DISTRIBUTION FUNCTION AND DENSITY OF POLLUTANTS AND AIR TEMPERATURE

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The data on concentration of some pollutants (CO, SO_2, NO_2, dust, phenol) measured in the city of St. Petersburg by means of the mobile ecological laboratory have been used for construction of the distribution function of these substances. The latter has been used for estimating the probability of exceeding the maximum permissible concentration (MPC) of these substances. The important property of the distribution function is revealed. It is the same (automodel) within the limits of measurement error and the accuracy of calculation (taking into account the limited number of samples) either for different ingredients or for different observation sites, if it is constructed for the deviation of the concentration from the average value normalized to the root–mean–square (standard) deviation. Most exactly the empirical distribution function can be approximated by the lognormal distribution.

One of the important problems being solved by the service of environmental protection is to estimate the probability of exceeding the maximum permissible concentration (MPC) of a particular pollution substance (admixture). One can give the most complete answer to this question if the distribution function of the concentration (q) of a pollution substances is known.

The aim of this paper is to construct and to analyze the distribution functions of the most important pollution substances as well as of the difference of air temperature in the city and its suburbs. The latter makes it possible to draw a conclusion about the role of different factors influencing on the formation of the heat area (island) over the city.

Concentration of pollution substances. The data measured during 1989–1991 in the Frunzenskii district of St. Petersburg served as a basis for constructing of the distribution functions of q. The ecological situation in this district has been a subject of a special investigation. In addition to the data obtained at stationary points, measurements of the concentration of carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), phenol, dust and others made by means of a mobile ecological laboratory (MEL) have been involved into the analysis. During 1989 and 1990 measurements by means of the MEL have been carried out in two sites near crossroads with a heavy traffic, during May and June 1991 – in 10 sites spreaded within the district area quite uniformly (totally 138 measurements of the concentration of each ingredient).

Here we present only the data on the distribution functions of the pollution substances from all the results of the comprehensive study of the ecological situation in this district that is one of the most polluted districts of St. Petersburg due to the great number of industrial enterprises and heavy traffic.

The distribution function $F(q \le Q)$ is the probability that the concentration q does not exceed a given value Q. Naturally, the function F of any pollution substance differs from that of another one. For example, let us present the distribution functions of some ingredients from the data obtained by MEL during 1991.

1) carbon monoxide (CO), $\overline{q} = 3.3$, $\sigma_q = 2.7$:

Q	0.1	1	2	3	4	5	6	7	8	9	10
F	11	28	44	56	72	83	89	91	93	94	100

2) nitrogen dioxide (NO_2), $\overline{q} = 0.13$, $\sigma_q = 0.06$:

Q	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.20	0.26
F	6	8	11	27	33	44	56	83	94	100

3) dust, $\overline{q} = 0.42$, $\sigma_q = 0.19$:

Q	0.1	0.2	0.3	0.4	0.5	0.6	0.7
F	6	11	50	67	72	88	100

Here $\overline{q}$ is the mean value of the concentration, σ_q is the root–mean–square deviation, F is given in percent, Q, $\overline{q}$, and σ_q are given in $\mu g/m^3$. The functions F are different not only for different substances, but also they are different in different seasons and in different sites.

The distribution functions for the normalized values of the concentration q_n are more general. These values are the differences between q and its mean values $\overline{q}$ related to the root–mean–square deviation σ_q:

$$q_n = (q - \overline{q}) / \sigma_q .$$

The analysis shows that the function $F(q_n \le Q_n)$ of the normalized concentration has the very important property. It is practically the same (within the limits of measurement error) for different components of the pollution, different seasons, and different observation sites. This property of the distribution function is referred to as automodelity. As an example, the distribution function for different substances is presented in Fig. 1 based on data measured at the same site. That for one and the same substance (CO) measured at different points is presented in Fig. 2. Since the concentration is measured with the certain error and the number of samples (effecting on the calculation accuracy) is not quite great, one should acknowledge that the automodel property is satisfied with a quite high accuracy.

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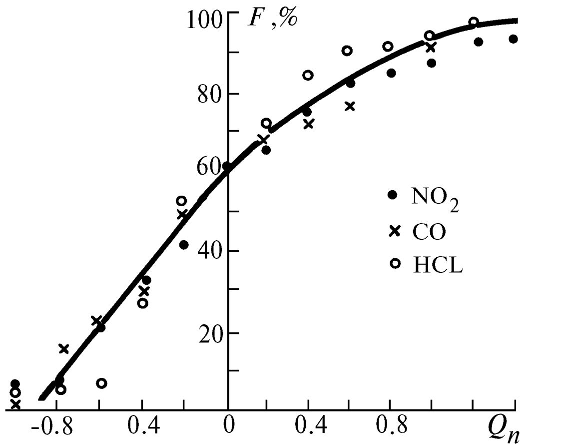

FIG. 1. Distribution function of the normalized concentration of different pollution substances from the data of measurements at the same site.

