STATISTICAL ANALYSIS OF AIR POLLUTION IN THE ATMOSPHERE OVER AN INDUSTRIAL CENTER

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In this paper we present analysis of observational data on some pollutants (NO_2, SO_2, H_2S, and dust) in the atmosphere over the city of Naberezhnye Chelny. The mean values, rms deviations, asymmetry, excess and the distribution functions of pollutant concentration are obtained. The distribution function of normalized concentration has an important property of automodelity. It is practically the same within the measurement error both for different ingredients and different observation points. The distribution function is used to determine the probability of exceeding the maximum permissible concentration of pollutants.

As industry, transport, and power production develop the amount of pollutants emitted into the atmosphere increases. Meteorological conditions, such as wind speed and turbulence, thermal stratification, clouds, fogs and precipitation,[1–4] essentially affect spreading of pollution as well as temporal variations of their content. In its turn, the cloud of impurities formed just over the city affects the atmosphere, i.e. its temperature and humidity fields, optical and radiative characteristics, conditions of cloud and fog formation, moistening regime.[5–7]

Practically all impurities of anthropogenic origin exhibit deteriorating effect upon human, flora and fauna.[8,9]

This paper deals with the statistical analysis of the pollutant content in the city of Naberezhnye Chelny (Republic of Tatarstan), the industrial center with the population in excess of 500 thousand people. The main sources of pollutants are motor-car construction enterprises (joint-stock company KAMAZ and power production complex, as well as all kinds of transport (motor transport, first of all).

The impurity concentration was measured at two posts of hydrometeorological service at 7, 13, and 19 hours of local time. The paper also uses the data of one post of KAMAZ Company. The posts Nos. 1 and 2 were situated in the residential section at a distance of 2 to 6 km from the KAMAZ plants. The post No. 3 was situated at the plant territory.

The data of observations in 1988–1993 at posts Nos. 1 and 2 and in 1989–1992 at post No. 3 are used in this paper. The observations of nitrogen dioxide NO_2, sulfur dioxide SO_2, hydrogen sulfide H_2S, and dust at posts Nos. 1 and 2 and NO_2 and SO_2 at post No. 3 are analyzed. Carbon monoxide CO is always in the atmosphere in addition to the aforementioned substances. Its concentration was also measured. Since the error in measuring CO concentration was not greater than 1 mg/m^3, the data of observations contain only the values q equal to 0 or 1 mg/m^3 (rarely more than 1 mg/m^3). Naturally, it is practically impossible to construct the distribution function of q based on such measurement data. For this reason, for CO only $\overline{q}$, σ_q, A_q, and E_q are determined.

The data on the mean values of concentration ($\overline{q}$), rms deviations (σ_q), asymmetry A_q, and excess E_q are given in Table I. The values $\overline{q}$ and σ_q at all three posts are close to each other. The exceptions are the values of $\overline{q}$ and σ_q at post No. 3, which essentially exceed the data from other posts. Asymmetry and excess for all impurities are significantly greater than zero, what is indicative of the fact that the distribution of q essentially differs from the normal one.

TABLE I. The values of $10^2\ \overline{q}$ (mg/m^3), $10^2\ \sigma_q$ (mg/m^3), A_q, *and* e_q *(N is sampling size).*

Pollutant	post No. 1					post No. 2					post No. 3				
	$\overline{q}$	σ_q	A_q	e_q	N	$\overline{q}$	σ_q	A_q	e_q	N	$\overline{q}$	σ_q	A_q	e_q	N
NO_2	4.9	4.8	2.5	9.9	5267	4.9	4.8	3.0	14.4	5394	3.2	3.7	2.2	7.2	2524
SO_2	1.5	1.4	3.9	38.9	5256	1.4	1.3	3.5	31.6	5409	12.9	14.2	3.4	14.7	2548
H_2S	0.2	0.1	2.1	12.3	5265	0.2	0.1	1.7	11.3	5412					
dust	19.1	17.2	2.4	3.6	3339	20.6	19.7	1.5	2.6	5010					
q n	64.9	65.9	0.9	2.4	5240	65.7	67.5	0.8	1.2	5386					

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Along with the mean value and variance, the distribution function and the density of pollutant concentration distribution are of great interest. The probability of exceeding the maximum permissible concentration of one or another impurity can be estimated only based on the distribution function.

The distribution function $F(q \le Q)$ is the probability of the event when the concentration q does not exceed the given value Q. It varies from 0 for Q=0 to 1 (or 100%) at a great Q value: $0 \le F \le 1$. Let us present for example the values of the distribution function for some ingredients at the posts Nos. 1 and 2.

