Modeling the dynamics of comfort thermal conditions in Arctic cities under regional climate change

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Abstract: This work is devoted to modeling of characteristics of comfort thermal conditions in some Arctic cities under climate change. In this paper, the authors try to solve the problem of scarce meteorological observing stations in the cities by modeling thermal comfort indices in the Arctic urban landscape. For this, seven Arctic cities are classified according to a universally accepted classification of local climatic zones (LCZs) to identify the zones that best characterize each of the cities. Building data and data from the weather stations closest to the cities are included in a diagnostic microclimatic model RayMan. As a result of the experiments, air temperature trends and bioclimatic environmental comfort indices for the Arctic cities from 1966 to 2017 have been obtained. An assessment of the evolution of the indices has shown that the transitional seasons (April-May and October-November) make the greatest contribution to the change in comfort of the Arctic cities, and the number of days with severe cold stress decreases in all these cities of the Russian Arctic.

1. Introduction & motivation

The Arctic region stands out especially brightly against the background of global climate change. It is well-known that the rate of temperature increase in this region is higher than the average for the globe[1]. Temperature as a climatic resource largely determines the conditions of human life and the possibility of economic development for the territories. However, the well-being of each individual is affected not only by temperature, but by all meteorological parameters as a whole. Therefore, thermal comfort indices are used to assess its impact on a person, his health, and life expectancy. These are climatic indicators characterizing a state of comfort in which an optimal level of physiological functions of the body is formed, while a person is neither cold nor hot [2].

In Russia, about 74% of the population lives in cities. In the Arctic zone, due to the specifics of its development, this figure reaches 85% [3]. Therefore, the assessment of thermal comfort conditions in applied bioclimatology can be considered an urgent issue not only on average for the territory, but also for urbanized areas separately. In these territories the effect of urban heat islands is strongly affected [4],[5], and the majority of the region’s population lives in addition to general climate warming.

In studying the climate of urbanized territories, there appears the problem that weather stations are located outside the city limits almost in all cities. These weather stations cannot characterize the weather conditions of the whole city. Therefore, there are almost no data on the climate of urban areas in the Arctic. This work provides an example of a solution to this problem. For the study, the territory that officially entered the Arctic zone of the Russian Federation by the decree of the President of the Russian Federation dated May 2, 2014 was chosen, and the following cities were selected: Murmansk, Kandalaksha, Arkhangelsk, Naryan-Mar, Salekhard, Anadyr, and Nadym, also included in the Arctic zone [6]. These cities were selected on the basis of the presence of a weather station within the city limits or within a 50-km radius with a complete climatic range of data for 1966-2017 (Figure 1).
2. Data and methods

2.1 Assessment of temperature trends
At the beginning of the work, an analysis of the average annual temperature trends in different regions of the Arctic zone of the Russian Federation was made. To do this, we used data from the reanalysis database of the National Centers for Environmental Information, NCEI NOAA [7] and data from the weather stations of the Roshydromet network closest to the cities under the study (the data were obtained from the VNIIGMI-WDC [8] resource). According to the reanalysis data and the data from weather stations, the comparison between the rates of temperature growth showed that the rates are of the same order: about 0.3 ° - 0.55 ° C / 10 years over 52 years in all areas of the Russian Arctic zone.

It can be concluded that there are no representative data on what is happening directly in the cities: first, urban weather stations do not capture what is happening with the temperature in each particular city and, second, the spatial scale of almost all bases existing today does not allow one to capture the climatic changes occurring specifically in the cities (the size of the city is much smaller than the step of the reanalysis grid).

2.2 Modeling the parameters of the urban environment
To solve the problem of lack of meteorological data within urban landscapes and for further modeling of climate and comfort, an attempt to model the urban environment was made. For this, zoning of 7 Arctic cities by local climatic zones (LCZs) [9] was carried out.
Local climatic zones (LCZs) are areas with a relatively homogeneous surface coverage: density and height of buildings, the number of green spaces, building materials and a certain nature of human activity, which have a special type of interaction with the surface layer of the atmosphere and, in aggregate, have a specific effect on the local climatic characteristics. In total, 17 types of zones are distinguished in the LCZ system on a local scale from 100 to 10 000 m: 10 zones with urban development and 7 natural zones [10], [11]. For all 17 zones, the characteristics of the underlying surface (for example, albedo) and the thermophysical parameters of the environment, as well as the degree of human transformation were calculated [9]. The zoning was carried out manually, according to the instructions of the WUDAPT project (www.wudapt.org). For manual zoning, Google Earth software, Landsat 7 images, and SAGA-GIS were used (Figure 2a).
During the zoning process (Figure 2), it was found that in all selected cities LCZ 5 and LCZ 6 climatic zones are predominant. The most distinctive zone for most cities is the LCZ 5 zone (wide streets with houses about 10-25 meters high). That is ordinary city blocks. The exception is Naryan-Mar, for which the most characteristic is “LCZ 6” (wide streets with dense buildings and houses 1-3 floors high).

