Comparative estimate of different methods for objective analysis of temperature and wind fields in the problems of mesoscale diagnostics and forecast of atmospheric pollution processes

V.S. Komarov and A.V. Kreminskii

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk

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We present a statistical approach to estimating the quality and efficiency of different methods for objective three or four-dimension analysis of mesoscale fields of temperature and wind. The methods use optimal interpolation and extrapolation of a random process as well as modified method of clustering of arguments (MMCA) developed for meteorological support in the problems of ecological diagnostics and forecast of the processes of atmospheric polluting. Statistical analysis of these methods has been conducted based on many-year radiosonde observations at 5 aerological stations and has shown that the method MMCA is the best in three-dimension case (together with the method of optimal interpolation). In the four-dimension case the best results were obtained with the same complex algorithm, but extended by the method of optimal extrapolation of a random process used only in ground measurements.

1. Introduction

The objective analysis of the field of meteorological parameters, which is the procedure of obtaining the values of these parameters at the nodes of some regular grid from the measurement data obtained at the stations, are now being widely used not only in practice of numerical weather forecast,[1,2] but also in the problems of mesoscale diagnostics and forecast of the processes of pollution of the atmosphere.[3] Obviously, when using one or another method of objective analysis one needs to know beforehand, what accuracy of construction of the field does this method provide.

Here one should pay attention to one important circumstance. So far the assessments of different methods of objective analysis were carried out principally on the example of the geopotential field at the isobaric surface of 500 hPa (~ 5.5 km), which plays the important role in numerical weather forecast.[1] The peculiarity of such an assessment is in the fact that it is performed only for macroscale fields formed under the effect of synoptic processes, the horizontal size of which is about 1000 km.[4]

However, considering the problems of mesoscale diagnostics and forecasting of the processes of pollution of the atmosphere to be solved by means of the admixture transfer equation in the boundary layer of the atmosphere[5,6] (technogenic pollutants principally spread here) using meteorological parameters (such as temperature and wind), we deal with objective analysis of stronger varying fields formed under the effect of mesoscale atmospheric processes of the characteristics size about 100 km.[4]

Taking into account all the aforementioned, as well as the fact that objective analysis of mesoscale fields in the atmosphere is not appropriately developed yet, we tried to estimate the success of such analysis (on the example of mesoscale temperature and wind fields) using the alternative methods for spatial forecast, namely, the method of optimal interpolation (MOI)[7] that has been widely used in practice, as well as the complex technique based on the procedure of optimal integration of the modified method of clustering of arguments (MMCA)[8] with the algorithm MOI.

Let us note first that the pioneering results of such an estimate performed as applied to objective 3D analysis[9] were obtained from the aerological data of very limited size.

Besides, one should pay attention to one more very important circumstance. When solving the problem of numerical forecast of the processes of pollution of the atmosphere, one needs to have the data not only on spatial, but also on temporal variations of mesoscale temperature and wind fields. Hence, to support this problem, it is necessary to realize the procedure of objective 4D analysis.

All these facts are the reasons for statistical assessment of the quality of the objective analysis based on the procedure of 4D interpolation (extrapolation) of the temperature and wind fields.

In this paper we consider some aspects of a technique and the results of numerical estimation of the quality of alternative methods for objective 3D and 4D analysis of the mesoscale temperature and wind fields. In contrast to Ref. 9, it is carried out on significantly larger bulk of empirical data.

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2. Some aspects of a technique for solving the problems formulated

Before discussing the results of numerical estimation of the accuracy of alternative methods of objective analysis, one should briefly consider some aspects of a technique for solving the formulated problems.

Let us first consider the main idea of the estimated methods on the basis of a general approach to the solution of the problem of interpolation of meteorological fields that makes up the basis for their objective analysis.

