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GEOPHYSICS

Heat Island Structure over Russian Towns Based on Mobile Laboratory Observations

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We analyze the spatial structure of urban heat island (HI) and its time variations. This research is based on the data of measurements of surface temperature, solar irradiance, and atmospheric composition carried out onboard a mobile railway laboratory in 1996–2009 along the Trans-Siberian Railway (experiments TRanscontinental Observations Into the Chemistry of the Atmosphere (TROICA)). The characteristics of HI were obtained for large, intermediate, and small cities in different seasons and times of the day. The maximum differences in the surface temperature between the urban and rural territories (ΔT) were observed at night in summer. The mean values (ΔT) over the urban territory during the night in summer are, respectively, 1.9, 0.9, and 0.7°C, while in the daytime they are 0.5, 0.3, and 0.5°C. The estimate of the influence of different factors on HI formation shows that absorption of the outgoing IR-radiation by the greenhouse gases and anthropogenic heat fluxes play the main role in this process.

A heat island is a characteristic peculiarity of the meteorological and climatic regimes in cities. Numerous comparisons of the data of meteorological stations located in cities and outside their limits have demonstrated that an increase in the surface temperature is on average from tenths of a degree to a few degrees, while the temperature field has a nonuniform spatial structure and changes significantly depending on the size of the city, season, time of the day, state of the surface, and different meteorological and anthropogenic factors [1–5]. The vertical scope of the HI covers a significant part of the atmospheric boundary layer spreading over a few hundred meters [6].

In the past year, interest in research on HI has increased sharply because, firstly, the temperature regime in the cities influences the air quality, and secondly, the values of parameters measured at meteorological stations located in cities can influence the estimates of variations in the regional and global climate. We revealed a number of factors that were previously not taken into account in the analysis of the data or were taken into account incorrectly. These are the discrepancy between the time of measurements at different stations, the differences in the height and latitude of observation points, application of different types of thermometers, and different methods of measurements and data processing. The authors of [7] demonstrated on the basis of 289 stations in the US united into 40 urban clusters that the differences between the urban and rural stations almost disappear if the inhomogeneities in the temporal, spatial, and methodological data are excluded. This does not mean that the HI does not exist but emphasizes the significant inhomogeneity of the temperature field within the city and surrounding rural territory. In particular, the urban stations located in the territories of the parks frequently give lower temperature values compared with the rural territories. The results obtained in [7] give grounds to conclude that local impacts on the temperature regime in the US dominate over the mesoscale impacts.

At the same time, analysis of the global network data of meteorological stations given in [8] revealed a significant impact of the variations in the state of the Earth's surface related to socio-economical activity. According to [8], accounting for the influence of anthropogenic factors resulted in a twofold decrease in the positive global temperature trend at the Earth's surface during the period from 1980 to 2002. This anthropogenic effect is observed in developed and developing countries.

The main cause of the differences in the estimates of the HI is the comparison of strongly nonuniform temperature fields in the cities and beyond their limits based on the data of observations from a low number of meteorological stations (sometimes only two–three as was done, for example, in [3, 4]). In this work, we present the characteristic features of the spatial structure of the temperature regime on the territory of the Russian cities obtained using the unique railway laboratory (TROICA experiments [9]). We used the data of 10 expeditions in 1996–2009 along the Trans-Siberian Railway (two of them were held in the winter period,

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Table 1. Towns divided into three groups depending on the population (in thousands of people)