2.3 Modeling the conditions of thermal comfort in the Arctic cities

To calculate the biometeorological indices, the diagnostic model RayManPro 3.1 [12] was used. This model calculates radiant temperature, average radiation fluxes, and biometeorological indices (PET, PMV, and UTCI) based on the equation of the energy balance of a human body in a particular place at a specific moment in time for a particular person, as well as short-wave and long-wave radiation fluxes. The model is compatible with Microsoft Windows and can analyze complex urban structures and other environments.

Data on the thermophysical properties of the surface were obtained on the basis of information about the distinct type of development for each city with the type of development most characteristic of each city. Data on the closed horizon and building altitude were obtained from the OpenStreetMap city database. Using a script in the QGIS environment, it was possible to create files with a simulated urban area characteristic for each particular city — “typical building areas” (Figure 2b).

This information, as well as regular data from meteorological observations with 3-hour resolution in 1966-2017, were used for modeling in a three-dimensional block model RayMan Pro 3.1[13]. In this work, we used the most modern bioclimatic indices that take into account the individual characteristics of a person as much as possible. These indices are based on the heat balance equation of a person and take into account physiological processes (metabolism, sweating, etc.) under the influence of different meteorological factors.

1) PET - Physiologically Equivalent Temperature. This is a measure of the thermal sensation of a person at rest conditions. This is an indicator characterizing the complex effect of temperature, air humidity, wind speed, radiation flows on a person and take into account the degree of physiological activity of a person and the degree of thermoregulatory properties of clothes [14]. This index can detect levels of thermal exposure to the environment (heat stress), if they exist [15].

2) UTCI is a universal index of thermal comfort. It was developed as a concept of “equivalent temperature”: it includes the definition of a basic condition against which all other climatic conditions will be compared [16].

To assess the dynamics of cold stress separately, the Wind chill index was calculated [17]. This is an indicator that reflects the sensations of a person with simultaneous exposure to wind and low temperature. The subjective sensation by a person of the air temperature in an open area of the skin is estimated taking into account the wind speed. This is a cold index and it is not physiologically founded.

3. Results and discussion

As a result of the work, it became possible to simulate the dynamics of thermal comfort conditions in the cities of the Arctic zone for the first time ever (Figure 3).

The graphs show that, despite a significant interannual dynamics, there is an increase in the temperature and an increase in the simulated indices. The indices in all studied cities have a growth rate comparable to the growth rate of the surface air temperature.
Figure 3. Average annual trends in temperature and simulated indices of thermal comfort for Arctic cities.

The results can be divided into two groups. The reason for this heterogeneity is probably both regional and microclimatic (urban landscape) features. The first group is Arkhangelsk, Kandalaksha, Salekhard, and Naryan-Mar, where the trends of the PET and UTCI indices grow faster than the air temperature. This suggests that in these cities the level of comfort, on average, improves faster than the air temperature rises.

The second group is the cities of Murmansk, Nadym, and Anadyr, where the temperature graph and the PET and UTCI index graphs are almost parallel. This means that changes in the temperature and thermal comfort conditions in combination with other parameters embedded in these indices occur at the same rate. For convenience of evaluating the results, a table of the rates of temperature change and the comfort indicators for 10 and 50 years was compiled (Table 1).

Table 1. The growth rate of temperature and indices for 10 years and for 50 years.

| City         | ΔT For 10 years | ΔPET For 10 years | ΔPET For 50 years | ΔUTCI For 10 years | ΔUTCI For 50 years | ΔWind Chill For 10 years | ΔWind Chill For 50 years |
|--------------|----------------|------------------|------------------|-------------------|-------------------|-------------------------|--------------------------|
| Murmansk     | 0.45           | 0.54             | 2.71             | 0.68              | 3.42              | 0.60                    | 2.99                     |
| Kandalaksha  | 0.45           | 0.61             | 3.05             | 1.10              | 5.48              | 0.65                    | 3.25                     |
| Arkhangelsk  | 0.45           | 0.69             | 3.47             | 1.22              | 6.10              | 0.72                    | 3.60                     |
| Naryan-Mar   | 0.52           | 0.78             | 3.90             | 1.68              | 8.41              | 0.93                    | 4.65                     |
| Salekhard    | 0.53           | 0.67             | 3.33             | 0.82              | 4.08              | 0.41                    | 2.04                     |
| Nadym        | 0.54           | 0.50             | 2.51             | 0.47              | 2.36              | 0.60                    | 2.99                     |
| Anadyr       | 0.36           | 0.30             | 1.48             | 0.29              | 1.47              | 0.56                    | 2.79                     |