According to Ref. 7, interpolation (or extrapolation) of meteorological parameters, in general case, can be carried out in four dimensions of three spatial coordinates and time. Let us denote the radius-vector of a point in such a space as r. Then the interpolation of a meteorological parameter ξ to the point r_0 from its known values at the points $r_1, r_2, \ldots, r_n$ is performed by the formula

$$\xi(r_0) = \Xi[\xi(r_1), \xi(r_2), \ldots, \xi(r_n)] , \qquad (1)$$

where the form of the function Ξ is determined by the interpolation method applied and by the arrangement of the point sequence $r_0, r_1, r_2, \ldots, r_n$.

Based on this condition, the method of optimal interpolation (first of the methods we estimate) is based on the procedure of determining the value of the field at the point $r_0 \in W_x \subset R^m$ from the data on its values measured at the points r_i (here $i = 1, 2, \ldots, n$ is the number of points in some closed set W_x of a finite-dimension Euclidean space R^m) by the following formula[7]:

$$\xi(r_0) = \bar{\xi}(r_0) + \sum_{i=1}^{n} a_i(\xi(r_i) - \bar{\xi}(r_i)) = \bar{\xi} + \sum_{i=1}^{n} a_i\, \xi'(r_i) , \qquad (2)$$

where $\xi(r_0)$ is the sought value of the meteorological parameter at the node of a regular grid, $\bar{\xi}(r_0)$ is the mean value (norm) of the same meteorological parameter at the sought node of the regular grid, $\bar{\xi}(r_0) = \bar{\xi}(r_i) = \bar{\xi}$ for a meteorological polygon[7]; $\xi'(r_i) = \xi(r_i) - \bar{\xi}(r_i)$ is the deviation of the meteorological parameter from the norm at the ith point, and a_i are the weight coefficients to be determined.

For the optimal estimation of the field values ξ at the point r_0 it is necessary to satisfy the condition

$$E[a] = M\{[\tilde{\xi}(r_0) - a\, \xi(r_i)]^2\} \to \min. \qquad (3)$$

Here $E[a]$ is the error of optimal interpolation, $\tilde{\xi}(r_0)$ is the observed value of the field ξ at the point r_0, and M is the operator of mathematical expectation. To determine the weight coefficients, a_i, one should use the system of linear equations of the form[2]

$$\sum_{j=1}^{n} a_j\, \mu_{ij} + a_i\, \eta^2 = \mu_{0i} \quad (i = 1, 2, \ldots, n) , \qquad (4)$$

where μ_{ii} and μ_0 are the values of the autocorrelation functions of the meteorological parameter, and $\eta^2 = \Delta^2/\sigma_\xi^2$ (Δ^2 is the variance of the measurement errors, and σ^2 is the variance of this parameter). To estimate μ, the analytical relations are used[10]

$$\mu_T(\rho) = [\exp(-\alpha\rho)] \cos(\beta\rho) \qquad (5)$$

for temperature, and

$$\mu_{V_x}(\rho) = \mu_{V_y}(\rho) = (1 - \alpha\, \rho) \exp(-\rho)^2, \qquad (6)$$

for zonal, (V_x), and meridional, (V_y), wind. Here ρ is the distance in thousand kilometers, $\alpha = 0.436$ and $\beta = 0.863$ for temperature, and $\alpha = 1.162$ for the wind velocity components.

The detailed description of the algorithm of optimal interpolation can be found in Refs. 8 and 9.

The second of the methods is the modified method of clustering of arguments, described for the first time in Ref. 11. It is based on the combined difference dynamic-stochastic model

$$\xi_0(h, N+1) = \sum_{\tau=1}^{N^*} A(h, \tau)\, \xi_i(h, N+1-\tau) + \sum_{j=0}^{h-1} B(h, j)\, \xi_i(h, N+1) + \varepsilon(h, N+1) , \qquad (7)$$

where h is the height, τ is the temporal step, $N^* < [N - h - 1]/2$ is the order of the time delay, $A(h, 1), \ldots, A(h, N^*)$ and $b(h, 0), \ldots, b(h, h-1)$ are the unknown parameters of the model, $\varepsilon(h, N+1)$ is the discrepancy of the model. In selecting and constructing of such a model we took the spatiotemporal observations of the form

$$\{\xi_i(h, t),\ h = 0, 1, \ldots, h_k;\ t = 1, 2, \ldots, N\},$$
$$\{\xi_0(h, t),\ h = 0, 1, \ldots, \bar{h} \le h_k;\ t = N+1\} \qquad (8)$$

(t is time), as well as two methods for constructing the best model, i.e., the method of directed group looking over (for optimization of the model structure) and the method of minimax estimation for obtaining the estimates of its parameters, which guarantee the quality of the forecast.

