Abstract

The main goal of the study is the assessment of modern bioclimatic conditions (1966-2015) for determining the level of comfort in large Russian cities based on the observations at the meteorological stations, including Physiological Equivalent Temperature (PET) for the main extent of thermal comfort. According to the distribution of thermal stress events (calculated for meteorological fix hours, 8 times per day) the authors created the comfort diagram for each city during daytime heat wave period and evaluated their comfort conditions. In the current research we are operating with WMO climatic data for eleven biggest cities of the Russian Federation: from the European part (Moscow, Saint-Petersburg, Ekaterinburg, Voronezh, Volgograd, Kazan, Nizhny Novgorod, Perm, Ufa) and from Siberia (Omsk and Krasnoyarsk). The most interesting result of the comparison of the long-period (50 years) urban trends (PET-index and Air Temperature) in different parts of Russia is its extraordinary cross-shaped form in Moscow (in other cities the trends lines are practically parallel to each other). It means that at the level of the average annual values, only in Moscow the PET index (and, hence, potentially the thermal stress) grows faster than the regional climate warms. In other cities this tendency is much weaker (N.Novgorod) or not significant. This interesting tendency is caused by both Moscow related urban planning dynamics in post-USSR period and by regional climate dynamics.

Keywords: Physiological Equivalent Temperature (PET); regional urban climate; urban thermal comfort

Introduction

In recent times, the urban climate studies have inevitably shifted the emphasis towards the problems of sustainable development of (mega)cities. Such concept is closely connected with the studies of the human comfort in large cities in Europe and Asia. It is a rational approach to the resettlement and peaceful coexistence of a large number of people within the confines of a small territory (villages, cities, metropolises, etc.). From this point of view, the cities of the Russian Federation are an ideal monitoring platform, since the concept process of their development has just started. At the same time, it should be taken into account that the Russian Federation is a highly urbanized country (Kolosov & Nefedova, 2014), and this process has been connected to internal migration of the population since the 1970s.

Rapid urbanization in Russian Federation led to cities growth and its economic advance. Alongside this population of big cities (>1 000 000 inhabitants) is quite vulnerable to heat wave events due to intensive urban heat island event (Kislov & Konstantinov, 2011). In July and August 2010 in the biggest city in Russia – Moscow, where more than 11 million people live, the longest and the strongest heat wave as well as the warmest day (29th of July 2010) were recorded since the meteorological observations in Russia (Konstan-
This study is based on the characterization of the climatic trends of human thermal comfort and its assessment during heat wave periods. From the standpoint of human health heat wave is a period of time in which an excessive stress of thermoregulation of the body is accessed, as well as an increased risk of morbidity and mortality, especially from respiratory and cardiovascular diseases (Robinson, 2001; Arsenović et al., 2010). The same index was applied in Freiburg, Germany, or, more precisely, in the center of this city. The frequency of observed certain gradations of the comfort level by the PET index was calculated with Rayman, as well as the local maps of the bioclimatic comfort of this area (Frohlich & Matzarakis, 2010). The same index was applied in 2010 for the detailed analysis of the bioclimatic conditions of Freiburg for the conditions of the modern climate (period 1961-1990) and the forecast period (2071-2100) based on IPCC scenarios (Matzarakis & Endler, 2010). In general, the results show that the number of days with heat stress conditions has increased.

Another example of using this index with RayMan is the study based on the data analysis of 33,212 hospitalizations among people over 60 years old in São Paulo, Brazil between 2003 and 2007. (Silva & Ribeiro, 2012). The results of the study showed the increase in the probability of hospitalization among the group of people in unsatisfactory socio-economic conditions background of administrative influence on the part of the government. This allows to identify in which geographical regions the traditional type of city management is more successful from a bioclimatic point of view. In other words, in which regions conditions of thermal comfort in cities is a successor of air temperature trends and in which not.

Of course, within the framework of this study, we accept the hypothesis that changes in the trends of thermal comfort in Russian cities are associated with both the change in the regional climate and with the change of land-use properties in the urban environment. However, since the natural factor acts with approximately the same strength, noticeable differences in trends (if they are detected) can be generated by the influence of the urban microclimate, which is indirectly related to urban development strategies.

