PECULIARITIES OF THE FORMATION OF THE URBAN TEMPERATURE AND HUMIDITY REGIMES

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The data of observations on the temperature and humidity of air in St. Petersburg and its environs are analyzed. The probability density functions are calculated for the temperature and water vapor pressure differences (ΔT and Δe, respectively) in St. Petersburg and two stations located in its environs. Analysis of these functions for day and night times and two seasons of the year as well as a statistical correlation between Δe and ΔT leads to a conclusion that meteorological factors and primarily variations of the effective emissivity of the underlying surface caused by the difference Δe and of the evaporation rate are decisive for the formation of the urban temperature field (heat island).

Peculiarities of the formation of the urban temperature regime have been already studied by us in ample detail[1,2] by the example of Leningrad. In the present paper, most attention is concentrated on an analysis of the humidity field in St. Petersburg and its environs as well as on the effect of this field on the air temperature regime.

To estimate the correlation between the humidity and temperature, the differences of these meteorological parameters measured in St. Petersburg and at two stations located ~80 km to the north and to the south of the city were calculated from the data of ground-based observations performed 8 times a day in St. Petersburg and Belogorka in 1975–1979 and in Sosnovo in 1977–1980.

The number of samples used to calculate the statistical characteristics of the differences of meteorological parameters (air temperature T, water vapor pressure e, and relative humidity f) was 3608 in winter and 3680 in summer for Belogorka (B) and 1920 in winter (December–February) and 2208 in summer (July–August) for Sosnovo (S). Observations at 21, 00, 03, and 06 h were considered as nighttime and observations at 09, 12, 15, and 18 h were considered as daytime.

AIR HUMIDITY

The regime of air humidity in St. Petersburg differed significantly from that in its environs. When fuel (coal, petroleum, gas, or wood) burns, a significant amount of water vapor is produced along with carbon oxide and dioxide (CO and CO_2) and other gaseous and solid pollutants: in combustion of 1 kg of gasoline, 1.3 kg of water vapor is released, 1 kg of natural gas produces 1 kg of water vapor, and 1 kg of dry wood produces 0.3 kg of water vapor.

It is natural that the total content of water vapor in air is increased due to the water vapor of anthropogenic origin released into the atmosphere. Any change of the urban underlying surface affects the rate of soil evaporation and plays an important role. The data on the water vapor pressure difference Δe in St. Petersburg and its environs are tabulated in Table I.

TABLE I. Average seasonal values of the difference $100\cdot\Delta e$, *in* hPa: $\Delta e_1 = e_{\mathrm{Pb}} - e_{\mathrm{B}}$ *and* $\Delta e_2 = e_{\mathrm{Pb}} - e_{\mathrm{S}}$.

	Season	Time, h								Night-time	Day-time	Daily
		00	03	06	09	12	15	18	21			
Δe_1	Winter	35	32	32	33	29	21	34	33	33	29	31
	Summer	35	87	86	−16	−8	−7	−7	−29	45	−10	18
Δe_2	Winter	27	27	30	30	26	19	27	26	28	23	25
	Summer	113	150	123	17	23	17	7	17	101	16	58

In winter the evaporation conditions in the city do not differ significantly from those in the environs (the Earth's surface is covered with snow and there is no grass), and the anthropogenic factor makes a dominant contribution to variations of the parameter e. Because of this, the water vapor content in the city becomes higher than in the environs during the entire period of observations in winter ($e_{\mathrm{Pb}} > e_{\mathrm{env}}$ and $\Delta e > 0$). At night under conditions of prevailing temperature inversion, gentle wind, and weak turbulent exchange, evaporation

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has insignificant effect in winter and in summer; therefore, at that time $\Delta e > 0$.

In the daytime and in the evening under conditions of developed turbulent exchange the rate of soil evaporation (turbulent water vapor flux from the underlying surface) starts to play more significant role in the formation of Δe. It is less in the city than in its environs: a large part of precipitated water is carried away through a sewerage system and does not evaporate, an area of the plant cover is much smaller, and so on. For this reason in summer the difference Δe_2 in the daytime and evening is by a factor of 5–15 smaller than at night, whereas the difference Δe_1 even changes its sign in comparison with nighttime ($\Delta e_1 < 0$). We noted that any nighttime (00–06 h) Δe is greater than any daytime (12–18 h) value of this parameter.