The detailed description of MMCA is presented in Ref. 8. One should note that, to realize the procedure of objective 3D analysis based on this algorithm, one needs the values of the field ξ measured at the time moment $t = N + 1$ at the ground level, as well as the results of its interpolation in the nodes of a regular grid. So, to construct the near-ground field of the considered meteorological parameter (temperature and wind velocity components in our case), we applied the method of optimal interpolation. The obtained results, together with the set of spatiotemporal observation of the form (8) taken at the station nearest to the node, were used for selection and construction the best forecasting model MMCA, as well as for realization of the procedure of objective 3D analysis of mesoscale temperature and wind fields.

The third of the methods is the method of optimal extrapolation of a random process used when constructing the algorithm for objective 4D analysis. It is based on the procedure of numerical determination of the value of a meteorological parameter ξ at time moment $t + l$ from the data of its measurements at previous time moments $t - k$ (here $k = 0, 1, 2, ..., n$) by the relation of the form[12]

$$\xi(t + l) = \bar{\xi}(t) + \sum_{k=0}^{n} a_k \xi(t - k) , \qquad (9)$$

where $\bar{\xi}(t)$ is the mean value of the meteorological parameter ($\bar{\xi} = \text{const}$ for a stationary process[12]); $\xi(t - k)$ are the values of deviation of the parameter from its mean value at the previous time moments $t - k$; a_k are some weight coefficients to be determined by the system of equations

$$\sum_{j=0}^{n} a_j \, \mu_\xi(k - j) = \mu_\xi(l + k), \; k = 0, 1, 2, ..., n, \qquad (10)$$

where μ_ξ are the temporal autocorrelation functions of the meteorological parameter. To calculate them, the following analytical formulas were used:

$$\mu_T(\tau) = (1 + d) \exp(-d), \qquad (11)$$

for temperature (here τ is the value of advance (hour); $d = \sqrt{(\tau/\tau_0)^2}$ is the coefficient; τ_0 is the temporal correlation scale equal to 48 hours [13]), and

$$\mu_{V_x}(\tau) = \mu_{V_y}(\tau) = \exp [-\alpha(\tau)], \qquad (12)$$

for the wind velocity components, where $\alpha = 0.275$ for the zonal component, and $\alpha = 0.537$ for the meridional component.[14]

Using Eqs. (9)–(12), one can easily realize the temporal extrapolation of the near-ground values of temperature and zonal and meridional wind at the points r_i, and then one can realize the whole procedure of objective 4D analysis by means of complex technique using optimal integration of the algorithms MMCA and MOI. This approach to the technique for objective 4D analysis of temperature and wind fields was applied in this paper.

Let us now briefly consider the technique we used for estimation of the accuracy of methods of the objective analysis. It is known that several techniques are used in practice for such estimations.[7] Two of them received most wide acceptance. One of them is based on the procedure of comparison of the results of objective and synoptic analysis,[15] and the second is based on the procedure of determination of the values of meteorological parameter at the control station from the data of neighboring stations, without calculation of these values at the nodes of a regular grid.[7]

As the second technique is more reliable and objective, we used it for estimation of the accuracy of the methods of objective analysis. The accuracy of different methods of objective analysis was estimated by means of the rms error of such analysis determined by the relation

$$\delta_\xi = [\frac{1}{n} \sum_{i=0}^{n} (\Delta\xi_i)^2]^{1/2} \qquad (13)$$

($\Delta\xi = \xi_i^* - \xi_i$ is the ith deviation of the value of the meteorological parameter ξ_i^* obtained by interpolation from its measured value ξ_i, and n is the number of the used realizations), as well as by the relative error determined by the formula

$$\Theta_\xi = \delta_\xi / \sigma_\xi \; ,\% \; , \qquad (14)$$

where σ_ξ is the rms error that characterizes the natural variability of the meteorological parameter.