Large	Intermediate	Small
Yekaterinburg, 1343.8	Anzhero-Sudzhensk, 82.6	Barabinsk, 30.3
Krasnoyarsk, 962.5	Achinsk, 110.1	Zima, 34.1
N. Novgorod, 1271.0	Birobidzhan, 75.4	Kotel'nich, 25.9
Novosibirsk, 1409.1	Vladimir, 337.7	Marrinsk, 41.6
Omsk, 1127.7	Glazov, 96.6	Nizhneudinsk, 36.7
Perm 986.5	Ishim, 64.1	Skovorodino, 9.5
Tyumen, 580.2	Kansk, 96.6	Taiga, 25
Khabarovsk, 580.7	Kirov, 463.9	Taisht, 36.3
Yaroslavl, 606.9	Kungur, 67.9	Tulun, 46.8
	Ulan-Ude, 377.1	Shimanovsk, 21.6
	Cheremkhovo, 53.6	
	Chita, 308.8	
	Yurga, 83.8	

one in spring, five in summer, and two in autumn) [9]. In order to explain the causes of HI formation and variability of the structure, we applied the data of simultaneous measurements of solar irradiance fluxes and concentration of low admixtures in the surface air.

The laboratory route from Moscow to Vladivostok crossed a total of 110 towns. Thirty-two towns located in the latitudinal zone 48°–58° N were selected to estimate the HI. They were divided into three groups by population (Table 1). The first group included all large cities with a population exceeding 580 000 people, excluding Irkutsk whose main territory is located far from the railway. Those intermediate and small towns were selected where the railroad passed through the central part of the towns and the whole city was not under the influence of larger towns. Each town was crossed 10 times in the easterly direction and 10 times in the westerly direction. The observations cover the period from February to October.

The temperature sensors were installed at a distance of 40–50 cm over the roof of the test coach and 5 m over the railroad surface. The vertical temperature profile up to a height of 600 m was determined using the microwave profiler MTP-5. The instruments to measure the concentration of gases and aerosol, solar irradiance, and other atmospheric characteristics are described in [9]. The periodicity of recording the measured parameters is 10 s, while the vertical temperature profile was measured with a time interval of 2.5 min. The test coach laboratory was always located immediately after the locomotive. The temperature sensors and the system of air sampling were above the perturbation zone induced by the locomotive [9].

The intensity of the HI was estimated from the difference in the surface temperatures on the territory of the town with industrial suburbs and the mean temperature for the surrounding rural territory. We excluded the influence of the daily temperature cycle and variations in the altitude of the railroad above sea level. These data as well as the other navigation parameters were determined on the GPS basis. The diurnal cycle was restored using the running averaging over two hours of data measured outside the towns. The vertical temperature gradient was assumed equal to 6°C/km. Figure 1 shows marks between the sections used to determine the HI by means of averaging over individual parts of the towns. Mark (0) corresponds to the location of the station, which is usually in the central part of the town (–1; 1); the business part of the town corresponds to the interval (–2; 2); the main territory of the town corresponds to (–3; 3); the industrial zone and the suburbs occupy intervals (–3; –5) and (3; 5). The rural territory before and after crossing the town, relative to which we determined the HI, occupies the intervals (–5; –6) and (5; 6). Their lengths are equal to one-third of the town diameter. The temperature over the territory of the town was averaged over the number of values that fall within one interval of sections: 0–1, 1–2, etc. Due to different size of towns and varying speed of travelling, number of values in each crossing varied from 8 to 115. In order to analyze the diurnal cycle of ΔT, the day was divided into periods of the local time: 05–09 h (morning); 09–13 h (day); 18–23 h (evening), and 23–05 (night).

The heat island is characteristic of all three town groups. The values of ΔT averaged over all expeditions are presented in Table 2. They are maximal in the central part of the towns and decrease with an increase in the territory used for averaging. The nighttime values of ΔT exceed significantly the daytime values. In the daytime, ΔT decreases when the sizes of the towns decrease. At night, ΔT in the intermediate-size towns is smaller than in the small towns due to more powerful and long temperature inversions in the latter.

