Local climate zones in the city of Nur-Sultan (Kazakhstan) and their connections with urban heat island and thermal comfort

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Abstract. Nowadays, under the conditions of modern development, an increase in population leads to a significant increase in urban settlements with their specific characteristics, which in turn may have a significant impact on the formation of special microclimatic conditions within cities. Due to territorial expansion of cities, most of them are developed at a significantly high speed, which may lead to dramatic changes both for the residents and for the environment within the cities. Since urban planning has been developing for a rather long time, there are many ways to regulate this process by taking into account local physical and geographical features. This work is devoted to relationships between various microclimatic indicators of changes in the structure of buildings. It is shown that an increase in the share of compact high-rise (local climate zone (LCZ)-1) and mid-rise (LCZ-2) buildings is reflected in an increase in the intensity of the urban heat island, both in average annual (+0.4…+0.5°C) and seasonal variations (+0.75°C for summer). This in turn causes an increase in the PET (Physiological Equivalent Temperature) thermal index (increasing of frequency of strong and extreme heat stress conditions) and a decrease in the UTCI (Universal Thermal Climate Index).

1. Introduction and motivation

In connection with the increase in the population, there is a need for territorial expansion of cities, most of which settle at a significantly high speed, which can lead to dramatic changes in the microclimatic conditions within cities. When considering changes in the microclimate, special attention should be given to the structure and layout of buildings. Today, the most urgent task is to make reasonable design decisions in the area of the building structure, which, if possible, should not disturb the natural course of processes in the environment [7].

The capital of the Republic of Kazakhstan, the city of Nur-Sultan, was chosen as the object of research in this work. It is of particular interest due to a relatively fast growth rate of the population, the influx of which is increasing from year to year (from 550 438 people in 2006 to 1 078 384 in 2019). Nur-Sultan stands on the banks of the Ishim River in the northern part of Kazakhstan (Figure 1). The purpose of this work is to identify the connection between the phenomenon of heat island and the conditions of thermal comfort with the change in urban development in the city of Nur-Sultan.
Urban climatology is used in the study of climatic features in cities, whose main task is to study the relationship of urban development with its environment [10].

One of the characteristics of microclimatic conditions is the urban heat island (UHI) [14]. This is an area in the inner part of a large city characterized by higher air temperatures compared to the periphery [6]. According to the vertical section of the heat island, the maximum air temperature values are observed in areas with more dense and high-rise buildings, while a sharp drop in the temperatures is observed in areas more remote from the city [9]. There are some works on UHI modeling in ex-USSR capitals, Nur Sultan [11], Moscow [4, 16, 17] and its connections with the thermal comfort conditions [5].

In the course of research on the phenomenon of heat island, many scientists drew attention to the possibility of impact of the urban environment on the comfort of the city residents [8]. Thermal comfort is those environmental conditions that ensure optimal functioning of the body without stressing the thermoregulatory apparatus [15]. Within the framework of this work, 2 bioclimatic comfort indices were considered: the PET thermal index and the UTCI cold index.

The PET is the physiological temperature at a given place equivalent to the air temperature, at which, under normal room conditions, the human thermal balance is maintained by the temperature of the skin and internal organs, which is equivalent to the estimates of these temperatures [1]. Some works allow one to use the PET as a predictor for additional mortality during heat waves in some continental big cities [13].

The UTCI is defined as the air temperature under standard conditions, resulting in the same physiological response as under actual conditions [2].

Both indices take into account:
- the whole set of meteorological parameters
- human physiological characteristics
- insulation capacity of clothing.

Local climate zoning implies the division of the city's territory into "local climate zones"; this is a microclimatic type of development, which designates a territory with uniform properties of the underlying surface over which a unique air temperature is formed, and depending on the density and height of the buildings [3].

According to the classification of local climate zones, 16 types of zones are conditionally divided into anthropogenic and natural landscapes. It is believed that the main contribution to the
change in the microclimate in the city is made by the compact high-rise and compact mid-rise type of building, i.e. LCZ-1 and LCZ-2.

2. Materials and methods

Within the framework of this work, the methodological part of the study consisted of three parts; the first one is devoted to local climate zoning, the second one is to determine the intensity of the urban heat island, and the third one is to calculate the thermal comfort.