It should be added that first the estimation of the accuracy of objective analysis was carried out for the case of the 3D, but not 2D type of interpolation of the temperature and wind fields, because the results of this analysis should be used for solving the problems of diagnostics of the spatial spread of technogenic pollutants. According to Ref. 16, in this case we deal not with the data on temperature and wind at separate levels, but with their averages over some vertical layers of the atmosphere. The procedure of such averaging of temperature T and wind velocity components V_x and V_y is based on the relations of the form

$$<\xi>_{h_0,h} = \frac{1}{h - h_0} \int_{h_0}^{h} \xi(z) \, dz, \qquad (15)$$

where z is the height, and the sign $<\bullet>$ means the procedure of averaging the data over vertical direction in some layer of the atmosphere. In our case it is the layer $h - h_0$, where h is the height of the upper boundary of the layer considered, and h_0 is the height of the lower boundary of the layer, which usually coincides with the ground level.

The following layers were considered in calculating the mean values: 0–100, 0–200, 0–400, 0–800, 0–1200, and 0–1600 m. To obtain the values of temperature and wind velocity at the initial heights 0, 100, 200, 400, 800, 1200, and 1600 m, which fully cover the boundary layer of the atmosphere, we preliminary used the procedure of linear interpolation of the meteorological parameters from isobaric surfaces and specific levels to the above geometrical heights.

3. Results of numerical experiments on estimation of the accuracy of alternative methods of the 3D objective analysis of temperature and wind fields

Let us consider the results of numerical experiments on estimation of the accuracy of the objective analysis carried out using, as an example, the temperature and wind fields by use of the method of optimal interpolation and the complex method based on integration of the MMCA and MOI algorithms.

To estimate the accuracy of the alternative methods, we used the long-term (1971–1975) radiosonde data obtained at five aerological stations: Warsaw (52°11′N, 20°58′E), Kaunas (54°53′N, 29°53′E), Brest (52°07′N, 23°41′E), Minsk (53°11′N, 27°2′E), and L'vov (49°48′N, 23°57′E), which form typical mesometeorological polygon (its pattern is shown in the Figure 1). The station in Brest was accepted as a control point r_0, and the total size of synchronized measurements at the neighboring stations r_i is 360 realizations in winter and 380 in summer.

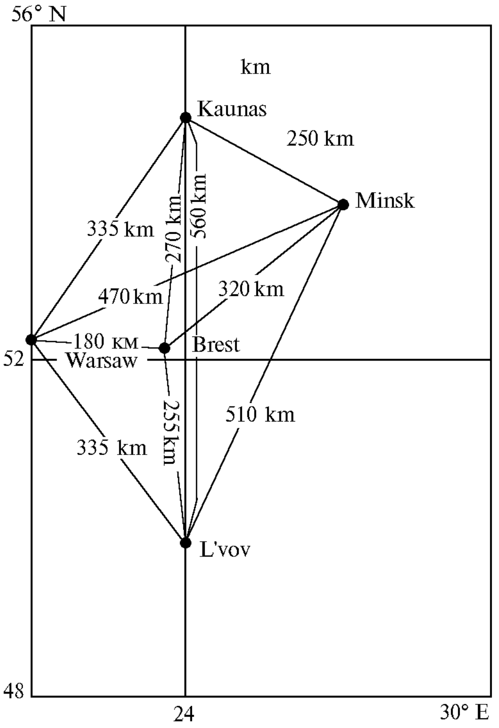

Fig. 1. Pattern of a typical mesometeorological polygon.