Nitrogen dioxide

Q, mg/m^3	0.01	0.02	0.03	0.04	0.05	0.06	0.07
F, % p.1	18.2	33.0	47.1	68.5	68.5	75.6	81.9
p.2	16.8	30.8	46.2	68.4	68.4	76.0	82.8
Q, mg/m^3	0.08	0.09	0.10	0.12	0.14	0.16	0.18
F, % p.1	87.5	89.8	35.5	94.2	96.0	97.5	98.2
p.2	89.7	91.8	35.7	94.6	96.7	97.2	97.8
Q, mg/m^3	0.20	0.24	0.28	0.32	0.36	0.40	
F, % p.1	98.8	99.3	99.6	99.8	99.9	100	
p.2	98.3	98.7	99.1	99.3	99.8	100	

Sulfur dioxide

10^2 Q, mg/m^3	0.2	0.4	0.6	0.8	1.0	1.2	1.4
F, % p.1	14.8	16.7	21.9	23.9	50.4	53.0	58.5
p.2	15.4	18.1	23.3	25.7	52.6	55.7	61.6
10^2 Q, mg/m^3	1.6	1.8	2.0	3.0	4.0	6.0	8.0
F, % p.1	62.4	63.9	85.5	94.4	98.0	99.1	99.6
p.2	65.4	66.9	81.1	92.6	97.1	99.1	99.5

10^2 Q, mg/m^3	1.0	2.0	3.0
F, % p.1	99.7	99.9	100
p.2	99.7	100	

Hydrogen sulfide

10^2 Q, mg/m^3	0.1	0.2	0.3	0.4	0.5	0.6
F, % p.1	44.7	75.9	90.6	96.3	98.3	99.0
p.2	44.9	75.2	91.1	96.0	98.8	98.8
10^2 Q, mg/m^3	0.7	0.8	0.9	1.0	1.5	2.0
F, % p.1	99.6	99.8	99.8	99.9	99.9	100
p.2	99.7	99.8	99.8	99.9	99.9	100

Dust

Q, mg/m^3	0.1	0.2	0.3	0.4	0.5	0.6	0.7
F, % p.1	49.2	70.3	83.3	91.1	97.3	98.5	99.1
p.2	47.0	66.7	80.7	88.5	95.3	96.6	97.9
Q, mg/m^3	0.8	0.9	1.0	1.1	1.2	1.3	
F, % p.1	99.3	99.6	99.8	99.9	100		
p.2	98.7	99.1	99.7	99.8	99.9	100	

The characteristic peculiarity of all impurities distribution is fast increase of the distribution function at small q and very slow increase of F at large q.

The functions F are different not only for different pollutants, but for different points, seasons, etc., as well.

The distribution functions constructed for normalized concentration values, q_n, have more general properties:

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

Mean values of the normalized concentration is equal to zero, and its rms deviation is equal to unity.

The distribution functions $F(q \le Q_n)$ of the normalized concentration q_n of four different substances constructed from the data of measurements at fixed points are shown in Fig. 1, and the distribution functions of one and the same substance at different points are shown in Fig. 2.

Taking into account that the impurity concentration was measured with some error, and the sampling size was limited, one should admit that the impurity distribution has the property of automodelity, i.e., the distribution function of the normalized concentration is practically (within the limits of the measurement error) the same for different impurities at a fixed point and for the same pollutant at different points.

These data confirm the conclusion of Ref. 10 drawn based on the data on the pollution of the atmosphere over the city of St. Petersburg.

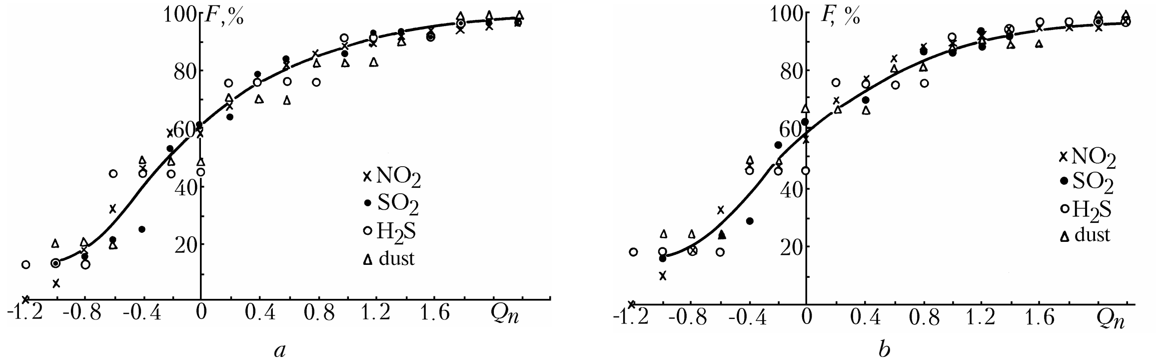

FIG. 1. Distribution functions of the normalized concentration of different substances constructed from measurement data: a) post No. 1; b) post No. 2.