For the local climate zoning the authors used a methodology developed within the framework of the World Urban Database and Access Portal Tools (WUDAPT) project aimed at obtaining a global database of cities. The initial data were Landsat satellite images of different times for 2006, 2011, 2016, and 2019. Based on the developed classification of local climatic zones, the areas of the study city were digitized in Google Earth. A different way (using Open Street Map – OSM technology) was described in [12]. Next, an automatic and trained classification was performed using the Local Climate Zone Classification tool in the SAGA GIS software. The proportion of each LCZ was calculated based on the number of pixels in each zone, which is displayed in the layer properties when exporting data from Saga GIS to ArcGIS.

To study the heat island phenomenon, the mean annual and typical diurnal variations and seasonal variability of the heat island intensity were considered. The initial data were taken from the “Weather schedule.rp5”, “Gismeteo” and “Kazhydromet” services. The settlements of Akkol and Arshaly located to the northwest and southeast of Nur-Sultan, respectively, were selected as background territories [11]. The main criteria for their selection are:

- their assignment to one natural zone (in this case, to the steppe)
- finding them to the city within no more than a hundred kilometers proximity
- proximity of values of absolute heights of meteorological stations
- position inside residential buildings.

When choosing a station in the city, 3 criteria were taken into account:
1. The station is located as close as possible to the city center
2. The station is located inside the urban area
3. The operation period of the station is not less than 10 years.

As a result, a weather station in the city center was selected for the study.

To calculate the thermal and cold comfort, the Rayman calculation model was used. The input data were the following parameters:

- geographic coordinates of the study area
- meteorological parameters of the environment in the research object
- physiological characteristics of the human body
- heat resistance of clothing.

As meteorological data, the program included such meteorological parameters as air temperature, relative humidity, average wind speed, and total amount of cloudiness in octants.

3. Results

As a result of zoning, 4 maps of local climate zones were obtained.

On the map for 2006 (Figure 2a), it can be noted that in the peripheral part of the city low-rise buildings of various densities prevailed, represented by the private sector. The central parts of the city were dominated by open mid-rise buildings. Thus, in total, 74% of the territory was occupied by low-rise buildings of various densities, while the share of mid-rise and high-rise buildings accounted for only 17%, and there were no compact high-rise buildings at all.

In 2011, the share of scattered and open low-rise buildings decreased (Figure 2b). In comparison with 2006, the left bank of the city began to rapidly build up with various multi-storey buildings. The total share of low-rise buildings was 63%. The share of compact and open mid-rise and high-rise buildings increased.

2016 saw the consolidation of a dispersed private sector. In the city center, the share of compact high-rise and mid-rise buildings increased (Figure 2c).
In 2019 (Figure 2d), the territory of the left bank was built up quite actively, which led to the presence of compact high-rise buildings here, low-rise buildings still prevail in the peripheral areas of the city, and a rather colorful set of local climate zones is noted on the right bank.

![Local climate zoning of Nur-Sultan, 2006](image1)
![Local climate zoning of Nur-Sultan, 2011](image2)
![Local climate zoning of Nur-Sultan, 2016](image3)
![Local climate zoning of Nur-Sultan, 2019](image4)

**Figure 2.** Local climate zone classification of Nur-Sultan for 2006, 2011, 2016 and 2019.

On the graph of the relationship between the average annual intensity of an urban heat island with changes in urban development (Figure 3a), there is a tendency to an increase in the intensity of this phenomenon, and it can also be seen that the intensity increases simultaneously with an increase in the proportion of dense buildings, which indicates the presence of a direct relationship between the formation of a heat island and changes in the nature of urban development.
The graph of the daily variation of the heat island intensity shows that the day and night variation of this phenomenon also has a direct relationship with the increase in the proportion of dense buildings (Figure 3b). The night course reflects the difference between the urban and rural areas more clearly, since buildings accumulate thermal energy throughout the day and, therefore, the urban area is cooled down more slowly during the night, creating a significant difference in temperature values with the background area. Whereas the temperature difference during the daytime is not very large, since solar radiation is distributed more or less evenly.

![Figure 3](image-url)

**Figure 3.** a) relationship between the average annual UHI intensity and changes in compact high-rise (LCZ-1) and mid-rise (LCZ-2) buildings (2006-2019); b) relationship between the average annual daily and night intensity of UHI and changes in compact high-rise (LCZ-1) and mid-rise (LCZ-2) buildings in 2006-2019.

The seasonal variability of the heat island and the compaction of buildings are also characterized by a direct relationship (Figure 4), and this relationship is most clearly reflected in the winter and summer periods. In winter, this is due to a large amount of anthropogenic heat flow in the city, the heating system, and, therefore, a long period for heat accumulation.
Figure 4. Relationship between the average annual UHI intensity for (a) winter, (b) spring, (c) summer and (d) autumn periods with changes in compact high-rise (LCZ-1) and mid-rise (LCZ-2) buildings (2006-2019).