As the principal transfer of technogenic pollutants in big cities and their vicinities occurs in the lower layer of the atmosphere,[17] to examine the accuracy of the methods used for objective analysis, we took the results of the estimation in two atmospheric layers, up to 100 m, where the role of the peculiarities of the underlying surface is significant and leads to a noticeable decrease (in comparison with the free atmosphere) of the size of the areas of local homogeneity of temperature and wind fields,[7] and the layer up to 800 m where its effect becomes significantly weaker.

The numerical experiments on estimating the accuracy of the alternative methods of the objective analysis of the mesoscale fields of mean temperature $<T>_{h_0,h}$, mean zonal, $<V_x>_{h_0,h}$, and meridional, $<V_y>_{h_0,h}$, wind allowed us to reveal (see Table 1) that:

– the complex algorithm of objective analysis based on the procedure of integration of MMCA with the method of optimal filtration is sufficiently accurate and effective, because the value of the relative error (θ) in temperature at the control point r_0 is about 18–42% and the error in wind velocity components is 35–54% independently of season. It is significantly less than the limit for maximum permissible value from the standpoint of the statistical forecast (θ_0 = 66%);

– the complex algorithm significantly refines (in comparison with the method of optimal interpolation) the quality of the 3D objective analysis of mesoscale fields of temperature, zonal and meridional wind. Indeed, it is seen in Table 1 that the rms error in objective 3D analysis of the considered fields at the control point r_0 carried out by means of the complex algorithm is significantly less (by 1.4–2.4 times) than the analogous errors obtained by the method of optimal interpolation.

Table 1. Rms (δ) and relative (θ, %) errors in objective 3D analysis of the fields of temperature, zonal and meridional wind carried out on the basis of the complex algorithm (1) and the method of optimal interpolation (2)

Layer of the atmosphere, m	Winter				Summer			
	δ		θ		δ		θ	
	1	2	1	2	1	2	1	2
	Temperature T, °q							
0–100	1.4	2.5	29	53	0.8	1.9	18	43
0–800	1.6	2.2	38	51	1.6	2.2	42	59
	Zonal wind V_x, m/s							
0–100	1.5	2.5	39	63	1.6	2.5	44	69
0–800	2.0	2.9	38	55	1.8	2.7	35	52
	Meridional wind V_y, m/s							
0–100	1.8	2.7	52	76	1.7	2.6	54	84
0–800	2.1	3.1	45	66	2.0	2.9	45	66

All this is the evidence of the fact that the complex algorithm provides quite an acceptable accuracy of construction of the considered mesometeorological fields. Moreover, it provides more reliable results than the method of optimal interpolation. Hence, it follows from the above said that this algorithm is better for use in the 3D objective analysis of mesoscale fields of temperature and wind in the interests of numerical forecasting of the level of pollution of the atmosphere on a limited area (for example, a big city or an industrial center).

4. Accuracy of objective 4D analysis of mesoscale fields of temperature and wind at different intervals of the time advance

Along with the ecological diagnostics, the problem on forecasting the processes of pollution of the atmosphere at the local level is also very important in ecological monitoring of a limited air basin.

In this case, for providing a meteorological support for the solution of this problem, it is necessary to preliminary carry out objective 4D analysis of mesoscale fields of temperature and wind. So the problem arises on numerical estimation of the quality of the complex technique (let us remind that it is based on three methods, MOI, MMCA, and the optimal extrapolation of a random process).

Taking into account this fact, we have carried out numerical experiments on estimation of the accuracy of a refined complex algorithm applied to objective 4D analysis of mesoscale fields of temperature and wind. It was performed for different advance times $\tau = 12, 24, \dots, 60$ hours.

As to the 3D objective analysis, in this case we used the same bulks of radiosonde data obtained at 5 aerological stations, which form a typical mesometeorological polygon (Fig. 1).

The results of statistical estimation of the quality of the complex technique used for 4D analysis of mesoscale fields of temperature and wind at different advance times are given in Tables 2 and 3. The rms (δ) and relative (θ, %) errors were accepted as characteristics of the accuracy. As the estimate of accuracy of the complex technique of objective 4D analysis was performed for the first time, the errors of this analysis are shown for all considered layers of the atmosphere.