Analysis of the recurrence and distribution function of Δe (Table II) demonstrates that in winter the maximum of recurrence of Δe_1 lies between 0.25–0.50 hPa at night and in the daytime, whereas the maximum of recurrence of Δe_2 lies between 0–0.25 hPa.

In winter the maximum and minimum values of Δe_1 are 7.0 and 3.0 hPa, whereas of Δe_2 (−4.0) and (−6.0) hPa. In summer the maximum of recurrence of Δe is less pronounced than in winter. The difference Δe_1 most often lies between 0.25 and 0.50 hPa at night and between −0.25 and 0 hPa in the daytime, whereas Δe_2 lies between 0.75–1.00 hPa at night and 0.25–0.50 hPa in the daytime. In summer the minimum value of Δe_1 is (−14) hPa and its maximum value is 9 hPa, whereas the minimum of Δe_2 is (−4) hPa and its maximum is 5 hPa.

The probability of occurrence of positive values of Δe, equal to $1 - F(\Delta e \leq 0)$, is fairly stable in winter: it is equal to 75–78% at night and to 74% in the daytime. In summer it varies in wide limits: from 62 to 81% at night and from 46 to 56% in the daytime.

As can be seen from the data presented in Table II, the relative air humidity in St. Petersburg is by several per cent less than in Sosnovo in winter and in summer at any time of the day (because all $\Delta f_2 < 0$). In summer the relative humidity in St. Petersburg is also less than f_B in Belogorka ($\Delta f_1 < 0$). However, in winter f_{Pb} is by 1–1.5% greater than f_B ($\Delta f_1 > 0$).

TABLE II. Recurrence (the number of cases m) and the distribution function (F, %) of the differences Δe_1 and Δe_2. Here, n denotes night and d denotes day.

			Range of variations of Δe, hPa													
			< −3	(−3)–(−2)	(−2)–(−1)	(−1)–(−0.5)	(−0.5)–(−0.25)	(−0.25)–0.0	0.0–0.25	0.25–0.50	0.5–0.75	0.75–1.0	1.0–1.5	1.5–2.0	2–3	>3
Winter																
Δe_1	n	*m*	–	–	10	33	65	297	414	515	218	133	100	14	3	2
		F	–	–	1	2	6	22	45	74	86	93	99	100	100	100
	d	*m*	–	1	6	40	81	327	427	436	233	143	83	14	2	1
		F	–	0	0	3	8	26	50	74	87	94	99	100	100	100
Δe_2	n	*m*	8	–	11	38	53	134	252	230	122	49	43	11	7	2
		F	1	–	2	6	11	25	52	76	88	94	98	99	100	100
	d	*m*	2	–	5	30	67	138	254	199	128	65	38	25	4	–
		F	0	–	1	5	12	26	53	74	87	93	98	100	100	–
Summer																
Δe_1	n	*m*	67	48	171	174	101	142	131	153	95	153	172	136	165	132
		F	4	6	16	25	30	38	45	54	59	67	76	84	93	100
	d	*m*	77	120	253	236	110	193	116	148	86	122	139	85	103	52
		F	4	11	24	37	43	54	60	68	73	79	87	92	97	100
Δe_2	n	*m*	1	10	50	53	29	68	64	105	92	108	123	110	143	144
		F	0	1	6	10	13	19	25	34	43	52	64	74	87	100
	d	*m*	9	41	115	155	68	96	65	111	84	76	103	72	62	46
		F	1	4	15	29	35	44	50	60	67	74	83	90	96	100

The relative air humidity $f = e/E(T)$ is a function of the absolute content of water vapor e and of the air temperature (indirect dependence through the saturated vapor pressure E which depends on T). In most cases, as can be seen from Table III, f and $\Delta f = f_{Pb} - f_{env}$ are primarily affected by the air temperature: its increase in St. Petersburg leads to the decrease of f_{Pb} and negative values of Δf. Only in winter the increase of e_{Pb} in comparison with e_B has a determining effect on Δf_1.

TABLE III. Average seasonal values of the difference Δf (%): $\Delta f_1 = f_{\mathrm{Pb}} - f_{\mathrm{B}}$ *and* $\Delta f_2 = f_{\mathrm{Pb}} - f_{\mathrm{S}}$.