The average annual temperature for all cities changes at a rate of 0.47 °C / 10 years over 52 years (Table 1). The indices change, on average, at a rate of 0.57 °C / 10 years (PET) and 0.9 °C / 10 years (UTCI). It can be assumed that these are the average rates of change of the comfort indicators in the Arctic region. It is worth noting that an increase in the trends of the calculated indices can be
dangerous, since the spread of values (variance) also increases, that is, the number of very cold and very warm days that leads to thermal stress. In all respects, comfort in the city of Naryan-Mar is changing most rapidly. An analysis of the trends in the wind speed and relative humidity in Naryan-Mar has shown a steady and significant trend towards a decrease in the wind speed (the determination coefficient is 0.86) and a slightly less significant trend towards a decrease in the relative humidity. A change in these meteorological parameters included in the calculated indicators influenced the change in comfort in this city. In other cities of significant trends, changes in the wind speed and relative humidity are practically not observed (Figure 4).

According to the Wind Chill index, steady growth of this indicator is also observed in all cities (Table 1). These changes are comparable to the rate of change of the air temperature. Salekhard stands out separately, where this indicator grows more slowly than the temperature. The highest growth rates for changes in this index are in Arkhangelsk and Naryan-Mar: the growth is about 1.5 times faster than that of the temperature.

The results obtained may indicate that in the average annual climate of cities in the Arctic zone is becoming less rigid and more comfortable for living in this region.

3.1 Assessment of the dynamics of heat and cold stress
In order to assess which season of the year and which level of discomfort affects the change in comfort in the Arctic region, we analyzed the dynamics of the number of days with thermal stress according to UTCI and PET, as well as the number of days with cold stress according to UTCI and Wind Chill separately. Moreover, an analysis of the annual progress of these indicators was made. Assessment of the dynamics of the comfort indicators in the Arctic cities showed:

- A decrease in the number of days with severe cold stress in all cities of the Russian Arctic. The risk of hypothermia (according to the Wind Chill index and UTCI) and cold stress are most pronounced in Anadyr and Nadym, and least of all in Arkhangelsk, Kandalaksha, and Murmansk. On average, cold stress lasts 8 months a year with a maximum in January (Figure 5).
Figure 5. The dynamics of the number of days with very strong and extreme cold stress (UTCI < -27 and < -40) in the cities of the Arctic zone.

Figure 6. The number of days with strong heat exposure (PET > 35).

- An increase in the number of days with severe heat stress in Nadyom, Salekhard, Naryan-Mar, and Arkhangelsk (PET > 35). In Kandalaksha and Murmansk, such days are almost completely absent, while in Anadyr there are none at all. During the year, heat stress in most cities can be observed only in the summer months, with a maximum in July (Figure 6).
- Transitional seasons (April-May and October-November) make the largest contribution to the change in comfort in the Arctic cities (Salekhard) (Figure 7).
4. Conclusions
For the first time, a classification of local climatic zones (LCZs) was carried out for some cities of the Arctic zone of the Russian Federation. It was determined that the best characteristic for most of the cities is a “LCZ 5” zone (wide streets with houses about 10-25 meters high).

Using building data in each of the cities in a three-dimensional block of the RayMan diagnostic model, most common bioclimatic environmental comfort indices were calculated for 7 cities of the Arctic zone of the Russian Federation for 52 years: from 1966 to 2017. As a result, it was found that there are trends in an increase in the average annual temperature at a rate of 0.3-0.55 °C / 10 years. Despite this fact, almost throughout the whole Arctic zone of the Russian Federation the indices of thermal comfort in the cities of the Arctic are changing differently. Thus, in Arkhangelsk, Kandalaksha, Salekhard, and Naryan-Mar the PET and UTCI indices grow 1.5-3 times faster than the air temperature. This suggests that comfort in these cities, on average, improves faster than the air temperature rises. In Murmansk, Nadym, and Anadyr the trends in temperature and all three indices are almost parallel. This means that the changes in temperature and thermal comfort conditions, in combination with the other parameters embedded in these indices, take place at the same rate. This heterogeneity is caused by regional and microclimatic (urban landscape) features. The results obtained indicate that, on average, climate of the cities in the Arctic zone is becoming less rigid and more comfortable.

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