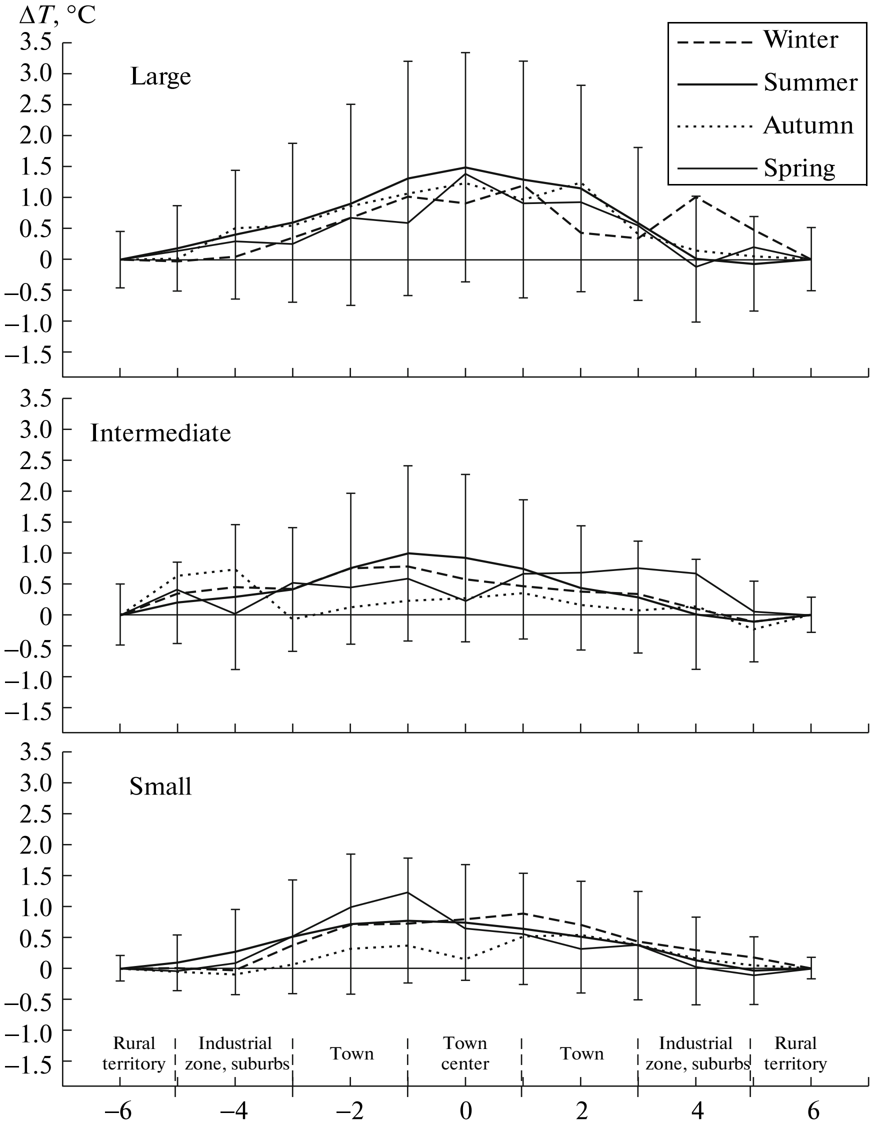

Fig. 1. Structure of a heat island (daily mean values of ΔT) over large, intermediate, and small towns in different seasons. MSWD are given for the summer period.

The distribution of average values of ΔT over the territories of towns in different seasons is shown in Fig. 1. In the summer time, the maxima of ΔT are confined to the central regions of the towns. In almost all cases, the HI covers the whole territory of the towns, while in the large cities it also covers part of the suburbs occupied by the industrial zones. The weakest HI with a limited territory was observed in the transition seasons: in spring (in the large cities) and in autumn (in the intermediate and small towns). The values of ΔT averaged over the whole territory of the towns (−3; 3) and their center (−1; 1) in different seasons and times of day are presented in Table 3.