	Season	Time, h								Night-time	Day-time	Daily
		00	03	06	09	12	15	18	21			
Δf_1	Winter	1.2	1.1	1.4	1.2	00	1.2	1.7	1.1	1.2	1.0	1.1
	Summer	−8.6	−7.9	−6.8	−5.7	−2.0	−0.7	−1.1	−4.3	−6.9	−2.4	−4.7
Δf_2	Winter	−1.7	−2.2	−2.0	−1.9	−1.8	−2.2	−1.9	−2.4	−2.1	−2.0	−2.0
	Summer	−7.4	−6.0	−5.0	−4.6	−2.6	−2.3	−3.2	−6.0	−6.1	−3.2	−4.6

AIR TEMPERATURE

According to the data given in Table IV, the average values of the temperature difference $\Delta T = T_{\mathrm{Pb}} - T_{\mathrm{env}}$ in St. Petersburg and its environs (T_{B} and T_{S}) are positive in winter and in summer ($\Delta T > 0$) throughout the observations, that is, the city is warmer than its environs. In winter the difference ΔT changes insignificantly: the average nighttime values of ΔT_1 and ΔT_2 exceed their average daytime values only by 0.5 and 0.3°C, respectively (although sometimes this increase can be more pronounced; thus, ΔT_1 at 03 h is two times greater than at 15 h).

TABLE IV. Average seasonal values of the differences $\Delta T_1 = T_{\mathrm{Pb}} - T_{\mathrm{B}}$ *and* $\Delta T_2 = T_{\mathrm{Pb}} - T_{\mathrm{S}}$, *in* °C.

	Season	Time, h								Nighttime	Daytime	Daily
		00	03	06	09	12	15	18	21			
ΔT_1	Winter	1.7	1.8	1.6	1.6	1.3	0.9	1.2	1.6	1.7	1.2	1.5
	Summer	2.2	2.5	2.2	0.9	0.2	0.1	0.0	0.6	1.9	0.3	1.1
ΔT_2	Winter	1.7	1.7	1.7	1.4	1.5	1.4	1.5	1.6	1.7	1.4	1.6
	Summer	2.6	3.1	2.3	1.1	0.9	0.7	0.9	1.2	2.3	0.9	1.6

TABLE V. Recurrence (the number of cases m) and distribution function (F, %) of the temperature differences $\Delta T_1 = \Delta T_{\mathrm{Pb}} - \Delta T_{\mathrm{B}}$ *and* $\Delta T_2 = \Delta T_{\mathrm{Pb}} - \Delta T_{\mathrm{S}}$. *Here, n denotes night and d denotes day.*

			Range of variation of ΔT,°C											
			(−3)–(−2)	(−2)–(−1.5)	(−1.5)–(−1.0)	(−1.0)–(−0.5)	(−0.5)–0.0	0.0–0.5	0.5–1.0	1.0–1.5	1.5–2.0	2.0–3.0	3.0–4.0	4.0–5.0
Winter														
ΔT_1	n	*m*	41	45	59	77	150	189	263	270	154	175	113	62
		F	4	7	10	14	22	33	48	62	71	81	87	90
	d	*m*	53	48	75	89	140	215	258	248	175	163	113	69
		F	5	8	12	17	25	37	51	65	74	84	90	94
ΔT_2	n	*m*	18	20	45	43	51	100	120	108	92	116	90	44
		F	4	7	11	16	21	32	44	55	65	77	86	92
	d	*m*	29	26	27	45	60	94	102	113	121	112	112	76
		F	6	8	11	16	22	32	42	54	67	78	78	86
Summer														
ΔT_1	n	*m*	23	15	45	40	104	146	197	222	218	313	219	136
		F	3	4	6	9	14	22	33	45	57	74	86	93
	d	*m*	75	60	109	145	229	241	274	208	179	140	56	19
		F	9	12	18	26	38	51	66	77	87	95	98	99
ΔT_2	n	*m*	12	13	14	25	49	78	114	134	133	249	143	68
		F	2	3	4	6	11	18	28	40	52	80	89	92
	d	*m*	22	36	48	63	82	144	178	156	128	145	61	30
		F	3	6	11	16	24	37	53	67	79	92	94	97

However, ΔT changes most significantly during a day in summer: the average daytime values of ΔT_1 are by 1.6°C smaller than the corresponding nighttime values, whereas the average daytime values of ΔT_2 are by 1.4°C smaller than the nighttime ones. Sometimes, the daytime values of ΔT are 5–25 times less than the corresponding nighttime ones. The values of ΔT_1 at 12–18 h are decreased down to 0–0.2°C. In both seasons any nighttime value of ΔT (at 00, 03, or 06 h) is greater than any daytime value of ΔT (at 12, 15, or 18 h).