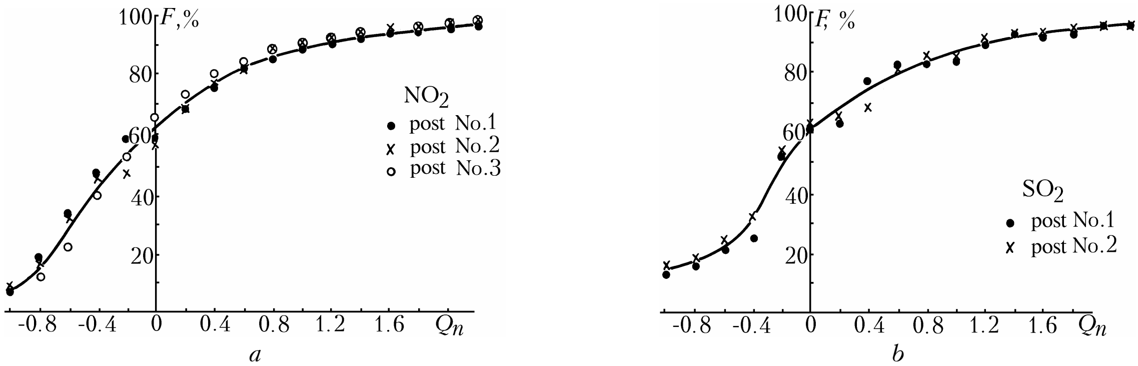

FIG. 2. Distribution functions of the normalized concentration from measurements at all posts: a) NO_2, *b)* SO_2.

The function F averaged over the posts Nos. 1 and 2 and four impurities has the following values:

Q_n	−1.2	−1.1	−1.0	−0.9	−0.8	−0.7	−0.6	−0.5	−0.4	−0.3
F, %	3.9	6.5	14.9	15.1	17.9	18.4	26.9	237.3	41.6	48.1
Q_n	−0.2	−0.1	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
F, %	49.6	52.2	55.3	61.1	69.1	71.5	73.2	78.8	79.3	81.9
Q_n	0.8	0.9	1.0	1.2	1.4	1.6	1.8	2.0	2.2	
F, %	82.3	85.0	87.8	90.2	91.8	92.9	94.8	96.3	96.7	

The mean absolute deviations $\delta_f = \Sigma|(F_i - \bar{F})|/N_f$ of the function F from the values $\bar{F}$ averaged over four impurities (the solid curves drawn in Fig. 1) and the rms deviations $\sigma_f = [\Sigma(F_i - \bar{F})^2]^{1/2}/N_f$ are given in Table II (N_f is the number of intervals, on which the observational series is divided, and for which the values F_i are determined).

TABLE II. Mean absolute (δ_f) *and rms* (σ_f) *deviations (%) of the distribution function F.*

Pollutant	post No. 1 (N_f = 29)		post No. 2 (N_f = 29)		post No. 3 (N_f = 29)	
	δ_f	σ_f	δ_f	σ_f	δ_f	σ_f
NO_2	3.2	2.4	3.3	2.2	7.3	6.4
SO_2	3.9	3.8	3.5	3.4	7.2	6.5
H_2S	4.5	4.1	4.8	4.0		
dust	4.2	3.4	3.8	2.5		

It is easy to see that mostly both absolute and rms deviations of the function F do not exceed 3–4%. These deviations reach 6–7% only at the post No. 3, where the number of observations is much smaller.

The distribution function q or q_n is just the parameter that allows most reliable estimate of the probability of exceeding any given value of concentration, in particular, maximum permissible concentration.

As known, the one-time maximum and daily average maximum permissible concentrations (MPC) are introduced to estimate the effect of pollution on the human organism.