The variability in the surface air temperature along the route of the study that crosses the towns and from one pass through the town to another is very strong. It is seen in Fig. 1 from the root-mean-square deviations for the summer season, which reach ±2°C. The recurrences of ΔT averaged over the entire territory of the town (−3; 3) in each season are presented in Table 4. In all town groups and in all seasons, the maximum number of measurements falls in the interval 0–1°C. The larger the city, the more frequently high positive values of ΔT are found, and vice versa, negative values are rarer. The recurrence of ΔT averaged over the business part (−2; 2) and central parts (−1; 1) of the towns is displaced to high values. In winter, in the centers of large cities, it can be as high as 34.8% in the interval 1–2°C. At the same time, the distributions of ΔT values in all three groups of the cities are very close in summer, while for the middle intervals 0–1°C and 1–2°C, they coincide. This indicates that the mechanism of HI formation in the summer period is approximately the same for the towns of arbitrary size.

The value of HI is different at different times of day. In all groups of towns and seasons, the maximum ΔT are revealed at night (sometimes in the evening), while the minimum ones are found in the daytime or in the morning. An example of daily variations in ΔT for large cities is shown in Fig. 2. The daily maxima of ΔT are found in summer in the central parts of towns at night (reaching 3.2°C), while in the morning ΔT values are close to zero over the entire territory. In the other seasons, the character of variations in the distribution of ΔT over the territory of large cities is approximately the same.

In the towns of intermediate size, the maximum nighttime values of ΔT, which are approximately equal to 2.0°C, were recorded in winter. It was also found that the HI phenomenon was not recorded in the morning hours in winter. The distribution of ΔT over the territory of small cities at different times of day has its own specific peculiarities related to widely used oven heating and increased stability of the nighttime atmospheric boundary layer. All this supports the idea that the temporal and spatial variability of temperature in the towns is closely related to their infrastructure and micro-meteorological processes.

The main factors determining the difference in the temperature regime in the towns from the rural territory include the following: high fluxes of anthropogenic heat, decreased solar insolation due to air pollution, decreased IR-radiation of the underlying surface owing to the higher concentration of greenhouse gases in the air and smaller openness of the sky, lower heat losses for evaporation due to the fast removal of precipitation and smaller area of the vegetative cover. Assuming that the entire energy consumed in the city is transferred to heat, it is possible to estimate the flux of anthropogenic heat Q_a and induced variation in temperature ΔT_a.

In order to estimate this, the authors of [10] suggest using the published data about the energy consumption per capita in Russia (EU), which is equal to 4424 kg of oil equivalent. Taking into account the sizes of towns and population density (as in 2002), we obtain that the mean values of Q_a in the large, intermediate, and small cities are equal to 11.7, 5.2, and 3.2 W/m^2, respectively.

The measurements of vertical temperature profiles in the TROICA experiments show that the influence of the HI over the towns spreads to the altitudes reaching from 50 to 600 m depending on the time of observations, meteorological conditions, and terrain topography. The daily average wind velocity in the towns located along the Trans-Siberian Railway changes from 3 m/s in the winter months to 2.3 m/s in summer. By knowing the size of the towns, one can estimate the time of the air mass lifetime over the territory of the town and calculate the surface air temperature increase from the known anthropogenic heat flux similarly to the method used in [4]. The maximum heating of an air mass that passes over a town depends on the wind velocity and vertical stratification given above and changes from 0.1 to 1.8°C for large cities, from 0.05 to 0.7°C for intermediate-size towns, and from 0.02 to 0.3°C for small towns. The nighttime temperature inversions accompanied with light winds cannot notably increase the upper estimate of ΔT because anthropogenic fluxes are weaker at night than in the daytime. However, if temperature inversions exist during the daytime as was observed in the summer of 2010 in Moscow [11], the value of ΔT can go beyond the given limits of variations.