Along with the average values, of interest are the recurrences of the difference ΔT and its distribution function F that specifies the probability that the difference ΔT does not exceed the upper bounds of the preset ranges of variation of ΔT.

According to Table V, in winter the probabilities that $\Delta T \le 0$ are close in values for both stations (23.6 and 21.5% respectively). In this case, there are no significant differences between the nighttime and daytime values of $F(\Delta T \le 0)$. The maximum of recurrence of ΔT in winter is practically the same for the ranges 0.5–1.0 and 1.0–1.5°C. Only in the daytime the maximum difference ΔT_2 is shifted toward the ranges 1.0–1.5 and 1.5–2.0°C. The limiting values of ΔT_1 in winter are (–3.0) and 7.0°C, whereas for ΔT_2 they are (–6) and 12°C.

In summer the distributions of ΔT are more diversified. The negative values of ΔT are less common in this season of the year. They are observed in 14.2 and 10.9% of all cases for ΔT_1 and ΔT_2, respectively. At the same time, in the daytime the probability that $\Delta T_1 \le 0$ and $\Delta T_2 \le 0$ are 38.1 and 23.8%, respectively. The maximum of recurrence of ΔT lies between 1.0–1.5°C at night and between 0.5 and 1°C in the daytime.

CORRELATION BETWEEN THE THERMAL AND HUMIDITY REGIMES

Not only the average values of the difference ΔT, but also its distributions unambiguously point out that the city is overheated stronger at night than in the daytime in comparison with its environs. In its turn, this testifies that direct release of heat does not play a decisive role in the formation of heat island, because industry and especially traffic release much more heat in the daytime than at night.

L.T. Matveev[1] has already pointed out that the main role in the increase of the urban temperature plays the change of the radiative regime under the effect of atmospheric pollutants. The data presented here allow us to conclude that an important role in the change of the radiative and thereby thermal regime is played by the excess amount of water vapor produced in the combustion of different fuels and then released into the atmosphere.

Already comparison of the average values of the differences Δe and ΔT, tabulated in Tables I and IV, demonstrates a fairly close correlation between these values: for the given season when we turn from any nighttime (00–06 h) observation to any daytime (12–18 h) observation, or for the fixed observation time when we turn from winter to summer, Δe and ΔT change in one direction. The limiting values of Δe and ΔT are observed at the same times or at times that are delayed by no more than 3 h. A close correlation between Δe and ΔT also can be seen from the data tabulated in Tables II and V. Thus, in winter $F(\Delta e \le 0)$ and $F(\Delta T \le 0)$ – the probabilities that Δe and ΔT are negative – differ by no more than 1–4% at night and in the daytime. In summer, they differ stronger (their difference reaches 10–20%). However, when we turn from daytime to nighttime, $F(\Delta e \le 0)$ and $F(\Delta T \le 0)$ change in one direction.

To estimate the correlation between humidity and heat regimes, we calculated the correlation coefficient r for Δe and ΔT. According to the data presented in Table VI, in winter ΔT_2 and Δe_2 are fairly close correlated: the values of r are between 0.55 at 15 h and 0.72 at 03 h during the entire period of observations.

TABLE VI. Coefficients of correlation (in %) between ΔT_2 and Δe_2 for fixed times of observations in January 1977 – February 1980.

Season	Time, h								Night-time	Day-time	Daily
	00	03	06	09	12	15	18	21			
Winter	64	72	71	65	65	55	58	55	66	61	63
Summer	39	68	72	29	−1	−10	−21	−7	43	−1	21

At night (00–06 h) a close correlation of ΔT_2 and Δe_2 is also observed in summer. However, in the daytime (12–21 h) the correlation between ΔT_2 and Δe_2 is reverse to the nighttime correlation and is very weak (because the correlation coefficients are negative and their absolute values are small).