Naturally, to estimate the probability of exceeding the one-time MPC one should use the distribution functions q or q_n constructed from the data of observations at a fixed time. The one-time MPC values for the substances we analyze are equal to: 0.085 mg/m^3 for NO_2, 0.5 mg/m^3 for SO_2, 0.008 mg/m^3 for H_2S, and 0.5 mg/m^3 for dust. After determining the normalized values (Q = MPC − $\bar{q}$)/σ_q by means of the plots presented in Fig. 1 (solid curves), let us determine the probability of exceeding the MPC, which is equal to 100−F. Then let us determine the probability of exceeding 2MPC from the values Q = (2MPC − $\bar{q}$)/σ_q, and so on. The probability of exceeding MPC is small, it is 18 and 5% for NO_2 and dust, respectively.

However, since the population is under these conditions for a long time, one should compare the impurity concentration with daily average MPC (equal to 0.04 mg/m^3 for NO_2, 0.05 mg/m^3 for SO_2, and 0.15 mg/m^3 for dust). It is natural that one should construct the distribution functions from daily average values of q.

Let us present the distribution functions of daily average values of q at the post No. 2 as an example.

Nitrogen dioxide $\bar{q}$ = 0.049 mg/m^3, σ_q = 0.042 mg/m^3, N = 1803

Q, mg/m^3	0.01	0.02	0.03	0.04	0.05	0.06	0.07
F, %	6.2	18.1	34.1	50.7	66.1	76.7	83.4
Q, mg/m^3	0.08	0.09	0.10	0.12	0.14	0.16	0.18
F, %	87.8	90.7	92.9	95.7	96.6	97.6	97.9
Q, mg/m^3	0.20	0.24	0.28	0.32	0.36	0.40	
F, %	98.3	98.9	99.3	99.6	99.8	100	

Dust $\bar{q}$ = 0.21 mg/m^3, σ_q = 0.165 mg/m^3, N = 1674

Q, mg/m^3	0.1	0.2	0.3	0.4	0.5	0.6	0.7
F, %	33.1	62.7	79.7	89.6	95.7	97.6	98.6
Q, mg/m^3	0.8	0.9	0.1	1.1			
F, %	99.1	99.3	99.7	100			

Distribution functions of the normalized daily average concentrations averaged over all impurities have the following values:

Q_n		−1.2	−1.1	−1.0	−0.9	−0.8	−0.7	−0.6	−0.5
F, %	p.1	3.6	7.7	9.7	10.9	16.2	23.0	28.0	30.2
	p.2	4.8	7.4	10.2	10.6	15.3	23.3	27.4	29.4
Q_n		−0.4	−0.3	−0.2	−0.1	0.0	0.1	0.2	0.3
F, %	p.1	41.7	45.2	47.5	56.7	58.9	62.2	65.8	70.5
	p.2	39.8	43.7	48.0	54.0	60.5	62.4	65.5	70.9

Q_n	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.2
F, % p.1	72.9	74.7	79.8	80.8	83.5	85.7	86.0	88.4
p.2	73.9	74.7	79.6	81.5	83.1	85.5	87.5	89.4

Q_n	1.4	1.6	1.8	2.0	2.2
F, % p.1	91.4	93.4	94.7	96.1	96.4
p.2	92.4	94.3	95.3	96.4	96.8

Using these functions, according to the technique described above, let us determine the probability of exceeding daily average MPC. According to the data given in Table III, the most significant excess over MPC is observed for NO_2 and dust. Their concentrations exceed MPC in 52% and 55% of events, respectively, at the post No. 1 and in 53% and 57% of events at the post No. 2. On the whole, the city of Naberezhnye Chelny, where the free rare building with good blowing of the residential section, is less dirty city than, for example, some districts of St. Petersburg, where the probability of exceeding MPC by NO_2 and dust reaches 90%, 2MPC – 60%, and 3MPC – more than 30% of events.[10]

TABLE III. Probability of exceeding (%) daily overage MPC.

Pollutant	Post No. 1			Post No. 2		
	MPC	2MPC	3MPC	MPC	2MPC	3MPC
NO_2	52	19	7	53	19	7
SO_2	2	0	0	2	0	0
H_2S	0	0	0	0	0	0
Dust	55	17	6	57	26	8

The attempt is undertaken to approximate the distribution function by lognormal distribution of the following form:

$$F_{\lg n}(y) = \frac{1}{\sqrt{2\pi}} \int\limits_{-\infty}^{y} \exp\left(-\frac{\tau^2}{2}\right) d\tau, \qquad (1)$$

where $y = (\ln q - \ln q_0)/\sigma_{\ln q}$; $\ln q_0$ is the mean arithmetic value of the logarithm of concentration; $\ln q_0 = (\ln q_1 + \ln q_2 + \ldots + \ln q_n)/N$; $\sigma_{\ln q}$ is the mean square deviation of the logarithm of concentration; and $\sigma_{\ln q} = [\Sigma(\ln q_i - \ln q_0)^2]/N$.