### Materials and Methods

This study is based on the characterization of the climatic trends of human thermal comfort and its assessment during heat wave periods. From the standpoint of human health heat wave is a period of time in which an excessive stress of thermoregulation of the body is accessed, as well as an increased risk of morbidity and mortality, especially from respiratory and cardiovascular diseases (Robinson, 2001; Arsenović et al., 2010). The same index was applied in Freiburg, Germany, or, more precisely, in the center of this city. The frequency of observed certain gradations of the comfort level by the PET index was calculated with Rayman, as well as the local maps of the bioclimatic comfort of this area (Frohlich & Matzarakis, 2010). The same index was applied in 2010 for the detailed analysis of the bioclimatic conditions of Freiburg for the conditions of the modern climate (period 1961-1990) and the forecast period (2071-2100) based on IPCC scenarios (Matzarakis & Endler, 2010). In general, the results show that the number of days with heat stress conditions has increased.

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by 12% with the increase in the value of the bioclimatic index by 10°C.

In this study, we use the Rayman model on a one-dimensional scale, without taking into account environmental obstacles and SVF in WMO-station standard environment.

Since there is no other long-term data for a similar period on the territory of the studied cities, it is assumed in the study that the measurement data characterize the city climate quite reliably. According to LCZ climate zones classification (Stewart & Oke, 2012), WMO station areas in cities, selected for long-term trend investigation (Moscow, Saint-Petersburg, Nizhny Novgorod, Perm, Ekaterinburg and Krasnoyarsk) are situated in Type 6 (Open low-rise) and Type 9 (Sparsely built) – see Fig.1.
Results

According to the distribution of thermal stress events it is possible to create comfort diagram for each city during daytime heat wave period (for Moscow and Saint-Petersburg see Fig.2). This plot shows that in both capitals the greatest frequency during daytime is in strong heat stress area (33.3% and 39.6%). Frequency of extreme heat stress in Moscow is 13.8% and in Saint-Petersburg 5.3%. The cases of comfortable sensations in the period of heat waves for the whole warm period in Moscow constitute only 6.9%. The lowest frequency is graded as “a slightly cold stress” which corresponds to a slight cold exposure (0.2%).

In general, we can say that in Moscow during the period of heat waves people in 47.5% of cases is vul-

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Figure 1. Satellite images of the cities, considered in the study (taken from Google maps) with locations of the used weather stations indicated by asterisk symbols (right panels). Right panes shows satellite images of the nearest surrounding of the weather stations (area within yellows squares in the left panels)

Figure 2. Frequency of PET grades in Moscow and Saint-Petersburg in the day time during heat waves (1966 - 2015 period)
nerable to heat stress. In Saint-Petersburg this value is 44.9%.

Based on the results obtained in the process of the PET index calculation we plotted a map-diagram which shows the distribution of various degrees of heat stress in 11 large cities of Russia. (Fig.3)

Proceeding from this, we can conclude that the most inclined to heat stress city in the daytime is Volgograd, as Volgograd is one of the hottest cities in Russia. Main PET and air temperature trend results can be briefly summarized in Table 2.

### Discussion

So, what if we decide to take a look at long period trends of PET and air temperature in cities of different parts of Russia? We know that climate is changing, air temperature rises in most parts of the Russia (Federal Service for Hydrometeorology and Environmental Monitoring, Roshydromet, 2014). But the thermal comfort is complex characteristic and its trend can clarify the real tendencies of human comfort sensation against the background of regional climate change (see Fig.4).

It is well known that the cities’ growth leads to the increase in trends of warming of the local urban climate, which is due to the joint impact of the global climate trends and the impact of the urban heat island (Kataoka et al., 2009). However, practically nothing is known about the relationship between temperature growth and changes in comfort parameters on the territory of Russia.