Our conclusions about the close correlation between ΔT and Δe at night and in the daytime in winter and at night in summer as well as about the absence of this correlation in the daytime in summer have received further support through the data tabulated in Table VII in which the values of r are given for every month in 1977–1979 and two months in 1980.

In addition, we estimated the error in determining the correlation coefficients given in Tables VI and VII. The number of samples N was 330 in winter and 276 in summer (see Table VI). According to the well-known formula for the standard deviation

$$\sigma_r = (1 - r^2)/\sqrt{N} \tag{1}$$

we obtain the following estimates of the error in determining r presented in Table VI: $2.7 \le \sigma_r \le 3.9\%$ in winter and $2.9 \le \sigma_r \le 5.1\%$ at night in summer. The values of σ_r at night and in the daytime are half as many as these estimates, whereas their daily values are smaller by a factor of 2.8.

TABLE VII. Average monthly coefficients of correlation between ΔT_2 and Δe_2.

Period of observations	Date of observations (year, month)										
	1977			1978			1979			1980	
	I	II	XII	I	II	XII	I	II	XII	I	II
Nighttime	59	60	68	57	58	79	62	58	74	64	74
Daytime	55	59	62	50	58	73	58	50	78	55	62
Daily	57	60	65	54	58	76	60	54	76	60	68
	VI	VII	VIII	VI	VII	VIII	VI	VII	VIII		
Nighttime	49	54	59	32	16	45	46	48	47	–	
Daytime	−2	1	5	−3	−11	1	3	0	5	–	
Daily	23	28	32	14	3	23	25	24	26	–	

The number of samples for night and day times and fixed month (see Table VII) was 112 in February and 124 in January, July, August, and December. From Eq. (1) we obtained the following estimates for σ_r and r tabulated in Table VII: $3.4 \le \sigma_r \le 7.1\%$ (at night and in the daytime) and $5.8 \le \sigma_r \le 8.8\%$ in summer (at night).

Our data about the differences ΔT and Δe demonstrate the close correlation between the temperature and humidity fields. However, water vapor itself has no direct effect on the temperature field. Its effect is manifested through a change of the effective emissivity of the Earth's surface. The difference ΔB of the effective emissivity values in the city and its environs estimated using any well-known (Angström or Brunt) formula or radiative diagrams leads us to a conclusion that for values of Δe, given in Tables I and II, it causes the temperature difference ΔT, which is comparable to the observed values of ΔT (see Tables IV and V).

Let us give some examples. Thus, on February 13, 1976 the water vapor pressure was very low in Sosnovo (0.25–0.45 hPa). As a consequence, the air temperature at night (from 00 to 06 h) decreased by 5.5°C (from −28.6 down to −34.1°C). At the same station on January 7 the temperature decreased at night by 2°C (from −22.0 down to −24°C) at $e \sim 0.70$–0.85 hPa, whereas on January 4 – only by 0.5°C (from −15.4 down to −15.9°C) at $e \sim 1.40$–1.50 hPa. The weather was calm (the wind velocity was less than 1 m/s, which practically excluded the effect of advection on the temperature change) and the cloud amounts were small during those days.

It follows from these data that the water vapor pressure increase by 0.5–1 hPa may engender the change of the effective emissivity which leads to the decrease of the temperature difference (in the given examples, with time) by several degrees. It is natural that the spatial difference of the vapor pressure of the same order may cause the temperature difference of several degrees between the city and its environs.

CONCLUSION

Not only anthropogenic factors (the increase of the vapor mass in combustion of various fuels), but also the decrease of the evaporation rate from the underlying surface in comparison with the environs play significant roles in the formation of the urban humidity field. This humidity field has a decisive effect on the radiative regime, primarily on the effective emissivity of the Earth's surface, and thereby on the formation of the heat island, that is, the temperature difference between the city and its environs.

It should be specially emphasized that consideration of the effect of differences Δe and ΔT allows us to elucidate the main reason for the formation of the cold island, that is, negative values of ΔT, whose probability lies between 11 and 38%. Negative values of ΔT are especially convincingly rule out the hypothesis found in the literature that the cold island is formed due to direct release of heat of anthropogenic origin.

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