated 10% more often than in the botanical garden. It is also worth noting that at the first point the number of cases of extreme heat stress (PET> 41°C) is 10, and at the second one it is 0.

This confirms the conclusion that in the summer in Moscow in the open area it is much more dangerous than in the shaded one. Moreover, if we are talking about a football field, a person receives heat not only due to microclimatic features, but also due to increased physical activity. This can lead to health problems, and in the case of abuse of activity in a non-shaded area, also to more serious illnesses (heat strokes, etc.).

5. Conclusions
The main result of this study is the following: for the first time in Russia, a real-time prediction technology of thermal comfort conditions has been developed. The result is illustrated in a form that is visually understandable to the common user. In the future, the technology can be applied not only to the campus of Moscow State University, but also to any other subject with the necessary input data: an obstacle file, a file of forecast meteorological parameters. Also, if desired, the user can set other physiological parameters in order to project the obtained PET-values for a specific person.

Also, a sensitivity test was carried out, which showed a great dependence on the meteorological parameters of the PET index compared to the UTCI and mPET. On the activity of a person using the 3 considered indices, only the latter depends. A strong sensitivity of all 3 indices to changes in wind speed has been obtained.

Calculations based on climatic data for the 2 most different in terms of shade points were made. It has been shown that there are 10% more cases at an open point with conditions of weak, moderate, and severe heat stress than at a point covered with tree crowns.

This work can be continued for other cities, as well as megacities. As part of the technology, in the future it is possible to use the outputs of regional models as initial data, which ultimately may lead to an improvement in the quality of climate services for the population of Moscow and the Moscow region. Real-time forecasting is a new direction in biometeorology and, quite possibly, it will continue to be of particular importance for urban infrastructure.

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