The most interesting result of the comparison of the urban trends (PET-index and Air Temperature) in different parts of Russia is its extraordinary cross-shaped form in Moscow (in other cities the trends lines are practically parallel to each other): in further research we plan to investigate such phenomenon by using different thermal comfort indices (UTCI etc) It can be caused just as by Moscow related urban planning dynamics in post-USSR period so by regional climate dynamics. The more detailed analysis of the dynamics of PET-predictors (direct solar radiation, wind speed), indicates that its growth is due to the presence of significant negative trends for wind speed and a score of lower clouds. The obvious, at first glance, the explanation of such well-pronounced wind speed trends - an increase in the roughness in the vicinity of the stations against the background of local land use change. However, the obtained trends for the Moscow region are in good agreement with the estimates from (Federal Service for Hydrometeorology and Environmental Monitoring, Roshydromet, 2014) and (Meshcherskaya, 2004; 2006), according to which the decrease in wind speed with speeds of 0.1-0.5 m/s/10 years over the last decades is typical for the European territory of Russia.

The trend of the decrease in the lower cloudiness in Moscow is making the greatest contribution to the
relative discomfort in summer is manifested more evi-
dently. The similar changes are consistent with the
trend of increasing duration sunshine against the
background of the increase in the total cloud score for
Moscow and Kazan (Gorbarenko et al., 2017; Sidoren-
ko et al., 2012) and the trend of erythema ultraviolet
radiation (Chubarova et al., 2018).

We used a small number of cities in our research
and can not say about the global trends in the coun-
try, nevertheless it is possible to make some valuable
conclusions.

The high probability of the heat stress is more evi-
dent for large and fast-evolving cities of Central Rus-
sia. The faster growth of PET temperatures is observed
as compared to air temperatures. This is confirmed by
the examples of Moscow and Nizhny Novgorod (PET-
warming trend is two times more intensive than ther-
mal one). We can suggest that the cross-shaped form of
T and PET can be noticed in Nizhny Novgorod soon.

The maritime climate of Saint Petersburg (the only
city with this type of climate among the observed) has
the impact on the conditions of thermal comfort. De-
spite the increase of T the significant changes in PET
(feeling of heat for human) did not occur. The proba-
bility of heat stress in this city is inconsiderable.

Perm and Yekaterinburg are both located in the
area of the Ural Mountains and have similar trends
in PET values. We can observe the increase in PET
greatly correlated with temperature changes without
any unusual effects.

Krasnoyarsk has the most continental climate type
among the cities reviewed. We can observe small dif-
ference between T and PET in addition to the growth
of both parameters. Krasnoyarsk can be considered as
the city with the lowest probability of heat stress.

An argumentative issue, of course, is the choice
of this particular parameter (the frequencies of PET
grades) for determining the relative risk of thermal
discomfort phenomenon. However, taking into ac-
count the absolute temperature values of thermal
waves is also not ideal - because of both the adapta-
tion of the population of more southern regions to hot
weather, and the vulnerability of the criterion (Frich
et al., 2002) for determining heat waves in the nor-
thern regions.

The obtained results can be considered in the fur-
ther analysis with larger number of weather stations
and can used for categorization of cities according to
the level and the dynamics of thermal comfort con-
ditions.

Conclusions

Within the frames of this study, the PET equivalent-phys-
iological temperature index was calculated for each day
of the warm period for 11 biggest cities of Russia. Based
on the results of the calculations, we have plotted the dia-
grams with the frequency of occurrence of extreme ther-
mal events during the heat waves for each town.

Also showed that at the level of the average annu-
al values, only in Moscow-city the PET index (and,
would, potentially the thermal stress) grows faster
than the regional climate warming (0.93 °C/10yr for PET
and 0.36 °C/10yr for air temperature). In other cities
this tendency is much more weak (N.Novgorod) or
not significant. The most inclined to risk city during
the heat waves in the daytime is Volgograd, while St.
Petersburg can be considered the safest, since the fre-
quency of thermal stress even in this dangerous peri-
od does not exceed 5.3% of all the cases.

The main result achieved during the study is the
creation of Russia’s first comparative climatology of
comfort in biggest cities and the determination of the
relative danger of heat waves for each of them based
on the analysis of 50 year time series, as well as the de-
termination of the dynamics of heat comfort indices
for the last 50 years (1966-2015).

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Author Contributions

Pavel Konstantinov and Natalia Shartova conceived and designed the experiments; Diana Tattimbetova per-
formed the experiments with Rayman model for warm season periods; Pavel Konstantinov and Mikhail Varentsov
analyzed the data; Pavel Konstantinov finally wrote the paper.
References