Table 2. Values of temperature excess in towns ΔT over all expeditions for large, intermediate, and small towns in daytime and nighttime

Category of towns	ΔT, °C			
	(–1; 1)	(–2; 2)	(–3; 3)	(–5; 5)
Large	$\frac{0.67}{1.89}$	$\frac{0.53}{1.8}$	$\frac{0.44}{1.43}$	$\frac{0.34}{0.83}$
Intermediate	$\frac{0.3}{0.82}$	$\frac{0.32}{0.67}$	$\frac{0.31}{0.49}$	$\frac{0.18}{0.31}$
Small	$\frac{0.14}{0.9}$	$\frac{0.1}{0.87}$	$\frac{0.08}{0.75}$	$\frac{0.03}{0.51}$

Note: Here and in Table 3, the daytime values are above the bar and nighttime values are below the bar.

Table 3. Mean values of ΔT for the centers of towns (–1; 1) and total territory (–3; 3) for three groups of towns, different seasons, in daytime and nighttime

Category of towns	Winter	Spring	Summer	Autumn
Centers of towns				
Large	$\frac{0.7}{1.15}$	$\frac{0.96}{1.61}$	$\frac{0.77}{2.74}$	$\frac{0.26}{2.07}$
Intermediate	$\frac{0.47}{0.71}$	$\frac{-0.04}{1.12}$	$\frac{0.47}{1.05}$	$\frac{0.3}{0.4}$
Small	$\frac{0.21}{1.2}$	$\frac{-0.14}{1.29}$	$\frac{0.54}{0.82}$	$\frac{-0.05}{0.27}$
Total territory of towns				
Large	$\frac{0.34}{0.86}$	$\frac{0.79}{1.31}$	$\frac{0.51}{1.94}$	$\frac{0.11}{1.61}$
Intermediate	$\frac{0.46}{0.55}$	$\frac{0.11}{0.39}$	$\frac{0.26}{0.85}$	$\frac{0.4}{0.15}$
Small	$\frac{0.17}{0.96}$	$\frac{-0.24}{1.01}$	$\frac{0.45}{0.75}$	$\frac{-0.08}{0.29}$

In order to estimate the temperature variations ΔT caused by a decrease in the solar irradiance flux ΔQ_s caused by air pollution, we used the data of observa-

Table 4. Recurrence of daily mean values of ΔT averaged over the town territory (–3; 3) and seasons

Category of towns	Season	Recurrence ΔT, %				
		<0°C	0–1°C	1–2°C	2–3°C	>3°C
Large	Winter	13.1	60.9	17.4	4.3	4.3
	Spring	0.0	77.0	5.1	9.0	8.9
	Summer	9.8	52.5	21.3	8.2	8.2
	Autumn	21.8	34.5	25.0	12.5	6.2
Intermediate	Winter	23.8	59.5	9.5	7.2	0.0
	Spring	36.4	54.5	4.5	4.6	0.0
	Summer	21.5	52.1	21.5	3.9	1.0
	Autumn	20.5	61.3	15.9	0.0	2.3
Small	Winter	30.8	46.1	12.9	7.7	2.5
	Spring	25.0	50.0	25.0	0.0	0.0
	Summer	21.8	52.9	21.9	3.4	0.0
	Autumn	32.4	54.1	8.1	5.4	0.0

tions in the TROICA expeditions. Owing to the strong variability in the irradiance fluxes over the territories of towns, significant estimates of ΔQ_s were obtained only for the joint group of large and intermediate towns. The mean values of ΔQ_s for the summer season were approximately 6% or 9 W/m^2. This value is close to the results in [12] based on the analysis of the world network of actinometric stations in the urban regions in the latitudinal zone 40°–70° N. Using the data of expeditions and data in [12], one can estimate the cooling of an air mass that passes over a town for the large, intermediate, and small towns: it is equal to –0.4, –0.2, and –0.1°C; i.e., a decrease in the solar irradiance flux compensates for the influence of anthropogenic heat fluxes.

At present, it is difficult to calculate the quantitative estimate of the contribution of other factors to HI formation on the basis of data of the TROICA experiments. However, the correlation between ΔT and the concentration of greenhouse gases (carbon dioxide, water vapor, methane, and others) and soot compounds in the atmosphere is clear. The distributions of these admixtures were obtained on the territories of all three groups of towns in different seasons and times of day. Figure 3 presents the distribution of the water vapor over the territories of large cities at different times of day for the winter and summer seasons. Night and day excess of the water vapor content in the urban atmosphere related to the rural regions in winter is a characteristic peculiarity of this distribution in winter.