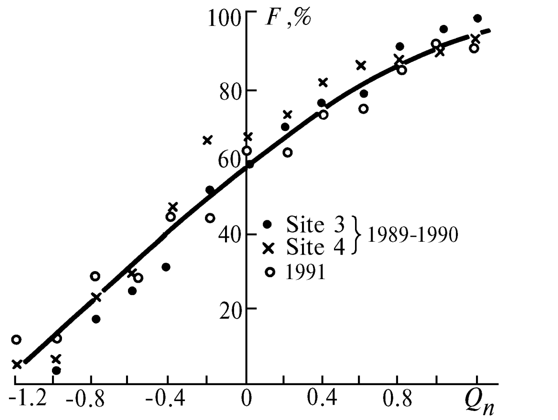

FIG. 2. Distribution function of the normalized concentration of carbon oxide (CO) from the data of measurements at different sites.

Using, in addition, the data of measurements by stationary points and MEL we have constructed a generalized distribution function of the normalized concentration of pollution substances:

Q_n	−1.2	−1.0	−0.8	−0.6	−0.4	−0.2	0.0	0.2	0.4
F, %	2	6	15	24	33	46	57	66	73

Q_n	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2
F, %	80	86	90	92	94	96	97	98	99

In order to pass from these values of the function $F(q_n \le Q_n)$ to the distribution function $F(q \le Q)$ for a particular substance it is necessary to know only the mean value $\overline{q}$ and the rms deviation σ_q of the concentration of this substance (these values are determined sufficiently accurate over much shorter observation series than that used for the function F). So, the value $F(q_n \le -0.4) = 33\%$ corresponds to the non–normalized concentration $Q = -0.4\,\sigma_q + \overline{q}$.

Assuming Q to be equal to the maximum permissible concentration (3 for CO; 0.05 for SO_2, 0.04 for NO_2, 0.15 for dust, and 0.003 μg/m^3 for phenol) and using the values of the distribution function determined we have found the probability (%) of exceeding the MPC (daily averaged) and its multiple values over the Frunzenskii district for different pollutants:

	1 MPC	2 MPC	3 MPC	4 MPC
CO	57	26	10	5
NO_2	91	63	40	15
Dust	90	56	31	12
Phenol	25	12	–	–

It is easily seen that the concentrations of dust and NO_2 exceed the MPC practically always (in 90 and 91% of cases, respectively) and exceeded 2 MPC in more than a half of cases (56 and 63% of cases, respectively). The concentration of CO exceeds the MPC and 2 MPC in 57 and 26% of cases, respectively.

An attempt has been undertaken to approximate the function F by an analytical expression. After a number of comparisons of calculated (theoretical) values of F with the empirical ones we have concluded that the loganormal distribution suits the description of the latter ones best of all

$$F(q \le Q) = \frac{1}{\sqrt{2\pi}} \int\limits_{-\infty}^{Q} \exp\left(-\tau^2/2\right) d\tau , \qquad (1)$$

where $Q = (\ln q - \ln q^*)/\sigma_{\ln q}$, $\ln q^*$ is the average (arithmetic) value of the logarithm of the normalized concentration, $q^* = (q_1\, q_2 \dots q_n)^{1/N}$ is the geometric average value of q, $\sigma_{\ln q}$ is the variance of ln q.

Omitting some details of the discussion, let us present the results of a comparison made between the empirical F_{emp} and the theoretical (determined by the formula (1)) F_{theor} values of the function F:

1) carbon monoxide CO; $\overline{q} = 4.6$ μg/m^3; $\sigma_q = 3.8$ μg/m^3, $N = 199$

Q,μg/m^3	0.8	1.6	2.3	3.1	3.8	4.6	5.4	6.1	6.9	8.4
F_{emp}, %	4	20	29	37	45	58	68	75	82	92
F_{theor}, %	3	16	25	39	49	59	70	80	84	95

2) Nitrogen dioxide NO_2; $\overline{q} = 0.094$ μg/m^3; $\sigma_q = 0.062$ μg/m^3:

Q, μg/m^3	0.003	0.04	0.06	0.07	0.08	0.09	0.11	0.12	0.13	0.16
F_{emp}, %	8	10	20	29	33	56	64	72	79	88
F_{theor}, %	7	12	26	36	40	60	70	78	82	90