Table 2. Rms (δ) and relative (θ, %) errors in objective 4D analysis of the mesoscale fields of temperature, zonal and meridional wind calculated for different advance time (τ). Winter

Layer of the atmosphere, m	Advance time (τ), hour									
	12		24		36		48		60	
	δ	θ	δ	θ	δ	θ	δ	θ	δ	θ
	Temperature T, °q									
0–100	1.2	26	1.2	26	1.5	32	2.0	43	2.7	57
0–200	1.3	28	1.3	28	1.6	35	2.1	46	2.8	61
0–400	1.3	30	1.3	30	1.6	36	2.2	50	2.8	64
0–800	1.4	33	1.4	33	1.7	40	2.3	53	2.9	67
0–1200	1.6	39	1.6	39	1.8	44	2.4	58	3.0	73
0–1600	1.8	43	1.8	44	2.0	49	2.5	61	3.2	78
	Zonal wind V_x, m/s									
0–100	1.8	46	1.9	49	2.4	62	2.8	72	3.3	85
0–200	1.8	45	1.9	48	2.4	60	2.8	70	3.3	83
0–400	1.9	40	1.9	40	2.5	53	3.0	64	3.5	74
0–800	2.0	37	2.0	37	2.7	51	3.3	62	3.9	74
0–1200	2.1	37	2.1	37	2.7	48	3.5	62	4.1	73
0–1600	2.2	38	2.2	38	2.8	48	3.7	64	4.3	74
	Meridional wind V_y, m/s									
0–100	2.0	57	2.0	57	2.6	72	3.0	86	3.1	89
0–200	2.0	57	2.0	57	2.6	72	3.0	86	3.1	89
0–400	2.1	51	2.1	51	2.7	66	3.2	78	3.4	83
0–800	2.3	49	2.4	51	2.9	61	3.5	74	3.8	81
0–1200	2.3	45	2.4	47	3.0	59	3.7	73	4.1	80
0–1600	2.4	44	2.5	46	3.1	57	4.0	74	4.4	81

From analysis of data given in Tables 2 and 3, one can draw the following conclusions:

a) the complex technique when used in objective analysis in combination with the method of optimal extrapolation of a random process provides for quite an acceptable accuracy (θ of about 32–63%) of 4D construction of mesoscale fields of temperature and wind velocity components at the advance time 36 and 24 hours, respectively;

b) the complex refined algorithm provides the best results of objective 4D analysis of temperature field in winter, when the relative error in such analysis is significantly less than the maximum permissible one (for statistical forecast) equal to 66% even at the advance time of 48 hours, independent of the layer of the atmosphere.

Table 3. Rms (δ) and relative (θ, %) errors in objective 4D analysis of the mesoscale fields of temperature, zonal and meridional wind calculated for different intervals of advance time (τ). Summer

Layer of the atmosphere, m	Advance time (τ), hour									
	12		24		36		48		60	
	δ	θ	δ	θ	δ	θ	δ	θ	δ	θ
	Temperature T, °q									
0–100	1.1	24	1.2	27	1.6	36	2.2	49	2.5	56
0–200	1.2	27	1.3	30	1.7	40	2.3	53	2.6	59
0–400	1.2	29	1.3	32	1.8	44	2.4	58	2.7	66
0–800	1.3	32	1.3	32	1.9	48	2.6	65	2.9	72
0–1200	1.4	38	1.4	38	2.0	54	2.6	70	2.9	78
0–1600	1.5	42	1.6	44	2.1	58	2.6	72	2.9	80
	Zonal wind V_x, m/s									
0–100	1.8	47	1.9	50	2.2	58	2.4	63	2.8	74
0–200	1.8	45	1.9	48	2.2	55	2.5	62	2.9	72
0–400	1.9	41	2.0	43	2.3	50	2.6	57	3.1	67
0–800	2.1	40	2.1	40	2.5	48	2.8	55	3.5	67
0–1200	2.1	40	2.1	40	2.5	48	2.9	55	3.6	68
0–1600	2.2	41	2.2	41	2.6	49	3.0	57	3.7	70
	Meridional wind V_y, m/s									
0–100	2.1	63	2.1	63	2.4	73	2.8	85	3.2	97
0–200	2.2	62	2.2	62	2.5	71	2.9	83	3.3	94
0–400	2.2	55	2.2	55	2.6	65	3.0	75	3.4	85
0–800	2.3	52	2.3	52	2.7	64	3.1	70	3.6	82
0–1200	2.3	53	2.3	53	2.7	63	3.1	72	3.6	84
0–1600	2.4	57	2.4	57	2.8	67	3.2	76	3.7	88