To identify the relationship between changes in the heat stress and changes in the building density, the frequency of occurrence of extreme and strong heat stress, as well as the frequency of occurrence of conditions without heat stress, were calculated. These data will make it possible to understand whether the heat sensation and the degree of thermal stress of the population change under the changes in the building structure. Based on the graph in Figure 5, it can be seen that the percentage of time with extreme and strong heat stress tends to increase, synchronously increasing with the compaction of high-rise and mid-rise buildings. It is reasonable to assume that if heat stress increases with the compaction of buildings, then, on the contrary, the percentage of time without heat stress will decrease, this is confirmed by the graph on Figure 5, where an inverse relationship of 2 indicators is noted.
Figure 5. Relationship between the frequency of recurrence of extreme and strong heat stress and conditions without heat stress over summer according to PET with changes in compact high-rise (LCZ-1) and mid-rise (LCZ-2) buildings in 2006-2019.

4. Conclusions
An increase in the share of compact high-rise (LCZ-1) and mid-rise (LCZ-2) buildings was reflected in an increase in the intensity of the urban heat island, both in average annual (+0.4…+0.5°C) and seasonal temperature variations (+0.75°C for summer), which in turn caused an increase in the PET thermal index and a decrease in the UTCI. This study can be used in urban planning to assist in the development of specific mitigation strategies for each local climate zone in order to stabilize intra-urban meteorological parameters (air temperature, wind speed, etc.) which in turn may have a direct impact on thermal comfort.

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References
[1] Ashrae 2009 Physiological principles, comfort and health Handb. Fundam
[2] Błażejczyk K, Jendritzky G, Bröde P, Fiala D, Havenith G, Epstein Y, Psikuta A, Kampmann B 2013 An introduction to the Universal Thermal Climate Index (UTCI) Geogr Pol 5-10
[3] Stewart I D, Oke T R 2012 Local climate zones for urban temperature studies (Vancouver: University of British Columbia) p 93
[4] Kislov A V and Konstantinov P I 2011 Detailed spatial modeling of temperature in Moscow Russ Meteorol Hydrol 300-306
[5] Konstantinov P I, Varentsov M I and Malinina E P 2014 Modeling of thermal comfort conditions inside the urban boundary layer during Moscow’s 2010 summer heat wave (case-study) Urban Clim 10
[6] Matzarakis A, Amelung B, Blażejczyk K 2007 Climate Change and Tourism – Assessment and Coping Strategies Maastricht Warsaw Freiburg 227
[7] Mills G 2009 Luke Howard, Tim Oke and the study of urban climates IAUC newsletter 9
[8] Myrup L O 1969 A numerical model of the urban heat island J. Appl. Meteorol. 908-18
[9] Nunez M, Oke T R 1977 The energy balance of an urban canyon J. Appl. Meteorol. 11–19
[10] Oke T R 1987 Boundary layer climates Library of Congress 2 435
[11] Konstantinov P, Akhmetova A and Tattimbetova D 2016 Urban heat island and outdoor thermal comfort indices in extreme continental climate zone (Astana case-study) EMS Annual Meeting Abstracts p 47
[12] Samsonov T E, Konstantinov P I and Varentsov M I 2015 Object-oriented approach to urban canyon analysis and its applications in meteorological modeling Urban Clim. 13 122–139
[13] Shartova N, Shaposhnikov D, Konstantinov P and Revich B 2018 Cardiovascular mortality during heat waves in temperate climate: an association with bioclimatic indices Int. J. Environ. Health Res. 28 522–34
[14] Stewart I D 2011 Redefining the urban heat island Doct. Dissert (Vancouver: University of British Columbia) 368 p
[15] Taha H 1997 Urban climates and heat island: albedo, evapotranspiration, and anthropogenic heat Energy and buildings 99-103
[16] Varentsov M I, Konstantinov P I and Samsonov T E 2017 Mesoscale modelling of the summer climate response of Moscow metropolitan area to urban expansion IOP Conference Series: Earth and Environmental Science 96 doi:10.1088/1755-1315/96/1/012009
[17] Varentsov M, Wouters H, Platonov V and Konstantinov P 2018 Megacity-induced mesoclimatic effects in the lower atmosphere: A modeling study for multiple summers over Moscow Russia Atmosphere (Basel) 9