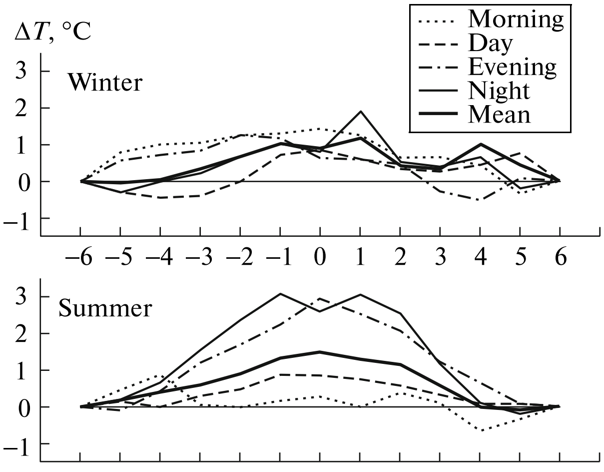

Fig. 2. Structure of a heat island over large cities at different times of day in winter and summer.

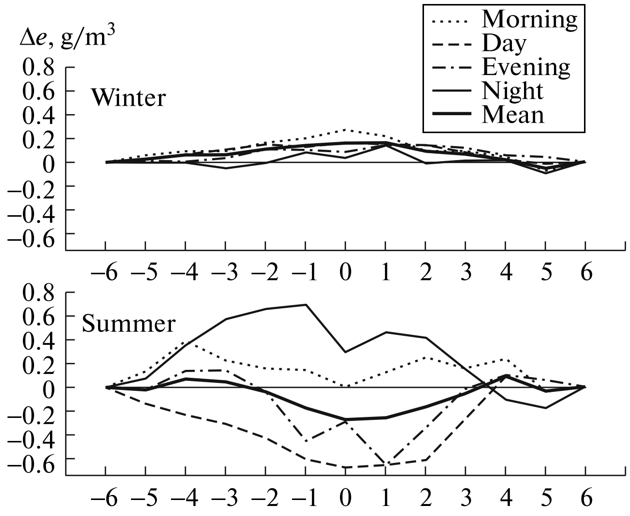

Fig. 3. Daily variations in the difference of water vapor content in the towns and rural territories (Δe) for large cities in winter and summer.

In summer, this is observed only at night and in the morning hours. This is a result of the significant amount of water vapor released during fuel combustion and the low rate of evaporation in the daytime compared to the rural regions. The water vapor gives the greatest contribution to the absorption of IR-radiation of the underlying surface. Its prevalence in the urban atmosphere and the time variability influence significantly the formation of HI. The authors of [4] correlate the HI solely with the influence of the water vapor. The presence of other greenhouse gases in the urban atmosphere and their typical variability confirm their influence on HI formation. The observations of CO_2, the second important greenhouse gas, during the TROICA expeditions confirm that its concentration is also increased in the air of the towns during the whole day in winter. In summer, such an excess is observed only in the daytime because nighttime emissions of CO_2 from vegetation in the towns are much weaker than beyond the town boundaries. Daytime domination of CO_2 compensates for the daytime weakening of the greenhouse effect caused by a decrease in the concentration of water vapor at that time of day. Sharply increased concentrations of methane and soot aerosols [9] in the air of the towns also facilitate formation of HI.

Heating of buildings due to the absorption of solar irradiance and intensity of turbulent mixing, which is different from the rural regions can also influence the heat balance in towns. However, detailed analysis of the spatial and temporal structure of the urban HI provides evidence about the dominating role of the anthropogenic heat fluxes and greenhouse effect caused by the absorption of IR-radiation from the underlying surface by the water vapor, carbon dioxide, and soot aerosols.

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