Thus, the numerical estimate of the quality of a complex technique combined with the method of optimal extrapolation of a random process is an evidence of the possibility and sufficient efficiency of its use in 4D objective analysis of mesoscale fields of temperature and wind, but within a limited advance time of 36 and 24 hours, respectively. Hence, it follows that this technique can be applied to preparation of the forecast of spatially distributed parameters (such as temperature and wind velocity components), which are related to the parameters of the models of transfer of an admixture and are necessary for numerical forecast of the level of pollution of the atmosphere over a limited area, especially under the conditions of emergency emissions.

References

1. P.N. Belov, *Practical Techniques for Numerical Forecast of Weather* (Gidrometeoizdat, Leningrad, 1967), 335 pp.
2. V.A. Gordin, *Mathematical Problems in Hydrodynamic Forecast of Weather* (Gidrometeoizdat, Leningrad, 1987), 264 pp.
3. V.S. Komarov, S.A. Soldatenko, and O.M. Sobolevskii, Atmos. Oceanic Opt. **9**, No. 4, 278–281 (1996).

4. P.N. Belov, E.P. Borisenkov, and B.D. Panin, *Numerical Methods for Weather Forecast* (Gidrometeoizdat, Leningrad, 1989), 376 pp.

5. M.E. Berlyand, *Forecast and Regulation of the Atmospheric Pollution* (Gidrometeoizdat, Leningrad, 1985), 272 pp.

6. P.N. Belov and V.S. Komarov, Atmos. Oceanic Opt. **8**, No. 7, 519–522 (1995).

7. L.S. Gandin and R.L. Kagan, *Statistical Methods for Interpolation of Meteorological Data* (Gidrometeoizdat, Leningrad, 1976), 359 pp.

8. V.S. Komarov, *Statistics as Applied to the Problems of Applied Meteorology* (Publishing House of SB RAS, Tomsk, 1997), 225 pp.

9. V.S. Komarov and A.V. Kreminskii, Atmos. Oceanic Opt. **9**, No. 4, 262–268 (1996).

10. V.S. Komarov and Yu.B. Popov, Atmos. Oceanic Opt. **11**, No. 8, 686–691 (1998).

11. V.S. Komarov, V.I. Askelevich, and A.V. Kreminskii, Atmos. Oceanic Opt. **7**, No. 2, 121–124 (1994).

12. D.I. Kazakevich, *Principles of the Theory of Random Functions and Their Application to Hydrometeorology* (Gidrometeoizdat, Leningrad, 1977), 319 pp.

13. S. Panchev, *Random Functions and Turbulence* (Gidrometeoizdat, Leningrad, 1967), 447 pp.

14. V.S. Komarov, A.V. Kreminskii, N.Ya. Lomakina, and G.G. Matvienko, Atmos. Oceanic Opt. **9**, No. 4, 344–347 (1996).

15. I.A. Chetverikova, Trudy CIP, issue 102, 3–12 (1962).

16. F.F. Bryukhan, *Methods for Climatic Processing and Analyzing the Aerological Data* (Gidrometeoizdat, Leningrad, 1983), 112 pp.

17. A.M. Vladimirov, Yu.N. Lyakhin, L.T. Matveev, and V.T. Orlov, *Preservation of Environment* (Gidrometeoizdat, Leningrad, 1991), 423 pp.