Air temperature. It is known[1,2,4] that the fields of meteorological parameters such as air temperature, humidity, visibility range, and velocity of air motion undergo essential changes under the impact of the pollution of the atmosphere by the admixtures of anthropogenic origin. The pollution substances strongly effect on the fluxes and inflows of solar and terrestrial radiation, radiation budget of the surface and atmospheric boundary layer, on the conditions of genesis of fogs, clouds, and precipitations. The answer to the question what factors influence on the formation of the difference ΔT between air temperature in the city (T_{cit}) and its outskirts (T_{out}) is of a cognitive and practical interest:

$$\Delta T = T_{cit} - T_{out} .$$

There exists a common opinion (though, it is not confirmed by quantitative estimates) that the direct emissions of heat produced when burning different kinds of fuel (coal, oil, gas, wood) play the decisive role in increasing air temperature in the city in comparison with its suburbs. Naturally, the difference ΔT should be for such approach always greater than zero; the city is warmer than the outskirts (heat island).

An attempt to investigate this problem was undertaken in Ref. 3. Not only the average values of ΔT have been presented there, but the distribution function and the probability density for ΔT have been constructed for the first time. As we know, St. Petersburg is the only city for which this function is determined.

Recent investigations of the difference ΔT are being continued, and now the data on ΔT are available for two five–year periods: 1970–1974 and 1975–1979. The first period has been analyzed in Ref. 3. During subsequent five years there were not essential changes in thermal regime of the city.

It has been obtained for the values ΔT,°C for different observation time during 1975–1979 averaged over all four sites (Sosnovo, Belogorka, Volkhov, Voeikovo):

Time of day, h	00	03	06	09	12	15	18	21
Winter	1.7	1.7	1.6	1.6	1.3	1.0	1.4	1.6°C
Summer	2.3	2.8	2.4	0.8	0.5	0.4	0.5	1.2°C

These values are different from the values ΔT given in Ref. 3 not more than in 0.1–0.2°C (as a rule, in the increase direction).

According to these data, the difference ΔT reaches the greatest values at night and in the morning, and the least values are reached in the day time. Since the industrial enterprises, heating systems, and especially the traffic, of course, emit significantly more heat during the day–time than at night (for no other reason than the greatest part of the motor transport that produces more than 70% of all emission of heat and admixtures does not work at night), it follows from the presented data that in any case the direct anthropogenic supply of heat does not play the determining role in the formation of the difference ΔT. The comparison of the values ΔT in winter and in summer is evidence of the same; at night (00, 03, and 06 h) when the principal heat sources are the industrial enterprises and heating systems (including the housing estate), the amount of fuel burnt and heat emitted is larger in winter than in summer. Nevertheless, the difference ΔT at night is approximately 1.5 times less in winter than in summer.

The following values are obtained for the distribution function $F(\Delta T \leq X)$ of the difference ΔT from the data of 1975–1979.

	X,°C	−6	−4	−2	0	2	4	6	8	10
F,°C	Summer	0.1	0.7	2.6	17	74	91	97	98.9	99.7
	Winter	0.1	0.6	2.9	20	68	92	98	99.7	100

As follows from these data the statement "the city is warmer than the outskirts" is correct in 83% in winter and in 80% in summer. However, very often (17% cases in winter and 20% in summer) the city is cooler than the suburbs. This result not only disagrees with the hypothesis about the predominating effect of the emission of heat on ΔT, but contradicts it.

Thus, though the hypothesis about the predominating role of the additional heat sources (in comparison with the outskirts) in the increase of temperature in the city seems to be evident, it should be rejected.

Simultaneously it should be noted that the direct estimate of this heat emitted from the great amount of sources in a big city (including houses) is hardly possible. However, there is another approach to estimate the anthropogenic heat. It is possible to estimate use the data on the amount of the fuel burnt in the city. Knowing the heat production ability of different fuels (coal, oil, gas, and wood) and their mass, it is easy to estimate the total amount of heat emitted into the atmosphere from all sources. Such estimate shows that the anthropogenic emissions of heat in St. Petersburg can increase temperature in the city by the value that is 5–10% of the observed values of the difference ΔT.

The geophysical factors play the decisive role in the formation of the difference ΔT. They are the variations of the radiation budget (first of all, the effective radiance and the albedo) of the earth surface and the atmospheric boundary layer under the impact of the pollution substances whose optical properties are essentially different from the properties of clean atmospheric air.

The evaporation conditions and roughness of the earth surface, different in the city and in the outskirts, influence on ΔT. The optical properties of the surface, especially the snow cover, are strongly changed under the effect of the pollution. Sharp decrease of the reflection ability of the latter under the effect of sedimentating solid admixtures (soot, dust) favor earlier thawing of the snow in the spring and later establishment of the snow cover in the autumn in the city. In turn, that results in the increase of the difference of air temperature between the city and its suburbs.

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