Theoretical values of the distribution function were obtained by Eq. (1). Let us present examples of these values:

Nitrogen dioxide

Q, mg/m^3	0.01	0.02	0.03	0.04	0.05	0.06	0.07
$F_{\lg n}$, % p.1	13.3	32.6	47.2	57.5	65.9	71.9	76.7
p.2	12.7	31.9	46.8	57.5	65.9	71.9	76.7
Q, mg/m^3	0.08	0.09	0.10	0.12	0.14	0.16	0.18
$F_{\lg n}$, % p.1	80.2	83.1	85.5	89.1	91.0	93.4	94.6
p.2	80.3	83.4	85.7	89.2	91.8	93.6	94.9
Q, mg/m^3	0.20	0.24	0.28	0.32	0.36	0.40	
$F_{\lg n}$, % p.1	95.7	97.0	97.8	98.5	98.8	99.1	
p.2	95.9	97.2	98.0	98.5	98.9	99.2	

Sulfur dioxide

10^2 Q, mg/m^3	0.2	0.4	0.6	0.8	1.0	1.2
$F_{\lg n}$, % p.1	7.6	20.9	32.9	42.5	50.0	56.3
p.2	8.0	22.1	34.1	44.0	51.6	58.3
10^2 Q, mg/m^3	1.4	1.6	1.8	2.0	3.0	4.0
$F_{\lg n}$, % p.1	61.7	66.3	69.8	73.2	83.6	89.2
p.2	63.6	68.1	71.6	74.8	84.8	90.1
10^2 Q, mg/m^3	6.0	8.0	1.0	2.0	3.0	
$F_{\lg n}$, % p.1	94.5	96.8	98.0	99.6	99.8	
p.2	95.1	97.3	98.3	99.7	99.9	

Hydrogen sulfide

10^2 Q, mg/m^3	0.1	0.2	0.3	0.4	0.5	0.6
$F_{\lg n}$, % p.1	35.2	66.3	81.8	89.2	93.3	95.7
p.2	37.4	7.32	81.8	89.0	93.0	95.6
10^2 Q, mg/m^3	0.7	0.8	0.9	1.0	1.5	2.0
$F_{\lg n}$, % p.1	97.1	98.0	98.6	98.9	99.7	99.9
p.2	96.8	97.7	98.4	98.8	99.7	99.8

Dust

Q, mg/m^3	0.1	0.2	0.3	0.4	0.5	0.6	0.7
$F_{\lg n}$, % p.1	40.1	66.3	79.4	86.6	90.8	93.4	95.2
p.2	39.3	64.4	77.3	84.7	89.0	91.9	93.8
Q, mg/m^3	0.8	0.9	1.0	1.1	1.2	1.3	
$F_{\lg n}$, % p.1	96.3	97.2	97.8	98.3	98.6	98.8	
p.2	95.2	96.2	96.9	97.5	97.9	98.3	

When comparing these values with the aforementioned empirical values of the distribution function, the mean absolute Δ_f and rms σ_f deviations of the distribution function from its approximated values were calculated (Table IV). It is seen that the mean absolute deviations do not exceed 4–5%, and the rms deviations do not exceed 3–4%.

TABLE IV. Mean absolute (Δ_f) and rms (σ_f) deviations the distribution function F from its approximated values with using lognormal distribution.

Pollutant	Post No. 1		Post No. 2	
	Δ_f	σ_f	Δ_f	σ_f
NO_2	3.7	2.6	3.8	2.9
SO_2	5.8	4.9	4.8	4.4
H_2S	3.5	3.3	4.0	3.1
Dust	3.7	2.1	3.6	1.6

On the other hand, normal law does not satisfy the approximation of the function F. Let us present as an example the results of approximation of F by means of the normal law.

Nitrogen dioxide

Q, mg/m^3	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08
F_n, %	23	31	39	47	55	63	71	77
Q, mg/m^3	0.09	0.10	0.12	0.14	0.16	0.18	0.20	0.24
F_n, %	83	88	94	97	99	99	99	100

Dust

Q, mg/m^3	0.1	0.2	0.3	0.4	0.5	0.6	0.7
F_n, %	23	27	33	39	44	50	56
Q, mg/m^3	0.8	0.9	1.0	1.1	1.2	1.3	
F_n, %	61	67	72	77	81	85	

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